УДК 621.039.5

WWER-1000 CORE LOADING CHARACTERISTIC INFLUENCE ON IRRADIATION CONDITIONS OF SURVEILLANCE SPECIMENS AND REACTOR PRESSURE VESSEL

V. N. Bukanov, V. L. Diemokhin, O. V. Grytsenko, O. G. Vasylieva, S. M. Pugach

Institute for Nuclear Research, National Academy of Sciences of Ukraine, Kyiv

Irradiation conditions of WWER-1000 surveillance specimens and reactor pressure vessel are comparative analyzed for various core loadings. It is proved that the fluences onto specimens don't correlate with ones onto pressure vessel. It is shown that the reconstitution technique using to surveillance specimens of the standard program implemented at the most of the power units with WWER-1000 allows obtaining reliable information on the reactor pressure vessel metal state.

Introduction

Reactor facility operation safety depends mainly on reliability of the protective barriers preventing nuclear fission products outcome into the environment. Reactor pressure vessel (RPV) is one of the main protective barriers for nuclear power units with water-water reactors. Surveillance specimen (SS) program is an important source of information on RPV metal state.

According to the standard SS program implemented at the majority of the power units with WWER-1000 type reactors irradiated specimens are located above the reactor core on the baffle. Each of 6 SS sets loaded into WWER-1000 is placed absolutely equally in its reactor 60-degrees symmetry sector and consists of 5 cylindrical container assemblies (CAs) numbered from L1 up to L5. Containers of 3 sets are located on two floors and the others are only on the upper floor as its SSs and RPV are assumed by the standard program to be irradiated with the same flux. On each floor there are 6 containers located equidistant from CA axis on its perimeter and containing two SS. Tests of these specimens give the most important information on changes of RPV metal properties.

Dosimetry of SS loaded into WWER-1000 requires the application of special neutron transport calculational methodologies. Such methodology whose main positions are described in Ref. [1] have been developed by us and used for the realizations of the standard surveillance program at the Ukrainian NPPs. Values of the neutron flux functionals (NFFs) characterizing the SS irradiation conditions was obtained by this methodology for each fuel cycles when tested specimens had been irradiated in a reactor. As a result of this, the array of data for 50 over various cycles has been formed.

Only in the case if the irradiation conditions of SSs and RPV are comparable the data obtained with SS tests may be directly transferred to the RPV metal. This requires the information on the irradiation conditions of not only the specimens but also the RPV.

The methodology to determine irradiation conditions of WWER-1000 RPV has been developed and successfully used for 10 over years by us. It includes the neutron transport calculations in the reactor near-vessel space and ex-vessel dosimetry at operating units [2]. By now the array of data on the RPV irradiation conditions of 120 over various WWER-1000 fuel cycles including whose when SS sets had been irradiated is accumulated.

In the standard surveillance program there are some essential deficiencies decreasing the reliability of the RPV metal property changes data obtained with its help. Now a number of methods to increase the informativity of the SS test results are proposed. Therefore, carrying out the complex analysis of the available data on the SS and RPV irradiation conditions as well as estimating the efficiency of these methods and the tested specimen reconstitution technique, in particular, are supposed to be expedient.

Comparability of the irradiation conditions of SS and RPV of WWER-1000

First of all, it should be noted there are only three vector variables that are arguments of any NFF describing SS and/or RPV irradiation conditions: **S**, **V**, **R** are respectively the set of the parameters of the reactor core as a neutron source, the set of the geometrical and material parameters of the reactor, and the set of the coordinates of the volume where NFF value is determined.

Secondly, a SS set number is of no importance since only the two-floor CA irradiation conditions were analyzed. Therefore, the obtained array of the values of any NFF is divided into 5 subarrays according to the quantity of the assemblies in a set.

The primary analysis of the subarrays shows that the values of relative NFFs (i.e. spectral and spatial indexes) in the region of each CA with number L are hardly dependent on the core state as well as the geometrical and material parameters of the reactor. This means that any NFF in the region of each CA with the sufficiently high accuracy (not worse than 2 %) can be presented in the form

$$F_L(\mathbf{S}, \mathbf{V}, \mathbf{R}) = F_L(\mathbf{S}, \mathbf{V})\, f_L(\mathbf{R}), \qquad (1)$$

where $F_L(\mathbf{S}, \mathbf{V})$ is the same NFF averaged over the same CA for the neutron source parameter set **S** and the geometrical and material parameter set **V**, $f_L(\mathbf{R})$ is the normalized distribution of the functional in the assembly. The latter function is the main for the analysis of the SS irradiation conditions. Instead, the first is the main for their comparative analysis with RPV ones.

