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Neutron Damage Production of Various Nuclear Reactor Environments

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1. Introduction

The primary threat of materials in nuclear reactor environments is a high flux of fast neutrons produced by the fission reaction. Neutron radiation damage in materials results from nuclear collisions and reactions which produce energetic recoils atoms of the host materials or reaction products. The effect of neutron irradiation on materials depends on two factors; the neutron spectrum and the period of irradiation. The difference in the neutron spectrum leads to the different amount of damage to the materials. For example, we cannot compare an irradiation at a 14 MeV neutron source with one at a commercial light water reactor because 14 MeV neutrons produce much more damage per neutron than lower energy neutrons. Moreover, the nuclear transmutation may be different depending on the reactor type. While a commercial pressurized water reactor (PWR) spectrum has a small amount of fast neutrons (E_n > 1 MeV) outside the reactor core region, a sodium fast reactor (SFR) has a relatively larger amount of fast neutrons. It is expected that the fast neutrons will produce high-energy primary knock-on atoms (PKAs), followed by displacement cascades.

The present paper is intended to describe the neutron damage production in various reactor environments, including a commercial PWR, a SFR, a very-high temperature gas-cooled reactor (VHTR) and a research reactor. Two parameters are evaluated as neutron damage ones; the PKA energy and the amount of transmutation gas. The neutron irradiation exposure parameters can be used to correlate materials effects between different types of reactors and to predict materials effects in other facilities.

2. Neutron Spectra

The neutron energy spectrum describes the energy dependence of the neutron flux. Neutron energies of interest typically range from 0.025 eV up to 20 MeV. The most common neutron reactions include scattering, inelastic scattering, and neutron capture. Following neutron capture, the excited nucleus undergo gamma emission, charged particle reactions (proton or alpha particle emission), or multiple neutron emission. Usually, the transmuted elements, derived from the charged particle reactions, may be radioactive isotope. In that such reactions are dependent on the energy of neutrons, the neutron spectrum is the most important factor to affect the neutron damage production.

Neutrons are produced from nuclear fission of heavy elements such as uranium. Two or more neurons are generated per a fission process. The fission neutron energy spectrum is known to have a Maxwellian distribution. Fast reactors such as SFR are cooled by liquid sodium and do not have significant moderation of fast neutrons. On the other hand, the common types of fission reactors including most commercial reactors as well as research ones, are water-cooled in which fast neutrons are substantially moderated. The normalized neutron spectra are illustrated in Fig. 1.

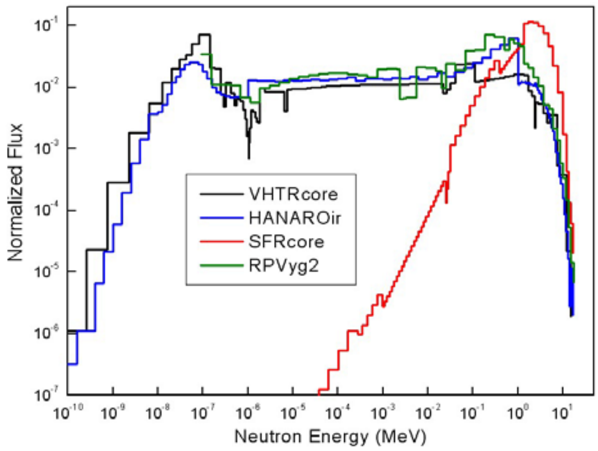

Fig. 1. Comparison of neutron spectra for the fast reactor (SFR) and the thermal reactors (LWR, VHTR, and HANARO research reactor). All flux values are normalized by the total flux.

All fluxes are evaluated by the neutron transport code. Generally, the flux distribution changes significantly depending on the location of the same reactors. The neutron flux in the LWR was estimated near the inner surface of the reactor pressure vessels. The normalized flux for the HANARO research reactor (IR-hole region) and the VHTR (near the core) looks similar. However, a big difference between fast and mixed-spectrum reactors could be seen in the normalized neutron flux in Fig. 1. The peak neutron energy of the SFR is located in the MeV energy region. The fraction of fast neutron (E_n > 1 MeV) flux in the SFR is about 3.3 times greater than that in the LWR, which is influential in inducing the displacement cascade reactions. The basic irradiation damage parameters are calculated using the computer code, SPECTER [1], by inputting the various neutron spectra shown in Fig. 1.

