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SAFETY GUIDE IN THE USE OF ATOMIC ENERGY

"ACCOUNT OF FAST NEUTRON FLUENCE OF VESSELS AND EVIDENCE SAMPLES OF VVER FOR
FOLLOW-UP FORECAST OF RADIATION LIFE TIME OF VESSELS"

(RB-007-99)

EFFECTIVE
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This regulatory document viz. the safety guide is aimed at enforcement of the provisions and requirements of the Federal Rules and Regulations in the field of atomic energy use (OPB-88/97, PBYa RU AS-89, PNAE G-7-002-86, PNAE G-7-008-89, PNAE G-01-036-95) for accounting fast neutron fluence. The Safety Guide contains the recommendations determining the procedure and organization of fast neutron fluence VVER surveillance samples and vessel for subsequent prediction of radiation durability of the reactor vessel and recommendations for accounting fast neutron fluence during the reactor design and operation.

The Safety Guide is published for the first time.

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LIST OF ABBREVIATIONS AND BASIC NOTATIONS

VVER – Water Cooled Water Moderated Power Reactor

RPV - Reactor Pressure Vessel

SS - Surveillane Specimens

NFD - neutron flux density fluence, neutrons/(cm2·sec)

Ф - accumulation rate of neutron fluence, neutrons/(cm2·sec)

dpa, dpa/c - number an rate (с-1) of displacement for atom

E - energy of neutrons, MeV

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

Ri - specific reaction velocity in i-th neutron activation detector, Bq/nucleus

SIE - spectral index, relative units

t - time, sec

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.

1. Fast fluence F is the total number of fast neutrons with energy greater than the specific selected energy, which passes through unit area for the exposure duration. Fast fluence is expressed by a definite time integral depending on the time of neutron flux density with energy greater than the defined selected energy.

2. Accumulated fast fluence Ft is the actual fast fluence accumulated to a specific reactor operation time.

3. 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.

4. Spectral index SIE is the ratio of Ф neutrons with energy greater than E to Ф neutrons with energy greater than 0.5 MeV.

5. RPV radiation lifetime is the predicted reactor operation time at rated power during which the conditions are met whereby the brittle fracture resistance of RPV is provided.

6. Factor of margin is a dimensionless quantity which is greater than 1 and shows what fold it is required to change the value of the appraised parameter so that the results overlapped the maximum deviations of the parameter conditioned by the uncertainties in the parameter appraisal, observing the conservation principle of the quantity considered in the security criteria evaluations, and on calculation thereof the appraised parameter is used.

1. GENERAL

1.1. This Safety Guide (hereinafter the Safety Guide) has been developed for implementation assurance of the provisions and requirements of the Federal Rules and Regulations in the field of atomic energy use (OPB-88/97, PBYa RU AS-89, Strength calculation norms of equipment and piping of nuclear power installations (PNAE G-7-008-89), Requirements for the content of NPP safety report with VVER type reactors (PNAE G-01-036-95) for accounting fast fluence. The recommended approaches specify, develop and improve the implementation paths of the provisions and requirements of the Federal Rules and Regulations in the field of atomic energy accepted in practice for assuring reliable determination and control of fluence and other characteristics of fast neutron field on VVER RPV and SS, accepted for use during prediction of RPV radiation lifetime.

If for performing the relevant provisions and requirements of the Federal Rules and Regulations in the field of nuclear energy use the organization carrying out activity in the field of nuclear energy use use other procedures and methods than those recommended in the Safety Guide, they should be justified by showing that the selected procedures and methods ensure fulfilment of the requirements of the Federal Rules and Regulations in the field of atomic energy use

1.2. The Safety Guide determines the procedure and organization of fast fluence accounting on VVER RPV and SS for predicting the radiation lifetime of RPV, and contain recommendations for fast fluence accounting during reactor design, operation (including operation after RPV thermal annealing) including for:

- procedure and organization of fast fluence accounting;

- prediction of fast fluence during design;

- accounting of fast fluence during operation, accounting procedures and their justification

- assessment of the values of fast neutron field characteristics for predicting the radiation lifetime of RPV.

1.3. The provisions of the Safety Guide are applicable for VVER of nuclear power plants, for the reactor pressure vessels thereof brittle fracture resistance calculation is made considering the brittle to ductile transition temperature following impact of exposure (in accordance with the section 5.8 PNAE G-7-002-86 and section 8 of Appendix 2 of PNAE G-7-002-86), as well as on VVER of nuclear power plants on which the program of monitoring over RPV metal condition during operation is made by tests of SS installed in the reactor (in accordance with the section 7 PNAE G-7-008-89).

