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Determination of Relative Axial Distribution of Thermal Neutron Flux Using Wire Neutron Activation Analysis

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Abstract: **In thermal reactors, the spatial change of thermal neutron flux (TNF) is significant. A non-uniform TNF distribution is unfavorable, since it results in non-uniform burn-up of the fuel rods. This problem may be eased by using a reflector surrounding the reactor. Neutron Activation Analysis (NAA) have been used to measure TNF. The activation cross section of dysprosium is very large and the activity of such material is proportional to the TNF. Therefore, the induced activity values can be directly used to represent the relative thermal flux distribution. Furthermore identical experimental conditions (i.e.: identical volume of sample, identical irradiation time, etc.) are provided by using a wire sample. In this work a rare application of NAA is made by using a Dy-Al alloy wire. The wire is placed vertically in the core. Special arrangement is made in measuring the induced activity of the wire taken into account decay during measurement. Finally the so called refractor saving is approximated.**

Keywords: **thermal reactors, thermal neutron flux (TNF), Neutron Activation Analysis (NAA).**

1. INTRODUCTION

In case of a parallelepiped-shaped uniform, bare (without reflector) reactor core. The distribution of thermal neutron flux, according to basic reactor theory, is given by the following:

$\varphi_{th}(x,y,z) = \varphi_{th}(0,0,0)\cos(\pi x/a)\cos(\pi y/b)\cos(\pi z/c)$

Here $a = a' + 2\sigma$ (1)

$b = b' + 2\sigma$

$c = c' + 2\sigma$

a’ , b’ , c’ - actual physical dimensions of the core

σ - extrapolation distance.

Accordingly, the axial distribution of neutron flux along (z) axis at a given place x_0, y_0 can be written as:

$\varphi_{th}(x_0, y_0, z) = \varphi_0 \cos(\pi z/c)$. (2)

Here

$\varphi_0 = \varphi_{th}(0,0,0)\cos(\pi x_0/a)\cos(\pi y_0/b)$.

It’s clear that a cosine function describes the TNF vertical distribution in the reactor. This non-uniform functional dependency of TNF is expected for the (x), (y) axis. So fuel at outer layers of the core is subject to lower TNF. As a result fuel inside the core will be burned faster, this raises a practical problems for power reactors as far as fuel economy is concerned.

A reflector is made up of material scattering a considerable part of neutrons leaking through the reactor boundary back into the core, increasing the TNF at the edges. This increase helps to make the TNF more uniform in the core, however some non-uniform stricture will still exist as shown on the schematic prediction fig. 1.

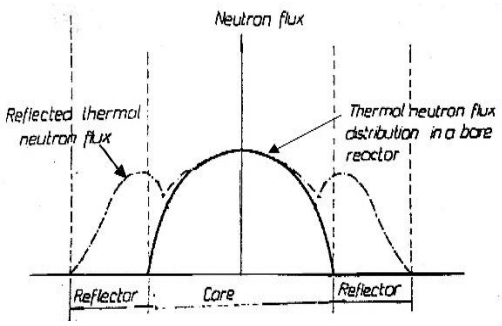

Fig 1: Expected effect of reflector on TNF in the core

The use of a reflector improves economy of the reactor construction as less fuel is required to achieve the critical mass. Reflector saving means the decrease of the linear dimensions of the critical reactor due to the reflector. It can be approximated by fitting the results using a cosine function in accordance with equation (2).

The use of reflectors may ease the problem but can't solve it. In practice non-uniform distribution of TNF necessitates fuel rods repositioning to improve fuel economy in power reactors . In such procedure outer fuel rods and inner ones are exchanged. This will result in a uniform burn up of the fuel rods which helps fuel economy, since refueling is costly.

2. NEUTRON ACTIVATION ANALYSIS

NAA is widely used in determining trace composition of unknown sample such procedures requires information on neutron flux at irradiation position. There is a diverse use of this method, in chemical characterization of Micronesian ceramics [Descantes, 2001], in fat mass assessment by in vivo NAA and DXA [valtuena, 2003], and recently NAA is utilized in detection of landmines and radio isotope power generation [David, 2004].

In reactor physics we are interested in the neutron flux . so we use a known sample for activation. Usually NAA uses a foil samples positioned at desirable locations. The use of foil NAA in measurement of axial and radial TNF distribution in a cylindrical assembly is reported by [Marechal,2015]. A set of uranium foils were used in each dimension. A unique application of NAA is made in this work using a Dy-Al alloy wire sample. The alloyed sample is used to reduce self-shielding effect.

