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Tests of Neutron Cross Sections

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Carroll B. Mills

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ABSTRACT

Analyses involving the interaction of neutrons with matter over the energy range of 0 to 14 MeV require a knowledge of differential neutron cross sections as well as the results of measurements showing the kinds and magnitudes of these interactions. The study of integral experimental results on neutron multiplication in a variety of assemblies and of the effects of inserting a variety of materials into these assemblies permits examination of cross sections for improved accuracy. These improvements are qualitative and indicate areas of interest for supplementary differential measurements. Materials of interest to power breeder reactor physics and for application to high-temperature, gas-cooled reactors were tested for accuracy by perturbation theory methods. The values were generally found to be approximately correct.

I. INTRODUCTION

Neutron cross sections may be measured directly, or they may be calculated from critical measurements of material activation and reactivity value. Because the intermediate energy range of 10 to 10^5 eV is very difficult for quantitative resonance cross-section determinations, direct energy-dependent measurements of fission, capture, and inelastic and elastic scattering are supplemented by reactivity value studies. Analyses of these data permit first- to second-order corrections to nuclear resonance integrals and total cross sections in the resolved (0 to 100 eV) and unresolved (0.1 to 100 keV) energy regions, and above. Nuclear resonance states above 10 keV become strongly overlapping, and hence are smooth. Perturbation theory is the analytical tool for reactivity measurements.

Perturbation theory has been described in detail by Weinberg and Wigner[1] and others. Recent formulations by Hansen[2] give a simple picture of the results of applying perturbation theory methods to experiments on fast (greater than 0.1 MeV) and resonance energy (1 to 10^5 eV) neutrons. The major portion of our results will be separated into appendixes because extensive calculations are required for a systematic approach to cross-section evaluation.

II. COMPONENTS OF INTEGRAL EVALUATIONS

A. Fission Spectrum

The neutron flux, ϕ, is the integral of the prompt fission spectrum weighted by scattering, and prompt fission spectrum and the value of the delayed neutrons in terms of neutron multiplication depends upon the flux spectrum. According to Terrell,[3] the prompt neutron spectrum is well represented by

$$N(E) = (4E/\pi T^3)^{1/2} \exp(-E/T),$$

where $T = 2/3\ \bar{E}$ and the average energy, $\bar{E}$, is related to the average number, $\bar{\nu}$, of prompt neutrons by

$$\bar{E} = 0.75 + 0.65(\bar{\nu} + 1)^{1/2}\ \text{MeV}.$$

The production of prompt neutrons increases with the energy, E, of the neutron causing fission

$\bar{\nu} = a + bE,$

and the nuclear temperature T also increases. These constants for the fissionable isotopes have been given by Terrell[3] and Bernard[4] as shown in Table I.

TABLE I

CONSTANTS FOR FISSIONABLE ISOTOPES

Isotope	a	b	T(MeV)	dT/dE
^{233}U	2.47	0.149	1.36	0.02
^{235}U	2.35	0.160	1.30	0.005
^{238}U	2.313	0.154	1.29	0.016
^{239}Pu	2.94	0.129	1.39	0.0135
^{240}Pu	2.19	0.1	1.19	0.01

The increase in $\bar{E}$ is about 0.025/MeV of incident neutron energy.

The values of the delayed neutron fraction, as computed from the neutron flux in several critical assemblies by using the prompt fission neutron spectrum from these constants, are given in Table II.

TABLE II

DELAYED NEUTRON VALUE IN TERMS OF Δk

Assembly	Δk/dollar Calculated	Δk/dollar Experimental[2]
^{233}U Godiva	0.0029	0.0029
^{235}U Godiva	0.0060	0.0065
^{239}Pu Jezebel	0.001875	0.00191
^{235}U ^{238}U Topsy	0.00586	0.0062
^{235}U ZPR-III Assembly 12	0.00538	0.00538
^{235}U ZPR-III Assembly 29	0.0060	0.00538

B. Numerical Transport Codes

The discrete ordinate multigroup transport code for neutrons in homogeneous, one-dimensional media, as specialized by Carlson and Lathrop[5] and Sandmeier et al.[6] to include anisotropic scattering, was used for this study.

The possibility of introducing errors by the use of numerical matrix mesh sizes appropriate to the specific application was examined by a simple comparison of integral k_{eff} values. Table III compares the results for 6 and 24 energy groups over the range $0.1 < E < 10$ MeV. In addition, the effect of neutron capture below 0.1 MeV was found by adding 12 groups including $0 < E < 0.1$ MeV (see the "18 group" column).

III. NEUTRON CROSS SECTIONS

Effective multiplication constant values, k_{eff}, were computed by using the appropriate fission neutron-energy spectrum with multigroup-multitable cross sections from the Los Alamos Cross-Section Library file (LAZ).* Most of the evaluated data in this file were provided by the University of California at Livermore and by the Atomic Energy Research Establishment of Great Britain. Critical experiments 1 through 25 were provided by Paxton,[7] and experiments 26 through 28 were provided by Davey of the Argonne National Laboratory.[8] Atomic densities of component isotopes and radii are given in Appendix A. The small differences in integral values of neutron production, k_{eff}, in Table III were examined in terms of (n,γ) capture and total neutron production for the separate isotopes, as shown in Appendix B. It appears that a comparison of these integral values gives little insight into the causes of neutron cross-section errors. The energy-dependent magnitudes of cross sections of these isotopes from the several sources, as illustrated in Appendix C, show that the complex energy dependence cannot be resolved by this simple procedure. We are forced to use perturbation theory.

IV. PERTURBATION THEORY

Perturbation of the composition or geometry of a just-critical reactor changes the neutron multiplication factor, k, and starts a change in the

*The Master Data Tape contains AWRE, LRL, and LASL evaluated data. Details on its contents are available from Louis Rosen, Leona Stewart, and Roger Lazarus, Los Alamos Scientific Laboratory.

TABLE III

SUMMARY K-EFF TABLE FOR FAST ASSEMBLIES

		GROUPS		
	EXPT	6	24	18
1	U-233	1.01063	1.01151	1.01074
2	GODIVA	0.99484	0.99122	0.99529
3	JEMIMA(0.375)	0.98634	0.98548	0.98665
4	JEZEBEL	1.00453	1.00392	1.00480
5	U-233,OY	1.01199	1.01232	1.01232
6	JEMINA(0.1625)	0.99238	0.98926	0.98608
7	OY-0.7 IN.TU	0.99394	0.99067	0.99430
8	OY-1.8 IN.TU	0.99706	0.99423	0.99697
9	OY-3.5 IN.TU	0.99709	0.99393	0.99520
10	TOPSY	0.99655	0.99071	0.99001
11	OY,CH2 REFL	0.9792	0.9844	0.9839
12	OY,CH2 REFL	0.9834	0.9831	0.9846
13	OY,BE REFL	1.0140	1.0168	1.0143
14	OY,BE REFL	1.0005	1.0172	1.0026
15	OY,C REFL	0.9987	0.9961	1.0151
16	OY,C REFL	0.9962	1.0033	0.9970
17	OY,D2O REFL	1.0053	1.0011	1.0077
18	OY,D2O REFL	0.9824	0.9792	0.9925
19	OY,AL REFL	0.9997	0.9955	0.9996
20	OY,NI REFL	1.0075	1.0049	1.0083
21	OY,FE REFL	0.9805	0.9756	0.9809
22	OY, W REFL	1.0049	1.0027	1.0047
23	OY,TH REFL	0.9934	0.9905	0.9936
24	ZPR III(12)	0.9841	0.9802	0.9711
25	ZPR III(29)	0.9447	0.9552	0.9323
26	ZPR III(48)	1.0619	1.0159	1.0396

neutron population. The rate of change of neutron population is a measure of the reactivity of the material introduced, and is a function of the neutron cross section of this material. Perturbation theory deals with very small changes in neutron spectrum $\phi(E,\underset{\sim}{r},\underset{\sim}{\Omega})$ from that in a just-critical reactor of any size and composition. The probability of a neutron causing a fission has been shown[1] to be proportional to the adjoint flux; so that the perturbation theory consists of a calculation of the product of the probability of an event $\varphi\sigma_x$ and the adjoint flux φ^+. The reactivity value $\Delta k/k$ is expressed in units of the delayed neutron fraction in the assembly (see Table II for the experimental values used). The integral form expressed in the multitable-multigroup numerical summations[2] consistent with the discrete-ordinates solution of the neutron transport equation is

$$\frac{\Delta k}{k} = \frac{\sum_V (F\cdot A - T)\,\Delta V}{\sum_V ncF\cdot A\;\Delta V} ,$$

where

$$F\cdot A = \left(\sum_g N_{og}\cdot\nu\sigma_g^f\right)\cdot\left(\sum_g X_g\, N_{og}^+\right) ,$$

and

$$T = \sum_{\ell}\sum_{g} (2\ell+1)\left(N_{\ell g}\,\sigma_g^t - \sum_{g'} \sigma_{\ell g'\to g}\, N_{g'}\right)N_{\ell g}^+ .$$

The terms are defined as

ΔV is the volume element;

g is the group number;

$N_{\ell g} = \varphi_{\ell g}\Delta u_g$ is the total flux in group g;

$\phi_{\ell g}$ is the flux per unit lethargy in group-width Δu and Legendre expansion term ℓ;

ν is the number of neutrons produced per fission corresponding to fission cross section σ_g^f in group g;

N_g^+ is the adjoint flux in group g;

$\sigma_{n,g'\to g}$ is the scattering cross sections from group g' to g;

σ_g^t is the total cross section;

n is the atomic density of fissionable atoms;

c is the value of the delayed neutrons times a constant such that $\Delta k/k$ has units of ¢/kg ($\delta k_{del} = 100$¢). The product $\sum_V \Delta VnF = \sum_V \Delta V \sum_g N_{og}(n\ \nu\sigma_g^f)$ is the total neutron multiplication constant of the assembly.

Two sensitive functions are clear from the form of the equation for $\Delta k/k$. First, if (as is the case for fissionable heavy isotopes) $\sigma_{g'\to g} \ll \sigma_a$, because $\sigma^t = \sigma_a + \sum_{g'} \sigma_{g'\to g}$, the value of the volume integral for $N \approx N^+$ determining neutron multiplication changes

$$\frac{\Delta k}{k} \sim \frac{\Delta(\nu\sigma_f - \sigma_f - \sigma_c)}{\nu\sigma_f} \sim \alpha;$$

or $\Delta k \sim (\nu - 1 - \alpha)\sigma_f \sim \alpha$ is very sensitive to the capture to fission ratio $\alpha = \sigma_c/\sigma_f$. Second, if (as is the case for light, noncapturing elements) $\sigma_s \gg \sigma_c$, the integral $\Delta k/k$ is sensitive to the change in scattering cross section times flux from group to group, and to terms higher than first-order in the Legendre expansion of the scattering cross section, that is, to the neutron current.

Experimental measurements have been primarily concerned with the product $\sum_{V} hF$, the effective neutron multiplication constant shown in Table III, and only occasionally with the adjoint flux dependent measurements of reactivity $\Delta k/k$. Because the latter adds a strongly energy-dependent integral function, these measurements are important as integral tests of the energy dependence of the neutron cross sections of the elements.

Table IV provides a direct comparison of central reactivity values using Davey's results[8] compared to experimental data and computed results by using the Los Alamos Cross-Section Data File (LAZ). It is clear that two different flux spectra in ZPR-III assemblies 12 and 29 give no simple indication of the error source. The large number of components in these experiments (Appendix A) also makes it extremely difficult to infer any improvements although Davey[8] has had some success. Relatively simple Los Alamos experiments were examined in detail by using LAZ cross sections, the Los Alamos transport code (DTF-IV),[5] and auxiliary codes,[9] which provided weighting functions, reactivity, and fission neutron spectra.

Central reactivity values of selected isotopes (Orndoff[10]) are tabulated in Appendix D-1, -2, -3, in a manner such that neutron flux spectra and numerical matrix approximation effects are exhibited. These central values strongly deemphasize scattering effects because of the very small neutron flux gradients in the center of symmetric (multiplying) assemblies. Although many neutron cross sections are very accurate, there are surprising lapses. First-order corrections are attempted in Table V.

TABLE IV

REACTIVITY REFERRED TO ^{239}Pu

Assembly ZPR-III	12		29	
$(\nu - 1 - \alpha)\sigma_f$	Davey	LAZ	Davey	LAZ
value (mb)	3411	3081	3388	3082
Reactivity (central, LAZ, ¢/mol)		43.51		26.50
Material reactivity (mb)				

	Expt	Davey	LAZ[a]	Expt	Davey	LAZ[a]
^{235}U	1921	1910	2016	2012	1895	2112
^{238}U	- 78	- 81	- 89	- 104	- 93	- 78
^{232}Th	--	- 231	- 287	--	- 229	- 295
^{10}B	-1399	-1068	-1380	-1744	-1315	-1710
Ta	- 344	- 298	- 372	- 386	- 323	- 415
Nb	- 120	- 113	- 96	- 117	- 113	- 78
Mo	- 83	- 82	- 47	- 74	- 68	- 29

[a]Referred to Davey's values above in millibarns (Ref. 8).

Scattering effects may be examined by comparing experimental data with computed spatial distributions of material reactivity. These spatial values of reactivity are sensitive to neutron flux gradients in space (currents) and energy. Appendix E shows this comparison (also for LAZ cross sections and DTF-IV transport code) and strikingly demonstrates the general excellence of the listed neutron cross sections. The most surprising errors are those found in the frequently studied isotopes ^{10}B, ^{238}U, and ^{240}Pu.

It should be possible to make first-order corrections to the neutron cross sections by evaluating the effects of small and arbitrary changes in cross-section magnitude as weighted by the several neutron flux spectra in which measurements are available.

