Measurement of the spatial-energy distribution of neutrons in the irradiation channel of the critical facility

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Abstract. One of the basic installations of the Republican State Enterprise "Institute of Nuclear Physics" of the Ministry of Energy of the Republic of Kazakhstan is a critical assembly, which is a zero-power reactor. Desalinated water and beryllium serve as moderators and neutrons reflectors. The energy spectrum of neutrons in the core is thermal. The main purpose and area of application is the modeling and study of the neutronic characteristics of the cores of water-moderated research reactors of various types.

The paper presents the results of experimental measurements of the spatial-energy distribution of neutrons in the dry, central channel of the critical assembly. Measurements of the neutron flux were carried out using activation foils for three energy groups of neutrons: thermal, epithermal, and fast.

The measured thermal neutrons flux in the irradiation channel is $\sim 3 \cdot 10^8$ cm$^{-2}$s$^{-1}$, and fast neutrons flux (with energies above 0.7 MeV) is $\sim 8 \cdot 10^8$ cm$^{-2}$s$^{-1}$. The fraction of thermal neutrons in the integral flux was 0.23%, and the fraction of fast neutrons was 0.62%. In the axial distribution of thermal and fast neutrons, the maximum value of the neutron flux is 50 mm below the midplane of the core.

1. Introduction

The spectral characteristic of the neutron field of a nuclear reactor is important and necessary information for evaluating the results of the effect of neutron irradiation on materials. In particular, it will be possible to interpret the results of radiation damage to materials, production of radioisotopes, etc. There are various experimental techniques for measuring the energy distribution of neutrons in a nuclear reactor. One of these techniques is the neutron activation method [1, 2]. The advantages of this method include the following: small size of the detectors; passive method for measuring the neutron flux, which does not require bulky equipment; energy breakdown of the measured value; simplicity and ease of use; acceptable measurement accuracy.

While using the neutron activation method, it is necessary to take into account the physical features of a nuclear reactor. Therefore, it is necessary to select a set of activation foils, to select and adapt the irradiation regimes, to select a technique for measuring the neutron flux in the epithermal region, as well as to search for and adapt nuclear constants. This approach will provide reliable data with acceptable accuracy.

The critical assembly is zero-power nuclear reactors and represent a facility for the experimental study of neutron-multiplying media. The critical facility of the Institute of Nuclear Physics is the only one in the Republic of Kazakhstan [3]. Its main purpose and field of application is to study the neutron-
physical characteristics of the cores of light water reactors, to verify the design codes and to justify the safety of nuclear-hazardous experiments carried out at the WWR-K reactor [4-6].

This paper presents the results of measuring the spatial-energy distribution of neutrons in the dry irradiation channel of the critical assembly.

2. Materials and methods

2.1. Critical facility

The critical facility was commissioned in 1972. The critical assembly of the critical facility can, in some cases, completely simulate the core of the research reactor WWR-K. The moderator and reflector of the critical assembly is also water and/or beryllium. There is no water circulation through the core. Heat exchange is carried out by convective method [7]. The main physical and technical characteristics of the critical assembly are shown in Table 1.

| Parameter                              | Value                        |
|----------------------------------------|------------------------------|
| Reactor type                           | tank                         |
| Thermal power, W                       | 100                          |
| Reflector of neutrons                  | light water and/or beryllium |
| Neutron moderator                      | light water and/or beryllium |
| Maximum thermal neutron flux, cm$^{-2}$s$^{-1}$ | $3 \times 10^9$             |
| Maximum fast neutron flux, cm$^{-2}$s$^{-1}$ | $2 \times 10^8$             |
| Fuel composition                       | UO$_2$+Al                    |
| Enrichment in isotope U-235, %         | 19.7                         |
| Diameter of the experimental channels, mm | 65, 96, 140                  |

The layout of the core of the critical assembly for experimental measurement of the neutron flux is shown in Figure 1.

![Figure 1](image-url)
The core consists of 13 fuel assemblies of the first type and 10 fuel assemblies of the second type. The side reflector of neutrons is light water. The reactivity margin of the core is 3.3% $\Delta k/k$.

