Summary Report on the

Fusion Prototypic Neutron Source Workshop

Held at the

Gaithersburg Marriott Washingtonian Center
Gaithersburg, MD
August 20-22, 2018

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Organized by the

VLT
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U.S. DEPARTMENT OF ENERGY | Office of Science

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SUMMARY

This workshop was organized by the US Virtual Laboratory for Technology (VLT) for the Department of Energy (DOE) Office of Fusion Energy Sciences (FES) to discuss the need for a fusion prototypic neutron source, FPNS. While there are a variety of uses for FPNS neutrons, the main driver of US interest is expanding the scientific understanding of materials degradation in the harsh D-T fusion environment. FPNS will also help to build the scientific foundation required to enable design of a next step fusion device, such as a Fusion Nuclear Science Facility (FNSF), and to design and build the more advanced fusion neutron facilities under consideration internationally. The need for this knowledge has been identified in numerous past community meetings and reports but has yet to be met. Developing the scientific understanding is a prerequisite to developing an engineering database to enable the design and construction of a reliable and economic fusion energy system. Contributing to this required engineering data base is the primary mission of concepts such as the International Fusion Materials Irradiation Facility (IFMIF) which would follow a FPNS. The purpose of the workshop was to determine if the US fusion materials community believed a FPNS focused on the scientific understanding of materials degradation in a fusion environment was a priority and the parameters ranges required to fill this need.

Thirty-three participating scientists included principal investigators of the fusion materials program, members of the VLT, and representatives of recently active fusion neutron source design studies. Presentations and discussions covered questions a FPNS could address experimentally and benchmark computationally, needs for metals and ceramics, how experiment design advances may modify requirements for FPNS, and how complementary experimental techniques can enhance the FPNS value.

The workshop reached the unanimous conclusion that a near term, moderate cost FPNS would advance our scientific understanding of materials degradation in the intense fusion neutron environment and would be an asset to the US program. FPNS is a potential intermediate step to next generation sources such as IFMIF/DONES/A-FNS, if it becomes available near-term. Achieving this role requires start of construction within about three years from a decision.

The following guidelines for key parameters of FPNS are the consensus results of the workshop:

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	~300-1000°C
Temperature control	3 independently monitored and controlled regions
Flux gradient	≤ 20%/cm in the plane of the sample

INTRODUCTION

The focus of the workshop was on determining if the US fusion materials community considered a FPNS focused on the scientific understanding of materials degradation in a fusion environment to be a priority for the field. Presentations and discussion were organized to answer this question. Given the consensus agreement that such a facility would be a high priority, discussion turned to the desired specifications of the FPNS, within the limits of what such a device is likely to be able to achieve.

SETTING THE STAGE

The workshop agenda is given as Attachment A; most listed people were in attendance at the workshop. Attachment B is the issue paper developed by Gene Nardella and Daniel Clark of DOE-FES that outlined the purpose of the workshop and the DOE-OFES expectation of the workshop deliberations. The issue paper is largely based on the Zinkle, Moeslang publication "Evaluation of irradiation facility options for fusion materials research and development" [1].

The US materials science program is currently in a worldwide leadership position due to the knowledgeable personnel and the High Flux Isotope Reactor (HFIR), which provides a world class neutron irradiation facility in a fission spectrum and is supported by a network of similarly world-leading post-irradiation examination facilities.

A FPNS and materials testing in such a facility has been motivated in many reports such as *Gaps and Priority [2], ReNeW [3], FESAC Materials Opportunities [4]*, and others. The US has a long history in developing (and trying to establish) fusion relevant neutron irradiation platforms: FMITS, RTNS-I & II, MTS (LANCSE) and SNS. The FY19 DOE-FES study to evaluate options for a fusion relevant neutron source for materials studies represents an opportunity for the US program to extend the US program to fusion prototypic neutron irradiations and obtain first-of-a-kind high-flux scientific fusion materials testing.

