Fusion Materials Qualification with a Spallation Neutron Source Facility

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Developing a Strategic Plan for US Fusion Research in the ITER era:

Specially designed target irradiations in a spallation neutron source facility can be used to address many critical issues and gaps towards a long range strategic plan for fusion energy identified in the Greenwald report. These mission gaps include the following:

1. Qualifying materials under a high fluence neutron environment including:
    a. Structural materials (e.g. ferritic steels)
    b. Materials under high heat loads (e.g. refractory alloys)
    c. Insulator materials
    d. Welds and brazes
2. Determining the effects of fusion relevant environments on the sintering behavior of tritium breeding materials (e.g. Li-containing ceramics and Be compounds)
3. Determining the effects of irradiation on specific properties of structural materials including
    a. Void swelling
    b. Optical and electrical resistivity
    c. Thermal conductivity
4. Measuring chemical compatibility in an irradiation environment (e.g. corrosion in liquid metals and He gas coolants)

Designing a Spallation Target Facility to obtain Fusion Relevant Irradiation Data:

Although some understanding of irradiation effects in materials can be obtained through direct irradiations in a spallation spectrum [1, 2], through appropriate target design, a fusion relevant spectrum can be obtained in a spallation source. Recent calculations by Pitcher[3] show that a target design for the Materials Test Station (MTS) which uses the proton accelerator (800 MeV, 1.25 mA) at the Los Alamos Neutron Science Center can produce a peak neutron flux of 1.6 x 10^{15} n/cm^2/s. Damage calculations show that a max displacement damage of 35 dpa per full power year can be obtained at such flux. The effect of the high energy spectrum on steel samples with respect to spallation production of helium and hydrogen will be similar to that predicted in a fusion spectrum. Helium production levels in this peak flux position would be 13.4 appm He/dpa and depending on the irradiation location can range from 4 to 25 appm He/dpa. Such positions would be valuable for performing fundamental studies of the effects of helium on materials properties.

There are differences between the flux spectrum produced by a spallation source compared to that predicted in a fusion reactor. Compared to a fusion spectrum from 14 MeV neutrons, the spectrum from a spallation source will have a small percentage of higher energy protons and neutrons. Calculations have shown that the damage produced from a high energy particle occurs through many smaller subcascades as the particle traverses through the material[4]. So, although the initial energy may be higher, the damage production within the material is controlled at the subcascade level which would be very similar in both spectra.

The higher energy particles may also have a larger cross section for production of impurities by spallation. The most prominent nuclide produced by spallation will have the atom number (Z-1). So, for typical Fe-based alloys, some “burn-in” of Mn would be expected. Calculations for an MTS spectrum on Fe expect a burn-in of Mn of ~10 appm/dpa. Thus an irradiation to ~50 dpa would produce 0.05% Mn from spallation. Typical Fe-alloys such as T91 already have 0.5% Mn. So, this increase in impurities would not be expected to affect the irradiation response in this alloy. A detailed calculation of impurity production in T91 for both MTS and IFMIF spectra is shown in Fig. 1 for an irradiation to 25 dpa. Calculations of impurity production in an MTS spectrum were also performed for SiC, Nb-1Zr and V-4Cr-4Ti and, in general, very little differences are observed compared to those calculated for an IFMIF spectrum.

The proton beam used for a spallation irradiation facility such as MTS will be pulsed at a frequency of 100 Hz. This pulse frequency does not affect the irradiation temperature and a constant specimen temperature can be obtained during irradiation. In the magnetic confinement fusion concept, a continuous neutron flux environment is expected while other fusion concepts (e.g. inertial confinement fusion) would have a pulsed nature to their neutron flux environment. The materials response from interaction with a 100 Hz pulsed beam is expected to very similar to that observed in a continuous beam. For example, one property that can be affected by a pulsed neutron flux is void growth during swelling. Modeling has shown that low pulse frequencies can lead to reduced void growth at high irradiation temperatures but at frequencies less than 10 Hz. Very little effect on void growth would be expected from neutron flux pulsed at 100 Hz[5].

As is common with high-power accelerators, the LANSCE accelerator experiences of order 6 beam trips daily. These are typically short in duration (~10 s). During the trip, materials samples will cool from their operating temperature to the inlet coolant temperature with a time constant of order 30 s. This same time constant applies to the return of the materials samples to their steady-state irradiation temperature once the beam is turned back on. Thus the samples will be irradiated at less than the desired irradiation temperature for approximately ten minutes per day (ten trips per day with one minute transient period each). That is, for less than 0.5% of the irradiation time, the samples will likely be at less than the desired irradiation temperature, which should be acceptable in terms of prototypicality.