The study of the neutron energy distribution was conducted in the central irradiation channel of the core (see. Fig. 1). The irradiation channel is a hexagonal tube with an external dimension of 65.3 mm. The channel is made of SAV-1 aluminum alloy and is filled with air. Outside, the channel is cooled by water.

2.2. Neutron flux measurement method
The neutron activation method consists in irradiating the selected foils in the studied neutron field, measuring the activity of the radionuclide formed in the foils as a result of a nuclear reaction, and then calculating the characteristics of the neutron field [8]. The study of the energy spectrum of neutrons was carried out for three ranges: the thermal region ($E_n<0.625$ eV), the epithermal region (for the energies of the three resonance integrals 1.46 eV, 4.9 eV, 337 eV) and the fast region (above $E_n>0.7$ MeV).

The following factors were taken into account in the selection of foils [9]:
- the half-life of the generated radionuclide is convenient for irradiation and calculation;
- the required energies and intensities of the registered gamma quanta;
- the ability to be activated in a selected range of neutron energies optimal for spectrum registration by a gamma spectrometer;
- a sufficient value of the activation cross section in the thermal region or a sufficient value of the resonance activation integral.

The neutron flux in the thermal region was studied by the cadmium difference method using an activation foil made of gold according to the $^{197}$Au($n, \gamma$)$^{198}$Au nuclear reaction. The method consists in the simultaneous irradiation of two foils. One foil was placed in a 0.5 mm thick cadmium shield, and the second was irradiated without a cadmium shield. Since the absorption cross section of cadmium is large at low energies, and at energies above 0.5 eV, it begins to fall sharply, therefore, it can be assumed that cadmium absorbs all thermal neutrons and transmits epithermal ones. The thermal neutron flux was determined from the difference in the activation of the foils.

The neutron flux in the epithermal region was studied using the sandwich method, using activation foils made of gold ($^{197}$Au($n, \gamma$)$^{198}$Au), indium ($^{115}$In($n, \gamma$)$^{116m}$In) and manganese ($^{55}$Mn($n, \gamma$)$^{56}$Mn). The method is as follows: three identical activation foils are placed in a cadmium shield with a thickness of 0.5 mm, as shown in Fig. 2. A cadmium shield with foils was placed on a holder along the central plane of the core. The induced activity of each foil was measured as: (1) the activity corresponding to the main resonance, and (2) the activity corresponding to the remaining minor resonances and the 1/v cross section. The induced activity for the measured range of neutron energies corresponding to the main resonance is calculated by subtracting the induced activity of foil No. 1 or No. 3 and foil No. 2 (see Fig. 2) [10, 11].

Figure 2. Schematic view of the arrangement of foils in a cadmium shield

To determine the neutron flux in the fast region, the following threshold foils and nuclear reactions were chosen: rhodium $^{103}$Rh($n, n'$)$^{103m}$Rh, reaction with effective threshold energy $E = 0.7$ MeV; indium $^{115}$In($n, n'$)$^{115m}$In, reaction with effective threshold energy $E = 1.15$ MeV; nickel $^{58}$Ni($n, p$)$^{58}$Co, reaction with effective threshold energy $E = 2.7$ MeV and iron $^{56}$Fe($n, p$)$^{56}$Mn, reaction with effective threshold energy $E = 6.2$ MeV. Activation foils were irradiated in a cadmium shield and installed along the central plane of the core.
Axial distribution of thermal neutrons was measured using a dysprosium foils (nuclear reaction $^{164}$Dy(n,$\gamma$$^{165}$Dy), which were mounted on a holder with a step of 50 mm in height. Axial distribution of fast neutrons was measured using a sulfur foils (nuclear reaction $^{32}$S(n,p)$^{32}$P), which were installed in the same way as dysprosium foils. The foils were irradiated in a cadmium shield.

The nuclear-physical characteristics of the used activation foils are shown in Table 2.

