THE EXPERIMENTAL DETERMINATION
OF FAST FISSION EFFECT IN GRAPHITE
MODERATED, WATER COOLED, SLIGHTLY
ENRICHED URANIUM LATTICES

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IN GRAPHITE MODERATED, WATER COOLED, SLIGHTLY ENRICHED URANIUM LATTICES

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I. INTRODUCTION

Experimental measurements have been made on several graphite moderated, water cooled, slightly enriched uranium lattices in the Physical Constants Test Reactor (PCTR) in which data was obtained for the determination of the fast fission effect. The term, "fast fission," is generally applied to fissions that occur in ^{238}U , since only fast neutrons can cause fission in this isotope. Fast fission can also occur in ^{235}U , but most of the fissions in this isotope are caused by neutrons of thermal energy.

The techniques and results of measuring the ratio of the number of fissions in ^{238}U to the number of fissions in ^{235}U , δ^{28} , within a given fuel element, are reported for four different lattices. The quantity, δ^{28} , is directly related to the fast fission factor.

II. SUMMARY

The fast fission factor, ϵ^{28} , cannot be measured directly but is related to the measured quantity, δ^{28} , by an equation of the form, $\epsilon^{28} = 1 + C\delta^{28}$, where C is a constant involving nuclear properties of ^{235}U and ^{238}U . Hence, it is now customary to report measured values of δ^{28} , which can be compared directly with calculations, rather than inferred values for ϵ^{28} . The measurement of the standard value of δ^{28} was obtained from the ^{140}La 1.60 Mev gamma ray activation technique developed by J. R. Wolberg, et al,⁽¹⁾ which eliminates the need for a normalizing fission chamber experiment. This standard measurement was then used to normalize the δ^{28} measurements in the other three lattices.

The standard value of δ^{28} was obtained in the uranium fuel (0.947% enriched in ^{235}U) used for the Bismuth-KVE Supercell PCTR Experiments. The function $F(t)$ defined as the ratio, at time t after irradiation, of counts originating from ^{238}U fission products to counts from ^{235}U fission products in a foil of the same

composition as the fuel, was determined for each of the four lattices. The function $P(t)$ is defined as the gamma ray count rate (from 510 to 675 Kev) at time t per ^{235}U fission, divided by the gamma ray count rate (from 510 to 675 Kev) at time t per ^{238}U fission. This function was determined from the standard value of δ^{28} and the function $F(t)$, since $\delta^{28} = P(t) F(t)$. It has been shown that the effect of the neutron energy spectrum on the function $P(t)$ is negligible for slightly enriched uranium in well moderated systems.⁽¹⁾ Thus, the function $P(t)$, once determined, was used for all lattices. Results of these measurements are presented in Table I.

TABLE I
Results of Fast Fission Effect Measurements

Lattice Description	Uranium Fuel Enrichment	Coolant Channel Condition	δ^{28}	ϵ^{28}
Bismuth-KVE ⁽⁵⁾ (2-3 Supercell)	0.947%	Wet	$0.081 \pm .002$	1.045
Uranium-Lithium ⁽⁶⁾ (3-1 Supercell)	2.1%	Wet	$0.082 \pm .004$	1.045
Uranium-Thoria ⁽⁷⁾ (3-1 Supercell)	1.25%	Wet Dry	$0.064 \pm .003$ $0.074 \pm .003$	1.035 1.041
Tubular Element ^(8,9) with Integral Target	2.1%	Wet	$0.053 \pm .003$	1.029

III. EXPERIMENTAL TECHNIQUES

A. The Method for Determining the Fast Fission Factor

The fast fission factor, ϵ^{28} , is the term used to include the contribution of neutrons produced by fast fissions of ^{238}U in the calculation of the infinite medium neutron multiplication factor, k_{∞} . The fast fission factor cannot be measured directly, but is related to a measured quantity, δ^{28} , by the equation,

$$\epsilon^{28} = 1 + \left(\frac{\nu^{28} - 1 - \alpha^{28}}{\nu^{25}} \right) \delta^{28} \quad (1)$$

where ν^{28} and ν^{25} are equal to the average number of neutrons emitted per fission of ^{238}U and ^{235}U , respectively, and

$$\alpha^{28} = \frac{\int_{E_t}^{\infty} \phi(E) \sigma_c^{28}(E) dE}{\int_{E_t}^{\infty} \phi(E) \sigma_f^{28}(E) dE} \quad (2)$$

The fission neutron energy spectrum of ^{235}U was used for $\phi(E)$, where $\sigma_c^{28}(E)$ and $\sigma_f^{28}(E)$ are the energy dependent cross sections for radiative capture and fission, respectively. The ^{238}U fission threshold energy, E_t , of 0.498 Mev was used in equation (2).

