ABOUT THE USE OF UNITS DISPLACEMENT PER ATOM AND FLUENCE FOR DEFINITION OF THE DAMAGE EXPOSURE IN REACTOR MATERIALS

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ABSTRACT

The problem of definition of natural units for estimation of the damage exposure is discussed on an example of the WWER-1000 reactor pressure vessel (RPV) irradiation. We have found that the use of the fast neutrons fluence (FNF) units is not fully adequate in some cases as this measure cannot include essential thermal neutrons exposure in the vicinity of surveillance specimens and the internal surface of the pressure vessel. The use of the displacement per atom (DPA) units seems more general and adequate measure of the damage exposure, as it takes into account all available neutrons. Some numerical examples of calculation of the FNF and DPA spatial distributions and neutron spectra in the vicinity of the WWER-1000 RPV by the discrete ordinates method are given. In all calculations the neutron thermalization have been taken into account. The accuracy of multigroup calculations with the use of the problem dependent BGL1000 cross-sections library (that consists of 47 neutron and 20 photon groups) has been estimated by a comparison with the results of the fine energy mesh calculations with the use of the last version of the 299 neutron groups ABBN93-2a library.

1. INTRODUCTION

The problem of a unified estimation of the damage exposure for all elements of nuclear reactor construction is an actual problem in nuclear engineering. Reliable and accurate information about this quantity should promote decrease in the number of possible accidents and validation of decision in prolongation of the lifetime of elements of the reactor construction.

The main goal of this investigation is to find an answer on the following questions. What are the more natural units for definition of the damage exposure: the DPA or the FNF units? In what extent the use of both these units is interchangeable in normative formulas? In the world practice both units are used.

We have tried here to find an answer on these questions for the case of the WWER-1000 RPV irradiation.

2. APPROXIMATIONS USED IN THE WWER-1000 RPV DOSIMETRY CALCULATIONS

The used model of WWER-1000 reactor can be well approximated in the three-dimensional (r, ϑ, z) geometry and for solving the above mentioned problem neutron and photon fluxes for this model should be calculated. The full 3D calculation of the problem is quite expensive. We hope to perform it in the future work by the use of the new 3D transport code KATRIN. Here we present only results for the case, where the approximate 3D distributions have been received using the 3D synthesis [1] of 2D (r, ϑ) and (r, z) and 1D cylindrical (r) solutions

$$\varphi(r, \vartheta, z, E) \approx \varphi_{2D}(r, \vartheta, E) \frac{\varphi_{2D}(r, z, E)}{\varphi_{1D}(r, E)}, \qquad (1)$$

those have been calculated by the discrete ordinates codes KASKAD-S-2 and ROZ-6.5. These codes are the current versions of codes described in [2, 3].

For fission source calculations the standard Russian code BIPR has been used. BIPR code gives the three-dimensional assembly-wise source distribution in a core. The special utility has been used for transforming the source distribution, obtained by this code, to the r, ϑ grid of transport codes. Source distribution for transport calculations has been specified proportional to average power during equilibrium fuel cycle. The source spectrum was chosen identical to the ^{235}U fission spectrum. The transport calculations in the vicinity of RPV have been carried out for 30° sector of symmetry of WWER-1000 core (see Figure 1).