TABLE V

CONSTANT TRIAL FACTOR ON CROSS SECTIONS

Factor on Capt	Fiss	g-g'	n,2n	Isotope	JEZEBEL Orig	JEZEBEL Calc	JEZEBEL Expt	GODIVA Orig	GODIVA Calc	GODIVA Expt	ZPR-III ASS. 48 Orig	ZPR-III ASS. 48 Calc	ZPR-III ASS. 48 Expt
1.	1.	0.77	1.	H	45.362	45.184	62.800	50.462	49.346	47.800	-1.350	-1.350	-0.000
				D	-5.902	-3.986	-5.300	23.024	17.392	17.800	-.533	-.408	-0.000
				T	-25.591	-25.490	-0.000	3.679	3.598	-0.000	-.305	-.305	-0.000
				HE3	-398.270	-396.703	-0.000	-74.962	-73.304	-0.000	-22.981	-22.979	-0.000
				LI6	-210.360	-209.537	-0.000	-47.135	-46.093	-0.000	-9.912	-9.911	-0.000
				LI7	-11.459	-11.414	-0.000	2.040	1.995	-0.000	-.149	-.149	-0.000
1.	1.	1.292	1.[a]	BE	17.248	15.436	15.500	6.233	7.120	7.300	-.075	-.127	-0.000
1.33	1.	1.	1.	B10	-190.740	-249.972	-251.000	-40.866	-53.979	-55.300	-16.478	-21.909	-30.840
1.33	1.	1.	1.	B	-46.048	-45.867	-0.000	-1.396	-1.365	-6.900	-.368	-.368	-6.000
1.	1.	.947	1.	C	-7.285	-6.871	-6.900	1.702	1.576	2.400	-.125	-.118	-.017
				O LRL	-8.778	-8.744	-9.900	2.043	1.998	-0.000	-.105	-.105	-0.000
				O UK	-9.989	-9.949	-9.900	2.014	1.970	-0.000	-.112	-.112	-0.000
				NA	-12.865	-12.815	-0.000	.119	.116	-0.000	-.127	-.127	-.046
.8	1.	1.	1.	AL	-14.651	-14.072	-14.100	-.110	-.044	.500	-.149	-.142	-0.000
				MN	-16.097	-16.034	-0.000	4.228	4.135	-0.000	-.461	-.461	-0.000
.6	1.	.97	1.	FE	-22.174	-20.638	-21.500	-1.679	-1.450	-.200	-.227	-.198	-.204
.63	1.	1.28	1.	NI	-54.555	-47.570	-48.000	-5.626	-4.288	-4.400	-.419	-.377	-.325
				NB	-60.153	-59.917	-0.000	-4.201	-4.108	-0.000	-1.120	-1.120	-0.000
1.	1.	.898	1.	MO	-48.416	-43.847	-44.000	-3.326	-3.055	-0.000	-.610	-.576	-1.270
.78	1.	1.	1.	TA LRL	-112.830	-100.067	100.500	-13.833	-10.577	-0.000	-4.695	-3.763	-0.000
2.	1.	1.01	1.	W	-88.426	-112.493	-82.300	.566	-4.790	-4.000	-2.027	-3.508	-0.000
.6	1.	1.	1.	TH	-85.343	-62.113	-64.700	-10.019	-4.676	-1.400	-3.836	-2.432	-0.000
				U233 LRL	1357.600	1352.261	1359.000	254.840	249.200	-0.000	41.549	41.546	-0.000
.95	1.05	1.	1.	U233 UK	1245.200	1306.286	1359.000	236.970	243.782	-0.000	41.736	44.023	-0.000
				U234	725.320	722.478	-0.000	120.750	118.074	-0.000	4.276	4.276	-0.000
1.	1.023	1.	1.	U235 LRL	797.770	815.250	804.000	146.260	146.643	149.300	25.369	26.072	24.100
.6	1.	1.	1.	ZR	-36.678	-34.128	-35.600	-2.904	-2.441	-0.000	-.316	-.279	-0.000
				TA UK	-120.280	-119.812	-100.500	-13.798	-13.492	-0.000	-4.602	-4.602	-0.000
1.	.987	1.	1.	U235 UK	820.610	805.793	804.000	152.880	147.440	149.300	24.646	24.272	24.100
				U236	207.180	296.011	-0.000	53.022	51.849	-0.000	.596	.596	-0.000
.85	1.2	1.	1.	U238 UK	102.650	147.212	114.000	18.571	24.611	24.300	-1.696	-1.099	-1.800
1.	1.	1.	1.	U238 LRL	98.037	97.653	114.000	23.653	23.129	24.300	-1.458	-1.458	-1.800
1.	1.	1.	1.	PU239 LRL	1591.100	1584.884	1592.000	285.850	279.528	285.200	37.430	37.426	32.200
.56	1.13	1.	1.	PU240 LRL	854.870	1032.705	1038.000	132.680	163.269	170.000	-3.977	2.817	5.870
1.	1.022	1.	1.	PU239 UK	1556.800	1585.892	1592.000	281.230	281.166	285.200	34.075	34.882	32.200
1.	1.07	1.	1.	PU240 UK	982.890	1054.648	1038.000	157.620	165.879	170.000	5.744	6.462	5.870
				PU241	1646.800	1640.351	-0.000	314.780	307.818	-0.000	60.718	60.713	-0.000
				PU241	1494.800	1488.942	-0.000	275.570	269.473	-0.000	54.922	54.917	-0.000

[a] 1.0774

That was attempted in Table V. Columns 1 through 4 show the first-order correction factor used on absorption (n,γ capture + n,f fission), fission, down scattering (total), and the (n,2n) reaction. The effects upon central reactivity are shown in this table. Improvements were made by the simple procedure of changing neutron cross sections by a single factor, but the correction factors made are nonphysical, and are generally unacceptably large. Supplementary information is given in Appendix F, which shows first the effects of a simple increase of 10% in each of several cross sections for each of several multiplying assemblies. The central reactivity distribution in energy $\varphi\varphi^*$ is also shown graphically for these experiments. Note that the energy distribution of the weighting function is $\varphi\varphi^*/\Delta u$, where φ is flux, φ^* is adjoint flux, and Δu is the lethargy width of the group. Neutron group-averaged cross sections used in this study may be found in part in Ref. 9, and all are available in LAZ.

V. SUMMARY

Perturbation theory increases the sensitivity of energy dependence of integrals involving neutron cross sections in multiplying assemblies. The systematic, comparative evaluation of large blocks of data permits some insight into the magnitude of errors and the energy region where differential cross-section studies should be concentrated. Remarkably good values are now available for neutron cross sections in the energy region above 0.017 MeV, but many errors remain for magnitudes within our ability to improve. A few examples may be found in Table V, where the original reactivity calculations must be redone with sometimes large and nonphysical factors on one or more of the different kinds of neutron interaction so that the experimental values might be approached. Current associated work using the simple change in multiplication constant[8,11] suggests that the perturbation theory approaches are less successful once a particular area of interest has been determined. However, extension of this work into the very important resonance region will require that the relatively efficient perturbation theory approach be used.

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APPENDIX A

REACTOR CRITICAL EXPERIMENT DESCRIPTION

EXPT.	CORE(ISOTOPE:NXE-24) / REFL.	RADIUS(CM)	REF.
U-233	233(.04678), 234(.00059), 235(.00001), 238(.00029)	5.9647	LA-3067
GODIVA	234(.00048), 235(.04508), 238(.00245)	8.710	HANSEN
JEMIMA(.375)	234(.00018), 235(.01814), 238(.02934)	14.57	HANSEN
JEZEBEL	239(.03752), 240(.001924)	6.285	NSE8,525
JEMIMA(.162)	234(.00007), 235(.00777), 238(.0397) 235(.00034), 238(.04721)	20.32 27.94	HANSEN
OY-TU(.7 IN)	234(.00045), 235(.04511), 238(.00245) 235(.000346), 238(.047694)	7.725 9.49	HANSEN
OY-TU(1.7 IN)	234(.00045), 235(.04511), 238(.00245) 235(.000346), 238(.047694)	6.962 11.432	HANSEN
OY-TU(3.5 IN)	234(.00045), 235(.04511), 238(.00245) 235(.000346), 238(.047694)	6.391 15.344	HANSEN
TOPSY	234(.00045), 235(.04511), 238(.00245) 235(.000346), 238(.047694)	6.045 28.905	HANSEN
OY-CH2	235(.0430),238(.0031) H(.0790),C(.0395)	7.477 10.017	HANSEN
OY-CH2	235(.0450),238(.0031) H(.0790),C(.0395)	8.016 9.286	HANSEN
OY-D2O	235(.04448), 238(.00285) C(.0667), O(.0333)	6.841 15.172	LA-3067
OY-D2O	235(.04443),238(.00285) D(.0667),O(.0333)	6.171 23.54	LA-3067
OY-BE	235(.04448),238(.00285) BE(.1229)	5.648 17.43	
OY-BE	235(.04448),238(.00285) BE(.1229)	6.697 11.40	LA-3067
OY-C	235(.04496),238(.00289) C(.0837)	7.382 12.46	LA-3067
OY-C	235(.04496),238(.00289) C(.0837)	6.424 26.74	LA-3067
OY-AL	235(.0439), 238(.00286) AL(.0583)	7.846 14.48	LA-3067
OY-FE	235(.04472),238(.00287) FE(.0772)	7.39 12.47	LA-3067
OY-NI	235(.04424),238(.00284) NI(.0856)	7.251 12.331	LA-3067
OY-W	235(.04508),238(.00289) W(.05126),NI(.01248)	6.89 11.97	LA-3067
OY-TH	235(.04472),238(.00287) 232(.02980)	7.80 12.40	LA-3067

ZPRIII-12 C(.0257), FE(.00780), 235(.00451), 238(.0170) 28.5 NSE19,259
FE(.00620), 235(.0000911), 238(.03998) 58.5

ZPRIII-29 O(.01373), AL(.01451), FE(.02044), 235(.002246) ANL
238(.004949) 44.87
FE(.00620), 235(.000091), 238(.03998) 74.87

ZPRIII-48 C(.020765), NA(.00623), AL(.00011), FE(.01256), LABAUVE
NI(.001308), MO(.000206), 235(.000016), 238(.007406),
239(.001644), 240(.000106), 241(.00001) 47.42
FE(.005649), NI(.000588), 235(.000084), 238(.03998) 77.42

APPENDIX B

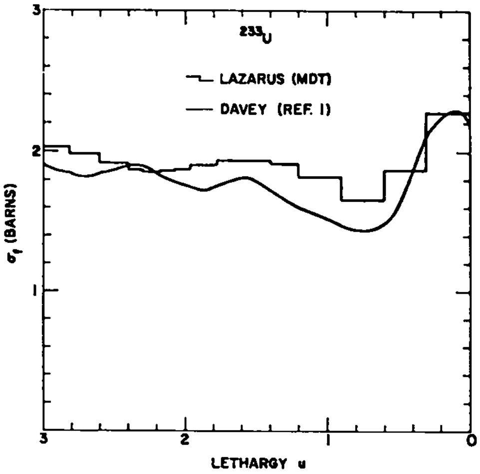
ABSORPTION AND FISSION NEUTRONS IN FAST SPECTRUM CRITICAL ASSEMBLIES

ISOTOPE	ABS 1	FISS 1	ABS 2	FISS 2	ABS 3	FISS 3	ETC. ...		ABS•FISS
1 6 G	0.3933	1.0027	0.0029	0.0071	0.0004	0.0008			U-233
1 12 G	0.3944	1.0031	0.0028	0.0070	0.0004	0.0008			U-233
1 24 G	0.3947	1.0037	0.0028	0.0070	0.0004	0.0008			U-233
1 18 G	0.3934	1.0028	0.0029	0.0071	0.0004	0.0008			U-233
2 6 G	0.0035	0.0083	0.4228	0.9978	0.0069	0.0086			U-235
2 12 G	0.0035	0.0082	0.4234	0.9736	0.0047	0.0083			U-235
2 24 G	0.0034	0.0081	0.4253	0.9749	0.0046	0.0082			U-235
2 18 G	0.0035	0.0083	0.4234	0.7983	0.0047	0.0086			U-235
3 6 G	0.0022	0.0048	0.3927	0.8467	0.0997	0.1349			JEMIMA
3 12 G	0.0022	0.0046	0.3945	0.8474	0.0991	0.1306			JEMIMA
3 24 G	0.0021	0.0046	0.3990	0.8521	0.0992	0.1228			JEMIMA
3 18 G	0.0022	0.0078	0.3937	0.8470	0.1004	0.1349			JEMIMA
4 6 G	0.3349	0.9736	0.0120	0.0307	0.0001	0.0002			JEZEBEL
4 12 G	0.3353	0.9728	0.0120	0.0305	0.0001	0.0002			JEZEBEL
4 24 G	0.3355	0.9732	0.0121	0.0305	0.0001	0.0002			JEZEBEL
4 18 G	0.3352	0.9739	0.0121	0.0307	0.0001	0.0002			JEZEBEL
10 6 G	0.0022	0.0050	0.3359	0.7464	0.0033	0.0053			TOPSY
10 12 G	0.0022	0.0049	0.3381	0.7479	0.0033	0.0052			TOPSY
10 24 G	0.0022	0.0048	0.3400	0.7486	0.0033	0.0051			TOPSY
10 18 G	0.0022	0.0050	0.3338	0.7414	0.0033	0.0053			TOPSY
10 6 G	0.0305	0.0589	0.4497	0.1809					TOPSY
10 12 G	0.0306	0.0590	0.4516	0.1746					TOPSY
10 24 G	0.0316	0.0600	0.4592	0.1721					TOPSY
10 18 G	0.0300	0.0574	0.4711	0.1809					TOPSY
26 6 G	0.0	0.0	0.0020	0.0	0.3771	0.7506	0.1648	0.1056	ZPRIII12
26 12 G	0.0	0.0	0.0020	0.0	0.3857	0.7594	0.1675	0.1002	ZPRIII12
26 24 G	0.0	0.0	0.0019	0.0	0.3914	0.7624	0.1693	0.0983	ZPRIII12
26 18 G	0.0	0.0	0.0019	0.0	0.3741	0.7390	0.1690	0.1057	ZPRIII12
26 6 G	0.0016	0.0	0.0089	0.0168	0.3879	0.0685			ZPRIII12
26 12 G	0.0016	0.0	0.0087	0.0163	0.3830	0.0640			ZPRIII12
26 24 G	0.0015	0.0	0.0087	0.0161	0.3819	0.0624			ZPRIII12
26 18G	0.0015	0.0	0.0084	0.0157	0.3990	0.0681			ZPRIII12
27 6 G	0.0013	0.0	0.0035	0.0	0.0106	0.0	0.3860	0.7706	ZPRIII29
27 12 G	0.0015	0.0	0.0039	0.0	0.0106	0.0	0.4070	0.7978	ZPRIII29
27 24 G	0.0011	0.0	0.0038	0.0	0.0102	0.0	0.4132	0.7994	ZPRIII29
27 18 G	0.0013	0.0	0.0033	0.0	0.0105	0.0	0.3849	0.7600	ZPRIII29
27 6 G	0.1009	0.0703							ZPRIII29
27 12 G	0.1057	0.0653							ZPRIII29
27 24 G	0.1080	0.0634							ZPRIII29
27 18 G	0.1047	0.0705							ZPRIII29
27 6 G	0.0018	0.0	0.0098	0.0185	0.4294	0.0853			ZPRIII29
27 12 G	0.0017	0.0	0.0093	0.0174	0.4121	0.0773			ZPRIII29
27 24 G	0.0016	0.0	0.0092	0.0170	0.4111	0.075			ZPRIII29
27 18 G	0.0017	0.0	0.0092	0.0171	0.4391	0.0848			ZPRIII29

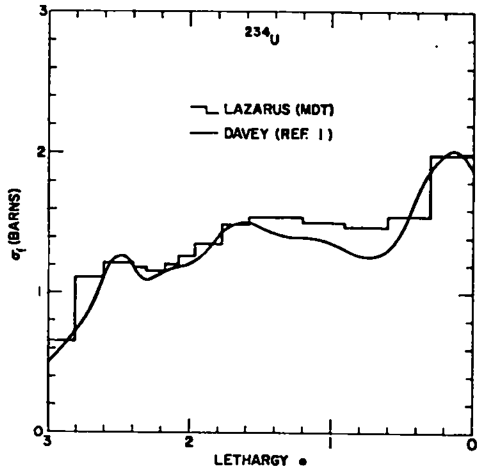
APPENDIX C

A COMPARISON OF NEUTRON CROSS SECTIONS

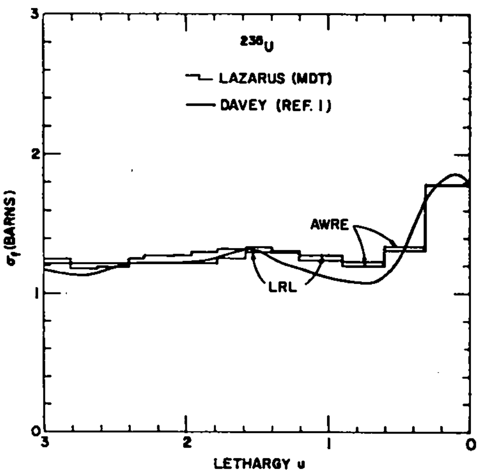
Master Data Tape group averaged neutron cross sections from Livermore (LRL), AWRE (Aldermaston), and Davey* are compared.



