Fusion Nuclear Science Facility (FNSF) Overview, Physics Assumptions and Operating Space

C. E. Kessel and the FESS Team


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 must fill the tremendous gap between ITER and DEMO by providing the break-in to the fusion nuclear regime.

First strongly burning plasma

<table>
<thead>
<tr>
<th>ITER</th>
<th>FNSF</th>
<th>DEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max damage</td>
<td>3 dpa</td>
<td>37-74 dpa</td>
</tr>
<tr>
<td>Max plasma pulse</td>
<td>500-3000s</td>
<td>1-15 days</td>
</tr>
<tr>
<td>TBR</td>
<td>~ 0</td>
<td>~ 1.0</td>
</tr>
<tr>
<td>T_{blanket}, T_{cool,exit}</td>
<td>285C, 150C</td>
<td>550C, 650C</td>
</tr>
<tr>
<td>Materials</td>
<td>316SS, CuCrZr, Be, W, H_2O, SS304, SS430</td>
<td></td>
</tr>
</tbody>
</table>

Demonstrate routine Power Plant Ops

No technical gaps

Power Plant
A nearer term facility like the FNSF requires a number of technical philosophies/approaches to be defined/explored

**Facility missions and metrics** – what progress does the facility make on the pathway to a power plant

**Physics strategy** – how do we choose plasma parameters, what’s their impact

**Long term power plant relevance** – design choices are made to keep the scientific/technology development on track, avoid diversions that do not contribute to the power plant vision

- Minimal, Moderate, and Maximal FNSF

**Qualification requirements to install a component/material in the FNSF** – fusion neutron exposure to the dpa level, highly integrated non-nuclear testing....*plasma-vacuum systems are not consistent with “cook and look” approach to FNS, remote-maintenance*

**FNSF program plan** – phases, material/temperature/dpa evolution, operation and maintenance

**Blanket (divertor/launchers) choices and testing strategy** – provide the process by which we test and advance fusion core components, and backups

**Hot Cell** – how do we access and process the information from the FNSF operation

**Pre-FNSF R&D** – how do we see the R&D evolution to prepare us for the FNSF, design and operation
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 $\beta_N \leq \text{no wall limit}$ to accomplish mission, but install appropriate feedback or other capability to exceed no wall limit by how much?

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

Operate below the Greenwald density limit $n/n_{Gr} < 1$, 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

Peak heat flux tolerated in the divertor $< 10 \text{ MW/m}^2$, 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>$\sim 60%$</td>
<td></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>
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<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>1.5</td>
<td>$\sim 1.0$</td>
<td>1.4</td>
<td></td>
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</tr>
</tbody>
</table>

- $\sim$ steady state
- steady state

**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**
A = 4

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

\langle j_{TF} \rangle = 15 \text{ MA/m}^2
f_{\text{div,rad}} = 90\% (\lambda_{\text{pow}}^{\text{Fundamenski}})

Filters for solutions
\beta_N \leq 2.6^*
q_{\text{div,peak}} \leq 10 \text{ MW/m}^2
N_{\text{w,peak}} \geq 1.5 \text{ MW/m}^2
B_T^{\text{coil}} \leq 16 \text{ T (LTSC)}

IB Radial build from neutronics:
\Delta_{\text{FW/blkt}} = 50 \text{ cm}
\Delta_{\text{SR}} = 20 \text{ cm}
\Delta_{\text{VV}} = 10 \text{ cm}
\Delta_{\text{LT shield}} = 23 \text{ cm}
\Delta_{\text{gaps}} = 20 \text{ cm}

*examining benefits of RWM feedback to raise this toward 2.8-3.2
The FNSF Would Be Smaller Than a DEMO Plant, to Reduce Cost and Facilitate a Break-in Program

Configuration for the FNSF study:

- Conventional aspect ratio (= 4)
- Conservative tokamak physics basis with extensions to higher performance ($\beta_N < 2.6$)
- 100% non-inductive plasma current
- Low temperature superconducting coils, advanced Nb$_3$Sn
- Helium cooling in blanket, shield, divertor, and vacuum vessel
- Focus on DCLL blanket concept with backup concepts (HCLL, HCCB/PB)
- Net electricity is NOT a facility target, but electricity generation can be demonstrated
What is the actual maximum heat flux tolerable in the divertor, what can be developed from engr design and plasma physics optimization

Our present assumption for the peak allowed divertor heat flux is 10 MW/m².

This represents the maximum capability of the plate jet divertor design....beyond this the thimble jet design is usually required.

To achieve this we know that Engineering design Plasma material interactions Divertor/SOL plasma physics are all required to reach a solution.

What if we can not reach the 10 MW/m² that we desire.....

Taking a radiating divertor as the reference for FNSF

\[ \beta_N \leq 2.6 \]
\[ B_T \leq 16 \, T \]
\[ f_{div,rad} = 0.9 \]

\[ q_{div}^{\text{peak}} \leq 10 \, \text{MW/m}^2 \]
\[ q_{div} \leq 7.5 \, \text{MW/m}^2 \]
\[ q_{div} \leq 5.0 \, \text{MW/m}^2 \]

\[ f_{div,rad} = 0.95 \]

\[ R = 4.8 \, \text{m} \]
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.

