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SAFETY GUIDE IN THE USE OF ATOMIC ENERGY

"PROCEDURE OF NEUTRON CONTROL ON THE OUTER SURFACE OF WATER-COOLED WATER-MODERATED POWER REACTORS OF NPP"

(RB-018-01)

PUT INTO EFFECT

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The Safety Guide "Procedure of neutron control on the outer surface of the pressure vessels of pressurized water reactors of NPP" is designed for experimental verification of the calculation methods used for determining the predictive data on fluence of fast neutrons at the critical points of the pressure vessels of water cooled water moderated power reactors, and may be used for justification of radiation load of the VVER reactor pressure vessel for validity test of the declared life.

This Safety Guide has been developed for implementing the requirements of the norms of strength calculation of equipment and piping of nuclear power generating facilities (PNAE G-7-002-86), Rules for design and safe operation of equipment and piping of nuclear power generating facilities (PNAE G-7-008-89).

The document is issued for the first time.

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LIST OF ABBREVIATIONS AND BASIC NOTATIONS

NPP – Nuclear Power Plant

VVER – Water Cooled Water Moderated Power Reactor

MP - Measuring Procedure

NFD - Neutron Flux Density, neutrons/(cm2·sec)

FAP - Full Absorption Peak

FA - Fuel Assembly

F - Accumulation rate of Neutron Fluence, neutrons/(cm2·sec)

 - activity in the i-th neutron activation detector, given at the end of irradiation and for one nuclei, Bq/nuclei

E - energy of neutrons, MeV

F - integral for energy fluence of neutrons, neutrons/(cm2·sec)

P - confidence level.

TERMS AND DEFINITIONS <\*>

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<\*> The terms and definitions having general value and determined in GOSTs or in other regulatory documetns are not given in the section.

Monitor detector is a neutron activation detector irradiated jointly with other detectors or sets of detectors, measurement results thereof are used for reducing the measurement results of different detectors for same condition of irradiation for space variable (for example, for accounting space gradient of fast neutron field).

The neutron fluence detectors are neutron activation detectors, which are irradiated for a long period (for example, during the reactor operation campaign) and half-life of reaction product which are comparable with the exposure time.

History of reactor power is change of the full reactor thermal output relative to the nominal value recorded over time.

Neutron control is determination of neutron fluence detector response based on measurements of their activity and subsequent calculation and experimental assessment of time integral characteristics of the neutron field (fluence, fluence accumulation rate).

Detector response is functionally dependent on the neutron field characteristics detector exposure characteristic (for example, number of reactions for the exposure time or average reaction rate for the exposure time under the action of neutrons).

Fast neutrons fluence accumulation rate Ф is the average during accumulation of fast neutron fluence (for example, campaign or exposure time) NFD reduced to the nominal level of reactor thermal power.

1. GENERAL

1.1. This Safety Guide "Procedure of neutron control on the outer surface of the vessels of water-water power reactors of NPP" (hereinafter the Safety Guide) has been developed for the purpose of implementation of the requirements of the Codes of strength design of equipment and piping of nuclear power installation (PNAE G-7-002-86), Rules for design and safe operation of equipment and piping of nuclear power installations (PNAE G-7-008-89).

1.2. The Safety Guide contains the procedure of neutron control, designed for experimental verification of the calculation methods used for determining the predictive data on fluence of fast neutrons at the critical points of the VVER type reactor vessels.

1.3. The Safety Guide determines the procedure and methodological conditions of performing activity measurements and neutron fluence detector response, and the methodological conditions for calculation and experimental assessment of fluence, rate of fluence accumulation and spectral characteristics of the field of neutrons with the use of neutron activation detectors installed on the outer surface of the VVER vessels of operating NPP. The controlled energy field of neutron is determined by its significance from the point of view of radiation damage of the reactor vessel steel and comparison with the design results.

1.4. The Safety Guide is applicable to operating NPP reactors of VVER-440 and VVER-1000 type.

1.5. The Safety Guide may be used for justification of radiation load of the VVER reactor vessel for verification of the justification of declared life.