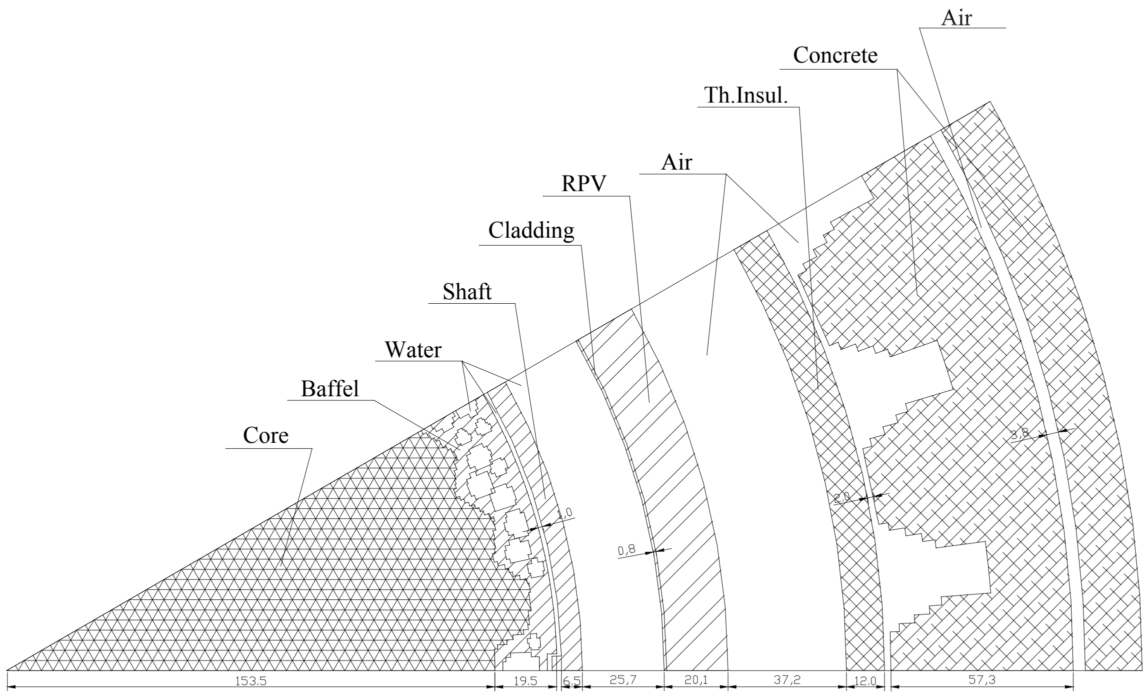

Figure 1. An approximation of the 30° symmetry sector of the WWER-1000 in (r, ϑ) geometry.

For the base calculations the broad group BGL-1000 neutron/photon cross-section library [5] has been chosen, where neutron thermalization is taken into account. This library has been produced by collapsing the fine-group VITAMIN-B6 library (199 neutron and 42 gamma groups) [6] to 67 group structure (47 neutron and 20 gamma groups) with weighting spectra, typical for main material zones of WWER-1000. The 67 group structure of BGL-1000 is the same as used in BUGLE-96 library [7]. All calculations have been performed with the use of P_5S_8 approximation and point-wise convergence criterion 10^{-4} for inner iterations and 10^{-3} for outer upscattering iterations in thermal region. The adaptive WDD scheme and the consistent P_1SA scheme for acceleration of inner (and outer for the case of ROZ-6.5 code) iterations convergence have been used in these calculations. The spatial mesh was chosen sufficiently fine.

To estimate the accuracy of the broad group BGL-1000 calculations, the last version of the fine-group ABBN93-2a library (299 neutron and 15 gamma groups) [8] has been used to perform calculations with neutron thermalization in 1D cylindrical geometry. Our experience has shown that the use of fine-group libraries with upscattering in thermal region requires the presence of a sufficiently efficient upscattering iterations acceleration algorithm in the code used. The consistent P_1SA upscattering acceleration scheme [9] that is available in ROZ-6.5 code works quite efficient in the problem studied. The fine-group 2D calculations with the current version of KASKAD-S code, due the absence of upscattering iterations acceleration scheme implemented, are very expensive in thermal region and not presented here.

Next, the radial function $K(r)$ that defines the ratio between the damage exposure in DPA units and in FNF units for some given axial and circular points z and ϑ for the same time of irradiation has been calculated

$$K(r) = \int_{E_T}^{20MeV} \varphi(r,E)\sigma_{DPA}^{Fe}(E)dE \Bigg/ \int_{E_{fast}}^{20MeV} \varphi(r,E)dE\,, \tag{2}$$

where $\sigma_{DPA}^{Fe}(E)$ is the value of DPA cross-section for iron, taken from library [4] (see Figure 2), E_{fast} is the chosen lower energy boundary of the fast neutrons region and E_T is the lower energy boundary of the cross-section library used. The boundary E_{fast} is not strictly defined. Typically used values of E_{fast} are 0.1, 0.5 and 1.0 MeV. In Russian normative documents E_{fast} = 0.5 MeV.

It is important to note that in calculation of the group averaged DPA cross-sections the standard spectrum (with Maxwellian spectrum for temperature T=300°K in thermal region (below 0.125 eV)) from VITAMIN-B6 library [6] has been used. These cross-sections are needed for calculation of $K(r)$, given by Eq. (2).

3. RESULTS OF THE WWER-1000 RPV DOSIMETRY CALCULATIONS

In Figure 3 the results of calculations of function $K(r)$ with the use of BGL-1000 cross-section library in the point $\vartheta = 10°$, $z = 211.8$ cm, where the maximum of the FNF with E_{fast} = 0.5 MeV is achieved, are depicted.

