International Atomic Energy Agency

INDC(CCP)-272/G

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

# MEASUREMENT OF NEUTRON LEAKAGE FROM $^{238}$U, $^{232}$Th AND Be SPHERICAL ASSEMBLIES WITH A CENTRAL 14-MeV SOURCE

V.A. Zagryadskij, M.I. Krajnev, D.V. Markovskij
V.M. Novikov, D.Yu. Chuvilin and G.E. Shatalov

I.V. Kurchatov Atomic Energy Institute

Moscow 1985

Translated from Russian by the
International Atomic Energy Agency

April 1987

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

Printed by the IAEA in Austria
April 1987

INDC(CCP)-272/G

# MEASUREMENT OF NEUTRON LEAKAGE FROM $^{238}$U, $^{232}$Th AND Be SPHERICAL ASSEMBLIES WITH A CENTRAL 14-MeV SOURCE

V.A. Zagryadskij, M.I. Krajnev, D.V. Markovskij
V.M. Novikov, D.Yu. Chuvilin and G.E. Shatalov

I.V. Kurchatov Atomic Energy Institute
Moscow 1985

Translated from Russian by the
International Atomic Energy Agency

April 1987

86-13432 (1366e/0144e)
Translated from Russian

Report IAEh-4222/8

UDC 621.039.512.44

# MEASUREMENT OF NEUTRON LEAKAGE FROM $^{238}U$, $^{232}Th$ AND Be SPHERICAL ASSEMBLIES WITH A CENTRAL 14-MeV SOURCE

V.A. Zagryadskij, M.I. Krajnev, D.V. Markovskij
V.M. Novikov, D.Yu. Chuvilin and G.E. Shatalov

I.V. Kurchatov Atomic Energy Institute
Moscow, 1985

## ABSTRACT

The report reviews integral neutron physics experiments on $^{238}U$, $^{232}Th$ and Be assemblies with a 14-MeV neutron source. It is concluded that additional integral experiments should be performed with these materials. The method of measuring neutron leakage from spherical assemblies ("boron tank" method) is described in brief. The authors give the results of measurement by this method of neutron leakage from $^{238}U$, $^{232}Th$ and Be spherical assemblies of different thicknesses with normalization to one source neutron. They compare the experimental results with calculation by the BLANK program using the ENDL and UKNDL library data. The comparison shows that the values of leakage for $^{238}U$ and Be spheres and, in the case of small thicknesses, for $^{232}Th$ are reproduced satisfactorily by calculation. In the case of the thorium sphere with a 10 cm thickness of the multiplication zone, the calculated neutron leakage is 7% lower than the experimental value.

## 1. REVIEW OF STUDIES AND STATEMENT OF THE PROBLEM

Uranium, thorium and beryllium are promising materials for neutron multipliers in the fusion reactor blanket. The first two can be used in a hybrid blanket and as starting material for accumulation of $^{239}Pu$ and $^{233}U$. Beryllium is of interest for blankets with suppressed fission.

One of the basic questions in the fusion reactor blanket physics is to what extent the neutron physics calculation with the relevant nuclear data files is adequate for the physical characteristics of the compositions studied under conditions of interaction with 14-MeV neutrons. It can be answered partially by comparing the calculated evaluations with the results of integral neutron physics experiments on models with homogeneous materials [1]. A number of studies giving the results of experiments on $^{238}$U, $^{232}$Th and Be assemblies have now been published.

Uranium-238

In Ref. [2] Weale and co-workers studied an assembly in the form of a large cylinder consisting of uranium blocks with a length of 106 cm. It had a total weight of 19.3 t and an effective density of 16.3 g/cm$^3$. The 14-MeV neutron distribution over the assembly was measured with $^{63}$Cu(n,2n) foils. The rates of the (n,3n) and (n,2n) reactions were obtained by multiplying the 14-MeV neutron flux by the corresponding cross-sections of 0.69 and 0.95 b. The rate of the (n,$\gamma$) reaction was determined from the $\beta$-activity of $^{239}$Np. Neptunium was first separated chemically from the irradiated uranium pellets. The rate of the (n,f) reaction was measured with a fission chamber having an external diameter of 2.98 cm and an active-layer thickness of 6.05 cm, while neutron leakage was measured with a "long" counter at different angles to the assembly. The main sources of error in interpreting this experiment can be the heterogeneity and anisotropicity of the assembly and also the use of an experimental technique which is less perfect by contemporary standards. Consequently, the rates of the (n,2n) and (n,3n) processes were obtained by calculation with the use of cross-sections. The fission rate was measured with a chamber of a comparatively large size; this could be the reason for the perturbation of the spectrum at the measurement point and it also introduced an uncertainty into the co-ordinate at the measurement point. This effect is particularly significant for points close to the source, where the variation of the 14-MeV neutron flux with source distance is especially large.

Haight and co-workers [3] performed calculations for this experiment with the different data libraries. The results of the experiment and calculation with normalization to one source neutron are summarized in Table 1.

