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Calculation of neutron and gamma fluences on VVER reactor pressure vessel

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Abstract: Embrittlement is one of the most important effects affecting reactor pressure vessel (RPV) aging. RPV is irradiated with neutrons and gammas, especially fast neutrons, which mainly lead to embrittlement of RPV during operation lifetime of nuclear reactors. Therefore, the radiation-induced embrittlement of the RPV should be carefully evaluated. In this paper, a preliminary calculation was performed using the MCNP5 code to identify the areas in the RPV of the VVER-1000/V320 reactor where the neutron and gamma fluxes are maximum. Also, the neutron and gamma fluence distributions on the RPV were investigated and evaluated along with their energy spectra. These calculations are the starting point for the evaluation of radiation damage to RPV of VVER reactors.

Keywords: *VVER, reactor pressure vessel embrittlement, neutron and gamma fluences.*

I. INTRODUCTION

Reactor pressure vessel (RPV) is an unreplaceable component in nuclear power plants. There are many key design requirements to keep the integrity of the RPV during reactor operation. RPV must tolerate high pressure, high temperature, chemical corrosion, embrittlement, some types of deformation, etc. It is wellknown that the lifetime of the RPV mainly depends on the impact of the neutron and gamma radiation. Thus, the most important design requirements for the RPV are ensuring the integrity of RPV which is threatened by the radiation-induced embrittlement. In this regard, investigating the influence of neutron and gamma radiation on the RPV is necessary.

As reported by the OECD/NEA state-of-the-art report in 1996 [1], computation techniques for calculating neutron/gamma radiation dose to reactor presure vessel and internals were reviewed and the methods used in NEA Member countries for computing long-term cumulative dose rates were described. The report showed the results of neutron/gamma fluence and radiation doses within 20 percent difference between calculations and measurements or between calculations with different computer codes, significantly higher and lower values are also reported. Moreover, the numbers reported are difficult to compare to each other, since each country has its own methodology including different reactors, computer codes, nuclear data sets and measurement procedures. On that basis, the conclusion was that no firm judgement could be formed on the current international level of accuracy in pressure vessel fluence calculations. In 2002, Boehmer et al. [2] presented the results of neutron and gamma

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spectra, several fluence integrals and radiation damage parameters of ex-core components of Russian (VVER-1000) and German (1300 MW PWR and 900 MW BWR) light water reactors, with special interest in the relative contributions of gamma radiation to the sum of gamma and neutron contributions. However, the neutron and gamma flux ditributions at the RPV were not reported and consequently the areas in the RPV where the maximum of displacement-per-atom (DPA) were not identified. Recently, the calculation of DPA in the RPV of the Argentinian Atucha II reactor (PHWR type) [3] was performed using the Monte Carlo code MCNP, determining the areas where the RPV neutron radiation is maximum and the DPA rate in those areas. Nevertheless, the calculation was made using the fresh fuel element and the effect of fuel burnup has not yet been examined.

Accordingly, it is well known that studies on cumulative effects of radiation on the RPV and reactor internals are indispensable to ensure the integrity of the reactor during operation and to reveal information on radiation-induced embrittlement of reactor components. In this paper, we performed a preliminary calculation to identify the maxima of neutron and gamma fluxes in the RPV of a Russian pressurized water reactor, the VVER-1000/V320 [4], using the MCNP5 code [5]. In addition, the neutron and gamma fluence distributions on the RPV were investigated and evaluated along with their energy spectra. This study is considered as the starting point for the evaluation of radiation damage to the RPV of VVER reactors in particular and of pressurized water reactors in general.

II. CALCULATION METHODOLOGY

Neutron and gamma data for this calculation were taken from the ENDF/B-VII library. The NJOY code was used to process the ENDF/B-VII for the continuous energy MCNP5 calculations. To determine the average neutron and gamma fluxes on the RPV of the VVER-1000/V320 reactor, the FMESH 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 and gamma fluxes calculated by the MCNP5 code were plotted using the "pcolor" graphics module of the Matlab-like open-source Scilab [6].

The VVER-1000/V320 was modeled with hexagonal assemblies and full reactor core, including the complex steel baffle, steel barrel, water hole, etc. The configuration of the VVER-1000/V320 is shown in Fig. 1, representing its one-sixth symmetry. Tables I and II show the main VVER-1000/V320 reactor design and fuel assembly parameters respectively. A more detailed description of the reactor materials can be found in [4].

