Draft Opinion paper for Snowmass Chamber Science and Technology Key Question #4: Neutron Sources and Large-Scale Technology Facilities (S.J. Zinkle and A. Ying, cochairs)

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1. Technical Issues and Types of Testing

Fusion nuclear technology feasibility and attractiveness issues have been identified and characterized in several studies (e.g. [1-5]). Feasibility issues are those whose negative resolution will have the following impact [5]:

a. may close the design window
b. may result in unacceptable safety risk
c. may result in unacceptable reliability, availability or lifetime.

These technology issues are analogous to the *Concept Exploration and Proof of Principle Stages* in plasma physics R&D studies. Attractiveness issues are analogous to the *Proof of Performance Stage* in plasma physics R&D studies, and their negative resolution would result in [5]:

a. reduced system performance
b. reduced component lifetime
c. increased system cost
d. less desirable safety or environmental implications.

The reactor components affected by the nuclear environment include blanket/first wall components (generally considered the critical path for fusion nuclear technology development), plasma interactive and high heat flux components (divertor, limiter, rf antennas, launchers, waveguides), shield components, tritium processing systems, heat transport and power conversion systems, and diagnostic and control systems. A summary of the critical issues of fusion nuclear technology is given in Table 1. In many cases, these critical issues are linked to a particular design concept (e.g., MHD insulators for liquid metal coolant/breeder).

The testing needs for fusion nuclear technology have also been addressed in previous studies (e.g. references 1-5). During the initial stages of a testing program, it is natural to focus on single-variable tests in order to understand the controlling features for a given physical process. However, synergistic interaction effects require all loading conditions of the fusion environment and interactions among all physical elements of the components to be adequately simulated in follow-on advanced tests. The key fusion environmental conditions include neutron-related effects (radiation effects, nuclear heating, tritium breeding), surface heating and erosion of plasma-facing components, magnetic field effects, mechanical forces, and chemical compatibility.

Table 1. Summary of Critical R&D Issues for Fusion Nuclear Technology (extended from ref. [5])

1. Tritium issues	
➢ D-T fuel cycle **neutronics**	Proof of Principle
➢ Tritium **inventory and recovery in the solid breeder** under actual operating conditions	Proof of Principle
➢ Tritium **inventory and recovery in the liquid breeder** under actual operating conditions	Proof of Principle
➢ Tritium **permeation and inventory** in the structure	Proof of Principle
2. **F**irst wall and blanket materials science	
➢ Materials **compatibility**	Concept Exploration
➢ Development of self-healing MHD **insulators** for liquid metal blankets, including thermal/mechanical/electrical/nuclear loading	Concept Exploration
➢ Operating limits & lifetime of first wall and blanket components	Proof of Principle
➢ **Thermomechanical** loadings and response of blanket components under normal and off-normal operation	Proof of Principle
3. Divertor high heat flux component thermomechanical response and lifetime	
➢ Liquid Divertor	Concept Exploration
➢ Solid Divertor	Proof of Principle
4. RAM issues	
➢ Identification and characterization of **failure modes, effects, and rates**	Proof of Principle
➢ Remote maintenance with acceptable machine shutdown time	Proof of Performance
5. Radiation Shielding: accuracy of prediction and quantification of radiation protection requirements	Proof of Performance
6. MFE Liquid Walls	
➢ Plasma Liquid Interactions	Concept Exploration
➢ Free Surface Temperature Limits and Choice of Liquid	Concept Exploration
➢ Hydrodynamics Feasibility	Proof of Principle
➢ Materials for Thick Liquid Walls	Proof of Principle
7. IFE Liquid Walls	
Liquid Chamber Clearing (including vaporized materials and splashed liquid droplets)	
➢ Vapor condensation experiments	Concept Exploration
➢ Partial-pocket experiments (0.25 scale)	Proof of Principle
➢ Complete pocket experiments (0.42 scale)	Proof of Performance
8. IFE Target Fabrication and Injection	Concept Exploration
9. Final focus design and survivability for laser-driven IFE	Concept Exploration
10. Prediction of nuclear parameters: tritium production, radioactivity build up, transmutation	Concept Exploration

Table 2. Test Categories for Blanket R&D (after ref. [5])

Basic test (Concept exploration)

- Basic or intrinsic property data on a single material
- Examples: thermal conductivity; neutron absorption cross section, tensile properties