It will be seen from Table 1 that there is a considerable difference between calculation and experiment using different versions of data: by more than 40% for the rates of the (n,2n) and (n,3n) reactions with the $^{238}U$ nuclei, by 17% for the $^{238}U(n,f)$ reaction and by 70% for leakage. The rate of the (n,f) process is described better with the ENDL library data - the difference is 6%, while it is 20% in the calculation with the ENDF/B-IV data. The $(n,\gamma)$ process is described better with the ENDF/B-IV data - the difference is 5%. Neither calculation satisfactorily describes the (n,2n) and (n,3n) processes and leakage.

Allen and co-workers [4] measured neutron leakage from spherical assemblies of different thicknesses made of natural uranium with a 14-MeV neutron source. The assembly dimensions are given in Table 2.

The measurements were carried out with a "long" counter. The response of this counter to 14-MeV neutrons and to fission spectrum neutrons was first obtained. It was assumed that the fission neutron spectrum did not differ strongly from the spectrum of inelastically-scattered neutrons, and the counter's response to the latter was obtained by making a calculated correction in the counter's response to fission neutrons. The value of the 14-MeV neutron transmission T was obtained by calculation. The results given in Ref. [4] were calculated by the BLANK program with the ENDL (1975) data. The experimental values of leakage from Rev. [4] and the values calculated by BLANK are given in Table 3.

It will be seen from Table 3 that the calculation satisfactorily describes the experimental results of Ref. [4]. At the same time, there are situations which are not quite fully reflected in Ref. [4] and which could, in our opinion, affect the accuracy of the experiment.

1. The correction of the counter's response to inelastically-scattered neutrons was obtained using the dependence of the "long" counter

efficiency on neutron energy and the energy distributions of inelastically-scattered neutrons and the fission spectrum. Allen [4] does not indicate how accurately the inelastic-scattering spectrum is known. Usually the dependence of efficiency is irregular in nature and, therefore, in the 0.01-1 MeV region three experimental points are not sufficient. At 24, 220 and 830 keV the efficiency was calibrated with photo-neutron sources, whose yield depends on their design and preparation technology. The short lifetime of these sources makes their reliable standardization difficult; it is therefore quite complicated, in our opinion, to obtain a ~ 2.5% accuracy in determining the yield of such sources. Moreover, the study does not indicate the type of source simulating the fission spectrum; consequently, it is difficult to judge how close the spectrum of the source used is to the fission spectrum.

2. To obtain the "long" counter's response to fission neutrons and 14-MeV neutrons the counter was positioned at different distances from the source. Since the "long" counter is sensitive to orientation in relation to the source, its response to the same group of neutrons may differ in the case of a "naked" source and a source with a uranium multiplier assembly; therefore, the counter was moved in relation to the assembly and the position from where the response ceased to change was found. This means that the assembly in relation to the detector could be regarded as a point assembly and the transfer of the response obtained for the "naked" source could be considered valid. In Ref. [4] it has been shown that for a 15 cm diameter assembly this distance is 103 cm. In the case of the biggest assembly with a diameter of 32 cm this distance (although not given in the study) should increase noticeably. At large distances the effect-background relationship becomes substantially worse, and since the backgrounds of the "naked" source and the assembly are not identical, the calibration (determination of the counter response for the "naked" source) may cease to be valid. This factor could introduce further error.

Hansen and co-workers [5] give the measurements of the neutron leakage spectra for spherical uranium metal assemblies with a 14-MeV neutron source by the time-of-flight technique in the 0.8-15 MeV region. The assemblies had a composition of 99% $^{238}$U and 1% C and Si,

$R_{ext}$ =3.64, 10.91 cm, $R_{int}$ = 0.5 cm and a path length of 10 m. Stilbene and the NE-213 liquid scintillator were used as detectors. The measurements were performed at an angle of 26° to the deuteron beam. The results of the experiments and calculations by the ENDF/B-IV, ENDF/B-V and ENDL (1975) data are given in Table 4.

Table 4 shows that the calculated integral in the 0.8-15 MeV region for the ENDF/B-V version exceeds by 11% the experimental value for the thick assembly. In the case of the ENDF/B-IV, the greater difference (~ 9%) corresponds to the thin assembly. Calculation by the BLANK program gives a 21% higher value for the thick assembly.

In spite of the detailed spectrum data that can be obtained from this experiment, it cannot be used to evaluate the leakage of neutrons below 0.8 MeV. In accordance with calculated evaluations by BLANK, 55% of the total number of neutrons and 60% of secondary neutrons lie in this region for the thick assembly (26 and 41%, respectively, for the thin assembly).

Broder and co-workers [6] measured the neutron leakage spectrum for a spherical uranium assembly with a central 14-MeV source, using a scintillation spectrometer with s stilbene crystal. The assembly had an $R_{int}$ = 10 cm and $R_{ext}$ = 14 cm. The neutron spectrum was measured in the 0.6-15 MeV region. The experimental results were compared with those of Ref. [5] and with calculation by the BLANK program. Calculation and experiment differ in the 3.5-5.0 MeV region and at energies above 7 MeV. The results of Refs [5,6] differ only in the 3-4.7 MeV region. It is concluded that the considerably lower values in the calculations of neutron fluxes with $E_n$ > 7 MeV in comparison with the results of Refs [5,6] are due to insufficient account being taken of the direct processes of fast neutron interaction. However, very few neutrons are in this energy region so that the error of prediction of their numbers cannot appreciably affect such an integral parameter as the total neutron leakage from the assembly.

