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Investigation of DPA in the reactor pressure vessel of VVER-1000/V320

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Abstract: The most important ageing effect on the reactor pressure vessel (RPV) is radiation embrittlement, which is mainly caused by fast neutrons during operation lifetime of nuclear reactors. The aim of this study was to investigate the DPA (displacement per atom) rate, an important parameter describing radiation damage to the RPV, and identify the position of the maximum DPA rate in the RPV of the VVER-1000/V320 reactor using the Monte Carlo code MCNP5. To reduce statistical errors in the MCNP5 simulation, the weight window technique was applied to non-repeated structures outside the reactor core. The results showed the distribution of the DPA rate in the RPV and the maximum DPA rate was found to be at the first millimeters of the RPV. Consequently, these calculations could be useful for assessment of radiation damage to the RPV of VVER reactors.

Keywords*: VVER, reactor pressure vessel embrittlement, DPA rate, weight window technique.*

I. INTRODUCTION

During the operation of nuclear power plants (NPPs), assessment of radiation embrittlement of the structure materials and reactor pressure vessels (RPVs) by neutron and gamma is one of the most important issues to ensure their integrity. In particular, it is widely recognized that the service lifetime of an RPV is limited by neutron irradiation embrittlement [1].

As of 2014, there have been more than 100 serious nuclear accidents and incidents from the use of NPPs, including the Three Mile Island (1979), Chernobyl (1986), and Fukushima Daiichi (2011) accidents. The RPV acts as a barrier that keeps radioactive fuel contained and out of the environment, and therefore ensuring the integrity of the RPV during normal operation of NPPs or under accident conditions is indispensable. To this end, investigating the displacement per atom (DPA) rate in the RPV, which is a key parameter describing radiation embrittlement of the RPV, has received much attention so far [2]-[4].

As published by the OECD/NEA state-of-the-art report in 1996 [2], the introduction of DPA to represent the metal damaging effects of neutrons at all neutron energy levels was presented. Besides, the reconsideration of the computation techniques for calculating neutron/gamma radiation damage to RPV and the methods used in the NEA member countries for computing long-term cumulative dose rates were also reported. The report

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disclosed that the results of neutron/gamma fluence and radiation doses were within 20 percent difference when compared between calculations and measurements or calculations with different computer codes. Another report of Boehmer et al [3] showed the results such as the neutron/gamma spectra, several fluence integrals, and the DPA and freely migrating defect (FMD) rates of ex-core components of Russian (VVER-1000) and German light water reactors (1300 MW PWR and 900 MW BWR). Nonetheless, the neutron fluence and DPA ditributions at the RPV have not been shown. Recently, the calculation of DPA in the RPV of the Argentinian Atucha II reactor (PHWR type) [4] was performed using the Monte Carlo code MCNP, determining the areas at the RPV where the neutron fluence and DPA rate are maximum. However, application of variance reduction techniques (VRTs) to reduce statistical errors and computational time for such neutron deep penetration calculation with MCNP has not been mentioned.

In this paper, we aim to investigate the DPA distributions on RPV of a Russian pressurized water reactor, the VVER-1000/V320 [5], using the Monte Carlo code MCNP5 [6], thereby identifying the maximum radiation exposure areas in the RPV. In the MCNP5 simulation, the weight window VRT was applied to non-repeated structures outside the reactor core, leading to a significant decrease of statistical errors in the neutron fluence and DPA calculations. As a result, the maximum neutron fluence and DPA rate were found at the first millimeters of the RPV areas that are nearest to the peripheral fuel assemblies.

II. CALCULATION METHODOLOGY

The VVER-1000 reactor core consists of 163 fuel assemblies (FA). Each FA has 312 fuel rods and 18 guiding channels. The main characteristics of VVER reactor core and FA parameters are described in Table I and Table II, respectively. Detailed description of the reactor core materials can be found in [5].

