Irradiation of structural materials in spallation neutron sources

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1 Introduction

In principle, intense spallation neutron sources can be used not only to irradiate materials (e.g. window materials) and to validate different target geometries/concepts, but also to irradiate structural materials (samples, pins or even full assemblies) in order to characterize their behavior under irradiation (in a fast neutron field). However, a question arises concerning the "representativity" of such irradiations to reproduce the conditions encountered in a typical fast reactor.

The present paper documents an investigation aimed at understanding phenomena related to the representativity of an irradiation using an intense spallation source, with regards to neutron damage and Helium production. Two different designs of a spallation neutron source are considered. The first is an Intense Spallation Neutron Source (ISNS) proposed at CEA, France as a potential irradiation tool. The second is one of the current models for the TMT (Target for Material Testing) of the ADTF (Accelerator Driven Test Facility) program. In our calculations we used the MCNPX Version 2.1.5 Monte Carlo code[1].

2 Helium production to neutron-induced damage ratios for iron in the ISNS

The geometry for the ISNS is taken from the CEA design.[2] In our work, we assume a proton beam with an intensity of 33 mA and energy 1.2 GeV per particle (linear accelerator power of 39.6 MW). These high values were chosen in order to increase neutron fluxes at potential irradiation positions. The target, which is a cylinder 125 cm in radius and 250 cm in height, is filled with lead-bismuth eutectic (LBE). A window is placed at the center of the cylinder to permit passage of protons to the interior of the target. The radius of the beam is 13.5 cm. An irradiation sample is placed in the proximity of the conducting window.

The fraction of high-energy neutrons (above 20 MeV) constitutes, at best, 1.5-2 % of the total. As neutrons migrate in the diffusive LBE medium, the neutron spectrum becomes softer and a thermal-neutron component (below 0.625 eV) appears.

In the following discussion we consider an irradiation "sample" situated at 10 cm distance from the conducting window. The simulated irradiation zone is bulk natural iron with dimensions 1 x 1 x 40 cm. The average neutron damage rate over the entire volume of the irradiation sample was found to be 66 dpa/y.

The ENDF/B-V library for natural iron was used to calculate Helium production at low neutron energies (below 20 MeV). At higher energies (up to 3 GeV), tabulated cross-sections provided by Los Alamos National Laboratory were used.[3] In our work the results on Helium production are most probably underestimated. This is due to the fact that in the energy range 20-150 MeV the new LA 150 evaluations predict higher (n,α) and $(n, {}^3He)$ cross sections than the set of nuclear data used in this work. The average Helium production rate over the whole volume of the irradiation sample is 25.1 appm/y for low-energy neutrons and 30 appm/y for high-energy neutrons.

The important indicator of the representativity of an irradiation is the ratio of Helium production in a sample to the induced dpa rate (appm/dpa). The first set of results in Table 1 gives the values of this ratio. The average value of this ratio over the whole irradiation volume is 0.83. These calculated values are slightly higher than those typically observed in a fast-reactor spectrum for a ferritic martensitic steel (a value of around 0.5).

Height of the sample (cm) from the closest to the proton beam end (the sample is 40 cm long)	ISNS appm/dpa	TMT appm/dpa
0-5	0.72	3.52
5-10	0.78	3.50
10-15	0.82	3.56
15-20	0.82	3.56
20-25	0.93	3.66
25-30	0.90	3.49
30-35	0.90	3.70
35-40	0.80	3.53

Table 1 Neutron damage to Helium production ratios in the bulk of natural iron (1 x 1 x 40 cm)

3 Helium production to neutron-induced damage ratios for iron in the TMT

The geometry for the TMT facility was partially taken from a recent Los Alamos National Laboratory design.[4] The proton beam (5.3 cm wide and 38 cm long) with intensity of 13.3 mA (power ~8 MW) strikes the LBE target and produces neutrons via spallation reactions. The LBE target is confined within 20 tubes of 2.05 cm in radius and 2000 cm in length. Reference 4 provides further details on physical characteristics of this system.

In this study, LBE tubes are confined between two bulk components (18.325 x 200 x 62 cm) of reflector material containing Nickel in order to increase the effective use of spallation neutrons. An irradiation "sample" (an iron parallelepiped 1 x 1 x 40 cm) is placed inside one of these bulk objects.

The maximum Helium production rates are found to be of the order of 70-80 appm/y at the potential irradiation positions for the TMT model. The corresponding neutron damage rate reaches a value of approximately 20 dpa/y.

As in the case of the ISNS, we report the ratio of neutron-induced Helium production in a sample to the neutron-induced dpa rate (appm/dpa). The second set of results in Table 1 gives values of this ratio for the iron irradiation sample. It is seen that the appm/dpa ration is high and does not reproduce the irradiation conditions typically present in a fast reactor. Further optimization has to be envisaged in order to reduce the high-energy neutron induced production of Helium.

4 Conclusion

To obtain a high rates of damage and Helium production one needs a very intense proton beam, with a power higher than 30-40 MW. This high power allows one to produce a high neutron flux level (>5*10^{15} n/s/cm^2) over a relatively significant volume without strong spatial gradients. High level of neutron flux allows one to choose the radiation positions in a way to produce a fairly representative ratio between Helium production and damage in terms of dpa. This last result is due to the fact that one can choose a geometrical arrangement of the irradiation zone inside the overall target volume that minimizes both the high energy neutrons and, in particular, the proton interactions at the irradiation positions. Helium production is strongly reduced with respect to the case where the irradiation position is kept very close to the spallation target, to avoid neutron flux level degradation. This is due to the shift of the neutron spectrum to a lower energy domain.

5 References

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