The primary mission of FPNS is to establish the materials science knowledge base to understand materials degradation in a D-T fusion environment. That base will support design for a next step device, such as FNSF, a proposed experimental fusion reactor that will help bridge the gap between ITER and DEMO by advancing fusion nuclear science and technology. However, in order for FNSF to fulfil this bridging function, it requires fusion-relevant neutron irradiation studies on the structural and functional materials to at least tens of dpa in a relatively short period. Materials required for the currently discussed FNSF concept include the current and next generation RAFM steels, SiC composite, bainitic steel, and tungsten-based plasma-facing material. FPNS will also help provide the scientific foundation to design and build the more advanced fusion neutron facilities under consideration internationally.

Materials Science Issues That Drive the Need for FPNS Key issues that can be addressed using FPNS can be summarized in a few key categories of experimental and modeling/simulation topics. These were addressed by two speakers at the workshop, and are given in Appendix C as slide material extracted from the presentations.

Future International Source Projects Main ongoing irradiation facilities for fusion are being studied by the international fusion community. The most advanced is the International Fusion Materials Irradiation Facility (IFMIF) [5,6] with an estimated cost of $1.25B, and consists of five main components:

1. Two 40 MeV 125 mA deuteron linear accelerators;
2. Flowing Li target cell;
3. Material test cell / post-irradiation examination facilities / remote handling facilities;
4. Lithium target facility;
5. Conventional facility.

IFMIF was adopted as the reference concept by the international community in 1994, and has the following parameters:

- 20 dpa/FPY, with a flux gradient of 20-25%
    - Note that depending on how the high flux zone is used, much higher damage levels could be achieved in reduced volumes
- 12-14 appm-He/dpa (Fe)
- 500 cm^3 (0.5 liter) high flux region with a capacity of approximately 1000 specimens
    - Much larger volumes with lower neutron flux levels can be used to meet many of the other important needs of the fusion programs
- 250-1000 °C +/- 3% temperature
- Target footprint of 20 cm x 6 cm

Other reduced cost, reduced capability facility concepts include:

- The EU Demo-Oriented Neutron Source (DONES) [7,8], approximately one-half of IFMIF with a 300 cm^3 volume (500-800 specimens) at 12-25 dpa/FPY.
- The EU Early Neutron Source (ENS) [9] with a 75 cm^3 volume (80 specimens) at 8-11 dpa/FPY
- Japan's A-FNS-26 MeV and A-FNS-9 MeV [10] at 14 and 1.5 dpa/fpy
- China's HINEG-1,2 and 3; HINEG-1 has lower n/s rate than 1980's US RTNS-II

Fission Test Reactors The US materials science program is currently in a worldwide leadership position. The High Flux Isotope Reactor (HFIR) provides a world class neutron irradiation facility in a fission spectrum and has a network of associated post-irradiation examination facilities. It is widely used in the US fusion materials program, and in collaboration with international partner programs.

A review of the Versatile Test Reactor, a project of the US DOE Office of Nuclear Energy program, presented the status of this US fast fission reactor. The VTR will have a fast flux of approximately 4 x 10^{15} n cm^{-2} s^{-1} and has an estimated operational date of 2026.

KEY PARAMETERS FOR FPNS

The workshop reached the unanimous conclusion that a near term, moderate cost (FPNS) will advance our scientific understanding of materials degradation in the intense fusion neutron environment and will be an asset to the US program. This conclusion grew out of the presentations and discussions of the needs of the fusion materials program, the critical issues that require a prototypic D-T fusion spectrum for access, and the range of methods and experience in using alternate means of simulating the fusion environment. The guidelines developed for the key parameters of FPNS, the consensus results of the workshop, are in the following table. These guidelines will now be examined and expanded, explaining the basis for each one.

Guidelines on Minimum Parameters for FPNS

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	~300-1000°C
Temperature control	3 independently monitored and controlled regions
Flux gradient	≤ 20%/cm in the plane of the sample

**Where materials-dependent parameters are considered, these are given for Fe, as a stand-in for the steels most commonly assumed to be the candidate structural materials for early-generation fusion power systems. Dpa rates and He transmutation rates are the most important of these materials-dependent parameters.*

Damage Rate Damage rate targets are set to allow experiments to reach total neutron exposures to interrogate critical property change phenomena of the target material. For example, swelling measurements may need to access steady state swelling rates after exceeding any incubation dose, and embrittlement regimes may only be reached after exceeding critical fluence-dependent hardening levels. Damage levels beyond these possible threshold levels are needed to assure that important property change phenomena are evaluated, providing guidance for the next stage of experiments that may eventually develop the data base for power reactor design.

