APPROVED
by order of Federal Environmental, Industrial and Nuclear Supervision Service

No. 79 of 15 March 2022

Safety Guide in the Use of Atomic Energy "Accounting for the Fluence of Fast Neutrons on VVER Pressure Vessels and Surveillance Specimens for Subsequent Prediction of Radiation Durability of the Pressure Vessels" (RB-007-22)

I. General

1. The Safety Guide in the use of atomic energy "Accounting for the Fluence of Fast Neutrons on VVER Pressure Vessels and Surveillance Specimens for Subsequent Prediction of Radiation Durability of the Pressure Vessels" (RB-007-22) (hereinafter referred to as the Safety Guide) has been developed in accordance with Article 6 of the Federal Law "On the Use of Atomic Energy" No. 170-FZ of November 21, 1995 in order to promote compliance with the requirements of federal rules and regulations in the field of the use of atomic energy "Rules for the control of the base metal, welded joints and deposited surfaces during the operation of equipment, pipelines and other elements of nuclear plants" (NP-084-15) approved by order of Federal Environmental, Industrial and Nuclear Supervision Service No. 502 of December 7, 2015 (registered by the Ministry of Justice of the Russian Federation on March 10, 2016, registration No. 41366) (hereinafter referred to as NP-084-15) and federal rules and regulations in the field of the use of atomic energy "Rules for the design and safe operation of equipment and pipelines of nuclear power plants" (NP-089-15) approved by order of Federal Environmental, Industrial and Nuclear Supervision Service No. 521 of December 17, 2015 (registered by the Ministry of Justice of the Russian Federation on February 9, 2016, registration No. 41010) (as amended by orders of Federal Environmental, Industrial and Nuclear Supervision Service No. 11 of January 17, 2017 (registered by the Ministry of Justice of the

Russian Federation on March 22, 2017, registration No. 46096) and No. 442 of November 19, 2019 (registered by the Ministry of Justice of the Russian Federation on December 25, 2019, registration No. 56980) (hereinafter referred to as NP-089-15).

2. This Safety Guide contains recommendations of Federal Environmental, Industrial and Nuclear Supervision Service on accounting for the fluence of neutrons with an energy greater than or equal to 0.5 MeV (hereinafter referred to as the fluence of fast neutrons) on the pressure vessels and surveillance specimens of VVER reactors for subsequent forecast of radiation durability of the pressure vessels.

3. This Safety Guide applies to the pressure vessels and surveillance specimens of VVER reactors, for which it is necessary to take into account the fluence of fast neutrons for subsequent prediction of radiation durability of the pressure vessels in accordance with the requirements of NP-084-15 and NP-089-15.

4. The provisions of this Safety Guide should be taken into account when developing requirements of the operating organization for accounting and forecasting the fluence of fast neutrons on reactor pressure vessels during the operation of nuclear power plants.

II. Organizing accounting for fluence of fast neutrons on VVER pressure vessels and surveillance specimens

5. Accounting for the fluence of fast neutrons on VVER reactor pressure vessels and surveillance specimens should be carried out in order to account for and control the residual life of reactor pressure vessels.

6. Forecasting of the fluence of fast neutrons at the design stage (the design values of the neutron field characteristics and predict the fluence values and the accumulation rate of the fluence of fast neutron on the reactor pressure vessels and surveillance specimens should be done) and accounting for the fluence of fast neutrons during reactor operation should be organized.

7. The operating organization should carry out work (in terms of organizational and technical issues) to account for the fluence of fast neutrons on the reactor pressure vessels and surveillance specimens of the operating nuclear power

units.

8. When organizing accounting for the fluence of fast neutrons on the reactor pressure vessels and surveillance specimens of VVER reactors, the following procedure should be provided:

determination of the characteristics of the neutron field at the characteristic points of a reactor pressure vessel and a witness sample;

control of changes in the characteristics of the neutron field during operation;

experimental verification of the characteristics of the neutron field;

forecast of the fluence values of fast neutrons (taking into account the conservative approach) corresponding to the end of the design life of the reactor pressure vessel (the end of the design life of the nuclear power unit), and their comparison with the design and/or maximum allowable values;

prediction of the fluence values of fast neutrons on the surveillance specimens by the time of the planned removal of the surveillance specimens from the reactor and comparison with the fluence values of fast neutrons set in the radiation embrittlement monitoring program;

representation of the characteristics of the neutron field with an indication of the error and documenting.

