Tritium Fuel Sustainability and Fusion Power Extraction Research

Scientific Mission

This white paper focuses on a set of multiple-effect and partially-integrated test facilities that are essential to advance scientific understanding of fusion nuclear science and technology beyond the lab, and to prepare for efficient and useful testing in the full fusion environment of an FNSF or ITER-TBM. The role of multiple-effect R&D and test facilities are to understand, demonstrate and, together with modeling initiatives, make predictable the performance, reliability, and failure modes and effects of in-vessel fusion power components and tritium extraction and processing systems, with:

- prototypic geometry, multi-material unit cells and mockups up to full size,
- simulated combined loads (thermal, mechanical, chemical, nuclear and EM load conditions) representative of fusion environment conditions.

The goal is to first understand dominant materials and components phenomena in relatively simple, separate effects test. Then, perform controlled scientific investigations of these phenomena under progressively more realistic and complex conditions using combined loads and prototypic geometries. Of particular interest will be the discovery of unanticipated synergistic effects. Three main experimental facilities have been recommended in recent panel assessments [1-3].

1. *Blanket Mockup Thermomechanics / Thermofluid Test Facility*
2. *Blanket Unit Cell and Tritium Extraction Test Facility*
3. *Tritium Fuel Cycle Development Facility*

To maximize results, these experimental efforts must be paired with the development of coupled models and predictive capabilities that can simulate time-varying temperature, mass transport, and mechanical response of multiple-effect experiments. Together these experimental and modeling capabilities will provide the basis for (a) designing and licensing experimental in-vessel and tritium systems to be tested in FNSF and ITER-TBM, and (b) for understanding and interpreting their testing results.

Mission Need and Recommendations from Recent Planning Efforts

"Power extraction" and "tritium sustainability" were identified as key fusion nuclear science areas in all recent studies and planning activities [1-4]. Fusion development in general, including all aspects of plasma physics research, requires authoritative information on fusion nuclear science to evaluate technological readiness and identify paths toward a successful DEMO. Research is needed to establish the scientific foundations of practical, safe and reliable processes and components that 1) harvest the heat produced by fusion, 2) create and extract tritium from lithium, 3) manage tritium (and other radionuclides) that circulates in the plant, and (4) confine other activated waste products produced from parasitic neutron capture and transmutations – all which must operate in the unique and complex fusion environment.

A scientific framework is required where experiments and modeling progress from basic and separate effect science in the lab, through multiple-effect and partially-integrated studies in specially designed test facilities, to experimentation and testing in the actual integrated fusion environment such as in ITER-TBM and FNSF. The recommendations of previous planning efforts [1-3] are summarized in the figure below, where the specific multiple effect test facilities needed in the 5 year time frame are identified.

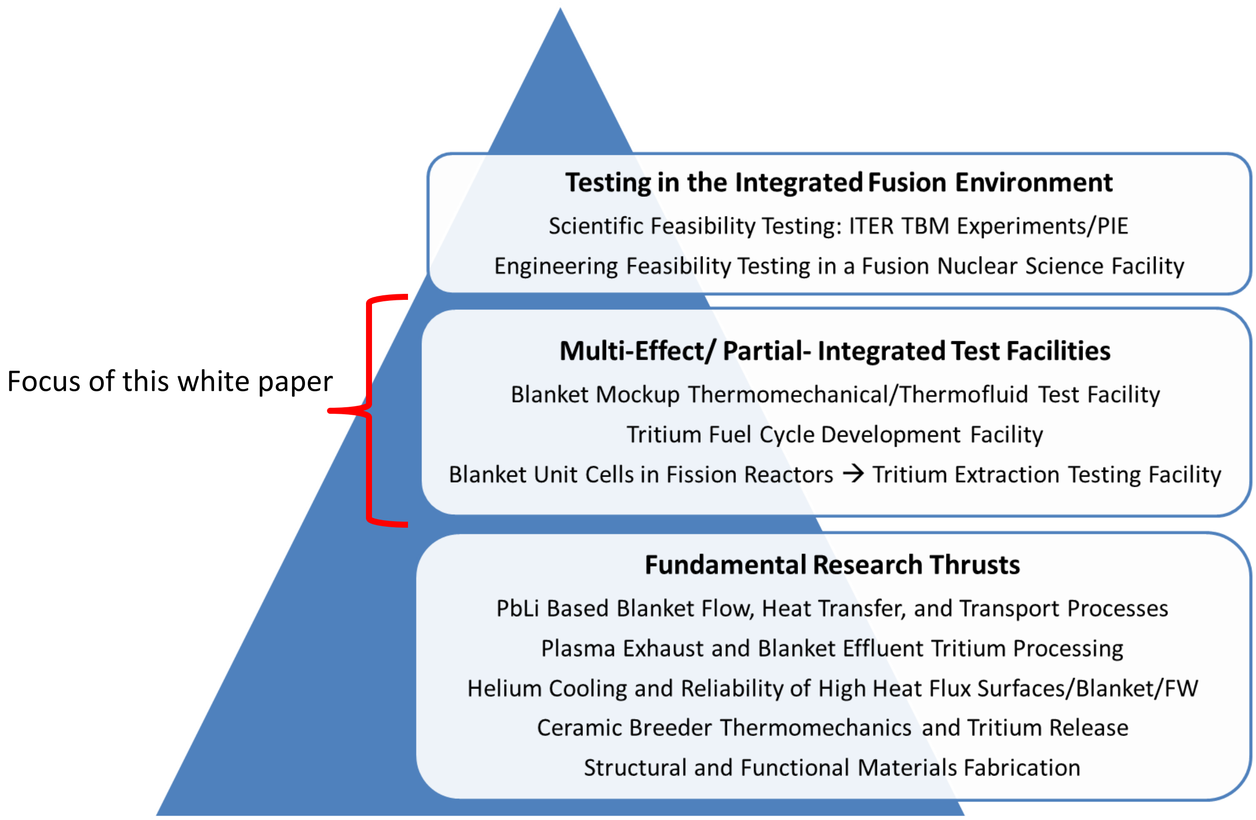

Fig. 1 Scientific framework and specific research thrusts and capabilities for advancing blanket/FW, divertor, and tritium processing and control for fusion