Based on these considerations, the workshop adopted a guideline for damage rate of ~8-11 dpa/calendar year (Fe). This is set to allow experiments with damage reaching into and above the critical range of 20 to 50 dpa, believed to be the upper limit for accurately predicting the behavior of RAFM iron-base alloys in their expected application range of ~250-550C from current fission irradiation data.

Neutron Energy Spectrum Several workshop presentations reviewed neutron irradiation impacts and regimes. While displacements caused by fissions or fusion neutrons are found to be equivalent in metals; transmutation and helium generation rate are not equivalent. Helium generation distinguishes fusion materials from fission materials. In spite of clever and insightful approaches in fission neutron irradiations to "simulate" the fusion regime, it is difficult to project the actual bulk material behavior and many questions remain. The generation rate of helium and its effects on materials properties requires a fusion prototypic neutron source to adequately evaluate effects on properties.

Thus the most important determinant of the required energy spectrum of a neutron source is the transmutation rate(s) producing helium, based on the well-established deleterious effects of helium on the material behavior. The guideline agreed to by the workshop participants is ~10 appm He/dpa (Fe).

Implicit in setting this value is that there are no other transmutation levels with known effects on the properties of the materials under study. This may require qualification for any candidate sources with significant population of neutrons outside of the D-T spectrum, at either lower or higher energies.

If FPNS is used for evaluation of other materials, for example W, SiC and others, the appropriateness of neutron spectra that differ from the D-T fusion spectra will require consideration. Achieving the fusion-relevant neutron energy spectrum may be more important for materials such as tungsten and ceramics, where solid transmutation products play key roles in irradiation-induced property degradation.

Sample Volume in the High Flux Zone While the experimenters' desideratum is always "as large of volume as possible" the focus of discussion was on minimum volume required to meet the goal of meaningful progress in developing the understanding of materials behavior in a D-T fusion environment. Limitations on these volumes has led to the focus of international efforts in Small Specimen Test Technology, SSTT, to maximize the value of irradiation sources with small experimental volumes.

Continuing efforts in miniaturization of test samples will improve the flexibility of an early neutron source in accommodating multiple specimens of several geometries in a small irradiation volume. Standardized miniature samples are currently being used effectively in fission irradiations. For example, the SS-2E tensile specimen is 2.6 x 7 mm, TEM specimens are 3 mm diameter by 0.5 mm thick and many other sizes and geometries are used, some with only µm dimensions. Conversely, handling of miniature samples in the post irradiation examination facilities is difficult and requires careful planning and unique handling apparatus.

Rapid advances in mechanical properties and microstructural characterization techniques will assist the analysis of irradiated samples. Simultaneous mechanical, structural, and chemical information will be obtained and probably analyzed in real time by the time a FPNS is available. The current instruments can drown the operator in data, but computers will likely handle the tedious and error-prone parts of data analysis.

Following these considerations, a guideline for the available volume in the high flux zone of ≥ 50 cm^3 was agreed by workshop participants. Note that this guideline interacts with the specifications on temperatures. Ingenuity will be required to achieve several temperatures and a mix of different specimen types within this limited volume.

With any FPNS concept, it is expected that there will be a significant volume of useable experimental space with medium and low flux in addition to the high flux region. These volumes would still provide a very useful capability as determined by the workshop and should not be overlooked. Some of the proposed FPNS solutions may not be able to achieve these secondary irradiation zones in conjunction with the high flux target, and this will have to be considered in evaluation of source concepts.

Temperature Range A dominant variable in determining a material response to neutron irradiation is the temperature during service. This is illustrated in Figure 1, showing the controlling degradation mechanism in determining component lifetime as a function of the operating temperature for a "generic" material.