TableI. A Brief information of VVER-1000/V320

Parameter	Value
Reactor type	VVER-1000
Version	V320
Nominal power, MW	3000
Nominal electric power, MW	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 Density, g/cm^3 Outer diameter, mm Wall thickness, mm	 Zirconium alloy (Zr+1%Nb) 6.52 9.1 0.65
Pellet: Material Density, g/cm^3 Outer diameter, mm Center hole diameter, mm Height of UO_2, mm Mass of UO_2, g	 UO_2 10.22 7.55 2.4 3550 1460

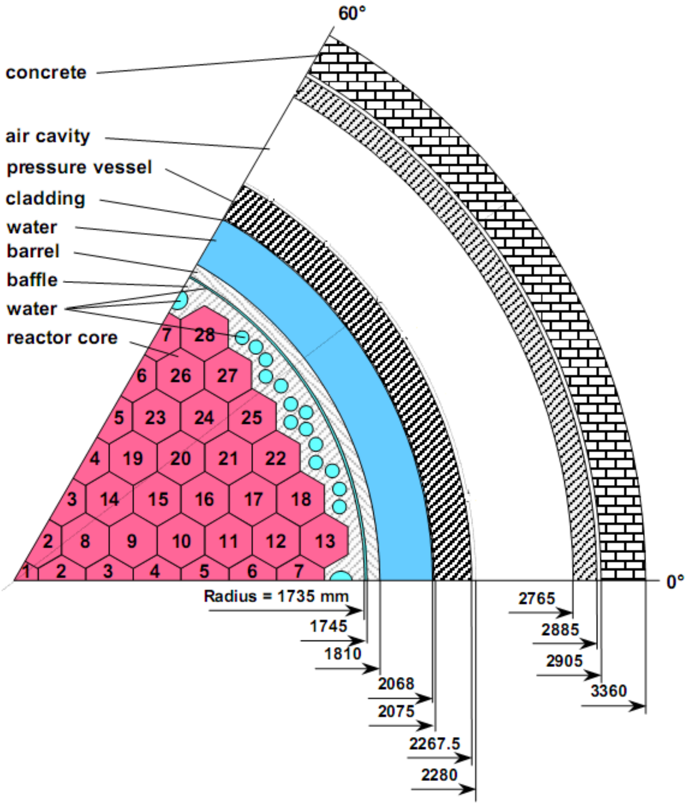

Fig. 1. VVER-1000/V320 core in 60^0 symmetry

III. CALCULATION RESULTS

The neutron and gamma fluences at the inner surface of RPV were investigated depending on the azimuthal angle (θ) and the reactor core axial position (z). The six azimuthal directions A, B, C, D, E, and F were described in Fig. 2a&2b. It can be noted that these six directions are used for prediction of the maxima of neutron and gamma fluences. Figs. 3 and 4 showed the neutron and gamma fluences, $\Phi_r(\theta, z)$, at the inner surface of RPV, where r_{inner} = 207.5 cm (inner radius of RPV); r_{outer} = 226.75 cm (outer radius of RPV).

