Update from the Fusion Prototypic Neutron Source Workshop

Presented to:

Fusion Energy Sciences Advisory Committee

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ORNL is managed by UT-Battelle, LLC for the US Department of Energy

Outline

- FES guidance
- Review of international concepts
- US background
- Workshop summary

Language from the FY 2019 Budget Request

- *"FES will initiate a study to evaluate options for a neutron source that will test materials in fusion-relevant environments."*

- *"A study will be initiated to evaluate options for a neutron source to test materials in fusion-relevant environments."*

Primary Considerations (presented at the workshop by FES)

- *Energy Spectrum*
- *Irradiation Volume*
- *Fluence/Damage per Year*
- *Cost (including all necessary infrastructure)*
- *Timing*
- *Risk*

Neutron sources and IFMIF Have been evolving for >40 years

- 1975-1984: IFMIF concept evolved from the US FMIT project
- 1988-1992: IEA Collaboration Project
- 1994: IFMIF adopted by international community as reference concept
- 1994-2003: Conceptual Design and Key Element technology phases
- 2007-present: EU/Japan Engineering Validation and Engineering Design Activities (EVEDA)

Rationale for DONES

- The full capabilities of IFMIF will be required to support the engineering design requirements for the EU program full DEMO
- A scaled-down version (Demo-Oriented Neutron Source) is proposed to support the material database to support design and licensing of the phase1 early DEMO
- Overcomes problems with heavy financial cost of IFMIF and also planned deployment schedule too long to support full DEMO
- Planned irradiation program focus is on data on RAFMs in the 20-30 dpa regime; capability for irradiation testing of W alloys also under development

Main characteristics of DONES

- Single 125 mA, 40-MeV deuteron accelerator with 10 cm x 5 cm beam footprint producing 50% IFMIF neutron flux and coupled to a single High Flux Test Module (HFTM)
- Specimen encapsulation, temperature measurement and control characteristic of IFMIF
- Utilizes validated IFMIF plant components and retains the potential for future conversion to the full-scale IFMIF

