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First wall material damage induced by fusion-fission neutron environment

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HIGHLIGHTS

- The highest damage and gas production rates are experienced within the first wall materials of a hybrid fusion-fission system.
- About ~2 times higher dpa and 4–5 higher He appm are expected compared to the values distinctive for a pure fusion system at the same DT-neutron wall loading.
- The specific nuclear heating may be increased by a factor of ~8–9 due to fusion and fission neutrons radiation capture in metal components of the first wall.

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ABSTRACT

Neutronic performance and inventory analyses were conducted to quantify the damage and gas production rates in candidate materials when used in a fusion-fission hybrid system first wall (FW). The structural materials considered are austenitic SS, Cu-alloy and V- alloys. Plasma facing materials included Be, and CFC composite and W. It is shown that the highest damage rates and gas particles production in materials are experienced within the FW region of a hybrid similar to a pure fusion system. They are greatly influenced by a combined neutron energy spectrum formed by the two-component fusion-fission neutron source in front of the FW and in a subcritical fission blanket behind. These characteristics are non-linear functions of the fission neutron source intensity. Atomic displacement damage production rate in the FW materials of a subcritical system (at the safe subcriticality limit of ~0.95 and the neutron multiplication factor of ~20) is almost ~2 times higher compared to the values distinctive for a pure fusion system at the same 14 MeV neutron FW loading. Both hydrogen (H) and helium (He) gas production rates are practically on the same level except of about ~4–5 times higher He-production in austenitic and reduced activation ferritic martensitic steels. A proper simulation of the damage environment in hybrid systems is required to evaluate the expected material performance and the structural component residence times.

1. Introduction

It is known from fusion system considerations that high-energy neutrons generated in the plasma by D-T fusion reactions cause atomic displacements within the materials, leading to the generation and accumulation of radiation defects and to radiogenic helium (He) and hydrogen (H) gas atom production that influence properties of materials over the projected lifetime of a fusion power plant. As shown e.g. in [1–4] even at low concentration, gas particle can have severe life-limiting consequence for structural component life-time.

In hybrid fusion-fission systems [5–8] not only do the incident D-T-neutrons but the "secondary" fission neutrons appeared in subcritical blankets may cause atomic displacements and transmutations within the materials having a significant effect on their properties.

This paper describes results from integrated studies for a simplified model of a hybrid system to define a possible variation in the first wall irradiation environment caused by two component D-T fusion and fission neutron sources in a plasma region and in fission blanket behind the first wall (FW) compared to the D-T fusion irradiation.

The analysis combines both fusion and fission neutron- and gamma-ray transport simulations and inventory calculations to quantify damage, transmutation and nuclear heating of various candidate structural and plasma facing materials for the first wall under identical first wall conditions.

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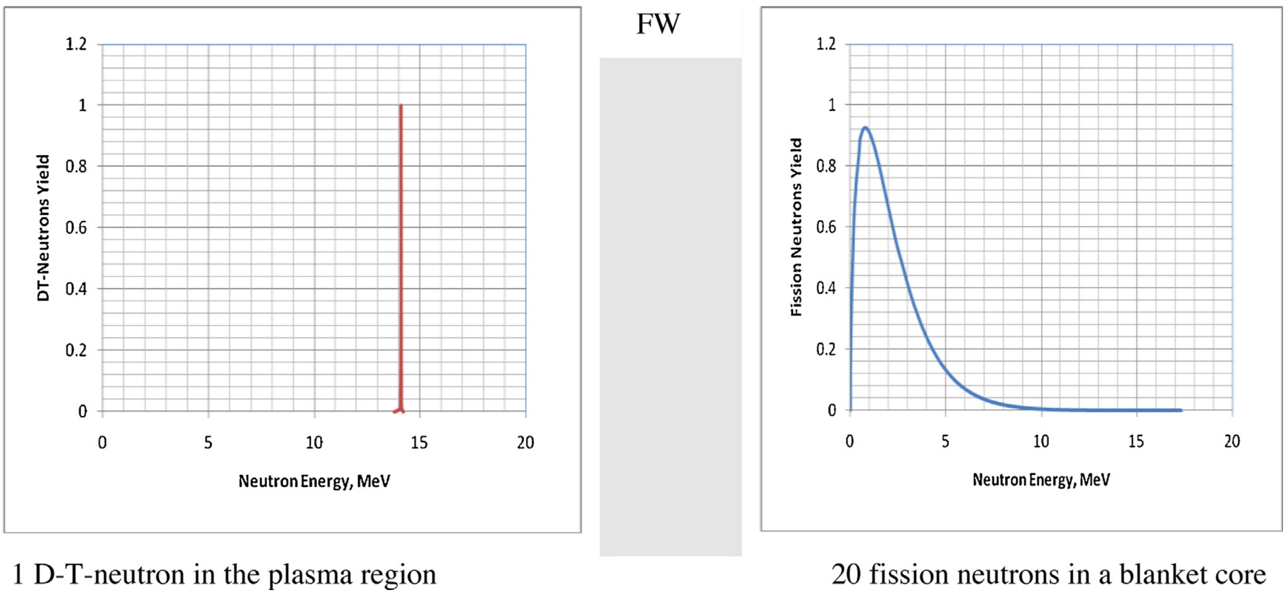

Fig. 1. Fusion and fission neutron sources in the plasma region and in the fission blanket core.