Table I. A brief information of VVER-1000/V320

Parameter	Value
Reactor type	VVER-1000
Version	V320
Nominal power, MWt	3000
Nominal electric power, MWe	1000
Coolant inlet temperature, ^{0}C	288
Number of fuel assemblies, pcs	163
Effective core radius, mm	1580
Pressure vessel inner radius, mm (without 7mm of cladding thickness)	2075
Pressure vessel outer radius, mm	2267.5

Table II. Fuel assembly (FA) description

Parameter	Value
FA pitch, mm	236
FA wrench size, mm	234
FA gap, mm	2
Number of fuel rods, pcs	312
Fuel pin pitch, mm	12.75
Fuel pin grid	triangular
Fuel pin	
Cladding:	
Material	Zirconium alloy (Zr+1%Nb)
Density, g/cm^3	6.52
Outer diameter, mm	9.1
Wall thickness, mm	0.65
Pellet:	
Material	UO_2
Density, g/cm^3	10.22
Outer diameter, mm	7.55
Center hole diameter, mm	2.4
Height of UO_2, mm	3550
Mass of UO_2, g	1460

The MCNP5 input file for VVER-1000/V320 reactor core modelled the fuel assemblies as repeated structures up to the steel baffle, while the regions outside the core from the baffle to the RPV (see Fig. 2a) were simulated as non-repeated structures. The full core model in MCNP5 for VVER-1000/V320 was described in Fig. 2b.

The nuclear data for this calculation were taken from the ENDF/B-VII.1 library. To calculate the neutron fluence on the RPV of the VVER-1000/V320 reactor, the FMESH tally card was utilized in the MCNP5 calculation. The FMESH card calculates the track length estimate of particle flux, averaged over a mesh cell, in units of particles/cm^2. This card can be used for the calculation of flux distributions, power peaking factor and power distributions. The neutron fluences calculated by the MCNP5 code were plotted using the "pcolor" graphics module of the Matlab-like open-source Scilab [7]. The formulae for calculating the neutron flux and DPA rate from the FMESH tally results are described as follows.

The neutron flux can be determined using the following equation.

$$\Phi(E_i) = \frac{\text{Pcore (W)} \cdot \nu \left(\frac{n}{\text{fission}}\right)}{1.6022.10^{-13} \left(\frac{J}{\text{MeV}}\right) . Q \left(\frac{\text{MeV}}{\text{fission}}\right)} \cdot \frac{1}{k_{eff}} \cdot \phi F_{MESH}^{E_i} \left(\frac{\text{particle}}{\text{cm}^2}\right), \quad (1)$$

where Q is the energy release in one fission, Pcore the thermal power of the reactor, ν the average number of neutrons emitted in one fission, and $\phi F_{MESH}^{E_i}$ is the fluence obtained by FMESH in neutron energy group i.

To calculate DPA (displacement per atom), which is the number of times an atom is displaced from the normal lattice by interaction with neutrons, the DPA cross-section for iron was used [8] (see Fig.1) and the following formula was applied.

$$R_{DPA} \cong \sum_{i=1}^{N} \bar{\sigma}_{Di} \int_{E_{i-1}}^{E_i} \Phi(E_i) dE_i = \sum_{i=1}^{N} \bar{\sigma}_{Di} \cdot \phi_i, \quad (2)$$

where $\bar{\sigma}_{Di}$ is the DPA microscopic cross-section, ϕ_i is the neutron flux in the i group (obtained from Eq. (1)), and N the number of neutron energy groups (N= 640 in this case).

Finally, the DPA rate can be calculated as follows.

$$DPA = \frac{R_{DPA}}{n}, \quad (3)$$

where n is the number of atoms.

