INTERNATIONAL NUCLEAR SAFETY JOURNAL
vol.4 issue 1, 2015, pp.11-17

ISSN 2285 – 8717
ISSN–L 2248 – 8717
http://www.insj.info

VVER-1000 Pressure Vessel and Surveillance Specimen Dosimetry for Lifetime Extension in Ukraine

V.N. Bukanov[1], V.L. Diemokhin[1], O.V. Grytsenko[1], V.V. Ilkovych[1], O.G. Kasatkin[2], A.M. Pugach[1], S.M. Pugach[1], O.G. Vasylieva[1]

[1] *Institute for nuclear research NAS of Ukraine*
[2] *E.O. Paton electric welding institute NAS of Ukraine*
Corresponding author: vbukanov@kinr.kiev.ua

Received: *4 February 2015*; accepted: *30 March 2015*

Abstract
A regular surveillance program for VVER-1000 and its shortages are described. The Methodology for determination of neutron flux functionals on surveillance specimens of VVER-1000 pressure vessel is presented. The radiation exposure monitoring system for VVER-1000 pressure vessel is described. The main principles of an additional surveillance program for VVER-1000 are presented. The Dosimetry Experiment, which is finished at Unit 3 of Rivne NPP, is described. The modernized one-floor container assembly 5L2 from Unit 1 of South-Ukrainian NPP is shown.

Keywords
VVER-1000, pressure vessel, surveillance specimens, neutron fluence, radiation exposure, TAREG, neutron transport, Monte Carlo method, ex-vessel dosimetry, life management, service lifetime

1. Introduction

Currently there are 15 operating power units at Ukrainian nuclear power plants (NPPs) including 13 units with VVER-1000 reactors and 2 units with VVER-440 reactors. They generate about half of the country's electric power.

Thus the Ukrainian Nuclear Industry is based mainly on VVER-1000, which is a reactor type with pressure vessel (PV). It is known that the life time of a reactor with PV mainly depends on the PV metal state.

During NPP operation, the monitoring of the PV metal state is realized by destructive and nondestructive testing. According to the requirements of the design documentations, in order to monitor the PV metal state by destructive testing, surveillance specimens (SSs) are installed into the reactor before the start of its operation. SSs are made from base metal, weld metal and heat-affected zone metal.

Occasionally container assemblies (CAs) with SSs are unloaded from a VVER-1000 and SSs are tested. Results of mechanical tests are used for determination of current PV metal state and for prediction of its changes. However interpretation of SS test results is correct only if there is reliable information about irradiation conditions of each specimen and particular PV.

"The irradiation conditions" are defined as a set of the neutron flux functionals (NFFs) for PV and SSs. The include:

- the neutron fluence with the energy E_n>0.5 MeV;
- the integrated neutron flux with E_n>0.5 MeV reduced to the nominal reactor power and averaged over the cycle;
- the spectral index calculated as the ratio between the neutron fluences with E_n>0.5 MeV and with E_n>3.0 MeV;
- the number of displacements per atom induced by neutrons with E_n>0.5 MeV in the PV metals;
- the accumulation rate of displacements per atom reduced to the nominal reactor power and averaged over the cycle.

2. Dosimetry of VVER-1000 Surveillance Specimens

A regular surveillance program (SP) is carried out at the majority of Ukrainian NPP units with VVER-1000. According to this program, SSs are installed between baffle and protective pipe block (Fig. 1). Six SS sets (1L–6L) are loaded into the reactor. Each set consists of five CAs. The containers used for first three sets are placed on two levels: one above the other. The SSs from the upper level are designed for determination of current PV metal state and the SSs from the lower level are designed for predictive estimates. The containers used for second three sets are placed only on the upper level. Thus 4L–6L SS sets do not allow obtaining information for predictive estimates.

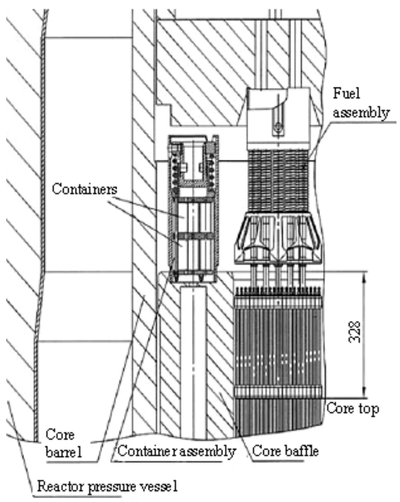


Figure 1. Location of container assemblies in VVER-1000 reactor.

