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Measurements of Thermal Neutron Spectrum Parameters in the TRIGA Mark II Reactor

Jae Choon Yang

Korea Atomic Energy Research Institute
Seoul, Korea

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Abstract

The relative reaction rates were measured in the TRIGA Mark II reactor core and analyzed to obtain the neutron spectrum parameters; relative neutron temperature T_n and epithermal index $r\sqrt{T_n/T_0}$. Measurements were made with the central thimble and the F2 position containing the light water.

The relative neutron temperature was represented by the activation ratio of Lu-Mn, and the epithermal index was measured by Au-Mn foil activation. The multichannel analyzer was used to measure the relative γ-rays of the detector foils. The results were compared with the calculated values.

요 약

TRIGA Mark II 원자로심에서 반응율을 측정하여 중성자 spectrum parameter인 상대적인 중성자 온도 T_n과 열외중성자 지수 $r\sqrt{T_n/T_0}$를 얻기 위해 해석하였다. 측정은 경수 환경하에 있는 central thimble과 F2 위치에서 수행되었다. 상대적인 중성자 온도는 Lu과 Mn의 방사화율로 표시되며 열외중성자 지수는 Au와 Mn의 반응율에 의해서 측정된다.

이들 검출박의 상대적인 γ-에너지는 multichannel analyzer에 의해서 분석되었다. 실험 결과는 이론적인 계산치와 비교 평가되었다.

I. Introduction

The thermal neutron spectrum in a reactor is important parameter to understand the reactor behavier. The neutron spectrum of thermal reactor can be analyzed into components that are by nature Maxwellian, $1/E$ and transition.

The Maxwellian component is identified by its dependence on neutron temperature T_n, and the $1/E$ component is characterized by an epithermal index r according to the Westcott model[1,2]. Thus, the measurements of two spectral parameters T_n and r are necessary to determine an unknown neutron spectrum from the experiment.

These parameters were measured at the central thimble and the F2 position of TRIGA Mark II reactor core (Fig. 1). The fuel rods were made up of 20% enriched, 1.4 in. diameter, 14 in. long uranium zirconium hydride, clad with aluminium of 0.03 in. wall thickness.

All experimental runs were carried out at the power 250 KW of the reactor.

The quantities to be measured directly were the activation ratio between non-$1/v$ and $1/v$ absorbers to determine the relative neutron temperature T_n, and a modified epithermal index

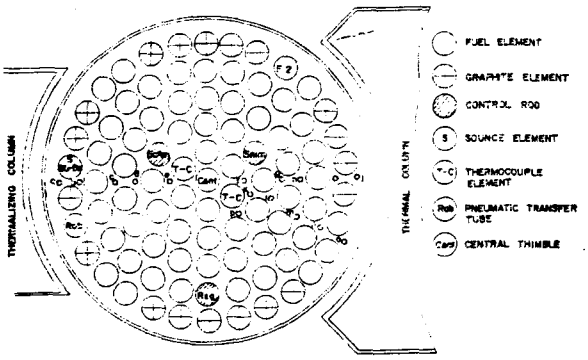

Fig. 1. TRIGA-Mark Ⅱ Reactor Core

$r\sqrt{T_n/T_0}$ which is a combination of Westcott's r and the neutron temperature T_n(T_0=293.59 K).

The detector foils to be used in the integral activation method were Lu-Mn foils for the relative neutron temperature and Au-Mn foils for the epithermal index.

For the reference point, the thermal column was used. It was assumed that the thermal neutron spectrum in the thermal column was pure Maxwellian. The temperature of the thermal colum gave the value of T_0. All experimental runs were normalized by a gold foil at a specific core location always.

Ⅱ. Experiment

1. Epithermal Index

The effective cross section, $\hat{\sigma}$, consisting of a Maxwellian component and a $1/E$ epithermal component was given by Westcott[2] as

$$\sigma=\sigma_0(g+r\cdot S_0\sqrt{T_n/T_0})=\sigma_0(g+r'S_0) \quad (1)$$

$$\left.\begin{aligned} S&=\frac{1}{\sigma_0}\sqrt{\frac{4}{\pi}\frac{T_n}{T_0}}\int_0^\infty\left[\sigma(v)-\hat{\sigma}_m\frac{v_0}{v}\right]\\ &\cdot\frac{\Delta}{E}dE\equiv\sqrt{T_n/T_0}\cdot S_0 \end{aligned}\right\} \quad (2)$$

