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Materials-engineering challenges for the fusion core and lifetime components of the fusion nuclear science facility☆

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ABSTRACT

From the perspective of materials research and development (R&D) for the fusion core and near-core lifetime components of deuterium-tritium fusion power systems, the Fusion Neutron Science Facility (FNSF) concept plays a very important function by generating the complete fusion in-service environment and providing a platform for materials component-level testing. The FNSF provides the critical link between the ITER-era and the electricity- producing facilities, DEMO and the commercial power plant. The main features of the FNSF are described and the rationale presented for the selection of structural materials to meet the challenges of the power core components and also for the system lifetime components. The calculated radiation damage parameters and potential operating temperatures requirements for each of the operational phases are presented ranging from nuclear break-in up to DEMO relevant conditions. The interdependence of the FNSF and fusion nuclear materials research are discussed, and examples of near-term materials R&D activities are outlined which could address several current FNSF-related design issues.

1. Introduction

The US Fusion Nuclear Science Facility (FNSF) concept [1] is envisioned as a critical intermediate step between ITER and an electricity-producing fusion demonstration power plant (DEMO). It will ultimately operate with a deuterium-tritium (D-T) plasma and is designed to achieve major advances in plasma duration and fusion nuclear environment through a phased program reaching power plant operating regimes over period of ~30 years. Successful design, construction, licensing, and operation of any next-step fusion nuclear facility, such as FNSF or DEMO, will require solutions to the materials challenges and basic science questions discussed in [2,3]. Fusion materials programs world-wide are making significant progress towards addressing these challenges. There is a strong inter-dependence between the FNSF and development of materials and components since the FNSF itself would provide the first opportunity for assessing the performance of materials and components in the fully integrated fusion environment, a necessary step before proceeding to a US DEMO and commercial power plants. While a comprehensive approach to an integrated materials-design effort is not currently funded in the US, there are opportunities to address some of the materials-related issues identified by the on-going FNSF design activities. Several of these intermediate term needs, and issues are discussed with focus on the first wall and blanket (FW/B), the structural ring (SR), and the vacuum vessel (VV), shown in Fig. 2.

2. The inter-dependence of the FNSF and fusion nuclear materials research

The development and testing of fusion- relevant materials, ultimately for fusion power plant applications, requires a program ranging from basic material behavior to operating experience in fusion nuclear plasma confinement devices that produce the complex environment of the fusion core. Fusion materials research has already spanned a few decades, but is now entering a more critical and focused phase, evidenced by the production of large heats of reduced activation ferritic martensitic RAFM steels [4], the push to construct fusion relevant neutron sources [5,6], the examination of testing strategies in the integrated fusion environment [1,7], broader research into multiple material issues including corrosion [8–11], plasma facing requirements [12], functional material aspects [13], and recent DEMO and next step facility designs [1,14–17].

