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Summary Report on the

Refined User Requirements for U.S. Fusion Prototypic Neutron Source

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1. Introduction

The Fusion Prototypic Neutron Source (FPNS) is proposed as an urgent near-term facility necessary for understanding D-T fusion neutron degradation processes in materials and for the development of high-performance radiation tolerant materials for fusion power reactors. This facility is central to our goal of predicting the behavior of materials in the harsh D-T neutron environment and calibrating and verifying the materials performance models necessary to support design of next-generation fusion reactors. Key FPNS performance metrics were previously defined [1] for the cost-efficient facility necessary to adequately and expediently resolve key materials science knowledge gaps required to move to next-step fusion devices. This brief report is intended to expand upon this previous metrics discussion as an aid to selecting the most desirable FPNS concept and enabling a facility that meets the program needs.

2. Guidelines for FPNS key requirements

The following guidelines on the minimum performance parameters, shown in Table 1, were previously agreed upon for FPNS [1].

Table 1. Guidelines on minimum parameters of FPNS agreed at 2018 FPNS Workshop [1].

Parameter	**Guideline**
Damage rate	~8-11 dpa/calendar year (Fe)
Spectrum	~10 appm He/dpa (Fe)
Sample volume in high flux zone	≥ 50 cm^3
Temperature range capability	~300-1000°C
Temperature control	3 independently monitored and controlled regions
Flux gradient	≤ 20%/cm over the tested portion of the sample

As no new scientific or technical information has become available which would influence the minimum performance parameters outlined above, the guidance remains unchanged from the workshop report.

3. Augmented requirements and refinements

While these minimum performance requirements remain unchanged, it is recognized that the performance metrics require improved clarity and rigor in definition in order to objectively evaluate potential concepts for an envisioned FPNS construction project. This would facilitate the selection of the most appropriate FPNS concept within schedule and budgetary realities in order to best achieve the fusion materials program research goals. Moreover, as the relative importance of each guideline is not equal, informing a more rigorous cost-benefit analysis that would arrive at an optimal technology and facility is warranted. As an example, while not fully meeting the guideline on damage rate or flux gradient is considered undesirable, issues related to non-representative transmutation products or defect configurations caused by spectrum and pulsed-irradiation effects are considered unacceptable as they could entirely compromise the mission of FPNS. The following discussion is intended to capture and quantify these issues, which were not conveyed in the original requirements summarized in Table 1 or found in the 2018 Workshop report.[1] Some background discussion on these topics is given elsewhere.[2,3]

3.1. Damage rate

Metric	**Integrated Damage Rate**
2018 Guideline	8-11 dpa/calendar year (Fe)
Augmented Requirement	8-11 dpa/calendar year in Fe within >70% of the minimum requirement sample zone volume. Facility duty cycle should be in excess of 75%.
Rationale for Augmented Requirement	The minimum damage accumulation of ~10 dpa/CY is required to achieve 50 dpa in 5 years. The original guideline 8-11 dpa/CY was agreed because up to 20% reduction from the reference target damage rate 10 dpa/CY may be acceptable though undesirable. For this reason, this damage rate requirement needs to be satisfied within the majority (>70% is considered reasonable) of the minimum requirement sample zone volume of 50 cm^3.
Criteria for Evaluation of Source/Target Concepts	Are all augmented requirements satisfied? Is instantaneous damage rate appropriate? Are basis for estimated damage rate and availability sound?
Additional note	Here, “instantaneous damage rate” is time-averaged damage rate during the beam-on period. Instantaneous damage rate in dpa/s is a materials-dependent parameter. This requirement is given for Fe (approximately valid for the steels that are most commonly assumed the candidate structural materials for early-generation fusion power systems).

Atomic displacement damage rate, types and rates of nuclear transmutations (n,α; n,p; etc), and temperature are the most fundamental parameters dictating the effects of fusion neutron irradiation in materials.