where, σ_0: Cross section for 2,200m/sec neutrons

v_0: Velocity for 2,200m/sec neutrons

$\hat{\sigma}_m$: Effective cross section for pure Maxwellian

r: Epithermal index that gives a measure of the proportion of epithermal neutrons in the reactor spectrum

g: Westcott's g-factor

T_n: Effective neutron temperature of the Maxwellian component

T_0: 293.59K

S_0: Proportional to the "above-$1/v$" resonance integral; (zero if the cross section follows the $1/v$ law in the epithermal region)

r': $r\sqrt{T_n/T_0}$

Δ: Cut-off function defined by Westcott.

There are two integral methods to obtain the epithermal index described by Westcott, *et al.* The first is to use Cd-covered detectors which have resonance in epithermal region: The relative capture rates between the Cd-covered and bare detectors are proportional to the resonance flux spectrum, except for a small correction for $1/v$ activation just above the Cd cut-off, and the epithermal index is calculated using the equation[3-7]

$$r\sqrt{T_n/T_0}=\frac{G_{th}(1-h\cdot CdR)}{(F\cdot CdR-1)\left(G_r\frac{S_0}{g}\right)+CdR[(1/K)\overline{-W}]}, \quad (3)$$

where,

G_{th}, G_r: Self-shielding factors in the detector foils for thermal and resonance neutrons, respectively

h, F: Transmissions of the Cd-filter for thermal and resonance neutrons, respectively

CdR: Cadmium ratio

$1/K$: Approximate density fraction of the epithermal neutrons transmitted by Cd

W: Correction for resonance activation at the foot of the resonance peak,

Table 1. Description of the detectors.

Reaction	Half life	Cross section[9]	γ-energy
$Au^{197}(n,\gamma)Au^{198}$	2.69days	98.8±0.3barns	0.411MeV
$Mn^{55}(n,\gamma)Mn^{56}$	2.58hours	13.3±0.1barns	0.845MeV
$Lu^{176}(n,\gamma)Lu^{177}$	6.8days	2100±150barns	0.208MeV

in the region below Cd cut-off energy.

This method gives an accurate results, but requires the use of Cd-filters.

The second method is to obtain the resonance flux spectrum from the relative capture rates in resonance and $1/v$ detectors without Cd-filters: If detectors which have $1/v$ characteristic in the thermal neutron energy region are used, and if the thermal neutron spectrum is purely Maxwellian, the epithermal index is obtained independently of neutron temperature. This method has been described in detail by Nisle[4,8]. The Au foil and Mn foil were used here as detectors (Table 1). The capture cross section of Au has a prominent resonance at 4.91 eV, while the first resonance of Mn, which is predominantly scattering, occurs at 337 eV[9]. The ratio of the capture rate of Au and Mn is, therefore, sensitive to the relative intensities of the epithermal and thermal components of the neutron energy spectrum. The ratio of Au-to-Mn capture rates in the reactor spectrum at neutron temperature T_1 is given by

$$\frac{N(\mathrm{Au})\hat{\sigma}(\mathrm{Au})}{N(\mathrm{Mn})\hat{\sigma}(\mathrm{Mn})} = \frac{N(\mathrm{Au})\sigma_0(\mathrm{Au})[g_{\mathrm{Au}}(T_1)+r'S_0(\mathrm{Au})]}{N(\mathrm{Mn})\sigma_0(\mathrm{Mn})[g_{\mathrm{Mn}}(T_1)+r'S_0(\mathrm{Mn})]} \equiv Y(r), \quad (4)$$

where, N: Number of atoms of the element. Similarly, the ratio of the capture rates in a purely thermal spectrum at neutron temperature T_2 is obtained,

$$\frac{N(\mathrm{Au})\sigma_0(\mathrm{Au})g_{\mathrm{Au}}(T_2)}{N(\mathrm{Mn})\sigma_0(\mathrm{Mn})g_{\mathrm{Mn}}(T_2)} \equiv Y(o) \quad (5)$$

If we define R as the ratio of the experimentally determined quantities $Y(r)$ and $Y(o)$, r' can be expressed in terms of R:

$$R \equiv \frac{Y(r)}{Y(o)}$$

Table 2. Irradiation of detector foils.

