INTRODUCTION

The knowledge about the absolute value of the flux and the fluence of thermal neutrons in experimental channels of reactors are necessary at the solution of many applied and fundamental tasks. Now, self-sufficient and not requiring calibration by means of other methods are activation methods (Bekurtz, 1968; Kramer-Agee, 1976; Yaryina, 1976) which are realized with the help of activation detectors, for example, of manganese, cobalt, copper, gold. These methods use the links between the induced activity of detectors and density of a flux (or a fluence) of neutrons.

So far, they are considered as reference methods. However, these methods are laborious and require the special equipment. Moreover, at an irradiation of samples they can’t always be used as tracking detectors for two reasons. Firstly, because the activity of the detector after irradiation depends not on a fluence during the whole time of irradiation, and only on a fluence for the last time equal to 3-4 half-life periods. Secondly, it isn’t always possible to determine a fluence of neutrons at the changing flux of neutrons during irradiation, for example, due to the stops of reactor at long irradiation. To a lesser extent it concerns the cobalt detector which has a long half-life period (5.28 years). However, its discard as a radioactive material is required due to a long half-life time after irradiation.

RESULTS AND DISCUSSION

At the irradiation of silicon with neutrons due to a reaction of radiation capture silicon-31 forms, which with β-decay (a half-life period-2.62 hours) converts into phosphorus-31. This transmutational impurity in the silicon monocrystals of n-type increases the specific electric conductivity (s.e.c.). 

This fact was the basis for a method of measurement of a neutron flux in relative units (Varlachev and Solodovnikov, 2009). For the measurement of absolute values of a fluence of thermal neutrons it is offered to irradiate silicon in the cadmium filter and without it as it done in an activation method, using its practices on a method of a cadmium difference (Bekurtz, 1968; Kramer-Agee, 1976; Yaryina, 1976). In relation to silicon the essence of a method is as follows.

It is possible to present a generated concentration of phosphorus-31 (C) during irradiation without cadmium filter in the form of two components: generated by thermal \( C_t \) and resonance \( C_{nt} \) neutrons

\[
C = C_t + C_{nt}
\]
C is linearly linked with change of s.e.c. (Varlachev and Solodovnikov, 2009).

\[ C = \frac{(\sigma - \sigma_0)}{e\mu_n}, \]  

where \( \sigma_0 \) - s.e.c. of silicon before and after irradiation, \( e, \mu_n \) - a charge and mobility of electrons respectively. It should be noted that a measurement of \( \sigma \) is carried out after the annealing of radiation defects at a temperature of 800°C, thereby exclude an influence of radiation defects from fast neutrons on the change of s.e.c. Now as an absorber it is accepted to use cadmium-113 due to the large on the change of s.e.c. Now as an absorber it is.

The concentration of phosphorus-31 is about 31 by thermal neutrons; \( \Phi_{eff} \) - an effective fluence of thermal neutrons; \( \Sigma \) - the macroscopic cross section of reaction at energy of a neutron, the corresponding to some effective temperature \( T_{eff} \) different from the environment temperature \( T \). \( \xi \) - Vestkott's factor taking into account the deviation of the dependence of the cross section of thermal neutrons (n, γ) - reaction on the silicon-31 from the law 1/\( \nu \), \( \chi \) - the coefficient of self-shielding of thermal neutrons (the ratio of the number of neutrons emitted from the silicon to the number of the entered neutrons). According to IAEA Nuclear Data Service the cross section of (n, γ) - reaction on silicon-30 in thermal area strictly follows to the law 1/\( \nu \), i.e. \( \xi = 1.0 \) for all monomeric nuclei of the moderator.

\[ \Sigma_a(kT_0)/\xi \Sigma_s < 0.2, \]  

where the mean log loss of energy

\[ \xi = 1 + [(A-1)^2/2.4]\ln[(A-1)/(A+1)], \]  

\( \Sigma_a, \Sigma_s \) - macroscopic sections of absorption and scattering of the moderator; \( k \) - Boltzmann's constant; \( A \) - mass number of nuclei of the moderator,

\[ T_{eff} = T_0[1+0.73\Delta A\Sigma_a(kT_0)/\Sigma_s] \]  

For example, for a beryllium moderator \( T_{eff} = 1.0066T_0 \), i.e. approximately on 2 °K.

From the expression (1, 3, 7)

\[ \chi_1\Sigma_1\Phi_{eff} = C - F_{Cd}C_{Cd} \]  

Then

\[ \Phi_{eff} = \frac{C}{\chi_1\Sigma_1}(1 - F_{Cd}), \]  

And taking into account expression (2) we will obtain an effective fluence of thermal neutrons. Silicon was irradiated with this fluence without cadmium filter,

\[ \Phi_{eff} = \frac{(\sigma - \sigma_0)}{e\mu_n\chi_1\Sigma_1}(1 - F_{Cd}), \]  

where

\[ R_{Cd} = C / C_{Cd} = (\sigma - \sigma_0)/(\sigma_{cd} - \sigma_0) \]  

is a cadmium ratio, which is determined by experimental values of s.e.c. From the effective fluence of thermal neutrons it is easy to pass to an average (for time of irradiation \( \tau \)) value of effective density of a flux of thermal neutrons (\( \varphi_{\theta} \)). By definition \( \varphi_{\theta} = \Phi_{eff} / \tau \). Thus \( \varphi_{\theta} \) is the multiplication of volume density of neutrons with
energy below boundary energy of cadmium on the
velocity of neutrons with energy $kT_{ef}$.

The values $F_{cd}$, $C_d$, and $E_{cd}$ for silicon had been defined
by us. Usually $F_{cd}$ is equal 1,01-1,04 (Nashelskyi,
1989). Therefore with an error up to 2% $F_{cd}$ can accept
$F_{cd}$ = 1,02.