Facility Descriptions

Facilities attempting to safely simulate the important environmental conditions that power extraction components and tritium systems will face in service must be substantial compared to the current investment in FNST in the US fusion program. Taken together these facilities represent a testing capability that would bring the US to the forefront of blanket/FW, divertor and tritium system research, especially for liquid metal blanket systems such as the Dual-Coolant Lead Lithium blanket system that is the primary focus of the research plan described here. It is certain that other ITER parties would collaborate in order to develop a better understanding of ITER TBMs and advanced blanket and tritium systems for DEMO. The anticipated cost of each a facility is in the ~$20-30M range, with an anticipated $4M/year operations, experiment fabrication, and research program. Given the funding of the basic research program, these new facilities would be needed and could be ready for construction in the next 5-year time frame.

Blanket Mockup Thermomechanics/Thermofluid Test Facility: This facility brings together simulated surface and volume heating and reactor-like magnetic fields with blanket/FW (and divertor) test mockups having prototypical size, scale and materials operated at prototypical flow rates, pressures and temperatures for extended periods.

- Mockup modules as large as a 2 m x 2 m
- PbLi and Helium cooling loops typical of size needed for single blanket module (other LMs for divertor)
- Magnetic field 5T (superconducting, large volume), additional magnet systems to simulate vertical and poloidal fields
- Surface heat source, 4MW (1 MW/m2 surface heat load, higher on concentrated areas)
- Simulated volumetric heat sources, 10 MW (2.5 MW/m2 neutron wall load equiv.)
- Simulated tritium transport (H,D) systems
- Mechanical loading systems (constraint, vibration, impulse)

The experimental program would be centered on developing understanding and predictive capability around the function, phenomena and failure rates, modes and effects under progressively more integrated conditions and prototypic geometries. Especially for liquid metal blankets, the complex MHD interactions that dominate pressure, stress, and transport behavior must be understood given the complexity of both blanket structure and magnetic field configuration. While volumetric nuclear heating cannot be perfectly simulated, the facility will employ various heating techniques such as specialty internal electrical heaters to mockup up volumetric heating effects.

There is no partially-integrated blanket facility of this type in the world, though there are some smaller scale LM flow facilities some of which are paired with limited magnetic field capabilities and some with surface or volume heating. Bringing together these conditions especially for LM blanket systems is an essential step to understand blanket thermomechanics and thermofluid behavior prior to fully integrated testing which will reduce risk, advance simulations, aid in interpretation of blanket/FW behavior in the fusion environment.

Blanket Unit Cell and Tritium Extraction Test Facility: This facility is proposed to irradiate breeding blanket unit cells with neutrons, and extract the resulting tritium. The current vision is for an actively controlled unit cell module irradiated by a neutron source such as a fission reactor (ATR, HFIR) linked by a coolant loop (e.g. PbLi) to an out-of-pile tritium extraction system. The in-pile unit cell will be used to study issues related to production, release and permeation in breeder materials, while the external systems will be used for experiments on bred tritium extraction and processing, chemistry control, and transmutation product removal. Scientific studies would include 1) He/T radiochemistry in PbLi breeder (including possible bubble formation) and related impacts on permeation inside and outside the unit cell, 2) tritium extraction effectiveness by techniques such as a high temperature vacuum permeator system, 3) gas accumulation and removal in the out-of-pile processing systems and 4) permeation through the high surface areas of heat extraction devices. Very little experience exists using PbLi in a neutron radiation environment, all tests thus far being static, without flow or continuous processing.

This facility should be as small as possible. For fission reactors like ATR, the largest flux trap bore hole available is 12.5 cm diameter, and the possible location and distances for locating ancillary coolant flow and tritium processing equipment is not known. Initial discussion with ATR engineers confirm that such a test system with external loop is possible, and other irradiation host facilities should be considered as well. Joint design and scoping efforts will be required to fully determine size and cost parameters.

Tritium Fuel Cycle Development Facility: This is envisioned as a hydrogen/deuterium facility that provides a flexible environment for "tritium" science and technology experiments. This facility will be used to develop and qualify new technologies and approaches for pumping, processing, and fueling of simulated plasma exhaust and blanket effluent as needed for DEMO, with capabilities beyond the duty cycle and throughput needed for ITER. Operation with H/D leads to lower-risk and lower cost research program, before new technologies and components are deployment in other facilities such as ITER/FNSF where final qualification with tritium is done.

The vision is for a facility which includes most or all of the technologies needed for the fusion fuel cycle. They would be interconnected, so systems-level experiments can be performed. The key primary processing systems include:

- Average total flowrate, 200 Pa m3/s
- Average pressure, 1.5 bar
- Composition
  - Burn and Dwell: Primarily H2 with He, D2 and impurities
  - Glow Discharge Wall Conditioning: Primarily He with HD and impurities, or Primarily D2 with impurities
  - Bake Out: HD and impurities
  - Vacuum Vessel Pump-out: Primarily air/N2 with HD and impurities

The facility would be flexible so that alternate technologies can readily be installed and would be a complement to substantial ITER capabilities on tritium processing.

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References:

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[2] C. E. Kessel (Chair), "Fusion Nuclear Science Pathways Assessment," Princeton Plasma Physics Report PPPL-4736 (2012).
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