Fusion Nuclear Science Research Thrust and the Required Full Fusion Nuclear Environment (FINAL – v6)

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Purpose and motivation of white paper

The purposes of this white paper are to identify example research thrusts in **Fusion Nuclear Science (FNS)**, and to describe the required R&D capabilities in a full fusion nuclear environment, aimed at closing the gaps in scientific knowledge between ITER and Demo in the Theme area of Harnessing Fusion Power, identified in the FESAC "Opportunities …" Report.

This gap in knowledge encompasses an extensive range of scientific disciplines of interest to the full nuclear environment of a fusion Demo. This environment is characterized by the simultaneous sustained presence of harsh fusion neutrons fluxes, increasing neutron fluences, a pervasive tritium distribution, high heat fluxes and temperatures, uncommon materials and their combinations, stringent safety requirements, and far-reaching capabilities in RAMI. This environment challenges many frontiers of science and technology, which inevitably creates new opportunities for scientific discovery, new learning, and innovation.

This environment equally challenges the scientific basis for all systems of interest to the Theme area of Taming the Plasma Material Interface.

FNS therefore deals with the "*Fusion 'Break-in' & **Scientific Exploration***" phase in a Component Test Facility (CTF), requiring at least a neutron fluence of ~0.3 MW-yr/m^2 [Abdou, Fusion Technol. **29** (1999) 1; Peng et al. paper FT/P3-14, Fusion Energy Conference 2008]. This phase is to be followed by the second and third phases of "***Engineering** Feasibility & Performance Verification*" and "*Component **Engineering** Development & **Reliability** Growth*", respectively. The latter two phases would require a total neutron fluence of ~6 MW-yr/m^2.

To begin the FNS R&D using a full fusion nuclear environment *for the first time*, up-to-date knowledge on fusion plasma science, enabling technology, and nuclear technology will be required to create this environment *in the first place*. This would begin the process to discover and understand the underpinning physical, chemical, and radiological properties, and to develop improved components, based on the new understanding, for further testing and discovery. A highly instrumented test environment would help validate predictive models for Demo. The FNS R&D phase would be completed when the new scientific knowledge gained becomes adequate to design and build Demo-capable components for testing in the succeeding phases of a CTF.

It is anticipated that the requirements to enable FNS R&D would be substantially reduced from those required to enable the second and third phases of R&D using a CTF. The purpose of this white paper is to provide an initial brief description of the FNS R&D requirements.

Example Gaps in Scientific Knowledge that Require a Full Fusion Nuclear Environment for Their Closure

It is helpful to identify example gaps in knowledge that will require for their closure a full fusion nuclear environment. Examples related to tritium are included here.

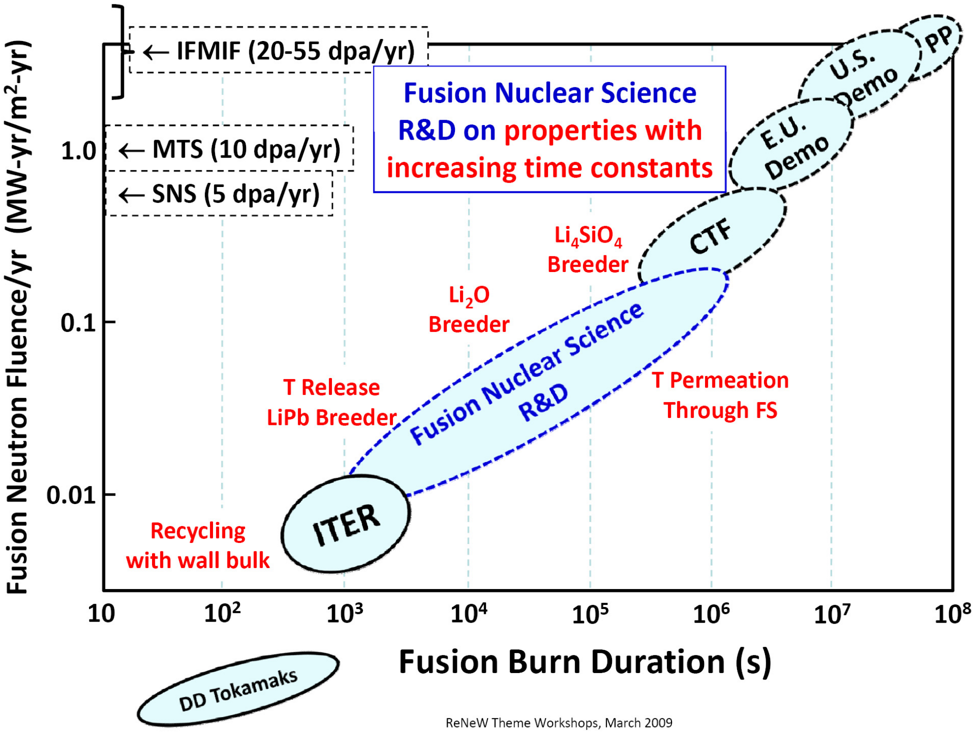
Fuel Cycle [B. Patton et al, white paper]: A scientific basis must be established to ensure that the tritium loss fraction from each cycle of tritium fueling, burn and collection in a full fusion nuclear environment, be much smaller than the tritium burn-up fraction per fuel cycle.