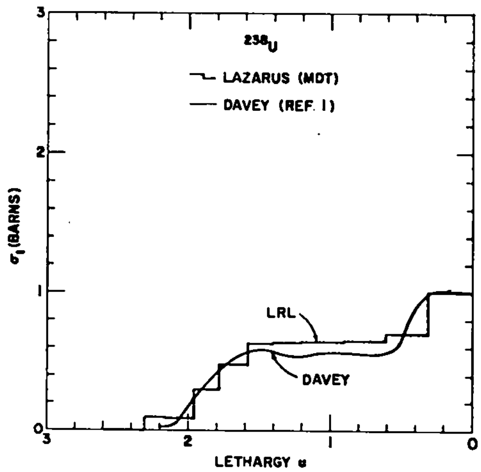
C-1



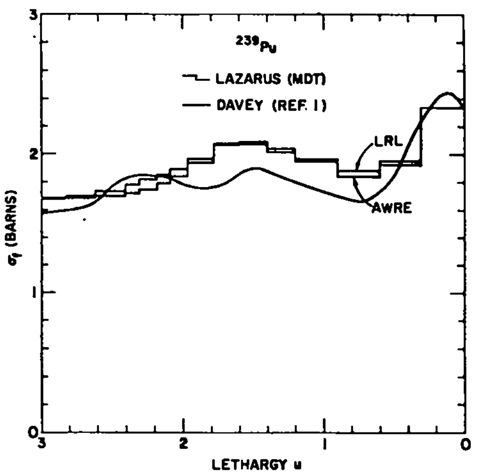
C-2



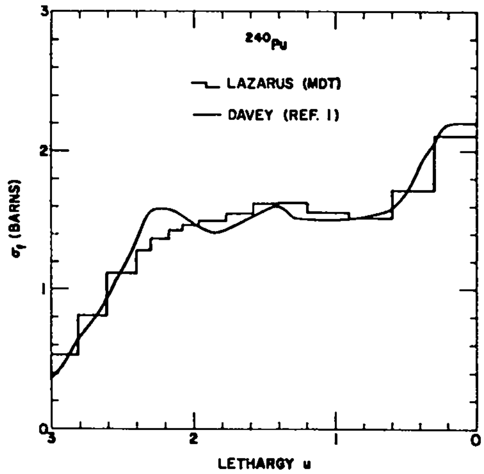
C-3



C-4

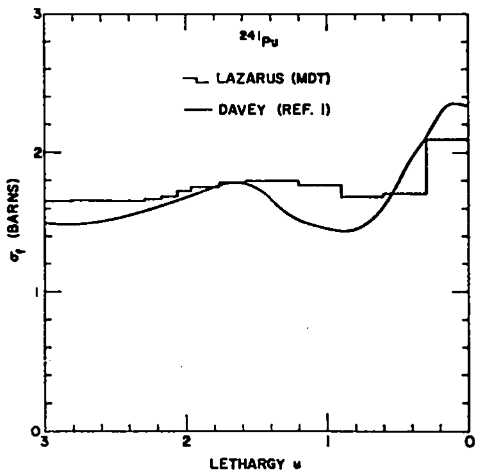


C-5



C-6

*W. G. Davey, "An Analysis of the Fission Cross Sections of ^{232}Th, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{237}Np, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu from 1 keV to 10 MeV," Nucl. Sci. Eng. 26, 149 (1966).



C-7

APPENDIX D-1

CENTRAL REACTIVITY VALUES (¢/MOLE)

ISOTCPE	NC.	GROUPS	EXPT.--- REACTIVITY(CENTS/MOLE) U233	U235	JEZBL	TOPSY	ZPR12	ZPR29	ZPR48
H	11	6G	100.58	35.10	12.41	48.30	3.33	2.92	.43
H	11	12G	142.43	46.05	39.24	65.98	4.71	3.14	.87
H	11	24G	155.46	50.46	45.36	72.47	3.67	.29	-.88
H	11	18G	123.95	37.72	34.07	55.18	3.20	2.89	-.19
H		EXPT.		47.8	62.8	67.6			
D	12	6G	53.00	15.47	-11.01	20.69	1.27	1.19	.08
D	12	12G	63.65	21.05	-7.22	28.70	1.81	1.26	.21
D	12	24G	67.25	23.02	-5.90	31.58	1.69	.55	-.16
D	12	18G	55.03	15.64	-9.61	21.60	1.21	1.16	.17
D		EXPT.	70.	17.8	-5.3	24.0			
T	13	6G	10.97	1.69	-25.12	1.67	.09	.21	-.10
T	13	12G	13.57	3.29	-24.84	4.07	.34	.34	-.04
T	13	24G	14.54	3.68	-25.59	4.73	.34	.16	-.14
T	13	18G	11.33	1.73	-24.67	1.83	.06	.20	.13
T		EXPT.							
HE3	21	6G	-270.49	-74.66	-389.17	-116.91	-21.92	-14.23	-17.86
HE3	21	12G	-273.78	-75.17	-394.51	-117.73	-23.54	-16.83	-21.64
HE3	21	24G	-274.66	-74.96	-398.27	-116.98	-24.37	-16.83	-22.82
HE3	21	18G	-270.98	-75.71	-394.85	-119.30	-23.45	-15.66	-24.76
HE3		EXPT.							
LI6	2214	6G	-163.19	-50.42	-212.36	-77.92	-13.98	-9.81	-11.00
LI6	2214	12G	-153.68	-47.30	-209.24	-72.87	-13.12	-8.71	-10.48
LI6	2214	24G	-154.71	-47.14	-210.36	-72.75	-13.32	-7.90	-10.54
LI6	2214	18G	-163.22	-50.52	-213.14	-78.94	-14.40	-10.14	-13.57
LI6		EXPT.				-130.4			
LI7	2215	6G	1.55	-.28	-10.83	-.67	-.06	.01	-.06
LI7	2215	12G	4.40	2.05	-11.15	2.79	.30	.21	-.01
LI7	2215	24G	4.23	2.04	-11.46	2.97	.32	.14	-.05
LI7	2215	18G	1.66	-.27	-10.65	-.65	-.07	.01	.11
LI7		EXPT.							
BE9	2008	6G	27.68	4.81	17.14	6.17	.22	.19	.05
BE9	2008	12G	30.72	5.94	17.33	8.12	.50	.39	.11
BE9	2008	24G	31.64	6.23	17.25	8.91	.63	.28	.04
BE9	2008	18G	28.25	4.87	17.64	6.43	.21	.19	.24
BE		EXPT.		7.3	15.5	9.2			

B10	8051	6G	-135.64	-39.74	-182.38	-66.06	-15.65	-10.22	-12.89
B10	8051	12G	-142.16	-40.51	-188.51	-67.38	-17.15	-12.34	-15.90
B10	8051	24G	-143.31	-40.87	-190.74	-67.11	-17.60	-12.26	-16.73
B10	8051	18G	-135.85	-40.42	-186.20	-67.29	-16.62	-11.14	-17.72
B10		EXPT.		-55.3	-251.		-18.6	-13.0	-30.84
B	LRL 61	6G	5.70	-1.59	-43.13	-3.28	-.25	-.01	-.19
B	LRL 61	12G	6.16	-1.07	-43.96	-2.61	-.13	.13	-.16
B	LRL 61	24G	6.63	-1.40	-46.05	-2.90	-.11	.07	-.21
B	LRL 61	18G	5.83	-1.54	-42.65	-3.24	-.28	-.02	.06
B		EXPT		-6.9		-12.2	-3.7	-2.6	-6.0
C12UK	2006	6G	3.86	.69	-6.48	.77	.03	.06	-.03
C12UK	2006	12G	5.23	1.46	-6.81	2.04	.21	.17	-.00
C12UK	2006	24G	5.75	1.70	-7.28	2.60	.30	.13	-.04
C12UK	2006	18G	4.25	.73	-6.18	.89	.02	.06	.06
C		EXPT.	3.	2.4	-6.9	2.4	0.41	0.245	-0.01
O16LRL	8081	6G	6.25	1.34	-8.62	1.62	.04	.06	-.06
O16LRL	8081	12G	5.91	2.08	-7.97	2.80	.24	.12	-.01
O16LRL	8081	24G	4.69	2.04	-8.78	2.88	.28	.09	-.04
O16LRL	8081	18G	6.50	1.37	-8.46	1.73	.03	.06	.01
O		EXPT.			-9.9	1.4		0.217	
O16UK	2037	6G	5.80	1.19	-10.65	1.40	.03	.06	-.07
O16UK	2037	12G	5.53	2.01	-9.56	2.68	.23	.12	-.02
O16UK	2037	24G	4.28	2.01	-9.99	2.83	.29	.09	-.04
O16UK	2037	18G	6.06	1.22	-10.48	1.51	.02	.06	.00
O		EXPT.			-9.9	1.4		0.217	
NA23	2182	6G	2.27	-.05	-10.41	-.34	-.05	.01	-.06
NA23	2182	12G	2.74	.28	-11.96	.23	.04	.10	-.05
NA23	2182	24G	2.56	.12	-12.87	.14	.07	.08	-.07
NA23	2182	18G	2.49	-.01	-9.98	-.24	-.06	.01	.06
NA		EXPT.						0.20	-0.046
AL27	2035	6G	-.74	-.78	-12.99	-1.36	-.11	-.02	-.08
AL27	2035	12G	-.52	-.32	-14.27	-.65	-.02	.04	-.08
AL27	2035	24G	-.30	-.11	-14.65	-.25	.04	.04	-.09
AL27	2035	18G	-.69	-.77	-12.86	-1.36	-.12	-.02	.10
AL		EXPT.		0.5	-14.1	0.7	-0.076	0.014	
MN55	251	6G	9.09	2.31	-20.32	2.24	-.06	.09	-.21
MN55	251	12G	15.35	4.00	-15.51	4.59	-.00	.06	-.23
MN55	251	24G	17.80	4.23	-16.10	5.02	-.08	-.11	-.36
MN55	251	18G	25.83	5.43	6.07	7.39	-.44	-.04	-.41
MN		EXPT.				-1.0			
FE	2036	6G	-2.18	-1.79	-19.84	-2.93	-.23	-.07	-.14
FE	2036	12G	-2.66	-1.71	-21.59	-2.81	-.20	-.05	-.15
FE	2036	24G	-2.54	-1.68	-22.17	-2.71	-.20	-.07	-.18
FE	2036	18G	-2.10	-1.77	-19.60	-2.94	-.24	-.08	.13
FE		EXPT.		-0.2	-21.5	-2.2			-0.204
NI	2046	6G	-23.98	-6.37	-54.07	-9.25	-.49	-.21	-.29
NI	2046	12G	-23.48	-5.98	-54.70	-8.68	-.44	-.17	-.30
NI	2046	24G	-22.69	-5.63	-54.56	-8.10	-.38	-.18	-.32
NI	2046	18G	-22.91	-6.28	-53.24	-9.16	-.52	-.23	-.06
NI		EXPT.		-4.4	-48.0	-7.3	-0.63	-0.86	-0.325
NB93	411	6G	-.62	-4.51	-57.27	-8.16	-1.22	-.61	-.89
NB93	411	12G	.13	-4.00	-58.44	-7.52	-1.23	-.59	-.98
NB93	411	24G	.92	-4.20	-60.15	-7.66	-1.21	-.56	-1.00
NB93	411	18G	-.47	-4.50	-56.88	-8.22	-1.30	-.66	-.66
NB		EXPT.				-7.5	-0.90	-0.90	
MO	420	6G	-3.77	-3.90	-46.14	-6.64	-.69	-.30	-.48
MO	420	12G	-3.26	-3.33	-47.25	-5.91	-.64	-.22	-.48
MO	420	24G	-2.88	-3.33	-48.42	-5.80	-.60	-.21	-.49
MO	420	18G	-3.65	-3.86	-45.70	-6.66	-.71	-.30	-.05
MO		EXPT.			-44.0	-3.5	-0.62	-0.54	-1.27