The quantities, ν^{28} and $\alpha_{\text{fast}}^{28}$, were calculated using computer code HRG.⁽²⁾ The quantity, ν^{25} , was calculated from the measured ^{235}U fission cadmium ratio in the fuel (CdR^{25}) and ν^{25} values from computer codes THERMOS⁽³⁾ and HRG⁽²⁾ by the equation,

$$\nu^{25} = \frac{\nu_{\text{THERMOS}}^{25} (\text{CdR}^{25} - 1) + \nu_{\text{HRG}}^{25}}{\text{CdR}^{25}} \quad (3)$$

The THERMOS calculation includes thermal neutron energies from 0 to 0.683 ev, and the HRG calculation includes all epi-thermal neutron energies from 0.683 ev to 10 Mev. Calculated values used to relate ϵ to δ^{28} are:

$$v^{25} = 2.4317$$

$$v^{28} = 2.7373$$

$$\alpha^{28} = 0.3928$$

The substitution of these numerical values into equation (1) gives,

$$\epsilon^{28} = 1 + 0.5529 \delta^{28} \quad (4)$$

Equation (4) is used to determine ϵ^{28} from the measured quantity, δ^{28} .

B. Measurement of the Standard Value of δ^{28}

The quantity, δ^{28} , is defined as the ratio of the number of fissions in ^{238}U to the number of fissions in ^{235}U within a given fuel element. The standard value of δ^{28} was determined by counting the 1.6 Mev gamma ray activity in two uranium foils of different enrichments after both had been irradiated simultaneously in the same fuel element. The ^{140}La gamma ray activity, shown in Figure 1, is fairly easily isolated and counted.

Over 97% of the ^{140}La produced by fission events is a daughter of ^{140}Ba in the decay chain, $^{140}\text{Xe} \text{ 16s} \rightarrow ^{140}\text{Cs} \text{ 66s} \rightarrow ^{140}\text{Ba} \text{ 12.8d} \rightarrow ^{140}\text{La} \text{ 40.2h} \rightarrow ^{140}\text{Ce} \text{ (stable)}$. The chosen ^{140}La gamma ray peak is at 1.595 Mev and was measured by counting between 1.505 and 1.700 Mev as shown in Figure 1. The ^{140}La activity reaches a maximum 136 hours after irradiation and assumes the 12.8 day half-life of ^{140}Ba at about 250 hours after irradiation. The 1.6 Mev peak for each foil was counted several times between 150 and 500 hours after irradiation. The specific activities of the two foils were then corrected for background and the natural activity of ^{238}U and ^{235}U . The results of these measurements are presented in Table II.

FIGURE 1
High Energy Gamma Ray Spectra from Uranium Foils

TABLE II

^{140}La Specific Activity Measurements

Depleted Uranium Foil (0.036% ^{235}U)		0.947% Enriched Uranium Fuel Foil	
Time After Irradiation (hrs)	^{140}La Specific Activity (cpm/gm)	Time After Irradiation (hrs)	^{140}La Specific Activity (cpm/gm)
174.3	72.99	161.0	975.6
340.1	46.54	208.9	883.4
366.3	42.35	236.4	818.7
486.5	30.15	328.3	654.1
500.4	27.35	376.2	576.1
		472.5	457.8

The 12.8 day half-life was fitted to the data by least squares fit (shown in Figure 2) to obtain relative values of the ^{140}La activity extrapolated back to zero elapsed time after irradiation.

The experimental standard value of δ^{28} was obtained from the equation,

$$\delta^{28} = \frac{\beta^{25}}{\beta^{28}} \frac{a\Gamma - S}{1 - a\Gamma}, \quad (5)$$

where β^{25} and β^{28} are the total ^{140}La fission yields from ^{235}U and ^{238}U , respectively. The quantity, "a," is a correction for the difference in atom concentration of ^{238}U between the depleted and fuel foil materials:

$$a = \frac{N_F^{28}}{N_D^{28}} \quad (6)$$

The quantity, S, is a correction for the differences in atom concentrations of both ^{238}U and ^{235}U between the two foils:

$$S = \frac{N_D^{25} N_F^{28}}{N_D^{28} N_F^{25}} \quad (7)$$

FIGURE 2
Specific Activity of 1.6 MeV Gamma Rays from La-140 in
Uranium Foils Irradiated in the Fuel

The quantity, Γ , is the ratio of the ^{140}La specific activities of the depleted uranium foil to the uranium fuel foil. Recommended values⁽⁴⁾ for the ^{140}La fission yields are:

$$\beta^{25} = 6.30\% \quad (\text{Thermal neutron spectrum})$$

$$\beta^{28} = 5.73\% \quad (\text{Fission neutron spectrum})$$

Although the above description implies that the standard value of δ^{28} is quite accurate, the given result has an uncertainty of at least $\pm 2.5\%$. Most of this error arises in the uncertainty in the values of ^{140}La fission yields which are known to no better than $\pm 2\%$. Counting statistics errors were less than 2%.

