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RESPONSE OF THE OAK RIDGE CRITICALITY FISSION FOIL MONITOR

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Bob Wayland

July 17, 1961

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ABSTRACT

The Oak Ridge criticality fission foil monitor was tested for response to photofission and the possibility of photofissions "masking" the neutron response. For radiation of energy less than 5 Mev, the response to neutrons will not be masked by the gammas. For energies greater than 5 Mev, the response to neutrons may be "masked" by photons if the abundance of photons is 10^3 as great as the neutrons.

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A. Introduction

G.S. Hurst et al, have developed a system of dosimetry to determine the radiation dosage received by persons involved in accidental criticality excursions.[1] Included in this system is a threshold detector developed by Hurst et al.[2] and Reinhardt and Davis[3] for measuring the neutron spectra. This threshold detector employs Pu^{239}, Np^{237}, and U^{238} foils enclosed in a boron shield, from which the fast neutron flux can be determined. However, there is also a definite probability for photofission that might mask the induced activity from the neutron dose (if the ratio gamma flux to neutron flux is, say, 10^3).

B. Expected Response of Fission Foils

In most criticality accidents the neutron and gamma-ray spectra are fission spectra. The general shape of the neutron spectra follows Watt's empirical expression for the U^{235} neutron spectrum:[4]

$$N(E) \propto \exp\left[\frac{-E}{0.965}\right](\sinh \sqrt{2.29}\ E).$$

Figure 1 shows an example of the resulting spectrum.

Hyde[6] and Allen and Hurkel[7] have analyzed the neutron spectra of fission neutrons from U^{235}, U^{233}, and Pu^{239} and found them to be very similar. It appears that Np^{237} is another member of this group, and for the purpose of calculation the spectra may be assumed equivalent. It is interesting to note that the Leachman expression,[8]

$$N(E) \propto \sqrt{E}\ e^{-E/(1.29)},$$

when analyzed by Terrell[9] for the spectra of U^{235}, U^{233}, and Pu^{239} gives a good fit to the experimental data when the nuclear temperature constant is set equal to 1.290 Mev, 1.307 Mev, and 1.333 Mev, respectively.

