Critical FNS Activities Required Over the Next Decade to Establish the Scientific Basis for a FNSF


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Context for the FNSF and Pre-Requisite Research

The Fusion Nuclear Science Facility (FNSF) is part of the US fusion development view, and is the first strongly fusion nuclear confinement facility.

The FNSF is an intermediate step to accommodate the extreme fusion nuclear environment and the complex integration of components and their environment, and the nuclear science and plasma physics.

The FNSF will operate with
- a very long pulse fusion neutron producing plasma and very high duty cycles,
- with completely integrated components first wall, blanket, shield, vacuum vessel, divertor, etc.,
- in the fully integrated environment (simultaneous) of fusion neutrons, volumetric and surface heating, hydrogen in materials, strong magnetic fields, pressure/stresses, high temperatures, vacuum interface with plasma, flowing breeder with material interactions, and PMI, all with significant gradients.

The FNSF is itself, a materials testing platform in the complete fusion environment.
Present and near term confinement devices, short pulse → to long pulse

Pre-FNSF R&D
- Fusion neutron material test facility, fission testing
- Liquid metal flow/corrosion/thermal/hydrogen facility(s)
- Tritium (hydrogen) extraction/permeation/handling facility(s)
- Magnet conductor/insulator/coil testing facility(s)
- Linear plasma/HHF/plasma loading simulator PFC facility(s)
- Heating/current drive, diagnostic, plasma fueling/exhaust test facilities

Parallel FNSF R&D
- Increasing integration
- Optimization/exploration

Integrated expt/theory, predictive computational development for physics and engineering

Facilities and Time-Scales
- ITER
- Non-DT, TBM
- DT, TBM
- FNSF
- DD, DT
- Pre-FNSF R&D
- Parallel FNSF R&D
- DEMO
Evolution of Fusion Nuclear Material Science Activities Leading Up to the FNSF

2015
- single-few effects
  - Fusion neutrons
  - Tritium
  - Liquid metal breeder
  - Plasma-material

2025
- partial integration expts
  - Accelerator based facilities
  - Linear Plasma & Tokamaks & Offline

2035
- maximum integration expts
  - Integration of FW/blanket
  - Fusion Nuclear Science Facility
  - Early DD phase of FNSF
  - Fusion neutron and integrated component testing facilities continue to operate in parallel with the FNSF

Aggregate of smaller materials focused facilities addressing 4 major areas
Integration facilities addressing blanket, divertor, and special components in non-nuclear environment
The Material and Fusion Nuclear Science are Driven by Four Primary Thrusts

1 - Fusion neutrons, are highly energetic particles that produce significant damage and transmutations (generating helium and hydrogen in solids) in all materials

**ACTION:** Pursue strategy for accelerator/target platform(s) to test materials with fusion relevant neutrons, in US and in coordination with international efforts, to address the multi-decade fusion materials development required to design, construct and operate the FNSF, and to continue to evolve toward higher neutron exposures on the FNSF and beyond.

2 - Tritium is a highly mobile radioactive isotope, which is produced in large quantities to provide the DT fuel, however, it will migrate throughout the fusion core of peripheral systems in the plant

**ACTION:** Build and operate small scale experiments on critical tritium issues, moving rapidly to more integrated tritium assemblies (T source, T permeation, T extraction, plasma T implantation, high temp...utilizing TPE and other facilities in STAR at INL, ultimately being part of an integrated non-nuclear blanket testing facility

Deuterium would likely serve as a surrogate for most of this research, although tritium would be examined in critical areas such as extraction
The Material and Fusion Nuclear Science are Driven by Four Primary Thrusts

3 - Liquid metal breeder, primarily Li$_{16}$Pb$_{84}$, is the tritium breeding material, but is a electrically conducting fluid moving through a strong magnetic field

**ACTION:** Build and operate small scale experiments on critical liquid metal breeder issues including

- PbLi constituency control with impurities and gases;

- Material interactions of PbLi with RAFM, SiC composites, coatings with varying temperature, flows and B-fields;

- PbLi flow assembly for complex 3D thermo-fluid behavior (MHD) at high temperatures, B-fields, with appropriate material contact utilizing MaPLE at UCLA; then moving to higher flow rates, higher temperatures, higher B-fields and larger magnetized test volumes

- PbLi safety science.....