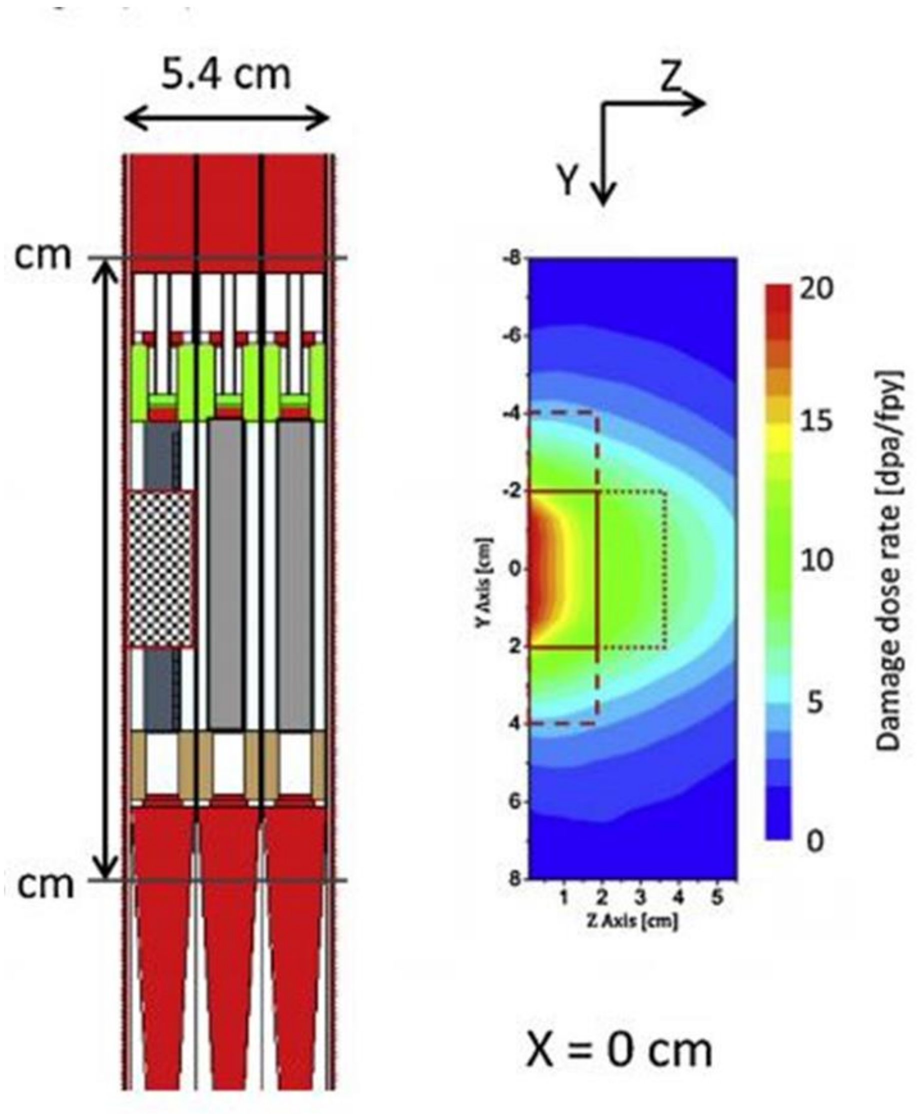
Summary of DONES irradiation conditions

- Central 4 x3 irradiation rigs provide highest quality conditions
- 12-25 dpa/fpy in a volume of ~300 cc (500-800 specimens)
- He production ~13 appm/dpa
- H production ~53 appm/dpa
- Specimen temperature range 250-550C; temperature control +/- 3% of K temp.
- Specimen in central regions with high volumetric heating encapsulated in Na
- Flux gradients; 20-25% difference in dpa per cm of specimen

Early Neutron Source (ENS): a lower cost concept considered by the EU

- LEFT: central area of HVTM front rig (hatched)

- RIGHT: damage rate map; front rig region(dashed), central area(full), middle rig region (dotted)



R.Heidinger et al. Fus .Eng. Des. 89 (2014) 2136

Main characteristics of ENS concept

- Utilizes a single 26.5 MeV accelerator with a beam footprint of 10 cm x 3 cm
- The payload is concentrated in the mid- region of the 2 central compartments of the IFMIF-HFTM
- Specimen encapsulation temperature measurement and control are the same as IFMIF
- Damage parameters:
  - 8-11dpa /fpy in a volume of ~ 75 cm^3 (~80 specimens)
  - He production 8-11 appm/dpa

Japan is also evaluating IFMIF-based options

	DONES	A-FNS-26MeV	A-FNS-9MeV
Neutron flux ($cm^{-2}\ s^{-1}$)	5.9×10^{14}	3.8×10^{14}	4.8×10^{13}
DPA/fpy	25	14	1.5
He production (appm/fpy)	3.1×10^{2}	1.2×10^{2}	6.6×10^{0}
He-prod./dpa	12	8.5	4.4
H production (appm/fpy)	1.4×10^{3}	5.6×10^{2}	3.4×10^{1}
Nuclear heating (W/g)	1.7	0.9	0.0064

*fpy: full power year

T. Nishitani et al., Fus. Sci. Tech. 68 (2015) 326

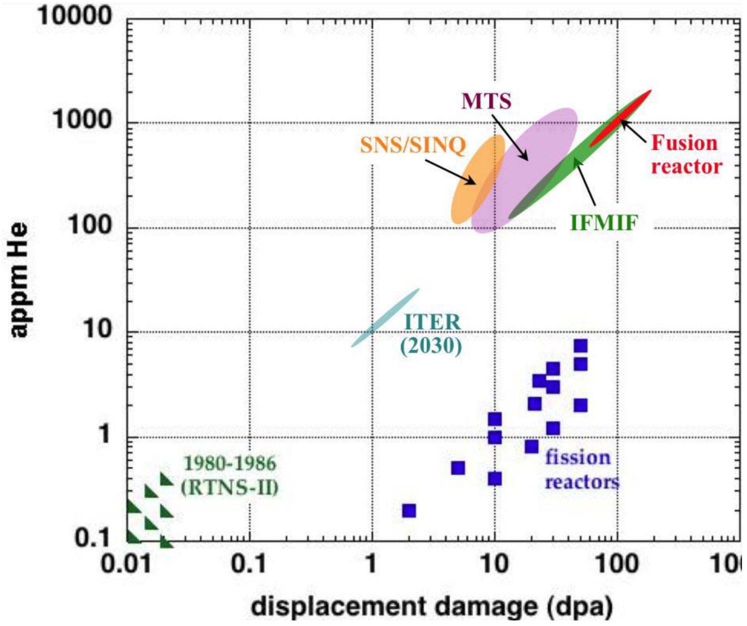
China is working on high-intensity neutron generators