In Ref. [7] we studied the neutron spectrum inside a spherical uranium assembly with a central 14-MeV source by the method of activation threshold detectors. The assembly had an $R_{int}$ = 10 cm and an $R_{ext}$ = 16 cm. The activation reaction rates of threshold detectors for $^{115}$In(n,n'), $^{103}$Rh(n,n'), $^{65}$Cu(n,2n) and $^{19}$F(n,2n) were measured at five points along the assembly thickness at an angle of 0° to the neutron generator deuteron beam and over the assembly surface at angles of 0, 45, 90 and 135°. The values for 180° were obtained by extrapolation of the angular dependence. In the calculations by the BLANK program it was shown that the relative distribution of the activation reaction rates of the threshold detectors used over the assembly radius was independent of source energy in the 13.4-14.7 MeV region and, consequently, of azimuthal angle $\Theta$. The activation reaction rates were therefore integrated over $\Theta$ for each R. The obtained results were compared with calculation by the BLANK program. The results for the $^{19}$F(n,2n) and $^{65}$Cu(n,2n) detectors agree within errors with calculation, indicating that the program satisfactorily describes the source neutron distribution over the assembly thickness. In the case of the indium and rhodium detectors, calculation and experiment differ by a factor of up to 1.5, owing possibly to unsatisfactory description of the secondary neutron spectra in the ENDL data. This experiment has a sufficiently high spectral sensitivity but does not allow the efficiency of multiplication for 14-MeV neutrons to be assessed.

The above-described integral experiments on uranium assemblies with a 14-MeV neutron source supply in principle fairly extensive and varied information on the interaction of neutrons with $^{238}$U. However, a review of these experiments revealed the limitation of the experimental methods and the contradictory character of the results: on the one hand, there is a difference between the calculation of Weale's experiment [2] by both the ENDF/B-IV and ENDL (1975) data and our experiment with activation detectors [7]; on the other hand, there is satisfactory agreement between the results of Allen's experiment [4] and calculation by the BLANK program with the same ENDL (1975) data.

The foregoing leads to the conclusion that the existing results from the integral experiments on uranium assemblies are insufficient, especially as regards neutron multiplication by the action of 14-MeV neutrons.

## Thorium-232

The $^{232}$Th data have until recently been verified only on the basis of two published integral experiments with 14-MeV neutrons.

Report [8] describes an experiment on a large Th-cylinder similar to Weale's experiment [2]. The cylinder consists of Th-blocks and has a $\Phi$ = 96.5 cm and a $\ell$ = 106.7 cm. The Th(n,$\gamma$) and Th(n,f) reactions were measured in the experiment. The (n,2n) and (n,3n) reactions were calculated from the 14-MeV neutron flux obtained with the $^{63}$Cu(n,2n) detector. The results of this experiment normalized to one 14-MeV neutron and the corresponding calculation with the ENDF/B-IV data are given in Table 5.

This experiment has the same drawbacks for data verification as Weale's experiments [2]. The large dimensions and inhomogeneity of the structure of the assembly and the absence of direct measurement of the rate of the (n,2n) process introduce an element of uncertainty into the divergences between calculation and experiment, especially for the (n,2n), (n,3n) processes and leakage.

Hansen and co-workers [5] used the time-of-flight technique to measure the neutron leakage spectrum for a $^{232}$Th sphere 67.13 g/cm$^2$ thick with a central 14-MeV source in the 0.8-15 MeV region. The experiment was conducted under conditions similar to the experiment on uranium. According to calculated evaluations for the assembly dimensions mentioned in this experiment, the leakage below 0.8 MeV was 28.6% of the total leakage and 50% of the number of secondary neutrons. The parameters of the assembly and the experimental and calculated results with different data libraries are given in Table 6.

It will be seen from Table 6 that the BLANK program gives results differing most from experiment. This refers both to fluxes in groups and to the integral as a whole in the 0.8-15 MeV region. It is difficult to assess what relationship exists between the experimental and calculated results for neutron leakage in the whole of the 0-15 MeV region since almost 30% of all leakage neutrons lie below the measurement threshold.

In view of the above-mentioned methodological features and the appreciable divergence between experiment and calculation these two integral experiments with thorium cannot claim to supply full experimental information for data calibration. Further integral experiments with thorium assemblies are obviously advisable.

Beryllium

Beryllium is regarded as the most promising neutron multiplier in the fusion reactor blanket with suppressed fission. According to the results of Bazu and co-workers [9] the experimentally measured multiplication for beryllium by the action of 14 MeV neutrons was 25% lower than calculation. The calculation was carried out with the ENDF/B-III library data. This integral experiment in a Be-assembly with a 14 MeV neutron source is so far the only one known to the authors from the published literature.

