LOS ALAMOS SCIENTIFIC LABORATORY

OF THE UNIVERSITY OF CALIFORNIA ○ LOS ALAMOS NEW MEXICO

REVISED NEUTRON FLUX, SPECTRUM, AND TISSUE DOSE MEASUREMENTS AT THE GODIVA II CRITICAL ASSEMBLY

(Addendum to Los Alamos Report LA-2310)

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Office of Technical Services
U. S. Department of Commerce
Washington 25, D. C.

LA-2432
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REPORT WRITTEN: April 1960

REPORT DISTRIBUTED: September 19, 1960

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by

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Contract W-7405-ENG. 36 with the U. S. Atomic Energy Commission

ABSTRACT

A revision of the fission foil system as originally proposed by Hurst and his co-workers is discussed. These revisions include the most recent fission cross section data averaged over fission spectra to obtain "best fit" values. These data are presented to provide calibration parameters for evaluation of neutron flux, spectra, and tissue dose by the Biomedical Research Group of this Laboratory.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the critical assembly group (N-2) and to Groups P-2, P-4, and H-4 for their assistance in these experiments.

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CHAPTER 1

INTRODUCTION

Since the original presentation of the fission foil system for measurement of neutron tissue dose by Hurst and his co-workers (1), several disagreements have been noted by investigators in this field (2,3). These disagreements involve the evaluation of flux and spectrum before computation of tissue dose. Although this method was designed primarily for evaluation of neutron tissue dose, it has been used extensively in the field for neutron flux determinations. Therefore, it appeared necessary to investigate a more exact approach to the foil technique in an attempt to draw a better correlation between flux, spectrum, and tissue dose. The original method adopted by this group followed that of Hurst and his co-workers (1) and is described in detail in Ref. 3.

CHAPTER 2

MATERIALS AND METHODS

According to the original calibration method adopted by the Oak Ridge and Los Alamos groups (1), it was thought that a single Pu^{239} foil sufficed for the calibration of the fission gamma counting system for the evaluation of fast neutron flux from the Pu^{239}, Np^{237}, and U^{238} foil activations. This procedure was adopted in view of the observation that the fast fission gamma decay curves of Pu^{239}, Np^{237}, and U^{238} were the same. In using this procedure, however, a discrepancy of approximately 50 per cent was always observed in the Np^{237} flux evaluation from the Godiva I and II critical assemblies (3,4), when compared with the film track measurements of Frye, Gammel, and Rosen (5). This discrepancy was believed to be due to an error in the Np^{237} fission cross section (6). In 1958, however, it was noted that the Pu^{239}, Np^{237}, and U^{238} fission gamma decay curves were not the same and that individual calibrations for each foil had to be achieved. The most recent calibration procedure is given in Ref. 7.

The Godiva spectrum as evaluated by Frye, Gammel, and Rosen (5) is shown in Fig. 1 and Table 1. An undegraded fission spectrum is also shown in Fig. 1 for comparison. The average energies of the two spectra are approximately 1.4 and 1.8 Mev, respectively.

The method of Hurst and his co-workers (7) was followed with modifications. The modifications included an averaging of the available fission cross sections for Pu^{239}, Np^{237}, and U^{238} (8,9) over the Godiva spectrum. These data are shown in Table 2. For comparison, the cross sections averaged over an undegraded U^{235} fission spectrum are also shown.

Calibration of the fission gamma counting system (3) for neutron flux evaluation from fission foil activity was achieved by irradiating Pu^{239}, Np^{237}, and U^{238} equivalent foils (7) with thermal neutrons. These equivalent foils were fabricated from calculated masses of Pu^{239} and U^{235} (7). The foil masses and their equivalence to a Pu^{239} foil are shown in Table 3. The fissionable material was plated on a 10 mil thick nickel backing. The foil plus nickel backing were canned in a 5 mil wall copper dish. The outer dimensions of the calibrating foils were approximately 3/4 in. Each foil was irradiated with approximately 1×10^{11} n_{th}/cm^2. To evaluate the flux depression and self-shielding of the foil