The analysis is expedient to begin with the comparison of the fluences accumulated by SSs and RPV during the irradiation. It showed the fluence averaged over the upper floor of an assembly to be close enough to the maximal fluence onto RPV as the standard program assumes, i.e. SSs and VVER-1000 RPV are irradiated in the comparable conditions in terms of the fluence. Similarly, the irradiation conditions are comparable in terms of the other linear NFFs. The issue of the comparability in terms of the spectral indexes will be considered a little below.

Moreover, the analysis shows there are not obvious correlation between fluences onto SS and RPV of WWER-1000. To carry out more detailed analysis the fluxes onto SS and RPV should be compared for various core loadings. The flux averaged over L1 assembly where base RPV metal Charpy type specimens are located vs maximal one onto RPV is represented at Fig. 1. It is clearly seen there isn't any correlation between these functionals. Besides, although the SS flux values are likely to be randomly distributed the RPV ones are obviously divided into two noncrossing groups, their average values differ about one third.

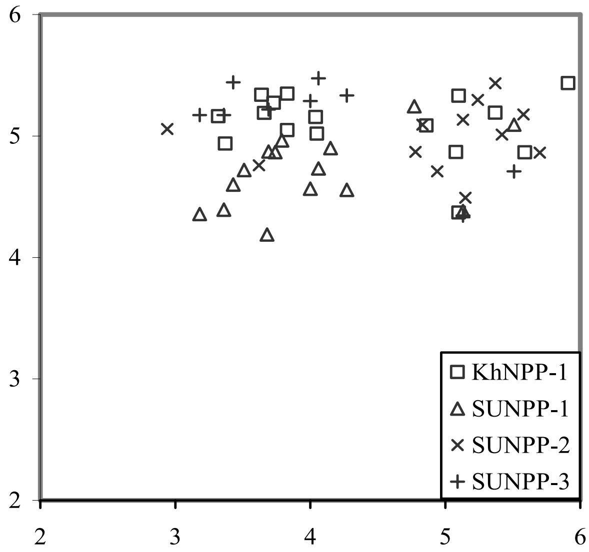

Fig. 1. The flux averaged over the upper floor of L1 assembly vs the maximal flux onto RPV for various Ukrainian units.

To research this fact the characteristics of 100 over WWER-1000 core loadings and related results of the RPV radiation exposure determination were jointly analyzed [3]. The difference between the geometrical and material parameters of the operating reactors was taken into account in the researches. With that end in view the results obtained for different reactors were reduced to the uniform base model using the sensitivity matrixes.

The forward fuel assembly relative power averaged through a fuel cycle was picked over as the main characteristic of a core loading for the analysis. It is visible at Fig. 2 the analyzed loadings are divided into two great groups with the average relative power ~0.75 and ~0.45. The proximity of the RPV neutron fluxes of the first group loadings to the project value allows terming them "usual loadings". The second group loadings are characterized by the significantly less fluxes and therefore, they may be termed "lower leakage loadings". The analysis shows such loadings are realized in cases if the forward assembly having the fuel enrichment more than 4 % is operated for the 3rd or 4th year and if the forward assembly having the fuel enrichment 2 - 4 % is operated for the 2nd or 3rd year.

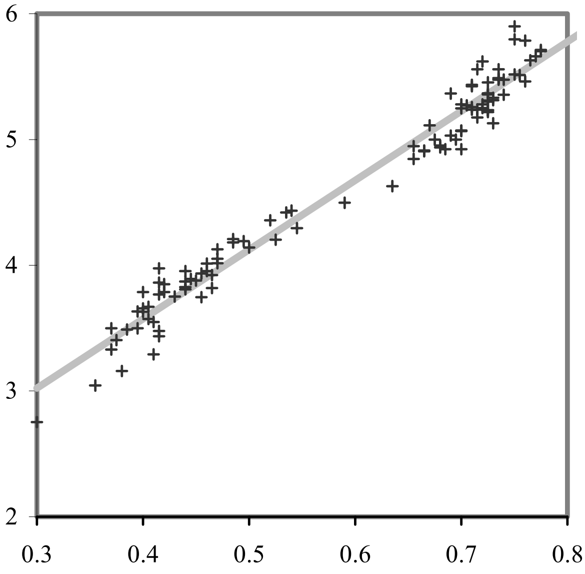

Fig. 2. The maximal flux one onto RPV vs the forward fuel assembly relative power averaged through a fuel cycle for various Ukrainian unit loadings.

