Impact of Neutron Irradiation on Plasma-Materials Interactions

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1. Background

1a. Progress since ReNeW

There have been significant findings of critical importance since the ReNeW exercises in areas of neutron irradiation effects in W, including the severe embrittlement, hydrogen isotope retention, helium-defect interaction, and nano/microstructures.

1b. Opportunities, National/International Context, Scientific Urgency

Neutron irradiation in fusion reactors will impose inevitable and critical impacts on the technical feasibility, performance, integrity, and service life of plasma-facing materials (PFM) and components (PFC). Such effects will not be limited to those on bulk properties but extend to the surface and near-surface PMI phenomena. Through the atomic displacements and transmutations, neutron irradiation has the potential to significantly alter the edge plasma-interaction phenomena in the plasma-facing near surfaces. However, the synergistic effects of intense neutron irradiation with the particles/heat fluxes from divertor plasma have so far been very insufficiently understood. This white paper is intended to discuss the updated research needs and opportunities related to the impact of neutrons on PMI phenomena, with somewhat more specific proposals given in the next section.

Recent research on W as a PFM, including the US-Japan TITAN/PHENIX projects, is producing new insights into neutron irradiation effects that have important implications. The recent findings include: 1) HFIR irradiation revealed very significant embrittlement in low-dose neutron irradiated W even at fairly high temperatures [1], 2) US-Japan collaboration research found major increases in solubility and high temperature retention of D in W [2], and 3) advanced materials characterization is revealing distinct differences between neutron and ion irradiated W nanostructures that likely affect all of He/H interactions, near-surface phenomena, and bulk properties [3]. All of these enhance the critical needs for research in areas of the neutron-edge plasma synergistic effects on PFM.

2. Specific Proposal

Neutrons cause many varied effects that have a very broad impact on the areas of PFC and PMI research. We propose a new initiative to study the critical PMI issues in the following areas through combining the scientific resources in the communities of plasma-surface interactions, fusion materials, and advanced materials characterization.
Direct interactions: The impact of neutron irradiation on PMI phenomena is very complex but can be classified into two categories: direct and indirect interactions. The direct neutron interactions include the production of large displacement cascades that alter the near-surface material evolutions [4], the presence and diffusion of vacancies that modify the fate of He/T/D injected from plasma and play a role in the dynamic evolutions of near-surface microstructures [5-7], the continuous generation of transmutation He/H by energetic neutrons in addition to the implantation of He/T/D from plasma [8], and the synergistic effect of solid transmutations (i.e., Re, Os) and atomic displacements resulting in peculiar nano-composited structures that can affect every near-surface phenomena [3]. The interplays among displacement damage, transmutations (both solid and gaseous products), and implanted He/T/D in the highly damaged W will also impact the injection of particles in the near-surface [9-11]. Note that these are only a few examples of a vast variety of the possible direct neutron effects that alter PMI and mechanisms.

Indirect interactions: Neutrons can also cause changes to the material that indirectly affect PMI. Neutron-induced bulk property changes in materials fall into this category. To name a few instances, the surface temperature increase arising from the thermal conductivity degradation in W [12] should affect most of the near-surface material evolutions; the irradiation embrittlement will affect cracking, exfoliation, and dust production behaviors [13, 14]. In order to understand these indirect interactions, both the near-surface plasma interactions and the bulk properties need to be studied with advanced materials science characterization methods to understand the physical processes.

Development of the optimal technical approach to address these complex issues is best derived from open scientific discussion involving key scientific experts in PMI, safety, and materials research. The first step should involve building a community that includes necessary expertise of materials and traditional plasma-surface interactions (PSI) sciences in both experiment and modeling. The near-term technical approach will utilize fission neutron irradiation combined with various post-irradiation and limited in-pile experimental techniques. Access to fusion spectrum neutrons needs to be pursued at the same time. Surrogate experiments (e.g., employing ions instead of neutrons) will be useful to study the physical processes while their limitations need to be better clarified. Modeling plays a key role of bridging the gap due to lack of venue for true synergistic experiments.

3. Anticipated Results and Impact

Direct interactions: Understanding the interactions among the neutron, particles, and heat fluxes on the near surface phenomena of PFM potentially has a tremendous impact on feasibility and/or performances of the current and future PFC concepts.

Indirect interactions and bulk irradiation effects: Advancing understanding of the effects of displacement damage and transmutation on the bulk properties and hydrogen isotope transport is an essential objective of the PFM research with important implications to PMI.

Community development: The proposed initiative will contribute toward building a cohesive community of edge plasma, materials sciences, and fusion fuel cycles and tritium safety in U.S.
4. References