Investigation of the SS sets unloaded from Ukrainian VVER-1000 reactors showed the following essential shortages of the regular SP:

- SS are irradiated in a neutron field with large neutron flux gradients;
- usually CA orientation with respect to the reactor core is unknown;
- the dosimetry part of the SS program does not allow obtaining fluences on the critical parts of the SS with the necessary accuracy.

Because of the described situation with a regular SP, the Methodology for determination of NFFs on SSs [1] was developed in INR NASU. The most important of the Methodology items are the following:

- neutron-transport calculation in the detailed 3D reactor model by own MCSS code realized using the Monte Carlo simulation;
- taking into account the changes of reactor core characteristics for every 40 effective days as a maximum;
- full core calculation for preparation of neutron source parameters in 9 (of 30) core layers in fuel assemblies of four periphery rows;
- approximation of axial power distribution from 9 to 90 core layers;
- taking into account the changes of neutron source parameters because of burn-up by WIMS-D4 [2] calculations of used fuel assemblies;
- taking into account the individual parameters of a given reactor;
- using of calculational-experimental technique for determination of CA orientation with respect to the core.

The Methodology reliability was verified in the framework of international project TAREG [3], which was performed by Russian and Ukrainian institutions with support from the European Commission.

3. The radiation exposure monitoring system for VVER-1000 pressure vessels

At At Ukrainian NPP units with VVER-1000 reactors there are no regular systems for the monitoring of PV radiation exposure. Nevertheless, according to the requirements of the nuclear power regulatory documents, the radiation exposure of the PV must be monitored at all units.

Direct experimental determination of characteristics of the neutron flux influencing the PV is practically excluded because of VVER-1000 reactor construction. Special methodologies should be applied to solve this problem [4]. Such a methodology has been developed and is continuously improved upon by INR NASU.

The methodology of the PV radiation exposure determination includes numerical calculations of neutron transport within VVER-1000 near-vessel space and ex-vessel dosimetry measurements at the operating power units. They are respectively performed by own MCPV code [5] realized using the Monte Carlo simulation and by neutron-activation method.

The experimental data from ex-vessel dosimetry are used for adaptation of the methodology to constructional features of a particular reactor and for reliability verification of the obtained values of NFFs. Carrying out complex research of the arrays of the experimental and calculational data has enabled to optimize the location scheme of the neutron activation detectors [6].

It is the main goal of PV radiation exposure monitoring to improve the safe operation of the Ukrainian nuclear reactors by obtaining the information that is necessary for the effective functioning of the program of the VVER-1000 PV life management, first of all:

- to compare irradiation conditions of SS and PV;
- to estimate the time to accumulate the permissible neutron fluence limit onto PV;
- to evaluate the effectiveness of actions reducing the PV radiation exposure.

Taking into account the features of SPs performed at the units with VVER-1000 reactors, the radiation exposure monitoring is carried out at the levels of the following characteristic zones:

- the zones of the welds No. 3 and 4 located opposite of the reactor core;
- the PV zones where current and/or accumulated radiation exposure has the maximal value.

The current radiation exposure is the maximum neutron fluence with E_n>0.5 MeV or the maximum number of displacements per atom induced by neutrons with E_n>0.5 MeV for the inner surface of the characteristic PV zones over the cycle. Accumulated radiation exposure is the maximum total neutron fluence for the inner surface of the characteristic PV zones or the maximum number of displacements per atom induced by neutrons with E_n> 0.5 MeV over the entire time of the unit operation.

The NFFs are determined over the perimeter of the characteristic zones for the cladding, inner PV surface, 1/4 and 3/4 PV wall thickness.

The developed methodology is described in the company standard STP 640.02.340.002-2003 "Quality system. VVER-1000 vessel radiation exposure determination" that was enacted in National Nuclear Energy Generating Company (NNEGC) Energoatom in 2003.

In accordance with the resolution of the Board of the State Nuclear Regulatory Committee of Ukraine, the verification and validation procedure of the methodology was developed and carried out in 2005. It was done on the basis of modern approaches to the software verification procedure and taking into consideration the requirements of the normative documents in the nuclear power engineering field in Ukraine and Russia. Validation of MCPV code was performed with the data obtained with the model experiment at the research reactor LR-0 [7], and the results of VVER-1000 ex-vessel dosimetry measurements for about 40 fuel cycles of various Ukrainian NPP units. Based on the procedure results NNEGC Energoatom has given permission to use the code MCPV to calculate the NFFs in the VVER-1000 near-vessel space for performing works related with justification of the nuclear unit safety.