Now lower leakage loadings are already regularly used at the majority of the Ukrainian NPPs. They allow to essentially decrease the RPV radiation exposure and thus to diminish its detrimental effect on the VVER-1000 serviceability. In this case it should be kept that the flux averaged over the upper floor of L1 assembly is visibly more than the maximal flux onto RPV (see Fig. 1) i.e. the comparability of the RPV and base metal Charpy type SS irradiation conditions in terms of fluences (and the other linear NFFs) is a little bit worse than for the usual loadings. It should be noted the noncomparability for other Charpy type specimens located in other CAs isn't so significant.

More detail analysis reveals the flux on SSs do not correlate with any NFF on RPV or any characteristic of the core as a neutron source. However, the correlation between the spectral indexes on SSs and RPV is detected (Fig. 3). About 10% difference of the spectral index values seen in the Figure cannot be termed "significant". Moreover, it follows from the VVER-1000 RPV radiation exposure determination results the spectral index value increases through RPV depth and at 3-4 cm from the inner RPV surface it reaches the same value as one averaged over CA.

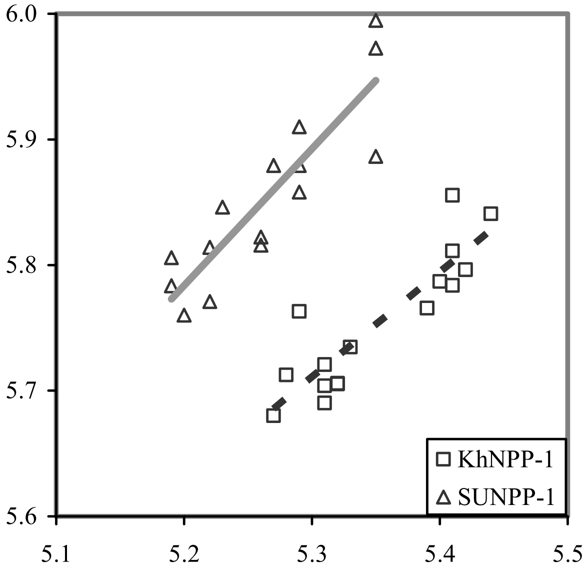

Fig. 3. The spectral index averaged over L1 assembly vs one on RPV for various Ukrainian units.

Thus, the fluence value averaged over CA and maximal one onto RPV as well as the related spectral indexes are close. This means that SSs and VVER-1000 RPV are irradiated in the comparable conditions. Hence, the data obtained with SS tests may be directly transferred to the RPV metal.

To estimate the efficiency of the tested SS reconstitution technology use to increase reliability of the RPV metal property changes data the irradiation conditions of SSs located in WWER-1000 reactor were analyzed themselves.

Irradiation conditions of SSs of the standard program

Use of the formula (1) allows to essentially reduce the volume of the data and parameters to carry out the analysis without decreasing the quality of its results. However, in this case their quantity remains still significant. Therefore, to additionally reduce them and to determine the general characteristics of the SS irradiation conditions it had been accepted to not take into account at the first stage of the researches the set features whose influence on these characteristics isn't believed essential. For example, in the further analysis a pair of SS in the container is supposed to be irradiated in the identical conditions. It should be noted a series of special performed calculational researches proved that the average value of any NFF on any CA level is practically independent on the SS orientation.

The analysis showed it is impossible for any CA to pick up the specimen representative group, i.e. twelve SSs of the same metal with the fluences above 0.5 MeV differing no more than 10 % from the average group value as the SS test practice requires. For any CA with any type metal such a group can include no more than four samples. Hence, even in case of unloading two sets that is realized at some units the representative groups consisting of twelve samples cannot be completed, too. This can be done only if the specimen reconstitution technique is applied.

Therefore, the data on the irradiation conditions of the SS parts with future V-notches of the reconstituted specimens were included to the further analysis. It should be noted the conclusions of the previous section remain without changes since the average NFF values vary insignificantly. It is caused by approximately linear axial dependence of NFFs within any container. For example, the neutron fluences above 0.5 MeV at three SS heights of interest are 1.15 : 1.00 : 0.87 with a fine accuracy for any container. In fact, this means two specimens reconstituted from one SS cannot be included to the same group. Besides, the more detail analysis showed a group cannot include specimens from the lower and upper floors of one CA simultaneously. Hence, no more than four representative groups can be formed from one CA.