Bazu and co-workers [9] studied the effect of multiplication of 14 MeV neutrons in Be-assemblies of different thicknesses. These assemblies were rectangular in form with multiplication zones having thicknesses of 8, 12 and 20 cm. They were located inside a polyethylene parallelepiped with the overall dimensions of 125 x 120 x 120 cm. The 14 MeV source was introduced into the middle of the assemblies through a special channel. The count rate distribution of the $BF_3$ counter was measured in one of the quadrants of this parallelepiped. This distribution was assumed to be valid also for the other quadrants. The count rate was then numerically integrated over the whole polyethylene volume. This measurement was carried out with and without the assembly. The ratio of the integrals with allowance for corrections for leakage from plolyethylene was the neutron multiplication effect. The corrections for leakage from polyethylene and for the influence of polyethylene on the reaction rates in beryllium were made by calculation. The absolute normalization of the 14 MeV neutron source was performed with the help of a $^{19}F(n,2n)$ detector located on the outer surface of the generator's target unit. The calculation for this experiment was made by the MORSE program with the ENDF/B-III data. The calculated experimental results for leakage are given in Table 7.

As Table 7 shows, the results of the experiment are on an average 25% lower than those of calculation. The reason for such a large difference may be sought both in calculation and in experiment. In our opinion, this experiment has at least three weak points, which may partly account for such a large difference from calculation.

1. The experiment was performed in an inconvenient geometry. Its calculation requires a three-dimensional program, and this may be the reason for an additional error not associated with constants.

2. The measurements were performed in one quadrant only. There is no explanation for the validity of transferring these results to the other quadrants under conditions of energy-angle dependence and the dependence of neutron yield of the source on azimuthal angle $\phi$.

3. Although the threshold of the $^{19}F(n,2n)$ reaction is sufficiently high, this detector could also record elastically-scattered neutrons. Unfortunately, the diameter of the target unit is not given in the study. But if we assume that it is approximately equal to the channel dimension in the Be-assemblies (14 cm), the contribution of the elastically scattered neutrons at such a distance to the $^{19}F(n,2n)$ detector activity could be considerable. This will lead to the experimental results being lower.

Thus, our review of integral experiments with neutron multiplier materials revealed the limitations of the experimental procedures used and showed considerable discrepancies between calculation and experiment. It is therefore advisable to carry out further experiments with assemblies of these materials with a view to studying neutron multiplication in the whole energy region and also to take a more accurate account of the different reactions.

The available integral experiments can be supplemented to a great extent by the experiment on the measurement of total neutron leakage from spherical $^{238}U$, $^{232}Th$ and Be assemblies of different thicknesses normalized to one 14 MeV source neutron.

Section 2 gives a brief description of the procedure of neutron leakage measurement for spherical assemblies. The results of the neutron leakage measurement and the conclusions are presented in Sections 3 and 4.

## 2. MEASUREMENT PROCEDURE

The absolute leakage from spherical $^{238}$U, $^{232}$Th and Be assemblies was measured by the "boron tank" method. In Ref. [10], where similar measurements were made on Pb and Bi assemblies, we have described in detail the experimental set-up and the measurement procedure. We briefly recapitulate the essentials of the method.

These assemblies, which were spheres of different thicknesses, were placed at the centre of a large volume having the shape of a spherical layer filled with an aqueous solution of boric acid. The dimensions and composition of the assemblies are given in Table 8.

The TiT target of the neutron generator, which was the source of 14 MeV neutrons, was placed at the centre of the assemblies. We measured the distribution of the count rate of the KNT-10 boron counter in the volume of the "boron tank" over the radius and the azimuthal angle $\phi$ with the deuteron beam direction. In order to normalize the KNT-10 count rate to one 14-MeV neutron, we calibrated the neutron yield monitor with reference to the associated alpha-particles, using a DKPs-25 silicon surface-barrier counter. The monitor was a KNT-5 fission chamber located in the "boron tank".

The leakage spectrum for the assemblies can be described as the super-position of the 14 MeV source neutron spectrum and the secondary neutron spectrum. The major part of the inelastically scattered secondary neutrons lie in the 0.01-6 MeV region.

In Ref. [11] we have shown that, in the case of the "boron tank" used in the present experiment, the number of neutrons captured by boron does not depend on the source energy in the 0.01-6 MeV region. When the 14 MeV source is located in the "boron tank", the integral of the KNT-10 count rate normalized to one 14 MeV neutron is proportional to the 14 MeV neutron recording efficiency of the "boron tank". The similar quantity obtained for the $^{252}$Cf source with a spectrum in the 0-6 MeV region is proportional to the secondary-neutron recording efficiency of the "boron tank". Obtaining from the experiment the integrals of the KNT-10 count rate over the "boron tank" volume for a "naked" 14-MeV neutron source and with the assembly under study for 14 MeV neutron sources and $^{252}$Cf, we can find the absolute neutron leakage from the assembly [10]:

$$M = T + N_{sec}$$

$$N_{sec} = (N - \varepsilon_{14\ MeV} \cdot T)\varepsilon_{Cf}$$

Here M is the absolute neutron leakage from the assembly, T the transmission function for 14 MeV neutrons, N the KNT-10 count rate integral over the "boron tank" volume with the assembly under study and the central 14 MeV source, $\varepsilon_{14\ MeV}$ the KNT-10 count rate integral over the "boron tank" volume with the 14 MeV source without the assemblies (the quantity proportional to the 14 MeV neutron recording efficiency of the "boron tank") and "boron tank" and $\varepsilon_{Cf}$ the KNT-10 count rate integral over the "boron tank" volume with the $^{252}$Cf source (the quantity proportional to the secondary-neutron recording efficiency of the "boron tank").