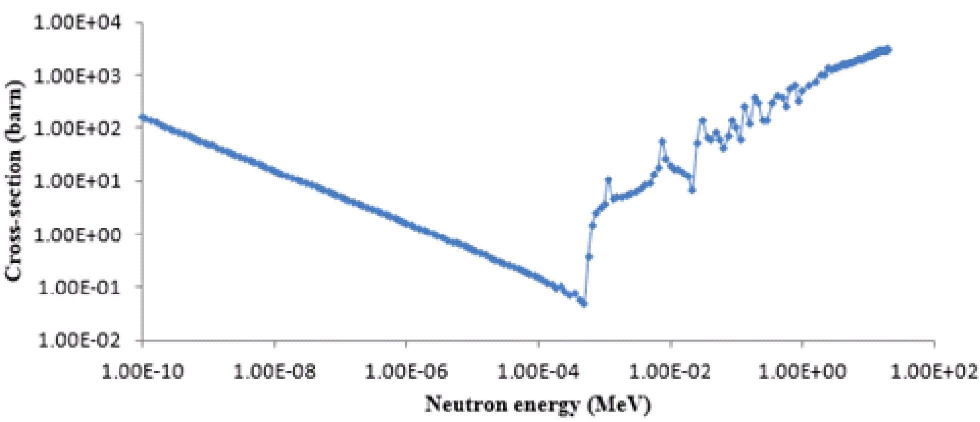

Fig 1. The DPA cross-section [8]

The statistical errors for the FMESH tally results were found as high as 0.1 without applying any VRT (with a huge number of neutron history of 10^9). To reduce the statistical errors and computational time in the MCNP5 calculation, the weight window generator, which outputs the reciprocal of the average score (importance) generated by particles entering a given phase-space region and helps correct poor track distributions [9], was applied in this study for the regions outside the reactor core (non-repeated structures).

The areas on the RPV inner surface where the neutron fluence is highest were identified at the core mid plane. Then the average DPA rate in the RPV thickness at the core mid plane was calculated to determine the position at which the DPA rate reaches maximum. The DPA spectrum was also evaluated to figure out contributions to the DPA rate from each neutron energy group. The calculation results are presented in the following Section.