The analysis of the SS irradiation conditions shows that the azimuthal dependence of the NFF values on the SS parts located in a plane of any CA is well described by the function (Fig. 4)

$$F(\alpha) = F_{\text{ave}} + \Delta F_{\max}\cdot\cos\alpha\ , \qquad (2)$$

where F_{ave} and $\Delta F_{\max}$ are some fitting parameters. The sense of these parameters is the average value of the functional on the plane and the maximal deviation from the average value, respectively.

Besides, the ratio of the maximal deviation to the average value of any NFF is practically constant for all levels of all CAs and, for example, it is equal to 0.30 ± 0.02 for the neutron fluences above 0.5 MeV.

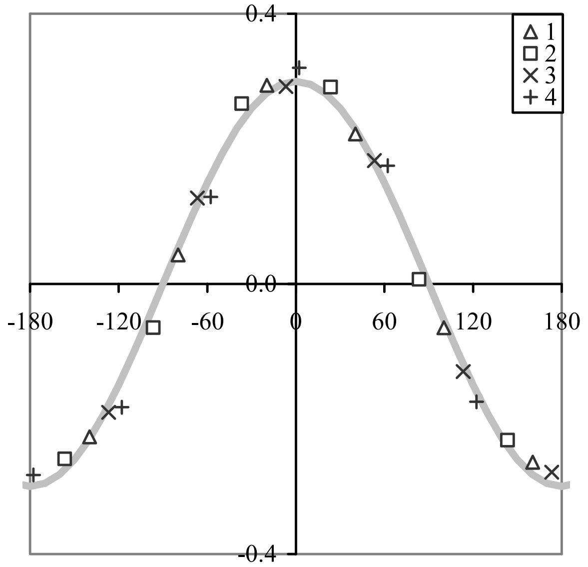

Fig. 4. The normalized flux in containers on the assembly level vs the container azimuthal angle for various Ukrainian units: *1* – KhNPP-1, 3L1 assembly, 1/4 lower floor; *2* – SUNPP-1, 3L3 assembly, 1/2 lower floor; *3* – SUNPP-2, 1L1 assembly, 3/4 upper floor; *4* – SUNPP-3, 2L2 assembly, 1/2 upper floor; and approximated curve.

The SS irradiation condition analysis results stated above allow to complete the groups from the specimens of an individual CA only having information on its orientation to the reactor core. The example of completing such groups for SSs located in 3L1 assembly of KhNPP-1 is presented in Table. The first variant is based on the intragroup dispersion minimization under the condition that all the specimens must be included into some group. In this case the intragroup semi-range of the neutron fluences above 0.5 MeV reaches 30 % that contradicts the SS testing practice. As it was specified above only four representative groups can be completed from the SS of any CA. One of such few allowable combinations is given in the second part of the table. For comparison the completing with normilized calculated fluence is presented in the third part of it.

The separations of samples of 3L1 assembly of KhNPP-1 into groups only with information on its orientation respecting to the reactor core

Conditional container number		6	1	5	2	4	3
floor	plane	normalized fluence					
The 1st variant - all samples must be separated into a group							
upper	3/4	**0.35**	**0.37**	**0.46**	**0.51**	**0.60**	**0.62**
	1/2	**0.40**	**0.43**	**0.53**	**0.59**	**0.68**	**0.71**
	1/4	**0.46**	**0.49**	**0.61**	**0.67**	**0.79**	**0.82**
lower	3/4	**0.89**	**0.96**	**1.18**	**1.31**	**1.53**	**1.59**
	1/2	**1.03**	**1.10**	**1.35**	**1.51**	**1.76**	**1.83**
	1/4	**1.18**	**1.27**	**1.56**	**1.73**	**2.02**	**2.11**
The 2nd variant – fluences approximated with formula (2) differ no more than 10 % from the average group value							
upper	3/4	0.35	0.37	**0.46**	**0.51**	**0.60**	**0.62**
	1/2	0.40	**0.43**	**0.53**	**0.59**	**0.68**	0.71
	1/4	**0.46**	**0.49**	**0.61**	**0.67**	0.79	0.82
lower	3/4	0.89	0.96	**1.18**	**1.31**	**1.53**	**1.59**
	1/2	1.03	**1.10**	**1.35**	**1.51**	**1.76**	1.83
	1/4	**1.18**	**1.27**	**1.56**	**1.73**	2.02	2.11
The 3rd variant – calculational fluences differ no more than 10 % from the average group value							
upper	3/4	0.36	0.38	**0.44**	**0.51**	**0.59**	**0.62**
	1/2	0.41	**0.44**	**0.50**	**0.59**	**0.68**	0.72
	1/4	**0.48**	**0.51**	**0.59**	**0.67**	0.78	0.82
lower	3/4	0.90	0.97	**1.16**	**1.30**	**1.53**	**1.62**
	1/2	1.05	**1.10**	**1.34**	**1.49**	**1.73**	1.83
	1/4	**1.21**	**1.28**	**1.54**	**1.72**	2.01	2.13