From Figure 3 it is possible to conclude that, generally, there is no linear dependence between damage exposure given in DPA and FNF units: $DPA \neq \alpha FNF$, where α is a constant. Specifically, the linear dependence is violated in the spatial zone, located in the vicinity of the internal side of reactor vessel and about 70 cm from its external side, where the neutron spectrum becomes softer and there is a number of thermal neutrons (see Figure 4). Really, from Figure 2 we can conclude that the value of $\sigma_{DPA}^{Fe}(E)$ is quite large for thermal region. So, the sufficiently large number of thermal neutrons can give an essential contribution in DPA that is comparable with the fast neutrons one.

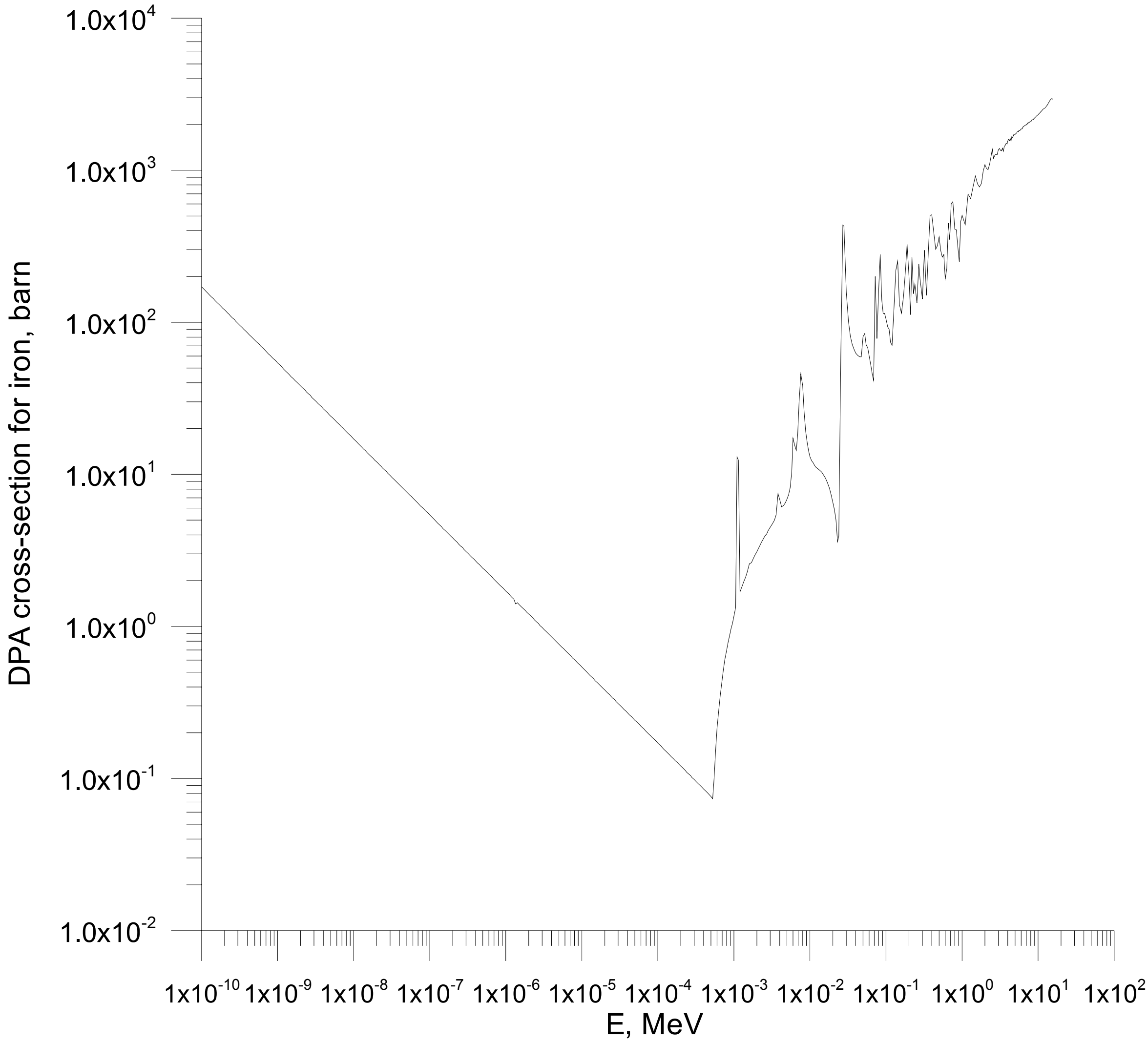

Figure 2. Energy dependence of the DPA cross-section for iron.