9. The values of the neutron field characteristics established with this account should be used to predict the fluence of fast neutrons on the reactor pressure vessel for the entire service life and to predict the radiation durability of the reactor pressure vessel.

10. To account for the fluence of fast neutrons on the reactor pressure vessels and surveillance specimens, the following characteristics of the neutron field, which are important from the point of view of accounting for the fluence of fast neutrons, should be used:

neutron fluence (hereinafter referred to as F) with an energy greater than or equal to 0.5 MeV;

accumulation rate of the neutron fluence (average (during the accumulation of the fluence of fast neutrons) neutron flux density with an energy greater than or equal to 0.5 MeV reduced to the nominal level of the thermal power of the reactor) (hereinafter referred to as Φ).

The parameters functionally related to the characteristics of the neutron field that can be used to confirm the conservatism of estimates of the fluence of fast neutrons are:

neutron spectrum;

spectral index (hereinafter referred to as SI_E);

displacement number per atom (hereinafter referred to as *dpa*);

displacement rate per atom per time unit (hereinafter referred to as *dpa/r*);

specific reaction rate in the *i*th neutron activation detector (hereinafter referred to as R^i).

11. The fluence of fast neutrons at the following characteristic points of the reactor pressure vessel and surveillance specimen should be accounted for:

points along the thickness of the wall of the reactor pressure vessel, starting from the point of the inner surface, at which the maximum fluence of fast neutrons is achieved;

points based on the worst conditions according to the criterion of brittle fracture for the calculated section of the reactor pressure vessel;

points of the outer surface of the reactor pressure vessel at which the maximum fluence of fast neutrons is achieved;

the center of the middle of an individual surveillance specimen of the reactor pressure vessel material (for a surveillance specimen with a notch, which is the center of the crack propagation plane) and the points in an individual examined sample, at which material properties are examined (in the planned area of destruction of the samples when examining).

12. The radiation durability of the reactor pressure vessel should be predicted using the values of the neutron field characteristics determined as a result of taking into account the critical point of the reactor pressure vessel, which is one of the points of the calculated section of the reactor pressure vessel, at which the limiting conditions for ensuring resistance to brittle fracture are achieved.

13. The design values of the characteristics of the neutron field on the reactor pressure vessel should be specified in the design documents for the reactor pressure vessel containing the rationale for the resistance to brittle fracture of the reactor pressure vessel. The design (target) values of the characteristics of the neutron field on the surveillance specimens should be specified in the programs for monitoring changes in the properties of the reactor pressure vessel metal. The results of accounting for the fluence of fast neutrons on the reactor pressure vessel during operation should be included in the documentation containing the rationale for the operation of the reactor in the next campaign, and also be used when updating the checklist of the reactor plant. The results of accounting for the fluence of fast neutrons on surveillance specimens during operation should be included in the reporting documentation for testing surveillance specimens.

III. Recommendations for predicting the fluence of fast neutrons on reactor pressure vessels and surveillance specimens at design stage

14. When designing VVER reactors, the fluence values and the accumulation rate of the fluence of fast neutrons on the reactor pressure vessels and surveillance specimens should be predicted.

15. When predicting the fluence of fast neutrons on reactor pressure vessels and surveillance specimens, the calculated values of the accumulation rate of the fluence and of the fluence of fast neutrons accumulated over the design service life of the reactor pressure vessel at the point of maximum distribution of the fluence of fast neutrons over the reactor pressure vessel for design operating modes should be specified, and also the error of these values of the accumulation rate of the fluence and of the fluence of fast neutrons should be estimated.

16. When predicting the fluence of fast neutrons, the values and errors in the values of the characteristics of the neutron field at the characteristic points of the reactor pressure vessel and surveillance specimen, such as F, Φ neutrons with an energy greater than or equal to 0.5 MeV, should be determined and substantiated.