In addition it should be noted that the analysis of one-floor CA irradiation conditions and their comparison with WWER-1000 RPV ones gave practically the same results as of two-floors CA irradiation conditions.

Conclusions

The performed researches have shown SSs of standard sets and RPV of VVER-1000 are irradiated in the comparable conditions for any loadings.

At the same time though RPV radiation exposure for a low leakage loading is about third less than for the usual loadings but the SS irradiation conditions don't practically vary. This fact is to be considered while planning the terms of SS unloading and testing.

To fulfill SS tests the reconstitution specimen technique should be applied to complete the representative groups consisting of twelve Charpy type specimens. In this case to complete four groups from specimens of any CA the data on its orientation to the core are sufficient.

Thus, the standard surveillance program implemented at the majority of the power units with VVER-1000 type reactors in spite of a lot of deficiencies allows obtaining the reliable information on the RPV metal state.

REFERENCES

1. *Grytsenko O. V., Bukanov V. N., Dyemokhin V. L. et al.* Dosimetry of Surveillance Specimens Irradiated at WWER-1000 Reactor // Current Problems in Nuclear Physics and Atomic Energy: Proc. of Int. Conf. (Kyiv, 29 May - 3 June, 2006). Part II. - Kyiv, 2007. - P. 686 - 691.
2. *Bukanov V. N., Dyemokhin V. L., Gavriljuk V. I. et al.* Overview of the Surveillance Dosimetry Activities in Ukraine // Reactor Dosimetry: Radiation Metrology and Assessment, ASTM STP 1398: Proc. 10th Int. Symp. on Reactor Dosimetry. - ASTM, West Conshohocken, PA, 2001. - P. 61 - 68.
3. *Bukanov V. N., Dyemokhin V. L., Korinny A. A.* Lower Neutron Leakage Fuel Loading Usage for ВВЭР-1000 Pressure Vessel Radiation Exposure Decreasing // Атомная энергия. - 2006. - Т. 101. - С. 93 - 97.

ВПЛИВ ХАРАКТЕРИСТИК ПАЛИВНИХ ЗАВАНТАЖЕНЬ РЕАКТОРА ВВЕР-1000 НА УМОВИ ОПРОМІНЕННЯ ЗРАЗКІВ-СВІДКІВ І КОРПУСА

В. М. Буканов, В. Л. Дємьохін, О. В. Гриценко, О. Г. Васильєва, С. М. Пугач

Проведено порівняльний аналіз умов опромінення зразків-свідків і корпуса ректора ВВЕР-1000 для різних варіантів паливних завантажень. Доведено, що флюенси на зразки-свідки не корелюють із флюенсами на корпус. Показано, що використання технології реконструкції для зразків-свідків штатної програми, реалізованої на більшості енергоблоків з реакторами ВВЕР-1000, дозволяє одержати надійну інформацію про стан металу корпуса.

ВЛИЯНИЕ ХАРАКТЕРИСТИК ТОПЛИВНЫХ ЗАГРУЗОК РЕАКТОРА ВВЭР-1000 НА УСЛОВИЯ ОБЛУЧЕНИЯ ОБРАЗЦОВ-СВИДЕТЕЛЕЙ И КОРПУСА

В. Н. Буканов, В. Л. Демехин, А. В. Гриценко, Е. Г. Васильева, С. М. Пугач

Проведен сравнительный анализ условий облучения образцов-свидетелей и корпуса ректора ВВЭР-1000 для различных вариантов топливных загрузок. Доказано, что флюэнсы на образцы-свидетели не коррелируют с флюэнсами на корпус. Показано, что использование технологии реконструкции для образцов-свидетелей штатной программы, реализуемой на большинстве энергоблоков с реакторами ВВЭР-1000, позволяет получить надежную информацию о состоянии металла корпуса.

Received 09.06.08,
revised - 31.03.09.