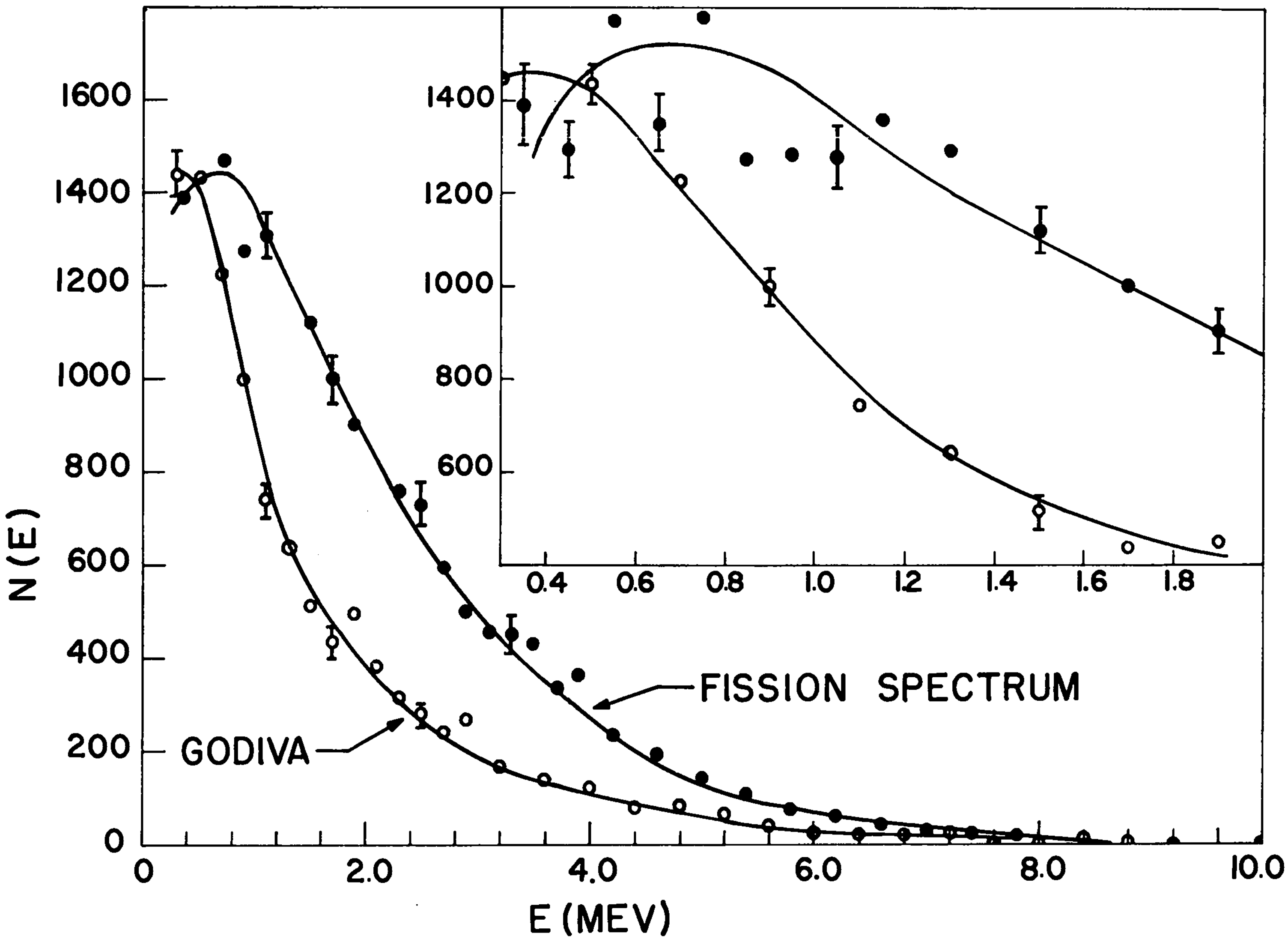

Fig. 1. Godiva and undegraded fission spectra (5).

TABLE 1. LEAKAGE SPECTRUM FROM THE GODIVA I CRITICAL ASSEMBLY (5)

Neutron Energy Interval, Mev	Observed Number of Neutrons	Statistical Uncertainty, per cent
0.2 - 0.4	1442	4
0.4 - 0.6	1436	3
0.6 - 0.8	1224	4
0.8 - 1.0	998	4
1.0 - 1.2	741	5
1.2 - 1.4	639	6
1.4 - 1.6	514	7
1.6 - 1.8	436	8
1.8 - 2.0	448	8
2.0 - 2.2	386	7
2.2 - 2.4	317	8
2.4 - 2.6	281	9
2.6 - 2.8	244	9
2.8 - 3.0	271	9
3.0 - 3.4	169	9
3.4 - 3.8	141	8
3.8 - 4.2	124	9
4.2 - 4.6	81	11
4.6 - 5.0	86	11
5.0 - 5.4	67	14
5.4 - 5.8	43	16
5.8 - 6.2	26	24
6.2 - 6.6	22	27
6.6 - 7.0	23	27
7.0 - 7.4	28	25
7.4 - 7.8	4	40
7.8 - 8.2	4	70
8.2 - 8.6	13	40
8.6 - 9.0	5	90