All quantities contained in the formula are normalized to one source neutron. T is the number of neutrons in the source group: these are either neutrons which passed through the assembly without interaction or neutrons which underwent elastic scattering but remained in the source group. The value of T in this study was taken from calculation. In Refs [10,11] we have discussed in principle the question of the influence of borated water on the absolute neutron leakage value measured for the assemblies. Here we shall return to this matter when we discuss the results for each element studied.

## 3. RESULTS OF EXPERIMENTS ON THE MEASUREMENT OF NEUTRON LEAKAGE FROM $^{238}$U, $^{232}$Th AND Be ASSEMBLIES BY THE "BORON TANK" METHOD

One of the main questions that arise in validating the "boron tank" method is to what degree borated water influences neutron leakage from the multiplier assemblies under study, i.e. the question of whether the leakage from the "naked" assemblies corresponds to the leakage measured by the "boron tank" method. In the case of uranium, the verification was performed by calculation and experiment. The BLANK program was used to calculate the rates of the main processes responsible for multiplication in the "naked" uranium assemblies and in the uranium assemblies located in the "boron tank". The corresponding results are given in Table 9.

It will be seen from Table 9 that the main processes are little sensitive to the assemblies being surrounded by borated water, except for the (n,γ) reaction. However, these changes have no practical effect on total leakage. The calculated values of leakage from assemblies without water were compared with the corresponding values for assemblies surrounded by borated water. The latter value was determined as $M_U = A_\Sigma + L_\Sigma - A_\Sigma$, where $M_U$ is the leakage from the $^{238}$U assemblies, $A_\Sigma$ the total absorption in the "boron tank" - assembly system, $L_\Sigma$ the leakage from the "boron tank" and $A_U$ the absorption in the uranium assembly. The results of the comparison are given in Table 10.

The influence of water was verified experimentally in the following manner. Since the near-surface region of the assemblies is most sensitive to neutrons reflected from water, a KNT-8 fission chamber was installed in one case, and a $^{65}$Cu(n,2n) activation detector in the other case, at the assembly surface at an angle of 90° to the deuteron beam. In both cases the measurements were performed with and without borated water. In the measurement with borated water the monitor was a KNT-5 fission chamber placed directly in the "boron tank". In the measurements without water the monitor was a KNT-10 chamber located in organic glass and placed at a distance of 3 m from the assemblies. Both monitors were calibrated with an alpha counter recording the associated alpha-particles from the T(d,n)α reaction. In the case of both the

$^{65}$Cu(n,2n) activation detector and the KNT-8 fission chamber, the ratios of photopeak areas and consequently the count rates with and without borated water, within errors, did not differ from unity. Because of the high threshold the $^{65}$Cu(n,2n) detector is sensitive in practice only to the source group neutrons. Therefore, the absence of the influence of water on the $^{65}$Cu(n,2n) reaction rate confirms the calculated conclusion that the $^{238}$U(n,2n) and $^{238}$U(n,3n) reactions are not sensitive to water in the "boron tank". The measurement of the ratio of fission rates by the KNT-8 chamber with and without water also confirms the conclusion that water does not influence the (n,f) process in the assembly, which is the main process of neutron multiplication.

The experimental evaluation of neutron yield from the D(d,n)$^{3}$He reaction was obtained in the same way as in Ref. [10] - from the ratio of the peak areas of the corresponding alpha-particles and protons. The neutron yield from this reaction did not exceed 1% of that from the T(d,n)α reaction. A correction taking into account the contribution of 2.5 MeV neutrons was made in the experimental results for leakage. The experimental and calculated values of neutron leakage M, the number of secondary neutrons $N_{sec}$ and transmission function T from spherical uranium assemblies of different thicknesses normalized to one 14-MeV neutron are given in Table 11.

It will be seen that the experimental results agree satisfactorily with calculation for all the assemblies. Moreover, they correlate with the results of Ref. [4]. It can be assumed that the earlier discussed methodological features of Allen's experiment [4] did not substantially affect the results of the study.

The result obtained thus leads to the conclusion that the BLANK program with the ENDL (1975) library data satisfactorily predicts the values of the neutron multiplication coefficients for uranium layer thicknesses of up to 10 cm.

Since the neutron leakage from assemblies is the combined result of several processes [(n,2n), (n,3n), (n,f) and (n,γ)], agreement between the results for leakage is a necessary but not sufficient condition for the accuracy of data. Considering that the experimental results with activation detectors [7] differ from calculation by a factor of 1.5, it is advisable to perform additional measurements of the process rates with uranium.

The absence of the influence of water on absolute leakage from Th assemblies was confirmed in the same manner as in the case of $^{238}U$. Instead of the KNT-8 chamber, a KNT-2 thorium fission chamber was used. Table 12 and 13 give the rate of the processes in $^{232}Th$ assemblies calculated by BLANK and the absolute leakages from these assemblies with and without water.