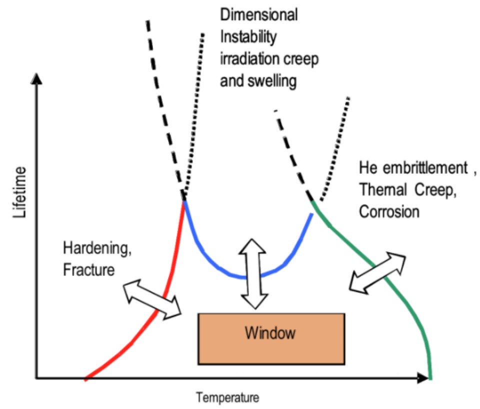

Figure 1: Schematic illustration of effects of irradiation temperature on controlling mechanisms of irradiation degradation of a typical structural material. From S. Zinkle, Fundamental Radiation Effects Questions that can be Addressed with a FPNS, Slide 2, Presented at the Workshop on Fusion Prototypic Neutron Sources, Gaithersburg, MD, August 20-22, 2018

The temperature range of interest for determining irradiation effects on properties is dependent on the material. For the RAFM steels of wide international interest, the range is approximately 300 to 550°C, set by embrittlement processes at the lower bound and by creep behavior at the upper bound. For tungsten and many ceramics and composites, the upper bound of interest can range to at least 1000°C.

Based on this range in materials of potential interest, a guideline for the FPNS temperature range of ~300-1000°C was established.

Temperature Control Three independently monitored and controlled regions of temperature are specified to allow evaluation of effects of irradiation temperature on properties of interest. Included in this specification is the assumption that these temperatures can be specified in design of experiments, then achieved in operation, and that they are approximately constant over some capsule/rig volume. The variation with time over long experiment residence is also assumed.

While not specifically considered at this workshop, acceptable limits on temperature variation must be evaluated in considering FPNS candidate systems. Short- and long-term temperature variation and variation across irradiation matrices are all of importance. For example, IFMIF specifies ± 3% of the irradiation temperature.

Neutron Flux Gradient Since most property changes during irradiation are expected to be sensitive to the neutron fluence/dpa level, the dose level should be reasonably constant across any one specimen. To assure this uniformity of irradiation exposure, a guideline of ≤ 20%/cm in the plane of the sample was specified.

CANDIDATE FPNS CONCEPTS

This workshop was not structured to consider possible candidate systems that could be developed as FPNS, nor were attendees recruited to advocate for or to critique candidates. However there was limited discussion of a few systems, with advocates presenting preliminary descriptions of several neutron source technologies.

Phoenix (formerly known as Phoenix Nuclear Labs) is commercially producing high intensity D-D neutron sources for applications internationally. A D-T version will be available in 2019 with a capability of 5×10^{13} n/s. The system is based on a 300 keV, 100 mA D^+ accelerator and a differentially pumped T gas target. Early conceptual design for a FPNS concepts estimated 5.5 dpa/yr at 10 appm He /dpa and a high flux volume of 40 cm^3. It could be built in 4 years for less than $50M, estimated by Phoenix.

The Rotating Target Neutron Source (RTNS-II), which operated from 1979 to 1987, produced D-T neutrons and was used for structure material experiments to determine the fusion versus fission effects. It produced 3.7×10^{13} n/s at an estimated flux of 1.2×10^{13} n cm^{-2} s^{-1}in a very small irradiation volume. The RTNS-II used a 400 keV 150 mA D^+/D^{2+} ion beam incident on a rotating water-cooled disk with a tritiated Ti coating. Discussion during the workshop stated the need for at least 100 times larger capability than available from RTNS-II.

The proposed Materials Test Station (MTS) at the LANSCE accelerator at LANL was reviewed. MTS would be driven by a pulsed 800 MeV proton beam from LANSCE at an average beam power of 1 MW causing spallation reactions on tungsten targets. Peak fast neutron flux greater than 10^{15} n cm^{-2} s^{-1} and in sample volume greater than 200 cm^3 is expected. The spectrum contains higher than 14 MeV neutrons resulting in a broad range of He/dpa ratios depending on sample location. Locations inside the irradiation volume can produce the fusion relevant 10 to 15 appm He / dpa ratio at an approximate dpa rate of 10 dpa/fpy. A 2012 cost estimate showed a total cost of an irradiation facility at $82.8M with commissioning of facility occurring 5 years after CD-1 approval.