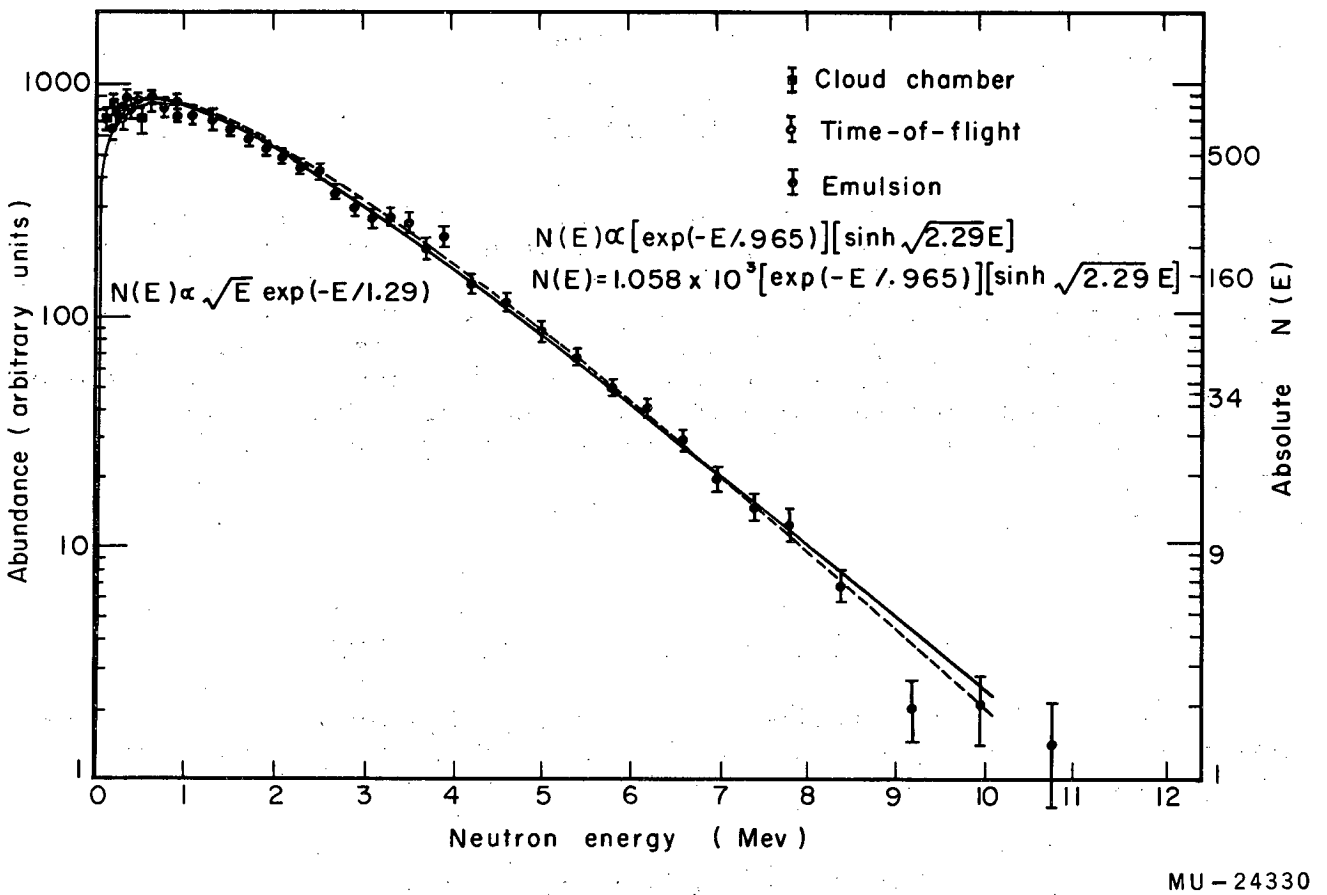

Fig. 1. Comparison of semi-empirical expression of the energy spectrum of fission neutrons with experimental measurements at Los Alamos on neutrons from thermal fission of U^{235}.

Table I. Cross sections of U^{238}, Np^{237}, and Pu^{239} at various energy ranges

ΔE (Mev)	Fission (barns)			Photofission (barns)		
	$\Delta_{U^{238}}$	$\sigma_{Np^{237}}$	$\sigma_{Pu^{239}}$	$\sigma_{U^{238}}$	$\sigma_{Np^{237}}$	$\sigma_{Pu^{239}}$
0.01→0.04						0[a]
0.04→0.07						0[a]
0.07→0.1						0.95[a]
0.1 →0.3						1.13[a]
0.3 →0.7		.5				1.3[a]
0.7 →1.1		1.45				1.6[a]
1.1 →1.5		1.59	1.93			
1.5 →2.0	0.5	1.68	1.93			
2.0 →2.5	.559	1.70	2.09			
2.5 →3.0	.564	1.70	2.04			
3.0 →3.5	.564	1.60	1.99			
3.5 →4.0	.564	1.60	1.94			
4.0 →4.5	.564	1.45	1.86			
4.5 →5.0	.564	1.45	1.84			
5→6	.59	1.50	1.82	0.0002	0.012	0.005
6→7	.79	1.79	1.92	0.0107	0.018	0.020
7→8	.975	2.0	2.23	0.0156	0.030	0.040
8→9	.99	2.2	2.39	0.0255	0.065	0.090
9→10	1.02	2.3	2.43	0.045	0.140	0.185
14.6		2.4		0.25	0.150	0.35

[a] Corrected for being in boron shield (see Ref. 14).

Table II. The product of N(E) and the cross sections from Table I

ΔE (Mev)	[a]N(E)σ for fission by neutrons of U^{235}(238?)	Np^{237}	Pu^{234}	[b]N(E)σ for fission by gammas of [c]U^{235}(238?)	[d]Np^{237}	[e]Pu^{239}
0.01→0.04						
0.04→0.07						
0.07→0.1			475			
0.1 →0.3			770			
0.3 →0.7		350	910			
0.7 →1.1		1030	1120			
1.1 →1.5		1120	1350			
1.5 →2.0	100	840	965			
2.0 →2.5	224	680	836			
2.5 →3.0	158	476	571			
3.0 →3.5	113	320	398			
3.5 →4.0	91	256	311			
4.0 →4.5	56	145	186			
4.5 →5.0	45	116	147			
5 →6	20	51	62	0.05×10^{-4}	3.0×10^{-4}	1.25×10^{-4}
6 →7	16	36	38	1.07×10^{-4}	1.8×10^{-4}	2.0×10^{-4}
7 →8	8.8	18	20	$.0156\times10^{-4}$	0.03×10^{-4}	0.04×10^{-4}
8 →9	3	6.6	7.2			
9 →10	1.84	4.14	4.37			

[a]Using N(E) from Fig. 1.