The similar results are available in 1D cylindrical geometry calculations. In Figures 5-7 the results of 1D calculations of function $K(r)$, fast and thermal neutrons radial distributions, and differential neutron spectra at the internal (r=207.9 cm) end external (r=226.32 cm) RPV surface with the use of BGL-1000 and ABBN93-2a cross-section libraries are depicted.

From Figures 5-6 we can conclude that the use of BGL-1000 and ABBN93-2a cross-section libraries gives similar results both for fast and thermal neutrons radial flux distributions. On the other hand, from Figure 7 we can find that the BGL-1000 energy mesh in thermal energy region seems quite rough to define correctly the spectrum of thermal neutrons.

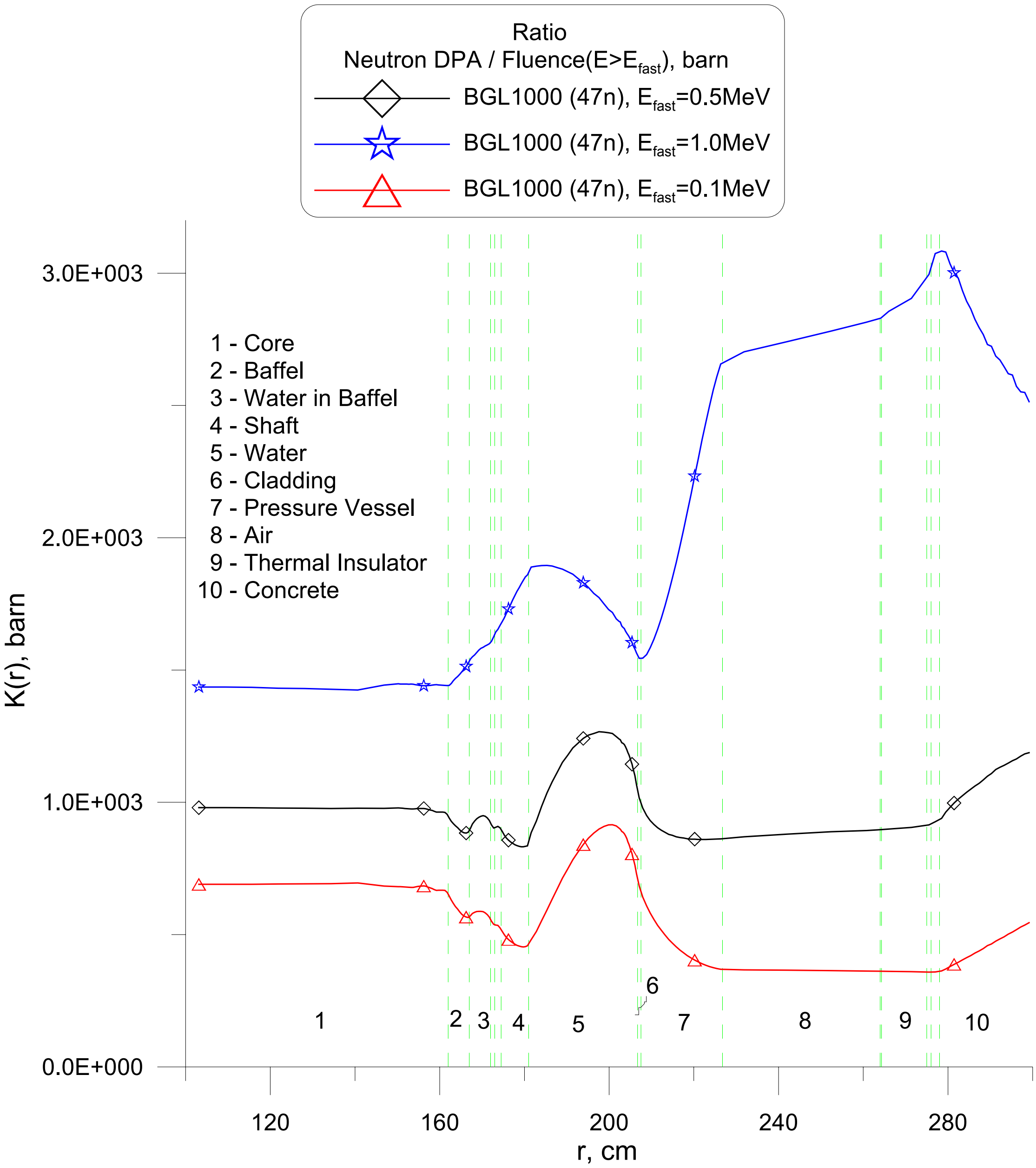

Figure 3. Ratio of the damage exposure in the DPA units to the one measured in the FNF units in the point $\vartheta = 10°$, $z = 211.8$ cm.