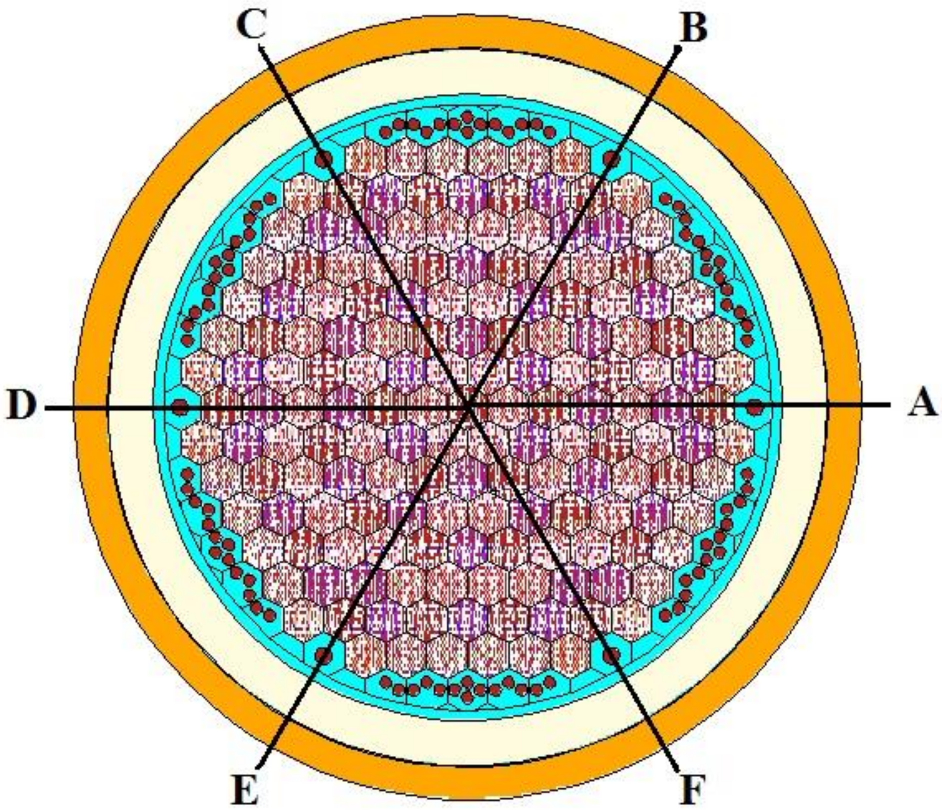

Fig. 2a. Six azimuthal directions for neutron and gamma fluence calculation

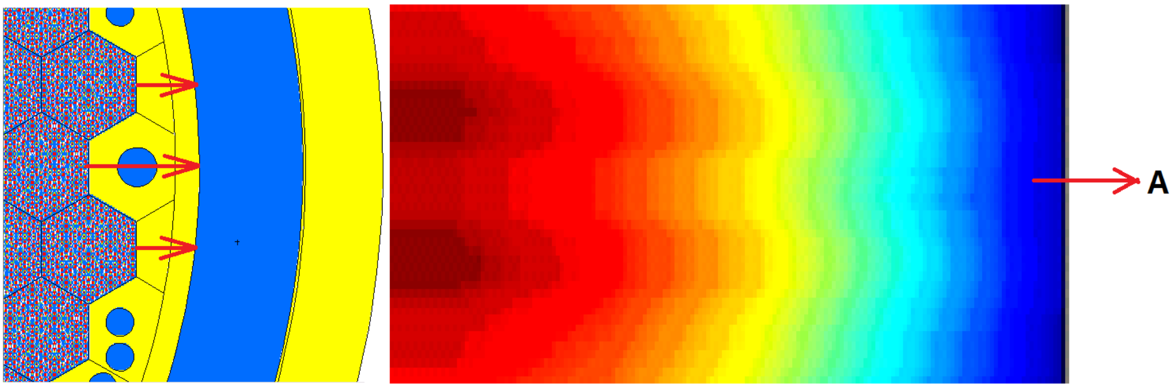

Fig. 2b. An example of azimuthal directions prediction

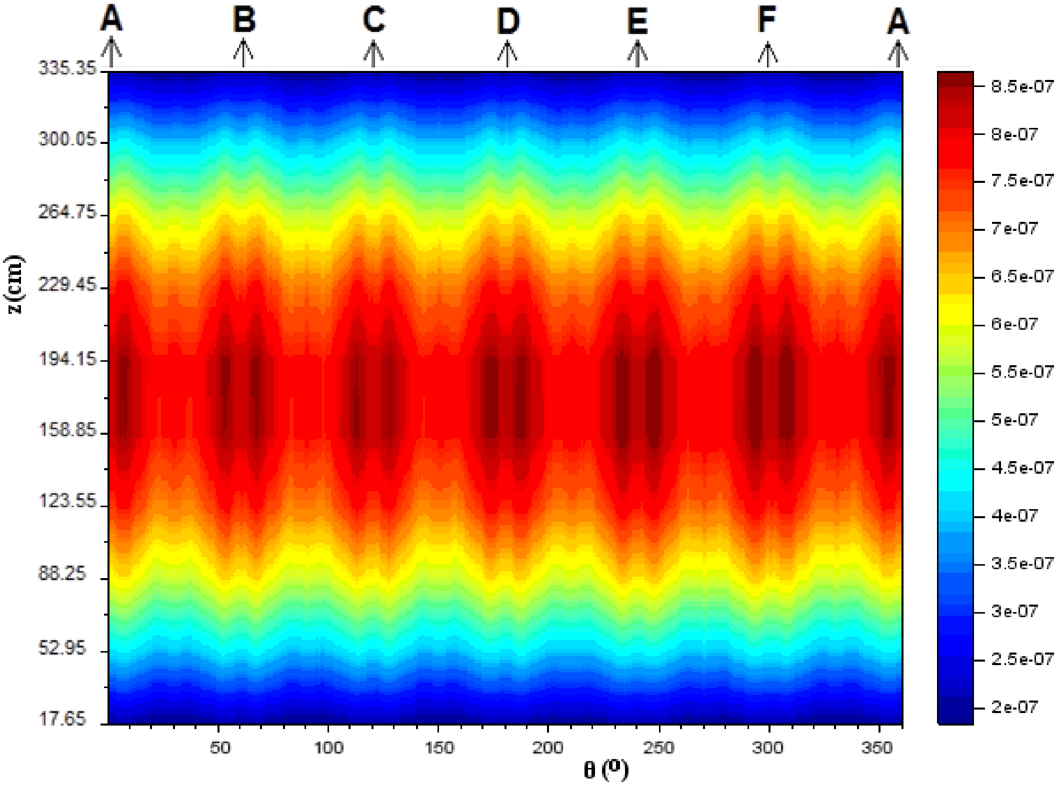

Fig. 3. Neutron fluence at the inner surface of RPV (1/cm^2)

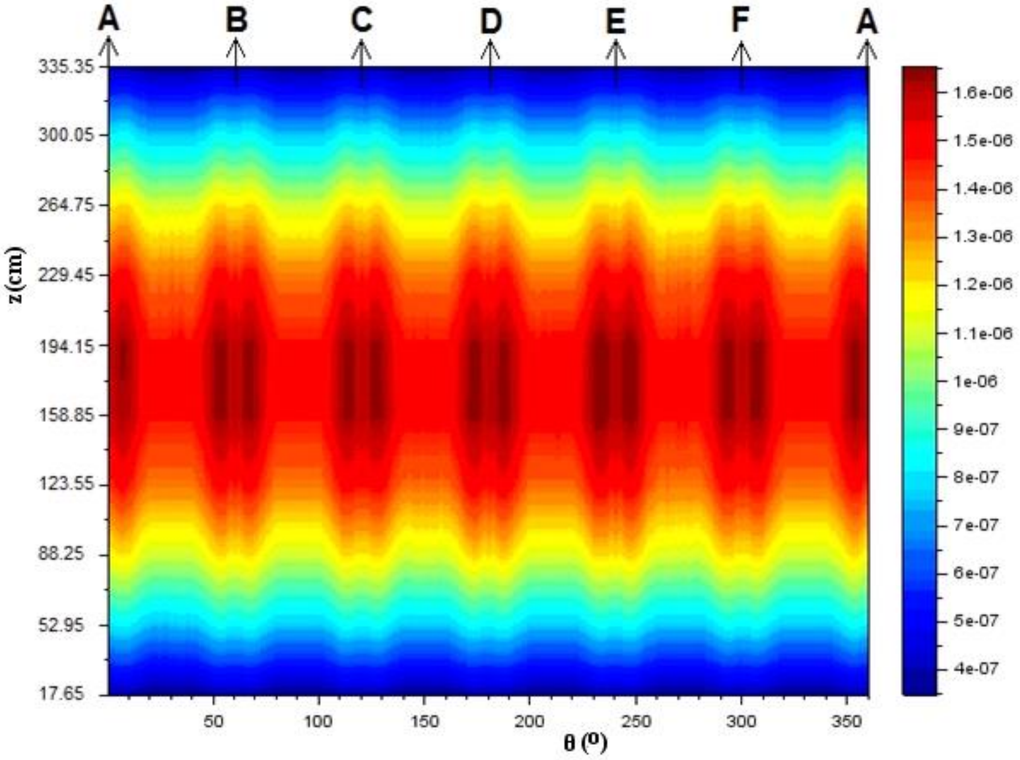

Fig. 4. Gamma fluence at the inner surface of RPV (1/cm^2)

As it was expected, the maxima of the neutron and gamma fluences were found in Figs.3 and 4 at the positions close to the six azimuthal angles A, B, C, D, E, and F, where the distance between RPV and fuel assemblies was shortest. It can be seen from these figures that each maximum was repeated every 60° due to the one-sixth symmetry of the core. Also, the neutron and gamma fluences were symmetric with respect to the core mid-plane (*z*=176.5 cm), mainly caused by the use of uniform coolant and fuel temperatures along the core axial direction in the MCNP5 calculation.