TABLE 2. EFFECTIVE CROSS SECTIONS IN B^{10} SPHERES*
WEIGHTED FOR DIFFERENT FISSION SPECTRA

Foil Type	$(\sigma_{eff})_{weighted}$, barns	
	Godiva Spectrum	Fission Spectrum
Pu^{239}	1.78	1.80
Np^{237}	1.71	1.66
U^{238}	0.55	0.53

*For a 2 cm B^{10} sphere of 1.1 g/cm^3 density.

TABLE 3. FOIL MASS DATA FOR CALIBRATION OF THE SINGLE TUBE FISSION GAMMA COUNTER

Foil No.	Mass Pu^{239}, mg	Mass U^{235}, mg	Ratio $\frac{Pu^{239}}{U^{235}}$	Equivalent Mass of Pu^{239}, mg
P-1	9.88	--	--	9.88
N-1	5.29	7.13	0.742	10.6
U-1	8.82	3.96	2.23	11.8

components, two 1/2 mil thick, 1/2 in. diameter, Au^{197} foils were pasted to the copper dish with a minute amount of Vaseline. After irradiation, all foils were washed with alcohol to remove the Vaseline. The induced gamma activity per unit mass in the 1/2 mil Au^{197} foils placed with the fission foil was compared with a similar foil irradiated with the same flux but with no fission foil present. The latter showed an activity per unit mass that was 7 per cent higher. Hence, a flux depression plus self-shielding factor of 1.07 was used. A blank foil containing the copper dish plus the 10 mil thick nickel backing, but with no fissionable material, was used to subtract the induced activity due to nonfissionable material. Figure 2 shows the decay curves obtained for the same irradiated thermal flux. The 3 hour point was arbitrarily chosen as our time of comparison. Figure 3 shows each decay curve normalized to the 3 hour activity, and Table 4 shows the calibration factors obtained. Measurements with S^{32} foils for evaluation of neutron flux greater than 2.5 Mev and bare and cadmium-clad Au^{197} foils for evaluation of the thermal flux were also accomplished. The calibration data are described in detail in Ref. 3.