CONCLUSIONS

From Figures 3 and 5 it is possible to conclude that, generally, there is no linear dependence between damage exposure given in DPA and FNF units: $DPA \neq \alpha FNF$, where α is a constant. Specifically, the linear dependence is violated in the spatial zones, where the neutron spectrum becomes softer and there is a number of thermal neutrons (see Figures 4 and 6). The sufficiently large number of thermal neutrons can give an essential contribution in DPA that is comparable with the fast neutrons one.

From this particular example follows: the FNF is not a universal quantity for definition of the damage exposure and the use of DPA for different elements of reactor construction seems more universal tool for this purpose, as it takes into account all available neutrons. Really, DPA is physically related with the damage and embrittlement of reactor construction materials and can be used as general characteristic of material damage. On the other hand, the fast spectrum lower boundary E_{fast} = 0.5 MeV in definition of the FNF seems as the best choice (from the standpoint of interchangeability in normative formulas) from the problem studied.

It seems that gamma-rays also contribute in the damage exposure, but their contribution is not well known now and the investigation of this problem is one of the goals of the future work.

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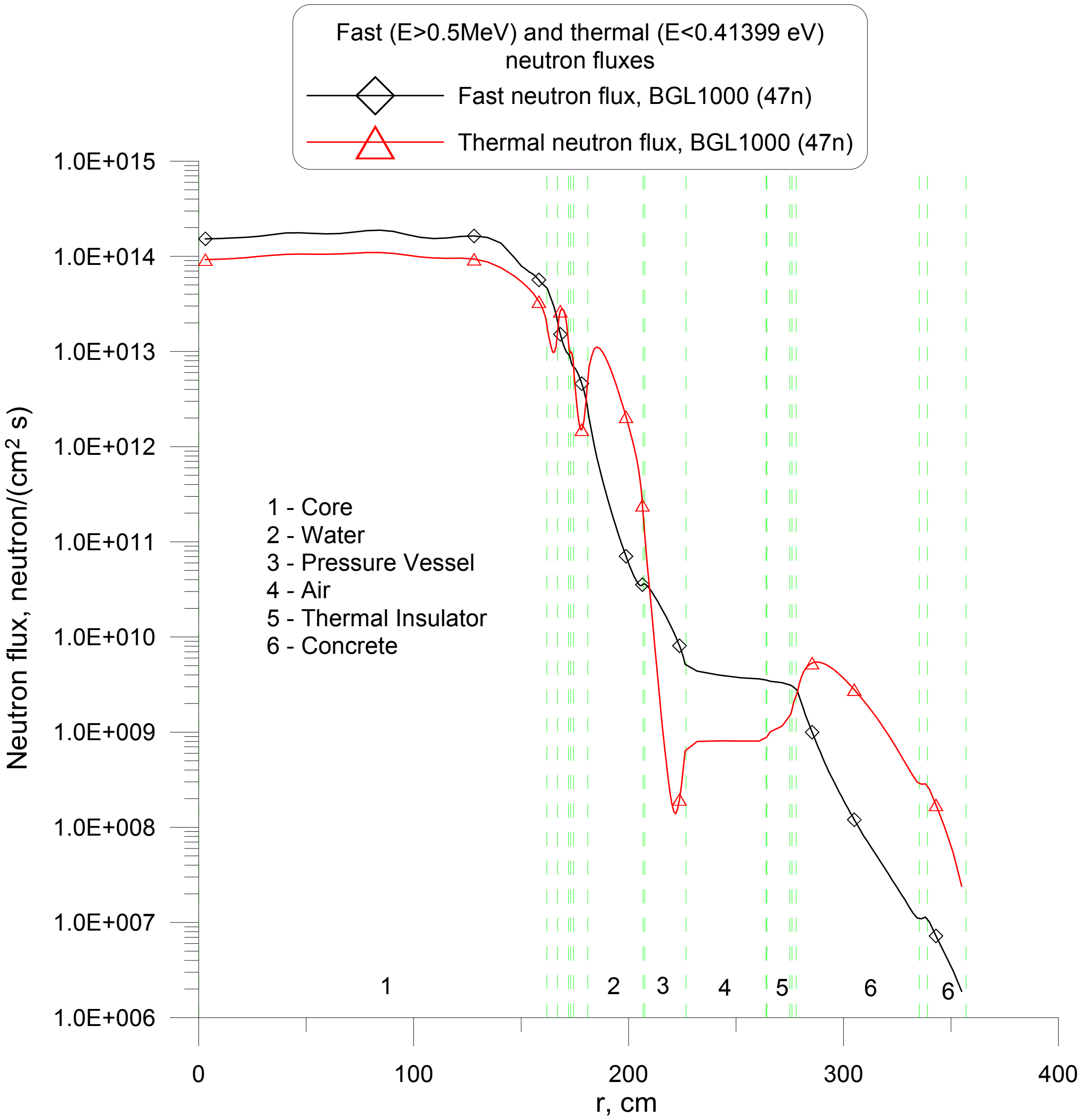