[b]Using N(E) from Fig. 3.

[c]Threshold at 5.08 Mev (Ref. 15), or 4.60 Mev (Ref. 13).

[d]Threshold at 4.74 Mev (Ref. 15).

[e]Threshold at ≈5.31 Mev (Ref. 15), or 4.74 Mev (Ref. 13).

The energy spectrum of gamma rays from the fission of U^{235} has been observed by Maienschein et al.,[10] who obtained the spectrum shown in Fig. 2. Because of the spectral similarity (and for convenience), it is this spectrum that is used in these computations.

The neutron fission cross sections can be obtained from standard references. However, the photofission cross sections given by Katz, Baerg, and Brown[13] are used here (see Fig. 4).

The main interest is in the relative response of the fission foils to photons and to neutrons. The determining quantities here are the number of photons (or neutrons) and the cross section of the process in question. For this reason, Table I shows the cross sections of the foils at different energies, and Table II shows the product of the number of photons (or neutrons) and the cross section.

C. Actual Response of the Fission Foils

The threshold of the lowest photon energy for which fission could be detected is listed in Table II. Accordingly, the foils should not respond to photons of less than 4.5 to 5 Mev. To test this the foils were encased in a 1-inch lead shield and exposed to a polonium beryllium source (1.5×10^5 n/cm^2 sec) for 8.6×10^4 sec, to give a total flux of 6.6×10^8 n/cm^2. In the same casing, the foils were also exposed to a Co^{60} source giving a total flux on the foils of 6.25×10^8 γ/cm^2. The β and γ activities of the foils (approx 1.0 g Pu^{239}, approx 0.1 g Np^{237}, and approx 5.0 g depleted U^{238}) were counted on a gas flow counter, yielding the following results:

Table III. Comparison of relative response of fission foils (increase in c(t) in counts/min)

	U^{238}	Pu^{239}	Np^{237}
PoBe at 6.0×10^8 n/cm^2	288 ± 132	637 ± 268	267 ± 332(?)
Co^{60} at 6.25×10^8 γ/cm^2	—	—	—

The increase in activity is very small, but the neutron flux of 6.6×10^8 n/cm^2 corresponds to approximately a 3-rad dose, which is close to the limit of detectability for this system.

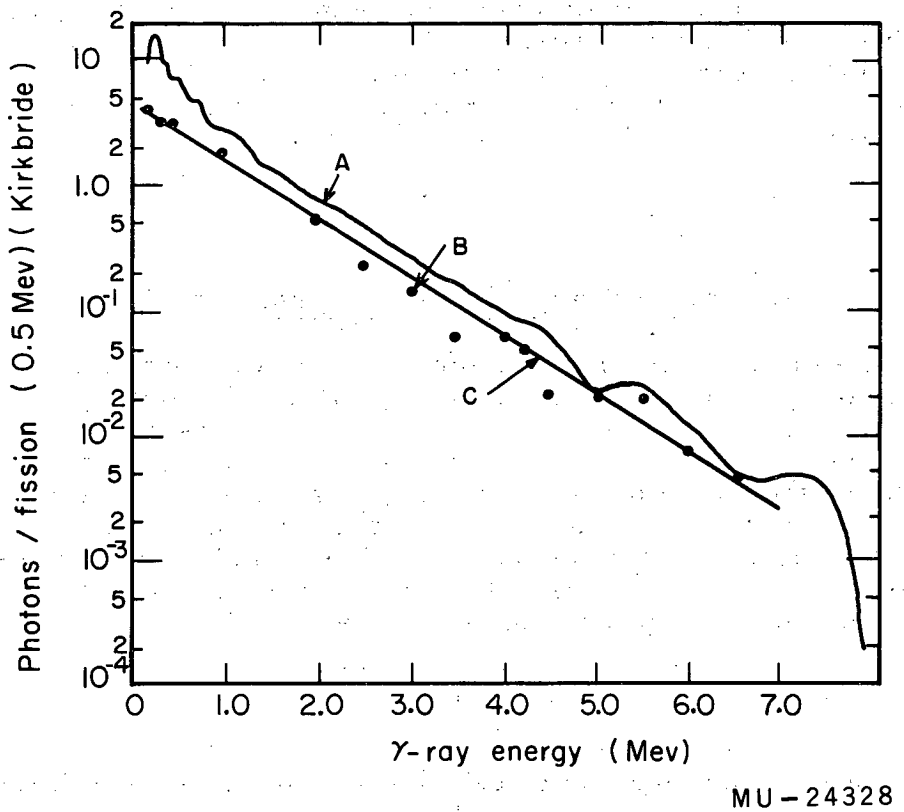

Fig. 2. Energy spectrum of γ rays from the fission of U^{236}. Curve A represents the spectrum observed by Maienschein et al. (Ref. 10). The curve of point B shows the results of R. Gamble for U^{235}. Curve C is the curve of prompt-fission γ photons from $U^{233,235}$ and Pu^{239}, as observed by J. Kirkbride (Ref. 11).