3.1. The main results of the VVER-1000 pressure vessel radiation exposure monitoring

At present the PV radiation exposure monitoring is carried out at all Ukrainian NPPs. For now about 4000 neutron-activation detectors have been irradiated and measured.

Data on the current and accumulated radiation exposure of the PVs have enabled obtaining the dynamics of the neutron fluence accumulation by the characteristic zones and the estimation of the time to reach the admissible limit fluence. It should be noted that for each reactor its own estimate value is obtained. This is, first of all, due to different dynamics of the neutron fluence accumulation by PV.

Comprehensive analysis of the results of the radiation exposure monitoring and the characteristics of the core as a neutron source has shown that the dynamic primarily depends on the maximum integrated flux, reduced to the nominal reactor power and averaged over the cycle, which in turn significantly depends on the forward fuel assembly relative power averaged over the fuel cycle q_i (see Fig. 2). The correlation coefficient between these values is almost 98% and the accuracy of the proposed linear approximation is about 7%. For convenience, the ratio of the maximum and designed fluxes φ_{rel} is used in Figure 2. Figure 2 shows that the analyzed fuel loadings may be divided into two great groups:

(i) φ_{rel} ~ 100%, q_i ~ 0.7–0.8,
(ii) φ_{rel} ~ 70%, q_i ~ 0.35–0.5.

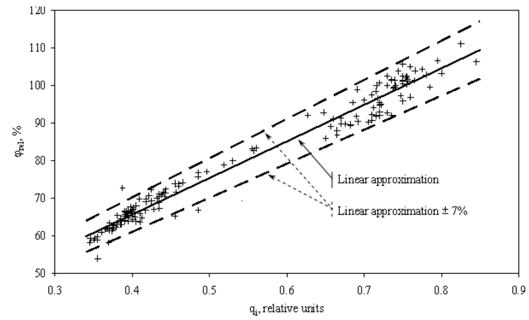


Figure 2. The maximal flux onto PV vs the forward fuel assembly relative power averaged through a fuel cycle for various Ukrainian unit loadings.

The proximity of the first group fluxes to the designed value allows to term them "ordinary loadings". The second group loadings are characterized by significantly less fluxes and therefore they may be termed "lower leakage loadings". As a conventional border between the groups, the point with φ_{rel} = 85% and q_i = 0.6 is chosen.

For now, according to our recommendations all fuel loadings used at Ukrainian NPPs are "lower leakage loadings".

4. Extension of service lifetime of VVER-1000 pressure vessel

A regular SP can support safety operation of VVER-1000 PV only during the design lifetime period because 4L–6L SS sets are installed into one-floor CAs (see Chapter 2). At the same time, there is a possibility to prolong PV operation over design lifetime period. The analysis of SS testing results and results of PV radiation exposure monitoring prove it. However for PV safety operation, the permanent control of its metal state is necessary. That is why, according to the Ukrainian regulatory requirements, after unloading of last two-floor SS set 3L, an additional SP must be developed and realized.

The main principles of an additional SP for VVER-1000 are developed by INR NASU specialists. The idea is to modernize one-floor CAs as shown in Figure 3. On first step, containers with SSs are moved to lower level. On second step, containers are turned around a central CA axis by 180°. As a result, to the end of irradiation SSs will accumulate fluences to be much larger than maximum fluence on PV. It will allow making predictive estimations. Moreover, SS fluences will get much closer to each other. It will allow the selection of a representative group of SSs for testing [8].

