This paper presents some results of using of the RETINA (KAB, Germany) code for fluence calculation. The paper describes the code accuracy assessment on a basis of the on-site experiments carried out at Ukrainian NPPs, calculation estimation of the accumulated fast neutron fluence at the WWER-1000 RPV of some Ukrainian NPPs. It briefly describes the current situation with fluence monitoring and developing requirements to calculational models for the fluence calculation.

The fluence accumulated by RPV during operation period is an essential and important information for its residual lifetime assessment. Taking into account substantial operation time of some units at Ukrainian NPPs this becomes a pressing question. Surveillance-specimens allow to define ductility behaviour of the vessel metal and welds under irradiation. But in order to define the actual RPV reference temperature for the ductility transition the value of the accumulated neutron fluence has to be determined.

Currently Ukrainian NPPs use calculation methods for fluence monitoring. At some plants has been introduced the method developed in NRI Ukrainian Academy of Science. In fact, this method consists in extrapolation of the cavity fluence measurements onto RPV inner surface using calculational data of NRI own code. Absence of the experimental data at the inner RPV surface cannot confirm the accuracy of such an approach. Thus, NRI method also determines fluence by calculation while cavity experiment being used for proving the input data correctness.

For fluence prediction SSTC uses DORT and RETINA codes. This paper presents some results of the RETINA [1] (KAB, Germany) code used for fluence calculation. This code defines neutron flux outside the core as superposition of point kernel sources. The Green function (point kernel) is defined on a basis of preliminary $S_N$-calculation of the spatial neutron flux distribution.

To validate and estimate the accuracy of the RETINA code in fast neutron fluence calculations for the WWER-440 and WWER-1000 RPV considerable work has been carried out on a basis of the on-site experiments.
The fig. 1 presents some results of the accuracy evaluation. It shows the comparison of the calculated and experimental detector activities and reaction rates that were obtained at the outer surface of WWER-1000 at South-Ukrainian NPP. Experimental data were obtained with threshold detectors made of $^{93}$Nb, $^{54}$Fe, $^{nat}$Ti и $^{63}$Cu throughout 5 campaigns at three units by the specialists of NRI Ukrainian Academy of Science and "KI". The detectors were set in 60-degrees bow-shaped holders located at the welds area and opposite maximal power layer (approx. 125 cm from the core bottom). In the most cases the deviation does not exceed 10%.

For the WWER-440 were also obtained satisfactory results:
- for the "full" core deviation between calculation and experiment constitutes 5-10%;
- in case of "reduced" core deviation higher, but does not exceed 20% [2, 3].

The data of the dosimetry benchmark carried out at experimental facility LR-0 [4] (NRI Rez, Czech Republic) were also used to validate and estimate the accuracy of the fluence prediction at WWER-1000 RPV. Although feature of the RETINA does not allow repeating this benchmark in full range, but the results confirm that the code quite correctly models the neutron transport in the metal construction. In the coolant the deviation with experimental data is significantly higher. Probably this caused an old cross-section library DCL-76/SAILOR [5], based on ENDF/B-IV that was used for calculation. All these works have demonstrated that this code ensures acceptable accuracy of the fluence calculation for different pattern of the WWER core layout and can be used in expert activity.

The RETINA code was used for the estimation of the accumulated fluence during operation for 9 units. The fig. 2 demonstrates the results of these calculations. The data were obtained at the inner surface at the welds area and opposite to the maximal power layer. The fig. 3 shows the average values of the fast neutron flux. Also maximal flux according to the WWER-1000 design is presented. According to the assessment carried out the intensity of the fluence accumulation is significantly lower than anticipated in the design.

The design values for vessel internals were used in these calculations for all units. And only for three units of ZNPP the actual RPV geometry dimensions were used. Taking into account that the producer gives rather sizeable tolerance on the RPV and vessel internals geometry and that the operator does not have as-built information these calculations are not conservative.