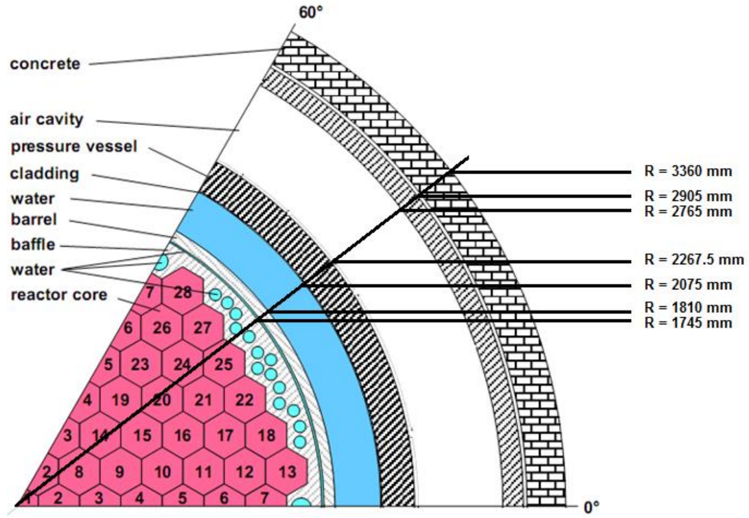

Fig. 2a VVER-1000/V320 core in 60^0 symmetry

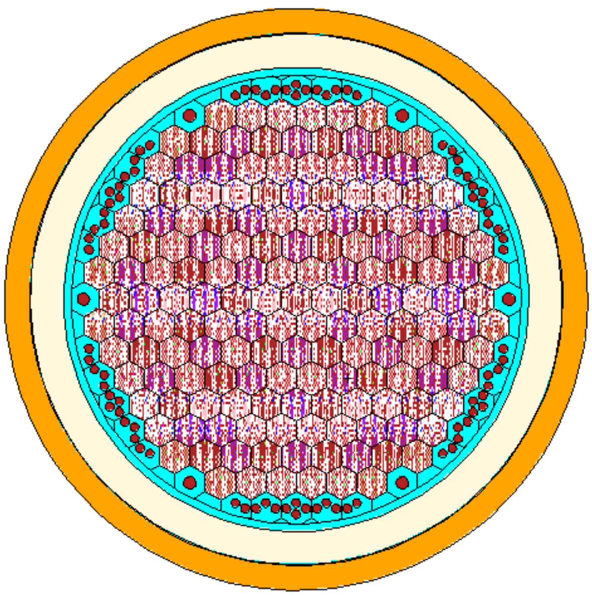

Fig. 2b The VVER-1000/V320 full core model in MCNP5

III. CALCULATION RESULTS

To identify the maximum neutron fluence in the RPV, the neutron fluence at the inner surface of the RPV was calculated and investigated depending on the azimuthal angle (θ) and the reactor core axial position (z). The long distance from the core center to the RPV outer surface of 226.75 cm (the thickness of RPV is 19.25 cm) requires application of advanced VRTs to reduce statistical errors in the neutron fluence calculation; otherwise, analog calculations without any VRTs for such a neutron deep penetration problem could lead to unreliable results even with a huge number of neutron history.

Specifically, the weight window generator was not produced for repeated structures, because the geometry splitting uses the product of the importance at different levels [6]. However, in our MCNP5 simulation, we used both repeated structures (reactor core) and non-repeated structures (regions outside the reactor core). Thus, it is possible to apply the weight window technique for the regions outside the reactor core in this study. First, we performed the analog calculation to produce the average score generated by particles entering a given phase-space region for all regions including fuel assemblies and the regions outside the reactor core. Second, the weight window lower bounds of the RPV cladding were observed and the weight window factors for the F4 tally region (the whole RPV) were determined. Table. 3 illustrated the neutron fluence calculation results for the whole RPV region in which using the weight windows significantly reduced the statistical error from 0.0682 to 0.0028.

Table III. The F4 tally results for the whole RPV region with and without weight windows technique (nps: total number of neutron histories, FOM: figure of merit)

No weight windows				Weight windows			
nps	mean	error	FOM	nps	mean	error	FOM
1024000	1.3140E-10	0.6321	3.6E-01	1024000	1.1405E-10	0.0540	9.0E-01
2048000	1.2170E-10	0.2186	6.4E-02	2048000	1.3746E-10	0.0088	7.1E-01
3072000	1.3742E-10	0.1400	8.2E-02	3072000	1.3931E-10	0.0062	7.2E-01
4096000	1.1784E-10	0.1207	7.4E-02	4096000	1.3954E-10	0.0051	7.1E-01
5120000	1.1846E-10	0.1057	7.3E-02	5120000	1.3755E-10	0.0044	7.2E-01
6144000	1.2638E-10	0.1003	6..5E-02	6144000	1.3782 E-10	0.0039	7.2E-01
7168000	1.3375E-10	0.0881	7.0E-02	7168000	1.3810 E-10	0.0036	7.2E-01
8192000	1.2626E-10	0.0826	6.9E-02	8192000	1.3779 E-10	0.0033	7.2E-01
9216000	1.2582E-10	0.0761	7.1E-02	9216000	1.3736 E-10	0.0031	7.2E-01
10240000	1.2432E-10	0.0712	7.2E-02	10240000	1.3734 E-10	0.0029	7.2E-01
10997019	**1.2432E-10**	**0.0682**	7.3E-02	10999762	**1.3713 E-10**	**0.0028**	7.2E-01

The FMESH tally was then applied to determine the neutron fluence and distribution of DPA rate in the RPV using the weight window technique. In this case, the neutron number history of 107 was chosen and the relative error of the FMESH tally results was found as low as less than 0.035. It is noted that we used a fine mesh for the FMESH tally (Δr, Δz, and Δθ = 0.5 cm, 35.3 cm, and 10 respectively) to obtain the distribution of DPA rate in the RPV; while the case in Table III used the F4 tally for the whole RPV region. As the FMESH tally was used, the relative error was as high as 0.1 without using the weight window technique.