There was also some general discussion of exploring a near-term D-Li source, but without any specific presentation of concepts.

A review of the application of a Gas Dynamic Trap as a neutron source for materials testing was presented that shows exciting developments in this technology. The general opinion was that this approach is at a lower readiness level than the accelerator-based solutions discussed, with unspecified/unknown time and cost horizons.

REFERENCES

[1] S.J. Zinkle, A. Moeslang, "Evaluation of irradiation facility options for fusion materials research and development," Fusion Eng. Des., 88 (2013) 472-482

[2] DOE/SC-0149 Fusion Energy Sciences Advisory Committee Report, "Opportunities for Fusion Materials Science and Technology Research Now and During the ITER Era" February 2012

[3] "Research Needs for Magnetic Fusion Energy Sciences," Report of the Research Needs Workshop (ReNeW), Bethesda, Maryland, June 8-12, 2009.

[4] FESAC report, "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy," October 2007.

[5] J. Knaster, A. Moeslang, T. Muroga, "Materials research for fusion," Nature Phys, 12 (2016) 424-434

[6] F. Arbeiter et al., “Design description and validation results for the IFMIF High Flux Test Module as outcome of the EVEDA phase,” Nucl. Mater. and Energy, 9 (2016) 59-65

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[8] A. Ibarra et al, “A stepped approach from IFMIF/EVEDA toward IFMIF,” Fus. Sci. Tech. 66 (2014) 252-259

[9] R. Heidinger et al., “Technical analysis of an early neutron source based on the enhancement of the IFMIF/EVEDA accelerator prototype,” Fus. Eng. Des. 89 (2014) 2136-2140

[10] T. Nishitani et al, “Neutron source for material-component tests by using IFMIF/EVEDA prototype accelerator,” Fus. Sci.Tech. 68 (2015) 326-330

Appendix A: Workshop Agenda

Fusion Prototypic Neutron Source (FPNS) Workshop
Washingtonian Marriott Gaithersburg
August 20-22, 2018

Monday, August 20, 2018

8:00	Welcome, logistics	Phil Ferguson	ORNL
8:15	FES perspective on fusion prototypic neutron source	Gene Nardella, Daniel Clark	DOE/FES
9:00	Fusion Nuclear Science Facility (FNSF) data needs	Chuck Kessel	PPPL
9:45	Status of international projects, specifications	Arthur Rowcliffe	FESS contractor
10:15	Discussion		
10:45	Coffee break		
11:00	Fundamental radiation effects questions that can be addressed with a FPNS	Steve Zinkle	UTK
12:00	Lunch		
13:00	Theory and modeling questions that require a FPNS	Brian Wirth	UTK
14:00	Discussion		
14:30	Coffee break		
15:00	Advancing the understanding for engineering uses of metal alloys	Rick Kurtz	PNNL
16:00	Issues and approaches for ceramics and composites	Yutai Katoh	ORNL
17:00	Discussion	Chuck Kessel	PPPL

Tuesday, August 21, 2018

8:00	Summary of Day 1	Chuck Kessel	PPPL
8:30	Effective use of small irradiation volumes	Kevin Field	ORNL
9:30	FPNS in context of other simulation techniques, 10 years from now (fission reactors, etc.)	Lance Snead	SBU
10:30	Coffee break		
11:00	FPNS in context of other simulation techniques, 10 years from now (ion beams, etc.)	Gary Was	UM
12:00	Discussion		
12:30	Lunch		
13:30	Projected advances in mechanical properties and microstructural characterization techniques available at the time of a FPNS	Chad Parish	ORNL
14:30	Impact of a FPNS on Plasma Facing Component development and design	JP Allain	U of I
15:00	FPNS needs for components	Susana Reyes	LBNL