Table 2. Nuclear-physical characteristics of activation detectors [12, 13].

| Detector type | Gold | Indium | Gold | Manganese |
|---------------|------|--------|------|-----------|
| Neutron region | Thermal | | Epithermal | |
| Effective threshold energy | $E_n<0.625$ eV | 1.46 eV | 4.9 eV | 337 eV |
| Nuclear reactions | $^{197}$Au(n,$\gamma$$^{198}$Au | $^{115}$In(n,$\gamma$$^{116}$In | $^{197}$Au(n,$\gamma$$^{198}$Au | $^{55}$Mn(n,$\gamma$$^{56}$Mn |
| Half life | 2.696 days | 54 min | 2.696 days | 2.579 h |
| Reaction cross section, barn | 98.7 | 3 221 | 1 544 | 14 |
| Detector type | Rhodium | Indium | Nickel | Iron |
| Neutron region | Fast | | | |
| Effective threshold energy | 0.7 MeV | 1.15 MeV | 2.7 MeV | 6.2 MeV |
| Nuclear reactions | $^{103}$Rh(n,n$'$)$^{103m}$Rh | $^{115}$In(n,n$'$)$^{115m}$In | $^{58}$Ni(n,p)$^{58}$Co | $^{56}$Fe(n,p)$^{56}$Mn |
| Half life | 56.114 min | 4.486 h | 70.86 days | 2.5789 h |
| Reaction cross section, barn | 0.96 | 0.286 | 0.286 | 0.0472 |

The induced activity of gamma-radiation foils measured by wide-range (from 3 keV to 3 MeV) germanium gamma spectrometer of Canberra GX 2518, with 25% relative efficiency. The gamma spectrometer was calibrated before starting work with set of reference sources OSGI.

The calculation of the activity of the sample at the moment of the beginning of the measurement was carried out as follows [9]:

$$A = \frac{n}{\varepsilon \eta} K_s K_i,$$

where $n$ – the count rate of gamma rays at the peak of total absorption, reduced to the moment of the start of measurement, $\varepsilon$ – the efficiency of registration of gamma radiation of the considered energy at the peak of total absorption, $\eta$ – the emission of registered gamma radiation per decay of the measured nuclide, $K_s$ – the correction factor taking into account self-absorption, $K_i$ – the correction factor that takes into account the difference between the measurement conditions of real samples and the calibration conditions.

The counting rate at the peak of total absorption is determined as follows [9]:

$$n = \frac{S}{\tau} K_s K_d,$$

where $S$ – the number of counts of the measuring device during the exposure from gamma quanta of a certain energy, $\tau$ – the exposure time, $K_s$ – the correction factor that takes into account the decay of
the measured nuclide during the measurement, \( K_d \) – the correction factor that takes into account the dead time of the installation.

The induced beta-radiation activity of the foils \(^{165}\text{Dy}, ^{32}\text{P}\) was measured with an RKS-AT1329B radiometer. The radiometer is designed to measure the beta activity of various samples. The range of recorded energies includes from 155 keV to 3.5 MeV with a relative efficiency of 20\%. The beta counter was calibrated before starting work using a reference source. For the calculation, such values are used as: the number of target nuclei in the activated sample (according to the passport for the activation foil), the activation reaction rate and neutron constants for the sample.

The reaction rate \( R \) is the number of events of a given interaction occurring in the sample per second per one target nucleus. This value is determined based on the activity induced in the sample as a result of its irradiation in the investigated field [12]:

\[
R = \frac{A}{N} \left( 1 - e^{-\lambda t_0} \right) e^{-\lambda t_e},
\]

where \( A \) is the activity of the sample, measured after the time \( t_e \) – after the end of the irradiation \( t_0 \) – duration of exposure; \( N \) – the number of target isotope nuclei in the sample; \( \lambda \) – the decay constant of the reaction product.

The activation foils were loaded into the core when the critical assembly was shutdown, therefore, during the irradiation time, it was corrected taking into account the release of the critical assembly to power. The correction of the irradiation time of the foils was carried out as follows [12]:

\[
t_{\text{eff}} = t_0 + \frac{1}{\lambda} \ln \left( 1 + 1.44 T_2 \right),
\]

where \( T_2 \) – the power doubling time, \( t_0 \) – the duration of irradiation, counted from the moment the reactor reaches power.