The damage rate here denotes the integrated damage rate, in dpa accumulated, over an integrated irradiation period (on the order of years) and includes the facility outage time:

(integrated damage rate) = (instantaneous damage rate) x (FPNS availability)

It is undesirable to utilize a FPNS facility with a duty cycle well below 50% (even if the annual dpa accumulation meets the ~10 dpa/yr specification) due to issues with interpretation of data obtained at damage rates far beyond fusion reactor first wall and blanket values.[4] This phenomenon is otherwise known as accelerated testing and is known to be problematic, especially in kinetic regimes consistent with void swelling. A facility with the potential for high availability (>75% of full year operation) at a constant delivered damage rate in the target region (<30% variability in flux) is strongly preferable to a facility with delivered damage rates that could vary by a factor of two or more over the course of ~1 year, and/or that has estimated annualized availability well below 50%.

The damage rate in units of dpa/s during the in-pulse period of pulsed beam irradiation (in-pulse damage rate) is another important factor impacting the resulting microstructural and mechanical property response to irradiation. In particular, it is deemed highly undesirable to utilize a damaging source whereby a pulsed source causes in-pulse highly accelerated damage followed by a relatively long irradiation-free annealing period. Limited theoretical and experimental evidence suggests such a scenario to be problematic.[5-7] Such an example is for one design neutron source concept utilizing the LANSCE facility [8] whereby a spallation neutron shower caused by an 850 μs, 78 Hz beam would result in an effective in-pulse damage acceleration. The inherent question in analyzing data emanating from such a source would be whether such an 15x "beam-on" acceleration followed by a longer duration beam-off annealing period would result in representative defect processes and resultant properties.[4]

Pulsed irradiation, as opposed to continuous irradiation, is known for the potential to remarkably alter the effects of irradiation in materials. While the magnitude of the effects of pulsed irradiation will vary depending on various conditions, repeated pulsed fluxes of multiple point defect species of different diffusivities are considered to be one of the primary fundamental causes of such effects. Additional consideration should be given to effects of higher flux within the pulse period, repetitive thermal annealing, and repetitive internal stresses. Systems with continuous, steady-state neutron flux are preferred. Non-steady state technologies for which irradiation flux can be demonstrated to effectively mimic steady state can be considered.

Satisfying the Guideline means an acceptable integrated dpa rate of (>~$3x10^{-7}$ dpa/s) as it does NOT represent appreciably accelerated irradiation conditions as compared to a fusion power system. In other words, the guidance is for FPNS to maintain target damage rates in reasonably close agreement to the anticipated range of damage rates ($1x10^{-7}$ to $1x10^{-6}$ dpa/s) for the first wall, breeding blanket structures, and plasma-facing components of DEMO/pilot plant fusion reactors.

3.2. Spectrum

Metric	Relevance of Transmutations
2018 Guideline	~10 appm He/dpa in Fe
Augmented Requirement	~10 appm He/dpa in Fe ~40 appm H/dpa in Fe ~0.1 - ~1 % solid transmutations per dpa in W Fusion-relevant transmutation burn-in/burn-out species and appm/dpa rates in leading candidate fusion structural and functional materials No significant irrelevant burn-in/burn-out
Rationale for Augmented Requirement	Relevance of elemental transmutations is of uppermost importance for FPNS. Specifying only He/dpa in Fe is insufficient.
Criteria for Evaluation of Source/Target Concepts	Are all augmented requirements satisfied? Basis for estimate of appm transmutations to dpa ratios sound? If spectrum is significantly irrelevant, is detailed information on transmutations available for materials of interest? Are such transmutations acceptable?
Additional note	Transmutation reactions and rates are material dependent. This requirement is given for Fe as a stand-in for the steels that are most

	commonly assumed the candidate structural materials for early-generation fusion power systems. However, attention is also needed to transmutations in other important material systems.

Relevance of neutron spectrum is of paramount importance for the FPNS as generation and effects of transmutation products are the central purpose of this device. In other words, the FPNS is the most critical experimental tool to develop and validate ***D-T fusion spectrum materials science*** upon which fusion power plant design and qualification must rely. While discovery of transmutation product effects for species, quantities, or ratios irrelevant to fusion may be scientifically meaningful, such findings outside the scope of the FPNS mission.