Taking into account such deficit of the input data, it was recommended to implement calculating fluence monitoring on a basis of a conservative model. The input data for the conservative model must be defined on a sensitivity analysis of the neutron flux to the data uncertainty. The sensitivity analysis should estimate the influence of all uncertainties of the reactor structure parameters on neutron flux attenuation. For evaluating the RPV condition should be taken parameters which lead to the maximal flux value at the vessel. The core neutron source also should account error of the neutronic calculations. Such an approach can guarantee that the actual RPV conditions are always better than got in strength analysis or residual life-time prediction. The conservatism of the fluence estimation for particular unit can be reduced only on a basis of reliable, verified and documented plant-specific data about reactor structure parameters that have an influence on the flux attenuation. It is necessary to mention that dosimetry measurements in the RPV cavity cannot be used as justification for reducing conservatism of the calculation model.

The results of the dosimetry benchmark modelling made with the DORT code can be used to explain such requirements. The fig. 4 demonstrates comparison of the calculated and experimental neutron spectra at the barrel and inner/outer vessel surfaces. While comparing the calculation results at the inner and outer surfaces of the vessel mock-up it is evident that in the downcomer - overprediction and in vessel - underprediction of the flux attenuation. This is also confirmed by the comparison of the integral values presented in a table. Thus, good
agreement between the calculated and measured data in the reactor cavity cannot guarantee the same accuracy at the RPV inner surface.

On a basis of the conservative model the accumulated fluence should be re-assessed.

These analyses and calculations caused a suggestion to Ukrainian Regulatory Authority about the necessity to issue guidance with general requirements and approaches to the vessel radiation charges monitoring systems. This document has to cover:

− requirements to calculation codes for vessel radiation charges and calculation procedure;
− requirements to the methods of dosimetry investigations;
− requirements to collecting, recording, keeping, and storing information necessary for carrying out calculation;
− requirements to reports.

REFERENCES

1. F. Seidel, RETINA- Ein Punktkernintegration program, (Modellbeschreibung) KKAB 106/86
5. RSIC Data Library Collection SAILOR, ORNL/DCL-76, April 1985
10. Development of Licensing and Inspection Capabilities. Implementation of New Methodology for Calculating Neutron Fluence on VVER Reactor Pressure Vessels.: Final report on R&D work NRA-01/05-00, 2003
<table>
<thead>
<tr>
<th>( E_{\text{thr}} ), MeV</th>
<th>( \delta, [%] )</th>
<th>( \delta, [%] )</th>
<th>( \delta, [%] )</th>
<th>( \delta, [%] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment in downcomer</td>
<td>DORT</td>
<td>RETINA</td>
<td>Experiment in RPV</td>
<td>DORT</td>
</tr>
<tr>
<td>3.01</td>
<td>18.03, 3.5</td>
<td>20.94, +16.1</td>
<td>15.58, -13.6</td>
<td>41.06, 3.3</td>
</tr>
<tr>
<td>1.00</td>
<td>35.12, 3.0</td>
<td>43.61, +24.2</td>
<td>25.34, -27.8</td>
<td>15.033, 3.0</td>
</tr>
<tr>
<td>0.498</td>
<td>49.61, 3.3</td>
<td>54.11, +9.1</td>
<td>31.34, -36.8</td>
<td>7.328, 3.5</td>
</tr>
<tr>
<td>0.111</td>
<td>59.10, 3.2</td>
<td>59.75, +1.1</td>
<td>34.56, -41.5</td>
<td>4.331, 3.4</td>
</tr>
</tbody>
</table>
Fig. 1 Comparison between measured data and predictions made with the RETINA code.
Fig. 2 Accumulated fast neutron fluence at the WWER-1000 RPV
Fig. 3 Average flux at the RPV inner surface
Fig. 4 LR-0 benchmark. Comparison between measured data and calculations made with the DORT code.