17. The safety analysis report of a unit of a nuclear power plant with a VVER reactor and/or in the documents on the basis of which it was developed should

contain information on substantiation of the design values of the fluence of fast neutrons on the reactor pressure vessel and surveillance specimen, as well as:

description of the calculation method for obtaining three-dimensional characteristics of the neutron field;

substantiation for the use of the specified calculation method;

spatial distributions of the accumulation rate of the fluence of fast neutrons (on the inner and outer surfaces, along the thickness of the reactor pressure vessel, along the height and thickness of an individual surveillance specimen), the values of *dpa*, *dpa/r*, R^i for selected points of the reactor pressure vessel and surveillance specimen (where there is substantiated information about the neutron spectrum), an estimate of their error, and methods for obtaining them. When using the results of neutron activation measurements, the contribution of the energy spectrum of fast neutrons to the reactions used should be estimated in order to use them to confirm the conservativeness of the estimate of the fluence of fast neutrons.

18. In order to substantiate the calculation methods, the values and errors in the values of the characteristics of the neutron field on the reactor pressure vessels and surveillance specimens, the calculated and experimental data obtained in the control and basic measurements should be compared. The following should be substantiated:

spectral indices and spatial coefficients (the ratio of neutron flux density values with energies greater than a certain selected energy, for example, 0.5 MeV, at two different characteristic spatial points) by experiments on models of VVER reactor pressure vessels at research reactors or installations;

absolute values of the characteristics of the neutron field (or R^i for characteristic reactions) by experiments on operating VVER reactors in the near-vessel space (for example, in the air gap behind the reactor pressure vessel).

IV. Recommendations for accounting for fluence of fast neutrons on reactor pressure vessels and surveillance specimens during reactor operation

19. Accounting for the fluence of fast neutrons at the characteristic points of each reactor pressure vessel and surveillance specimen during reactor operation

should be carried out according to methods using certified programs for electronic computers. The operating organization should organize the development of methods for accounting for the fluence of fast neutrons.

20. The method of accounting for the fluence of fast neutrons on the reactor pressure vessel, which provides for the possibility of determining, with a reasonable estimate, of the error of the accumulated fluence of fast neutrons, and the characteristics of the neutron field at the characteristic points of the reactor pressure vessel for each campaign separately should be used. It is allowed to determine the values of the characteristics averaged over a campaign, but the changes in the operation of the reactor over a campaign should be taken into account.

21. The method of taking into account the fluence of fast neutrons on witness samples, which provides for the determination, with a reasonable estimate of the error of the fluence of fast neutrons, of the characteristics of the neutron field at the characteristic points of a surveillance specimen averaged over the time of irradiation of the container with surveillance specimens in the reactor should be used.

22. The methods for taking into account the fluence of fast neutrons on reactor pressure vessels and surveillance specimens, which are experimentally substantiated, should be used. When substantiating the method for taking into account the fluence of fast neutrons on reactor pressure vessels and surveillance specimens, the following experimental results should be used:

basic experiments (using a wide range of neutron activation and other detectors) near the reactor pressure vessel and in the container with surveillance specimens;

monitoring experiments (possibly using a limited range of characteristic neutron activation detectors as monitors) near the reactor pressure vessel of each unit of a nuclear power plant;

measuring the activity of tracking detectors installed together with surveillance specimens and measuring the activity of the material of a surveillance specimen;

measuring the activity of samples of anticorrosive cladding of the reactor pressure vessel and/or samples of the metal of the reactor pressure vessel.

23. The method of setting up experiments, their composition, and frequency

of conduct on the basis of the requirements of regulatory documents should be chosen with due regard for control programs developed by the operating organization.

24. For basic and control experiments near VVER reactor pressure vessels, the air gap space behind the reactor pressure vessel should be used. The recommended sets of neutron activation detectors for experimental substantiation of the characteristics of the neutron field in the area of the VVER reactor pressure vessel and surveillance specimens are specified in Annex 1 to this Safety Guide.

25. When forecasting the fluence of fast neutrons on VVER reactor pressure vessels and surveillance specimens, the following procedure should be used:

analysis of the current values of the fluence of fast neutrons at the characteristic points of the reactor pressure vessel (at the end of the latest completed campaign);

forecast of the fluence of fast neutrons at the characteristic points of the reactor pressure vessel at the end of the next campaign (one next campaign after the completed one) and planned campaigns with specific loads (if any);

forecast of the fluence of fast neutrons at the end of the design life of the reactor pressure vessel (at the end of the design life of the nuclear power plant unit) at the points of the reactor pressure vessel, for which the design fluence of fast neutrons is determined;

comparison of the forecast values of the fluence of fast neutrons with the design values of the fluence of fast neutrons at the end of the design life of the reactor pressure vessel (at the end of the design life of the nuclear power plant unit) and/or with the maximum allowable values of the fluence of fast neutrons;

forecast of the fluence of fast neutrons on surveillance specimens by the time of the planned unloading, and comparison with the values established in the radiation embrittlement monitoring program;

analysis of the values of the lead factors of irradiation of the surveillance specimens for the reactor pressure vessel.