1.4. The Safety Guide is designed for the specialists of Gosatomnadzor of Russia, and operators and organizations performing works and rendering services to the operators.

2. PROCEDURE AND ORGANIZATION OF ACCOUNTING OF FAST FLUENCE

2.1. The accounting procedure of fast fluence on VVER RPV and SS shall include the determination of the neutron field characteristics, their control over time, presentation specifying the error, documentation.

2.2. The values of neutron field characteristics established herewith are used for prediction of fast fluence on RPV for the entire life and for forecasting the radiation resource of RPV.

2.3. The fast fluence accounting is organized during design (design values of neutron field characteristics are determined) and reactor operation.

2.4. Characteristics of neutron field important from the point of view of fast fluence accounting: neutron fluence F with energy more than 0.5 MeV, neutron fluence accumulation rate Ф with energy more than 0.5 MeV, neutron spectrum, spectral index SIE. Parameters important from the point of view of fast fluence accounting functionally related to the neutron field characteristics: dpa, dpa/c, Ri.

2.5. The fast fluence is accounted in the feature points of VVER RPV and SS, which must include:

- points along RPV wall thickness starting from the inner surface point where the neutron fluence with energy more than 0.5 MeV maximum is reached;

- points in accordance with p. 5,8,7.2 of PNAE G-7-002-86 for the RPV design section;

- RPV outer surface points where the neutron fluence maximum with energy more than 0.5 MeV is reached;

- midpoint center of RPV individual steel SS (for SS with indentation - crack propagation plane center) and points in the individual investigated SS in which the steel properties were studied (salient point, microstructure analysis etc.).

2.6. The prediction of RPV radiation lifetime with the use of the neutron field characteristics established following accounting of values shall be made for the critical point of RPV being one of the points of the RPV design section where the threshold requirement of brittle fracture resistance given in the section 5.8 of PNAE G-7-002-86 are reached based on the analysis of all possible modes.

2.7. The operator shall organize accounting of fast fluence.

2.8. The design values of the neutron field characteristics for RPV and SS are given in the VVER design and design documents for RPV containing the justification of RPV brittle fracture resistance. The accounting results of fast fluence on RPV during operation are entered in the documentation containing justification of reactor operation in the next cycle. The fast fluence accounting results on SS during operation are entered in the reports in accordance with p. 7.8 of PNAE G-7-008-89.

3. RECOMMENDATIONS FOR FAST FLUENCE PREDICTION ON RPV AND SS DURING DESIGN

3.1. The fluence values and fast fluence accumulation rates on RPV and SS shall be predicted during the design.

3.2. It is necessary:

- to give the estimated values of fluence accumulation rates, neutron fluence with energy more than 0.5 MeV accumulate for the estimated design life of RPV at the point of maximum distribution along RPV of neutron fluence with energy greater than 0.5 MeV for the design operation modes, and assess the error of these values of fluence accumulation rates and neutron fluence with energy more than 0.5 MeV;

- to determine and substantiate the field characteristic values of neutrons at the feature points of RPV and SS, such as F, Ф of neutrons with energy greater than 0.5 MeV, neutron spectrum (possible to consider multi-group spectrum for the selected RPV points (internal, external surface, 1/4 thickness) and SS (midpoint center), spectral indices SIE for neutron energy 0.1; 1; 3; 6 MeV and accumulation rate value of thermal neutron fluence.

3.3. Information on justification of fast fluence for RPV and SS should be given, and:

- description of the calculation procedure of getting 3D-characteristics of neutron field on RPV and SS;

- justification of the use of specified calculation procedure;

- space distributions of accumulation rate of neutron fluence with energy greater than 0.5 MeV and thermal neutrons (on the inner, outer surfaces of RPV, by RPV thickness, by height and thickness of individual SS);

- values of dpa, dpa/c, Ri for the selected points of RPV and SS (where evidence based information about the neutron spectrum is available). The recommended sets of neutron-activation detectors for experimental justification of the neutron field characteristics in the field of VVER RPV and SS are given in Appendix 1.

3.4. The design and experimental data obtained in the basic experiments (experiments using detector maximum possible by type, scope and nomenclature and with confirmation of the reliability of obtained results) must be compared for justifying the calculation procedures, values and error values of the neutron field characteristics on RPV and SS It is recommended to perform justification by:

- spectral indices and space coefficients (ratio of NFD values with energy greater than specific selected energy, for example 0.5 MeV, at two different characteristic spatial points) by experiments on VVER reactor pressure vessel simulators at the research reactors or installations;

- absolute values of neutron field characteristics (or Ri for characteristic reactions) by experiments on operating VVER (other modifications possible) in the near vessel space (for example, in the air gap outside RPV and on SS).