Power Extraction [G. Yoder et al, white paper]: A scientific basis must be established for extracting high grade from a power producing and tritium breeding blanket module while maintaining adequate tritium containment, extraction, and accountability in a full fusion nuclear environment.

Materials [details to be addressed in Materials Panel]: Tritium retention, transport, and permeation in the first wall and various blanket component materials, in the presence of intense fusion neutron irradiation and increasing density of transmutation products, must be understood to address the fuel cycle and safety issues.

Safety [K. Korsah et al, white paper]: The concentration and distribution of tritium on the surfaces of and in the material bulk of all the components and processing loops of a full fusion nuclear environment must be measured and determined with adequate tolerance to ensure compliance to tritium-related safety rules.
RAMI [T. Burgess et al, white paper]: The knowledge base for achieving high availability with short Mean-Time-To-Replace using tritium-accountable remote handling of a component must be tested in a full fusion nuclear environment before extending to Demo scale designs.
Neutronics [J. Wagner et al, white paper]: Advanced neutron transport simulation capabilities, coupled to nuclear transmutation codes, must be updated to enable accurate modeling of neutronic effects, transmutation products, and tritium inventories throughout the facility.

The FNS R&D requires an accumulated level of 3-5 dpa (0.3 – 0.5 MW-yr/m^2), which is within the materials damage data presently available from fission irradiation for fusion-relevant steel and copper, and may be feasible with adequate R&D for the design and construction of the required full fusion nuclear environment. Such an environment in principle can enable the study of materials properties of interest to Demo, under the simultaneous actions of neutron agitation, implanted tritium under the plasma-facing surface, high temperature and stress gradients, and an increasing level of material defects due to neutron damages. Burn durations of 10^3 s and eventually up to 10^6 s would enable studies, for example, of the rates of permeation through ferritic steel at high temperatures, in the full fusion nuclear environment. The following figure identifies example long time constant properties of interest, and relates the FNS R&D to other major components of fusion R&D program and future visions.



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Commonality in Knowledge Base for ST and Tokamak

The FESAC Toroidal Alternates Panel Report ascribed for Spherical Torus (ST) its R&D goal for the ITER era: to "*Establish the ST knowledge base to be ready to construct a low aspect-ratio fusion component testing facility that provides high heat flux, neutron flux, and duty factor needed to inform the design of a demonstration fusion power plant.*" The report further indicated the "*great commonality of underlying physics between the ST and the Tokamak*", and observed that the tokamak option provided an equally viable basis for a component testing facility. By inference, the tokamak option would provide an equally viable basis for FNS R&D.

The Report also identified for the ST four "Tier-1" issues (start-up, electron energy confinement, high heat flux, and magnets), where large gaps exist in this common knowledge base, and highlighted an urgent need to strengthen the theory, modeling and simulation predictive capabilities.

The discussions in this white paper therefore should apply equally to both the ST and the Tokamak applications to FNS R&D. The tradeoffs in aspect ratio in FNS R&D performance, cost and risk will require an assessment based on this common knowledge.

Required FNS R&D Capabilities of a Full Fusion Nuclear Environment

An **environment** aimed at testing and discovering the underlying physical properties of interest to fusion Demo must possess the following capabilities:

- Fusion neutron fluxes ranging from ~0.01 – 2 MW/m^2, depending on the physical processes of interest, which include such as the threshold to in-situ tritium monitoring at minimal level of tritium production, and the tritium permeation rates in ferritic steel as a function of weak to strong fusion neutron fluxes and fluences.
- Continuous operational durations that can be increased from 10^3 s progressively toward 10^6 s, to observe and measure a broad range of physical properties with increasing time constants of interest to the Demo knowledge base.
- Safe remote handling of test components (blankets, divertors, heating, current drive, fueling, measurement, and control systems) for removal to "remote handling laboratories" and replacement by new or improved components.
- Instrumentation of these components to measure in-situ physical properties of interest to Fuel Cycle, Power Extraction, Materials Properties, Safety, and RAMI.
- Irradiation of candidate fusion material specimens under precise temperature and environmental control to yield multi-parameter datasets for validation and verification of material and neutronics models and simulations.
- Safe remote handling laboratories with advanced manipulators and materials characterization instruments capable of scientific examinations at macro, micro, and nano scales of the physical properties of interest, under very high dose rates (up to ~10^6 Rem/hr) from activated components.
- A facility availability goal of 20-40% (1-2 times the ITER goal), and a remote handling capability to achieve adequate duty factor to allow effective progress in FNS R&D. It is likely that this duty factor goal should increase from ~ 1-2 percent (the ITER design goal) initially, toward ~10% near the completion of the FNS R&D phase.