15:30	Coffee break		
16:00	Discussion (specification ranges)	Phil Ferguson	ORNL

Wednesday, August 22, 2018

8:00	Review Days 1&2	Phil Ferguson	ORNL
8:30	Fusion safety implications for a FPNS	Brad Merrill	INL
9:00	Neutron generator concept from Phoenix Nuclear Lab	Ross Radel	PNL
9:30	Experience with ion sources for isotope production	Brian Egle	ORNL
10:00	Coffee break		
10:30	Materials Test Station (MTS) overview	Stuart Maloy	LANL
11:00	Fusion Materials Irradiation Test Station (FMITS) overview and other potential uses of SNS	Wei Lu	ORNL
11:30	Gas Dynamic Trap overview	Cary Forest	UW
12:00	Versatile Test Reactor (VTR) Overview	Kevan Weaver	INL
12:30	Discussion/Summary	Phil Ferguson	ORNL
13:00	Adjourn		

Appendix B: Fusion Neutron Source Issue Paper

<u>The Need and Opportunity for a Near-Term, Cost-Effective Fusion Relevant Neutron Source</u>

Daniel Clark & Gene Nardella, Office of Fusion Energy Science Technology Team

Materials partially taken from S.J. Zinkle, A. Möslang, "Evaluation of irradiation facility options for fusion materials research and development," Fusion Eng. Des., 88 (2013) 472-482,

A long-standing challenge for the successful development of fusion energy involves development of high-performance structural and plasma facing materials that exhibit dimensional stability and good resistance to deuterium–tritium fusion neutron degradation of mechanical and physical properties, along with exhibiting favorable environmental and safety characteristics such as low quantities of long-lived radioactivity, low concentrations of short-term volatile radioactive species and modest decay heat. The high levels of transmutation products associated with deuterium–tritium (D–T) fusion neutron reactions with materials, along with high operating temperatures of 300–1000◦C and the unprecedented displacement damage dose requirements up to 150–200 displacements per atom (dpa) for a fusion reactor, pose an extraordinary challenge and is currently one of the highest identified priorities for fusion energy research.

If fusion energy needed to be rapidly deployed without consideration towards cost or risk, it is conceivable that a next step nuclear device could be constructed without first investigating radiation degradation mechanisms and developing and qualifying materials on a dedicated fusion irradiation facility. However, this approach would introduce high levels of risk and significantly greater development cost due to the likely requirement to replace the blanket structures after relatively short operating periods (generating large volumes of spent blanket materials that would need to be recycled or disposed, and introducing low availability for the fusion energy machine). Numerous prior experiences with development of advanced technologies ranging from fission and fossil power plants to aerospace propulsion consistently have utilized a development path where the behavior of the structural materials under prototypic environmental conditions was first thoroughly examined before construction of components.

There are currently two major knowledge gaps regarding the performance of structural and plasma facing materials exposed to fusion-relevant irradiation conditions. The first category is associated with exploratory investigations of fundamental materials science phenomena focused on addressing the questions underpinning whether any structural material can be designed to survive for damage levels greater than 20–50 dpa in a fusion environment. The second category (which is dependent on successful resolution of the first topic) is focused on development of a robust engineering database needed for the engineering design and licensing of a fusion power plant. These dual roles, which could be addressed in either the same or complementary irradiation facilities, are estimated to represent the rate-controlling steps for the successful design and construction of a fusion power plant.

With this in mind, a wide variety of dedicated irradiation techniques and facilities are expected, or proposed, to be utilized in the investigation of materials science phenomena and to test and qualify materials for future fusion power plants. Facilities that are in use or have been proposed include fission reactors (including isotopic and spectral tailoring techniques to modify the rate of H and He production per dpa), dual- and triple-ion accelerator irradiation facilities that enable greatly accelerated irradiation studies with fusion-relevant H and He production rates per dpa within microscopic volumes, D–Li and spallation neutron sources, and plasma-based sources (including reversed-field pinches, high-density Z pinches, beam-plasma mirror configurations, and compact Tokamak devices). While ion accelerators and fission reactors are expected to continue to play an indispensable role in the development of fusion materials through their ability to perform timely and cost effective initial screening studies on the radiation stability of new materials, they have key limitations that will require the development of new, dedicated capabilities to explore the fusion relevant regime. Proposed solutions include D–Li neutron sources, spallation neutron sources, and plasma-based sources.