Single-effect test (Proof of Principle)

- Isolate a single variable, or the interaction of a limited number of phenomena, in order to develop understanding and models
- Examples: (a) pellet-in-can test of the thermal stress/creep interaction between solid breeder and clad; (b) electromagnetic response of bonded materials to a transient magnetic field; (c) tritium production rate in a slab of heterogeneous materials exposed to a point neutron source; (d) degradation of fracture toughness of structural BCC materials due to radiation hardening; (e) formation of single liquid jets at prototypical Reynolds and Weber numbers; (f) free surface heat transfer experiments for MFE liquid walls; (g) plasma- liquid wall interactions; (h) small-scale hydrodynamics feasibility assessment

Multiple-effect/multiple interaction test (Proof of Principle)

- Explores multiple environmental conditions and multiple interactions among physical elements in order to develop understanding and prediction capabilities
- Examples: (a) creep testing of alloys in the presence of coolants and/or irradiation (irradiation assisted stress corrosion cracking); (b) testing of an internally cooled first-wall section under a steady surface heat load and a time-dependent magnetic field; (c) application of scaled impulse loads to arrays of several liquid jets scaled to preserve gravity and inertia effects; (d) large-scale integrated thermal and hydrodynamics experiments for MFE liquid walls

Integrated test (Performance Extension)

- Concept verification and identification of unknowns; includes all key environmental conditions and physical elements, although often not full scale
- Examples: (a) in-situ measurement of tritium production and release in ceramic breeder mockups during irradiation at fusion-relevant conditions; (b) blanket module mockup test in a fusion test device; (c) disruption and regeneration of hydraulically and geometrically scaled thick-liquid pockets

Component test (Performance Extension)

- Design verification and reliability data on full-size component under prototypical operating conditions
- Examples: (a) an isolated blanket module with its own cooling system in a fusion test reactor; (b) a complete integrated blanket in an experimental power reactor

In general, the R&D on candidate materials or chamber technology components may be envisioned to proceed in a series of steps. The test categories adopted here are: basic, single effect, multiple effect/multiple interaction, integrated, and component tests. Table 2 summarizes the description of these categories. Note that the level of integration provides a rough measure of test complexity and an approximate indication of the chronological order. First, screening experiments are performed in the laboratory to establish the baseline feasibility (Concept Exploration). If satisfactory results are obtained, more advanced small-scale experiments are performed in order to identify promising concepts that perform well in a "single effect" environment (in irradiation and/or non-irradiation test facilities). These experiments along with focussed multiple-variable tests provide the basis for establishing the Proof of Principle for a given component of technology design concept. Finally, experiments with a prototypical test section in an environment that combines the appropriate nuclear, chemical, thermomechanical and magnetic field effects is necessary to establish the Proof of Performance. An important consideration is that integrated and component (Performance Extension) tests typically can be performed only in fusion devices. On the other hand, Concept Exploration and Proof of Principle experiments are relatively low in cost (particularly in non-neutron test stands) and they are important and useful in reducing the large costs and risks associated with future Proof of Performance tests. In a few cases, it might be argued that Concept Exploration experimental studies can only be adequately performed in a large-scale facility such as a volumetric neutron source (e.g., DT self-sufficiency studies on a blanket segment).

2. Technology test facilities

Non-fusion facilities play an important role in Concept Exploration and Proof of Principle stages of technology testing because of availability and low cost. Non-fusion facilities can provide essential screening of proposed components and help reduce the risks and costs of the more complex, integrated tests in the fusion environment. However, Proof of Performance generally can not be verified in non-fusion facilities, except for liquid-wall facilities where major issues center on fluid mechanics rather than radiation effects. Technology test facilities can be classified into: a) non-irradiation test facilities, b) fission reactors, c) accelerator-based neutron sources, and d) fusion test facilities. Each of these is discussed briefly below.

2.1 Non-irradiation Test Facilities

Non-irradiation test facilities can provide Concept Exploration and Proof of Principle test results on basic property data, single-effect experiments, and some of the multiple-effect/multiple interaction tests for which the neutron field is not important. Examples include scoping studies on MHD electrical insulators (including chemical compatibility, thermal cycling and self-healing studies), high heat flux testing of innovative materials/design concepts, investigation of thermohydraulic issues, plasma-material interaction studies (including liquid walls), etc.