3. Neutron Damage Calculations

The SPECTER code is a convenient tool to obtain damage parameters for various elements in a specified neutron spectrum. The neutron spectrum is the only input to the code. Since the absolute value of the flux for the SFR is not available, we used the normalized neutron flux in the code calculations. The output of interest includes displacement rate, helium production and spectral-averaged PKA energy, which will be compared with respect to various neutron spectra.

Fig. 2 shows the calculated displacement rate for three thermal neutron spectra. For the VHTR and HANARO spectra, the target materials are assumed to be silicon carbides. For the LWR, displacement rate is calculated for ferritic steels. As seen from Fig. 2, the displacement rate is proportional to the total neutron flux. The total flux for the HAANRO is two orders of magnitude higher than that for the LWR, which is represented by the displacement rate. The total neutron flux for the HANARO and LWR is 3.93×10^{14} n/cm^2s and 1.29×10^{12} n/cm^2s, respectively.

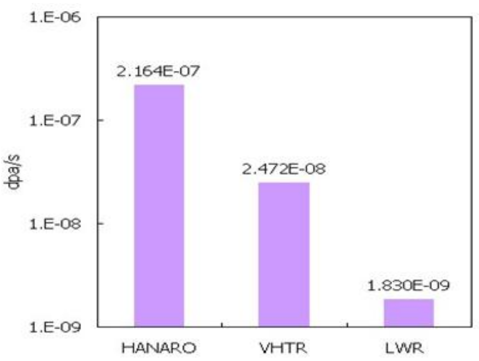

Fig. 2. Calculated displacement rate for the HANARO, VTHR and LWR spectra.

It is well known that nuclear transmutation will cause changes in properties of materials. Accurate information of such effects is important for materials performance in high fluence irradiation. The production rate of helium gas for thermal neutron flux was evaluated, which is displayed in Fig. 3. It is seen that the amount of helium production is strongly dependent on the target elements. The Si element is the dominant source of the helium production through the (n,α) reactions. The helium production from the transition metals is relatively minor.

One of the most important effects of neutron irradiation on materials is that atoms are displaced from their regular lattice sites due to the recoil energy following the nuclear reactions. The PKA energy distribution is determined by the sum of recoils from all the possible neutron reactions including elastic & inelastic scattering, capture, charged particle production and multiple neutron production. Although the PKA energy is distributed in a wide range of energy, we investigate the average PKA energy, which is a critical

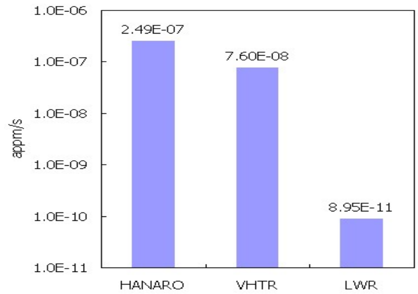

Fig. 3. Transmutation helium gas production rate for the HANARO, VTHR and LWR spectra.

parameter to estimate the primary damage quantitatively. Fig. 4 shows the calculated average PKA energy for four types of neutron spectra. For the SFR spectra, the target materials are assumed to be iron, as is the same case with the LWR spectra. There is a big difference in the PKA energy (5 vs. 38 keV) between two spectra. It is expected that more displacement damage will be created in the SFR environments for the same flux due to the neutron energy distribution. The PKA energy of Si or C for the HANARO spectra is higher than that for the VHTR spectra. The difference in the flux in the intermediate energy range (0.01 to 1 MeV) causes such a difference in the PKA energy.

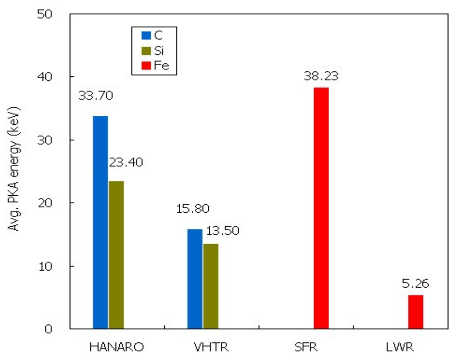

Fig. 4. Average PKA energy for four neutron spectra

4. Conclusions

Neutron sources are viewed in terms of their ability to produce radiation damage to materials. This study has attempted to describe the relationship between different types of neutron spectra and radiation damage. The results shown above will be useful in estimating the radiation damage to materials in nuclear environments.

REFERENCES

[1] L.R. Greenwood, R.K. Smither, SPECTER: Neutron Damage Calculations for Materials Irradiations, ANL/FPP/TM-197, Argonne National Laboratory, Argonne, IL, Jan. 1985.