Ultimately being part of an integrated non-nuclear blanket testing facility
The Material and Fusion Nuclear Science are Driven by Four Primary Thrusts

4 - **Plasma Material Interactions** on the **Plasma Facing Components**, in the ultra-long pulses envisioned for the FNSF, will produce unprecedented material evolution

Existing and *Possible* Facilities include:

- Linear plasma simulators,
- Existing and planned tokamaks, stellarators
  - US tokamaks (~5-10 s)
  - Long pulse tokamaks (~100-1000s)
  - ITER (~500-3000s)
- High Heat Flux facilities
- Liquid Metal PFC testing
- PFC/PMI facility
- DD Phase of the FNSF (~hours to days to weeks)

**ACTION:**

- Understanding the SOL-divertor plasma, and associated plasma material interactions and coupling to core plasma...existing tokamaks
- Begin to observe the long pulse issues of erosion/redep/migration, dust, and tritium retention....long pulse tokamaks and ITER, W7X, LHD
- Consult FESAC report on Opportunities for Fusion Materials Science and Technology Research (Zinkle), section 3.2, near, medium and long term.
Fusion Neutrons will Produce New Damage Regimes Compared to Fission

Before the FNSF, we expect to only have fusion relevant neutron irradiation of single materials, in combination with fission neutron exposure

→ Presently the US has no program to provide this testing platform to develop the materials database required for a FNSF

HOWEVER, fusion neutrons are difficult to produce, accelerators/targets are used to produce high energy neutrons in the fusion range, beyond the fission neutron energies

Criteria have been established for what is desired by such a facility

- Irradiation volumes
- Neutron flux, damage rate
- Damage, helium/damage, hydrogen/damage
- Availability
- Flux gradients,...

This research requires years to accumulate relevant neutron exposures, it requires iteration with multiple materials, temperatures, and material modifications/developments

Can we take advantage of a global network of accelerators/targets?

Accelerators/targets are outside FES (BES, HEP, NNSA)
Tritium Does Not Need a Crack, Hole or Gap to Move Around, It Moves Right Thru Solids

Tritium will be consumed (and produced) at a rate of $55.6 \text{ kg/GW}_{\text{fusion}}/\text{FPY}$ (full power year), while the average amount released by fission plants is $< 0.07 \text{ g/year/reactor}$.

The tritium injected into the plasma chamber, and exhausted is $\sim 10x$ larger than the $55.6 \text{ kg/GW}_{\text{fusion}}/\text{FPY}$ consumption, since the fraction of tritium burned is $\sim 10\%$.

Experimental facilities are needed to address many issues associated with tritium behavior from tritium extraction from the breeder, to tritium behavior through multi-materials interfaces, to tritium retention in dust in the plasma chamber.

The solubility of hydrogen in LiPb varies by at least 3 orders of magnitude.

Hydrogen retention in W matrix, similar to unirradiated.

Retention after irradiation in HFIR, produces higher energy traps.

The solubility of hydrogen in LiPb varies by at least 3 orders of magnitude.

State of the art database of hydrogen solubility in LLE.
Liquid Metal Breeders Will Demonstrate Complex Behavior

PbLi has advantages over pure Li liquid metal and solid breeders.

Our knowledge of the PbLi material is still immature to fully predict its behavior due to strong magnetic fields, flow, heating, and liquid-solid interactions.

Flowing liquid metal will experience 3D MHD effects, instabilities, buoyancy effects as it crosses and flows parallel to the magnetic field lines.

Interaction of RAFM and SiC with PbLi in a magnetic field at high temperatures, leads to new regimes.

Tritium interaction with helium bubbles, corrosion products and transmutations are unknown.

The properties of PbLi in the presence of these pollutants is also not known.

Smolentsev, UCLA
Plasma Facing Components Will Undergo Significant Surface Modification via PMI

Plasma facing components include the first wall, divertor, launching structures, and diagnostics.

The heat loading, particle loading, erosion, re-deposition, migration, implantation, tritium retention, and dust/debris production must all be understood to a level that allows the design of components for the ultra-long pulses of the FNSF.

Linear plasma simulators (like PISCES)
- High duty cycle and long exposures, multiple materials, variable plasma species, test irradiated samples

Tokamaks (NSTX-U, DIII-D, C-Mod)
- Correct magnetic and PFC geometries, coupled core-SOL-divertor, actual steady and transient plasma loading, able to examine advanced divertors

Offline facilities
- High Heat Flux facilities
- Liquid metal test facilities
- Dust/debris