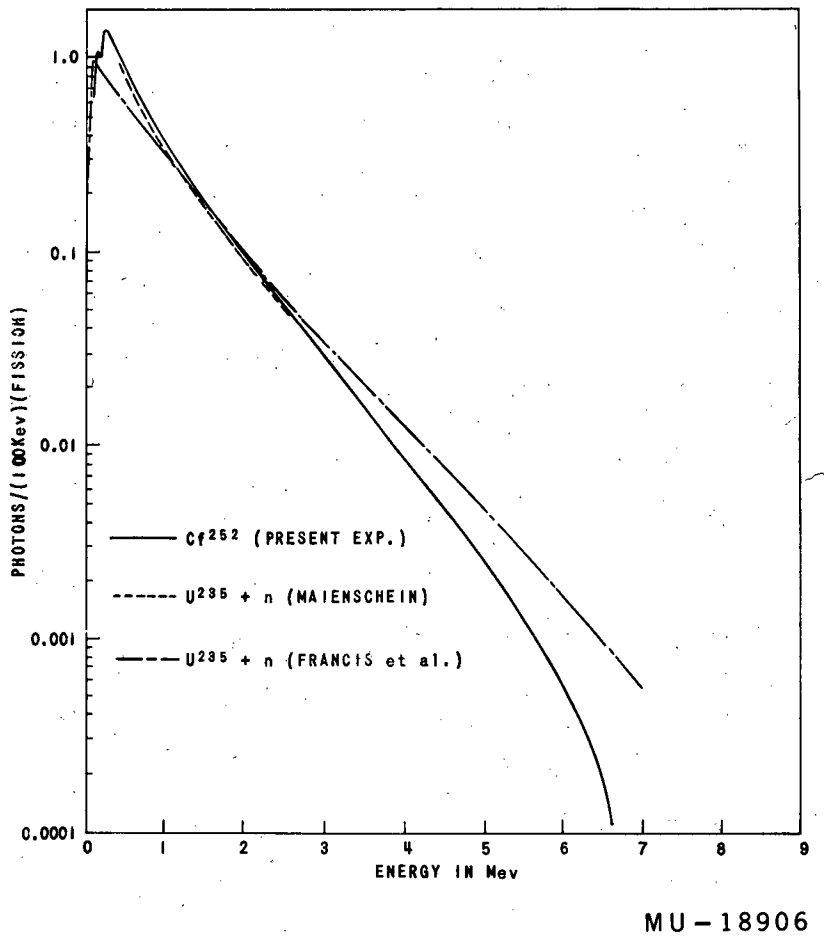

Fig. 3. Photon spectrum from the fission of Cs^{252} and U^{235} (from Smith, Fields, and Friedman; Ref. 12).