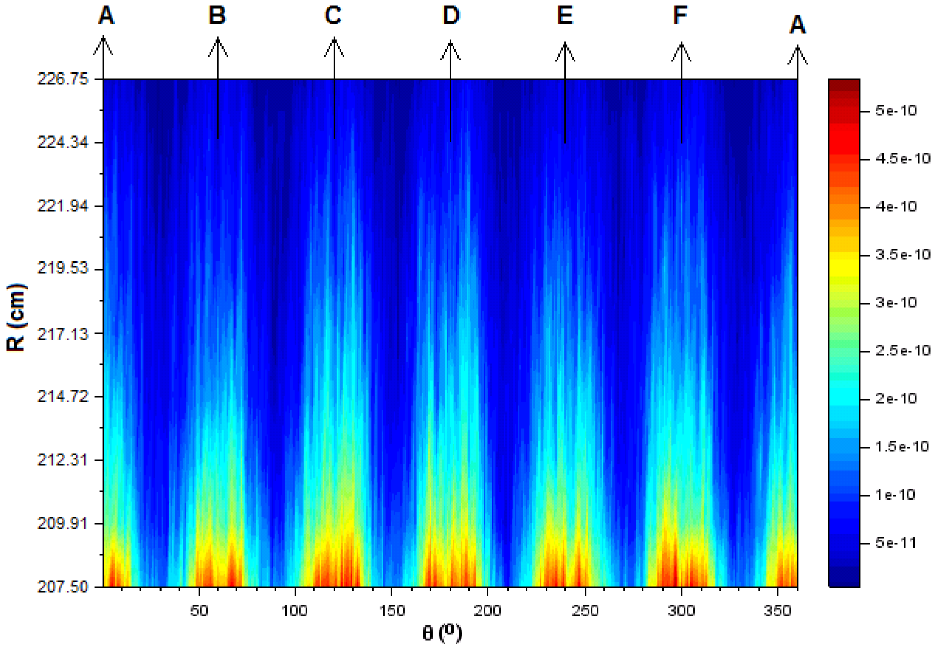

Fig. 5. Neutron fluence at the RPV on the core mid-plane (1/cm^2)

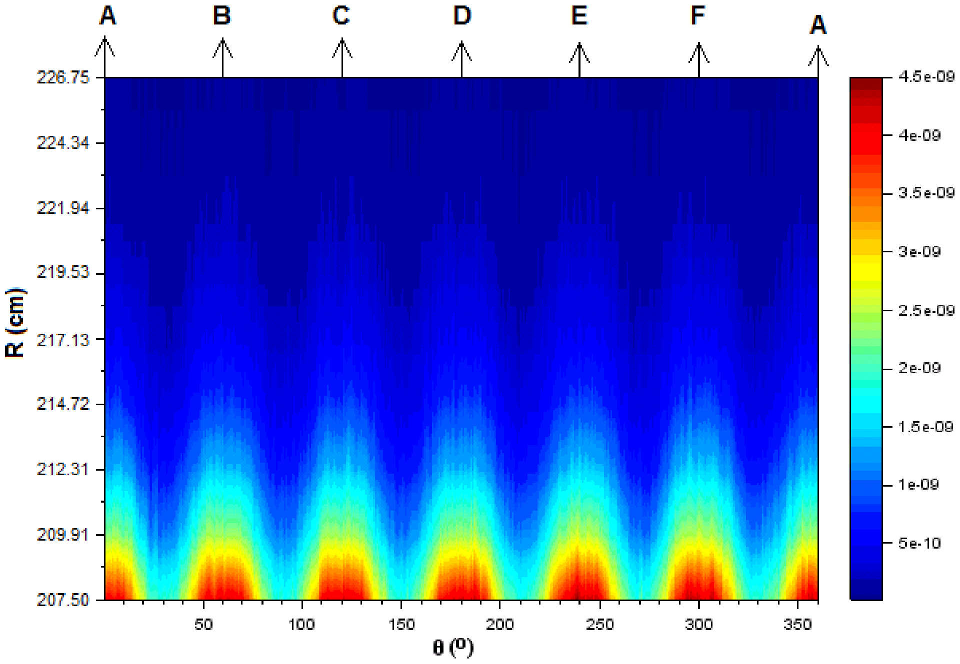

Fig. 6. Gamma fluence at theRPV on the core mid-plane (1/cm^2)

Figs. 5 and 6 showed the gamma and neutron distributions at the RPV on the mid-plane of the core. It was seen that the maxima of the neutron and gamma fluences appeared at the azimuthal angles A, B, C, D, E, and F. The maximum neutron and gamma fluences were identified at the first millimeters of the RPV. In addition, the gamma fluence was about one order higher than the relative neutron fluence, mainly because of the (n,γ) reaction of neutron with the iron composition in the vessel.