Figure 4. Fast and thermal neutron flux radial distributions in the point $\vartheta = 10°$, $z = 211.8$ cm.

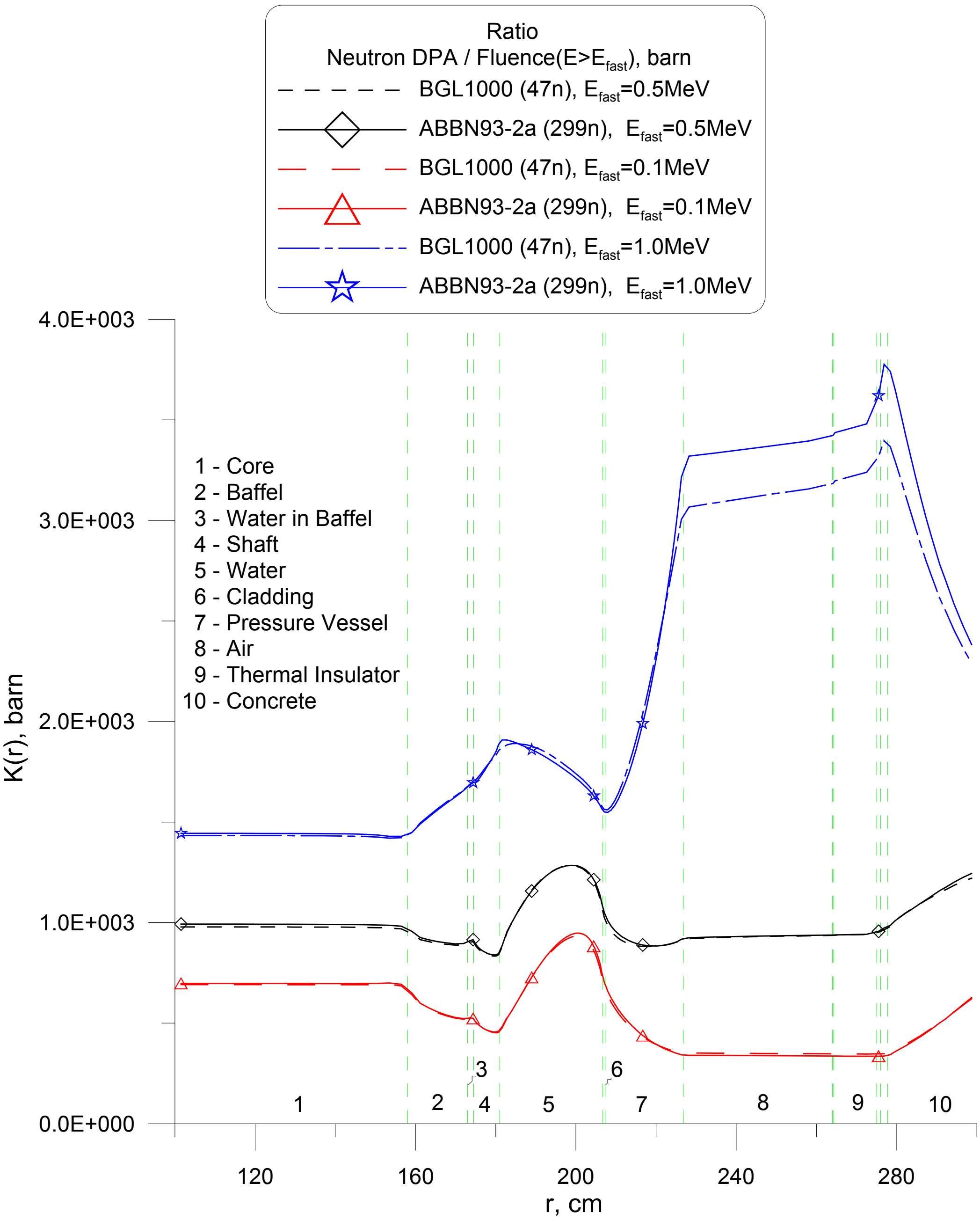

Figure 5. Ratio of the damage exposure in the DPA units to the one measured in the FNF units