Activation of dysprosium by neutrons is given by the following reaction :

$$^{164}_{66}Dy \xrightarrow[(n,\gamma)]{\phi\sigma} {}^{165m}_{66}Dy$$

$$^{165m}_{66}Dy \xrightarrow[T_{1/2} = 1.3\ \text{min}]{(\gamma)} {}^{165}_{66}Dy$$

$$^{165}_{66}Dy \xrightarrow[T_{1/2} = 2.35\ \text{h}]{(\beta,\gamma)} {}^{165}_{67}Ho$$

The measurement is made for the decay of Dy-165. A reasonable delay time (about 20 min) before start of measurement to allow the decay of Dy^{m}-165.

Activation of Aluminum by neutrons is given by the following reaction :

$$^{27}_{13}Al \xrightarrow{(n,\gamma)} {}^{28}_{13}Al$$

$$^{28}_{13}Al \xrightarrow[T_{1/2} = 2.24\ \text{min}]{(\beta,\gamma)} {}^{28}_{14}Si$$

Since the wire is made of Dy-Al activation of aluminum will produce another interfering radiation. One hour delay time is required for the aluminum radiation to die out, this time will cover the Dy^{m}-165 decay mentioned above.

The activation cross section of dysprosium is very large and have approximately 1/v-dependence throughout the neutron energy range fig. (2) [Radiation Center, 2003].

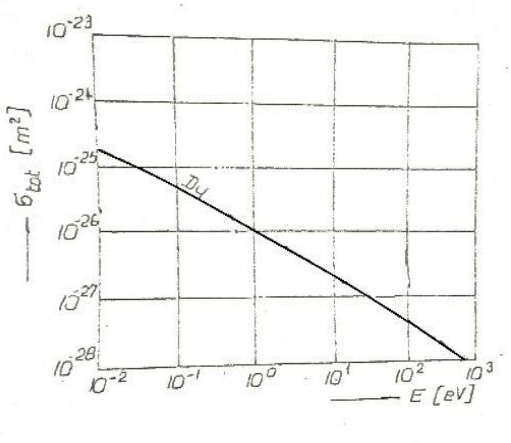

Fig 2: The activation cross section of dysprosium

Accordingly, the contribution of epithermal neutrons to its activity is negligible so we can represent the TNF directly by the measured activity of the sample. Indeed it will be shown below that with a special arrangement the total count will be proportional to TNF and will be used to represent it. For this reason dysprosium was chosen for activation.

3. CORRECTION FOR DECAY DURING MEASUREMENT

In measuring the activity of the irradiated wire sections, the activity of other sections decreases continuously in the course of measurement. A compensation must be made.

The induced activity of the sample at start of the measurements can be written as follows [Nuclear Science Division, 2000].

$$A(z, t) = \phi_{th}(z) \cdot G_{th}\, \sigma_{act}\, N_T \left(1 - e^{-\lambda\tau} \right) e^{-\lambda t} \qquad (3)$$

Here:

ϕ_{th} - thermal neutron flux (neutrons . cm^{-2} . s^{-1}).

G_{th} - thermal self-shielding factor.

σ_{act} - microscopic activation cross section (cm^2).

N_T - number of target atoms in the sample.

τ - Irradiation time (s).

t - Time at start of measurement (s).

Provided the activity of the sample is not reasonably large compared with the dead time of the counting system, the measured count rate R (t) will be proportional to the sample activity:

$$R(t) = \eta\, \gamma_a\, A(t) \qquad (4)$$

Here

η -efficiency of counting apparatus.

γ_a - gamma line abundance.

To account for decay during measurement of induced activity of different parts of the wire. Simple integration of the count rate R(t) over the measurement time (t_m) starting at time (t) gives the total count (B)

$B = \gamma_a \eta A(t) (1 - e^{-\lambda tm}) \lambda^{-1}$ (5)

For $\lambda tm \cong 0$ using the expansion of the exponential we have $B = \eta \gamma_a A(t) t_m$

Substituting for A (z, t) from equation (3) into equation (5) we get:

$B(z, t) = \phi_{th}(z) [\eta \gamma_a G_{th} \sigma_{act} N_T (1- e^{-\lambda\tau}) \lambda^{-1}] F(t_m,t)$ (6)

Where

$F(t_m, t) = (1 - e^{-\lambda tm}) e^{-\lambda t}$ (7)

The sub product in figure brackets in equation (6) is the same for each point of the wire. The total counts will be proportional to the TNF if the value of the function $F(t_m,t)$ is constant (k). This will be fulfilled if the measuring period (t_m) and the time at start of measurement (t) are related by:

$t_m(t) = (1/\lambda) \ln(1 / (1 - k . \exp(\lambda t)))$ (8)

This relationship controls the choice of measurement period t_m for a measurement starting at time (t) after irradiation. In this work the method used to ensure adequate measurement periods t_m is based on the use of same composition foil irradiated simultaneously with the wire to control its measurements this will be described below.