C. Consideration of the Function F(t)

The Physical Constants Test Reactor (PCTR) is a low power, bare, graphite moderated reactor in which one face of the reactor is moveable to allow access to the test core (see Figure 3). The thermal neutron flux level in the test core is limited to $\sim 10^8$ neutrons/cm²sec. Maximum irradiation times are limited to approximately two hours due to increasing personnel radiation exposure between faces of the reactor after irradiation. The neutron activation of the ^{140}La gamma ray from fission products at the maximum power level for two hours in the PCTR is sufficiently low so that extremely long count times (from 200 to 300 minutes per count) are required. It is, thus, necessary to measure the fission product activity integral in a given energy interval in order to obtain reasonable statistical results with short count times (approximately two minutes per count). This measurement is called the function F(t). As shown in Reference 1, it is only necessary to measure the absolute value of δ^{28} in one or two cases; then other values of δ^{28} for similar lattices can be obtained by measuring F(t).

The function $F(t)$ is the ratio, at time t after irradiation, of counts originating from ^{238}U fission products to counts from ^{235}U fission products in a foil of the same composition as the fuel. The specific gamma ray activities of two fission foils irradiated simultaneously in the same fuel element are used to measure $F(t)$. One foil was composed of uranium depleted to 0.036% ^{235}U ; the other foil was 0.947% enriched uranium to match the enrichment of the fuel element in which the foils were irradiated. The gamma ray activities were counted between 510 kev and 675 kev in order to exclude the ^{239}Np pile-up peaks at lower energies. The upper energy limit was chosen due to counting procedure considerations. Experimental values for $F(t)$ were obtained from the equation

$$F(t) = \frac{(1-E^{25})A_o^{28}(t)}{A_F(t) - (1-E^{25})A_o^{28}(t)} \quad (8)$$

where E^{25} is the atom percent enrichment of the fuel foil material. The quantity $A_F(t)$ is the specific activity of the fuel foil at time t after irradiation. The quantity $A_o^{28}(t)$ is the specific activity of a pure ^{238}U foil at time t after irradiation, determined by the equation

$$A_o^{28}(t) = \frac{A_F(t) - A_D(t)}{E^{25} - D^{25}} E^{25} \quad (9)$$

where $A_D(t)$ is the specific activity of the depleted uranium foil, at time t after irradiation, and D^{25} is the ^{235}U content of the depleted foil in atom percent.

The fuel foil and the depleted foil were counted at comparable times after irradiation and values for $F(t)$ were obtained from equation (8). Several fission products of widely differing half-lives and intensities produce gamma rays in the specified interval of energies between 510 and

FIGURE 3: Schematic View of PCTR

675 Kev. Measurements of the activity of more than one of these fission products is not truly representative of the relative fission rates of ^{238}U and ^{235}U because of the differing yields of each fission product in the two foils.

D. Determination of $P(t)$

In order to allow simple counting techniques, such as that utilized in the measurement of $F(t)$, in the determination of δ^{28} , the function $P(t)$ is introduced such that

$$\delta^{28} = P(t) F(t) \quad . \quad (10)$$

The function $P(t)$ is defined as the count rate in the energy interval (510 - 675 Kev) at time t per ^{235}U fission, divided by the count rate in the energy interval (510 - 675 Kev) at time t per ^{238}U fission. This function is obtained from the measurement of the standard value of δ^{28} by 1.6 Mev ^{140}La counting, and from the usual measurement of $F(t)$ on the same two foils. By rearranging equation (10), we get

$$P(t) = \frac{\delta^{28}}{F(t)} \quad . \quad (11)$$

This function was obtained from equation (11) for a time interval between 22 and 45 hours after irradiation and is shown in Figure 4. It has been shown that the effect of the neutron energy spectrum on the function $P(t)$ is negligible for slightly enriched uranium in well moderated systems.⁽¹⁾ Thus, the function, once determined, was used for all lattices to determine δ^{28} from the measurement of $F(t)$ by use of equation (10).

FIGURE 4
The Function $P(t)$

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