2D SOL analysis indicates:
- Fully detached radiates $\sim 100$
- ITER-like divertor radiates $\sim 75$

$$\beta_p < 2.6$$
$$B_T^{\text{coil}} < 16 \text{T}$$
$$q_{\text{div,peak}} < 10 \text{MW/m}^2$$

$$H98(y,2)$$ energy confinement multiplier

Greenwald density ratio, $n/n_{\text{Gr}}$

Fusion power, MW

Auxiliary power, MW

Peak divertor heat flux, MW/m$^2$

Average neutron wall load at plasma, MW/m$^2$
<table>
<thead>
<tr>
<th></th>
<th>He/H</th>
<th>DD</th>
<th>DT</th>
<th>DT</th>
<th>DT</th>
<th>DT</th>
<th>DT</th>
<th>Power Plant</th>
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<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yrs</td>
<td>1.5</td>
<td>2-3</td>
<td>2.5</td>
<td>4.2</td>
<td>4.2</td>
<td>5.9</td>
<td>5.9</td>
<td>40 FPY</td>
</tr>
<tr>
<td>Neutron wall load, MW/m²</td>
<td>1.78</td>
<td>1.78</td>
<td>1.78</td>
<td>1.78</td>
<td>1.78</td>
<td>1.78</td>
<td>1.78</td>
<td>2.25</td>
</tr>
<tr>
<td>Plasma on-time, % /year</td>
<td>10-25</td>
<td>10-50</td>
<td>15</td>
<td>25</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>85</td>
</tr>
<tr>
<td>Plasma pulse length, days</td>
<td>Up to 10</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>310</td>
</tr>
<tr>
<td>Plasma duty cycle, %</td>
<td>33-95</td>
<td>33</td>
<td>67</td>
<td>91</td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>100</td>
</tr>
<tr>
<td>Neutron damage, dpa</td>
<td></td>
<td></td>
<td>7</td>
<td>19</td>
<td>26</td>
<td>37</td>
<td>37 or 74</td>
<td>100-150</td>
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<tr>
<td>blanket</td>
<td>RAFM 400C</td>
<td>RAFM 400C</td>
<td>RAFM 400C</td>
<td>RAFM ODS 450C</td>
<td>RAFM ODS (NS) 500C</td>
<td>RAFM ODS (NS) 5500C</td>
<td>RAFM ODS (NS) 5500C</td>
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Plasma pulse extension 1 hr to 10 days

23 years of DT operations, 8.4 years of neutron exposure Higher $N_W$, faster plasma pulse development, and efficient maintenance/plasma operation distribution can reduce years
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, utilize higher diagnostic coverage

2) Provide higher or lower neutron wall loads would result in short or longer years to reach a dpa level

3) Low operating temperatures of the early DT phases require BOTH faster coolant flow and lower fusion power, longer time to reach dpa target

4) Desire to reach longest plasma durations early in the program, rather than spend the whole program progressively extending the plasma pulse length...still arriving at ~7 dpa at the end of the phase

5) Maintenance times associated with specific tasks (planned maintenance)
   Ex-vessel inspection
   In-vessel inspection
   Minor maintenance ex-vessel
   Minor maintenance in-vessel
   Major in-vessel maintenance (sector removal, 16 sector removal)
   → This should lead to a reduction in total operations time
Components in fusion core would be evolved and tested in the FNSF

We have concentrated on the blankets, but there are others that may have a testing sequence.....materials, temperatures, design, etc.
# Blanket Testing

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

- DCLL 400C RAFM/ **H&CD**
- DCLL 450C RAFM (higher T)
- DCLL 450C RAFM GIi (next phase T and FS)