Several large-scale non-irradiation test facilities are proposed for proof-of-principle experiments during the next decade. The objectives are to address multiple effect phenomena using scaled models, after the resolution of key feasibility issues. In particular, synergism between MFE and IFE liquid walls will allow experiments to be conducted at the same large-scale integrated thermofluid facility. Such a facility for Flibe liquid walls would require the following capabilities (for example):

- Liquid volumetric flow rate: 10 m^3/s
- Supply pressure: up to 2.5 atm
- Storage and vacuum receiver vessel volumes: 300 m^3 (transient flow option)

Other proposed facilities include an out-of-pile thermomechanics test facility for a solid breeder blanket mockup and a high heat flux component test facility.

2.2 Fission Reactors

Fission reactors provide neutrons in a moderate volume and are thus suitable for many Proof of Principle experiments. Table 3 summarizes the capabilities of several fission reactors available in the USA, Russia, and Europe for blanket tests. Testing in fission reactors suffers from several limitations which are listed in Table 4. For example, there is no fission reactor operating now anywhere in the world that can provide a test location with > 15 cm equivalent circular diameter at a fast neutron flux equivalent to 1 MW/m^2 wall loading (> 1×10^{15} $n \bullet cm^{-2} \bullet s^{-1}$ for Fe or V). This size limitation makes it difficult to evaluate the synergistic effects present in multiple-variable tests (e.g., magnetic field and mechanical forces). The well-publicized difference between the fission and DT fusion reactor neutron spectra leads to difficulties in simulating processes such as helium and tritium production, as well as atomic displacements. Despite these limitations, fission reactor testing is suitable for some multiple effect tests that are needed to establish the Proof of Principle for certain designs. Examples include tests of a unit cell of a solid breeder blanket to investigate tritium release behavior, and coolant-structure compatibility in the presence of mechanical stress and radiation.

Table 3. Capabilities of Several Fission Reactors Available for Blanket Tests

Reactor	Location	Reactor Power (MW)	Fast Flux, E>0.1 MeV (n/cm^2s)	Irradiation Capsule Diameter (cm)	Nuclear heating (W/g)	Core Height (cm)	Comments
HFIR-RB " -target	US	85 "	$4.4x10^{14}$ $1.1x10^{15}$	4.0 1.2	12 46	50 "	In-situ test cap.
ATR-ITV " –I holes	US	250 "	$4.5x10^{14}$ $3.0x10^{12}$	2.5 12.5	~20 1.5	122	In-situ test cap.
BOR-60	Russia	50	$2.0x10^{15}$	4.4 (hexag.)	8	45	
RBT-10	Russia	10	$4.4x10^{13}$	15.8 x 23.7	3	35	
SM-2	Russia	100	$2.2x10^{14}$	6 and 16	13-40	35	
IVV-2M	Russia	20	$7x10^{13}$	3.0-12.5	3.5	50	
PHENIX	France	250	$4.0x10^{15}$	4.0		80	
SILOE	France	35	$5.0x10^{14}$	5.6	2-12	60	
BR-2	Belgium	60	$6.0x10^{14}$	25		96	
HFR	Netherlands	20	$5.0x10^{14}$	14.5		60	

Table 4. Key Limitations of Fission Reactors (after ref. [5])

1. Small test volume
2. Lack of fusion-relevant radiation damage parameters
    a. neutron spectra
    b. He/dpa ratio and other transmutation differences
3. Lack of fusion-related (non-neutron) conditions
    a. magnetic field
    b. surface heat
    c. particle flux
    d. mechanical forces
    e. accessibility