The measurements with the KNT-2 and the $^{65}Cu(n,2n)$ detector (the (n,2n) and (n,3n) reactions in the case of thorium also occur predominantly with the source neutrons) confirmed the calculated conclusions that water had little influence on the rate of the multiplication processes in thorium. It can therefore be assumed that neutron leakage from the assemblies remains unchanged when the latter are located in a tank with water. The correction for the contribution of the 2.5 MeV neutrons to leakage was at the level of 1%. Table 14 gives the experimental values, corresponding to the calculated values obtained by BLANK, for the absolute neutron leakage and the number of secondary neutrons $N_{sec}$ from $^{232}Th$ spherical assemblies normalized to one 14-MeV source neutron and also the values of transmission function T.

The calculation was carried out with the thorium data from the ENDL (1975) library. From an analysis of the results it can be concluded that for small thicknesses the calculated and experimental values for leakage and proportion of secondary neutrons agree with each other within errors. The agreement is less satisfactory for a sphere with a multiplication zone thickness of 10 cm. The experimental leakage is 7% higher than calculation and the proportion of secondary neutrons in the experiment is 8% higher than the corresponding calculation.

The extent to which water influences the rate of the (n,2n) reaction and leakage for the beryllium assemblies was evaluated by calculation. The corresponding results are given in Table 15.

It follows from Table 15 that water has no noticeable influence either on the (n,2n) process or on leakage as a whole.

The experimental results for leakage M and the number of secondary neutron $N_{sec}$, the calculation of these quantities by BLANK with the UKNDL library data and also transmission functions T are given in Table 16.

The calculation describes satisfactorily, within errors, the experimental results obtained by the "boron tank" method. The leakage from the Be assembly is determined by the main (n,2n) process. The absorption of neutrons in the case of beryllium with charged-particle emission is insignificant, amounting only to 4% of the leakage for an 8 cm thick assembly. Consequently, it may be considered that the neutron balance in the Be assembly is described satisfactorily by calculation. However, agreement between the leakage values does not guarantee the correct reproduction of the neutron spectrum. Spectrally sensitive measurements have to be carried out in order to verify the accuracy of the spectrum.

## 4. CONCLUSIONS

(1) The review of integral experiments for $^{238}$U, $^{232}$Th and Be assemblies with a 14-MeV neutron source showed that the existing experimental results are not sufficient for the calibration of data and confirmed that further experiments ought to be performed with these materials.

(2) The "boron tank" method was used to obtain the values of neutron leakage from $^{238}$U, $^{232}$Th and Be spherical assemblies of different thicknesses normalized to one source neutron.

(3) Comparison of the experimental results with calculation by the BLANK program showed that the values of neutron leakage for $^{238}$U, Be and, in the case of small thicknesses, for $^{232}$Th are reproduced satisfactorily by calculation. For the thorium sphere with a

multiplication zone thickness of 10 cm the leakage is 7% lower in the calculation than in the experiment.

Additional experiments on the measurement of the process rates should be performed for $^{238}U$ and $^{232}Th$ assemblies in order to refine the neutron balance.

The agreement between the calculated and experimental results for leakage from Be assemblies indicates that the neutron balance is described satisfactorily by calculation. Spectrally sensitive measurements should be carried out in order to evaluate the correctness of the neutron spectrum description.

# REFERENCES

[1] MARIN, S.V., MARKOVSKIJ, D.V., SHATALOV, G.E., Neutron Physics Calculation of Some Integral Experiments in the 1-14 MeV Region. Report IAEh-2932, Moscow (1977) (in Russian).

2. Weale J.W. et al. Measurements of the reaction rate distribution produced by a source of 14 MeV neutrons at the centre of a uranium metal pile. — J. Nucl. Energy, part A, B, 1961, vol. 14, p. 91.

3. Haight R.C. et al. Reaction Rates in a Uranium Pile Surrounding a 14 MeV Neutron Source: Calculations of the Weale Experiment. — Nucl. Sci. Eng., 1976, vol. 61, N° 4, p. 53 — 59.

4. Allen K.W. et al. The interaction of 14 MeV neutrons with Uranium. — J. Nucl. Energy, 1961, part A, B, vol. 14, p. 100.

5. Hansen L. et al. Neutron and Gamma-Ray Spectra from $^{232}$Th, $^{235}$U, $^{238}$U and $^{239}$Pu after Bombardment with 14 MeV neutrons. — Nucl. Sci. Eng., 1979, vol. 72, N° 1, p. 35.

[6] BRODER, D.L., GOTTLIEB, A.S., GUREEV, V.I., "Neutron generation in uranium and aluminium by neutrons with 15 MeV initial energy" in: Neutron Physics. Proceedings of the Sixth All-Union Conference on Neutron Physics (Kiev, 2-6 October 1983), Moscow 4 (1984) 223 (in Russian).

[7] NOVIKOV, V.M., SHATALOV, G.E., ZAGRYADSKIJ, V.A., et al., Integral Experiment on a Spherical Assembly of Uranium-238 Metal with a 14 MeV Neutron Source. Report-IAEh 3919/8, Moscow (1984) (in Russian).