2. BASIC PRINCIPLES OF ORGANIZING EXPOSURE OF NEUTRON FLUENCE DETECTORS ON THE OUTER SURFACE OF VVER VESSELS

2.1. Placement principles of detector near the reactor vessel and their exposure

A special irradiation device is used for placement of the detector on the external surface of the vessel. It is installed in the air gap space free of standard measuring equipment. The clearance dimensions allow place the device with detector in such manner to exclude their impact on the operation of equipment and reactor systems during operation. Since the Safety Guide recommends the performance of one time measurements (for the duration of one reactor operation campaign), the irradiation device does not create disturbances during the performance of preventive routine maintenance in the gap, since its easy installation and removal must be provided during opening of access to the gap.

The recommended methods, procedure of installation and removal of devices, placement of detectors on the device are described in Appendix 1 (recommended). The spatial placement range of detectors is determined by the specific task on a specific reactor.

3. NEUTRON CONTROL METHOD AND BASIC OBJECTS OF METROLOGICAL ASSURANCE OF NEUTRON ACTIVATION MEASUREMENTS ON VVER VESSELS

3.1. The experimental method behind the neutron control is a method of neutron activation measurements. According to this method, the neutron activation detector (or neutron fluence detectors) are irradiated in the neutron field. The neutron activation or fission reaction takes place in the detectors.

The induced activity in the detector is measured after the end of exposure. The detector response is determined following the measurements i.e. the number of reactions for the exposure time or mean exposure reaction rate. The response values of detectors are primary quantity for comparing with design data.

The values of the number of reactions or rates of reaction may be used for calculation and experimental evaluation of the neutron fluence field characteristics and rate of accumulation of neutron fluence. The method of such assessment applicable to neutron control over VVER vessel may be the method of effective threshold cross sections, restoration method of the neutron spectra or comparison method with designed rate of reactions.

3.2. Specifics of neutron control over VVER vessels, which must be considered when selecting the detectors and processing of the measurement results:

- irradiation of the detectors continues as a rule or the entire reactor operation campaign (around 300 days);

- activity of detectors is measured after some time after the end of exposure (approximately after a week or more);

- fluid temperature during exposure up to 300°C;

- considerable gamma-background during exposure;

- source of reactor power may have complex unpredictable form, depending on the operation mode;

- using reactor data there is a possibility for calculating the multigroup spectra of neutrons and gamma-quantum at any point of the vessel and near vessel space.

3.3. The measurements and procedures must be metrologically assured. Three types of metrological assurance objects are highlighted in accordance with the specifics of the method of neutron activation measurements:

- regulated set of neutron activation detectors and irradiation device;

- specialized radiometric installation based on gamma-ray spectrometer with activity measurement procedure of exposed detectors;

- standard procedure for determining response of detectors and controlled characteristics of neutron field for measured activity of detectors.

The requirements to the specified objects are considered in the sections 4, 5 and 6.

REQUIREMENTS FOR NEUTRON-ACTIVATION INSTRUMENTATION

4.1. The neutron-activation measurements used during neutron control over VVER vessels include:

- regulated set of neutron activation detectors with gaging;

- irradiation device.

4.2. The use of standard neutron activation detectors is allowed. The detectors may represent disks with preferable diameter 3 or 10 mm.

The certified characteristics of the detectors is the number of nuclide target nuclei, weight (or mass thickness) of a detector; mass thickness for nuclide target for detectors according to reaction (n,). The detector must be checked for absence of intervening contaminants. The error of nuclei must be 1 - 4% (confidence level P is taken as equal to 0.95).

The use of non-standardized detectors after their certification in the established procedure is allowed.

4.3. Types of detectors in the set are selected according to the requirements of specific task from the activation reactions, the list thereof is given in Appendix 2 (recommended).

The expansion of the list with the testing of new reactions sensitive to the control range of energy of neutrons from 0.1 to 10 MeV. The reactions sensitive to the thermal neutrons should be included in the set of detectors.

Characteristics represented in the table P2-1  P2-3 should be use when planning experiments.