2.3 Accelerator-Based Neutron Sources

Accelerator based neutron sources produce neutrons in a volume that is smaller than typical fission reactors. Deuterium-Tritium accelerator sources produce 14 MeV neutrons, hence the correct fusion spectra, but are limited by target fabrication and cooling considerations to neutron fluxes that are orders of magnitude lower than that in a fusion reactor with 1 MW/m^2 wall load. However, the effects of neutrons/generated gammas can be detected at reasonable depth (~1.5 m) inside test assemblies. In addition, the FNS facility has advantage of producing a line source to better simulate the energy/angle distribution of incident neutrons generated from Tokamak plasmas. The existing DT neutron facilities include the RTNS-1 (US, Berkeley), FNS (JAERI, Japan), FNG (Frascati, Italy) and SNEG-13 (Near Moscow, RF). The neutron yield among these facilities varies (~5 x 10^{12} n/s, ~5 x 10^{11} n/s, and ~3 x 10^{13} n/s, respectively) and can be tailored for specific neutronic tests. The first two facilities can be used for verifying the prediction capability of present codes and databases for tritium production in solid breeder (or LM) to confirm tritium self-sufficiency issue and to generate safety factors for the design purposes. Additionally, irradiation of various samples for low-activation tests and updating/verification of our current dosimetry and activation/decay heat databases can be performed at these facilities. Because of the relatively high yield of the SNEG-13 facility, it is most suited for deep penetration tests such as verifying the adequacy of radiation protection schemes for machine components (e.g. superconducting magnets) and personnel from transported and/or streamed neutrons and gamma rays. It can also be used to quantify the peaking factors used in shielding design to account for streaming through openings and gaps between blanket segments.

A higher-flux high energy neutron source that has been in operation for over 10 years is the Los Alamos Spallation Radiation Effects Facility, which utilizes spallation neutrons created from the interaction of 750 MeV protons (~1 mA beam current) with a high-Z target. The irradiation parameters for LASREF are summarized in Table 5. This facility is well-suited for targeted studies on several key materials issues (e.g., the effect of He generation on low-temperature embrittlement of structural alloys), but it is currently limited to cumulative damage levels below ~10 displacements per atom. Recent calculations indicate that the neutron flux could be increased by more than a factor of two by utilizing a W target in the facility.

A high-current (~100 mA) accelerator designed to accelerate protons to 8-20 MeV has recently been constructed at Los Alamos as part of the Accelerator Production of Tritium project. This facility (LEDA) could potentially be used for fusion materials irradiation studies (NEED ADDITIONAL INFO—P. Lisowski/J. Anderson/W. Sommer).

Recently, an international design activity under the auspices of the International Energy Agency (IEA) was completed [6-8] for a D-Li source called IFMIF (International Fusion Material Irradiation Facility). In this concept, neutrons are produced by bombarding a flowing lithium target with energetic (~35-40 MeV) deuterons. The irradiation parameters for the IFMIF design are summarized in Table 5. Accelerated testing of an adequate number of internationally-accepted miniaturized mechanical property specimens for evaluation of DEMO structural materials, etc. can be performed in this facility [6-8]. Since this facility is largely based on technology already in-hand, its cost and availability can be estimated with high reliability compared to plasma-based high-intensity neutron sources.

There are several technical issues regarding the suitability of a D-Li source for fusion nuclear technology studies, including: 1) neutron spectrum, 2) steep flux gradient in the high-flux regions, and 3) the surface area and volume available for testing. Although there are uncertainties in the nuclear data above 14 MeV, the international consensus is that radiation effects observed with D-Li neutron spectra can be adequately correlated to those in a fusion reactor [9]. The most serious issues for Proof of Performance testing in a D-Li source is the limited volume and steep flux gradients in the high flux region.

Table 5. WORKING DRAFT Comparison of the Irradiation Parameters for Several High Energy Neutron Sources

Facility	Loca-tion	Power (MW_e)	Total neutron flux (n/cm^2s)	Irradiation Volume	Nuclear heating (W/g)	Capital Cost	Operating Cost	Comments
LASREF “, W target	LANL	~1?	5.0x10^{13} >1.0x1014	12x25x50cm^3 (~15 liters)	~0.4	15 M$	20 M$	Existing facility
LEDA	LANL		??	??	??			Existing accelerator
IFMIF (40 MeV deuterons)	---	10	>4.0x10^{14} (>20 dpa/FPY) 1-20 dpa/FPY 0.1-1 dpa/FPY <0.1 dpa/FPY	0.5 liters 6 liters ~10 liters >>10 liters	3.8 ~0.5-2	0.8 B$ (Including 0.17B$) reduced-0.5 B$(Including 0.15B$)	60 M$ 50 M$	>70% design availability; lower-fluence regions (<20 dpa/FPY) intended for in-situ studies on blanket components, magnets, etc.
laser	---	0.01	10^{14}-10^{15}	~0.5 cm^3				High-fluence fundamental studies on miniature spec.
D-T neutron RTNS-1 FNS FNG SNEG-13	US JAERI EU Russia		1x10^{12} <5x10^{12} <5x10^{12} <5x10^{12}	1 m x1 m 1 m x 1m 1 m x 1m				Existing facilities (< 100 keV deuterons) (330 keV deuterons) (100-300 keV deuterons)
GDT	---	<100	1-2 MW/m^2	~100 liters (1 m^2x0.1m)	~1	0.5 B$ (?)		<150 g T_2/year
ST-VNS	---	170-400	1-2 MW/m^2 (1-5 MW/m^2)	~1600 liters (16 m^2x0.1m)	~2	1.5 B$	180 M$	60% design availability
VNS	---	<400	1-2 MW/m^2	~1000 liters (10 m^2x0.1m)	~2	2 B$	250 M$	≥25% design availability construction date ~2015??
DEMO (2.2MW/m^2)	---		7.1x10^{14} (19 dpa/FPY)		2.8			