8. Reaction and Neutron Leakage rate for a Large Th metal assembly Surrounding a DT Neutron Source, AECL-6882. — Chalk River Nuclear Laboratories, 1980.

9. Bazu T.K. et al. Neutron Multiplication Studies in Beryllium for Fusion Reactor Blankets. — Nucl. Sci. Eng., 1979, vol. 70, N° 3, p. 309 — 313.

[10] ZAGRYADSKIJ, V.A., MARKOVSKIJ, D.V., NOVIKOV, V.M., et al., The Total Absorption Method in Measurements of the Multiplication Factor Using 14 MeV Neutrons. Report IAEh-4171/8, Moscow (1985) (in Russian).

[11] NOVIKOV, V.M., CHUVILIN, D.Yu., ZAGRYADSKIJ, V.A., et al., Measurement of the Multiplication Factor for 14 MeV Neutrons in the Pb and Bi Spherical Assemblies by the Total Absorption Method. Report IAEh-4197/78, Moscow (1985) (in Russian).

Table 1.

| Process | Process rate normalized to one 14-MeV neutron | | |
|---|---|---|---|
| | calculation | | experiment |
| | ENDF/B-IV | ENDL | |
| $^{238}$U(n, f) | 0,949 | 1,11 | 1,18 ± 0,06 |
| $^{238}$U(n, γ) | 4,27 | 4,36 | 4,08 ± 0,24 |
| $^{238}$U(n, 2n) | 0,358 | 0,388 | 0,277 ± 0,008 |
| $^{238}$U(n, 3n) | 0,176 | 0,195 | 0,327 ± 0,052 |
| Leakage | 0,296 | 0,504 | 0,42 ± 0,02 |

Table 2.

| Assembly No. | Assembly parameters, cm | | |
|---|---|---|---|
| | radius | | thickness |
| | internal | external | |
| 1 | 11,93 | 12,7 | 0,77 |
| 2 | 5,85 | 7,88 | 2,03 |
| 3 | 5,85 | 9,91 | 4,06 |
| 4 | 4,44 | 15,75 | 11,31 |

Table 3.

| Assembly thickness, cm | Value of leakage normalized to one 14-MeV neutron | | | |
|---|---|---|---|---|
| | experiment [4] | | BLANK | |
| | T | M | T | M |
| 0,77 | 0,905 | 0,904 | 1,224 | 1,223 |
| 2,03 | 0,752 | 0,746 | 1,568 | 1,581 |
| 4,06 | 0,557 | 0,558 | 1,990 | 2,057 |
| 11,31 | 0,171 | 0,184 | 2,809 | 2,817 |

Table 4.

| Assembly material | Assembly thickness, g/cm$^2$ | Value of leakage normalized to one 14-MeV neutron | | | | |
|---|---|---|---|---|---|---|
| | | ΔE, MeV | experiment* | ENDF/B-IV | ENDF/B-V | ENDL (BLANK) |
| $^{238}$U | 69,15 | 0,8 – 5,0 | 0,670 | 0,595 | 0,659 | 0,644 |
| | | 5,0 – 10,0 | 0,059 | 0,046 | 0,036 | 0,053 |
| | | 10,0 – 15,0 | 0,669 | 0,645 | 0,647 | 0,647 |
| | | 0,8 – 15,0 | 1,398 | 1,286 | 1,342 | 1,344 |
| $^{235}$U | 207,7 | 0,8 – 5,0 | 0,803 | 0,846 | 0,931 | 1,032 |
| | | 5,0 – 10,0 | 0,063 | 0,052 | 0,040 | 0,084 |
| | | 10,0 – 15,0 | 0,232 | 0,237 | 0,244 | 0,232 |
| | | 0,8 – 15,0 | 1,098 | 1,135 | 1,216 | 1,328 |

*Error ± 7%.

Table 5.

| Process | Process rate normalized to one 14-MeV neutron | |
|---|---|---|
| | calculation | experiment |
| $^{232}$Th (n, γ) | 1,670 ± 0,017 | 1,63 ± 0,1 |
| $^{232}$Th (n, f) | 0,171 ± 0,003 | 0,174 ± 0,01 |
| $^{232}$Th (n, 2n) | 0,504 ± 0,090 | 0,42 ± 0,04 |
| $^{232}$Th (n, 3n) | 0,205 ± 0,003 | 0,30 ± 0,05 |
| Leakage | 0,697 | 0,78 ± 0,04 |

Table 6.

| Th-assembly thickness, g/cm$^2$ | Value of leakage normalized to one 14-MeV neutron | | | | |
|---|---|---|---|---|---|
| | ΔE, MeV | experiment* | BLANK, ENDL | ENDF/B-IV | ENDF/B-V |
| 67,13 | 0,8 – 10,0 | 0,442 | 0,429 | 0,467 | 0,469 |
| | 5,0 – 10,0 | 0,039 | 0,017 | 0,02 | 0,039 |
| | 10,0 – 15,0 | 0,645 | 0,602 | 0,628 | 0,65 |
| | 0,8 – 15,0 | 1,126 | 1,014 | 1,115 | 1,158 |

*Error ± 7%.