4.4. Gaging in the assembly represents various capsules holders and cadmium screens designed for placement of the set of detectors in the irradition device.

The scope of assembly, geometry of filling, marking and other information are documented in the irradiation protocol.

4.5. The irradiation device is designed for fixing the assemblies during exposure. The recommendations for irradiation device are given in Appendix 1.

4.6. The required information on preparation and performing exposure of detectors must be presented in the exposure record. It should include: information on the formation of detector assemblies according to item 4.4; arrangement geometry of device on the reactor vessel; data on exposure time and history of reactor power for the time of exposure, values of qualified characteristics of detectors required for subsequent processing of the results (references may be given to the literature sources containing these data).

5. REQUIREMENTS FOR THE DETECTOR ACTIVITY MEASURING INSTRUMENTS AND PROCEDURE

5.1. Neutron activation detector (or neutron fluence detectors) after exposure represent sources of photon radiation. Characteristics of the radionuclides and activation and fission reaction products decay schemes are given in Appendix 2.

5.2. The activity of exposed detectors should be measured at a specialized radiometric installation (hereinafter the installation) based on gamma-spectrometer certified in the established procedure.

The installation must include the following mandatory components:

gamma-ray spectrometer;

- control source;

- MP.

In addition the installation may be completed with specialized standard measures of activity for implementation of the substitution method, if stipulated in MP. All the elements of the installation must have operation documentation and valid certificates for component sources provided together with the installation during its certification.

5.3. Gamma-ray spectrometer may include one or several measurement tracts gathered on the basis of spectrometric scintillation or semi-conductor detectors meeting the requirements of activity measurements of the sources according to item 5.1.

The standard measurement error of the external gamma-radiation from the exposed detectors must constitute 3 - 5% (confidence level P is taken as equal to 0.95).

5.4. The control source of gamma-radiation is designed for verification of the integrity of certified characteristics of the installation. The source activity must be optimum for loading characteristics of the measurement tract. The energy used for control of gamma-lines must conform to the middle of the operatinig energy range, and source design must be calculated for long-term intensive usage. The control source must be certified in the established procedure.

5.5. The activity measurement procedures of exposed detector may be implemented in the following three methods.

5.5.1. The first method is based on the use of gamma-ray spectrometer calibrated for photon detection efficiency in the operating range of energy characteristic for irradiation of the recommended nomenclature of activation reaction products. The detection efficiency is given for the conditions of point source located at a fixed distance from the detector crystal in the form of dependency from the energy of photons (E). In this case the experimentally determined quantity viz. the counting rate of impulses in FAP of energy of measured photons Sj is related to the activity by the ratio:



where (Ej) is the efficiency value for energy Ej taken from the dependency (E);

 - absolute intensity of photons with energy Ej for the measured radionuclide;

Cp - corrections for mismatch of detector and point source.

5.5.2. The second method is based on the use of discrete sensitivity , measured in (imp/sec)/Bq. The discrete sensitivity is given for the photon energy Ej from the "i" type radionuclide and connects the measured activity Ai with counting rate Sij in FAP from photons with energy Ej:



When using this method the error is automatically excluded due to approximation (E) and error , present in the first method, and correction for cascade addition.

5.5.3. The third method is related to the use of specialized standard gages of activity of the gamma-sources imitating the exposed detectors by radionuclide type and its design. The measurements are made by comparing the detector and measures on the comparator - gamma-ray spectrometer; the relevant counting rates of impulses Sj in FAP are used as the comparison parameter:



where Ae is the activity of standard gage at the time of measurement.

5.6. It is required to determine all the possible distinguishing factors of the measured specimen from the calibration conditions and specify the methods for determining the relevant corrections Cp or their specific values. The main factors requiring accounting in the corrections Cp are:

- difference of the diameter and thickness of measured detector from the calibrated source (or standard gage and detector);

- cascade addition of photons;

- possible effects from impurity emissions (for example, initiated characteristic irradiation in the detector made of niobium).