2.4 Laser point neutron source

A laser-based high-intensity neutron source has recently been proposed by LLNL researchers [10]. Due to recent rapid development in the field of short-pulse, high-intensity lasers, intensities of 10^{18} W/cm^2 are currently available from table-top lasers and systems capable of ~10^{21} W/cm^2 are now starting to come on line. Compared with conventional beam-target neutron sources with steady-state liquid cooling (e.g., IFMIF, RTNS-II), the driver energy here is removed by sacrificial vaporization of a target spot of a few-hundred-microns dimensions. In the present target concept, the laser energy interacts with a central DT gas cluster and the escaping fast ions are absorbed in a surrounding DT "collar" to produce 14 MeV beam-target neutrons [11]. The collar may be solid DT or simply a higher-density, concentric gas cluster. Preliminary predictions from a 1-D code for a full-scale D-T irradiation facility driven by a 100J, 100Hz (i.e., 10kW average power) diode-pumped solid state laser indicate that the steady-state, uncollided 14MeV neutron flux at a close-coupled material specimen is ~10^{15}cm-2s-1 at a laser intensity of ~10^{17}W/cm^2. For comparison, the time-averaged uncollided 14 MeV flux at the first wall of a typical MFE or IFE reactor is ~1-4x10^{14}cm^{-2}s^{-1}. The resulting small source volumes offer the potential for a high flux of 14MeV neutrons at close-coupled, micro (<1mm) test specimens of fusion-relevant, single materials (e.g., vanadium alloys, SiC-SiC and C-C composites, etc). This facility offers the potential for relatively low-cost construction and operation, but the high-flux volume is restricted to ~0.5 cm^3 with steep flux gradients. This facility may be useful for fundamental radiation effects studies on microstructure stability, tensile properties, etc. that are needed for Concept Exploration analyses.

Future work includes the performance of computational modeling and experimental investigations to predict neutron fluxes and fluences ultimately obtainable in a production level facility as a function of laser and targets conditions. Of course, the potential modest size/cost of such a facility (<$100M) and low overall power input (~10kW average) means that high neutron fluxes are obtainable only over small specimen volumes. A complementary materials science and computational modeling program is therefore necessary to validate damage models and provide a multiscale predictive capability for the extrapolated behavior of engineering-scale components.

Such a coupled irradiation-computation program might partially compensate for the absence of large scale testing with high-fluence, volumetric fusion plasmas.

2.5 Plasma-based facilities

Several different plasma-based neutron sources have been proposed for the testing of fusion technology components, including the gas dynamic trap and several variants of a “volumetric neutron source”. Although the likely construction time frame for these sources (~2015) is outside the R&D time period specifically covered by Snowmass, the proposed roles for a plasma-based facility must be included for overall planning purposes for the coming ten years.

The Gas Dynamic Trap Neutron Source (GDTNS) is a volumetric plasma (14 MeV) source with a neutron spectrum and intensity very close to that predicted for ITER and fusion reactor designs. The neutron production is by a nonMaxwellian ion tail in a dense, nearly Maxwellian plasma. Energetic ions are produced by neutral beam injected at 30-45° to the magnetic field in an axisymmetric mirror machine, with most neutrons produced at the sloshing-ion turning points near the mirrors. MHD stability is produced by the out-flow of dense plasma through one of the mirrors into a magnetic cusp, with the flow momentum in the good-curvature part of the field dominating the plasma instability drive in the bad curvature part of the confined volume. Calculations and extrapolation of experiments indicate that 1-2 MW/m^2 of uncollided 14 MeV neutrons can be produced in a 100 liter volume with small tritium consumption (< 150 g/year at 100% availability) and intrinsically steady-state operation. Positive ion-based neutral beams (< 65 keV, 60 MW) can be used at mirror fields of 13 T (mirror ratio 10); upgrades to 20 T and 250 keV negative-ion based neutral beams could produce as much as 4 MW/m^2 of 14 MeV neutrons.