4. IRRADIATION

Irradiation is performed at the Budapest Technical University (BTU) research reactor fig. (3).

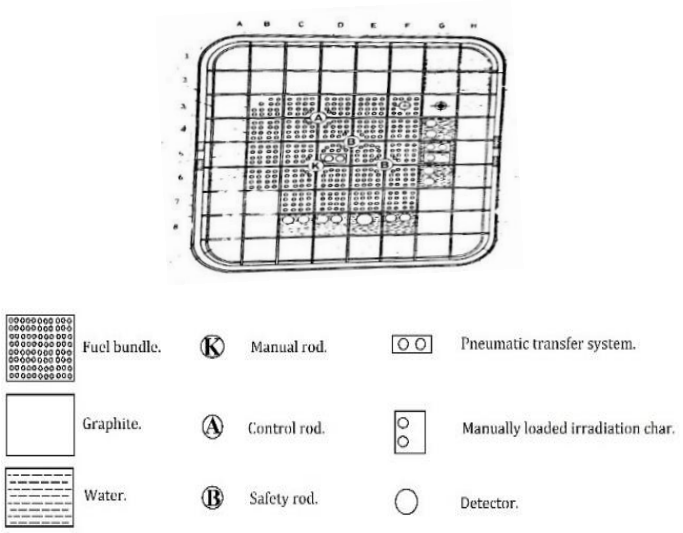

Fig 3: BTU research reactor

This reactor is a swimming pool type. The fuel is 10% enriched in ^{235}U (UO2). ^{235}U content being 8g per fuel element. The reactor uses desalted water H2O as coolant, moderator and main reflector (beside graphite). Maximum reactor power is 100KW and maximum permissible temperature 60^o.

In preparing for irradiation, the wire is placed in the Plexiglas rod. The moderation properties of Plexiglas are similar to those of water and thus the disturbance of the flux distribution in the core will be negligible. The rod is then placed in the core position E6 of the reactor. Simultaneously a dysprosium foil is activated in the core position D5. The wire and the foil were irradiated for 390 S at 1KW reactor power. The foil is needed to control measurement of induced wire activity.

5. MEASUREMENT OF THE INDUCED WIRE ACTIVITY

The samples have to rest for at least one hour after irradiation to permit the interfering radiation to decay ($t_{1/2}$ of AL=2.24min and $t_{1/2}$ of Dy^m-165=1.3 min).

Equations (7,8) guaranty the choice of (t_m) at each (t), however in practice we use measurement of a preset total; count of a foil activated under identical conditions. The preset total count will comply with equation (8) accounting for decay during measurement. For the foil equation (6) will guaranty that $F(t_m,t)$ is constant if the total count is constant since other

parameters (including TNF) are the same for all points in the wire. The foil and the wire were irradiated and measured simultaneously there for $F(t_m,t)$ is also constant for the wire. Now turning to equation (6) again but with respect to the wire we see that if $F(t_m,t)$ is constant then TNF is proportional to total count. Therefore, total count can be used directly to represent flux.

A special setup is prepared for the measurement of the wire activity. The wire is removed from the rod and placed into the wire activity measuring setup fig.(4).

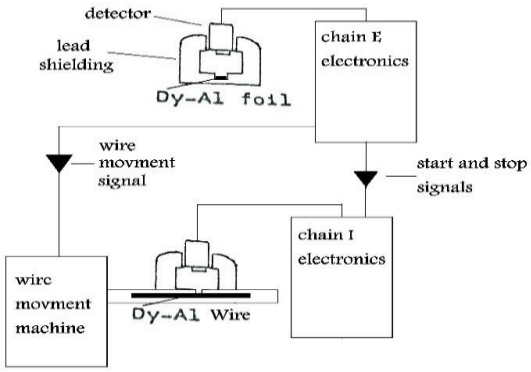

Fig 4: Wire measurement setup

The setup contains two measuring chains, one to measure the activity of the wire (chain E) recording the count B coming from the scanned part of the wire and the timer (chain I), taking the counts B_I proportional to the activity of a foil made of the same material and activated simultaneously with the wire.