TA181LRL8731 6G	-36.23	-14.59	-107.84	-24.03	-4.37	-2.66	-3.51
TA181LRL8731 12G	-35.85	-13.37	-110.33	-22.44	-4.56	-3.03	-4.25
TA181LRL8731 24G	-35.24	-13.83	-112.82	-22.91	-4.75	-2.99	-4.54
TA181LRL8731 18G	-36.28	-14.92	-109.07	-24.81	-5.02	-3.28	-5.33
TA EXPT.			-100.5	-17.2	-4.6	-2.87	
W 8740 6G	15.64	-1.98	-86.57	-5.71	-1.69	-.77	-1.51
W 8740 12G	19.82	.05	-87.11	-3.26	-1.78	-.86	-1.72
W 8740 24G	21.94	.57	-88.43	-2.41	-1.77	-.89	-1.81
W 8740 18G	15.92	-2.05	-86.33	-5.86	-4.20	-1.91	-3.59
W EXPT.		-4.0	-82.3	-10.8			
TH232 2022 6G	-10.13	-10.41	-83.34	-18.25	-3.65	-2.12	-2.87
TH232 2022 12G	-9.24	-9.86	-83.52	-17.44	-3.80	-2.43	-3.42
TH232 2022 24G	-9.14	-10.02	-85.34	-17.46	-3.91	-2.47	-3.64
TH232 2022 18G	-9.81	-10.54	-83.47	-18.56	-3.97	-2.38	-3.37
TH EXPT.		-1.4	-64.7	-7.6		-1.69	
U233LRL8921 6G	976.26	254.14	1354.82	362.89	45.55	27.36	37.41
U233LRL8921 12G	977.67	252.97	1357.17	361.71	44.93	26.63	38.63
U233LRL8921 24G	977.88	254.83	1357.56	364.05	45.05	26.07	39.72
U233LRL8921 18G	976.28	253.86	1355.31	367.25	46.86	27.96	34.24
U233 EXPT			1359.	358.7	48.5	27.8	
U233UK 2202 6G	890.86	235.54	1240.17	337.58	44.30	26.40	36.75
U233UK 2202 12G	892.39	234.92	1244.28	337.13	43.88	25.83	38.48
U233UK 2202 24G	892.56	236.96	1245.26	339.72	44.18	25.53	39.94
U233UK 2202 18G	891.21	235.39	1241.35	341.76	45.67	27.14	33.81
U233 EXPT	955.		1359.	358.7	48.5	27.8	
U234 922 6G	552.48	123.17	733.24	163.73	6.59	4.21	3.75
U234 922 12G	548.10	121.48	727.45	161.47	5.53	3.57	2.61
U234 922 24G	548.41	120.75	725.32	160.93	5.28	3.31	2.37
U234 922 18G	552.65	123.04	732.93	166.37	6.78	4.27	3.19
U234 EXPT.							
U235LRL923 6G	593.20	147.71	798.23	209.01	25.72	15.14	21.76
U235LRL923 12G	592.82	145.78	798.55	206.65	25.32	14.83	22.84
U235LRL923 24G	593.80	146.26	797.77	207.25	25.52	14.97	23.91
U235LRL923 18G	594.11	147.54	798.93	211.50	26.40	15.41	19.30
U235 EXPT.		149.3	804.	208.4	25.52	14.97	24.1
ZR 2009 6G	-3.77	-3.08	-35.11	-5.02	-.39	-.13	-.24
ZR 2009 12G	-4.08	-2.85	-36.02	-4.69	-.34	-.08	-.23
ZR 2009 24G	-4.04	-2.90	-36.68	-4.69	-.32	-.08	-.24
ZR 2009 18G	-3.63	-3.07	-34.78	-5.07	-.43	-.15	.08
ZR EXPT.			-35.6	-2.4		-0.05	
TA UK 2328 6G	-27.12	-14.22	-117.47	-24.00	-4.36	-2.60	-3.43
TA UK 2328 12G	-27.00	-13.47	-117.87	-23.04	-4.63	-2.98	-4.15
TA UK 2328 24G	-26.83	-13.80	-120.28	-23.26	-4.76	-2.96	-4.44
TA UK 2328 18G	-27.00	-14.55	-118.45	-24.75	-5.02	-3.20	-5.04
TA EXPT.			-100.5	-17.2	-4.6	-2.87	
U235UK 2030 6G	602.46	152.68	819.29	216.17	26.00	15.53	21.60
U235UK 2030 12G	602.98	151.87	820.69	215.42	25.68	15.12	22.43
U235UK 2030 24G	603.42	152.88	820.61	216.76	25.79	14.96	23.29
U235UK 2030 18G	602.65	152.58	819.99	218.98	26.88	16.01	19.88
U235 EXPT.		149.3	804.	208.4	25.52	14.97	24.1
U236 924 6G	278.32	52.71	300.63	68.07	.93	1.09	.07
U236 924 12G	279.01	52.85	298.11	68.15	.72	.91	-.11
U236 924 24G	280.97	53.02	297.18	68.67	.70	.81	-.15
U236 924 18G	278.61	52.54	300.28	69.03	.55	.62	-1.69
U236 EXPT.							
U238UK 2005 6G	133.18	18.92	106.69	21.72	-1.60	-.70	-1.45
U238UK 2005 12G	132.49	19.00	104.87	21.86	-1.71	-.92	-1.78
U238UK 2005 24G	133.00	18.57	102.64	21.54	-1.75	-.95	-1.87
U238UK 2005 18G	133.65	18.95	107.20	22.31	-1.75	-.78	-1.43
U238 EXPT.	135.	24.3	114.	26.7	-1.04	-0.77	-1.80

U238LRL8926	6G	141.91	22.60	100.48	27.21	-.90	-.18	-1.15
U238LRL8926	12G	143.76	23.26	98.65	27.92	-1.10	-.45	-1.43
U238LRL8926	24G	145.86	23.65	98.04	28.71	-1.13	-.57	-1.56
U238LRL8926	18G	142.44	22.58	100.85	27.84	-1.06	-.28	-1.12
U238	EXPT.	135.	24.3	114.	26.7	-1.04	-0.77	-1.80
PU239LRL942	6G	1139.50	287.57	1592.54	405.14	43.51	26.50	34.72
PU239LRL942	12G	1136.10	285.46	1592.34	402.76	42.31	25.21	34.69
PU239LRL942	24G	1135.70	285.85	1591.10	403.35	42.07	24.28	34.98
PU239LRL942	18G	1140.60	287.27	1592.83	410.34	44.54	26.92	31.94
PU239	EXPT.		285.2	1592.	402.6	45.2	25.3	32.2
PU240LRL943	6G	643.29	136.96	868.57	173.75	-1.65	-1.19	-3.48
PU240LRL943	12G	633.42	134.53	858.92	170.21	-3.77	-3.07	-6.35
PU240LRL943	24G	632.82	132.68	854.87	168.38	-4.47	-3.12	-7.00
PU240LRL943	18G	643.12	136.44	866.02	176.52	-1.83	-1.51	-6.51
PU240	EXPT.		170.	1038.	386.			5.87
PU239UK 2329	6G	1119.90	282.14	1558.76	397.13	41.70	25.67	32.87
PU239UK2329	12G	1117.80	280.59	1557.68	395.69	40.44	24.27	32.06
PU239UK 2329	24G	1118.00	281.22	1556.84	396.44	39.86	23.02	31.87
PU239UK 2329	18G	1119.90	281.44	1557.19	401.52	42.34	25.72	29.79
PU239	EXPT.		285.2	1592.	402.6	45.2	25.3	32.2
PU240UK 2201	6G	730.05	161.10	991.10	214.19	7.98	5.34	4.61
PU240UK 2201	12G	724.61	158.82	985.42	211.40	6.81	4.62	3.26
PU240UK 2201	24G	724.63	157.62	982.85	210.43	6.48	4.27	2.94
PU240UK 2201	18G	730.44	160.99	990.90	217.79	8.27	5.49	3.97
PU240	EXPT.		170.	1038.	386.			5.87
PU241UK 2040	6G	1193.10	311.00	1631.70	448.76	61.22	36.82	51.32
PU241UK 2040	12G	1205.00	312.03	1643.35	451.07	62.00	38.02	55.98
PU241UK 2040	24G	1209.30	314.78	1646.86	454.58	62.90	37.96	58.23
PU241UK 2040	18G	1195.00	310.76	1633.66	453.74	62.49	37.32	47.69
PU241	EXPT.							
PU241LRL944	6G	1069.50	275.87	1487.97	397.78	54.60	32.44	46.30
PU241LRL944	12G	1074.50	273.98	1493.85	396.04	55.07	33.42	50.24
PU241LRL944	24G	1076.50	275.57	1494.80	397.93	55.89	33.67	52.52
PU241LRL944	18G	1069.50	275.60	1489.05	402.06	55.88	32.97	42.19
PU241	EXPT.							

APPENDIX D-2

ISOTOPE	NC.	GROUPS	EXPT.--- REACTIVITY(CENTS/MOLE) U233	U235	JEZ8L	TOPSY	ZPR12	ZPR29	ZPR48
H	11	6G	130.38	26.98	-1.85	35.66	.78	1.73	-1.88
H		EXPT.		47.8	62.8	67.6			
D	12	6G	71.95	13.33	-14.27	16.95	.26	.70	-.87
D		EXPT.	70.	17.8	-5.3	24.0			
T	13	6G	21.52	2.22	-23.82	2.11	-.19	.11	-.34
T		EXPT.							
HE3	21	6G	-273.71	-77.92	-396.53	-117.28	-18.90	-12.59	-14.73
HE3		EXPT.							
LI6	2214	6G	-161.32	-49.89	-219.18	-79.15	-14.93	-10.36	-11.05
LI6		EXPT.				-130.4			
LI7	2215	6G	5.53	.23	-8.94	-.07	-.10	-.00	-.09
LI7		EXPT.							
BE9	2008	6G	34.30	5.16	18.67	6.38	.15	.14	-.03
BE		EXPT.		7.3	15.5	9.2			
B10	8051	6G	-138.02	-42.00	-189.01	-65.84	-12.77	-8.90	-10.15
B10		EXPT.		-55.3	-251.		-18.6	-13.0	-30.84
B LRL	61	6G	18.37	-.77	-43.94	-2.33	-.50	-.06	-.35
B		EXPT		-6.9		-12.2	-3.7	-2.6	-6.0

C12UK	2006	6G	6.89	.97	-5.04	1.08	-.01	.04	-.08
C		EXPT.	3.	2.4	-6.9	2.4	0.41	0.245	-0.017
O16LRL	8081	6G	9.23	1.68	-7.07	2.06	.06	.04	-.08
O		EXPT.			-9.9	1.4		0.217	
O16UK	2037	6G	8.99	1.53	-9.23	1.84	.04	.04	-.09
O		EXPT.			-9.9	1.4		0.217	
NA23	2182	6G	5.85	.40	-8.80	.21	-.07	.00	-.09
NA		EXPT.						0.20	-0.046
AL27	2035	6G	3.34	-.18	-10.83	-.66	-.15	-.02	-.11
AL		EXPT.		0.5	-14.1	0.7	-0.076	0.014	
MN55	251	6G	19.52	2.02	-19.84	1.63	-.34	.00	-.41
MN		EXPT.				-1.0			
FE	2036	6G	4.21	-.83	-16.72	-1.82	-.30	-.08	-.18
FE		EXPT.		-0.2	-21.5	-2.2			-0.204
NI	2046	6G	-17.21	-5.26	-50.31	-7.84	-.63	-.21	-.37
NI		EXPT.		-4.4	-48.0	-7.3	-0.63	-0.86	-0.325
NB93	411	6G	17.16	-2.54	-54.46	-6.02	-1.38	-.60	-.93
NB		EXPT.				-7.5	-0.90	-0.90	
MO	420	6G	9.83	-2.14	-42.01	-4.62	-.86	-.31	-.56
MO		EXPT.			-44.0	-3.5	-0.62	-0.54	-1.27
TA181LRL	8731	6G	-18.73	-12.74	-104.06	-21.64	-4.19	-2.51	-3.19
TA		EXPT.			-100.5	-17.2	-4.6	-2.87	
W	8740	6G	44.19	.06	-84.74	-3.85	-1.98	-.85	-1.70
W		EXPT.		-4.0	-82.3	-10.8			
TH232	2022	6G	12.77	-8.38	-80.69	-16.04	-3.62	-1.99	-2.64
TH		EXPT.		-1.4	-64.7	-7.6		-1.69	
U233LRL	8921	6G	999.06	250.73	1356.68	361.55	49.77	28.51	37.66
U233		EXPT			1359.	358.7	48.5	27.8	
U233UK	2202	6G	909.83	231.70	1243.19	335.73	47.87	27.44	36.57
U233		EXPT	955.		1359.	358.7	48.5	27.8	
U234	922	6G	586.71	123.94	720.86	164.10	9.84	4.51	5.55
U234		EXPT.							
U235LRL	923	6G	616.98	147.23	799.97	209.50	27.82	15.71	21.63
U235		EXPT.		149.3	804.	208.4	25.52	14.97	24.1
ZR	2009	6G	6.35	-1.68	-31.46	-3.43	-.53	-.15	-.31
ZR		EXPT.			-35.6	-2.4		-0.05	
TA UK	2328	6G	-3.60	-12.10	-115.36	-21.46	-4.25	-2.44	-3.13
TA		EXPT.			-100.5	-17.2	-4.6	-2.87	
U235UK	2030	6G	624.14	151.62	821.36	216.39	28.66	16.27	21.87
U235		EXPT.		149.3	804.	208.4	25.52	14.97	24.1
U236	924	6G	316.68	56.15	297.96	70.18	1.79	.95	.57
U236		EXPT.							
U238UK	2005	6G	163.91	21.87	106.52	24.05	-1.16	-.64	-1.02
U238		EXPT.	135.	24.3	114.	26.7	-1.04	-0.77	-1.80
U238LRL	8926	6G	175.17	24.82	99.12	28.31	-.85	-.32	-1.10
U238		EXPT.	135.	24.3	114.	26.7	-1.04	-0.77	-1.80
PU239LRL	942	6G	1169.80	284.70	1587.66	404.14	49.07	27.72	36.05
PU239		EXPT.		285.2	1592.	402.6	45.2	25.3	32.2

PU240LRL943	6G	684.27	137.16	846.10	174.41	4.03	-.26	.34
PU240	EXPT.		170.	1038.	386.			5.87
PU239UK 2329	6G	1151.70	279.69	1553.60	396.50	47.43	26.92	34.48
PU239	EXPT.		285.2	1592.	402.6	45.2	25.3	32.2
PU240UK 2201	6G	773.92	163.77	976.44	216.41	12.60	5.79	7.28
PU240	EXPT.		170.	1038.	386.			5.87
PU241UK 2040	6G	1228.70	309.03	1637.73	446.32	62.78	36.80	48.66
PU241	EXPT.							
PU241LRL944	6G	1095.10	275.11	1494.99	397.73	56.70	32.75	44.45
PU241	EXPT.							

APPENDIX D-3

CENTRAL PERTURBATION CROSS SECTIONS IN ASSEMBLY 48

$$\sigma_p = \text{Total } P_2 \text{ Reactivity per Atom}/\sum_i \varphi_i \varphi_i^+$$

	σ_p(LAZ)	σ_p(Expt[a])		σ_p(LAZ)	σ_p(Expt[a])
H	-0.0888		Ta(LRL)	- 0.460	-0.976
D	-0.0161		Ta(UK)	- 0.450	-0.976
T	-0.0140		W	- 0.1834	
^{6}Li	-1.068		^{232}Th	- 0.369	
^{7}Li	-0.0047		^{233}U(LRL)	4.03	
^{10}B	-1.696	-2.94	^{233}U(UK)	4.05	
C	-0.0040	-0.0018	^{234}U	0.2401	
O(LRL)	-0.0040	-0.0036	^{235}U(LRL)	2.423	2.62
O(UK)	-0.0044		^{235}U(UK)	2.360	2.62
Na	-0.0076	-0.0048	^{238}U(UK)	-0.1897	-0.194
Al	-0.0089		^{238}U(LRL)	-0.1578	-0.194
Mn	-0.0364	-0.0387	^{239}Pu(LRL)	3.55	3.50
Fe	-0.0184	-0.022	^{239}Pu(UK)	3.23	3.50
Ni	-0.0321	-0.0161	^{240}Pu(LRL)	0.709	0.640
Nb	-0.1015		^{240}Pu(UK)	0.298	0.640
Mo	-0.0494	-0.137			
Zr	-0.0240				

[a] Davey, ANL-7320, p. 57. Proceedings of the International Conference on Fast Critical Experiments and Their Analysis, October 10-13, 1966.