Table 7.

| Be-assembly thickness, cm | Value of leakage normlized to one 14-MeV neutron | |
|---|---|---|
| | experiment | calculation |
| 8 | 1,35 | 1,79 |
| 12 | 1,58 | 2,03 |
| 20 | 1,62 | 2,25 |

Table 8.

| Assembly No. | Assembly composition | Assembly parameters, cm | | |
|---|---|---|---|---|
| | | internal | external | thickness |
| 1 | 99,6% $^{238}U$ | 10 | 11 | 1 |
| 2 | 0,4% $^{235}U$ | 10 | 12 | 2 |
| 3 | | 4 | 12 | 8 |
| 1 | | 3 | 6 | 3 |
| 2 | 100% Th | 6 | 13 | 7 |
| 3 | | 3 | 13 | 10 |
| 1 | | 3 | 4,5 | 1,5 |
| 2 | 100% Be | 6 | 11 | 5 |
| 3 | | 3 | 11 | 8 |

Table 9.

| Thickness, cm | Process rate normalized to one 14-MeV neutron | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | without water | | | | with water | | | |
| | $(n,\gamma)$ | $(n,f)$ | $(n,2n)$ | $(n,3n)$ | $(n,\gamma)$ | $(n,f)$ | $(n,2n)$ | $(n,3n)$ |
| 1 | 0,072 | 0,066 | 0,039 | 0,023 | 0,081 | 0,068 | 0,04 | 0,023 |
| 2 | 0,161 | 0,139 | 0,075 | 0,043 | 0,181 | 0,141 | 0,077 | 0,043 |
| 8 | 0,804 | 0,52 | 0,222 | 0,121 | 0,871 | 0,521 | 0,222 | 0,120 |

Table 10.

| Thickness, cm | Value of leakage normalized to one 14-MeV neutron | |
|---|---|---|
| | with water | without water |
| 1 | 1,307 | 1,308 |
| 2 | 1,574 | 1,591 |
| 8 | 2,616 | 2,681 |

Table 11.

| Assembly thickness, cm | Neutron multiplication | | | | |
|---|---|---|---|---|---|
| | experiment | | BLANK | | |
| | M | $N_{sec}$ | M | $N_{sec}$ | T |
| 1 | 1,331 ± 0,054 | 0,491 ± 0,053 | 1,308 | 0,468 | 0,84 |
| 2 | 1,569 ± 0,059 | 0,857 ± 0,058 | 1,601 | 0,889 | 0,712 |
| 8 | 2,668 ± 0,073 | 2,365 ± 0,073 | 2,681 | 2,378 | 0,303 |

Table 12.

| Assembly thickness, cm | Process rate normalized to one 14-MeV neutron | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | without water | | | | with water | | | |
| | (n, γ) | (n, f) | (n, 2n) | (n, 3n) | (n, γ) | (n, f) | (n, 2n) | (n, 3n) |
| 3 | 0,0142 | 0,035 | 0,119 | 0,064 | 0,0161 | 0,036 | 0,120 | 0,059 |
| 7 | 0,121 | 0,082 | 0,283 | 0,131 | 0,155 | 0,084 | 0,270 | 0,126 |
| 10 | 0,213 | 0,106 | 0,336 | 0,154 | 0,262 | 0,107 | 0,341 | 0,155 |

Table 13.

| Assembly thickness, cm | Value of leakage normalized to one 14-MeV neutron | |
|---|---|---|
| | with water | without water |
| 3 | 1,336 | 1,351 |
| 7 | 1,592 | 1,634 |
| 10 | 1,676 | 1,702 |

Table 14.

| Assembly thickness, cm | Neutron multiplication | | | | |
|---|---|---|---|---|---|
| | experiment | | BLANK | | |
| | M | $N_{sec}$ | M | $N_{sec}$ | T |
| 3 | 1,341 ± 0,038 | 0,639 ± 0,037 | 1,351 | 0,649 | 0,702 |
| 7 | 1,645 ± 0,043 | 1,207 ± 0,042 | 1,634 | 1,196 | 0,438 |
| 10 | 1,829 ± 0,050 | 1,500 ± 0,050 | 1,702 | 1,373 | 0,329 |

Table 15.

| Assembly thickness, cm | Process rate normalized to one 14-MeV neutron | | | |
|---|---|---|---|---|
| | without water | | with water | |
| | (n, 2n) | leakage | (n, 2n) | leakage |
| 1,5 | 0,107 | 1,12 | 0,107 | 1,111 |
| 5 | 0,394 | 1,362 | 0,395 | 1,373 |
| 8 | 0,602 | 1,524 | 0,607 | 1,544 |

Table 16.

| Assembly thickness, cm | Neutron multiplication | | | | |
|---|---|---|---|---|---|
| | experiment | | BLANK | | |
| | M | $N_{sec}$ | M | $N_{sec}$ | T |
| 1,5 | 1,144 ± 0,036 | 0,320 ± 0,035 | 1,12 | 0,296 | 0,824 |
| 5 | 1,365 ± 0,040 | 0,762 ± 0,039 | 1,362 | 0,760 | 0,6025 |
| 8 | 1,529 ± 0,043 | 1,066 ± 0,042 | 1,524 | 1,061 | 0,463 |