TORT APPLICATION IN RPV NEUTRON FLUX CALCULATIONS

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ABSTRACT

The neutron flux values onto RPV for VVER-1000 and VVER-440 reactors, at the places important for the metal embrittlement surveillance, have been calculated by 3D code TORT and synthesis method. The comparison of the results received by both methods confirms their good consistency.

The determination of the neutron flux onto the VVER pressure vessel is an essential part of the Reactor Pressure Vessel (RPV) Surveillance Program. The main tools for determining the pressure vessel flux are the neutron transport calculations.

The discrete ordinate Sn method has been successfully applied in one (1D) and two (2D) dimensional geometry nowadays. The synthesis [1, 2] of the 2D and 1D solution for three dimensional geometry (synthesis method) has been applied in neutron flux assessment. The adequate determination of neutron flux depends on the choice of Pn, Sn approximations, multigroup libraries of neutron constants, mesh of variables discretization, the choice of neutron source, based on the power distribution. A more correct description of neutron flux distribution is expected to be obtained by direct three dimensional (3D) solving of the problem.

The comparison of neutron flux calculational results on RPV for VVER-440 and VVER-1000 reactors, at the places important for the metal embrittlement surveillance, with 3D code TORT [3] and the synthesis method is presented in this paper.

The code TORT version 1.5.11 (for IBM RISC Sistem/6000, from RSIC ORNL) has been ported by us to the 386/486 personal computer and used for these 3D calculations.

The 3D neutron flux estimation in the synthesis method is based on the 2D and 1D DORT [4] solutions of the transport equation: radial-azimuthal $N_T(r,\Theta)$ radial-axial $N_Z(r,z)$ and radial $N_R(r)$, using the following expression [2]:

$$N(r,\Theta,z) = N_T(r,\Theta) N_Z(r,z) / N_R(r). \tag{1}$$

Such three dimensional flux representation is acceptable because the flux dependence on z and Θ is smoother than on r, but it is difficult to evaluate its accuracy because of the lack of exact limits definition of its application. The validity of (1) could be formally estimated in the case of the simplified description of the volume source as superposition of limited linear neutron sources and neglected self-absorption [2, 5]. For the complicate real geometry of VVER reactor the validity of (1) is suitable to be estimated by comparison with 3D code TORT results.

The calculations for both VVER-440 and VVER-1000 are performed considering a sector of 30° mirror symmetry including the reactor core, the inner vessel arrangement, the air shell between the vessel and the heat insulation and the part of the biological shield. The neutron fission source is represented by the power efficiency, averaged over the plane cross section of each cassette. The axial dependence is taken into consideration. The detailed geometry models we have used are described in [6] for VVER-440 and [7] for VVER-1000.

The integral neutron flux values

$$N(r,\Theta,z) = \int_{E_{min}}^{E_{max}} N(r,\Theta,z,E)dE \qquad (2)$$

at the places (Table 1), important for the metal embrittlement surveillance, in energy intervals from $E_{min} = 0.5, 1, 3, 5$ MeV to $E_{max} = 15$ MeV, have been calculated and compared.

TABLE 1. Places for the Test Comparison

Reactor	No	r, cm	Θ,°	z, cm	Comments
VVER-1000	1	207.35	8	*96.0	on RPV, azim max, axial max
	2	207.35	30	96.0	on RPV, azim min, axial max
VVER-440	1	178.40	30	29.5	on RPV, azim max, weld 4
	2	192.45	30	29.5	beh. RPV, azim max, weld 4
	3	178.40	13	29.5	on RPV, azim min, weld 4
	4	192.45	13	29.5	beh. RPV, azim min, weld 4

* z = 0 - core bottom

For description of the neutron scattering energy dependence a comparative analysis [6] have been carried out with the following libraries:

- VITAMIN/C [8]: 73 groups above 0.5 MeV; averaging multigroup constant spectrum is 1/E for the energy intervals 0 to 0.82 MeV, 10 to 12.6 MeV, and $E^{1/2}e^{-E/1.4}$ for 0.82 to 10 MeV,
- FLUNG [9]: 17 groups above 0.5 MeV, with the above mentioned averaging spectrum,
- DLC37F [10]: 36 groups above 0.5 MeV, 1/E averaging spectrum,
- L26P3S34 [11]: 13 groups above 0.5 MeV, 1/E averaging spectrum.

