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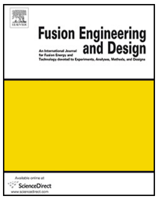

Materials challenges for the fusion nuclear science facility☆

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HIGHLIGHTS

- The FNSF materials strategy must bridge the gap between ITER and DEMO.
- Advanced materials beyond pure tungsten are needed for the first wall and divertor.
- Starting with a Gen-1 RAFM blanket, advanced alloys will be progressively introduced.
- SiC flow channel inserts meet many requirements but require more development.
- The vacuum vessel receives a low dose but must last the full device lifetime.

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ABSTRACT

The phased development and component testing mission of the Fusion Nuclear Science Facility (FNSF) implies a unique scenario for the development of structural and plasma-facing materials. The phased development of the machine and the capability to periodically remove and replace power core sectors allows for the introduction of materials and components with progressively improved operating characteristics throughout the lifetime of the machine. In addition, the machine components removed at each operational phase will provide the first opportunity to test and examine materials irradiated to useful neutron fluences in a fully integrated fusion environment. Options for structural and plasma-facing materials are considered and a preliminary set of materials identified to meet the challenges of power core components and for the machine-lifetime components such as the vacuum vessel and the structural ring. The status of FNSF-relevant materials research and development within the US fusion material program is summarized, and future directions for developing advanced materials to enable the long-term missions of an FNSF are discussed.

1. Introduction

This paper presents a preliminary evaluation of the materials challenges presented by the conceptual design [1] for a Fusion Nuclear Science Facility (FNSF) to bridge the development gap between ITER and a demonstration power plant (DEMO). Here the FNSF specifically denotes the concept that has been studied in the recent Fusion Energy System Studies (FESS) supported by the US Department of Energy, also called the FESS–FNSF, which is examining a conventional aspect ratio tokamak. The FNSF is an experimental machine designed to establish the reliable performance of the critical fusion system technologies required in DEMO and power plants. The FNSF horizontal maintenance system [2] allows for periodic removal, examination, and replacement of full power core sectors.

These activities will provide critical information on material performance in a fully integrated system to complement the single-effects irradiation database on candidate materials generated by any of the proposed accelerator based, intense, 14 MeV neutron sources such as the European proposed DEMO-Oriented Neutron Source (DONES), the Japanese proposed advanced fusion neutron source (A-FNS), or the International Fusion Materials Irradiation Facility (IFMIF) [3]. It is considered essential to have information from both a FNSF facility and a separate 14 MeV neutron facility before proceeding to the final engineering design of a fusion

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nuclear power plant. Throughout the lifetime of the FNSF, there will be a continuing requirement for access to a fusion-relevant neutron source to validate the performance of the advanced materials required to sustain the increasingly aggressive requirements of the phased development of power core components.

Based on an initially conservative set of operating conditions (operating temperature range, neutron damage, helium generation levels, and mechanical loading) the available materials choices are considered for the removable power core components (first wall (FW), blanket, divertor),the flow channel inserts (insulators) for the dual-coolant lead–lithium (DCLL) blanket, and the machine-lifetime components (vacuum vessel, structural ring, low-temperature magnet shield). Possible options are considered for more advanced materials to meet the requirements of the phased increases in operating temperatures and neutron damage exposure in the progression toward DEMO-like conditions. Recent progress on these FNSF-relevant options is summarized. There are numerous other materials that are essential yet require significant research and development (R&D) to enable engineering design of the FNSF, such as for diagnostic systems, magnets, radio frequency (RF) launchers, heat exchangers, and tritium controls. However, discussion of challenges for these materials is outside the scope of the present article.

2. First wall and divertor materials

2.1. First wall

The FNSF FW concept is a thin tungsten (W) layer coated on a RAFM steel structural material. The purpose of the W layer on the FW is to (1) protect the blanket components from temperature excursions during any transient (edge localized modes, ELMs) and off-normal events (disruptions) in the device and (2) protect the blanket from erosion from ions impacting the wall. A thin W layer is advantageous to maximize the number of neutrons reaching the breeding zone, whereas a thicker W layer has the advantage of further reducing the temperature in the steel components of the FW. Additionally, the thickness of the W layer has to be sufficient to not be eroded during the lifetime of the component. The temperature gradient through the FW layer depends on the thickness of the layer, and thus different thicknesses would have a different stress state. In turn, designs with different temperature profiles could lead to different neutron-irradiated property changes because irradiation defects have temperature dependent formation. The optimal FW layer thickness must be a balance of all these factors. As a starting point of comparing the effects of different FW thicknesses, simulations for the FNSF project have used a 2, 0.5, or 0.2 mm thickness for the W layer.