5.7. The procedure for performing activity measurements of neutron-activation detectors for specific actuation must conform to GOST R8.563-96 "State System for Ensuring Uniform Measurements. Procedures for performing measurements" and contain:

- purpose and scope of application;

- measurement principle (method);

- description of the loads (neutron activated detectors);

- brief description of the installation;

- description of the system of regulated characteristics of the installation for implementing the procedures;

- rules for preparation and performance of measurements including control measurements;

- spectrogram processing method and algorithm;

- list of corrections and methods of their determination;

- ratios for determining the total activity error for the confidence level 0.95;

- requirements for presentation of results;

- requirements for qualification of the employees.

The references to standardized procedures or private procedures and rules having undergone metrological expertise are allowed, as well as the possibility of stating individual provisions of the procedure in the form of appendices.

Metrological expertise and validation of MP are given in the established procedure.

5.8. The detailed activity measurement results are recorded in the working protocols. The master record of activity measurement of detectors must be documented for subsequent processing of the results, wherein the marking of the detector, measured activity A, its error and activity value of the detector given at the end of its exposure A0 are specified:



where tв, - holding time from the end of exposure to the start of activity measurement;

 - decay constant of activation reaction product.

6. REQUIREMENTS OF THE STANDARD PROCEDURE FOR DETERMINING DETECTOR RESPONSE AND NEUTRON FIELD CHARACTERISTICS ASSESSMENT

6.1. The standard procedure of determining the detector response and assessment of the characteristics of neutron field regulates the method for determining the responses of detectors and controlled neutron quantities following neutron activation measurements near the VVER vessel by a set of fluence detectors.

6.2. The procedure assumes the availability of information about the reactor power history and assessment of the change for the exposure time of local neutron flux density at the place of detector exposure with respect to the full thermal power (history of local power), and data on change of coolant temperature at the input to the reactor during exposure.

6.3. The procedure assumes the availability of a design-basis or received by other methods (for example, experiments on simulation devices) information on the spectrum of neutrons and gamma quantum at the place of detector exposure (for example in multigroup approximation).

6.4. The activity in the neutron activation detector given at the end of exposure time A0, information thereof is entered in the Master Record according to the item 5.8 is the source experimental information for subsequent processing and calculations according to this procedure.

6.5. The standard procedure for determination of response of detectors and assessment of the neutron field characteristics is given in Appendix 3 (recommended).

6.6. The result of procedure implementation must be Master Record where all the results of determination of detector response and assessment of the neutron field characteristics are entered. The mandatory quantity given in the Master Record must be the activity of detectors , given at the end of exposure and for one nuclide target nucleus, with assessed error for P equal to 0.95.

7. RECOMMENDATIONS FOR USE OF THE MEASUREMENT RESULTS FOR VERIFICATION OF THE JUSTIFICATIONS OF FAST FLUENCES AT THE CRITICAL POINTS OF VVER VESSEL

7.1. The fast fluences at the critical points of VVER vessel may be obtained from the calculations of neutron transport. The experimental data obtained at the points on the outer surface of the vessel may be used for comparing with the design-basis values obtained for these points.

7.2. It is recommended to use experimental data received from the outer surface of the vessel, to the extent possible near the critical points (for example, for VVER-440 - opposite to the azimuthal maximum of fast fluence at the welded seam level No. 4; for VVER-1000 - opposite to the height and azimuthal maximums of the fast fluence) for verification of the justifications of design-basis fluence at the critical points of the vessel.

7.3. It is recommended to use the activity , given at the end of exposure and for one nucleus as the experimental result. The comparison of absolute values and relative spatial distributions of the activities of detectors monitors should be made.

7.4. The following ratio should be used during the analysis of justifications of fluence or rate of accumulation of fast fluence corresponding to the effective threshold energy of a specific detector Eэфф.i.



characterizing the degree of deviation of calculation from the experiment.

