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Integrity Assessment of Fusion Reactor Structures Using Arc-dpa Cross Section

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1. Introduction

There are still many obstacles to realizing the nuclear fusion reactor. For a material perspective, radiation damage is an important issue, which determines the lifetime of the structure, and it should be considered from the design stage. In particular, it is known that the radiation damage is more severe in the fusion reactor than in the fission reactor due to the high-energy neutrons generated by D-T reaction [1].

Displacement per atom (dpa) has been used as a representative index of radiation damage due to the difficulty in evaluating changes of material properties. A simple mathematical model was adopted as a standard by the IAEA and it was used for a long time to evaluate the dpa. This standard model has been widely used but has some fundamental limitations. It is not applicable to alloy and compound materials, and does not consider the recombination of atoms in the cascade process, so it differs from the experimental results. To overcome this problem, athermal recombination-corrected dpa (arc-dpa) based on molecular dynamic (MD) and binary collision approximation (BCA) has recently been proposed. In this study, the integrity of the fusion reactor blanket using arc-dpa cross section was evaluated as a part of the structure evaluation study.

2. Methods and Results

2.1 Radiation Damage

When an atom collides with an incident particle and receives more than displacement threshold energy, the atom escapes from the lattice and generates vacancies and interstitial atoms. These defects deteriorate the physical properties of the material, and the change in material properties is called radiation damage. The process by which an incident particle damages the material is shown in Figure 1. In this figure, primary knock-on atom (PKA), an atom that escapes by interacting with an incident particle, collides with other lattice atoms and creates a collision cascade.

2.2 Displacement per Atom

The displacement per atom (dpa) is defined as the frequency of escape from the lattice per atom and is calculated as Eq. (1).

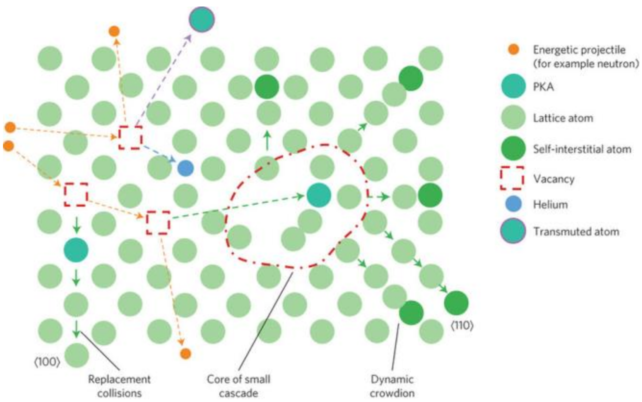

Fig. 1. Schematic Diagram of Radiation Damage [2]

$$dpa = \frac{N_d}{N} = \int_0^t \int_0^\infty \sum_i \int_{E_d}^{T_{max}} \phi(E,t) \frac{d\sigma_i(E,T)}{dT} \nu(T) dT\, dE\, dt \quad (1)$$

where N is atomic density, N_d is number of escaped atoms per unit volume, $\phi(E,t)$ is flux of incident particle, T_{max} is the maximum kinetic energy of PKA, E_d is the effective displacement threshold energy of material, $d\sigma_i(E,T)/dT$ is the recoil atom energy distribution for *i*th reaction, and $\nu(T)$ is the number of Frenkel pairs produced by a single PKA. Frenkel pair means a pair of stable atomic vacancy and interstitial atom.

The Kinchin-Pease model [3] is the simplest model for estimating the displacement damage function $\nu(T)$ based on the following assumptions; Cascade results from a chain collision between two atoms; if the target atom receives more than threshold energy, the atom escape from the lattice; the effect of the crystal structure is ignored; immediate recombination of atomic vacancy and interstitial atoms is ignored.

Norgett, Torren, and Robinson proposed a model called the NRT model which is similar to the Kinchin-Pease damage function by introducing the average energy delivered to the lattice atoms [4]. The damage function of the NRT model is described by Eq. (2).

$$\nu_{NRT}(T) = \frac{0.8T}{2E_d} \quad (2)$$

Because the NRT model has fundamental limitations in the assumptions described above, it is difficult to apply to compound materials and there is a difference between the experiments and the predicted values. To overcome this problem, athermal recombination-corrected dpa (arc-dpa) was developed that takes into account the recombination results of Frenkel pairs calculated from Molecular Dynamic (MD) and Binary Collision Approximation (BCA) simulations. Since arc-dpa simulates the atomic structure information, it has an advantage of better prediction than NRT model when simulating compound material and alloy [5].

When the displacement damage function and the PKA energy distribution are combined and stored as data, dpa can be easily evaluated as shown in Eq. (3). where σ_d is the dpa cross section and $\Psi(E)$ is particle fluence. Figure 2 shows the dpa cross section of EUROFER alloy in ENDF-6 format. As shown in the Figure, the MT number of the dpa cross section derived by using the BCA-MD method is assigned to 900.