Detector	Position	Weight	Thickness	Irradiation time
Au	Central thimble	0.865mg	0.01mm	18 minutes
	F2	0.905mg	0.01mm	18 minutes
	Thermal column	0.865mg	0.01mm	18 minutes
Mn	Central thimble	11.0mg	0.05mm	18 minutes
	F2	11.4mg	0.05mm	18 minutes
	Thermal column	11.0mg	0.05mm	30 minutes
Lu	Central thimble	40.3mg	0.1mm	18 minutes
	F2	42.0mg	0.1mm	18 minutes
	Thermal column	38.6mg	0.1mm	18 minutes

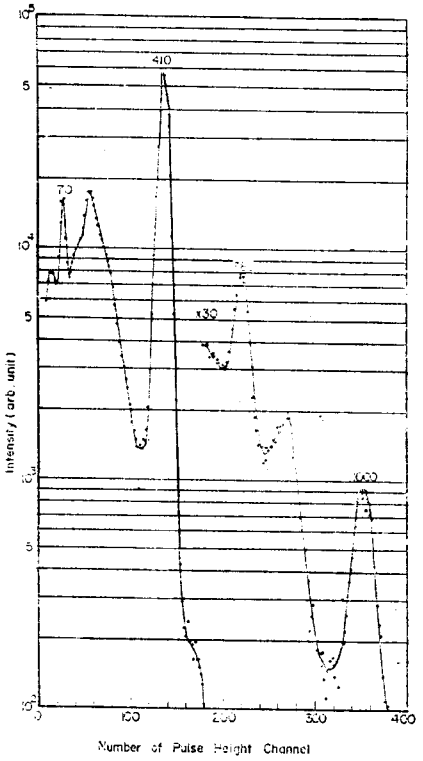

Fig. 2. γ-Ray Spectra of Au Foil.

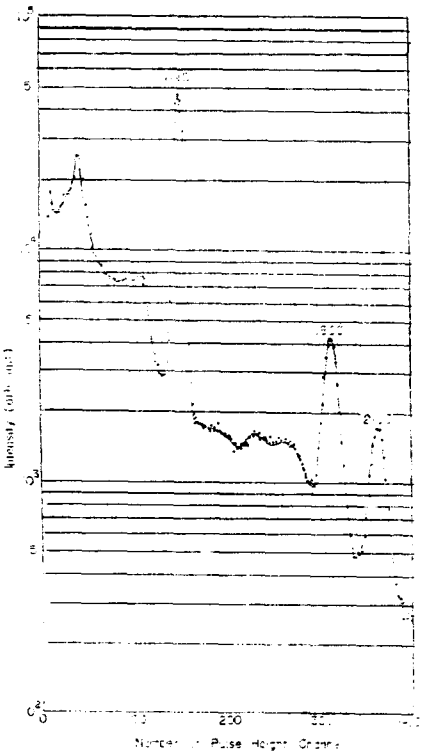

Fig. 3. γ-Ray Spectra of Mn Foil.

$$= \frac{g_{Mn}(T_2)[g_{Au}(T_1)+r'S_0(Au)]}{g_{Au}(T_2)[g_{Mn}(T_1)+r'S_0(Mn)]} \quad (6)$$

$$r' = r\sqrt{T_n/T_0}$$

$$= \frac{R\cdot g_{Mn}(T_1)g_{Au}(T_2)-g_{Au}(T_1)g_{Mn}(T_2)}{S_0(Au)g_{Mn}(T_2)-R\cdot g_{Au}(T_2)(Mn)} \quad (7)$$

In equatiens (4)-(7), g_{Au} and g_{Mn} are the g-factors of the Au and Mn detectors, respectively. The Au detector does not exactly obey the $1/v$ law in the thermal region, but the deviation is slight and can be corrected by g_{Au}-factor. As the g-factor of Mn is very close to unity, we assume that $g_{Mn}=1$.

A scintillation counter was used to measure the relative γ-ray activities of samples. It consisted of 2 in. diameter, 2 in. thick NaI (Tl) crystal. The routine employed in measuring the foil activities was to count the Mn activity 1 day after irradiation and to count that of Au after cooling about 1-2 days (Table 2). The γ-ray energy spectra of the Au and the Mn samples are shown in Fig. 2. and Fig. 3. The energy scale of the spectrometer was calibrated with C_s^{137}(660 KeV) and Co^{60}(1.17 and 1.33 MeV). The stability of the measuring apparatus was verified frequently by counting a reference source of C_s^{137} placed in the same position as the foils.