Appendix 1

(recommended)

PROCEDURE
FOR INSTALLATION AND REMOVAL OF IRRADIATION DEVICE, METHODS AND LAYOUTS OF DETECTORS OUTSIDE VVER VESSELS

P1.1. Location of detector with respect to reactor

Sets of neutron fluence detectors are packaged in capsules or containers, which are fixed to the irradiation device. This device for example may contain two required components viz. azimuthal and vertical masts. The device installation and removal is performed on shutdown reactor, usually during scheduled outage related to refueling. The exposure of detectors as a rule continues for the duration of reactor operation campaign. The experimental device may be manufactured in the form of frame or cross. The azimuthal mast may represent a rigid segment of circle with recommended angle of wrap 60°. The vertical mast must allow arrange the detectors along the entire core height. The number of vertical and azimuthal masts in the device are installed based on the requirements in resolving the specific task for a specific reactor. The capsules and irradiation device is recommended to manufacture using aluminium or its alloys (duraluminium).

The number of detector sets and monitors detectors, as well as their location with respect to the reactor are selected based on the resolution of a specific task. The sets of detectors are recommended to install opposite to the critical point of the vessel, in particular at each azimuthal maximum and minimum, height maximum and at the welded joint level based on the calculation. The monitors detector should be installed no closer than every 3° along the azimuth and no closer than 30 cm along the height.

Each set of neutron fluence detectors should be confined in a cadmium shield of thickness 0.5 mm. The neutron field with assumed low gradient of fluence (for example, filed along the height close to the core center) should be selected for assessment of the cadmium ratio for the thermal neutron detectors. As a minimum one set of such detectors should not be placed in the cadmium shield but place it a distance of 10 cm from the set covered with cadmium.

Each set must contain a monitor detector. The monitors detectors or surrounding of the monitors detectors may be placed both inside the container and outside, and if required also at any important points of the detector surrounding for determining the effect of neutron field perturbation by the material of container or detector surrounding.

P1.2. Methods and procedures for installation and removal of irradiation device near VVER vessel

Two process methods of installation of the irradiation device near the VVER vessel are recommended.

The first method is notionally named upper installation method. A flexible metal cable tie is fixed in the zone of coolant inlet branch pipes to the near vessel structures adjoining the vessel. It must withstand a load of weight approximately 20 kg during a long period (about a year). The cable tie is lowered down to the bottom of the vessel. The upper end of the device is fixed to this cable tie in a radiation-proof zone located near the vessel bottom. The irradiation device is pulled up and suspended at a predetermined height. The bottom end of the device is fixed to the floor of the below reactor space (VVER-1000) or to the special structures in the vessel bottom zone (VVER-440). The adherence to the vessel is provided by special braces. The sag of the structure due to thermal expansion is eliminated by tightening the spring. The device shall be removed in the reverse procedure to installation.

The second method is conditionally named as the method of lower installation. The irradiation device is installed on the supporting frame near the vessel bottom and lifted up to a specific height, for example, by process method.

The selection of the method is determined by the practical conditions at a specific time on a specific reactor.

The advantage of the first method is reliability of preservation of the vertical installation, guarantee of adherence to the vessel and possibility of placement of detector along the entire height from the bottom of the vessel to the branch pipe zone, including the entire core height and zone of supporting structures. Moreover, the dose intensity in the first method of installation is considerably lower than in the second method. The advantage of the second method is the possibility of installation of detectors at any azimuthal sector of the reactor.

The device is recommended to be removed after a week's cooling period after reactor shutdown.

P1.3. Recommendations for arrangement coordinates of the device near the VVER vessels

The recommended azimuthal coordinates of arrangement of the device with neutron fluence detectors near the outer surface of VVER vessels for first method of installation are given in the figure 1 - 3. The second method of installation does not have limitations for azimuthal arrangement of the detectors.