Fig. 3 showed the neutron fluence, $\Phi_r(\theta, z)$, at the inner surface of the RPV (inner radius of the RPV = 207.5 cm). As it was expected, the maxima of the neutron fluence were found at the positions close to the azimuthal angles where the distance between the RPV and the peripheral fuel assemblies was shortest. The peaks of the neutron fluence were found at z = 176.5cm (core mid-plane) and $\theta_1 = 7^0$, $\theta_2 = 53^0$, $\theta_3 = 67^0$, $\theta_4 = 1130$, $\theta_5 = 127^0$, $\theta_6 = 173^0$, $\theta_7 = 187^0$, $\theta_8 = 233^0$, $\theta_9 = 247^0$, $\theta_{10} = 293^0$, $\theta_{11} = 307^0$, $\theta_{12} = 353^0$. It can be seen that each peak was repeated every 60° due to the one-sixth symmetry of the core. Also, the neutron fluence were symmetric with respect to the core mid-plane, mainly caused by the use of uniform coolant and fuel temperatures along the core axial direction in the MCNP5 calculation.

Fig. 4 displayed the DPA rate at the RPV on the mid-plane of the core (outer radius of the RPV = 226.75 cm). It was found that the maxima of the DPA rate appeared at the same azimuthal positions with the peaks of the neutron fluence. In this case, the DPA was linearly dependent on the neutron fluences, because only one neutron energy group was used for calculation of the DPA rate (see Eq. (2)). In addition, the maximum neutron fluence and DPA rate were identified at the first millimeters of the RPV. The contribution of each neutron energy group to the DPA rate will be examined and presented below.

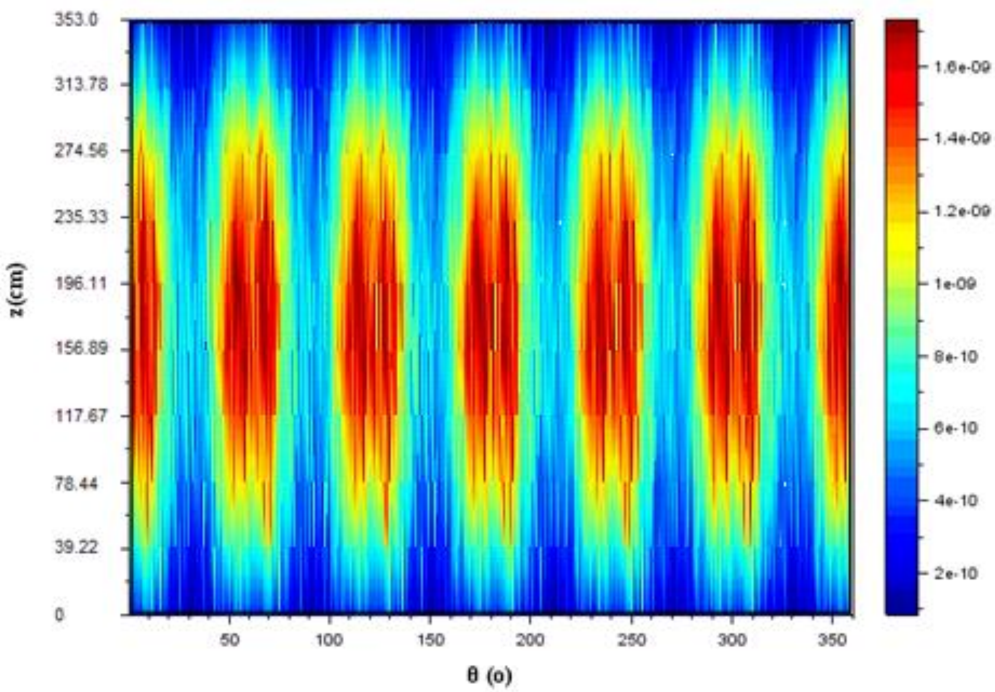

Fig. 3. The neutron fluence at the inner surface of the RPV (1/cm^2)