26. The fluence of fast neutrons at the critical point should be predicted for the design life of the reactor pressure vessel after the completion of each campaign. In doing so, the following principle should be followed.

If the operating mode in the subsequent campaigns corresponds to the mode in previous campaigns, the fluence F_τ predicted for the design lifetime (expressed by the effective time t_τ) (unless otherwise noted, hereinafter F and Φ of neutrons with and energy greater than or equal to 0.5 MeV are used) can be determined by the formula:

$$F_\tau = F_t + \Phi_{max} (t_\tau - t_t), \quad (1)$$

where

F_t is the accumulated fluence of fast neutrons at the end of the latest completed campaign;

Φ_{max} is the rate, which is maximum of the previous campaigns, of accumulation of the fluence of fast neutrons for the campaign; and

t_t is the effective operating time of the reactor at the time of determining the accumulated fluence of fast neutrons.

When forecasting the fluence of fast neutrons at the end of the design life of the reactor pressure vessel (at the end of the design life of the nuclear power plant unit), it is assumed that, in the remaining time of operation from the end of the last planned campaign to the end of the design life of the reactor pressure vessel (until the end of the design life of the nuclear power plant unit), the increment of the fluence of fast neutrons per unit of calendar time is equal to $\frac{\overline{F}_{пр}}{\tau}$. Then, after the completion of the N campaign, it is sufficient to control the fluence of fast neutrons forecasted at the end of the design life of the reactor pressure vessel (at the end of the design life of the nuclear power plant unit), which is expressed by the following formula, provided that the design and/or maximum allowable value (F_{max}) of the fluence of fast neutrons established as a result of the calculation for resistance to brittle fracture is not exceeded:

$$F_\tau = \frac{F_t + \sum_M F_j}{T_N + \frac{\sum_M \Delta t_j}{\text{КИМ}}} \cdot \tau \le \overline{F_{пр}}, \quad (2)$$

where

F_t is the current fluence of fast neutrons, which is determined by the formula F_t

$= \sum_{N} F_i$;

F_i is the fluence of fast neutrons accumulated over the latest completed ith campaign;

N is the number of past completed campaigns, the fluence for which is determined on the basis of the actual neutronics of the core and the operating mode;

M is the number of upcoming planned campaigns, including the ongoing campaign, during which the fluence was assessed, and the fluence, which was determined on the basis of the calculated neutronics of the core corresponding to the specific core load;

F_j is the fluence of fast neutrons accumulated for the ongoing or upcoming planned jth campaign ($j = N+1,\ldots, M$);

КИМ is the capacity factor for fluence forecast;

T_N is the calendar time of operation at the end of the Nth scheduled preventive maintenance following the completion of the Nth campaign; and

Δt_j is the effective reactor operation time in the jth campaign.

In this case:

$$F_i = \Phi_i \cdot \Delta t_i \; ;$$
$$F_j = \Phi_j \cdot \Delta t_j , \qquad (3)$$

where

Φ_i is the accumulation rate of the fluence of fast neutrons in the ith campaign determined on the basis of the actual neutronics of the core and the operating mode for the completed ith campaign;

Φ_j if the accumulation rate of the fluence of fast neutrons in jth campaign; and

Δt_i if the actual effective reactor operation time in the ith campaign, s.

27. If the predicted value of the fluence of fast neutrons at the end of the design life of the reactor pressure vessel (at the end of the design life of the nuclear power plant unit) determined according to formula (2) exceeds the maximum allowable value of the fluence of fast neutrons, taking into account the current value of the fluence of fast neutrons, preliminary calculation estimates of the fluence of fast neutrons with varying fuel arrangement in the core should be done for the forecasted

campaigns following the campaign number “N + M,” or for the M campaigns (when the campaign number “N + M” approaches the end of the design life of the reactor pressure vessel or the design life of the nuclear power plant) so that the forecasted value of the fluence of fast neutrons does not exceed the maximum allowable value of the fluence of fast neutrons.