in 1D cylindrical geometry calculations.

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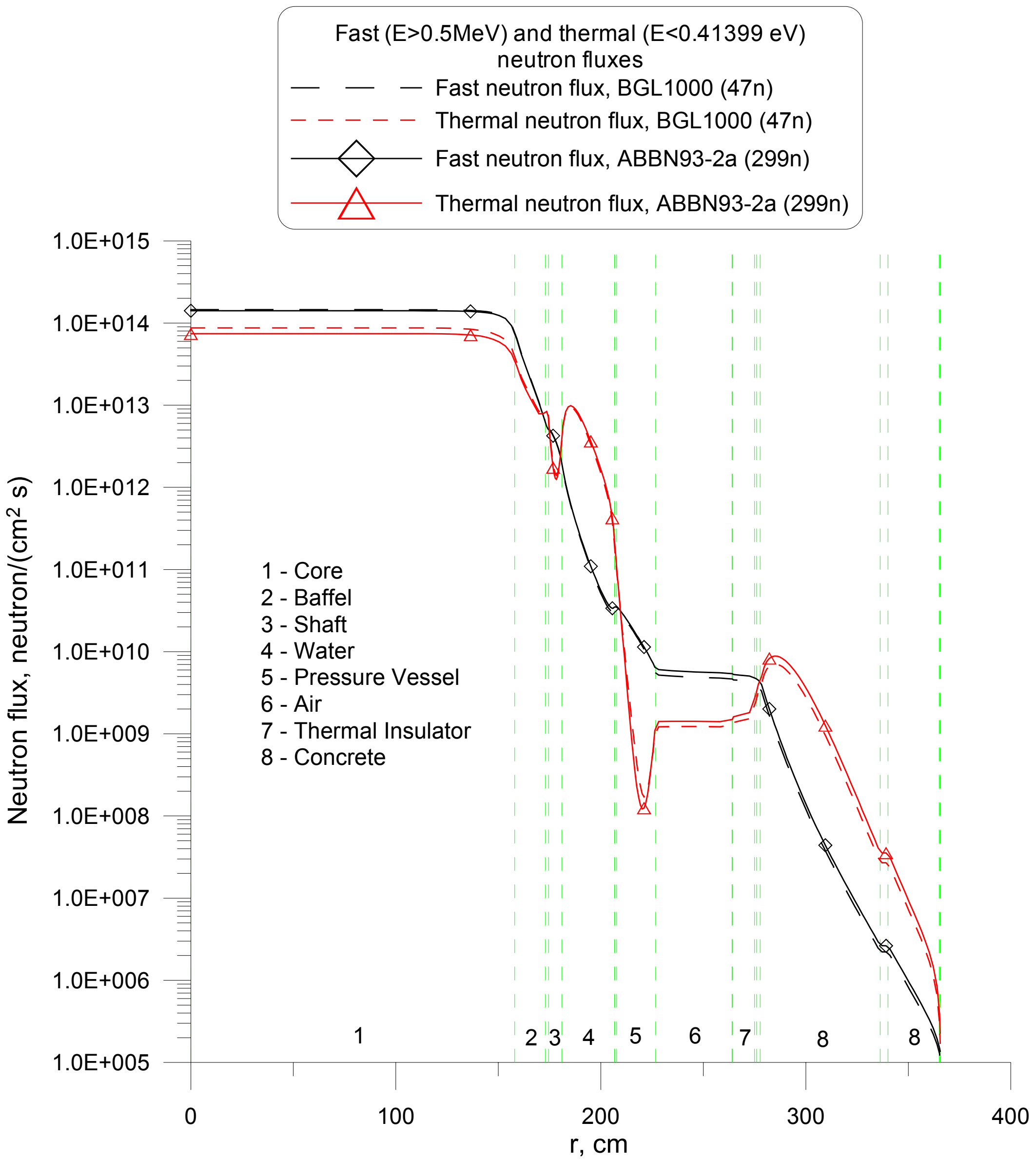

Figure 6. Fast and thermal neutron flux radial distributions in 1D cylindrical geometry calculations.