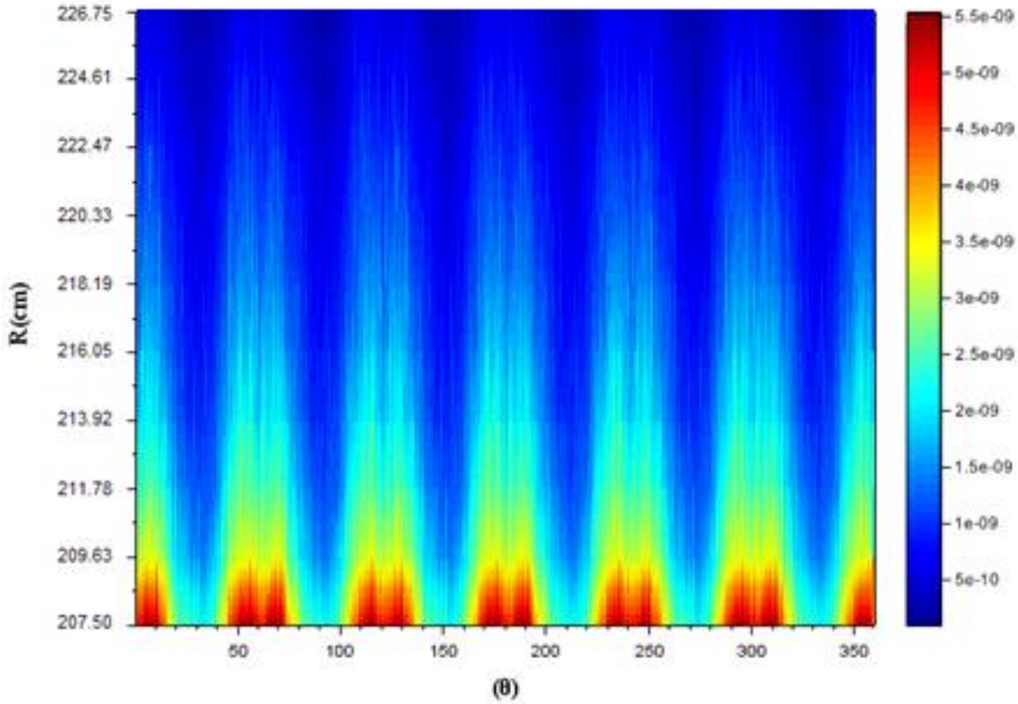

Fig. 4. The DPA rate at the RPV on the core mid-plane (s^{-1})