Fig. 1. Layout of irradiation device near VVER-440 vessel with standard loading: 1 - vessel; 2 - fuel assembly; 3 - azimuthal mast; 4 - vertical mast (not given)

Fig. 2. Layout of irradiation device near VVER-440 vessel with shields bundles: 1 - vessel; 2 - fuel assembly; 3 - azimuthal mast; 4 - vertical mast (not given)

Fig. 3. Layout of irradiation device near VVER-1000 vessel 1 - vessel; 2 - fuel assembly; 3 - azimuthal mast; 4 - vertical mast (not given)

Appendix 2

(recommended)

CHARACTERISTICS OF NEUTRON FLUENCE DETECTORS

Table P2-1

Set of neutron fluence detectors
and their assessment characteristics recommended for neutron control outside VVER vessels

|  |  |  |  |
| --- | --- | --- | --- |
| Detector, reaction | Half-life, days [1] | Effective energy <\*>, MeV | Effective cross-section <\*\*>, mb |
| VVER-440 | VVER-1000 |
| 237Np(n,f)137Cs | 11020 | 0.5 | 1407 | 1398 |
| 93Nb(n,n')93mNb | 5890 | 1.0 | 214 | 225 |
| 238U(n,f)137Cs | 11020 | 1.7 | 715 | 736 |
| 58Ni(n,p)58Co | 70.86 | 2.5 | 413 | 429 |
| 54Fe(n,p)54Mn | 312.3 | 3.0 | 439 | 440 |
| 46Ti(n,p)46Sc | 83.79 | 5.0 | 175 | 175 |
| 63Cu(n,base_1_306069_32786)60Co | 1925.5 | 6.1 | 20.4 | 20.6 |
| 59Co(n,base_1_306069_32787)60Co <\*\*\*> | 1925.5 | - | - | - |
| 93Nb(n,base_1_306069_32788)94Nb <\*\*\*> | 7.30·106 | - | - | - |

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<\*> The values have been selected as equal to the boundaries of energy groups of neutrons for the BUGLE-96 library format, and the effective cross-sections recommended in [2] are located.

<\*\*> The assessments have been made for the repair spectrum obtained under the DORT program with BUGLE-96 library.

<\*\*\*> Reaction for thermal and epithermal neutrons.

[1] X-ray and gamma-ray standards for detector calibration, IAEA-TECDOC-619. IAEA, VIENNA, 1991.

[2] Collection of articles: Metrology of neutron irradiation on reactors and accelerators". - Moscow, TsNIIatominform, 1983, vol. 2

Table P2-2

Characteristics of reaction products of neutron fluence detectors [1]

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Reaction product | Half-life, days | Reaction product yield, base_1_306069_32789 [3] | Photon energy, KeV | Photon emission |
| 137Cs | 11020 base_1_306069_32790 60 | 0.0617 base_1_306069_32791 0.0017 [237Np(n,f)]0.0602 base_1_306069_32792 0.0006 [238U(n,f)] | 661.660 | 0.851 base_1_306069_32793 0.002 |
| 93mNb | 5890 base_1_306069_32794 50 | 1 | 16.52 - 19.07 <\*> | 0.1104 base_1_306069_32795 0.0035 |
| 58Co | 70.86 base_1_306069_32796 0.07 | 1 | 810.775 | 0.9945 base_1_306069_32797 0.0001 |
| 54Mn | 312.3 base_1_306069_32798 0.4 | 1 | 834.843 | 0.99976 base_1_306069_32799 0.000024 |
| 46Sc | 83.79 base_1_306069_32800 0.04 | 1 | 889.2771120.545 | 0.99984 base_1_306069_32801 0.0000160.99987 base_1_306069_32802 0.000011 |
| 60Co | 1925.5 base_1_306069_32803 0.5 | 1 | 1173.2381332.502 | 0.99857 base_1_306069_32804 0.000220.99983 base_1_306069_32805 0.00006 |
| 94Nb | (7.3 base_1_306069_32806 0.9)·106 | 1 | 702.627871.099 | 0.9981 base_1_306069_32807 0.00050.9989 base_1_306069_32808 0.0005 |

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<\*> The total emission of all the photons in the given range of energies is given.

[3] T.R. England, B.F. Rider, "Evaluation and Compilation of Fission Product Yields", Report ENDF-349, 1989.