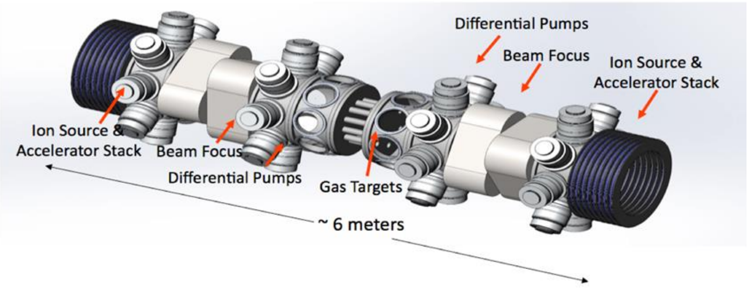
- HINEG-1 produces 6.4 x 10^{12} n/s; RTNS-II achieved > 3 x 10^{13} n/s
  - Designed and proposed concepts:
    - HINEG-II 10^{15} – 10^{16} n/s
    - HINEG-III > 10^{18} n/s
  - No information available on the schedule for China's advanced concepts

- BISOL-MAINS advanced neutron source
  - D-Li source for Multi-Aimed Intense Neutron Source
    - BISOL - Beijing Isotope-Separation-On-Line Neutron-Rich Beam Facility
  - Phased approach proposed
    - Phase-I (2026-2028): 40 MeV x 10 mA, ~1015 n/s, >8 dpa-steel x 12 cm3
    - 20 mA in Phase-II (~2030), 50 mA in Phase-III ("203?")

US scientists have been considering fusion prototypic neutron source possibilities for some time

- High displacement rate irradiations have been carried out in HFIR for decades
- A neutron source with the correct energy spectrum, producing gas synergistically with displacements, is needed to understand materials damage mechanisms
- IFMIF has been discussed for decades
- DONES/AFNS are the latest versions, with reduced scope but still costing hundreds of millions of dollars
- It is time to consider near term, moderate cost options to DONES/AFNS to provide understanding now
  - Phoenix Nuclear Labs has a proposal for a DT neutron generator
  - Spallation sources can provide low displacement data





Phoenix Nuclear Labs neutron generator concept

OAK RIDGE National Laboratory

Fusion Prototypic Neutron Source

- Initial discussions between the Virtual Laboratory for Technology (VLT) and FES led to language being inserted into the FY19 budget
- The VLT helped FES organize a workshop around the topic
- 33 members of the US fusion materials community, the VLT, and private industry met August 20-22, 2018, and discussed the possibility of the US developing a Fusion Prototypic Neutron Source (FPNS)
- Initial discussion indicated that the source would be a potential intermediate step to IFMIF/DONES/AFNS
  - The source must be “near term” and of moderate cost
  - The goal is to advance the scientific understanding of fusion neutron damage in prospective structural and blanket materials