Extensive evaluation of the effects of neutron irradiation on properties of fusion materials, other than the fusion spectrum effects, are studied using fission reactors. The primary differences between the fusion spectrum (for simplicity called 14 MeV neutrons) and various fission materials test reactor spectra are elemental transmutation rates. As example, for Fe-Cr-W reduced-activation ferritic/martensitic steels (RAFMS), a fusion spectrum causes significant production of helium and hydrogen whereas they are negligible in fission spectra. Similarly, transmutation behavior is strikingly different between the fusion and fission spectra in many materials, including but not limited to W, SiC, alumina-forming steels, insulating ceramics, and solid tritium breeders.

It is important that the FPNS only produces transmutation species expected from a fusion spectrum and not species at any significant quantity (e.g. $\geq$0.1 appm/dpa) which will be unknown to fusion structures (e.g., alkali, alkali earth, or halogen species). Moreover, it is necessary that FPNS produces relevant species: 1) at relevant rates, and 2) at relevant ratios of production to damage.

3.3. Sample zone volume

Metric	**Sample zone volume and target design flexibility**
2018 Guideline	High flux zone volume ≥ 50 cm^3
Augmented Requirement	High flux zone volume $\geq$ 50 cm^3 Ability to accommodate in situ control and measurement capabilities Availability of lower flux zone(s) for materials irradiation studies
Rationale for Augmented Requirement	In-pile capabilities are critical to study some mechanisms, e.g., dynamic helium-deformation interactions Availability of medium and low flux zones enables additional irradiations of significant scientific value to fusion systems
Criteria for Evaluation of Source/Target Concepts	Are the augmented requirements met? What is likelihood of successful implementation of in-pile creep or/and fatigue capabilities? What are the spatial constraints that limit creation of a lower flux zone or zones for additional materials irradiation?
Additional note	Greater specimen zone volume is always desirable for any flux zones

A greater specimen zone volume is always desirable since it potentially offers room for increased number of specimens, additional material variations, specimen type variations, larger and more ASTM-relevant sample sizes, improved temperature management, extended temperature capabilities, and more complex experiments. Moreover, utilizing an FPNS design architecture which allowed for increased capacity (adding flux) as an incremental upgrade would be highly desirable. In addition to the absolute volume of the high flux zone, geometry of the high flux zone and other design constraints on the materials irradiation target will pose significant impact on the overall value of the facility. Ideally, neutrons arriving from one direction in a uniform beam of well-defined geometry would give the best space utilization and design flexibility for the irradiation experiments. In addition, coordinating sample sizes in a manner consistent with ability to conduct post-neutron exposure experiments in linear plasma devices could prove advantageous to understand bulk-to-surface effects critical to PMI performance and PFM qualification.

Ability to accommodate in-situ experiments is highly desirable for the FPNS target. Whereas only limited knowledge now exists regarding the interactions among multiple operating environment factors, one potentially imminent threat is an accelerated helium embrittlement of structural alloys in dynamically stress-loaded environments. Austenitic stainless steels are known to be susceptible to high temperature helium embrittlement that can have drastic effects on creep and fatigue properties.[9] While this phenomenon has not been reported as a serious concern for the RAFMS,[10] further research at fusion-relevant conditions are needed to assess the magnitude of this issue. In addition, the ability to accommodate feed lines for gas, liquid, electricity, and additional instrumentations is desirable, as the FPP design may require data and knowledge on in-situ performance of, for example, tritium release and corrosion.

Although the high flux zone is undoubtedly the most important part of the FPNS materials irradiation target, availability of additional zones that offer lower neutron fluxes would be highly valuable. In fact, the existing target designs for IFMIF, DONES and A-FNS all accommodate reduced flux zones for additional materials irradiation capabilities. The medium and low flux zones often offer an order of magnitude greater volume than the high flux zone, and hence would be useful in accommodating additional experiments, in particular those requiring relatively large volume specimens (e.g., fracture mechanics specimens) and in-situ capabilities. It is important to note that the displacement damage levels achievable in the IFMIF medium flux zones (assumed ~1 dpa-Fe/yr) is still orders of magnitude greater than the highest 14 MeV neutron dose achieved in the history of fusion materials research.[11]