Table 3 shows the irradiation regimes for activation foils on the critical assembly. The power of the critical assembly and the irradiation time were selected taking into account the following requirements:

- the optimum activity of the foils for measurement should be \( 10^3 - 10^5 \) decays per second;
- the uncertainty during power-up of the critical assembly should be small compared to the irradiation time to ensure the highest measurement accuracy;
- the irradiation time should not exceed several half-lives of the isotope in order to avoid the influence of saturation of activation of nuclei.

| Nuclear reaction | Critical assembly power, % | Irradiation time, h | Shielding detectors thickness, mm |
|------------------|----------------------------|---------------------|----------------------------------|
| \(^{197}\text{Au(n,\gamma)}^{198}\text{Au}\) | 42 | 1 | 0.02 |
| \(^{115}\text{In(n,\gamma)}^{116m}\text{In}\) | 42 | 1 (0.25) | 0.4 |
| \(^{55}\text{Mn(n,\gamma)}^{56}\text{Mn}\) | 42 | 1 | 0.3 |
| \(^{58}\text{Ni(n,p)}^{59}\text{Co}\) | 42 | 1 | - |
| \(^{56}\text{Fe(n,p)}^{56}\text{Mn}\) | 42 | 1 | - |
| \(^{10}\text{Rh(n,\gamma)}^{103m}\text{Rh}\) | 42 | 1 | - |
| \(^{164}\text{Dy(n,\gamma)}^{165}\text{Dy}\) | 4.2 | 1 | - |
| \(^{32}\text{S(n,p)}^{33}\text{P}\) | 42 | 1 | - |

3. Results and discussions

Axial neutron flux distribution in the irradiation channel is shown in figure 3. A value of +250 mm corresponds to the top of the core and a value of -250 mm to the bottom of the core. As can be seen from Figure 3, the peak of the neutron flux is shifted by 50 mm downward relative to the central plane of the core. This is due to the influence of the critical assembly control rods, which were immersed in the core by 300 mm (corresponds to the point "0" in Figure 3).
The experimental values of neutron flux for the selected energy ranges is given in Table 4. From the data presented in Table 4, it can be seen that a hard neutron spectrum is formed in the dry irradiation channel.

**Table 4.** Distribution of neutrons in the irradiation channel for different energy groups

| Neutron energy (MeV) | Neutron flux, cm\(^{-2}\)s\(^{-1}\) |
|----------------------|--------------------------------------|
| <0.625               | \((2.92\pm0.21)\times10^8\)          |
| 1.46                 | \((8.80\pm0.72)\times10^6\)          |
| 4.9                  | \((4.41\pm0.36)\times10^7\)          |
| 337                  | \((1.44\pm0.24)\times10^8\)          |
| >0.7                 | \((7.98\pm1.24)\times10^8\)          |
| >1.15                | \((2.85\pm0.23)\times10^8\)          |
| >2.7                 | \((2.25\pm0.43)\times10^8\)          |
| >6.2                 | \((1.69\pm0.41)\times10^7\)          |

**4. Conclusions**

Measurements of the spatial-energy distribution of neutrons in the dry experimental channel by the midplane of the core of the critical assembly were carried out. Measurements of the neutron flux were carried out using activation foils for three energy ranges of neutrons: thermal, epithermal, and fast. The spatial distribution of neutrons over the channel height was measured for two energy ranges of neutrons: thermal and fast.

In the energy distribution, two maxima of the neutron flux are observed: in the thermal region \((E_n < 0.625 \text{ eV})\) and in the fast region \((E_n > 0.7 \text{ MeV})\). The measured flux of thermal neutrons in the irradiation channel is \(~3\times10^8\text{ cm}^2\text{s}^{-1}\), and fast (with energies above 0.7 MeV) \(~8\times10^8\text{ cm}^2\text{s}^{-1}\). The ratio of thermal neutrons in the integral flux is 0.23%, and the ratio of fast neutrons is 0.62%. The cadmium ratio for gold is 1.29.

In the axial distribution of thermal and fast neutrons, the maximum flux is 50 mm below the center of the core.
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