2. Combined fusion-fission neutron source in a hybrid system

A one-dimensional model First Wall panel (FW) considered here was structured as cylindrical rings: 1.9 mm layer of the 316L(N)-IG austenitic steel for the structure, 4 mm H_2O-coolant layer, 1.7 mm Cu- heat sink and 4 mm Be-armour on the side facing the plasma. This model replicates a radial build of the original first wall design of DEMO-FNS [8] in a simplified bulk geometry representation. Other FW materials recommended in [3,4] are also considered for a comparison.

Two types of neutron sources have to be accounted in the hybrid system [8] simultaneously: a D-T-fusion neutron source in the plasma region and a nuclear fission neutron source in a 30-cm neutron region behind the first wall, which may contain some fission materials (or lead for neutron multiplications).

According to the one-point approximation, the neutron multiplication in a subcritical system is usually expressed as follows: $M_{n\text{-}fiss} = 1/(1\text{-}k_{eff})$, where k_{eff} is the effective neutron multiplication factor in (n,f)-reactions. For the safety reasons k_{eff} has usually to be set to 0.95, that corresponds to $M_{n\text{-}fiss}$ ~20. This $M_{n\text{-}fiss}$ does not include the effect of the source position and neutron energy that significantly affects the neutron multiplication and other neutron multiplication types as (n,2n), (n,3n) reactions. Nevertheless for simplicity the total fusion neutron multiplication factor in a fission blanket M_n was proposed to be equal to 20 in this consideration. (The corresponding fusion energy multiplication factor in the subcritical blanket is expected to be high, ~90.)

The energy distribution of the D-T-fusion neutron source in the plasma region apart from the first wall and the fission neutron source in the subcritical blanket behind are shown in Fig. 1. It is seen from this figure that whereas the bulk neutron energy in the fission blanket is in the 2 MeV range, the 14.1 MeV neutrons are produced in the D-T fusion plasma.

3. Neutron spectra in the FW region

It is known also that atomic displacement damage and gas production rates are greatly influenced by neutron energy spectrum peculiarities [1,2].

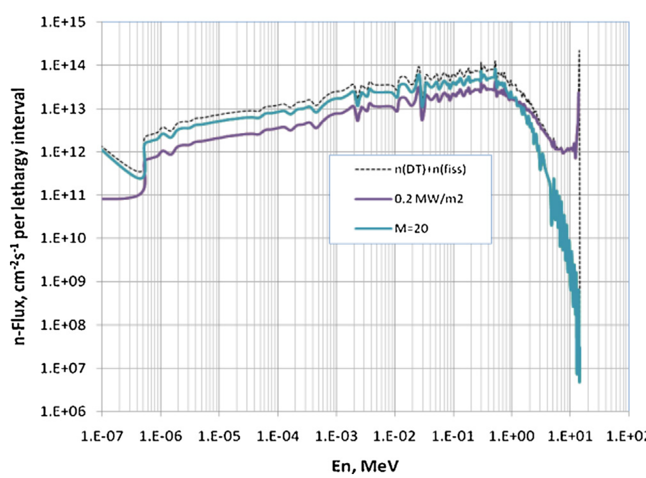

Fig. 2. Resultant spectra in the first wall region from the two component fusion-fission neutron source.

Two neutron spectra in the first wall region calculated separately for the D-T-fusion neutron source distributed in plasma chamber of DEMO-FNS model [8] and for the fission neutron source in the front zone of the subcritical blanket, as well as the resultant spectrum are shown in Fig. 2.

The fusion neutron source component in this analysis is normalized to the D-T-neutron wall loading value of 0.2 MW/m^2 that is almost by 10–15 times lower than for a fusion power reactor. The fission neutron yield in the blanket region behind the first wall corresponds to the M_n ~20.

4. Neutron fluxes in the first wall surrounding

Usually the neutron fluxes, damage and gas production rates and the nuclear heating rate in a fusion system reach their maximum values in different materials near the plasma facing regions. Then they are generally decrease almost in a quite exponential way along the radial direction with increasing distance from the First Wall.

But it is not true in a system with a fission blanket behind the first wall.