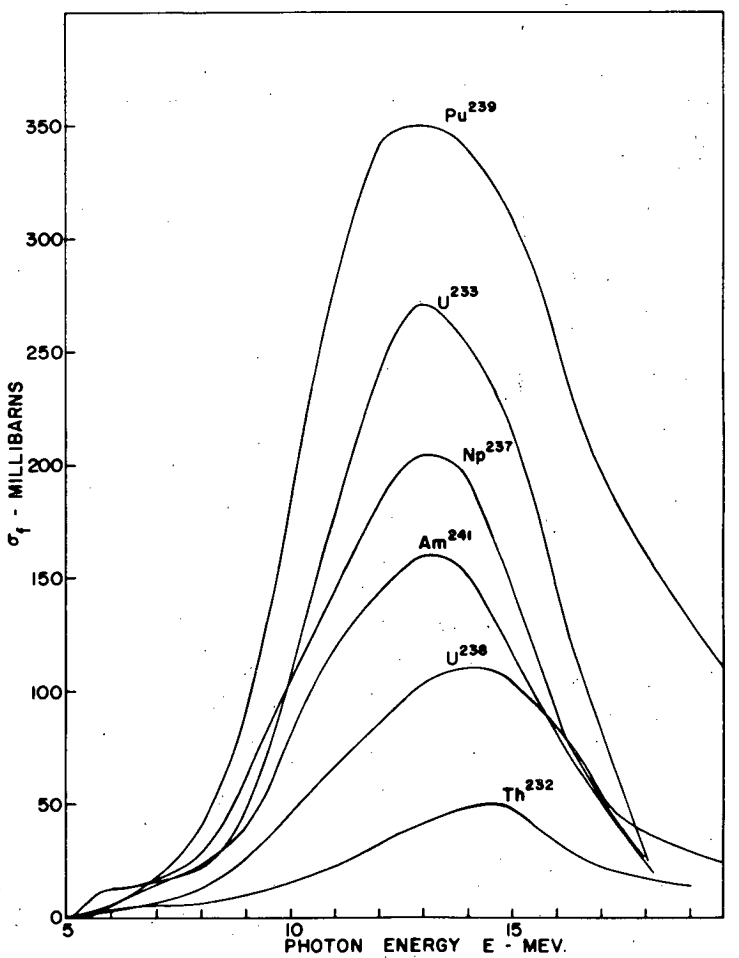

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Fig. 4. Photofission cross sections vs photon energy for Th^{232}, U^{238}, U^{233}, Np^{237}, Pu^{239}, and Am^{241} (from Katz, Baerg, and Brown). The N(E) formula, and the "Absolute N(E)" scale at the right side of the figure, are taken from Cranberg et al. (Ref. 5).

To test the response of the system to radiations of energy in excess of 5 Mev, the foils were exposed to a flux of 1.1×10^9 n/cm^2 of 14-Mev neutrons from a d-t reaction, and were then exposed to a gamma flux of 1.2×10^{12} γ/cm^2.[17] (this gives a ratio of the gamma to neutron flux of about 10^3). The results are given in Table IV.

The amount by which the neutron-flux associated with the above γ exposure could increase the activity of the foils is easily calculated. If we have $Q = 6 \times 10^4$ n/cm^2, and N = no. of atoms present, then σQN = the no. of events, and

(a) for U, assuming $\sigma \approx 0.6$ barns,

$$\sigma QN = (0.6 \times 10^{-24})(6 \times 10^4)(1.375 \times 10^{22}) = 494;$$

(b) for Np, assuming $\sigma \approx 1.3$ barns,

$$\sigma QN = (1.1 \times 10^{-24})(6 \times 10^4)(2.52 \times 10^{20}) = 26;$$

(c) and for Pu, assuming $\sigma \approx 2.0$ barns,

$$\sigma QN = (2.0 \times 10^{-24})(6 \times 10^4)(2.69 \times 10^{21}) = 323.$$

These increases of activity are small enough to be neglected safely. The above measurements were made with a Penco PA-4 pulse-height analyzer and two photomulitpliers, each with a 4-by-2-in. NaI scintillator crystal, as suggested by Hurst[1], et al. The resulting spectra for U and Pu, with the increase shown by the two shaded areas, are given in Fig. 5.

Because of the high threshold for photofission in any exposure of the foils to radiation of energy less than 5 Mev, the response to neutrons will not be "masked" by the gammas present. However, at energies greater than 5 Mev, the response to neutrons can be "masked" by photons if the abundance of photons is 10^3 as great as the neutrons. This is particularly true in the region of the giant peak of the photofission cross sections shown in Fig. 4.

Table IV. Results of the exposure of foils to neutrons and gamma rays

Foil	Activity before exposure to n's (counts/5 min)	Activity after exposure to n's (counts/5 min)	Increase in act. from n's (counts/5 min)	Activity before exposure to γ's (counts/5 min)	Activity after exposure to γ's (counts/5 min)	Increase in act. from γ's (counts/5 min)	$\sigma_{n,f}$ in barns (14 Mev)	$\sigma_{\gamma,f}$ in barns (5→8 Mev)	$\frac{\sigma_{\gamma,f} \times 10^3}{\sigma_{n,f}}$	Total increase in activity ratio γ flux/n flux
U^{238}	72219±269	98294±313	26075±582	69335±263	98285±313	28950±576	1.02	10.7	10.5	1.108
Np^{237}	792429±890	790602±889	(inconclusive) (1827±1793)(?)	381684±618	387267±622	5583±1240	2.4	18	7.5	(inconclusive) ≈ 7 (?)
Pu^{239}	395102±629	407793±639	12686±1268	225682±475	326359±570	100677±1045	2.4(?)	20	8.34	7.94