The steady state heat flux to the FW from plasma radiation is estimated to be approximately 0.25 MW/m^2. In addition to the heat flux from the plasma radiation, there will be a contribution to the heat flux from the flux of ions and neutral atoms incident on the FW. This contribution to the total heat flux on the FW from the particles cannot be neglected and would need to be modeled in more detail during the R&D phase of the FNSF design. Moreover, during plasma startup, power excursions, or other operations the heat flux to the FW will be higher than the steady state value. One of the acceptance criteria for any FW design would be withstanding the necessary steady state and off normal heat flux loads for the desired lifetime of the component without failure.

Table 1 lists some estimated steady state and off-normal temperature and stress values for the FW surface and at the interface with the steel, as calculated by Blanchard et al. using a 0.5 mm thick W layer [4]. The outboard (OB) values were the focus of that study because they are more severe than the inboard (IB) side values. The values summarized in Table 1 are the maximum values for the different modeled scenarios and do not capture the dynamic and spatially varied distribution of those properties after the off-normal events (found in Ref. [4]). The maximum values are of use here for the discussion of conditions the W components must withstand. As noted by Blanchard et al., for the disruption and ELM simulated, the temperatures for the surface of the FW are well below the melting temperature of W, but there would be plastic strain [4]. It is important to consider that temperatures above tungsten's recrystallization temperature (~1200–1500 °C depending on the microstructure) may be considered failure because of the negative mechanical property changes in W above recrystallization. More experimental testing would be needed to determine if recrystallization is allowable in the FW and divertor components of the FNSF. At the W-to-steel interface, the temperature rise after a disruption could damage the steel; but during steady state operation and after an ELM, there is no predicted failure [4]. The model used in Ref. [4] uses unirradiated properties of W. Because of the limited neutron irradiation data available, there is a need for experimental material science to develop constituency relationships for properties after neutron irradiation.

The neutron wall loads (NWL) and estimated displacement per atom (dpa) values for the OB and IB FW are listed in Table 2 for each of the phases of the FNSF program; a prototypical power plant estimate also is listed. For each successive phase of the FNSF, it is assumed that the FW, divertor, and other components inside the vacuum vessel would be replaced; so the dpa would accumulate during one phase before change-out. The dpa will increase as the phases continue because it is planned that the plasma on time, total length of phase, and other details of the plasma operation will increase in each operational phase. The FW and divertor will be rebuilt for each phase, which allows for design or material choice changes and upgrades in later phases; but those details have not been accounted for in the information in Table 2.

The NWL values in Table 2 were calculated by Davis et al. [5]. Their calculation assumed a 2 mm thick W layer on the FW. To estimate the dpa for all the components, first the neutron fluence to the blanket structural material (NWL × years of operation × percentage of plasma on time) was multiplied by ten to approximate the dpa for a RAFM type steel. Then, to estimate the OB FW W layer dpa, the blanket structural material dpa values were multiplied by a factor of 0.3, which is the relation found by Sawan as the ratio of steel dpa to W DPA for the same incoming magnetic fusion energy spectrum neutron flux [6]. Finally, the dpa estimates for the other W components were scaled based on the ratio of their NWLs and the NWL of the OB FW W. Of course, a more accurate estimate of the dpa in the W components would require a more detailed neutronics model of the full reactor system, but these values in Table 2 represent an order of magnitude indication of goals for designing W materials.

Again, note that the temperature and stress estimates in Table 1 were completed with a model of the FW using a 0.5 mm thick W layer, whereas the model used to calculate the NWL in Table 2 used a 2 mm thick W layer; but together they give an indication of the area in parameter space that is the goal of the FNSF FW W layer. Comparing the thermomechanical results from Table 1 with the expected dpa to the FW in Table 2, it is clear that the FW structure must withstand these temperature and stress excursions while under moderate to severe amounts of neutron irradiation, ranging from 2 dpa in the first nuclear phase to 25 dpa in the final phase, phase 7, for the OB FW W layer.

The FNSF design has not yet specified the fabrication method to be used for the thin W layer on the steel FW, so several possibilities are discussed here. The eventual selected FW material will have to meet many requirements including, but not limited to, sufficient thermal conductivity, crack resistance, neutron damage resistance, erosion resistance, and limited tritium retention. Because the exist-

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