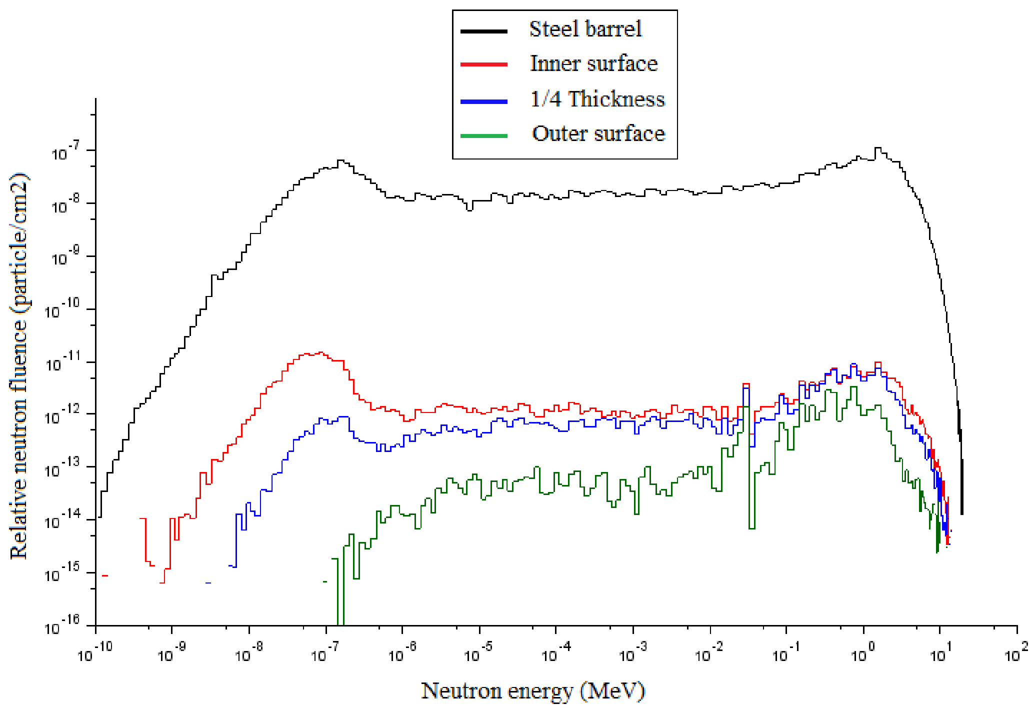

Fig. 5. The neutron flux spectra at the barrel and RPV

Fig.5 represented the neutron flux spectra at the steel barrel (r =181 cm), the inner surface of the RPV (r =207.5 cm), the 1/4 thickness of the RPV (r =212.31 cm), and the outer surface of the RPV (r =226.75 cm). It can be seen that the neutron spectrum was hardened as neutrons penetrated from the steel barrel into the RPV. The highest spectrum was at the steel barrel (before the down-comer region) and the lowest was identified at the outer surface of RPV. It can be explained by the presence of the down-comer region where the neutrons were slowed down and partially absorbed by the boric acid in the water.

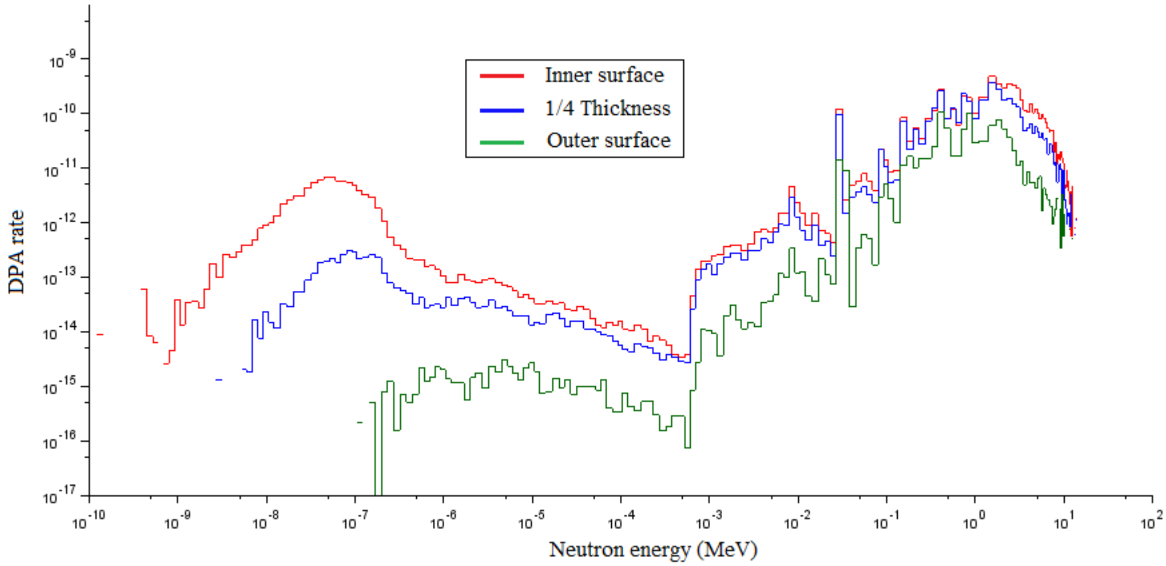

Fig. 6. The DPA rate at the inner surface, the 1/4T thickness and the outer surface of the RPV