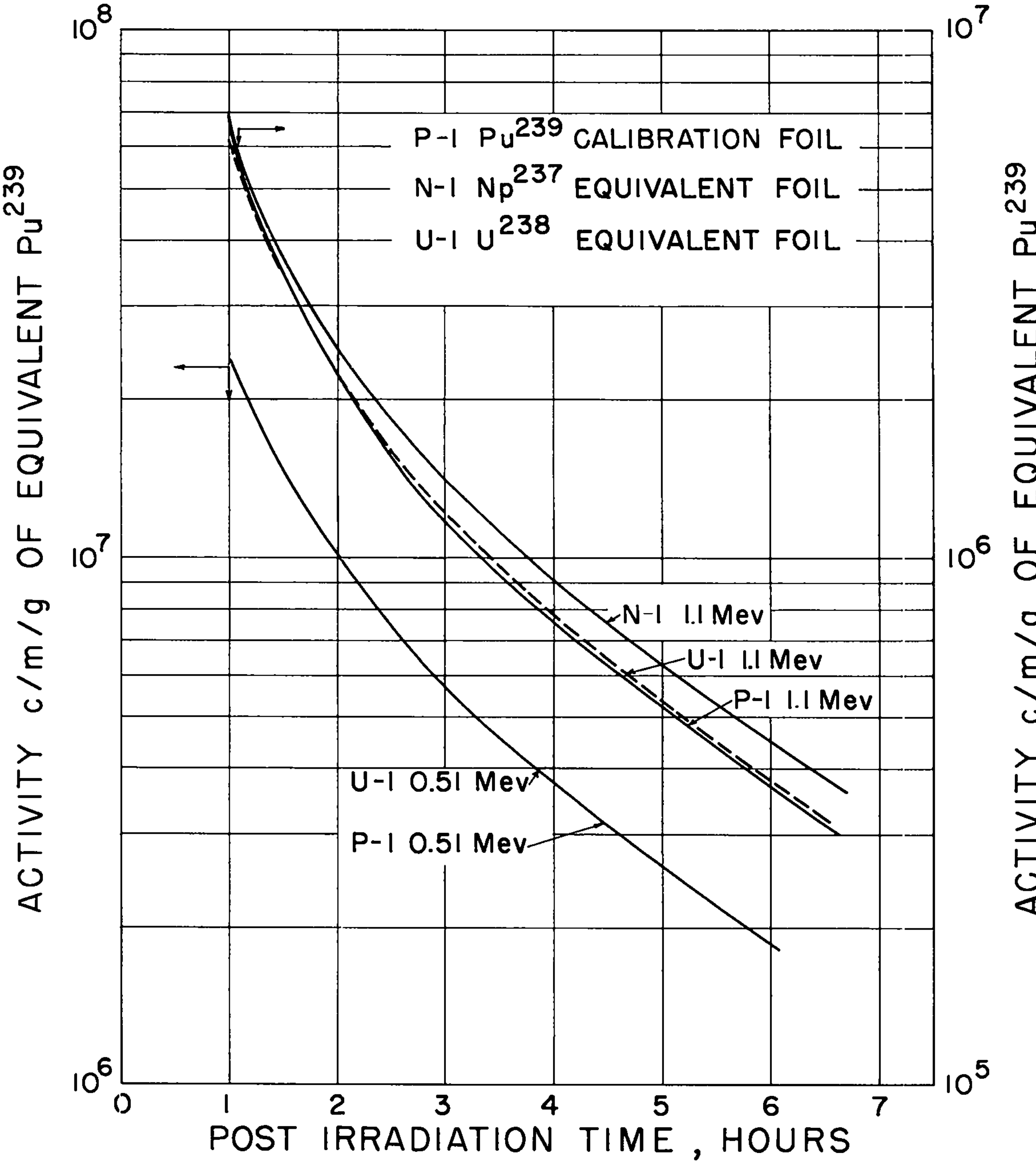

Fig. 2. Calibration decay curves of Pu^{239}, Np^{237}, and U^{238} for the single tube fission gamma counter.

