Fusion Material Irradiation Test Station (FMITS) at SNS

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The scientific demonstration of magnetic fusion energy as an environmentally sustainable and economically competitive energy source will require development of high-performance reduced-activation structural materials that exhibit unprecedented self-healing capability during prolonged exposure to intense D-T fusion neutrons that have energies up to 14 MeV. Unfortunately, due to the lack of a fusion-relevant intense neutron source, the maximum experimental 14 MeV neutron exposure levels achieved to date (~0.01 displacements per atom, dpa) are about 4 orders of magnitude below what will be required in a demonstration fusion reactor (Fig. 1). Computational modeling and experimental studies indicate the initial displacement damage structures for fission, 14 MeV D-T fusion, and spallation neutrons are similar [1-3] This suggests fission reactors can continue to provide valuable fundamental radiation-induced microstructural and mechanical property information on candidate fusion reactor materials. However, helium and hydrogen production levels due to nuclear transmutation with a DT neutron spectrum for candidate reduced activation materials (~10 and 40 appm/dpa, respectively for Fe) are factors of 10 to 100 higher per unit of displacement damage than those of a fission neutron spectrum (Fig. 1). These high H and He generation levels can have a pronounced effect on the radiation damage accumulation at high dose. For example, early work on a radiation-resistant austenitic steel developed for fast fission reactor applications found that the steel had poor void swelling resistance when exposed to a simulated fusion neutron spectrum [4]. The uncertain impact of these gaseous transmutation products is broadly recognized as the central unresolved issue regarding the potential suitability of structural materials in future fusion reactors, as discussed in recent FESAC [5] and ReNeW [6] panel reports.

There are several possible approaches to investigate fusion-relevant synergistic effects involving radiation damage and H, He production [5, 7]. In all cases, a combination of modeling and dual- or triple-ion-beam and specialized fission neutron irradiation experiments such as B doping [8] and He injector foil microstructural studies [9] are expected to play a significant role. While injector foils and ion irradiation facilities provide valuable fundamental microstructural information, the limited damage depth of a few micrometers does not allow critical mechanical property information such as fracture toughness and high temperature He embrittlement to be studied. The high damage rates associated with ion beam irradiations also make it difficult to quantitatively extrapolate observed phenomena to fusion-relevant conditions. Tailored additions of B or Ni prior to fission reactor irradiation can generate significant quantities of He, but the B and Ni tend to segregate (producing numerous experimental artifacts) and the He/dpa production rate varies during the irradiation.

Spallation neutron facilities offer the opportunity to explore microstructural evolution and bulk radiation damage phenomena at H and He production rates per dpa that are higher than the fusion relevant condition (by a factor of 3 to 10). This can provide valuable experimental information (in combination with fission reactor data) for the development of robust fusion materials radiation effects models. Existing spallation facilities can achieve damage levels of ~10 dpa for 1 to 2 year exposures, with simultaneous transmutant He levels of ~200-1000 appm.

Since radiation effects models and scoping experimental studies suggest helium effects become significant for concentrations above ~10-500 appm He (depending on temperature, material, etc.) [5,7-9], spallation irradiation facilities could provide key information on synergistic helium, hydrogen and displacement damage phenomena. Due to ongoing uncertainties about potential artifacts associated with beam pulsing, non-prototypic solid transmutation element production, and the high-energy (>20 MeV) neutrons in spallation sources, embarking on a major (~100 M class) spallation irradiation facility for fusion materials studies may be premature at this juncture. However, it may be highly valuable to leverage major investments by other agencies (e.g., 1.4 B by DOE-BES for the Spallation Neutron Source, SNS) to perform some high-quality, modest-cost spallation neutron irradiation experiments to dramatically improve our current understanding of helium-radiation defect interactions and to quantify any potential artifacts associated with spallation neutron irradiations.