The foil is placed below the detector of the timer (chain E). Timer chain contains a preset counts when reached sends signals to stop (chain I), forward the wire by the present increment of length, and start (chain I) again. The length of a step can be adjusted in the range of 1 to 100 mm we used 5mm intervals. The Measurement, of the decay of Dy-165 performed along the wire.

The total count as a function of position along the Dy-Al wire is measured. Radioactive decay during the measurement is automatically corrected by increasing the time of measurement of the subsequent wire sections, in compliance with relationship (equation 7). Setting the appropriate measuring periods is guaranteed by simultaneous measurement of the foil. The preset count were taken to be the first reading of (chain E). A total of 120 measurements were made along the wire. Experimental values of (t_m) and (t) satisfied equation (7) within 1% which validates the foil control procedures used.

6. RESULTS AND DISCUSSION

Equations (6) shows that total count is proportional to TNF after time corrections is made according to equation (7). Since other parameters are constants, values of total count of chain (E) can be used directly to represent TNF. The TNF relative distribution along a vertical axis in position E6 is shown in fig. 5. Keeping in mind that data of fig. 5. Only gives the shape of the TNF and not the values. The general shape is as expected with two clear reflector

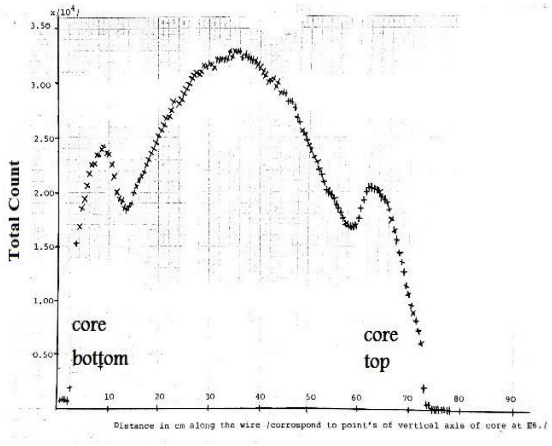

Fig 5: Distribution of TNF along a vertical axis in the core

This distribution shows asymmetric character. The reflector peak at the top is depressed relative to one at the bottom this can be attributed to the effect of the manual and safety rods near the irradiation position (see Fig.3).

The middle of the core was determined at the maximum value of the central peak, however, this point is shifted from the actual middle point due to the asymmetry mentioned above. The figure shows how reflector flux peaks on the sides helping to make the TNF more uniform in the core (which is desirable).

In frame of this work a special program SAVCAL is developed. The program reads data of fig.5, separates the three peaks: the central (bare), and two side peaks (reflector). The central peak readings is then fitted into a cosine function with maximum value at actual middle. From this fitting the program determines the value of the bare case dimension, and using actual corresponding value the reflector saving is then calculated. The program SAVCAL is made to take into account the asymmetry problem. Instead of fitting the whole data into one cosine function the program divides the data to upper and lower ones (referring to above the middle and below the middle of the core). Each set of data is then used for separate fitting procedures. The program calculate the reflector saving for each case and supply the average value. Reflector saving value obtained using lower data was higher than that obtained using upper data. This is expected since control rods in upper part absorbs neutrons and have the same effect as scattering out of the core. The reflector saving average value of 9.3 cm obtained in this work is typical one of this kind of water moderated and reflected nuclear reactors.

Absolute measurement of TNF using NAA has been made at different positions of the same reactor core [tashani]. Subsequent calculations of this measurements requires complete nuclear data [Herman, 2011] and a will defined Measurements conditions both introduce uncertainties. Relative measurements of TNF is easer, but the results cannot be used directly. The relative measurements results, however, can be calibrated with absolute peaks super imposed on the sides of a central peak (bare).

7. CONCLUSIONS

A unique and rare application of Neutron Activation Analysis is made here, using a wire instead of a foil. The wire allowed a continuous monitoring of TNF along vertical axis. The results agree with the expected behavior which verifies approximations and precautions made in irradiation and subsequent measurement of induced activity of the wire. The latter, introduced some difficulties due to decay during measurement of different parts of the wire. The activation of an identical foil to control these measurements have been successful. Final results shows asymmetry caused by manual and safety rods. A double fitting procedure is adopted to preform analysis in such cases.

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