An experiment operating at the Budker Institute of Nuclear Physics, Novosibirsk, Russia, has demonstrated much of the GDTNS physics with a pulse-length of 3-5 ms: Stability against MHD modes, stability against ion velocity-space modes so that the ions decay and scatter classically, and T_e =130 eV (equal to classical predictions for the available neutral beam power - 3.5 MW at 15 keV). Experiments at higher power are required to verify the extrapolation of the electron temperature to the neutron source regime. The proposed neutron source can test materials, reactor components, and many of the blanket systems and subsystems needed for a reactor. Tritium usage is low enough to be supported from supplies elsewhere in the world, without local production. Construction is relatively straightforward and the cost reasonable (~$500M) for a large 14 MeV neutron source.

A high volume plasma-based, deuterium and tritium (DT) fueled, 14 MeV neutron source (VNS) has been considered as a possible facility to support the development of the demonstration fusion power reactor (DEMO). It can be used to test and develop necessary fusion blanket and divertor components and provide sufficient database, particularly on the reliability of nuclear components necessary for DEMO. The spherical torus (ST) is a promising candidate for such a VNS [12,13]. A recent investigation, supported by the USDOE SBIR program, showed that it is cost effective and scientifically feasible to employ the ST based VNS for nuclear technology development [12]. In addition, the unique capability of the ST-VNS allows the development of needed fusion core components and related technologies for the DEMO in a reactor relevant environment [14]. During the Phase I of the STVNS study, a minimum cost ST-VNS was identified that could satisfy the minimum requirements identified in the IEA study. STVNS-I has a major radius of 0.8 m, aspect ratio of 1.33, and an on-axis magnetic field strength of 1.8 tesla. It will be operated with a single-turn (in the central post) normal copper magnet to produce 38 MW fusion power when driven and heated by 21 MW of neutral particles at 500 keV energy. The neutron wall loading at the 10 m^2 test section will reach 1 MW/m^2.

Research continues during Phase II of the SBIR study [15]. The effort focuses on the optimization and technological feasibility of the VNS with higher neutron wall loads. The motivation is to cover the entire range of neutron wall loading (0.5 - 5 MW/m^2) anticipated in future power reactors. A second goal of the high wall loading approach is to test the component performance in an environment approaching or exceeding the lifetime neutron fluence. To satisfy these goals, a slightly larger device is conceived during the Phase II study. The configuration of the STVNS-II has a major radius of 1.07 m and an aspect ratio of 1.4. The topics investigated during this second phase include physics and mechanical design analysis, materials selection, neutronics and activation analysis, availability assessment, and cost analysis [15].

During the initial operation, the availability can be very low due to lack of knowledge and experience in operating such a device. The ITER developed SS316 based shielding blanket materials can be used for all components except the test blanket section. The core components made of power reactor related materials such as ferritic steel and vanadium alloys will be employed in the test section. Feasible core component concepts can be tested and selected for higher neutron wall loading operation after about 0.5 $MW\text{-}y/m^2$ fluence. Tritium breeding in the shielding blanket region may not be needed at this stage because the needed tritium consumption is only 640 g/y (30% availability). The total tritium consumption in the initial stage is no more than 2.13 kg since it takes about 3.3 years to accumulate the fluence of 0.5 MW-y/m^2. Partial tritium breeding will be in fact available in the power reactor blanket being developed in the test section.

Higher wall loading operations can continue after the initial stage operation. At the higher wall loading stages, the outboard shielding blanket region other than the test section can begin to include power reactor relevant core components already tested and qualified in the test section. Another way to interpret it is that the fusion power blankets can be fabricated as blanket segments rather than modules and tested in the entire outboard region. The availability can be increased to 60% after significant experience learned from the operation of a power producing fusion device. During these stages, the qualified power blankets and divertor components will begin to be subjected to mean-time-to-failure testing. Reliability information of the fusion core components start to accumulate[16]. Tritium breeding will be available during these stages. Since the power blanket segment can be employed in the entire outboard region, an overall tritium breeding can be assessed. The self-sufficiency of tritium can thus be demonstrated for the relevant blanket concept.