**DCLL 400C RAFM/ MTM**

- DCLL 400C RAFM/ **TBM-HCLL**
- DCLL 400C RAFM/ **TBM-HCCB(PB)**

**DCLL 400C RAFM/ Diagnostic**

<table>
<thead>
<tr>
<th></th>
<th>Phase X – part 1</th>
<th>Phase X – part 2</th>
<th>Phase X – part 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
</tr>
<tr>
<td>S-2</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
</tr>
<tr>
<td>S-3-H/CD*</td>
<td>DCLL 400C RAFM – LH/EC</td>
<td>DCLL 400C RAFM – LH/EC</td>
<td>DCLL 400C RAFM – LH/EC</td>
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<tr>
<td>S-4-MTM*</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
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<tr>
<td>S-5</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
</tr>
<tr>
<td>S-6</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
</tr>
<tr>
<td>S-7</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
</tr>
<tr>
<td>S-8</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
<td>DCLL 400C RAFM</td>
</tr>
<tr>
<td>S-9</td>
<td>DCLL 450C RAFM</td>
<td>DCLL 450C RAFM</td>
<td>DCLL 450C RAFM</td>
</tr>
<tr>
<td>S-10-H/CD</td>
<td>DCLL 400C RAFM – NB</td>
<td>DCLL 400C RAFM – NB</td>
<td>DCLL 400C RAFM – NB</td>
</tr>
<tr>
<td>S-11-H/CD</td>
<td>DCLL 400C RAFM - IC</td>
<td>DCLL 400C RAFM - IC</td>
<td>DCLL 400C RAFM - IC</td>
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<td>S-12</td>
<td>DCLL 450C RAFM</td>
<td>DCLL 450C RAFM</td>
<td>DCLL 450C RAFM</td>
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<td>S-13-H/CD</td>
<td>DCLL 400C RAFM - NB</td>
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<td>S-14</td>
<td>DCLL 450C RAFM</td>
<td>DCLL 450C RAFM</td>
<td>DCLL 450C RAFM</td>
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<tr>
<td>S-15-TBM/HCCB</td>
<td>DCLL 400C RAFM / HCCB</td>
<td>DCLL 400C RAFM / HCCB</td>
<td>DCLL 400C RAFM / HCCB</td>
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<tr>
<td>S-16-TBM/HCLL*</td>
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<td>DCLL 400C RAFM / HCLL</td>
<td>HCLL 400C RAFM / HCLL</td>
</tr>
</tbody>
</table>
Divertor Testing, must fit into the allocated envelope

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

Will there be variants like RAFM?
Structure & armor

Magnetic geometries
Temperature ranges

Taken from Snead, 2016

W/RAF laminate (Garrison)
X-divertor, KDEMO Covelle, Univ Texas
FZJ

WC in Fe matrix (Álvarez et al., 2015)

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

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*
The Hot Cell – a critical aspect of the FNSF

The performance of materials in the components of the fusion core is not accessible prior to the FNSF

*What is accessible:* 1) DONES/IFMIF or similar fusion relevant neutron exposure, 2) fission neutron, ion and doping approaches testing, 3) non-nuclear highly integrated component testing.....*would we proceed if #1 was missing?*

The in-service conditions include more than neutrons and temperature (like IFMIF)

- Materials are under stress (pressure)
- Materials have hydrogen in their matrix, tritium and transmutation hydrogen
- Materials have contact with liquid metal in B-field (MHD, other flow properties, chemical reactions)
- Materials see strong neutron damage, and He production gradients into material
- Materials see heating, temperature and stress gradients

The sectors of the fusion core will be removed to determine property changes, surface changes, microstructure changes.....*this is done in the Hot Cell, and will produce the database upon which DEMO can be based*

*we need to make decisions about the materials/components behavior for next phases based on this information in the FNSF itself.....turnaround must be fast, materials will be HOT (radioactive)*
The Complex Variations of the Service Environment in a Blanket

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

H. Tanigawa, E. Wakai 2012
Pre-FNSF: Fusion Nuclear Materials Science, how do we see providing tested materials in the form of components to the FNSF

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

DD | DT | FNSF
7 dpa | 19 dpa | 26 dpa | 37 dpa | 37-74 dpa

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-1 development
Pre FNSF bainitic development
Pre FNSF tungsten-1 development
Pre FNSF tungsten-2 development

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

- SOL plasma experiments/diagnostics
- Divertor plasma experiments/core coupling
- Tokamaks
- SOL/divertor plasma simulations
- Plasma science
- Plasma material interaction/linear/ultra-long duration
- Plasma material interactions/tokamak/short pulse
- PMI science
- 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

Establish “translation” of linear results to tokamaks

Testing of PFC candidates in linear and tokamak facilities

Materials science and PFC component development
The FNSF is the Critical First Step into the Fusion Nuclear Regime and Fusion Power Production

The complex step of combining the fusion neutron, multi-factor environment, and integrated components requires the appropriate technical platform \( \rightarrow \text{this demands a smaller intermediate device step} \)

Explore the component material responses to the complete/correct FUSION environment

Establish the ultra-long plasma pulse length with associated plasma material interactions

Establish the credibility of generating tritium, predicting/controlling its movement and retention, and minimizing its losses plantwide

Strongly advancing most features toward a fusion power plant, with significant fusion relevance imposed in our technical choices

Understand the demands on the facility (hot cell, maintenance, diagnostics) to provide the needed measurement, inspection, access, and feedback on plasma and fusion core operations
TUESDAY 1:15 PM

L. El-Guebaly, Overview of Nuclear Analysis for US Next Step Facility
J. Blanchard, Effects of ELMs and Disruptions on FNSF Plasma Facing Components
L. Garrison, The Influence of Microstructure on Deuterium Retention in Polycrystalline Tungsten...poster Monday

Poster Tuesday, Y. Zhai, Modeling Imperfect Nb3Sn SC Wire Under Transverse Loading

WEDNESDAY 8:50 AM

P. Titus, IN-Plane and Out-of-Plane TF Coil Support for the US FNSF Reactor
A. Davis, Overview of State-of-the-Art Neutronics Code Development...poster Monday

WEDNESDAY 10:30 AM

P. Humrickhouse, Safety in the Fusion Nuclear Science Facility

THURSDAY 10:15 AM

Y. Katoh, Progress in US/JA PHENIX Project for the Technical Assessment of Plasma Facing Components for DEMO Reactor