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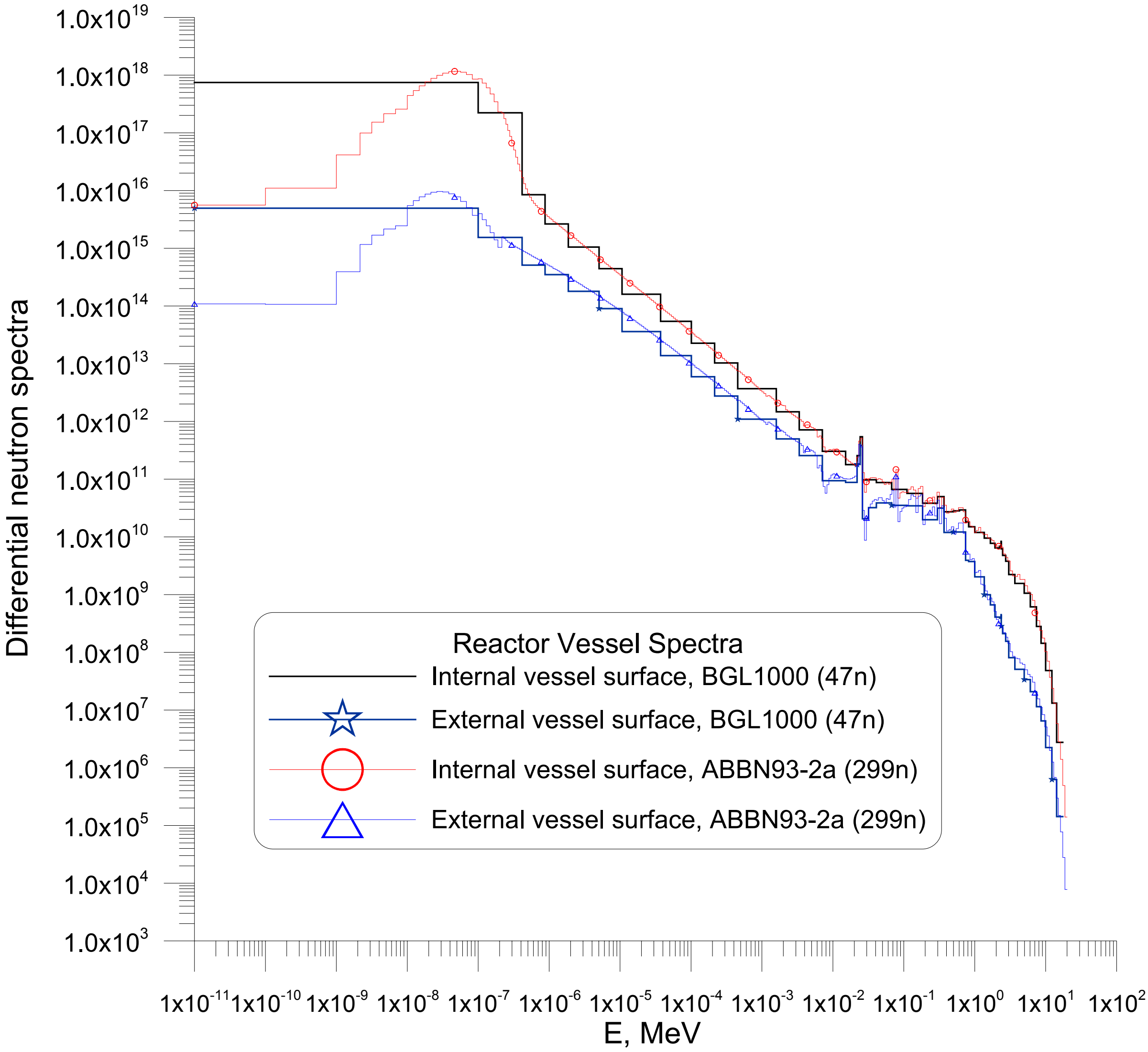

Figure 7. Differential neutron spectra at the internal (r=207.9 cm) end external (r=226.32 cm) RPV surface in 1D cylindrical geometry calculations.