The staged high wall loading operation of an ST-VNS can provide an accumulated neutron fluence of more than 30 MW-y/m2 in a power reactor relevant environment within about 20 years. Compared to a fixed neutron wall load device, the operating time is significantly reduced. The ST-VNS can provide a reactor relevant environment for the power core components to demonstrate all functions required for a power plant or DEMO through the start-up, transition, and steady-state operation at the designated power levels. Ultimate performance capability of promising power core components can thus be developed and demonstrated for the power plant application.

3. Suggested roles for the various technology test facilities

Fission reactors and accelerator- or laser-based neutron sources can provide meaningful data needed for Concept Evaluation and Proof of Principle studies on fusion technology issues. In contrast to the conclusions drawn in ref. [5], meaningful Proof of Principle tests on non-structural materials such as breeder and multiplier materials can also be performed in fission reactors and accelerator-based neutron sources (e.g., the “EXOTIC” irradiation series performed on ceramic breeders in the HFR reactor, and proposed irradiation tests on ceramic breeder submodules in the medium-flux region of IFMIF). However, it is generally agreed that a plasma-based source will be needed for the majority of the required Proof of Performance testing of fusion components. An optimized fusion technology testing strategy (roadmap) should include a mixture of non-irradiation, fission reactor, accelerator and/or laser-based neutron sources, and a plasma-based test facility. Further discussion of the interactive roles of the various proposed fusion technology facilities is given in the following.

The minimum volume requirements for a systematic evaluation of the key irradiated mechanical properties of seven different structural materials (two compositions each of ferritic/martensitic steel, vanadium alloys and SiC/SiC composites, and one unidentified alternative structural alloy) has been determined to be 0.5 liters (using realistic allowances for specimen packaging, coolant, etc.) [7,17]. Within this volume, the effects of irradiation on properties such as fracture toughness, fatigue, crack growth rate, irradiation creep, and tensile properties could be obtained for 5 different damage levels between 20 and 150 dpa (DEMO-relevant lifetime dose) and 6 irradiation temperatures within a time frame of 20 years, assuming a facility availability of 70% and an equivalent first wall neutron loading of $\geq$2 MW/m^2. This volume requirement is less than the 2 liters reported in ref. [5]. The main source of this discrepancy is that the analysis in ref. [17] utilized a staged insertion of specimens (as is typical for current fission reactor irradiation studies), whereas the analysis summarized in ref. [5] assumed that all of the specimens would be inserted at the same time. Smaller specimens (creep, fracture toughness, fatigue) and fewer irradiation temperatures were also used in ref. [17] compared to ref. [5].

As noted in section 1, the key experimental conditions for fusion nuclear component studies are: 1) neutron effects (radiation damage, tritium and helium production), 2) bulk heating (nuclear heating in a significant volume), 3) non-nuclear conditions (e.g. magnetic field, surface heat flux, particle flux, mechanical forces), 4) conditions for simulating thermal-mechanical-chemical-electrical interactions, and 5) conditions for integrated tests and synergistic effects. Non-plasma facilities are well-suited for single-variable tests and some multiple effect/multiple interaction experiments (Concept Evaluation and Proof of Principle tests). In particular, fission reactors and accelerator-based irradiation facilities provide a good simulation of the fusion bulk heating environment (cf. Table 5). In a few specific cases (e.g., in-situ measurement of tritium production and release in ceramic breeder mockup assemblies), accelerator-based irradiation facilities can investigate multiple-effects that can establish Proof of Performance for a given component. On the other hand, non-plasma facilities are not suitable for investigating the synergistic effects that occur in many other fusion components.