3.4. Temperature range, zones, and control

Metric	**Temperature zones and control**
2018 Guideline	3 independently monitored and controlled zones in range 300-1000°C
Augmented Requirement	3 independently monitored and controlled zones in range 300-1000 °C Ability to maintain within ±5% of the target temperature (Kelvin) at a reference point in each temperature zone throughout each irradiation cycle Ability to accommodate more than 1 online temperature monitor in each temperature zone

	Ability to achieve temperature uniformity within ±5% of the target temperature (Kelvin) within >70% of the minimum requirement sample zone volume Ability to reliably estimate the three-dimensional temperature distribution in relation to reference point temperature
Rationale for Augmented Requirement	Quantitative requirement on temperature control was not specified in the original guideline
Criteria for Evaluation of Source/Target Concepts	What is likelihood of successful, robust design and implementation of 3 temperature zones and temperature control? Does successful experience exist with design schemes relevant or similar to the presumed irradiation target? Are failed temperature management components replaceable?
Additional note	This augmented requirement will need additional refinement as concepts mature

As discussed earlier, temperature is one of the most important parameters that dictate materials behavior in radiation environments. For FPNS to serve for its purpose, it is essential that the irradiation temperatures are adequately managed, acknowledging that lack of adequate temperature control has compromised a number of earlier spallation-type and other irradiation experiments. Examples of the consequences of inadequate temperature management include unacceptable deviation of the actual irradiation temperature from the target temperature, spatial or temporal variation in temperature, and uncertainty in determining the actual temperature of individual specimens. These consequences will significantly degrade the ability of FPNS to achieve the primary objectives.

To ensure adequate temperature control, the requirements include but are not limited to 1) a robust heating/cooling scheme, 2) robust specimen compartment design, 3) reliable computational thermal analysis, 4) reliable online temperature monitoring, and 5) reliable post-mortem thermometry. The augmented requirements described above may not be sufficient to satisfy all of these generic requirements but are meant to capture them in somewhat quantitative manners.

Considering the current state-of-the-art of temperature management in irradiation studies using materials fission test reactors, ±5% of the target temperature (in unit of Kelvin; e.g., 573±29K or 873±44K) is a reasonable generic accuracy goal for the target temperatures.

3.5. Flux variations and stability

Metric	**Flux variations and stability**
2018 Guideline	Spatial variation <20% over the tested portion of sample
Augmented Requirement	Spatial variation < ±10% along a 6 mm length in the beam-normal plane within at least 70% volumes of all temperature zones Temporal variation < ±10% throughout repeated beam cycles Steady-state or effectively steady-state flux (integration of very short high intensity pulses highly undesirable) Anticipated frequency of beam outage <12 times/CY in normal operation

Rationale for Augmented Requirement	Sample size was not defined in the original guideline
Criteria for Evaluation of Source/Target Concepts	Is the spatial uniformity criterion met? Is the temporal variation criterion met? Is the beam considered continuous? If pulsed, is it considered equivalent to a continuous beam from radiation materials science standpoint? Is the estimated beam outage frequency acceptable? Is basis for estimate of spatial and temporal variations and frequency of beam outage sound?
Additional note	The augmented requirement can use additional refinement

Regarding the spatial variation of neutron flux, in order to define an accumulated dose on a sample and in order to minimize errors in dosimetry in general, neutron flux needs to be sufficiently uniform within the area of interest on a single sample. In many mechanical property specimens, it is crucial to obtain flux uniformity over a portion of the overall specimen volume. For example, uniform flux is important for the gage region of tensile specimens or in the tested volume of fracture toughness specimens, but the grip regions do not need to be exposed to a constant flux. As a rough guideline, ±10% uniformity along the gage length of Type SS-J tensile specimen (6 mm) may be appropriate for the purpose.

Temporal variations of neutron flux include time-dependent fluctuation and drift, both of which are undesirable because of the anticipated influence of dose rate on the effects of irradiation in materials. A ±10% uniformity, for the fluctuation and drift combined, during repeated beam cycles may be considered an appropriate acceptability criterion.