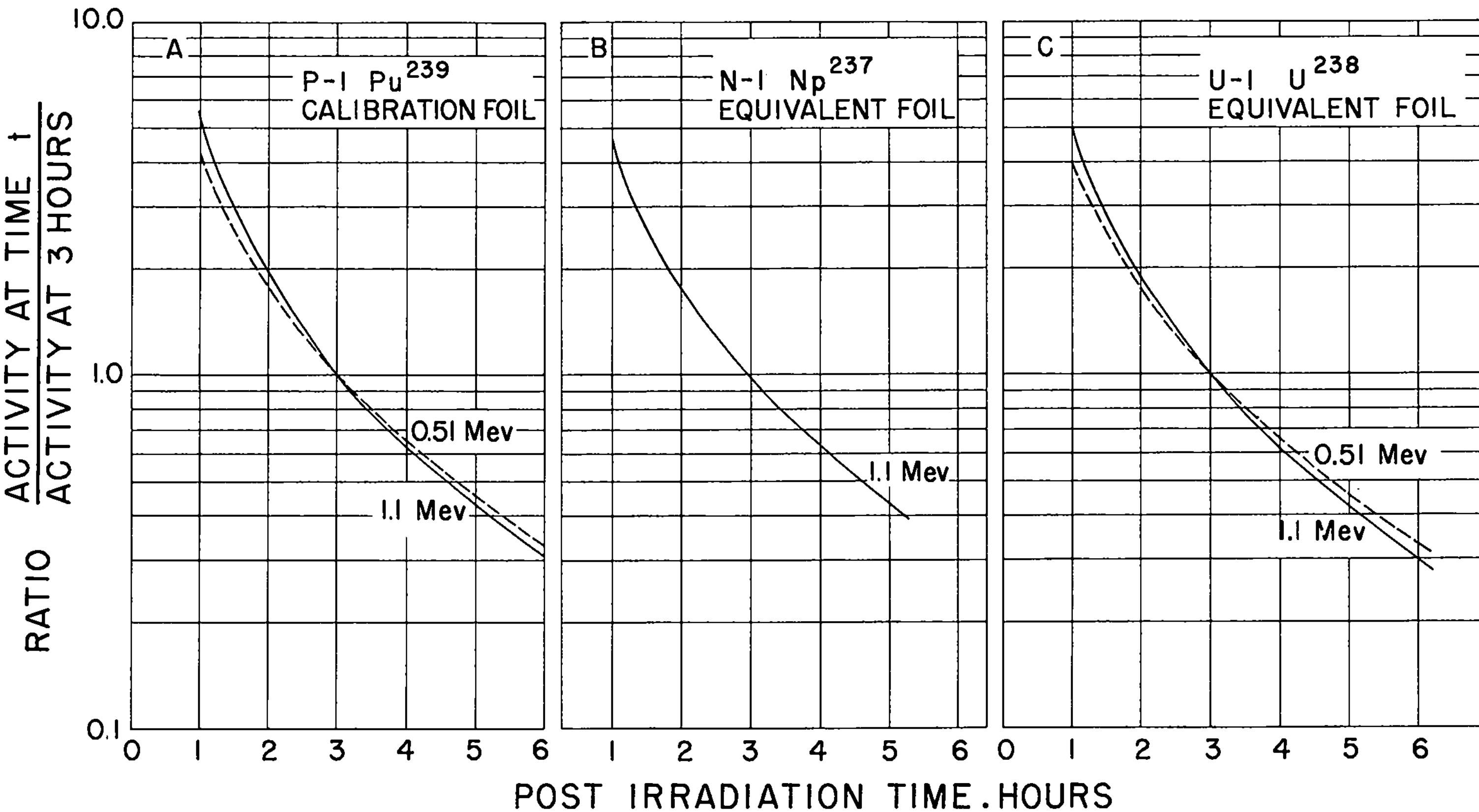

Fig. 3. Calibration decay curves normalized to 3 hours post irradiation time.

TABLE 4. REVISED CALIBRATION CONSTANTS FOR THE SINGLE TUBE FISSION GAMMA COUNTER FOR Pu^{239}, Np^{237}, AND U^{238}

	Counter Calibration Constant K*, n/cm^2/c/m/g		
	K_{Pu}	K_{Np}	K_U
0.51 Mev counter energy bias (natural counter background 100 c/m)	6.59×10^6	---	2.13×10^7
1.1 Mev counter energy bias (natural counter background 36 c/m)	3.15×10^7	2.66×10^7	9.63×10^7

*For 1/2 in. diameter foils used in the Godiva experiments. The difference between a 1/2 in. foil and 3/4 in. foil on a 1-1/2 x 1-3/4 in. diameter crystal was found to be 1.054.

CHAPTER 3

RESULTS

3.1 Neutron Flux and Spectrum Measurements at the Godiva II Critical Assembly

The neutron flux versus distance data are shown in Table 5. In Table 6 the flux values between 35 and 200 cm are averaged into energy intervals and compared with the spectral measurement of Frye, Gammel, and Rosen (5). The agreement appears to be good.

3.2 Evaluation of Neutron Tissue Dose

The first collision fast neutron tissue dose was evaluated from the equation

$$D = \left[1.28\ (F_{Pu} - F_{Np}) + 2.46\ (F_{Np} - F_{U}) + 2.97\ (F_{U} - F_{S}) + 3.84\ (F_{S})\right] \times 10^{-9} \text{ rads} \qquad \text{(Eq. 1)}$$

where F is the integral neutron flux measured by the threshold detectors Pu, Np, U, and S. The coefficients before the

TABLE 5. NEUTRON FLUX VERSUS DISTANCE RELATIONS FOR THE GODIVA II CRITICAL ASSEMBLY

Distance from Center (horizontal midplane), cm	Neutron Flux*, $n/cm^2 \times 10^9/°C$ of burst**			
	$E_n > 0.004$ Mev Pu^{239}	$E_n > 0.75$ Mev Np^{237}	$E_n > 1.5$ Mev U^{238}	$E_n > 2.5$ Mev S^{32}
15.8	101	59.0	38.2	18.4
17.0	87.8	48.2	30.6	17.0
35.0	16.9	10.3	6.53	3.58
50.0	8.89	5.38	3.38	1.69
65.0	4.94	2.99	1.88	0.924
75.0	3.92	2.30	1.40	0.671
100	2.32	1.25	0.788	0.434
125	1.49	0.900	0.528	0.276
150	1.05	0.548	0.349	0.181
200	0.633	0.313	0.190	0.0847
250	0.595	0.293	0.161	0.0500

*The foils of Pu^{239}, Np^{237}, and U^{238} were placed in B^{10} spheres. The S^{32} foil was placed in a separate container near the B^{10} sphere.