A **Driven-Burn Plasma** that is consistent with the above requirements will also be required and can be characterized by:

- Disruption-free plasma operation for durations over the range of $10^3 – 10^6$ s. In the case of ST and Tokamak, the operating plasma parameters must be controlled from far to significantly below known MHD and operational stability limits in beta, safety factor, density, field errors, etc.,
- Robust control of plasma profiles using long time scale actuators such as heating, current driving, fueling, pumping, etc., to keep the plasma in a strongly stable regime free of disruptions.
- In the case of the ST and for the example of ~1 MW/m^2 in fusion neutron flux, ~8 MA in plasma current, and ~2 in fusion Q, the FESAC Toroidal Alternates Panel (TAP) identified the following 4 Tier-1 gaps that need closing to enable the FNS R&D.
    - Start-up and ramp-upof plasma current with no or minimal central solenoid induction [A. Sontag et al, white paper]
    - Electron energy confinement where the ion energy confinement is near the neoclassical value – In such regimes, and especially under preferential electron heating and/or at low collisionality, the electron channel can dominate the energy loss from the plasma. Knowledge of the scaling of electron confinement with B_T, I_p, P_{aux} and collisionality is crucial to extrapolating to the FNS regimes with confidence. Equally important is developing a fundamental understanding of the

  source of turbulence causing this anomalous electron heat loss, and its dependencies on collisionality and finite-beta (i.e., electrostatic vs. electromagnetic). It is clear that multiple mechanisms drive electron transport in present day devices; it is therefore critical to determine the regimes for FNS R&D in which these mechanisms can become important. [Kaye, S.M. et al., Phys. Rev. Lett. **98** (2007) 175002; Mazzucato, E., et al., Phys. Rev. Lett. **101** (2008) 075001; Wong, K.L. et al., Phys. Rev. Lett. **99** (2007) 135003; Stutman, D. et al., accepted for publication in Phys. Rev. Lett. (2009)]
  - Solutions to limit the anticipated high heat flux on plasma facing components, to levels (<5-10 MW/m^2) appropriate for continuous operations up to 10^6 s [J. Canik et al, white paper submitted to Harnessing Fusion Power Theme area; L. R. Baylor, et al., “Research Thrust to Address PMI Knowledge Gaps for DEMO”, submitted to the Plasma Material Interface Theme area]
  - Special magnet requirements [M. Cole et al, white paper]
- The FESAC TAP also identified for all the alternate concepts including the ST, an urgent need for developing plasma modeling and simulation to enable predictive capabilities. Given the strong commonality of the ST and the Tokamak physics basis, emphasis should be applied to extending the present Tokamak fusion plasma simulation capabilities to the ST. [S. Diem et al, white paper]
- The full range of fusion neutron flux (0.01 – 2 MW/m^2) to enable the FNS R&D would apply the FESAC TAP recommendations to a broader range of fusion plasma performance: for neutron flux of 0.01 MW/m^2, a plasma current of 3 MA in D-D operation with trace tritium fueling (K-Star-level performance); for 0.3 MW/m^2, 4 MA and Q ~ 0.8 in D-T (JET-level performance); for 1 MW/m^2, 8 MA and Q ~ 2; and for 2 MW/m^2, 12 MA and Q ~ 3.5.
- The Tokamak plasma physics knowledge base for this range of plasma operation is more nearly complete, projecting in DT to as high as Q = 2-4 for a plasma current of 6.7 MA at a toroidal field of 6T with a neutron flux of 2 MW/m^2 in a device intermediate between DIII-D and JET in size.

A U.S. National Perspective of FNS R&D

With ITER forging ahead with the design and construction of a facility to test and understand magnetic fusion burning plasmas, the U.S. has a unique opportunity to begin the R&D for magnetic fusion energy, what the Idaho Reactor Testing Station (predecessor to INL) began in 1950 for fission energy, by creating *for the first time* a full fusion nuclear environment to test, discover, and understand the underlying scientific and technical knowledge needed for practical fusion power. The U.S. fusion R&D community are scientifically and technically ready to work together to clarify the benefit, cost and risks of all viable options of FNS R&D facilities.