Spallation neutron sources may provide some important niche information at moderate damage levels (~10 dpa), particularly in the near term, but at higher damage levels, there are concerns about the impact of non-prototypic gaseous and solid impurities produced by high energy spallation neutron transmutation reactions. This could lead to either overly conservative or overly optimistic estimations of the performance of model alloys and candidate structural materials under D–T fusion reactor conditions.

Plasma-based sources offer many attractive features, such as larger irradiation volumes and the opportunity for component testing, but need much further development before they are ready for implementation. Compared to other options, these facilities are expected to be relatively expensive, require relatively long design, construction, and initial start-up regimes, utilize significant quantities of tritium with little or no breeding capability, and will likely experience low availability during the first decade of operation. These facilities also tend to be much more integrated than accelerator based neutron sources, resulting in a higher risk as a first step into the fusion nuclear regime. Though ultimately integrated fusion nuclear devices will be required for component level testing, they would benefit significantly from being informed by fusion relevant neutron source materials science development.

An accelerator-based D–Li deuteron stripping source such as the proposed IFMIF is the most versatile and appropriate near-term, cost-effective option for a major dedicated fusion neutron irradiation facility that could simultaneously address the outstanding scientific and engineering design issues facing the international fusion materials program. This family of device has long been recognized by the international fusion materials community as the preferred development pathway and takes into account the key factors of cost, technology readiness, and sufficient irradiation volume for acquiring the materials engineering database for DEMO, and providing suitably prototypic irradiation conditions with respect to neutron spectrum and transmutations, while providing the capability for achieving moderately accelerated damage production compared to the fusion DEMO condition. This concept is currently being pursued by the EU-Japan Broader Approach IFMIF Engineering Validation and Engineering Design Activity, though commitment to the construction of the full IFMIF device continues to be postponed due to resource limitations (IFMIF is an estimated $1B+ class facility). Due to this continued delay, both the EU and Japan have expressed interest in a smaller, IFMIF-like device (estimated ~$0.5B class facility) which would fulfill the science exploration role, but would not allow for as aggressive an approach towards engineering design issues in order to save cost and accelerate schedule for construction. Likewise, the commitment to this pathway is also unclear, though somewhat more promising as a near term-solution.

Given the current state of affairs internationally, the US DOE Office of Fusion Energy Sciences sees a potential opportunity to expand US world leadership in fusion materials science by pursing a cost-effective, near-term fusion relevant neutron source aimed solely at fulfilling the exploratory materials science mission. Emphasis should be placed on cost-effective, near-term, with the goal of setting the materials science foundation to reduce risk with future thrusts at a US Fusion Nuclear Science Facility (FNSF), which is envisioned to be a plasma-based, component test facility.

Appendix C: Summary Needs for a Fusion Prototypic Neutron Source

Experimental questions that a FPNS could help answer (Workshop presentation by **S. Zinkle**)

• Low temperature phenomena: Hardening and embrittlement – Major effects observed in ferritic steels for C_{He}>500 appm – Due to increased matrix hardening and weakening of grain boundaries?

• Medium temperature phenomena: Cavity swelling – Major effects observed in austenitic steels for C_{He}>100 appm; ferritic steels for C_{He}>500 appm? – Synergistic effects for H & He?

• High temperature phenomena: High temperature He embrittlement of grain boundaries – Major effects observed in austenitic steels for C_{He}>1-100 appm; ferritic steels C_{He}>500 appm? (poorly understood)

• H trapping in cavities at intermediate temperatures can be an important safety issue for DT fusion energy systems

Modeling & simulation needs that may be addressed by a FPNS (Workshop presentation by **B. Wirth**)

•Significant development and recent successes in applying multiscale materials modeling that "begins" to converge with experimental observations of:

– Displacement cascade evolution & defect production in BCC materials that does not substantially depend on neutron energy spectrum

– Lack of temperature dependence of prismatic loop density with irradiation temperature in ferritic/martensitic steels & ability of temperature shift to compensate for dose rate effects at low T;

– <100> versus <111> prismatic loop populations in FeCrAl alloys;

– The intrinsic bias of small vacancy cavities for absorbing (self)-interstitials has been revealed thru atomistic modeling and has significant impact on cavity nucleation & void swelling in Fe-based alloys; and

– The impact of transmutants on defect evolution in tungsten

•But many challenges remain