The proposed Fusion Materials Irradiation Test Station (FMITS) at the SNS [10] would provide world-leading capability to explore fusion-relevant helium-hydrogen-radiation defect synergistic evolution in a range of materials. At the current time, there is only one spallation facility in operation worldwide that is being used for materials irradiations, i.e., the SINQ facility in Switzerland where damage levels of 10 dpa can be achieved after 1 to 2 years. Unfortunately, the irradiation temperature is not independently controlled; the sample temperature depends solely on a stagnant gas gap and nuclear heating from the incident proton beam. As a consequence, the irradiation temperature can vary widely due to the numerous beam trips (~50 per day) and variation in beam current, with calculated representative sample temperatures varying from 230°C to over 600°C for significant periods of the irradiation [11]. Such wide temperature variability is unacceptable for the purposes of model verification.

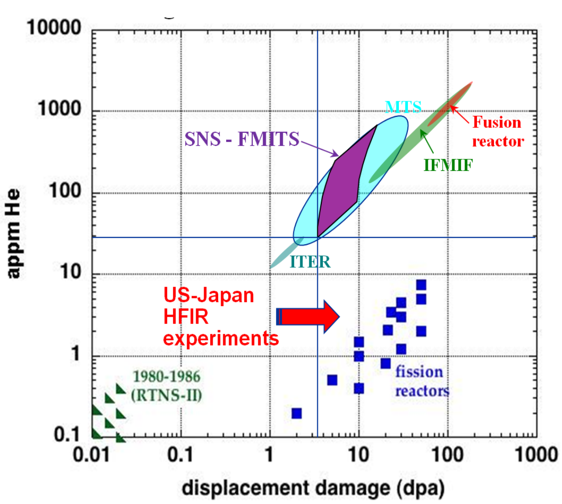
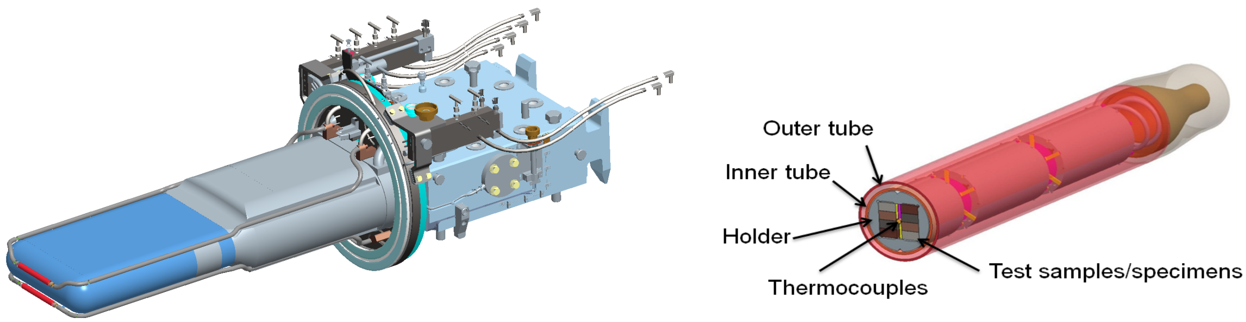


Figure 1 : Comparison of 2-4 year helium and dpa levels for ferritic steels in candidate irradiation facilities (adapted from [5]).

A key feature of the proposed FMITS is the possibility to explore near fusion-prototypic levels of helium and hydrogen in a range of materials with state-of-the-art temperature control at a per-experiment cost comparable with current fission neutron irradiation experiments. In Fig. 1, irradiation parameters for a 2-4 year irradiation at SNS running at 1 to 1.4 MW is compared with other facilities (Rotating Target Neutron Source, RTNS; Material Test Station, MTS; International Fusion Materials Irradiation Facility, IFMIF). FMITS will provide the opportunity for the US program to solidify our scientific leadership in this critical area of fusion structural materials development leveraging our current strength in modeling, irradiation materials science, and fusion materials development. By exploiting the understanding gained from moderate-dose FMITS data and from modeling, the US program will obtain crucial world-leading scientific insight on radiation effects phenomena under fusion-relevant conditions; such understanding is needed to design appropriate materials for fusion and to enable more rapid and effective use of a future large volume fusion engineering irradiation facility, such as IFMIF, when it becomes available.