4. ACCOUNTING OF FAST FLUENCE ON RPV and SS DURING REACTOR OPERATION

4.1. The accounting of fast fluence at the feature points of each RPV and SS during reactor operation must be performed according to the procedures develope by the operator and permitted for use. It is understood that:

4.1.1. The fast fluence accounting procedure on RPV must provide for the possibility of determining accumulated neutron fluence with energy greater than 0.5 MeV with justified error assessment, characteristic of the field of neutrons at the feature points of RPV for each campaign separately. It is allowed to determine the values of characteristics averaged for the campaign and reduced to the nominal power, but with due regard to all changes in the reactor operation over the campaign;

4.1.2. The accounting procedure of fast fluence for SS must stipulate the determination with justified estimate of neutron fluence with energy greater than 0.5 MeV, characteristics of neutron field at the characteristic points of SS, averaged for the exposure time of the container with SS in the reactor and reduced to rated power, as well as the assessment of fast fluence distribution by SS placement height.

4.1.3. The procedures must be experimentally justified. It is recommended to perform justification by:

- one-time standard experiments (using wide range of neutron activation and other detectors) near the RPV in the container with SS for the head units;

- control regular experiments (possible with the use of restricted set of characteristic neutron activation detectors as monitors) near RPV of each unit;

- activity measurements of tracking detectors installed together with SS and measurements of SS material activity.

The choice of experimental setup, their composition, periodicity is taken based on the engineering solution justified by the relevant studies. The experiments are performed considering p. 9.1.16 of PNAE G-7-008-89. The measurement procedure must meet GOST R 8.563-96.

The air clearance space behind RPV should be used for standard and control experiments near VVER RPV. The recommended set of neutron activation detector is given in Appendix 1 <1>.

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<1> Comparison of the design and measured specific activities of the reaction products given at the end of exposure of detectors should be made when using neutron activation detectors for experimental justification of the calculations.

4.2. Neutron fluence with energy more than 0.5 MeV at the critical point for the design lifetime of RPV after completion of each lifetime should be predicted. Besides, the below guideline should be followed:

4.2.1. If the operation mode in the subsequent lifetime shall conform to the regime in the previous lifetime, predicted for the design life time, expressed by the effective time , fluence  (hereinafter unless otherwise specified, F and Ф neutrons with energy greater than 0.5 MeV are used) may be determined using the formula:



where:

 - accumulated fast neutron fluence at the end of the last concluded lifetime;

Фmax - maximum from the previous lifetimes accumulation rate of fast fluence for the lifetime;

 - effective operation time of reactor at time of determination of the accumulated fast fluence.

4.2.2. It is required to use the values of neutron field characteristics considering their accuracy during fast fluence prediction for assuring conservatism when justifying the design lifetime of PRV. The following values should be used as the upper boundary:





where:

 - estimated errors of the respective values for the confidence level of 0.95.

4.2.3. The fast fluence values established after completion of the life time and predicted fast fluence values at the critical point should be compared with the maximum permissible value and used for subsequent prediction of the radiation lifetime of RPV. It is allowed to perform review of the radiation lifetime of RPV in accordance with the procedure given in Appendix 2.

4.3. The design data about the characteristics of neutron field for RPV and SS and results of determining the same quantities obtained during VVER operation and justified by standard experiments must be compared. The specification of design data is allowed depending in the comparison results. Required corrections may be made to the relevant documents according to the procedure determined in p. 9.2.2 of PNAE G-7-008-89.

It is required to perform calculation of fast neutron field characteristics for RPV when implementing the fuel loading modes differing from the design modes, or design changes impacting the fast neutron transition up to RPV. The necessity of their experimental justification during first trial operation of such VVER should be considered when justifying the design values of the fast neutron field characteristics for RPV. The results of this calculation and justification must be included in the set of documents presented for approved in the stipulated procedure for implementing a new fuel loaing mode or making design changes.

4.4. When determining and predicting the characteristics of neutron field the conservative factors of margin for these quantities for uncertainties due to specifics of reactor operation should be used if during fast fluence accounting due to any reasons (for example, if there is no information about the previous reactor operation) the use of the fast fluence accounting procedure is made difficult to the full extent on RPV and SS. Justification of used factors of margin must be confirmed

5. RECOMMENDATIONS FOR FAST NEUTRON FLUENCE ACCOUNTING ON RESOLUTION OF THE ISSUE ON POSSIBILITY OF PROLONGING RPV OPERATION AFTER THE EXPIRY OF OPERATION PERIOD ASSIGNED IN THE DESIGN

5.1. When resolving the issue on possibility of prolonging VVER RPV operation after the expiry of the operation period assigned in the design it is required to specify the values of neutron field characteristics at the feature points of RPV using the latest recommendations in neutron dosimetry of RPV.