**Temperature rise corresponds to peak temperature rise.

TABLE 6. COMPARATIVE NEUTRON FLUX AND TISSUE DOSE SPECTRA AT THE GODIVA II CRITICAL ASSEMBLY

Energy Interval, Mev	Per Cent Neutrons in Energy Interval		Per Cent Dose in Energy Interval	
	Threshold* Detectors	Film Track Data (5)	Threshold* Detectors	Film Track Data (5)
0.004 - 0.75	43	41	24	23
0.75 - 1.5	22	25	24	26
1.5 - 2.5	17	16	22	21
>2.5	18	18	30	30

*Average of data in Table 5 from 35 to 200 cm.

flux parentheses represent first collision tissue dose values. Combining like terms in Eq. (1), one obtains

$$D = \left[1.28\ F_{Pu} + 1.18\ F_{Np} + 0.51\ F_U + 0.87\ F_S\right] \times 10^{-9} \text{ rads} \qquad \text{(Eq. 2)}$$

The first collision dose coefficients with the energy intervals over which they were averaged are shown in Table 7. Values are also shown for an undegraded fission spectrum. The computed tissue dose values from the fission foil data are shown in Table 8. The dose spectrum with comparisons to values computed from the film track data of Frye, Gammel, and Rosen (5) are shown in Table 6.

3.3 Comparative Neutron Dosimetry

Neutron tissue dose measurements were also made with the Hurst proportional counter and beryllium-shelled tissue-equivalent and graphite-CO_2 ionization chambers. These measurements are described in detail in Ref. 3. The results normalized to per unit fission are shown in Table 9. The best fit for these data between 35 and 200 cm is

$$\frac{\text{tissue rad}}{\text{fission}} = 2.00 \times 10^{-10}\ d^{-1.92} \qquad \text{(Eq. 3)}$$

where d = distance in cm from the center of the assembly (in horizontal midplane)

TABLE 7. FIRST COLLISION DOSE COEFFICIENTS AVERAGED OVER DIFFERENT FISSION SPECTRA

Energy Interval, Mev	Tissue rad/n/cm^2 x 10^{-9}	
	Godiva Spectrum	Fission Spectrum
0.004 - 0.75	1.28	1.31
0.75 - 1.5	2.46	2.49
1.5 - 2.5	2.97	2.98
>2.5	3.84	3.78

TABLE 8. NEUTRON TISSUE DOSE VERSUS DISTANCE RELATIONS FOR THE GODIVA II CRITICAL ASSEMBLY

Distance from Center (horizontal midplane), cm	Tissue rad/°C of burst*
15.8	234
17.0	199
35.0	40.2
50.0	20.9
65.0	11.6
75.0	9.02
100	5.23
125	3.48
150	2.32
200	1.35
250	1.23

*Temperature rise corresponds to peak temperature rise. The peak temperature rise corresponding to 10^{16} fissions is 55°C (10).

TABLE 9. COMPARATIVE NEUTRON DOSIMETRY AT THE GODIVA II CRITICAL ASSEMBLY

Distance (horizontal midplane), cm	Tissue Dose*, rad/fission			
	Neutron			Gamma
	Threshold Detectors	Hurst Proportional Counter	Tissue-Equivalent Ionization Chamber	Graphite-CO_2 Ionization Chamber
15.8	1.29×10^{-12}			
17.0	1.09×10^{-12}			
35.0	2.21×10^{-13}			
50.0	1.15×10^{-13}	1.20×10^{-13}	1.16×10^{-13}	1.05×10^{-14}
65.0	6.38×10^{-14}			
75.0	4.96×10^{-14}			
100	2.88×10^{-14}	3.17×10^{-14}	2.95×10^{-14}	2.57×10^{-15}
125	1.91×10^{-14}			
150	1.28×10^{-14}	1.54×10^{-14}	1.35×10^{-14}	1.50×10^{-15}
200	7.43×10^{-15}	9.13×10^{-15}		
250	6.78×10^{-15}			

*For a tissue composition of 10 per cent hydrogen, 12 per cent carbon, 4 per cent nitrogen, and 73 per cent oxygen. The remaining 1 per cent of trace elements was neglected in the evaluations.

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