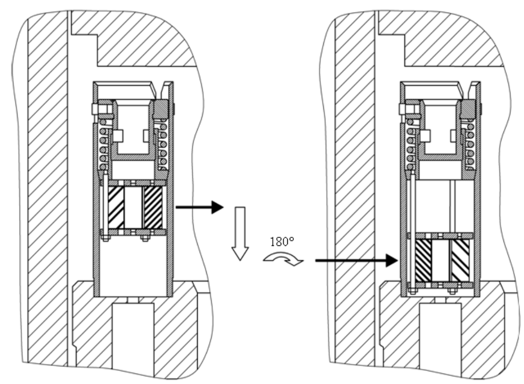


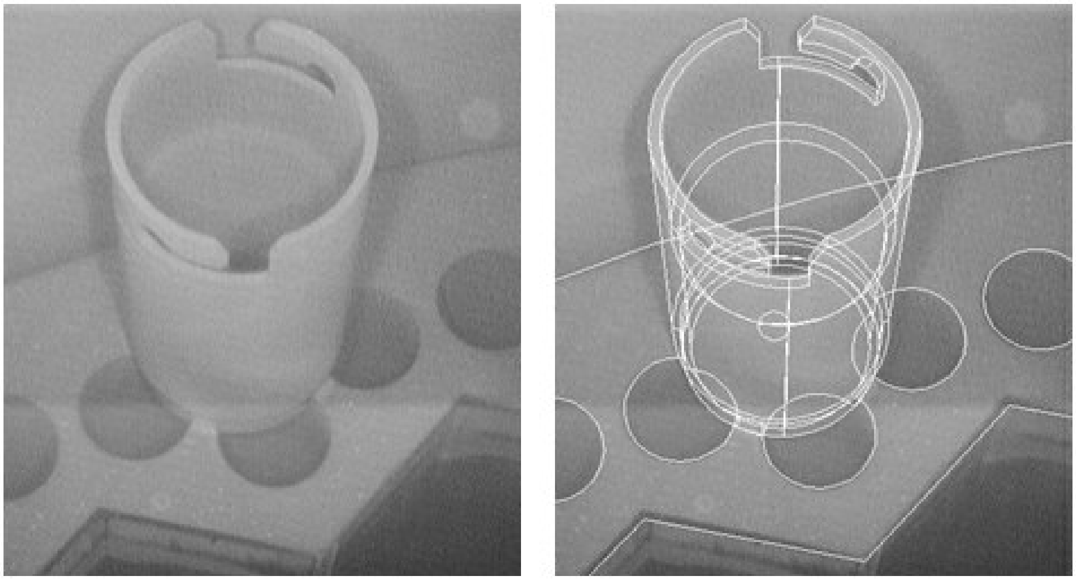
Figure 3. Modernization of container assemblies.

Because of individual features of each VVER-1000, the first stage of an additional SP is the Dosimetry Experiment, which will allow to obtain experimental data about SS irradiation conditions in a particular reactor. Installation and irradiation during one fuel cycle of three metrological CAs with extended sets of the neutron activation detectors are planned. For now such Dosimetry Experiment is finished at Unit 3 of Rivne NPP.

During the Dosimetry Experiment preparation, an unique technique, which allows to determine the orientation with respect to reactor core of CA's tubes, was developed and validated. The idea is to overlay 3D digital model on tube's photos as shown in Figure 4. The technique accuracy is about ±3°.

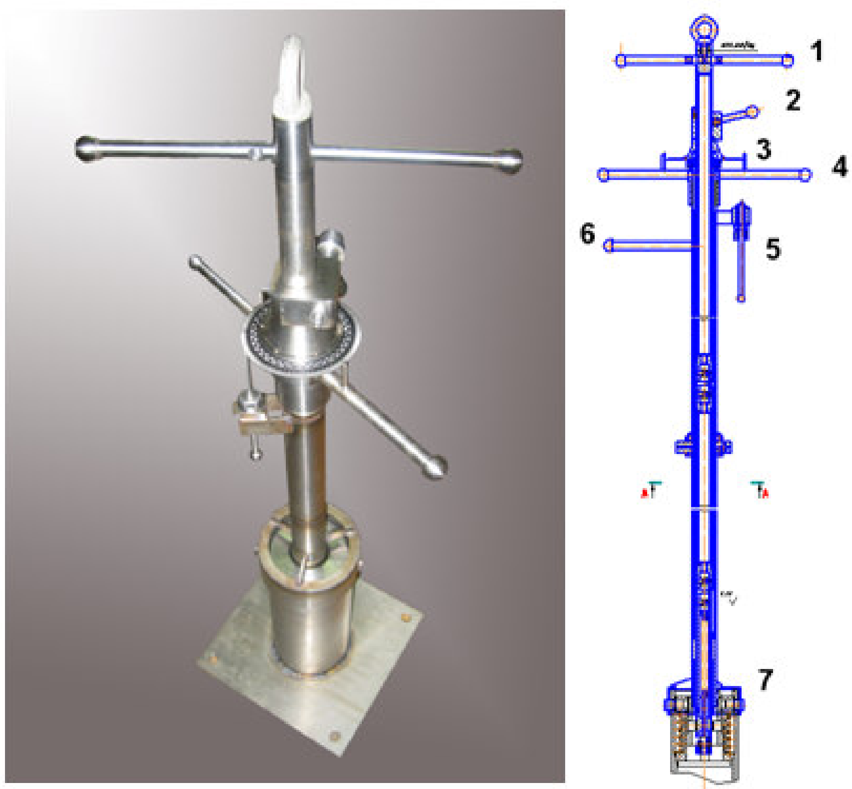
Moreover, CA's tops were modernized and special equipment for CA orientation was designed (see Fig. 5). Information about a tube orientation is used to orient CA with respect to reactor core by that equipment.