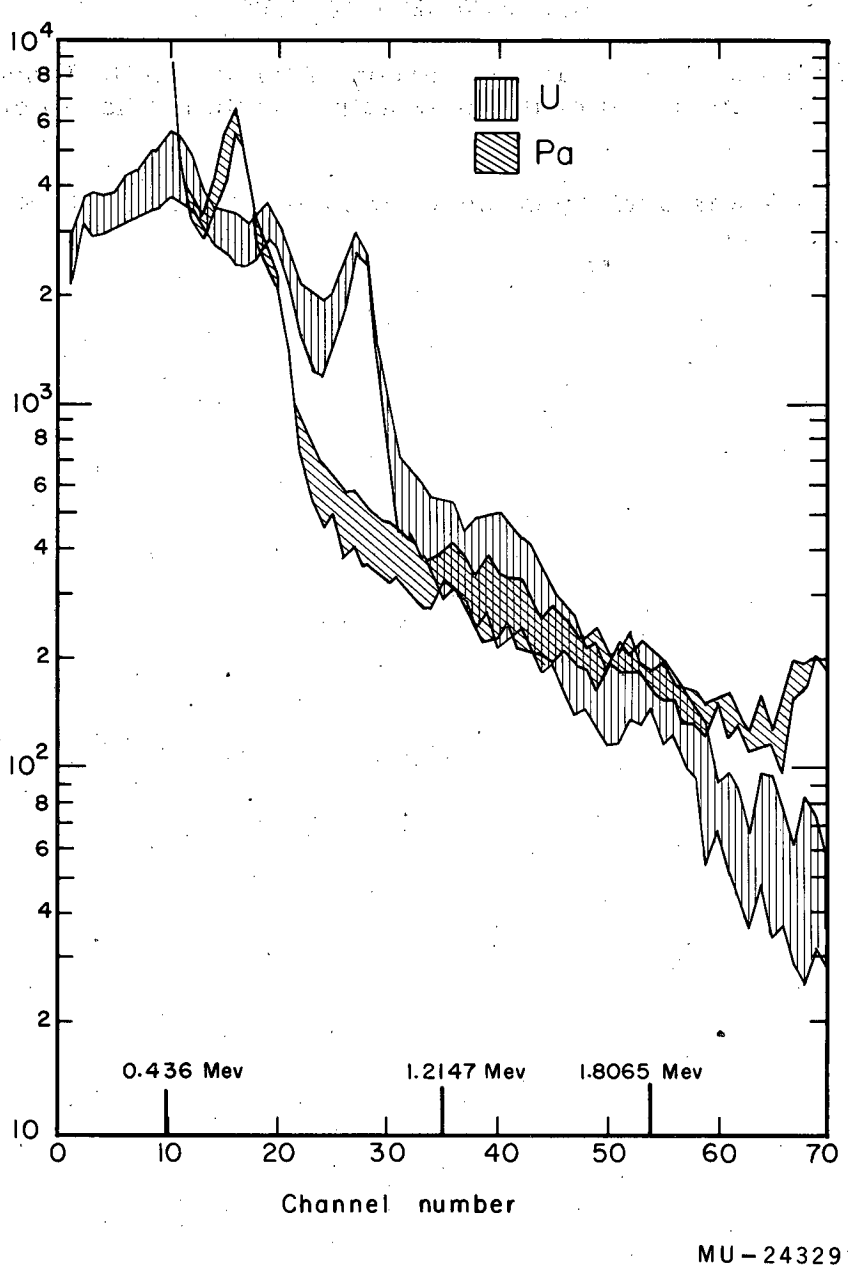

Fig. 5. Energy spectra for gamma rays for U^{238} and Pu^{239}, showing the increase resulting from exposure to a flux of 1.2×10^{12} γ/cm^2.

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14. See Ref. 1 above, Fig. 4, p. 27.

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16. Using the standard calibration by Richard Lehman of the Co^{60} used in the animal hut at UCRL, Berkeley.

17. This was the linear electron accelerator at Lawrence Radiation Laboratory (Livermore), using 8-Mev electrons at 1000 pps, 13 μa (on a tantalum target), and a 1.5 μsec pulse from which the bremsstrahlung spectrum above 5 Mev was used. A maximum neutron flux of 6×10^4 may also have been present.

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