5.2. It is required to forecast the fluence of neutrons with energy greater than 0.5 MeV at RPV corresponding to the end time of the prolonged operation life by analogy with the recommendations of p. 4.2 of the Safety Guide. The formula (1) should be used when determining the fast fluence, where instead of  it is required to use , where  is the proling operating lifetime.

5.3. It is required to maintain record of fast fluence on RPV for the lifetime in the process of each prolonged lifetime, besides the fast fluence must be experimentally justified. Experiment should be performed with installation of neutron activation detectors in the clearance near the external surface of RPV.

5.4. It is recommended to perform activity analysis if the swipes from the inner surface of RPV for validation of the accumulated fast fluence values on RPV of the fast fluence appraisal day for reaction 93Nb(n,n').

6. RECOMMENDATIONS FOR ACCOUNTING FAST NEUTRON FLUENCE ON RPV ON WHICH THERMAL ANNEALING IS MADE

6.1. During accounting of fast fluence on VVER RPV subject to thermal annealing, it is required to keep count of the fast fluence accumulation both at the start of operation and from the lifetime before which thermal annealing was performed.

6.2. It is required from the lifetime after annealing to perform fast fluence accounting at RPV with experimental justification of fast fluence, accumulated for the lifetime implemented after annealing.

6.3. It is necessary to predict the accumulated neutron fluence with energy greater than 0.5 MeV at the critical point of RPV in each lifetime planned after annealing, and after each lifetime starting from the time of annealing, predict the fast fluence at the time of completion of the last lifetime before expiry of the radiation durability. Moreover it is required to determine and justify the neutron fluence accumulation rate with energy more than 0.5 MeV and factor of margin for it at the critical point in each planned lifetime.

Appendix 1

(recommended)

to the Safety Guide "Accounting of fast fluence on reactor pressure vessels and surveillance specimens of VVER for follow-up prediction of radiation life time of reactor pressure vessels"

RECOMMENDED SETS OF
NEUTRON-ACTIVATION DETECTORS FOR EXPERIMENTAL JUSTIFICATION OF THE NEUTRON FIELD CHARACTERISTICS IN THE FIELD OF VVER RPV AND SS

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Detector, reaction | Half-life, days [1] | Effective energy, MeV [2] | Standard measurements in the clearance outside RPV | Control measurements in the clearance outside RPV | Measurements on SS | Analysis procedure of swipes with RPV |
| 237Np(n,f)137Cs | 11020 | 0.55 | + | + | + | - |
| 93Nb(n,n')93mNb | 5890 | 1.0 | + | + | + | + |
| 238U(n,f)137Cs | 11020 | 1.5 | + | - | + | - |
| 58Ni(n,p)58Co | 70.86 | 2.5 | + | - | - | - |
| 54Fe(n,p)54Mn | 312.3 | 3.0 | + | + | + | + |
| 46Ti(n,p)46Sc | 83.79 | 4.5 | + | - | - | - |
| 63Cu(n,base_1_306068_32779)60Co | 1925.5 | 7.0 | + | + | + | - |
| 55Mn(n,2n)54Mn | 312.3 | 11.6 | + | - | - | - |
| 59Co(n,base_1_306068_32780)60Co | 1925.5 | Reaction on thermal neutrons | + | + | + | + |

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2. V.P. Yaryna, E.I. Grigoriev, G.B. Tarnovsky. Methodological recommendations State system for ensuring the uniformity of measurements. Characteristics of reactor neutron fields. Methodology of neutron activation measurements. MI 1393-86 VNIIFTRI Moscow, 1986.

Appendix 2

(recommended)

to the Safety Guide "Accounting of fast fluence on reactor pressure vessels and surveillance specimens of VVER for follow-up prediction of radiation life time of reactor pressure vessels"

METHODOLOGY OF
RADIATION LIFETIME REVIEW OF VVER PRESSURE VESSELS

1. General

The procedure is designed for expert analysis of documents justifying brittle fracture resistance and radiation durability of VVER RPV both at the design stage and during operation. It may be used as elective when preparing the relevant documents at the operating organizations and organizations performing works and rendering services to the operators.

The procedure allows get a review of the radiation durability of RPV after each completed lifetime under known a priori qualities of steel, strength characteristics and accepted design-basis emergency modes, if assessments of accumulated fast fluence considering all the previous lifetimes.

The procedure is applicable for VVER RPV on which no thermal annealing was performed.