Given the inherent importance of uniform irradiation at constant temperature to understand the microstructural and mechanical property evolution in materials system, excursions which would lead to interrupted irradiation, thermal transients, and enhanced temperature drift during irradiation are undesirable. As scheduled or non-scheduled FPNS system outages or reduced-power events would contribute to these issues, a robust facility with a minimum of outages is desirable. Moreover, a goal of realizing a high-availability facility suggests the application of well-understood and demonstrated-robust technologies.

4. Additional requirements

4.1. Schedule

While the US fusion energy science program does not currently have an agreed upon schedule for the construction of a fusion pilot plant, the anticipated ability to meet the timing requirement (in other words, the schedule risk) should be an additional important consideration in identifying the desirable FPNS concept and its enabling technologies. The two main considerations in defining the timing requirements are consistency with timeline of US fusion energy development (currently notional) and the relationship (complementary and/or competitive) to other (European and Japanese) potential fusion spectrum materials irradiation facility projects. However, it is instructive to consider the timing required for the FPNS to support the next generation of high-fluence fusion devices. As a prerequisite the parallel roles of the FPNS must be defined and understood as follows:

- Serving to produce a relevant fusion neutron spectrum for fundamental studies of irradiation effects directly supporting the modeling of material behavior at varied time and length scales. This element is crucial insofar as, given the inherent volume limitations, it is assumed that a primary purpose of the facility is to provide the fundamental understanding and predictive capability to bridge from our mixed-spectrum database to fusion-prototypic behavior.
- Serving to provide prototypic high-dose and prototypic transmutation data on fusion materials to inform design.
- Serving as the primary tool to validate data utilized in design codes, including the relevance of extrapolation from the mixed-spectrum fission reactor database which will be utilized as the irradiation workhorse, for all regulatory and design-approval activities.

It follows that to fill these roles the FPNS must operate for a time consistent with the development of a robust fundamental understanding of fusion materials' behavior AND provide relevant high-dose data in time to support design of our next generation devices. If we assume the notional timeline for a Fusion Pilot Plant (FPP) to start operation in early 2040s [12,13], construction of the FPP needs to start by ~2035 or earlier. Final materials performance data to inform design must predate this construction, suggesting a date no later than ~ 2030. Assuming a minimum dose of 50 dpa (nominally 5 years) as the necessary target dose for data validation on RAFM steel, operation of the facility should begin no later than the middle of this decade, ~2025. This assumes that our ability to gain the fundamental understanding of transmutation effects (first bullet above) can proceed in parallel with the primary long-duration experiments. Considering an assumed FPNS construction period of ~5 years, even if the Critical Decision 0 is approved in 2021, the facility design and any major facility-enabling research and development (R&D) need to be completed within a 3-4 year period. Under these assumptions it is clear that the community, even in the event of a slippage of the FPP schedule, is facing a significantly compressed schedule of the requirement to realize the FPNS.

The 2018 workshop reached the unanimous conclusion that early deployment of the FPNS would allow the US to lead the world in advancing scientific understanding of materials behavior in the fusion neutron environment. Moreover, the FPNS is a potential intermediate step to next generation sources such as IFMIF, DONES or A-FNS, if it becomes available near-term. Achieving this role requires start of operation of the FPNS about 5 years ahead of these larger facilities. The current schedules of DONES/A-FNS projects imply start of construction within the ~2025 time frame.

4.2. Facility longevity

Once normal operation is started, the role of FPNS will evolve from bridging the most imminent knowledge gap for the design decisions of long-lead components for the first FPP in the first ~5 years to generating data and knowledge required for the design of an FPP licensing the FPP operation during the FPP construction period. At the same time, in parallel to the missions closely tied to the first FPP development and licensing, FPNS needs to operate to meet the extremely high demands of irradiating critical materials for FPPs. It will be the primary tool for fusion materials R&D, just like the historical and existing fission materials test reactors do for nuclear fission materials R&D. Although the absolute required longevity of FPNS may be argued, a highly credible prospect of continued facility availability for at least 20 years is a strong argument to justify the investment.

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