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

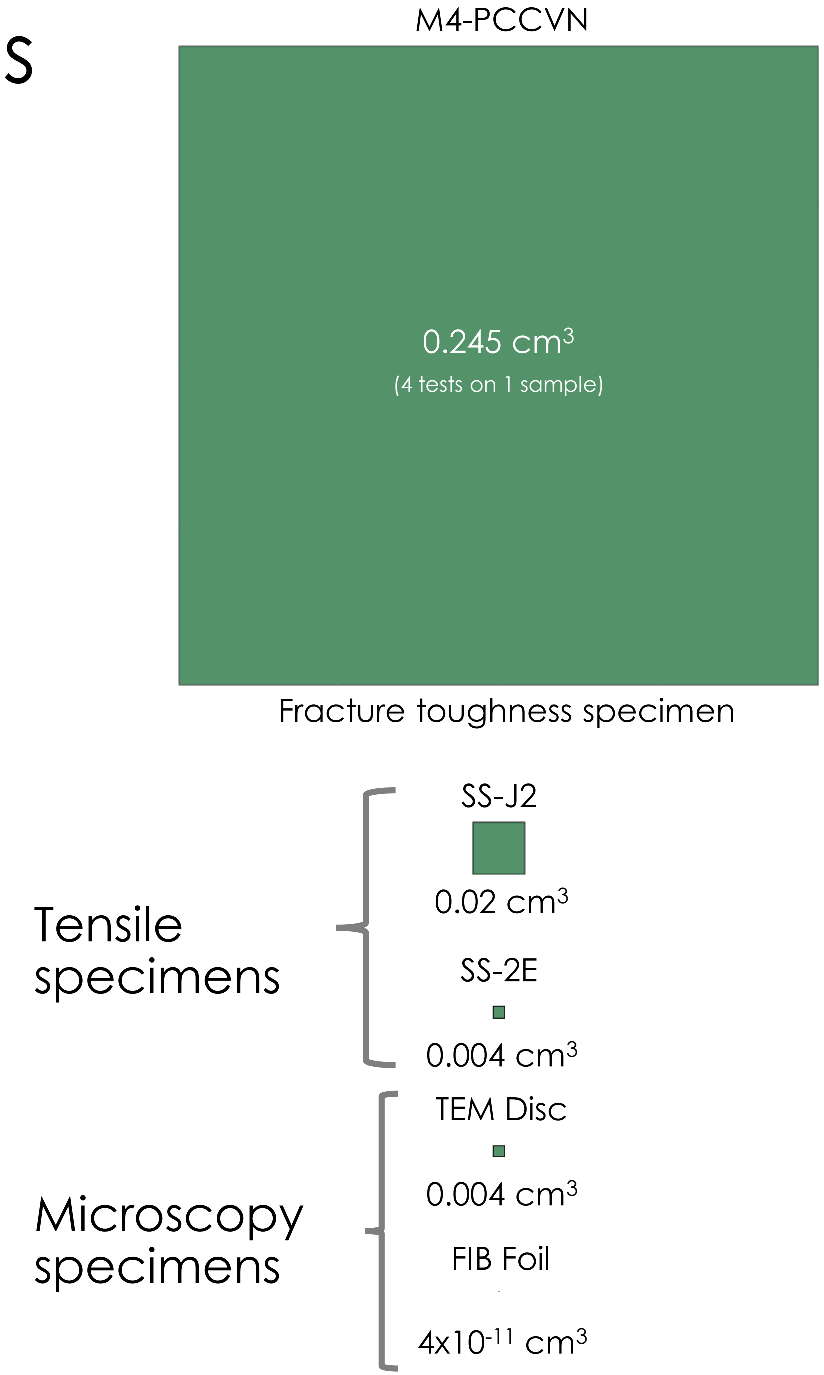
- **Low temperature phenomena: Hardening and embrittlement**
  - **Major effects observed in ferritic steels for C_{He}>500 appm**
  - **Due to increased matrix hardening and weakening of grain boundaries?**
- **Medium temperature phenomena: Cavity swelling**
  - **Major effects observed in austenitic 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**

Success in reducing sample size relaxes constraints on the source design

- Small specimens don't mean limited engineering or science
  - Combining modern materials science enables the determination of engineering data, mechanics data, and microstructure data resulting in effective determination of materials performance
  - Many factors need to be considered:
    - Radiation facility requirements
    - Hot cell facility requirements
    - Shipping/handling requirements
    - Many others…
- More data from the same sample volume



Workshop attendee stance on IFMIF

- Workshop attendees were polled as to their involvement with IFMIF or an IFMIF predecessor
  - Richard Nygren won the prize, starting work in 1977 (FMIT)
- There was universal concern as to when IFMIF/DONES would be constructed
- It was also noted that the goal of IFMIF is to provide the engineering database for a DEMO facility
  - Preferably this step would be preceded by a materials science facility
  - The US program aims to fill this need, possibly providing information to guide the design of the next US facility and IFMIF
- The point of a near term, moderate cost neutron source would be complimentary to IFMIF, not a replacement for IFMIF

FPNS parameter space

- After two days of presentations focused on materials issues, but also covering other needs for a fusion neutron source, a consensus was reached that *a fusion prototypic neutron source (FPNS) would be a significant benefit to the US program*
- For a FPNS to have maximum impact, a set of source characteristics were specified:
  - **8-11 dpa/CY in the high flux zone**
  - **~10 appm He/dpa in Fe**
  - **≥ 50 cm^3 in the high flux zone**
  - **300 – 1000 °C, with three independent temperature zones actively monitored and controlled**
  - **Flux gradient ≤ 20%/cm in the plane of the sample**
    - can be greater traveling away from the neutron source
- Note that these characteristics are similar to the European Early Neutron Source (ENS) which was considered but not pursued

Workshop follow up

- Distribute presentations from the VLT website
- Create a short (3-4 page) summary of the meeting
- Identify concepts/institutions that may have interest in participating in the FPNS concept discussion
- Start (continue) information gathering on neutron source concepts
  - Both FES and the VLT members
- Position FES to pursue CD-0 in FY19 should they choose this path

Summary

- Fusion neutron sources have been an identified need and topic of research, both in the US and internationally, for more than four decades (going on five…)
- Current large international activities are focused on generating the materials design database for DEMO
  - Some Chinese and Japanese options have different goals
- The US program has identified a gap that can be filled with a near term, moderate cost neutron source for materials science studies
  - Experimental and modeling & simulation needs have been identified
- Efforts are underway to support a CD-0 process should FES decide to pursue