Combining the neutron flux and DPA cross-section [9], the DPA rate distribution was calculated following the Eqs. (2) - (3). As shown in Fig. 6, the DPA rate in each energy group is plotted as a function of neutron energy at the inner surface of the RPV, 1/4 thickness of the RPV, and the outer surface of the RPV. The contributions of thermal neutrons to the DPA rate at the inner surface of the RPV and 1/4 thickness of the RPV were higher than that at the outer surface of the RPV. This difference was reduced in the intermediate and fast energy ranges.

Table IV. The neutron flux and DPA rate for inner surface and 1/4 thickness of the RPV

Energy group (MeV)	Neutron fluence (1/cm^2)				DPA rate (s^{-1})			
	Inner surface	%	1/4Thickness	%	Inner surface	%	1/4Thickness	%
0 to 4e-7	5.84E-10	44.9	3.09E-11	5.9	8.36E-11	1.5	3.44E-12	0.1
4e-7 to 0.1	3.23E-10	24.9	1.79E-10	34.1	2.22E-10	3.9	1.67E-10	4.4
0.1 to 1	2.39E-10	18.4	2.23E-10	42.6	1.67E-09	29.6	1.57E-09	41.6
1 to 20	1.53E-10	11.8	9.10E-11	17.4	3.68E-09	65.0	2.03E-09	53.9
Total	1.30E-09	100	5.2403E-10	100	5.656E-09	100	3.77E-09	100

The neutron fluence and DPA rate contributed from the four commonly used energy groups (thermal, epithermal, intermediate and fast neutron energies) for the inner surface and 1/4 thickness of the RPV were presented in Table IV. As shown in this

Table, significant contributions to the DPA rate on the inner surface of the RPV were from the fast neutrons (65.0% of the total DPA rate) and the intermediate neutrons (29.6% of the total DPA rate). These contributions from fast and intermediate neutrons correspond to their fraction of 30.2% of the total flux while the contribution from thermal and epithermal neutron groups (69.8% of the total flux) is small (only 5.4% of the total DPA rate). The same results were found at the 1/4 thickness of the RPV. However, the contribution from the fast neutrons to the DPA rate was decreased about 10% while that of the intermediate neutrons was increased about 10% as compared with the case at the inner surface.

IV. CONCLUSIONS

In this study, we performed the calculation of the neutron fluence and DPA rate on the RPV of the VVER-1000/V392 with the Monte Carlo code MCNP5. The neutron fluence and DPA rate at different positions in the RPV were investigated to figure out the position at which these quantities are maximum. The main results were summarized as follows:

- The weight window technique was applied to reduce statistical errors in the MCNP5 calculations. By using this VRT, the relative error of the FMESH tally results was reduced from 0.1 to an acceptable value of 0.035.
- The maxima of the neutron fluence and DPA rate were found at the same positions at the core mid-plane, which are close to the peripheral fuel assemblies.
- These maxima were identified at the first millimeters of the RPV. The DPA rate versus neutron energy was investigated in difference positions of the RPV including its inner surface, 1/4 thickness and the outer surface. It was found that the rate of DPA decreased when the neutron penetrated through the RPV. The results also showed that the main contribution to the DPA rate came from intermediate and fast neutron energy groups (94.6% at the inner surface of the RPV and 95.5% at 1/4 thickness of the RPV).

In future work, several VRTs will be applied together to further reduce the above-mentioned statistical error of the FMESH tally results. Additionally, verification calculation by using another nuclear code is also being planned along with using different nuclear data libraries.

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