$$dpa = \int_0^\infty \sigma_d(E)\Psi(E)dE \quad (3)$$

where

$$\sigma_d(E) = \sum_i \int_{E_d}^{T_{max}} \frac{d\sigma_i(E,T)}{dT}\nu(T)dT$$

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                                                                   0 0  0     0
 2.600100+4 5.516919+1         -1          0          0          0  70 1451    1
 0.000000+0 0.000000+0          0          0          0          6  70 1451    2
 1.000000+0 1.500000+8          0          0         10          1  70 1451    3
 3.000000+2 0.000000+0          0          0         17          3  70 1451    4
 EUROFER   KIT        EVAL-MMM13 A.Yu.Konobeyev, U.Fischer             70 1451    5
                      DIST-                             2013MMTT       70 1451    6
----DXS               MATERIAL   70                                    70 1451    7
-----INCIDENT NEUTRON DATA                                             70 1451    8
------ENDF-6 FORMAT                                                    70 1451    9
                                                                       70 1451   10
                                                                       70 1451   11
  Displacement cross-sections for EUROFER                              70 1451   12
                                                                       70 1451   13
                                                                       70 1451   14
  MF=3  MT=900  :  displacement cross-section [barn] prepared          70 1451   15
                   using combined BCA-MD method                        70 1451   16
                                                                       70 1451   17
  MF=3  MT=901  :  displacement cross-section [barn] prepared          70 1451   18
                   using the NRT model                                 70 1451   19
                                                                       70 1451   20
                                                                       70 1451   21
                                  1        451         24          0  70 1451   22
                                  3        900      33090          0  70 1451   23
                                  3        901      29630          0  70 1451   24
                                                                       70 1  099999
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Fig. 2. EUROFER dpa Cross Section in ENDF-6 Format

2.3 Integrity Assessment of Fusion Reactor Blanket

The blanket covering the vacuum vessel protects structures and superconducting toroidal field magnets from heat and high energy neutrons generated by the fusion reaction. The blanket converts the kinetic energy of neutrons into thermal energy and produces tritium, which is used as fuel for nuclear fusion. Each country participating in ITER is studying the blanket of several concepts. Korea proposed Helium Cooled Ceramic Reflector (HCCR) blanket concept to use neutrons efficiently by using graphite reflector [6]. The blanket is a layered structure of neutron multiplier and tritium breeder, which are made of pebbles, and helium is used as the coolant.

Figure 3 shows the dpa evaluation model developed from the HCCR concept. The thickness of each layer is shown in parentheses in centimeters. The materials and densities of the blanket components are listed in Table 1.

The neutron energy was set at 14.1 MeV assuming that all of the neutrons were emitted by the D-T reaction. The neutron intensity was perpendicularly injected into the blanket with neutron beam loading of 1.0 MW m^{-2} ($=4.427\times10^{13}$ $cm^{-2}sec^{-1}$).

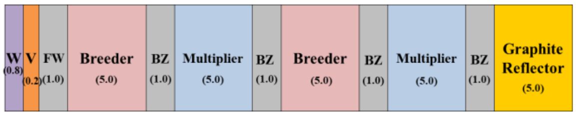

Fig. 3. Layout of the Blanket Model

Table I: Materials and Densities Used in the Blanket

Region	Material	Thickness (cm)	Density (g/cm^3)
Breeder	Li_2TiO_3	0.8	1.94
Multiplier	Be	0.2	1.16
First Wall	SS316	1.0	5.92
BZ plate	SS316	1.0	5.10
Graphite Reflector	Graphite	5.0	1.78
Tungsten layer	Tungsten Metal	5.0	19.2
Vanadium layer	Vanadium Metal	5.0	6.00

Neutron transport calculations were performed using MCNP6.1 [7] and the cross section data of the FENDL 3.1 library was used [8]. In the calculation of displacement damage, arc-dpa cross section provided by the IAEA data center was used. The MCNP F4 tally was used to calculate the neutron flux, and the following FM card was applied to the tally to multiply the dpa cross section with the neutron spectrum.

FM4 1 m 900

Figure 4 shows the neutron flux distribution according to the blanket depth. The neutron flux was tallied as a boundary of 1.8 MeV, which is the threshold energy of $^{9}Be(n, 2n)$ reaction. Neutron fluxes above 1.8 MeV decrease as the depth increases, confirming that the multiplier has no significant effect on the reproduction of the high energy neutrons. The dpa rate of the blanket structure and the dpa cross section used are listed in Table 2.

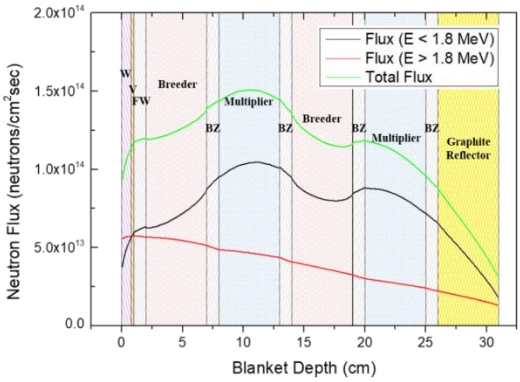

Fig. 4. Neutron Flux Distribution inside the Blanket; The boundary of the tungsten layer was taken as the origin.

Table II: The dpa Rate Evaluated Using arc-dpa Cross Section

Region	**dpa/y (y^{-1})**	**dpa XS** [9-10]
Tungsten layer	0.208	Tungsten Metal
Vanadium layer	1.839	Vanadium Metal
First Wall	1.205	EUROFAR alloy
BZ plate (1st layer)	1.040	
BZ plate (2nd layer)	0.881	
BZ plate (3rd layer)	0.655	
BZ plate (4th layer)	0.477	
Graphite Reflector	0.267	Carbon Ceramic

3. Conclusions

In this study, the integrity assessment of the fusion blanket structure was analyzed using the arc-dpa cross section. This result is expected to be useful for research on structural integrity of nuclear fusion reactor, which is difficult to experiment with research reactor.

Acknowledgements

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