APPENDIX D-4

SUMMARY K-EFF TABLE FOR FAST ASSEMBLIES

	EXPT. GROUPS	6	24	18
1	U-233	1.01063	1.01151	1.01074
2	GODIVA	0.99484	0.99122	0.99529
3	JEMIMA(0.375)	0.98634	0.98548	0.98665
4	JEZEBEL	1.00453	1.00392	1.00480
5	U-233,OY	1.01199	1.01232	1.01232
6	JEMIMA(0.1625)	0.99238	0.98926	0.98608
7	OY-0.7 IN.TU	0.99394	0.99067	0.99430

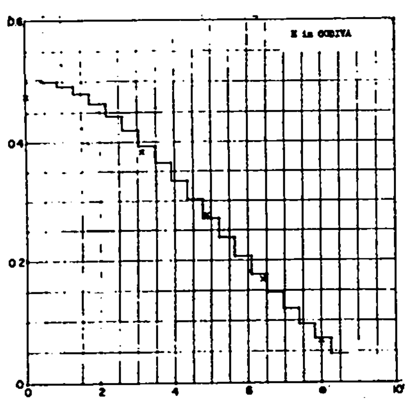
8	OY-1.8 IN.TU	0.99706	0.99423	0.99697
9	OY-3.5 IN.TU	0.99709	0.99393	0.99520
10	TOPSY	0.99655	0.99071	0.99001
11	OY,CH2 REFL	0.9792	0.9844	0.9839
12	OY,CH2 REFL	0.9834	0.9831	0.9846
13	OY,BE REFL	1.0140	1.0168	1.0143
14	OY,BE REFL	1.0005	1.0172	1.0026
15	OY,C REFL	0.9987	0.9961	1.0151
16	OY,C REFL	0.9962	1.0033	0.9970
17	OY,D20 REFL	1.0053	1.0011	1.0077
18	OY,D20 REFL	0.9824	0.9792	0.9925
19	OY,AL REFL	0.9997	0.9955	0.9996
20	OY,NI REFL	1.0075	1.0049	1.0083
21	OY,FE REFL	0.9805	0.9756	0.9809
22	OY, W REFL	1.0049	1.0027	1.0047
23	OY,TH REFL	0.9934	0.9905	0.9936
24	ZPR III(12)	0.9841	0.9802	0.9711
25	ZPR III(29)	0.9447	0.9552	0.9323
26	ZPR III(48)	1.0619	1.0159	1.0396

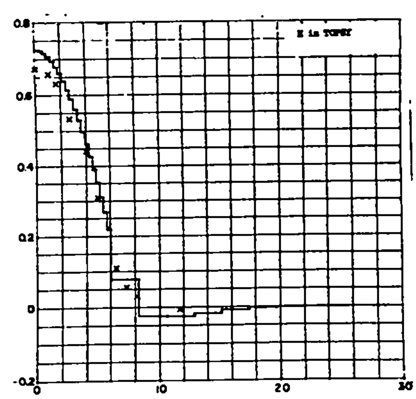
APPENDIX E

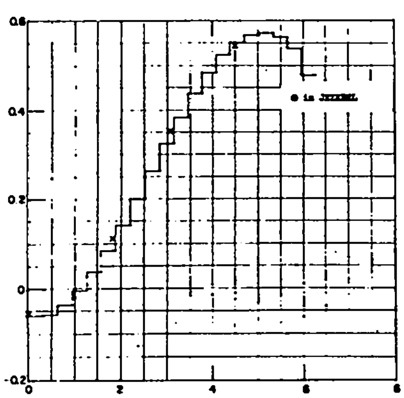
REACTIVITY VALUES AS A FUNCTION OF RADIUS

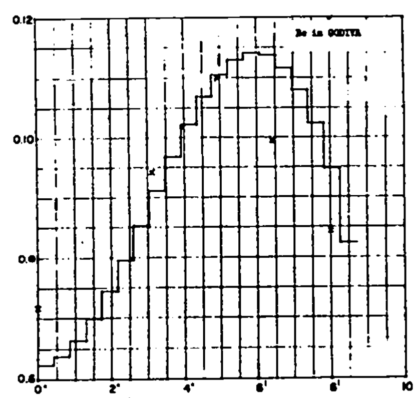
Coordinates of all figures are

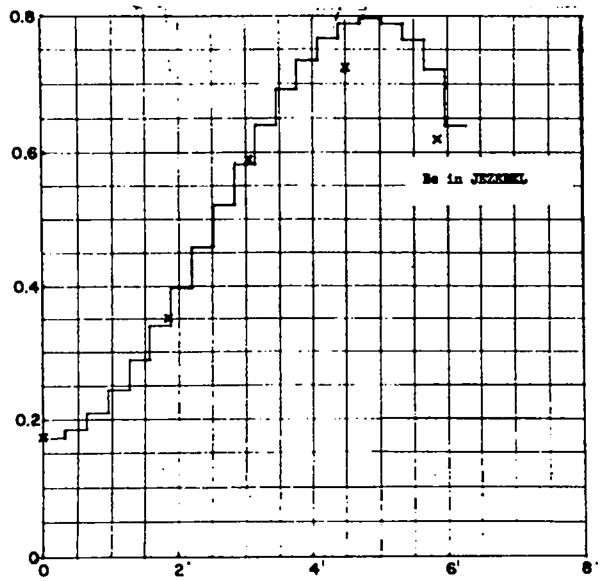
Abscissa: Radius (cm). Ordinate: Reactivity (\$/mol).







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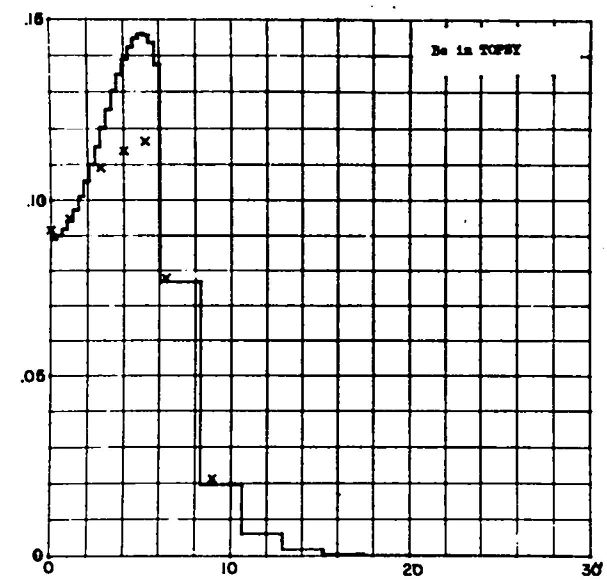
6
8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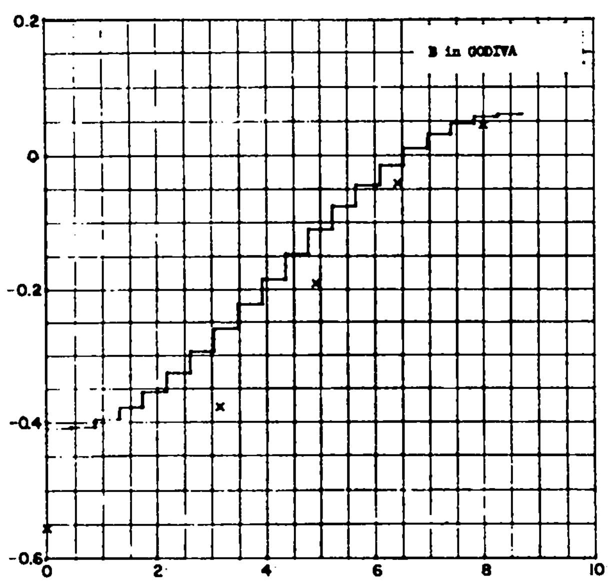
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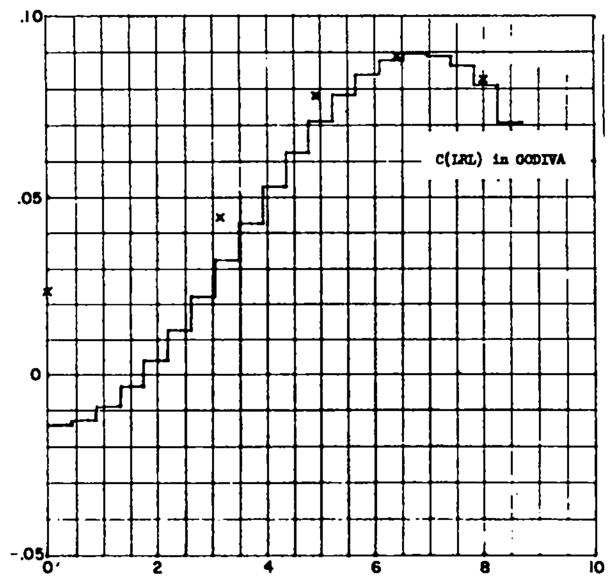
2
4
6
8
10