Table III:Neutron flux integrals on the mid-plane of VVER-1000/V320 (n/cm^2.s)

	Position	Φn, total	Φn, thermal	$\Phi n, E$>0.1 MeV	$\Phi n, E$>0.5 MeV	Φn,E>1 MeV
VVER standard (BUGLE)	Inner	2.65E+11	1.34E+11	7.00E+10	4.70E+10	3.08E+10
	1/4T	1.03E+11	8.15E+09	5.85E+10	3.41E+10	1.83E+10
	Outer	2.23E+10	1.41E+09	1.24E+10	5.45E+09	1.82E+09
VVER-1000/V320 (MCNP5)	Inner	2.56E+11	1.13E+11	6.27E+10	4.17E+10	2.71E+10
	1/4T	9.61E+10	6.61E+09	4.83E+10	2.86E+10	1.53E+10
	Outer	2.03E+10	1.07E+09	9.36E+09	4.23E+09	1.39E+09
Difference	Inner	-3.35%	-15.66%	-10.38%	-11.24%	-11.99%
	1/4T	-6.71%	-18.84%	-17.40%	-16.03%	-16.32%
	Outer	-9.16%	-23.83%	-24.50%	-22.44%	-23.74%

Table III compared the results of neutron flux integrals onthe core mid-plane between our MCNP5 calculations and those reported in [2]. As shown in this Table, the difference in the MCNP5 and BUGLE-96 values could reach about 25% at the outer surface of the RPV. The reason might be due to the discrepancy between our reactor core input data and those used in [2]. Namely, different core loading pattern, fuel assemblies, steel baffle, and water hole data were used in this calculation.

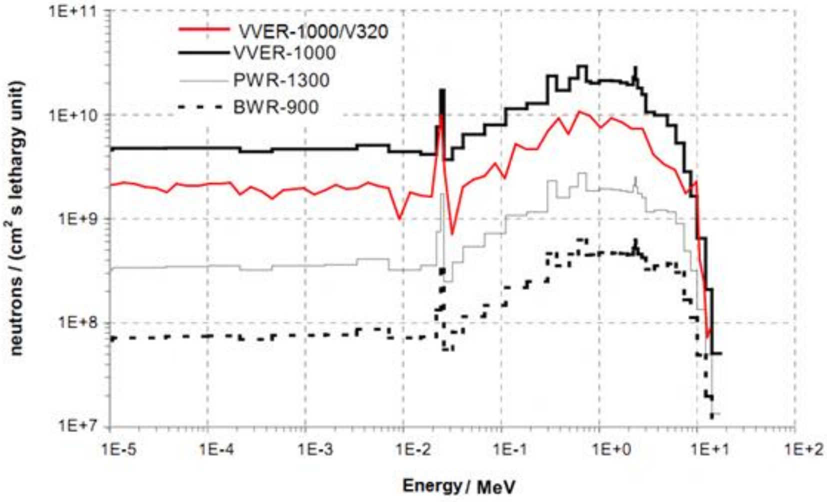

Fig. 7. Neutron flux spectra at the inner surface of RPV

Fig.7 displayed the neutron flux spectra at the inner RPV surface under the nominal power condition calculated using the MCNP5 code in relation to those published in [2]. The neutron spectra of the VVER-1000/V320 calculated using MCNP5 was similar in shape to that of the VVER-1000 standard [2]. However, there was still considerable difference in their magnitudes, which might arise from different uses of neutron energy group boundaries and reactor core input data.

IV. CONCLUSIONS

In this work, we have carried out, for the first time in Vietnam, a preliminary calculation of neutron and gamma fluences on the RPV of the VVER-1000/V320 using the MCNP5 code. It was found that the areas at the RPV where the neutron and gamma fluences are maximum were the positions nearest to the fuel assemblies. Furthermore, the maximum neutron and gamma fluxes were identified at the first millimeters of the RPV. The neutron flux integrals on the core mid-plane and the neutron flux spectra obtained herein with MCNP5 were in rough agreement with those published in [2] (within ~25% for the neutron flux integrals). It might be attributed to the discrepancy between our reactor core input data and neutron energy group boundaries and those used in [2]. For instance, we used different core loading pattern, fuel assemblies, steel baffle, and water hole data.

As above-mentioned, this calculation is the first step for evaluating radiation-embrittlement of the RPV of VVER reactors. In the next study, we will calculate and examine the radiation damage parameters to the RPV such as DPA and FMD (the numbers of freely migrating defects) rates in typical states of the VVER-1000/V320 reactor, e.g., at different burnup stages.

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