Basing on the described above main principles, the additional SP for Unit 1 of South-Ukrainian NPP is developed by INR NASU specialists and approved by NNEGC Energoatom. According to this SP the one-floor CA 5L2 was modernized (see Fig. 6) and loaded into reactor. Moreover, the Dosimetry Experiment, which is similar to one at Unit 3 of Rivne NPP, is being carried out at Unit 1 of South-Ukrainian NPP.



a b

Figure 4. Image obtained by television system of fuel-handling machine (a) and overlay of contour of 3D digital model on image (b).



a b

Figure 5. Test version of equipment for container assembly orientation (a) and draft of equipment for container assembly orientation (b): 1 – handles of inner pipe, 2 – handle of clamp, 3 – dial, 4 – handles for pulling inner pipe, 5 – indicator of angle, 6 – handle of outer pipe, 7 – ring.

a b

Figure 6. Container assembly 5L2 before (a) and after (b) modernization.

5. Conclusions

The Methodology for determination of NFFs on SSs of VVER-1000 PV is developed and validated. Besides, the radiation exposure monitoring system for VVER-1000 PV is developed, certified and used at all Ukrainian NPP Units. Thus, reliable control of PV metal state, which is necessary for efficient PV lifetime management, is ensured.

The main principles of an additional SP for VVER-1000, which will allow to ensure the control of VVER-1000 PV metal state during long term operation period, are developed.

The Dosimetry Experiment, which is the first stage of an additional SP, is already finished at Unit 3 of Rivne NPP.

The additional SP for Unit 1 of South-Ukrainian NPP is developed by INR NASU specialists and approved by NNEGC Energoatom. According to this SP the one-floor CA 5L2 was modernized.

References

1. Grytsenko O.V., Bukanov V.N., Dyemokhin V.L., Vasylyeva E.G., Mahlers. Yu.P. Dosimetry of Surveillance Specimens Irradiated at WWER-1000 Reactor // Proc. of Int. Conf. "Current Problems in Nuclear Physics and Atomic Energy", Part II, Kyiv, 29 May – 03 June 2006. – K., INR, 2007. p. 686–691.

2. Halsall M. J. A summary of WIMS-D4 input options: AEED-M1327, 1980.

3. Project TAREG 2.01/00 Validation of neutron embrittlement for VVER 1000 & 440/213 RPVs with emphasis on integrity assessment. Task 3.1.1

Development of the procedure for neutron doses upgrading and the neutron dose calculations for a reference unit. INR of NAS of Ukraine Report, Kyiv, 2008.
4. Minutes of WGRD-VVER Workshop on RPV Neutron Dosimetry. (Sandanski, Bulgaria, 1997).
5. MCPV Code for Neutron Flux Functionals Calculation of WWER-1000 Pressure Vessel / Bukanov, V. N., Grytsenko, O. V., Diemokhin, V. L., Pugach, S. M. – Kyiv, 2005. – 28 p. – (Prepr./ National Academy of Science of Ukraine. Institute for Nuclear Research; KINR-05-6) – (in Russian).
6. V.N.Bukanov, V.L.Diemokhin, O.G.Vasylieva, A.M.Pugach. Optimization of the Neutron Activation Detector Location Scheme for VVER-1000 Ex-vessel Dosimetry // Reactor Dosimetry: State of the Art 2008 (Proc. 13th Intern. Symp. on Reactor Dosimetry, Hotel Akersloot, the Netherlands, 25–30 May 2008) – World Scientific, 2009. p. 236-242.
7. B. Ošmera and S. Zaritsky, WWER-1000 Mock-up Experiment (Rev. 1, May 2002): Report / Nuclear Research Institute Řež plc, Czech Republic. – No. RER 4017-04583G. – Řež plc, Czech Republic, 2002.
8. Grytsenko O.V., Bukanov V.N., Pugach S.M. Irradiation Conditions for Surveillance Specimens Located into Plane Containers Installed in the WWER 1000 Reactor of Unit 2 of the South-Ukrainian NPP // Reactor Dosimetry: State of the Art 2008 (Proc. 13th Intern. Symp. on Reactor Dosimetry, Hotel Akersloot, the Netherlands, 25–30 May 2008) – World Scientific, 2009. p. 243–259.