This paper emphasizes the critical need to test materials in their full-

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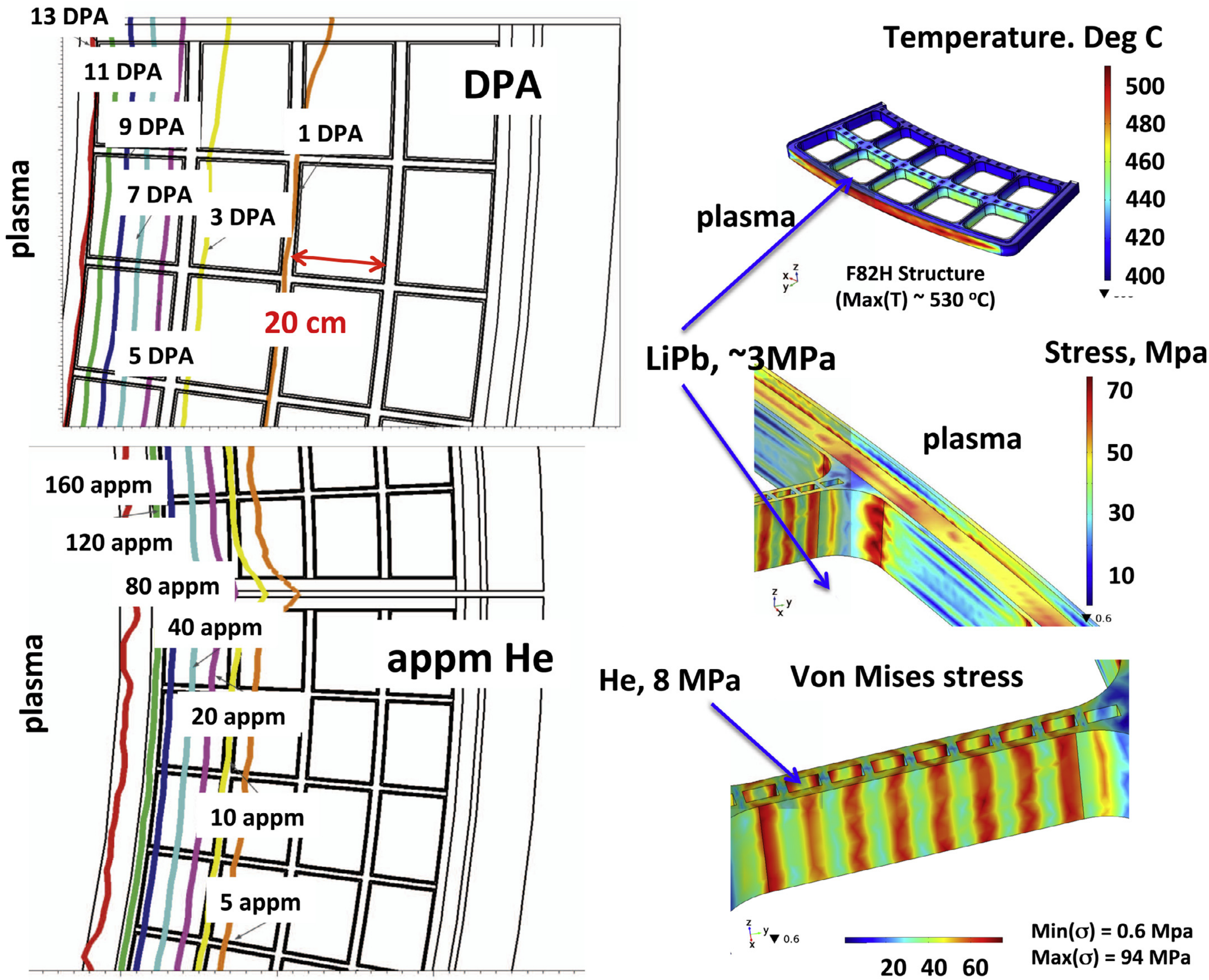

Fig. 1. The variation in dpa and appm helium in the vicinity of the first wall for the FNSF outboard DCLL blanket, (left). Thermo-mechanics analysis of a section through the inboard blanket shows the temperature variations between the first wall, inside the large Li-Pb conduits and the back of the blanket. In addition, zooming into the helium-cooled side wall of the LiPb conduit the Von Mises stress can be seen to oscillate between approximately 30 and 60 MPa, from Ref [19]. (Reprinted from Ref. [1] with permission from Elsevier).

size component form and in the complete fusion environment of a fusion core. This test program on the FNSF will be timed to follow a rigorous fusion materials R&D program supported by surrogate fusion neutron irradiation (e.g. fission reactors, multi-beam ion accelerators, spallation neutron sources), industrial-scale production of all fusion core components, non-nuclear partially integrated testing, and testing in fusion-relevant DT neutron irradiation facilities, such as the International Fusion Materials Irradiation Facility (IFMIF) [18].

The fusion core environment is complex due to the multiplicity of variables including neutrons, high temperatures, fluid pressures and flow rates, tritium, helium and solid transmutation production and corrosion interactions. Each of these variables has gradients poloidally and radially into the blanket and divertor which results in additional complexity. Fig. 1 shows the gradients in both displacement per atom (dpa) and helium production in atomic parts per million (appm) for the FNSF; temperature and stress gradients in the solid blanket structure are also shown. Fusion relevant neutron testing in facilities such as DONES (DEMO Oriented Neutron Source – IFMIF) [5,6] will provide single effects materials tests at appropriate temperatures and the highest fluences, but otherwise will not evaluate the simultaneous factors such as stress, hydrogen, coolant/breeder interactions or gradients. Testing in the 6-liter medium flux zone of IFMIF, will enable some level of integrated testing with limited sample numbers [20]. While the DONES-IFMIF database will be sufficient to pursue a research step such as the FNSF, a database on the materials in their component form exposed to the actual fusion environment is critical to providing the design and licensing basis for a US DEMO and commercial power plants. The integrated testing in non-nuclear environments is similarly critical to developing the confidence in component and material performance for an effective FNSF operations program. Fission reactor experience has shown that exposure to an integrated core nuclear environment can provide complex and unexpected material responses [21–23]. To meet this requirement for fusion, the FNSF provides the necessary combination of the multi-physics and neutron environments and is designed to allow the replacement of the fusion core components after each operational phase. In-depth post -irradiation examination of components will provide a unique basis for understanding and improving materials and advancing component design. In addition, a