C(LRL) in GODIVA
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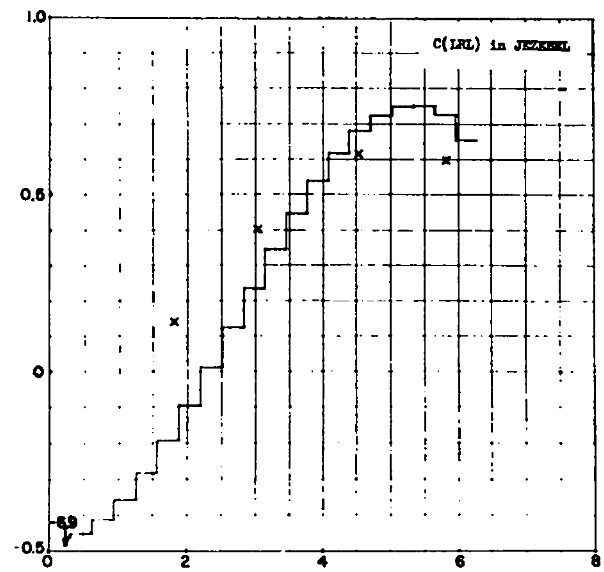
2
4
6
8
10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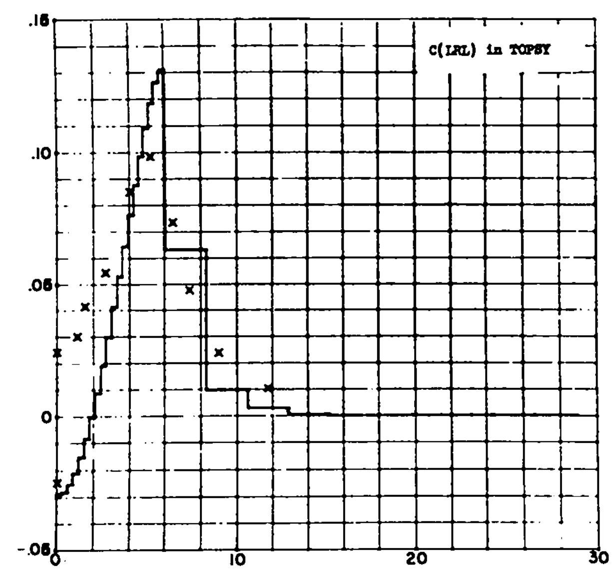
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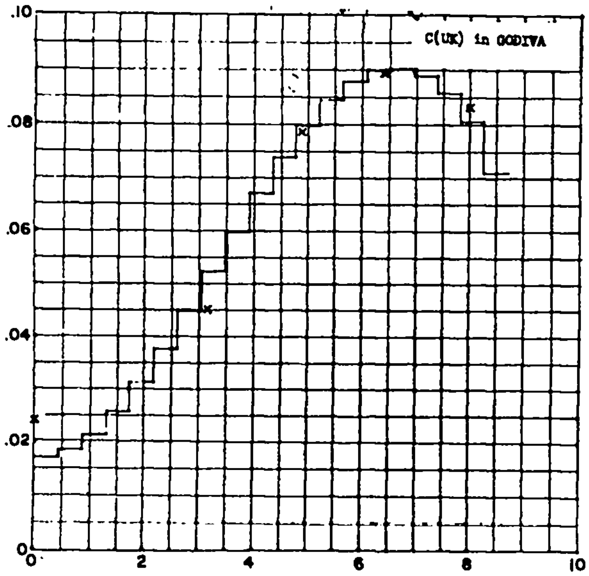
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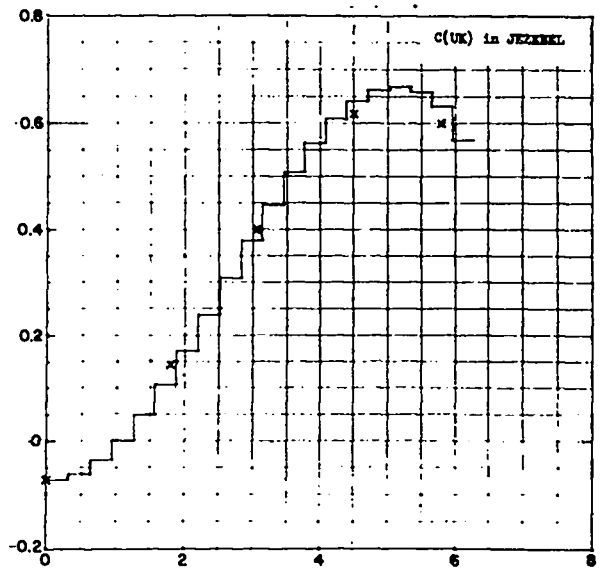
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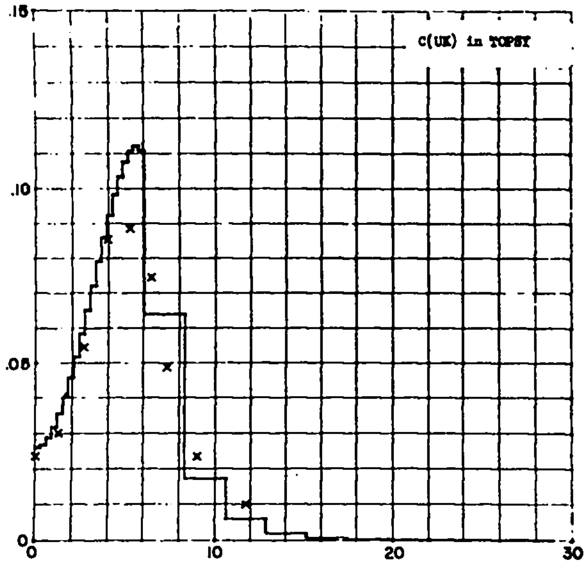
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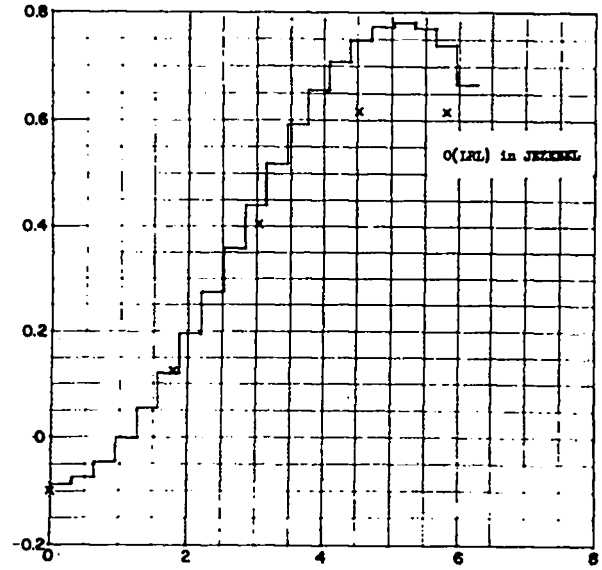
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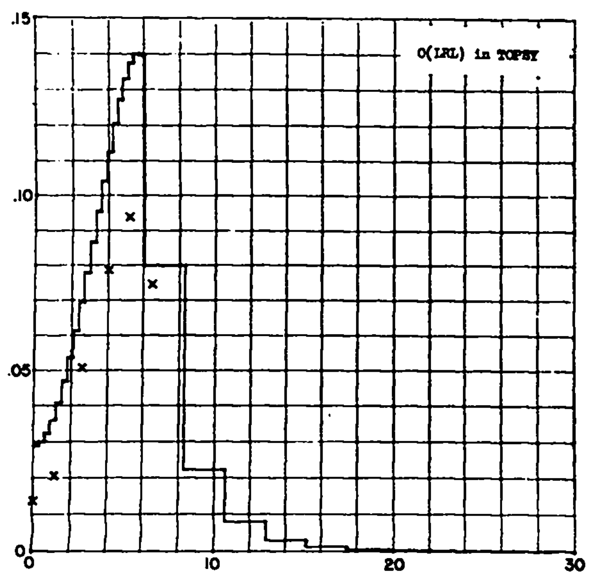
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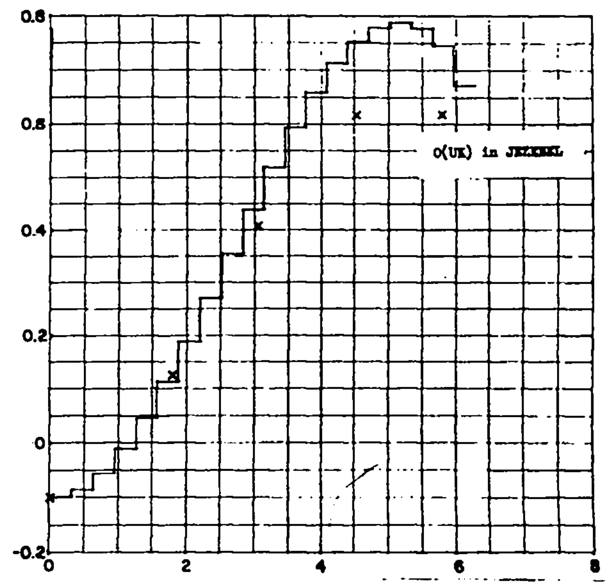
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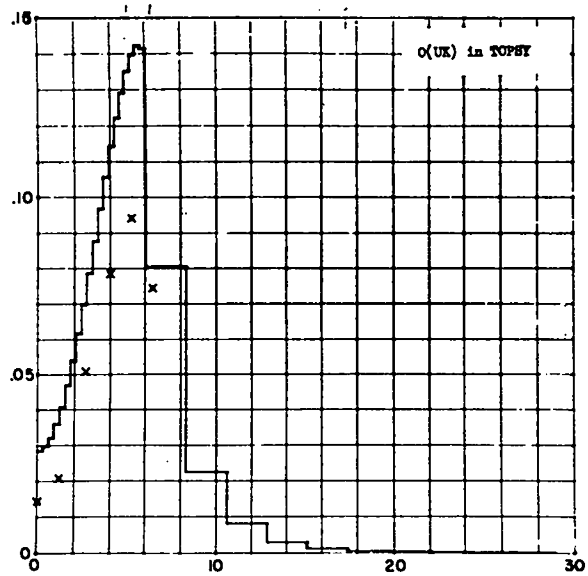
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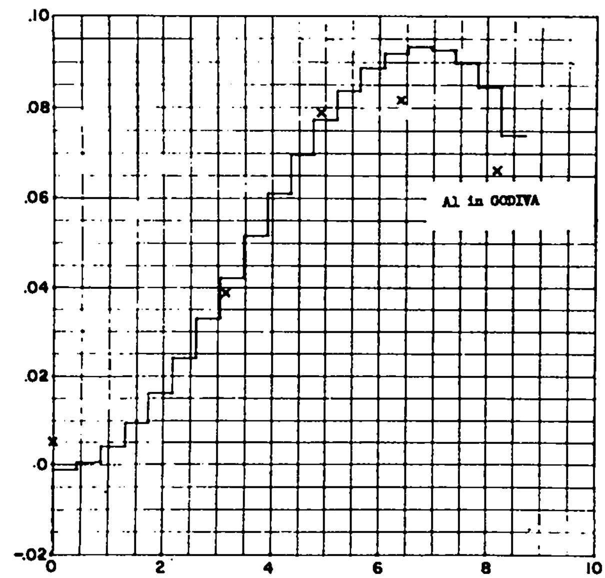
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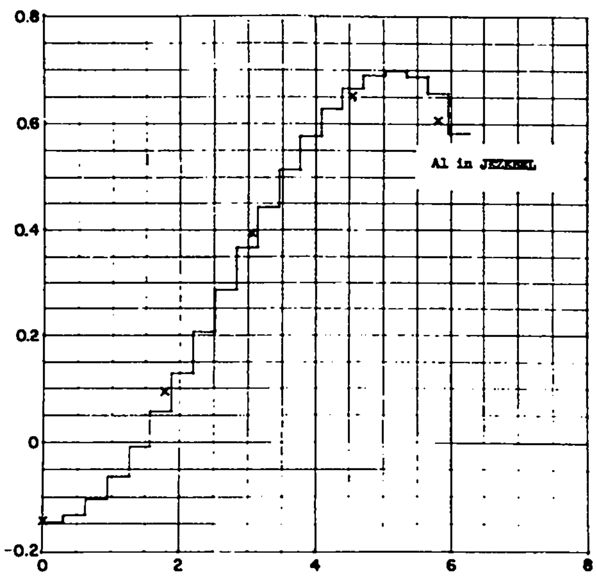
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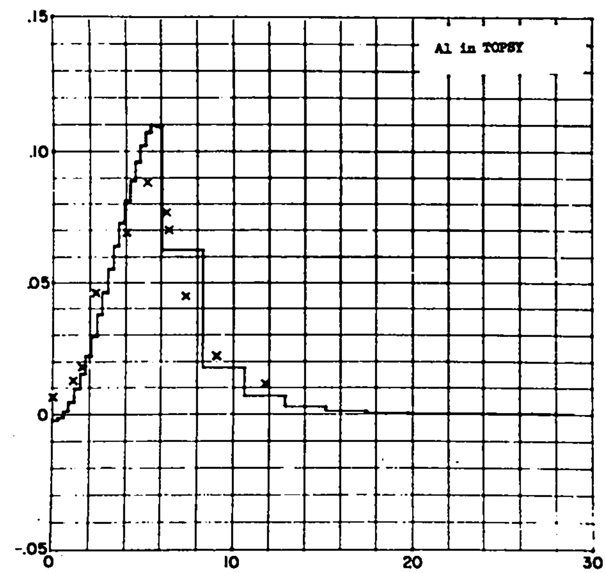
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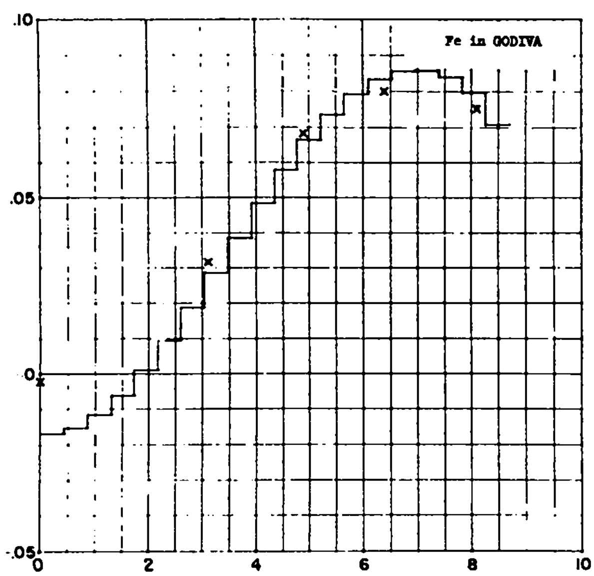
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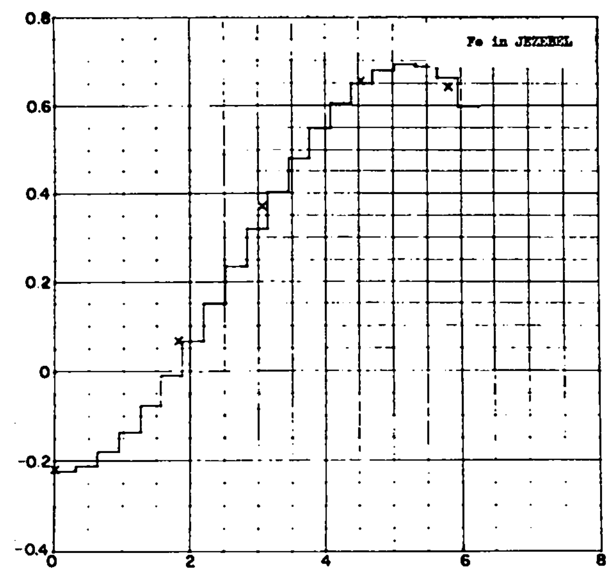
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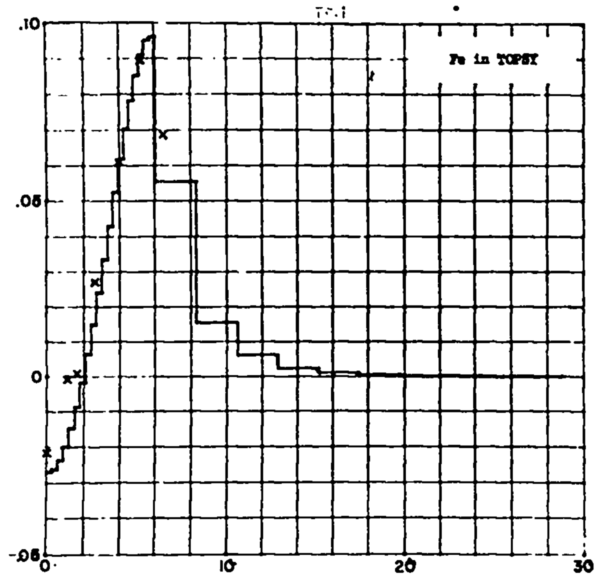
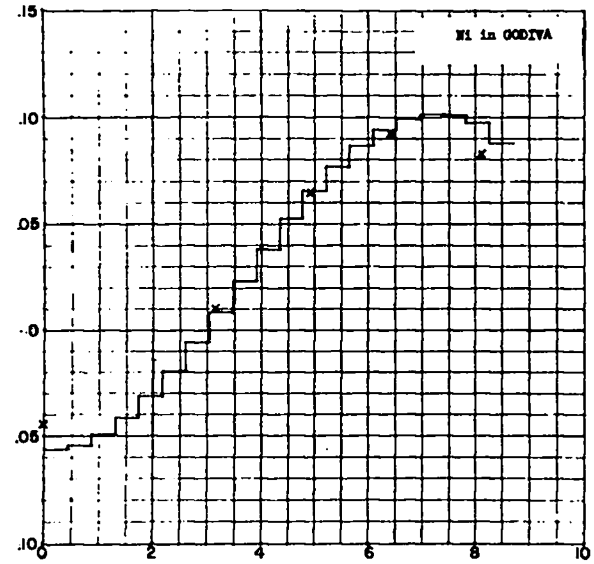
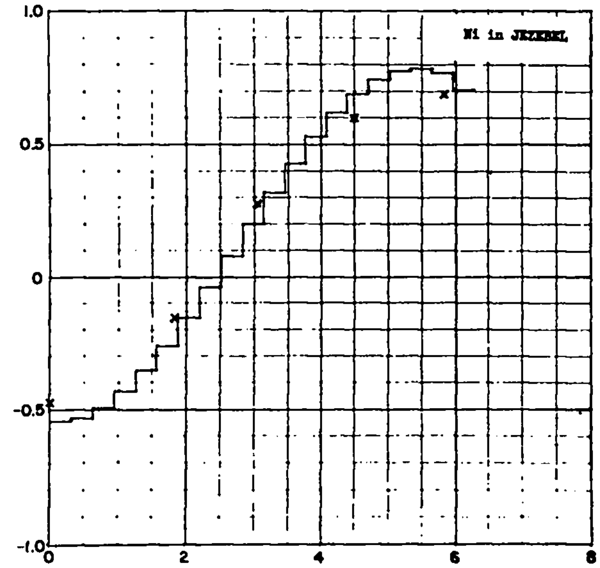
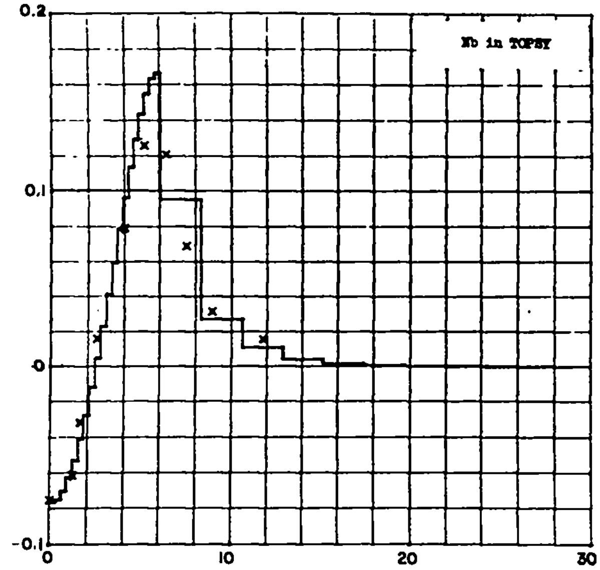
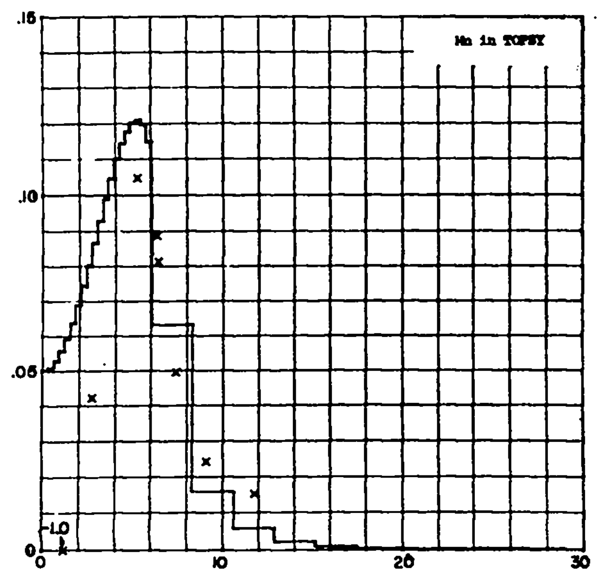
4
6
8