2. Relative Neutron Temperature

Neutron temperature is the temperature corresponding to the peak of the Maxwellian distribution, and is the quantity that uniquely determines the thermal component of the neutron flux. The method employed here was foil activation method which utilizes the relation between values obtained by $1/v$ and non-$1/v$

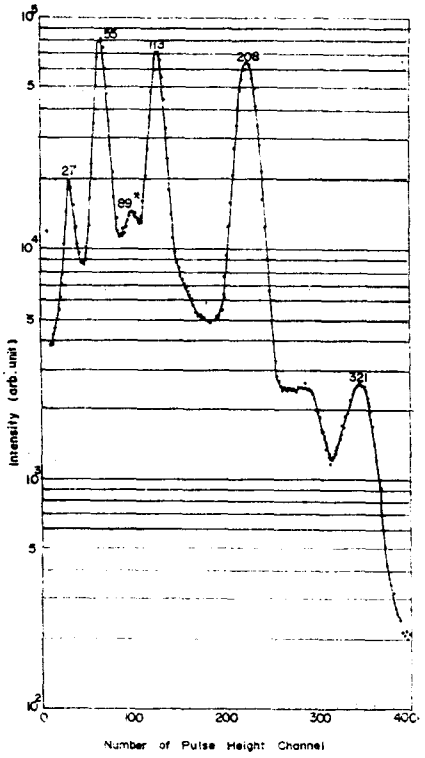

Fig. 4. γ-ray Spectra of Lu Foil.

absorbers. The latter absorber must be non-$1/v$ in the energy range over which the Maxwellian component is effective. In this respect, Lu had the required functional form of absorption cross section.

The ratio $\hat{\sigma}(Lu^{176})/\hat{\sigma}(Mn^{55})$ was measured to obtain the relative neutron temperatures in an unknown spectrum and in a known reference spectrum. The thermal reference spectrum was taken in the region of thermal column which consists of graphits.

As a measure of relative neutron temperature, the activation ratio AR was defined by

$$AR=\frac{\int_0^{E_{cd}}\sigma_{Lu}(E)\phi_x(\vec{r},E)dE}{\int_0^{E_{cd}}\sigma_{1/v}(E)\phi_x(\vec{r},E)dE}\Bigg/\frac{\int_0^{E_{cd}}\sigma_{Lu}(E)\phi_r(E)dE}{\int_0^{E_{cd}}\sigma_{1/v}(E)\phi_r(E)dE,} \quad (8)$$

where,

E_{cd}: Cd cut-off energy

σ_{Lu}, $\sigma_{1/v}$: Microscopic absorption cross section of Lu^{176} and $1/v$ detector, respectively

x, r: Notation of measured point and reference point, respectively.

Also, the activation ratio of the bare Lu to the sub-cadmium $1/v$ detector was defined as

$$AR'=\frac{\{\text{Activity of bare Lu}\}_x}{\{\text{Activity sub-Cd } 1/v\}_x}\Bigg/\frac{\{\text{Activity bare Lu}\}_r}{\{\text{Activity sub-Cd } 1/v\}_r} \quad (9)$$

and this is a measurable quantity.

AR was determined uniquely by the energy dependence of the cross section and the thermal neutron spectrum below the Cd cut-off energy.

Lu^{176} was used for the non-$1/v$ detector and Mn^{55} was used for $1/v$ detector foil. The Lu and Mn measurements were made with thin foils. The capture cross sections of Mn^{55} had very nearly $1/v$ characteristic free from strong temperature dependence. Foils of Lu and Mn were irradiated at the central thimble, F2 position and thermal column. A scintillation counter was used to measure the relative γ-rays of the detector foils. It consisted of a 2 in. diameter, 2 in. thick NaI (Tl) crystal. The multichannel analyzer was used to analyze the photo-peak.

The 6.8 days Lu^{177} activity was counted 3-6 days after irradiation, when shorter lived activities had decayed out. The Mn^{56} activity was counted a day after irradiation. The γ-ray energy spectra of the Lu^{177} sample are shown in Fig. 4.