Table P2-3

The assessed <\*> maximum neutron fluence accumulation rate on the outer surface of VVER vessel, neutrons/cm2·sec), and azimuth angles <\*\*> where these maximums are located

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Reactor | Maximum angle, deg. | E > 0.5 MeV | E > 1 MeV | E > 3 MeV |
| VVER-440Standard zone | 30 | 4·1010 | 1.5·1010 | 2·109 |
| VVER-440  | 13 | 1.5·1010 | 5·109 | 7·108 |
| VVER-1000 <\*\*\*> | 7 | 6·109 | 2·109 | 2·108 |

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<\*> The assessed values for standard loadings, which may be used for optimim selection of detectors.

<\*\*> For 30-degree symmetry sector (indication from axis I).

<\*\*\*> Except power unit 5 of Novovoronezh NPP

Appendix 3

(recommended)

STANDARD PROCEDURE
FOR DETERMINING DETECTOR RESPONSE AND NEUTRON FIELD CHARACTERISTICS ASSESSMENT

P3.1. Initial data

It is required to have the following input data and characteristics of detectors for performing the calculations:

A0i - activity with error i-th detector fluence measured in accordance with the section 5 at the radiation termination time;

Nяi - number of nuclide target nuclei in the i-th detector with error  (nominal data);

d - thickness of nuclide target detector for detectors for reaction (n, ) for accounting electronic self-shielding (nominal data), mg/cm2;

 - decay constants (or half-life periods T1/2) for activation reaction and fission products (Appendix 2);

,  - releases of Cs-137 in the fission reaction products for Np-237 and U-238 (Appendix 2);

Eэфф.i,  - effective thresholds and cross-sections;

T0, Tk,  - calendar time of exposure start and end time and calendar exposure duration;

P(t) - history of reactor power for the exposure time (dependency of reactor power from time);

f(t) - local power history for the exposure time;

Pном - declared nominal reactor power level. Information on exposure time and power are taken from the exposure record according to item 4.6.

P3.2. Determination of fluence detector response

P3.2.1. The fluence detector response is the number of activation reactions Q taking place in the detector for the exposure time calculated using one nuclide target nuclei. The popular name Q is the activation integral of activation reaction (detector).

P3.2.2. The activation interval Q is calculated using the input data given in the item P3.1, according to the formula:



where Mp - correction for reactor power and local power history, which considers the formation and activation reaction decay product on change of neutron flux density for the time of exposure at the place of detector exposure;

C - corrections, recommendations for determining thereof are given below;



The correction error  shall not exceed 1 - 2% (P=0.95) for the fluence detector conditions at  and precise calculation of the integrals in the formula (P3-2);

Cв - correction for fuel burnup, which considers the possibility of reducing the number of activation product nuclei due to the reaction (n,). The correction is significant for the reaction 58Ni(n,p)58Co at thermal neutron flux density more than 10 neutrons/(cm2·sec). At flow density 1013 neutrons/cm2·sec) and exposure duration from 50 to 300 days the correction Cв shall be 1.05 to 1.15. The correction Cв may be assessed experimentally or by calculation (for example, by the method stated in [3]. This correction can be ignored for the exposure conditions under this task;

Cf - correction for photo disintegration which considers the appearance of recorded fission product in the exposed detector due to reaction (,f). The correction Cf may be assessed by calculation based on known assessments of neutron spectrum  and foton spectrum , as well as cross-sections of reactions (n,f) -  and (, f) -  according to the formula:



If the spectra are known from the neutron and photon transport calculations in the multigroup approximation, the correction may be calculated according to the formula:



where ,  - group cross-sections of i-th photon and neutron fission reaction respectively:

Фg, Фn - design-basis group flux densities of photons and neutrons respectively;

Cсэ - correction for self-shielding related only to reaction detectors (n,). It leads the activation interval value to the thin detector conditions. The correction for self-shielding of resonances in the reaction cross-section (n,) is significant for the conditions of the considered task. The recommended approaches of such correction are given in [2]. The self-shielding of detector in the sphere of thermal neutrons for recommended activation reactions under this task may be neglected;

CГ - geometrical correction introduced for reducing all the measured activation intervals of the detector of one assembly to the irradiation conditions at a single spatial point where the main monitor detector was deployed. It takes into account the neutron flow density gradient. For i-th detector CГi is determined using the ratio of monitor readings near the detector Mi and main monitor M0:



The counting rate of impulses in the radiation counter reduced to one nuclei should be used as the readings of the monitors detectors. One of the threshold detectors of fluence (for example, Fe-54 detector) should be selected as the monitors detectors.