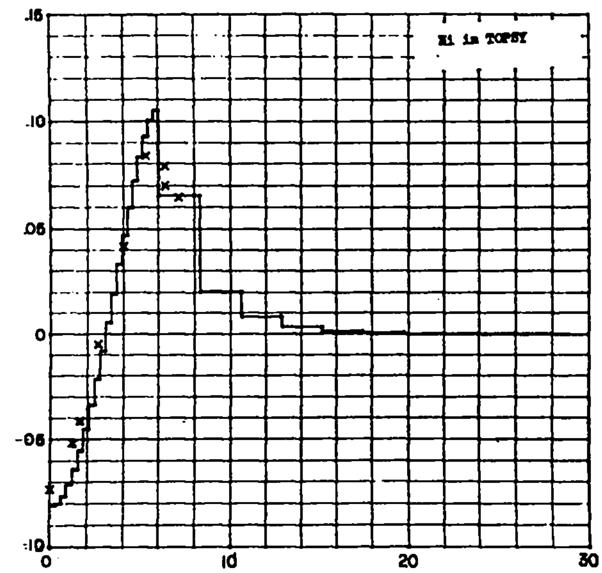

Fe in TOPSY

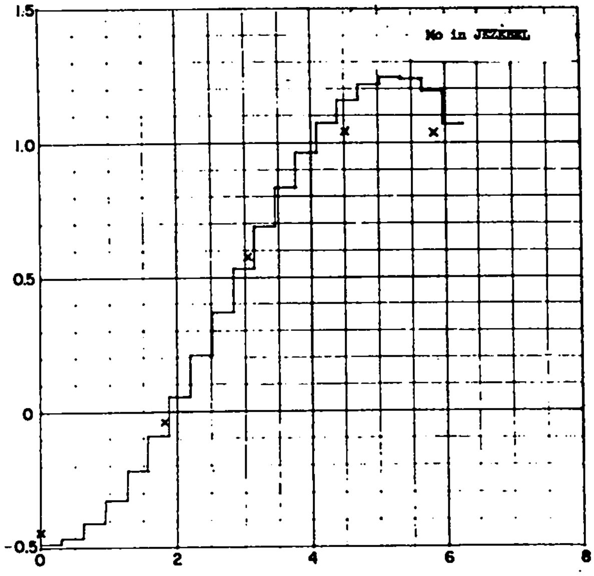

Ni in GODIVA

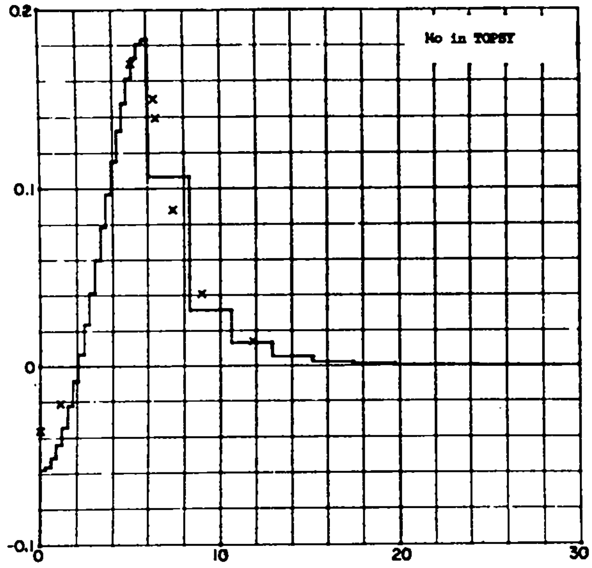

Ni in JEZEBEL

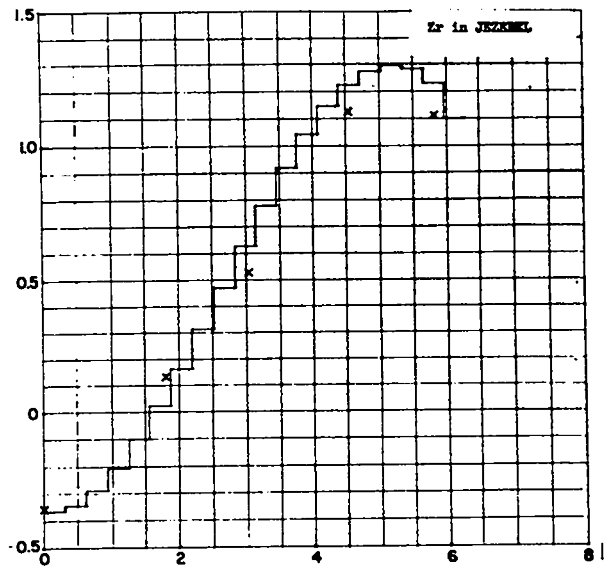

Nb in TOPSY

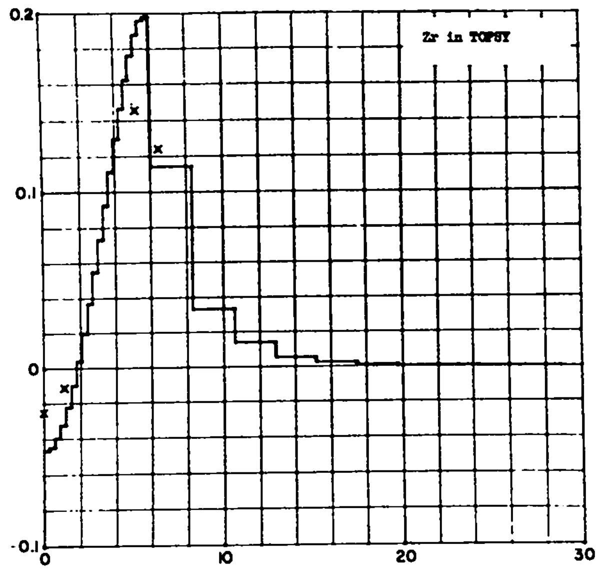

Mn in TOPSY

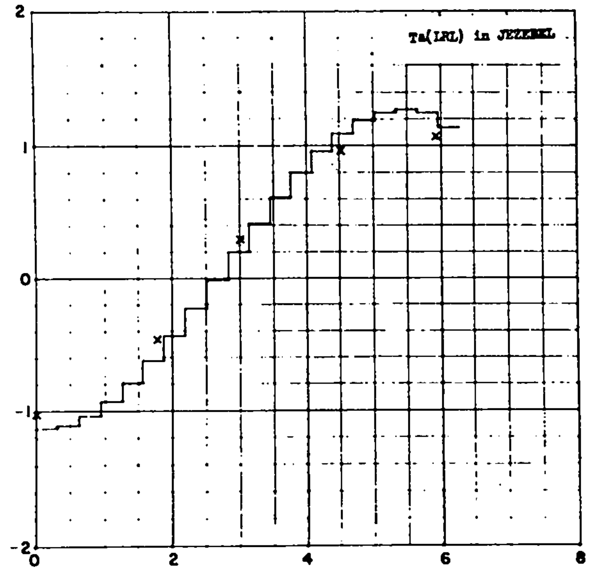

Ni in TOPSY

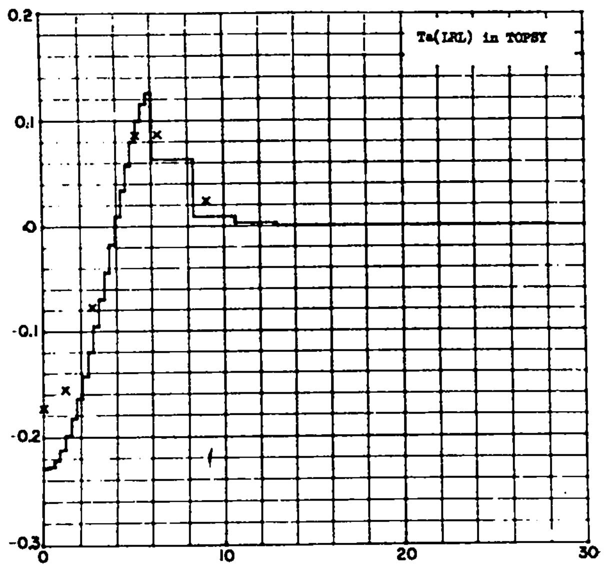

Mo in JEZEBEL
1.5
1.0
0.5
0
-0.5
0
2
4
6
8

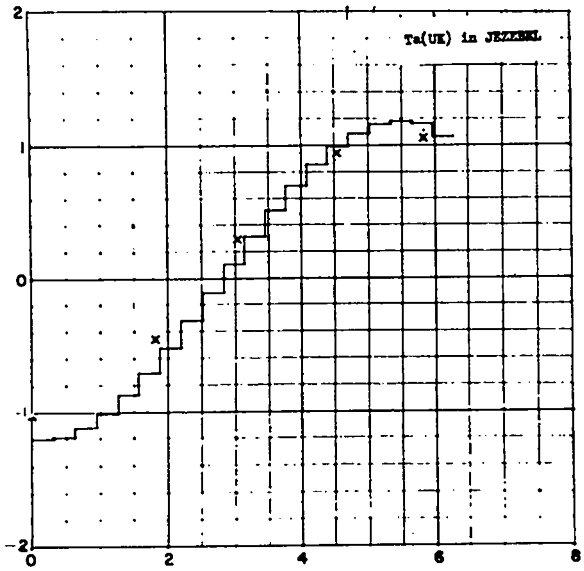

Mo in TOPSY
0.2
0.1
0
-0.1
0
10
20
30

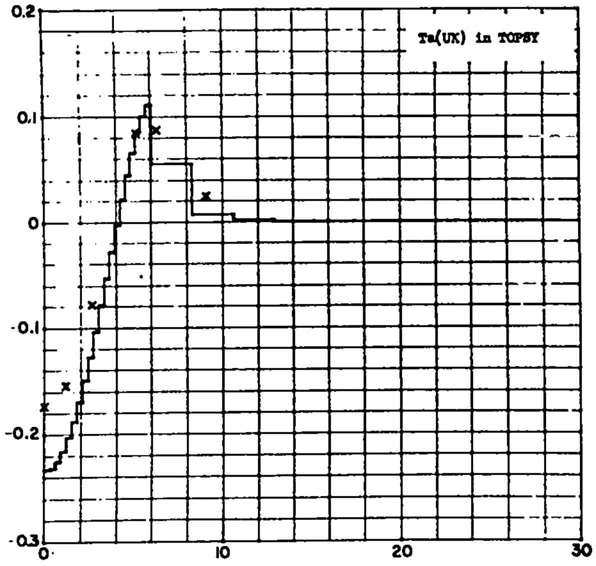

Zr in JEZEBEL
1.5
1.0
0.5
0
-0.5
0
2
4
6
8

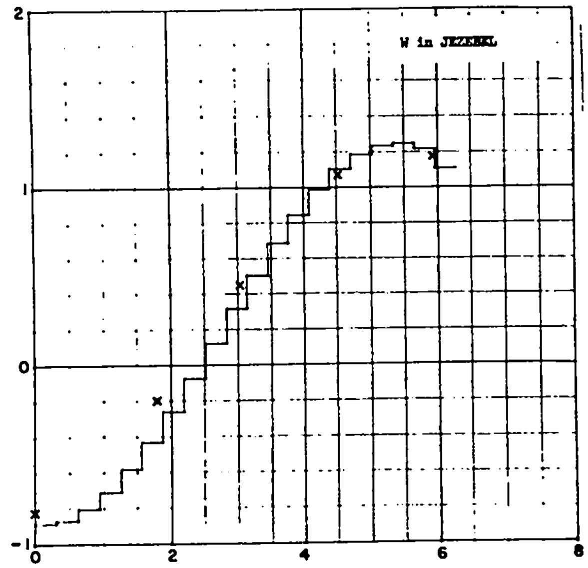

Zr in TOPSY
0.2
0.1
0
-0.1
0
10
20
30

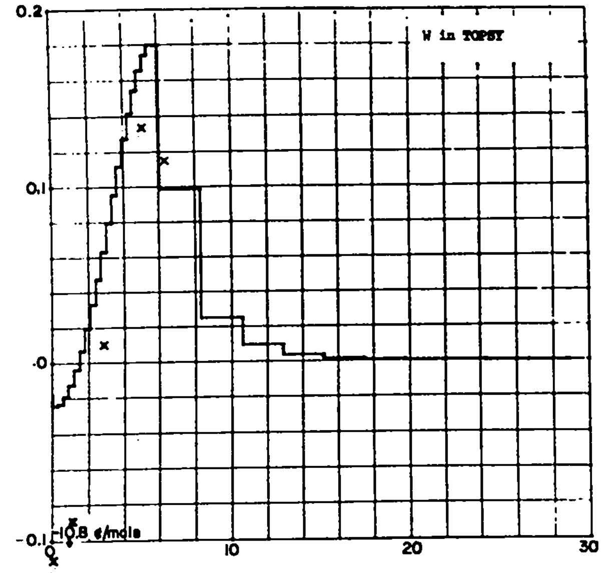

Ta(LRL) in JEZEBEL
2
1
0
-1
-2
0
2
4
6
8

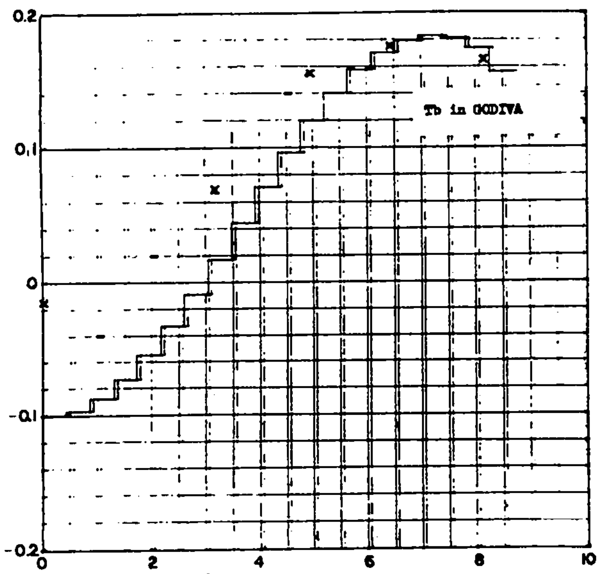

Ta(LRL) in TOPSY
0.2
0.1
0
-0.1
-0.2
-0.3
0
10
20
30

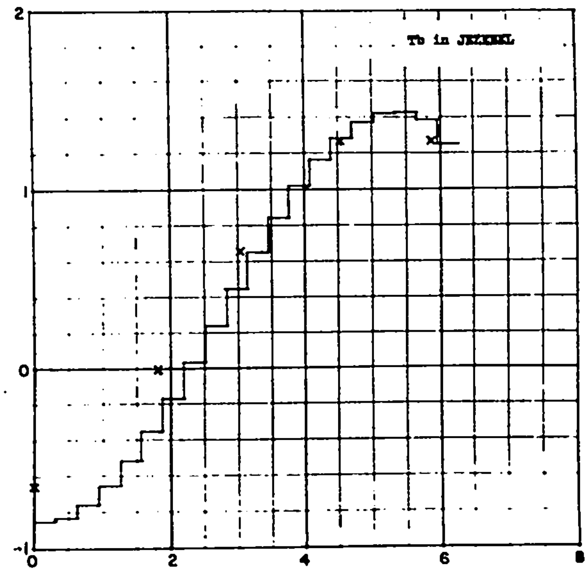

Ta(UK) in JEZEBEL

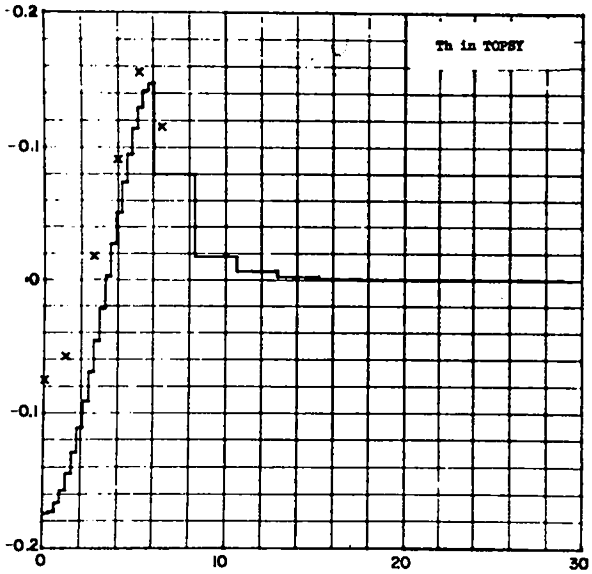