Qualification Testing on Materials:

To address the mission gap of qualifying materials under a fusion relevant high fluence environment, a matrix of test specimens could be placed into a spallation neutron source facility and held and monitored at specific irradiation temperatures using gas gaps and varying gas mixtures (to control the thermal conductivity). Mechanical property measurements such as tensile and fracture toughness can be measured through post irradiation testing of small scale specimens before and after irradiation. Small scale specimens such as the S-1 tensile (dimensions are 16 mm long, 5 mm gauge length, gauge cross section=0.25 mm x 1.2 mm) or subsize compact disk specimens (12.5 mm diameter, 2-4 mm thick) are small enough to obtain a uniform fluence of these specimens.

Some properties will develop in situ with irradiation such as thermal conductivity, sintering, creep, fatigue crack growth, stress corrosion cracking and corrosion. To test these properties, in situ measurements would be performed. Testing in a spallation source allows the flexibility of setting up dedicated loops for performing corrosion tests in situ or using linear variable displacement transducers (LVDT's) to measure displacement changes in situ required for monitoring sintering or fatigue and creep measurements.

Proposed Initiative:

Thus, to address the mission gaps discussed in the Greenwald report towards a long range strategic plan for fusion energy, it is proposed in coordination with development of a spallation neutron source facility (e.g. MTS), to design an irradiation matrix for qualification of materials (Structural materials (e.g. ferritic steels), materials under high heat loads (e.g. refractory alloys), insulator materials, and welds and brazes) under a high fluence fusion relevant neutron environment. This would include designing holders for uniformly irradiating materials under a constant, monitored irradiation temperature and designing in situ irradiation testing capabilities.

References:

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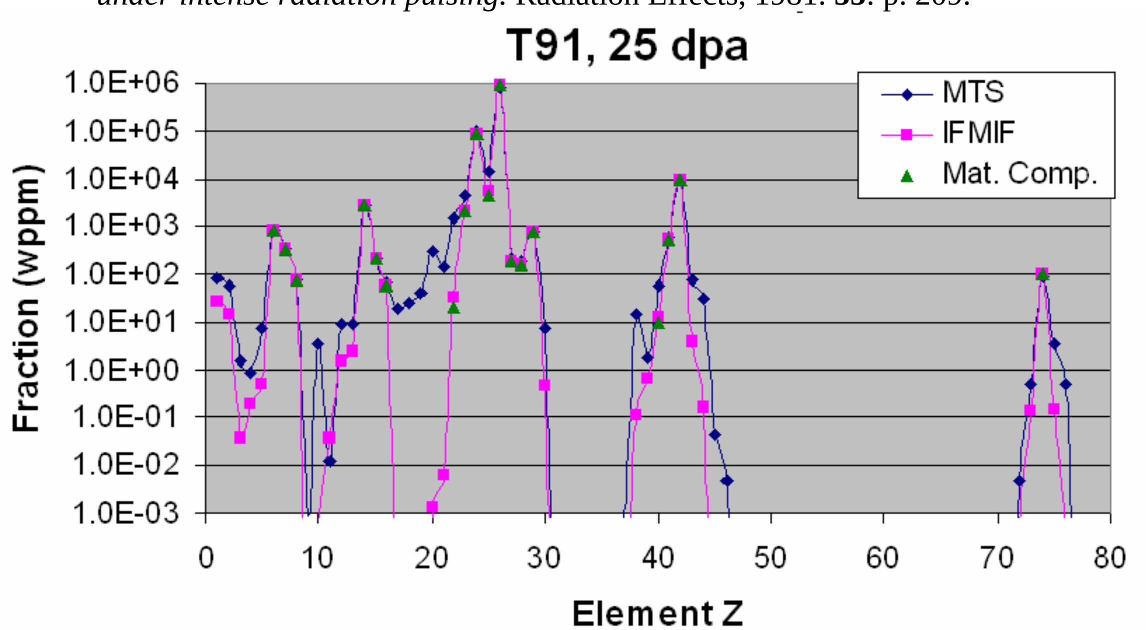

Figure 1 Graph showing calculation of impurity production in T91 from spallation in MTS and IFMIF spectra.