Table 6 shows the contribution of non-irradiation facilities, fission reactors and accelerator-based facilities as well as plasma-based neutron facilities to resolving the fusion nuclear technology critical issues. The following descriptive terms are used in Table 6 to classify the relative contribution of each facility toward resolving a given critical issue, in ascending order of their impact: none, limited, moderate, substantial, adequate. “Limited” denotes information that may provide some useful (but fragmented) underlying data, whereas “substantial” implies that the majority of the key phenomena are addressed (although not completely resolved). Valuable information needed to assess the Concept Exploration and Proof of Principle issues can be obtained using non-plasma-neutron of facilities. However, there is no critical issue that can be fully resolved by testing in non-plasma-neutron facilities alone. On the basis of cost considerations, non-plasma-neutron facilities can and should be used to narrow materials and design concept options. This approach clearly reduces the costs and risks of the more costly and complex tests in any high-intensity plasma-based facility. The key question that remains to be answered is what is the appropriate time frame for introduction of a high-intensity plasma-based test facility. Further development of an integrated fusion technology roadmap is needed before this question can be answered.

Table 6. WORKING DRAFT Contribution of Non-plasma Facilities to Resolving Critical Issues for Fusion Nuclear Technology Component Performance Demonstration (revised from Ref. [5])

Critical Issue	Non-neutron Test Stands	Fission Reactors	Laser-based Neutron Source	Accelerator Based Neutron Sources			Plasma-based neutron source	
				D-T	LASREF	D-Li, P-Li	GDT	VNS
1. Tritium issues								
➢ **D-T fuel cycle neutronics**	None	Moderate	Limited	Moderate	Moderate	Moderate	Substantial	Substantial
➢ **Tritium inventory** and recovery in the solid breeder under actual operating conditions	None	Moderate	Limited	Limited	Moderate	Moderate	Substantial	Substantial
➢ **Tritium inventory** and recovery in the liquid breeder under actual operating conditions	None	Moderate	Limited	Limited	Moderate	Moderate	Substantial	Substantial
➢ **Tritium permeation** and inventory in the structure								
2. First wall & blanket materials science								
➢ Materials **compatibility**	Moderate	Limited	Moderate	Limited	Moderate	Substantial	Moderate	Moderate
➢ Development of self-healing MHD **insulators** for liquid metal blankets, including thermal/mechanical/electrical/nuclear loading	Moderate	Limited	Limited	Limited	Moderate	Moderate	Substantial	Substantial
➢ Operating limits & lifetime of first wall and blanket components	None	Limited	None	None	Limited	Moderate	Moderate	Moderate
➢ **Thermomechanical** loadings and response of blanket components under normal and off-normal operation	Limited	Limited	None	None	Limited	Limited	Moderate	Moderate

3. Divertor HHF component thermo-mechanical response and lifetime								
➢ Solid divertors	Moderate	Limited	None	None	Limited	Limited	Substantial	Substantial
➢ Liquid divertors	Limited	Limited	None	None	Limited	Limited	Moderate	Substantial
4. RAM issues								
➢ Identification & characterization of **failure modes, effects, and rates**	Limited	Limited	Limited	Limited	Moderate	Moderate	Moderate	Substantial
➢ Remote maintenance with acceptable machine shutdown time	Moderate	Limited	None	None	Limited	Limited	Moderate	Substantial
5. Radiation Shielding: accuracy of prediction and quantification of radiation production requirements	None	Moderate	Limited	Moderate	Moderate	Moderate	Substantial	Substantial
6. MFE Liquid Walls								
➢ Plasma Liquid Interactions	None	None	None	None	None	None	Moderate	Substantial
➢ Free Surface Temperature Limits and Choice of Liquid	Substantial	None	None	None	None	None	Moderate	Substantial
➢ Hydrodynamics Feasibility	Substantial	None	None	None	None	Limited	Moderate	Substantial
➢ Materials for Thick Liquid Walls	Limited	Substantial	Limited	Limited	Moderate	Moderate	Substantial	Substantial
7. IFE Liquid Walls		None	None	None	None	None	None	None
Liquid Chamber Clearing (including vaporized materials and splashed liquid droplets)								
➢ Vapor condensation experiments	Moderate							
➢ Partial-pocket expts. (0.25 scale)	Moderate							
➢ Complete pocket expts. (0.42 scale)	Substantial							
8. IFE Target Fabrication and Injection	Moderate	None	None	None	None	None	None	None
9. Final focus design and survivability for laser-driven IFE	Moderate	None	None	None	None	None	None	None
10. Prediction of nuclear parameters: tritium production, radioactivity build up, transmutation	None	None	None	Moderate	Limited	Limited	Substantial	Substantial

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