Self-shielding coefficient of thermal neutrons $\chi_t$ (the
ratio of number of emitted neutrons from a silicon
washer to the number of the entered neutrons) was
determined by calculations in an isotropic neutron
field. Calculations were executed by the Monte-Carlo
method using direct modeling of neutron tracks in
natural silicon. The cross-sections were taken from
IAEA Nuclear Data Service. The history of a neutron
interrupted if either its absorption or an emission
from silicon. Radius and thickness of a washer were
the varied parameters. 107 neutron stories were
played for each variant. Results of calculations are
shown in Table 1. Also effective optical thicknesses
are given, i.e. average values of segments in a silicon
plate on a tracks of an entry of a neutron in it.

$E_{cd}$ of the cadmium cylindrical filter placed in an
isotropic neutron field is defined with expressions
(6,7). For example, in a standard set of detectors
AND-T there is a filter with a diameter of 15 mm, a
height of 10 mm and a wall thickness of 1 mm. When
using of this filter $E_{cd} = 0,55$ eV.

Beside that for definition of thermal neutrons fluence
we offered to manufacture the detector in the form
of a plate of the monocrystalline semiconductor with
ohmic contacts on all plane of each basis of a plate
which surfaces have to be parallel. It will allow to
establish the one-to-one association of electrical
resistance between the bases of a plate and specific
electrical resistance in volume of a semiconductor
monocrystal.

If the planes of the bases of a plate are parallel, and a
lateral area of a plate it is perpendicular to the planes
of the bases, according to an Ohm’s law specific
electrical resistance can be easily defined through
electrical resistance between the plate bases:

$$\rho = \frac{SR}{d} \quad (15)$$

where $\rho$ – specific electrical resistance, $R$ – electrical
resistance between the plate bases, $S$ – the area of the
basis of a plate, $d$ – thickness of the plate. Substituting
(15) to (13) and taking into account that $\sigma = 1/\rho$ we
obtain next

$$\Phi_{eff} = \frac{d \left( \frac{1}{R} - \frac{1}{R_0} \right)}{S e \mu_n R \chi_t \Sigma t} \left( 1 - \frac{F_{cd}}{R_{cd}} \right) \quad (16)$$

Table 1. Self-shielding coefficient $\chi_t$ and effective optical thicknesses $d_{opt}$ of silicon washer which has radius $r$ and thickness $d$.

<table>
<thead>
<tr>
<th>$r$, cm</th>
<th>0,5</th>
<th>0,6</th>
<th>0,7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$, cm</td>
<td>0,4</td>
<td>0,5</td>
<td>0,6</td>
</tr>
<tr>
<td>$\chi_t$</td>
<td>0,996</td>
<td>0,995</td>
<td>0,995</td>
</tr>
<tr>
<td>$d_{opt}$ cm</td>
<td>0,583</td>
<td>0,657</td>
<td>0,717</td>
</tr>
<tr>
<td>$r$, cm</td>
<td>0,8</td>
<td>0,9</td>
<td>1,0</td>
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<tr>
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<tr>
<td>$\chi_t$</td>
<td>0,995</td>
<td>0,994</td>
<td>0,994</td>
</tr>
<tr>
<td>$d_{opt}$ cm</td>
<td>0,7145</td>
<td>0,821</td>
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<tr>
<td>$\chi_t$</td>
<td>0,994</td>
<td>0,994</td>
<td>0,994</td>
</tr>
<tr>
<td>$d_{opt}$ cm</td>
<td>0,803</td>
<td>0,936</td>
<td>1,054</td>
</tr>
</tbody>
</table>

CONCLUSION

The possibility of implementation of the method was
confirmed by measurements of density of a flux of
thermal neutrons by offered and activation methods.
Measurements were carried out in the channel HEC-
4 of Tomsk research nuclear reactor with a power of
6 MW. The specific electrical resistance was measured
by the 4th probe method before and after irradiation

![Image](image_url)
and annealing of radiation defects at a temperature of 800°C within 2 hours. The error of measurement of an average on an end face of a washer of specific resistance didn’t exceed 3%. Continuous control of a fluence of thermal neutrons was exercised by means of regular chambers of fission of type CIT-4 used in technology of a neutron and transmutation doping of silicon.

During experiment the cadmium relation $R_{\text{Cd}}(\text{Si})$ for silicon was defined. For this purpose silicon exemplars, in a cadmium cylindrical case and without it, were symmetrically on an axis of the channel HEC-4 concerning the center of the fissile region of the reactor. The cylindrical case with 10 mm high, a diameter of 15 mm and wall thickness of 1 mm was used. The distance between exemplars was made 15 cm. Irradiation was carried out within 4 clocks at a power of 6 MW. Initial resistance of the exemplar irradiated in Cd the filter - 857 $\Omega \text{-cm}$, and without filter - 772 $\Omega \text{-cm}$. Terminating resistance - 593,5 $\Omega \text{-cm}$ and 99,5 $\Omega \text{-cm}$ respectively. From this $R_{\text{Cd}}(\text{Si}) = 16.9$, $\Phi = 2,14 \times 10^{17} \text{ cm}^{-2}$ and $\varphi = 1,48 \times 10^{13} \text{ cm}^{-2} \text{s}^{-1}$ follows.

Then took a similar washer with the ohmic contacts applied on it. In 4 hours initial resistance decreased from $R_0 = 141 \Omega$ to $R = 39 \Omega$. $R_{\text{Cd}} = 16.9$ at radiation at a power of 6 MW. From this follows $\Phi = 2,13 \times 10^{17} \text{ cm}^{-2}$ and $\varphi = 1,49 \times 10^{13} \text{ cm}^{-2} \text{s}^{-1}$ that corresponds to measurements by a standard method.

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