P3.2.3. The error of activation integrals for P equal to 0.95 should be assessed according to the formula:



where  - total error of detector activity measurement (taken from the master record for item 5.8);

 - error of the number of nuclide target nuclei in the detector (taken from the master record for item 4,6);

 - Cs-137 output error in the fission fragments (as per Appendix 2, table P2-2);

 - error of allowances M and C according to formula (P3-1).

P3.2.4. A master record of determining the activation integrals is made following the determination of fluence detector response, where the following must be specified: numbers of the irradiation points for which the values of activation integrals are defined; activity of detectors given for one nuclei; activation reaction; values of activation integrals and their error.

P3.3. Calculation and experimental assessment of the controlled field characteristic of fast neutrons

P3.3.1. The following quantities are the controlled neutron characteristics following neutron and activation measurements in the VVER reactors:

Fi - neutron fluences with energy greater than Eэфф.i - effective thresholds of activation reactions from the set of exposed detectors;

Фi - accumulation rates of fluences Fi,

 - standardized activation integrals of used detectors for the monitor reading.

The approximated values of fluence F(E) and fluence accumulation rate Ф(E) may be additional controlled characteristics determined based on directly measured quantities and calculation methods certified in the established procedure.

P.3.3.2. The neutron fluence with energy greater than Eэфф.i may be calculated using the formula:



where Qi is the activation integral of i-th threshold reaction of activation determined according to the formula (P3-1);

 - effective cross-section of reaction for the threshold Eэфф.i.

If the neutron spectrum is known the effective cross-section is calculated according to the formula:



where  - differential cross-section of dosimetric reaction;

 - differential neutron flow (neutron spectrum) density at the points behind the VVER vessel.

In multigroup representation the calculation is as follows:



where n = Eэфф.i implies that the sum is taken for the groups from the first group to the group n, lower boundary thereof is equal to Eэфф.i.

The error Fi for confidence probability 0.95 can be evaluated according to the formula:



where  - error of activation integral of i-th reaction (from the Master Record under item P3.2.4);

 - spread of values  at energy Eэфф.i ( for i-th reaction in the spectra of considered class (for example, refer V.P. Yarina and others. Methodical guidelines. State system for ensuring the uniformity of measurements. Characteristics of reactor neutron fields Methodology of neutron activation measurements. MI 1393-86 VNIIFTRI Moscow: 1986).

P.3.3.3. The fast fluence accumulation rate for i-th threshold detector may be calculated using the formula:



where  - effective exposure time, which is determined according to the formula:



The error Фi, for confidence probability P, equal to 0.95 can be evaluated according to the formula:



where  - fluence error Fi according to the item P.3.3.2;

 - error evaluation .

P.3.3.4. The activation intervals, standardized for monitor detector readings are spectral characteristics of the neutron field.

The activation intervals Qi determined according to paragraph P3.2.2 are given using correction factor CГi to the exposure conditions at the location of the main monitor detector in the assembly. The characteristics under control  - activation integrals of activation reactions, standardized for the monitor detector readings should be calculated according to the formula:



where QM is the activation interval of the threshold monitor detector.

Errors of standardized  are equal to the errors of the corresponding Qi (according to paragraph P3.2.3, including , equal to 1.

P3.3.5. The approximated values of controlled characteristics represent the neutron fluences with energy differing from effective thresholds of the detectors used. The most characteristic for materials science of VVER pressure vessels are the neutron fluences with energy greater than 0.1, 0.5 and 1 MeV respectively F0,1, F0,5 и F1. The activation intervals Qi (according to paragraph P3.2.2) or fluences Fi (according to paragraph P3.2.2.) are used as the source data for determining these quantities.