The differences between the integral energy flux values calculated by the mention libraries vary no more than 3%. The estimation of the integral flux with energy above 0.5 MeV differs less than 0.7%. The library FLUNG has been applied in all following flux calculations.

TABLE 2. Number of Mesh Intervals

Reactor	r	Θ	z
VVER-1000	95	30	71
VVER-440	93	30	60

There are not substantial differences (greater than 0.5%) in the integral neutron flux values with energy above 0.5 MeV calculated by P3S8 and P6S16 approximations both for VVER-440 and VVER-1000 [6, 7, 12, 13]. That is why, the P3S8 approximation has been used. The (r,Θ,z) coordinate meshes (Table 2) are chosen by the authors, so that the inaccuracy is less than 0.5%. The comparative calculations with the chosen azimuthal steps 1.0° and 0.3° for VVER-1000 / 0.5° for VVER-440 show that the differences are within 0.5%. The used value $d=0.01$ of the general convergence criteria provide the same flux value as $d=0.001$.

The flux values for VVER-1000 calculated by the 3D synthesis method and 3D code TORT are shown in Table 3. The comparison shows a good consistency within the limits of the solution accuracy. The differences diminish from 5% to 1% with enlarging the energy range limits.

TABLE 3. Neutron Fluxes on VVER-1000, 10^9 $cm^{-2}s^{-1}$

Point	Method	Energy range, Mev			
		>5.0	>3.0	>1.0	> 0.5
1	SYNT	4.73	11.0	37.6	57.0
	TORT	4.60	10.8	38.4	57.7
	SYNT/TORT	1.03	1.02	0.98	0.99
2	SYNT	1.38	2.91	9.93	14.6
	TORT	1.32	2.82	9.80	14.4
	SYNT/TORT	1.05	1.03	1.01	1.01

These results are expected for VVER-1000, because the places of interest are far from the reactor core axial edges.

The more important conclusion is connected with the good consistency of the flux values for VVER-440 in the places near the core bottom, the weld seam 4 (Table 4).

TABLE 4. Neutron Fluxes on VVER-440, 10^{10} $cm^{-2}s^{-1}$

Point	Method	Energy range, Mev			
		>5.0	>3.0	>1.0	> 0.5
1	SYNT	0.610	1.54	6.80	11.3
	TORT	0.628	1.59	7.01	11.6
	SYNT/TORT	0.971	0.969	0.970	0.974
2	SYNT	0.0448	0.112	0.937	2.69
	TORT	0.0471	0.117	0.970	2.79
	SYNT/TORT	0.951	0.957	0.966	0.964
3	SYNT	0.509	1.23	5.10	8.34
	TORT	0.530	1.28	5.27	8.60
	SYNT/TORT	0.960	0.961	0.968	0.970
2	SYNT	0.0376	0.0839	0.625	1.75
	TORT	0.0400	0.0883	0.649	1.81
	SYNT/TORT	0.940	0.950	0.963	0.967

In addition, it may be noted that the CPU time for the synthesis method calculations is about 18 times shorter than the TORT one. The accomplished comparison indicates that at reasonable cost the calculations necessary for the Metal Embrittlement Surveillance Program should be performed by the synthesis method.

This comparison, however, is not sufficient for estimating the inaccuracy of the neutron flux calculational results because it is based on one and the same calculational method of discrete ordinates.

Another way to prove the calculation validity in the real operation could be based on the comparisons with measurements of the threshold detector activities, placed behind the RPV. Such detectors have been already installed on VVER-440 reactor of Kozloduy NPP.

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