MONITORING OF NEUTRON FIELDS OF NUCLEAR REACTORS OF VVER-1000 TYPE WITH INCREASE OF NOMINAL POWER OF NUCLEAR REACTOR

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In this paper the experimental studies has been performed of fast neutron fluence determination for Block 1 of the Balakovo Nuclear Power Plant. Correlation between experimental and theoretical data it has been established.

Introduction

Even the first studies of reactor vessel materials showed that under the influence of reactor irradiation, the significant changes in the physico-mechanical properties of reactor steels occured, particularly in radiation embrittlement. Thus, the safe operation of nuclear power installations is inconceivable without constant monitoring of the steel state, as well as factors that affect its physical characteristics.

First of all, such factors include the flux and the fluence of fast neutrons.

Therefore, in connection with the implementation of the program to increase the capacity of WWER-1000 reactors, a need has arisen to determine the changed parameters of the neutron field of the reactor.

Main part

During the 22nd fuel cycle, neutron activation detectors (NAD) were irradiated at the outer surface of the reactor vessel of Block 1 of the Balakovo Nuclear Power Plant. Metal foils Fe, Ni, Nb were used as neutron activation detectors.

In 2016, during the period of regular monitoring NAD were dismantled from the irradiation device. Then these NAD were delivered to the Research Center "Kurchatov Institute". In order to determine the conditions for irradiation of the reactor vessel, the studies of specific activity of radionuclides generated in neutron-activation detectors as a result of ^{54}Fe (n, p) ^{54}Mn, ^{93}Nb (n, n) ^{93m}Nb and ^{58}Ni (n, p) have been performed.

An evaluation of the fluence and fast neutron flux on the inner surface of the reactor body for the 22nd campaign was performed with use of the results of measurements for the specific activities of NAD,

Measurements of the absolute activities of the iron NAD were carried out using the ^{54}Mn isotope produced by the ^{54}Fe (n, p) ^{54}Mn nuclear reaction. Measurements of the absolute activities of NAD of nickel were carried out using the ^{58}Co isotope produced by the ^{58}Ni (n, p) ^{58}Co nuclear reaction. The measurements were carried out using an ORTEC gamma spectrometer with a high-purity germanium crystal detector HPGe ORTEC GEM 35. The analyzer was a 16-channel ORTEC spectrometer.

The appearance of the gamma spectrometric complex is shown in the figure 1.

Fig. 1. ORTEC Gamma spectrometric complex

The obtained spectra were processed using the Gamma-Vision® software package. The time and geometry of the measurements were chosen so that the detectable area of the photopic of the characteristic gamma lines was not less than 10,000 pulses.

To measure the absolute activities of the studied nuclides, the gamma spectrometer was calibrated against the standard spectrometric gamma sources (OSGI), which included the isotopes ^{54}Mn, ^{60}Co, ^{137}Cs, and also the reference gamma source ^{152}Eu. The activity of the sources from the OSGI set has an error of 2.0-3.0% with a confidence probability of 0.95.

The value of the standard uncertainty for the number of pulses in the photopeak of the total absorption of the sample is determined as type A [2]:

$$U_A(S_m) = \sqrt{\frac{1}{n_i(n_i-1)}\sum_{q=1}^{n_i}(S_{m_{iq}} - \overline{S_i})^2},$$

$\overline{S_i} = \frac{1}{n_i}\sum_{q=1}^{n_i} S_{m_{iq}}$ - arithmetic mean of peak area measurements;

$S_{m_{iq}}$ - result of the i-th measurement;

n - number of measurements.

The total standard uncertainty of Uc activity is calculated (according to point 5 of the "National Standard of the Russian Federation GOST 54500.3-2011" [2]) by the formula:

$$U_c(A) = \sqrt{U_A(S_m) + U_c(\varepsilon)},$$

where $U_c(\varepsilon)$ - the extended standard uncertainty of registration efficiency is determined separately when the spectrometer is calibrated;

As an activity uncertainty, the extended standard uncertainty of U (A) activity is used. It is determined (according to point 6 of the "National Standard of the Russian Federation GOST 54500.3-2011") in accordance with the expression:

$$U(A) = k \times U_c,$$

where K = 2 (at P = 0.95) is the coverage factor used as a multiplier with the total standard uncertainty to obtain the expanded uncertainty.