System Design and Key Performance Measures

Conceptual and detailed target design of FMITS has been carried out to ensure the facility is viable with no technical obstacles to construction. The sample regions are contained within a tubular harness wrapping around the existing SNS target (Fig. 2(a).) The two sample regions may be located in different irradiation zones depending on their offset from the proton beam centerline, which could vary from 2 to 5 cm. The irradiation parameters for Fe in these two positions: 5-10 dpa per full power year, 20-75 appm He/dpa and 100-310 appm H/dpa [10]. Figure 2(b) shows the FMITS tubes in more detail. The test specimens will be spring-loaded into holders and stacked within an inner stainless steel tube pressurized with an inert gas mixture. Temperature control is achieved via computer-controlled gas blending to reach the needed thermal conductivity as is typically done in HFIR irradiation capsules (volumetric heating is provided by the incident beam); multiple zone irradiation are anticipated. Cooling water flows through the annulus between the inner and outer FMITS tubes. Sample temperature is determined by thermocouples terminated within the holder test zones.



(a) (b)

FIG. 2. FMITS assembly installed onto an SNS target module (a), and test section containing irradiated samples (b).The sample irradiation positions for the two tubes is highlighted in red in lower left of Fig. 3a

The irradiation capsule design will be based on proven methods used in the HFIR fission materials irradiation experiments providing microstructural and mechanical property data in the 100-1000°C range. Two sample regions, each typically 12-mm-diam by 175-mm-long, can accommodate more than one hundred materials samples per irradiation which will allow comprehensive microstructural, physical and mechanical property characterization; this volume is intermediate between typical HFIR target and hydraulic rabbit capsules [7]. The design will allow unmanned operation with machine failure protection and no impact on the safety and reliability of the SNS.

The FMITS assemblies will be compatible with existing SNS Target Service Bay remote handling equipment and amenable to reuse after irradiation, sample extraction and waste disposal. Multiple irradiation periods on consecutive targets will be possible for high exposure of sample sets. FMITS installation and replacement will have minimal impact on normal target replacement downtime. The initial installation of the FMITS hardware including replacement shield block and gas utilities will be performed during normal scheduled SNS outages.

An evaluation of off-normal events was performed and the SNS hazard analysis was revisited; no major problems were identified. A quantified risk assessment remains to be performed in the final design phase. To minimize potential operational outages due to the presence of FMITS, precautions in the form of mockups, qualifications, and design improvements have been included in the proposed cost/schedule.

Schedule and Cost

The schedule is for 30-months of design, fabrication, and installation. The plan requires 18 months of design with a review prior to procurement. In parallel with design, mockup testing for hydraulic performance and remote handling is necessary. The 14-month target fabrication is on the critical path for the FMITS schedule, so an early release to begin the target fabrication is beneficial. It is possible to complete all installation without affecting the SNS operations plan.

The total estimated one-time cost for the test facility is $10M including contingency [10]. Design and hardware costs were estimated at the component level and by project phase using rigorous SNS costing methods. Remote handling costs were based on the last 5 years operational experience. A preliminary cost estimate for performing subsequent irradiation experiments at the FMITS facility has been performed [10]. For a given experiment there is a cost for fabrication, installation and irradiation of the experimental hardware on a single target module. There is an additional cost for the assembly re-use with subsequent targets. The total for the first irradiation cycle for each experiment is $850K including 25% contingency. For each additional target cycle the cost is $130K including 25% contingency. This is comparable to the cost for HFIR removable beryllium instrumented capsules currently utilized by the fusion materials program. Disassembly of experiment and follow-on testing would utilize radiological facilities currently used by the fusion materials program.

Conclusions

An understanding of the effects of a fusion-relevant neutron spectrum on materials has been clearly identified by the fusion community as a critical area of research. The combination of the proposed facility, the current supporting radiological infrastructure, and a domestic materials science community that has historically led the field of irradiation materials science and fusion reactor materials development, will create a world leading capability. FMITS can be operational within 30 months of project authorization for $10M. The per-experiment costs are consistent with current in-core HFIR experiments mounted by the fusion materials program. The similarity between the current HFIR fusion materials experiments and those proposed for FMITS allows for significant technology transfer. The FMITS will have no significant impact on the SNS moderators, and therefore should not affect the quality of the SNS neutron science mission. Installation activities can be accomplished without additional shutdown periods.

References

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