III. Experimental Results

1. Modified Epithermal Index $r\sqrt{Tn/To}$

The directly observable quantity is the value of R in Eq. (6). In order to obtain the modified epithermal index $r\sqrt{T_n/T_0}$ in Eq. (7), the values of $S_0(Au)$, S_0 (Mn), $g_{Au}(T_1)$, and $g_{Au}(T_2)$ must be known. In analyzing the data from irradiation experiments, following values were adopted from Westcott[1]: $g_{Au}(T_1)=g_{Au}(T_2)=1.0053$, $S_0(Au)=17.3$ and $S_0(Mn)=0.666$. The reaction rate ratio $Y(0)$ for pure thermal specrtum was measured in the thermal column. The results obtained in central thimble and F2 position are given in Table 3.

2. Relative Neutron Temperature

The directly measured value is the activat-

Table 3. Summary of the experimental results.

Position	AR	AR′	$r\sqrt{T_n/T_0}$	T_n/T_0	r
Central thimble	1.7001±0.0938	1.7151±0.0947	0.0140±0.0005	1.6014	0.0111
F2	1.6598±0.0563	1.6652±0.0668	0.0140±0.0005	1.5639	0.0112

ion ratio AR or AR'-the latter being the activati on ratio between bare Lu and sub-cadmium. The values of T_n and r were derived from the measured quanties AR' and $r\sqrt{T_n/T_0}$, using Westcott's representation of the effective cross section.

According to Westcott's expression,

$$AR=\frac{[g(T_n)+r.S(T_n)]^{Lu}_x}{[g(T_n)-\frac{1}{K}r\sqrt{T_n/T_0}]x^{1/v}}\times$$

$$\times\frac{[g(T_n)-\frac{1}{K}r\sqrt{T_n/T_r}^{1/v}}{[g(T_n)+r.S(T_n]^{Lu}_r} \quad (10)$$

where, K is a coefficient relating $r\sqrt{T_n/T_0}$ to the Cd-ratio of perfect $1/v$ detector, and is 2.073 for a 0.5mm thick Cd-filter[1], while x and r denote the positions of the masured and reference points in reactor. Assuming $g(T_n)=1$ for $1/v$ detector, Eq. (10) can be rewritten

$$AR'=C\frac{[g(T_n)+r\sqrt{T_n/T_0}\cdot S(T_n)\sqrt{T_0/T_n}]_x^{Lu}}{[1-\frac{1}{K}r\sqrt{T_n/T_0}]x^{1/v}} \quad (11)$$

$$C=\frac{[1-\frac{1}{K}r\sqrt{T_n/T_0}]r^{1/v}}{[g(T_n)+r\sqrt{T_n/T_0}\cdot S(T_n)\sqrt{T_0/T_n}]_r^{Lu}} \quad (12)$$

Equation (12) has a constant value at the reference position.

Since g and $S(T_n)\sqrt{T_0/T_n}$-which are functions of T_n-are given by Westcott's tabulation, and AR' and $r\sqrt{T_n/T_0}$ were obitained by experiments, T_n could be derived by iterative calculation, and r could be obtained from the experimental value of $r\sqrt{T_n/T_0}$. The values to be odtained in central thimble and F2 position are given in Table 3.

Table 4. Experimental results compared with the calculated values.

Value \ Parameter		T_n [a]	E_n [b]	r
Experimental results	Central thimble	197°C	0.0405 eV	0.0111
	F2	186°C	0.0396 eV	0.0112
Calculated values (GATHER code)		196°C	0.0404 eV[c]	—

a) T_0=293.59 k b) E_n=kT
c) Fuel 200°C, water 23°C

IV. Conclusion

Integral reaction rate measurements have provided detailed information about neutron spectral parameters in the reactor core. An analysis based on Westcott's spectrum model gave a set of spectrum parameters, T_n and $r\sqrt{T_n/T_0}$, which are sufficient to determine the reaction rates required for usual reactor cores. If it is assumed that the neutron temperature of the thermal column is 20.44°C and that the spectrum is pure Maxwellian distribution in the thermal column, the relative neutron temperature for the central thimble and the F2 position at the power 250 KW of the reactor are 197°C and 186°C, respectively. These indicate that the neutron energies corresponding to the peak of Maxwellian distribution are 0.0405 eV and 0.0396 eV, respectively. The epithermal index which represents the relative strenth of epithermal component is slightly defferent from pure Maxwellian distribution.

Analyses of experimental results on spectral parameters measured by foil activation brought out the conclusion that thermal neutron spectrum in the TRIGA Mark II reactor core was the hardening compared with the pure Maxwellian distribution.

These measured values gave the result in good agreement with the theoretical result[10,11] calculated by General Atomic (Table 4).

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