28. In order to ensure conservatism in substantiating the design service life of the reactor pressure vessel, the values of the neutron field characteristics, with due regard for their error, should be used when predicting the fluence of fast neutrons and when assessing the fluence during operation. The following values as the upper limit should be used:

$$F_t^{*}=F_t + \delta F_t\,;$$

$$\Phi^{*}_{max} = \Phi_{max} + \delta\Phi_{max}\,, \qquad (4)$$

where

F_t^{*}, Φ^{*}_{max} – estimated conservative values of the fluence of fast neutrons and accumulation rate of the fluence;

δF_t , $\delta\Phi_{max}$ – estimated errors of the corresponding quantities for a confidence level of 0.95.

29. The values of the fluence of fast neutrons at the critical point of the reactor pressure vessel established after the completion of the campaign and the forecasted values should be compared with the design or maximum permissible value and used for subsequent forecast of the radiation durability of the reactor pressure vessel defined as the forecasted time of operation of the reactor at nominal power, during which the conditions are met, at which the preservation of the properties of the material of the reactor pressure vessel is ensured, depending on the degree of radiation damage, provided that the estimated value of the radiation durability parameter (the fluence of fast neutrons) does not achieve its limit value (the maximum permissible value at the design stage, and the design value at the operation stage). An expert assessment of the radiation durability of the VVER reactor pressure vessels should be carried out in accordance with the method specified in Appendix 2 to this Safety Guide.

30. The design data on the characteristics of the neutron field on the reactor pressure vessel and surveillance specimens and the results of determination of the same values obtained during the operation of VVER reactors and substantiated by basic and/or control experiments should be compared.

31. When introducing fuel loading regimes other than design or structural changes that affect the transfer of fast neutrons to the reactor pressure vessel and the locations of surveillance specimens (a characteristic change in the design of the core, the use of a new type of fuel or type of fuel assembly design, the installation of a burnt out (deeply burnt) fuel to the periphery of the core), the characteristics of the fast neutron field on the reactor pressure vessel and surveillance specimens should be calculated to confirm the design value of the fluence of fast neutrons. When substantiating the calculated values of the characteristics of the fast neutron field on the reactor pressure vessel, the need for their experimental confirmation during the first pilot operation of the VVER design in question should be considered. The results of this calculation and substantiation should be included in the set of documentation submitted for approval in the prescribed manner to introduce a new fuel loading regime or to make design changes.

32. If the use of the methods for taking into account the fluence of fast neutrons on the reactor pressure vessel is limited to the full extent for some reasons (for example, the absence of information about the previous history of reactor operation) when taking into account the fluence of fast neutrons, then when determining and forecasting the characteristics of the neutron field, it is recommended to use conservative coefficients margins for these values on the uncertainties due to the specifics of the reactor operation. Recommendations for determining conservative safety factors are specified in Section 2.4 of Annex 2 to this Safety Guide.

33. When neutron activation detectors are used for experimental substantiation of the calculations, the calculated and measured specific activities of the reaction products given at the end of irradiation of the detectors should be compared.

V. Recommendations for taking into account the fluence of fast neutrons on reactor vessels during the period of extended service life

34. When deciding if it possible to extending the operation of the VVER reactor vessel after the expiration of the reactor vessel service life specified in the design, the values of the neutron field characteristics at the characteristic points of the reactor vessel should be clarified.

35. The fluence of fast neutrons on the reactor pressure vessel corresponding to the end of the extended life of the nuclear power plant unit should be forecasted, similar to the recommendations in paragraphs 25 to 28 of this Safety Guide. When determining the fluence of fast neutrons, it is recommended to use formula (1), where $t_\tau + t^*$ should be used instead of t_τ, where t^* is the extended life of the nuclear power plant unit.

36. During each extended campaign, the fluence of fast neutrons on the reactor pressure vessel for the campaign should be recorded. An experiment with the installation of neutron activation detectors in the gap near the outer surface of the reactor pressure vessel should be conducted to confirm the fluence of fast neutrons on the reactor pressure vessel for the campaign.

37. To confirm the reliability of the values of the accumulated fluence of fast neutrons on the pressure vessel, the activity of sample scrapes from the inner surface of the reactor pressure vessel should be analyzed to assess the fluence of fast neutrons by the reaction $^{93}Nb(n,n')^{93m}Nb$.