The criteria and dependencies accepted in [1] have been used in the procedure.

2. Radiation durability assessment

2.1. Radiation durability of RPV and fast fluence

The residual radiation durability of VVER pressure vessel is determined from the ratio:



where:

[F] - maximum permissible neutron fluence at the critical point of the reactor pressure vessel (hence forward, unless otherwise stated F and Ф of neutrons with energy more than 0.5 MeV are used);

Ft - accumulated neutron fluence at the time of evaluation at the same point.

N - number of lifetimes of reactor operation in the remaining time before the expiry of radiation durability from the time of evaluation;

Фn - assumed rate of neutron fluence accumulation at the same point for the lifetime n;

tn is the assumed effective duration of the reactor during the lifetime n.

Then the residual radiation durability of RPV shall be equal to:



If the accumulation of the fast fluence in the remaining lifetime is taken as the same (for example, from conservative reasons the rate is taken as maximum from the selection of values for all possible lifetimes in the future), the radiation durability of RPV shall be determined as:



where:

Фmax is the accepted maximum fast fluence accumulation rate from all the possible lifetimes.

Considering that before the start of reactor operation is equal to zero, the design radiation durability of RPV shall be determined as:



Since all the values of the neutron field characteristics may be determined only with certain accuracy limit, on prolongation of fast fluence it is required to introduce conservative factors of margin for each component in the formula (P3) in order to predict te radiation durability of RPV with confidence:







where:

k[F], kF, kФ - conservative factors of margin (by value equal or greater than 1) for maximum allowed fluence, accumulate fluence and fast fluence accumulation rate;

[F]\*, ,  - assessed values of the maximum permissible fluence and fast fluence accumulation rate.

2.2. Determination of the maximum permissible neutron fluence

In accordance with the dependencies from [1] and taking into attention the approaches from [2,3], the maximum permissible fast fluence in the opinions may be assessed according to the formula:



where:

 - maximum permitted brittle to ductile transition temperature at the critical point;

Tk0 - brittle to ductile transition temperature in the initial (before exposure) state;

AF - coefficient of radiation induced embrittlement, °C;

F0 - constant, equal to 1018 neutron/cm2.

The minimum value is taken as the value based on the metal stress-strain state from all the thermohydraulic conditions analysis in the zone of postulated design defect [3] (value is known from the documents, justifying the design lifetime of RPV). The values Tk0 and AF are taken in accordance with p. 5.8.4.2 [1]. In addition it is assumed that the normative values , Tk0, AF have been determined with sufficient degree of conservatism. In this case k[F] may be taken as equal to one.

It should be noted that in accordance with the procedure of section 8 of annex 2 [1] on tests of SS, the embrittlement coefficient of SS material considering the transition of critical brittle temperature following impact of exposure  and fast fluence on SS FSS according to the formula:



where:

n - exponential quantity taken in accordance with [1].

In this case the value of FSS having certain inaccuracy must be used with a factor of margin in order to provide sufficient conservatism of the value , which is used for comparing with the standard value AF given in the qualification report in accordance with p. 5.8.4.2 [1]. The recommended value of the factor of margin for FSS is 1.3.

2.3. Determination of the accumulated fast fluence

The accumulated fast fluence at the critical point of RPV is determined following accounting of fast fluence during reactor operation (in accordance with p.4 of the Safety Guide). The accumulated fast fluence must be determined for each section separately and recorded as sequential set of values

{Fi}i=1...m,

where: m - quantity of implemented lifetimes before the time of evaluation of the accumulated fast fluence

2.4. Determination of the fast fluence accumulation rate

Prediction of the fast fluence accumulation in the remaining operation time is made from analysis of planned reactor core loadings. Besides the calculation results of the neutron field characteristics corresponding to these loads may be used.

If the operation mode shall correspond to the mode used in the previous loadings, the maximum value from the selection can be used as the maximum accumulation rate of fast fluence



where: ti - effective reactor operation time in the campaign i.

2.5. Determination factor of margin

Values of factors of margin kF and kФ in the expressions (P5) can be assessed from the analysis of calculation and experimental results of fast fluence determination obtained on a specific reactor. The surveys at the operating VVER for example [4 - 7] shows that the estimated and experimental data on the neutron field characteristics in KR (fluence and fast fluence accumulation rate) may differ by 10 - 20%. Besides the experimental data error is about 10%. Thus, the overall uncertainty of the values of the quick neutron field characteristics at the critical points may constitute 30%. Hence the values of these factors of margin not below 1.3 should be use for the reviews. Lower values must be justified and undergo experimental validation.

3. Reference list

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