The extended uncertainty of the result of measurements of the specific activity of ^{54}Mn and ^{58}Co on a semiconductor detector was determined according to [2] GOST R 54500.3-2011 and is 4.3% with k = 2.

To measure the specific activity of NAD, we weighed each detector on the Sartorius ME5 microbalance.

The fluence Φ of fast neutrons is determined by the formula:

$$\Phi = \varphi \cdot t,$$

φ - is the flux of fast neutrons;
t - is the time of irradiation;
The fast neutron flux is calculated from the expression:

$$\varphi = \frac{A_{eoi}}{\sigma \cdot K \cdot e^{-\lambda(t_2 - t_1)}},$$

σ is the nuclear reaction cross-section for a given isotope;
K is the reactor power factor;
t_2, t_1 - date of beginning and end of the fuel cycle.

The specific activity in the end of irradiation was determined by the formula:

$$A_{eoi} = \frac{S_{pp}}{\Delta t_m \cdot eff \cdot P \cdot N} \cdot e^{\lambda(t_m - t_{eoi})},$$

where S_{pp} is the measured area of the photo peak;
Δt_m - duration of measurement;
eff - measurement efficiency determined by OSGI;
P is the mass of NAD;
N is the concentration of the target isotope nuclei per 1 g of NAD;
λ is the decay constant of the measured isotope;
t_m - the end date of the measurement;
t_{eoi} - the end date of irradiation.

The absolute values of the activity of ^{54}Mn and ^{58}Co in NAD of iron and nickel are presented in Table 1.

To monitor the of fast neutrons flux in the region of the energy threshold more than 0.5 MeV, the nuclear reaction ^{93}Nb (n, n `) ^{93m}Nb is used. The advantages of this reaction are, first, in the long half-life of the reaction product ^{93m}Nb, equal to 16.13 years, and secondly, in the low threshold energy of the fast neutrons that caused this reaction (about 0.6 MeV).

Since the activity of the measured neutron-activation detectors is low, the ^{93m}Nb activity was measured by a liquid scintillation method with a high radiation detection efficiency.

Measurements of NAD activity by liquid scintillation were performed using a low-background alpha-beta radiometer of Quantulus 1220.

Specific activity of niobium ^{93m}Nb in the samples, shown at the end of irradiation, was determined by the ratio:

$$A_{eoi} = \frac{R}{eff \cdot M \cdot m_{specimen}} \cdot e^{\lambda(t_{izm} - t_{eoi})},$$

where R - pulse counting rate, 1/s;
eff - radiation detection efficiency;
M is the mass of niobium in the solution mass, g/g;
$m_{specimen}$ - sample mass for measurements, g (0.05 ml);
λ is the decay constant of the isotope ^{93m}Nb;
t_{izm} - date of measurement;
t_{eoi} - the end date of irradiation.

The results of measuring the activity of niobium samples are given in Table 1.

Table 1. Experimental values of the specific activities of ^{54}Mn, ^{93m}Nb and ^{58}Co in NAD

Distance from the bottom of the reactor core, cm	Specific activity ^{54}Mn, 10^{-17} Bq/ nucleus	Specific activity ^{93m}Nb, 10^{-17}. Bq/ nucleus	Specific activity ^{58}Co, 10^{-17} Bq/ nucleus
291.0	3.39	1.39	7.54
278.1	3.65	1.44	7.91
262.2	3.63	1.44	7.51
246.3	3.56	1.40	7.39
134.8	3.31	1.34	6.74
116.0	3.34	1.31	6.72
99.5	3.37	1.30	6.58
77.5	3.44	1.30	7.15
68.7	3.35	1.29	6.98

Conclusion

The performed work allowed to determine the key parameters of reactor irradiation. Results of these investigations will be used in future work to determine the change in the physico-mechanical properties of the materials of the VVER-1000 nuclear reactor vessel shells.

References

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