V. Recommendations for taking into account the fluence of fast neutrons on the reactor pressure vessels after the implementation of thermal annealing of the reactor pressure vessel

38. When taking into account the fluence of fast neutrons on the VVER pressure vessels, on which thermal annealing has been carried out, the accumulation of the fluence of fast neutrons should be counted both from the beginning of operation and from the beginning of the campaign before which thermal annealing was done.

39. From the subsequent campaign after annealing, the fluence of fast neutrons on the reactor pressure vessel should be taken into account with

experimental substantiation of the fluence of fast neutrons accumulated during the campaigns implemented after annealing.

40. The accumulation of the fluence of fast neutrons at the critical point of the reactor pressure vessel should be forecasted in each campaign planned after annealing, and after each campaign, starting from the moment of annealing, to predict the fluence of fast neutrons at the end of the latest one until the radiation durability of the campaign's reactor pressure vessel is exhausted. At the same time, the accumulation rate of the fluence of fast neutrons and the safety factor for it at the critical point in each planned campaign should be determined and substantiated.

41. When taking into account and forecasting the fluence of fast neutrons on the pressure vessels on which thermal annealing has been done, the total fluence of fast neutrons in the annealing positions should be estimated both from the beginning of operation and from the beginning of the campaign, before which thermal annealing was done.

APPENDIX 1
to Safety Guide in the use of atomic energy “Accounting for the Fluence of Fast Neutrons on VVER Pressure Vessels and Surveillance Specimens for Subsequent Prediction of Radiation Durability of the Pressure Vessels” approved by order of Federal Environmental, Industrial and Nuclear Supervision Service
No. 79 of 15 March 2022

Recommended sets of neutron activation detectors for experimental substantiation of the characteristics of the neutron field in the area of the reactor pressure vessel and surveillance specimens of VVER reactors

Detector, reaction	Half life, days	Effective energy, MeV	Basic measurement sin gap behind reactor pressure vessel	Control measurements in gap behind reactor pressure vessel	Measurements on surveillance specimens*	Method of analysis of sample scrapes from reactor pressure vessel
$^{237}Np(n,f)^{137}Cs$	11 020	0.55	+	+	–	–
$^{93}Nb(n,n')^{93m}Nb$	5 890	1.0	+	+	+	+
$^{238}U(n,f)^{137}Cs$	11 020	1.5	+	–	–	–
$^{58}Ni(n,p)^{58}Co$	70.86	2.5	+	–	–	–
$^{54}Fe(n,p)^{54}Mn$	312.3	3.0	+	+	+	+
$^{46}Ti(n,p)^{46}Sc$	83.79	4.5	+	–	–	–
$^{63}Cu(n,a)^{60}Co$	1,925.5	7.0	+	+	+	–
$^{55}Mn(n,2n)^{54}Mn$	312.3	11.6	+	–	–	–
$^{59}Co(n,y)^{60}Co$	1,925.5	reaction on thermal neutrons	+	+	+	+

Note.
* When forming irradiated assemblies with surveillance specimens, the final sets of neutron activation detectors should be installed with due regard for the conditions specified in the programs for monitoring changes in the properties of the pressure vessel metal.

APPENDIX 2
to Safety Guide on the use of atomic energy "Accounting for the Fluence of Fast Neutrons on VVER Pressure Vessels and Surveillance Specimens for Subsequent Prediction of Radiation Durability of the Pressure Vessels" approved by order of Federal Environmental, Industrial and Nuclear Supervision Service No. 79 of 15 March 2022

Recommended Methodology for Expert Assessment of Radiation Durability of VVER Reactor Pressure Vessels

1. General

1.1. The methodology is intended for expert analysis of documents substantiating the resistance to brittle fracture and the radiation durability of VVER reactor pressure vessels both at the design stage and during operation. The methodology can be used as optional when preparing relevant documents in operating organizations and organizations that perform work and provide services to operating organizations.

1.2. The methodology makes it possible to obtain an expert assessment of the radiation durability of the reactor pressure vessel after each completed campaign, if estimates of the accumulated fluence of fast neutrons are obtained, with due regard for all previous campaigns.

1.3. The methodology is applicable to VVER reactor pressure vessels that have not been thermally annealed.

2. Estimating radiation durability of reactor pressure vessel

2.1. Radiation durability of reactor pressure vessel and fluence of fast neutrons

2.1.1. In expert estimations, the residual radiation durability of the VVER pressure vessel during operation should be determined from the ratio:

$$F_d - F_t - \sum_{n=1}^{N} \Phi_n t_n = 0\,, \quad (1)$$

where

F_d is the design value of the fluence of fast neutrons at the end of the substantiated design life of the reactor pressure vessel;

F_t is accumulated neutron fluence at the time of expert estimation at the same point;

N is the number of reactor operation campaigns in the time remaining until the exhaustion of the radiation durability from the moment of the expert estimation;

Φ_n if the estimated accumulation rate of the neutron fluence at the same point during campaign n;

t_n if the estimated effective operating time of the reactor during the campaign n.

2.1.2. To determine the residual radiation durability of the reactor pressure vessel, the following ratio should be used:

$$\tau = \sum_{n=1}^{N} t_n \quad . \tag{2}$$

2.1.3. If the accumulation rate of the fluence of fast neutrons in the remaining campaigns is assumed to be the same (for example, for reasons of conservatism, the rate is assumed to be the maximum from a selection of values for all possible future campaigns), the following ratio should be used to determine the radiation durability of the reactor pressure vessel:

$$\tau = \frac{F_{\text{пр}} - F_t}{\Phi_{max}}, \tag{3}$$

where Φ_{max} is the accepted maximum accumulation rate of the neutron fluence from all possible campaigns.

2.1.4. Considering that F_t is equal to zero before the start of reactor operation, the following relation should be used to determine the design radiation durability of the reactor pressure vessel:

$$\tau = \frac{[F]}{\Phi_{max}}, \tag{4}$$

where $[F]$ is the maximum allowable fluence of fast neutrons determined in accordance with calculations for resistance to brittle fracture.

2.1.5. Since all values of the neutron field characteristics can only be determined with some error, when predicting the fluence of fast neutrons, it is necessary to introduce conservative safety factors for each component in formula (3) of this appendix in order to predict the radiation durability of the reactor pressure vessel:

$$F_t = k_F F_t^* ; \qquad (5)$$

$$\Phi_{max} = k_\Phi \Phi^*_{max} ,$$

where

k_F, k_Φ, are conservative safety factors (equal or greater than unity) for the accumulated fluence and the rate of accumulation of the fluence of fast neutrons;

F_t^* Φ^*_{max} are estimated values of the accumulated fluence and the accumulation rate of the fluence of fast neutrons.

2.2. Determining the design and accumulated fluence of fast neutrons

2.2.1. The design value of the fluence of fast neutrons at the critical point of the reactor pressure vessel is determined at the design stage to confirm that the criteria of resistance to brittle fracture are met.

2.2.2. The accumulated fluence of fast neutrons at the critical point of the reactor pressure vessel is determined by taking into account the fluence of fast neutrons during reactor operation. In this case, the accumulated fluences of fast neutrons should be determined separately for each campaign and recorded as a sequential set of values $\{F_i\}_{i=1....m}$, where m is the number of implemented campaigns until the moment of estimating the accumulated fluence of fast neutrons.

2.3. Determining the accumulation rate of the fluence of fast neutrons

Forecasting the accumulation rate of the fluence of fast neutrons in the remaining time of operation is carried out from the analysis of the planned loads of the reactor cores. In this case, the results of calculating the characteristics of the neutron field corresponding to these loads can be used.

If the operating mode corresponds to the mode used in previous loads, the maximum value from the selection $\left\{\frac{F_i}{t_i}\right\}_{i=1....m}$ can be used as the maximum accumulation rate of the fluence of fast neutrons, where t_i is effective time of reactor operation in the campaign *i*.

2.4. Determining the safety factors

The values of the safety factors k_F and k_Φ in expressions (5) of this appendix can be estimated from the analysis of the calculated and experimental results of determining the fluence of fast neutrons obtained at a particular reactor. The discrepancy between the calculated and experimental data on the characteristics of the neutron field in the region of the reactor pressure vessel can reach 10 to 20%. In this case, the uncertainty of experimental data can reach 10%. The general uncertainty of the values of the characteristics of the field of fast neutrons at the critical points can be 30%. For expert estimations, the values of these safety factors not lower than 1.3 should be used. Lower values of the safety factors should be substantiated using experimental validation.