Ta(UK) in TOPSY

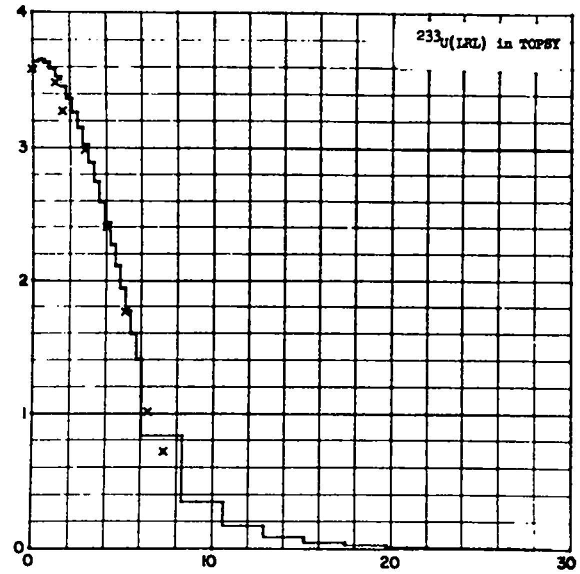

W in JEZEBEL

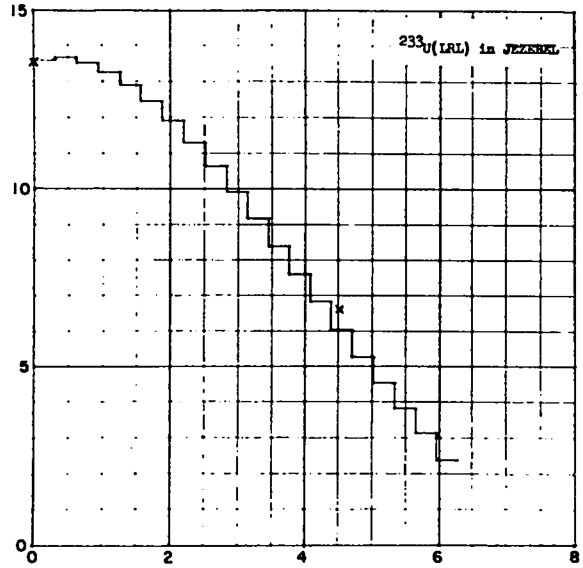

W in TOPSY

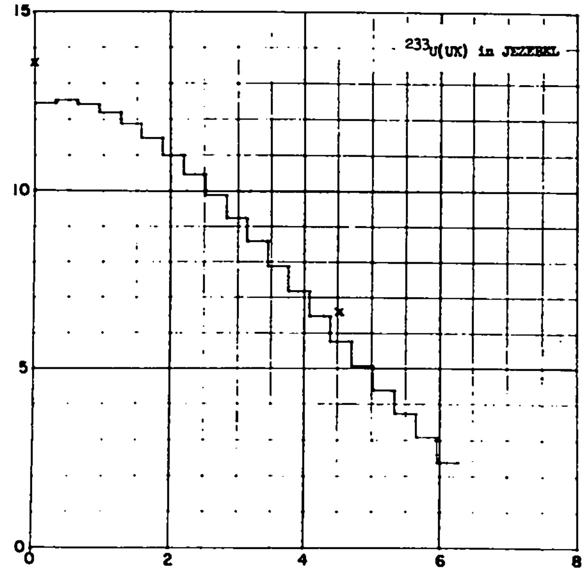

Tb in GODIVA

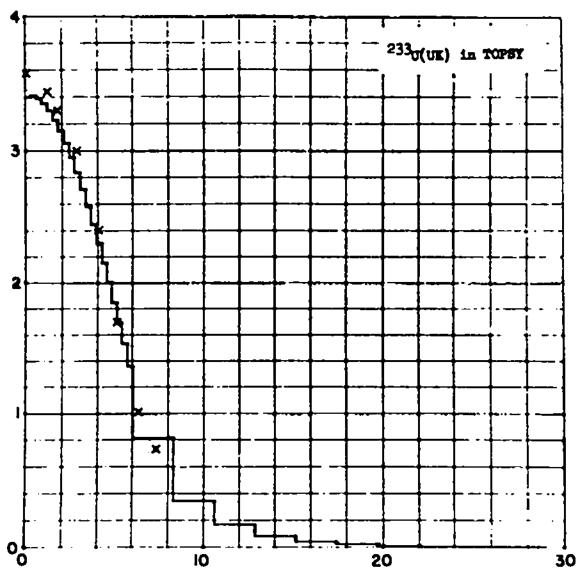

Tb in JEZEBEL

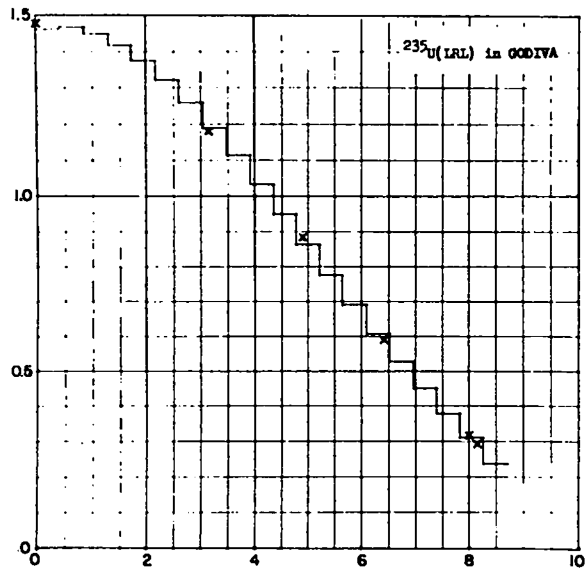

Th in TOPSY
0.2
0.1
0
0.1
0.2
0
10
20
30

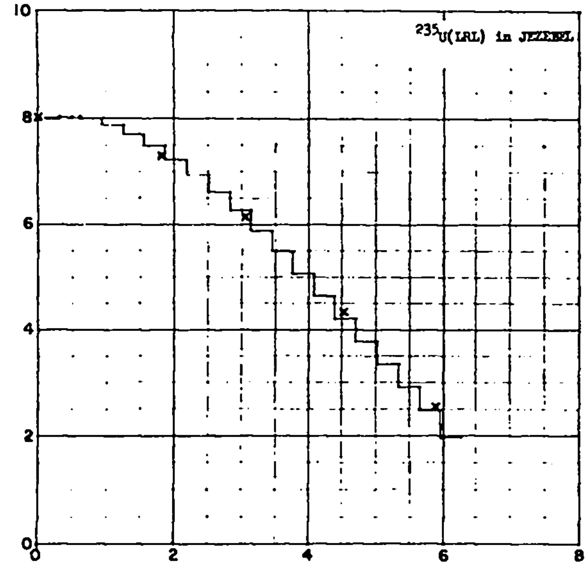

233U(LRL) in TOPSY
4
3
2
1
0
0
10
20
30


233U(LRL) in JEZEBEL
15
10
5
0
0
2
4
6
8

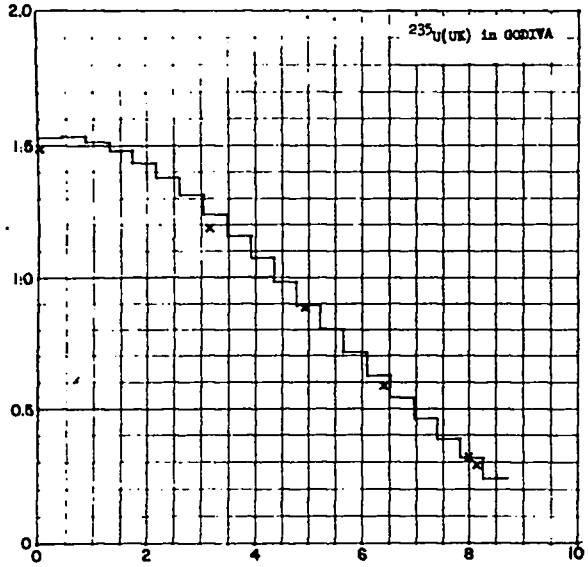

233U(UK) in JEZEBEL
15
10
5
0
0
2
4
6
8

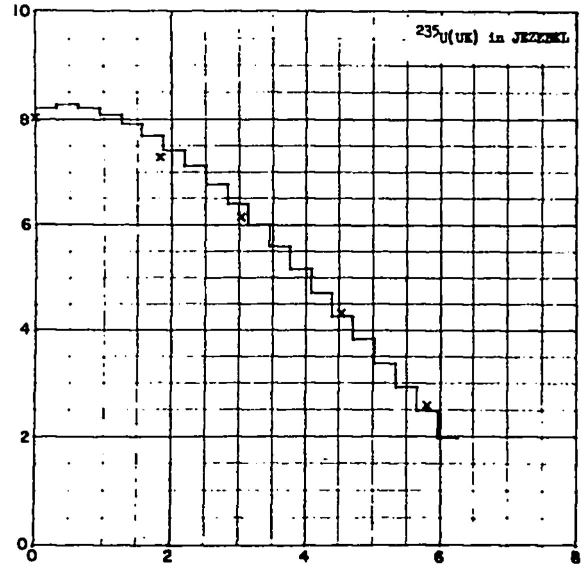

233U(UK) in TOPSY
4
3
2
1
0
0
10
20
30

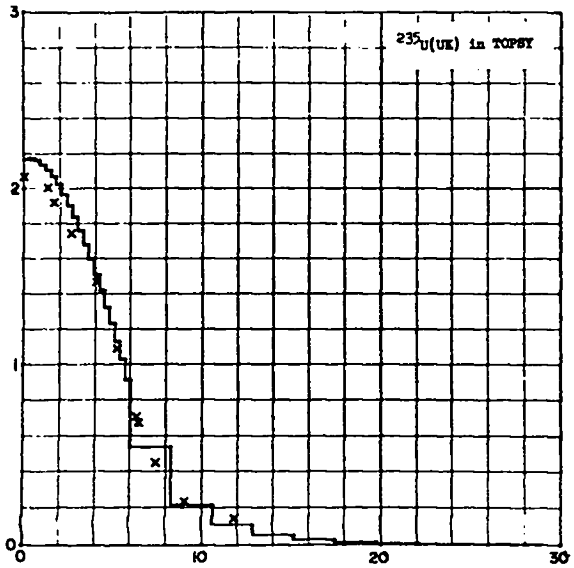

235U(LRL) in GODIVA
1.5
1.0
0.5
0
0
2
4
6
8
10

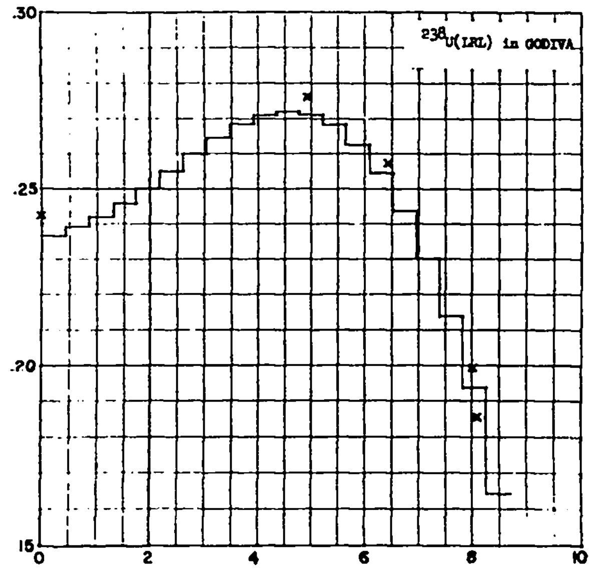

235U(LRL) in JEZEBEL
10
8
6
4
2
0
0
2
4
6
8

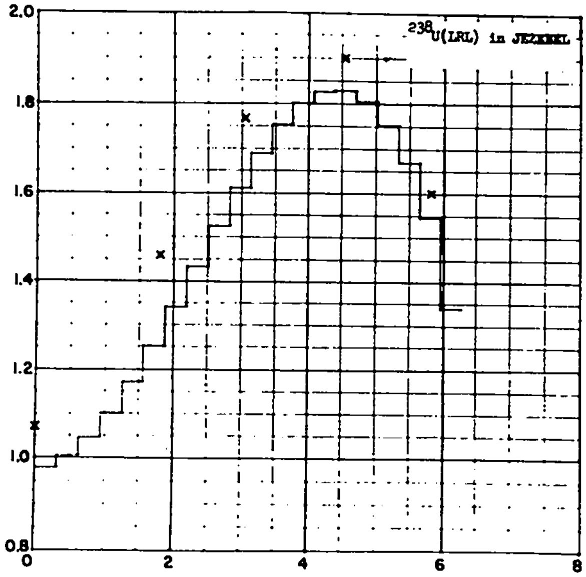

235U(LRL) in TOPSY
3
2
1
0
0
10
20
30

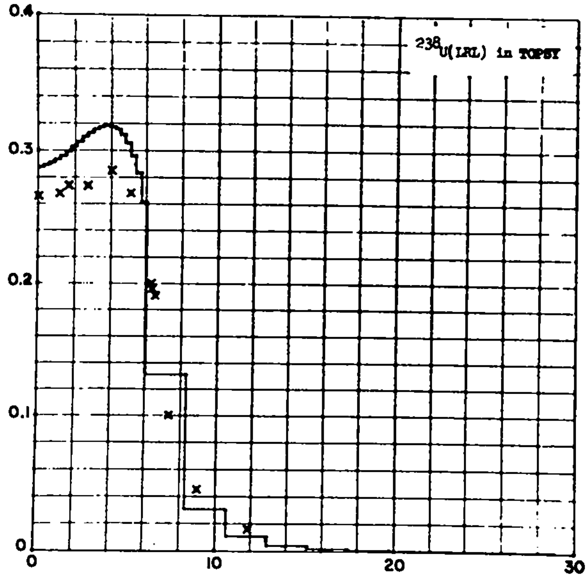

235U(UK) in GODIVA
2.0
1.5
1.0
0.5
0
0
2
4
6
8
10

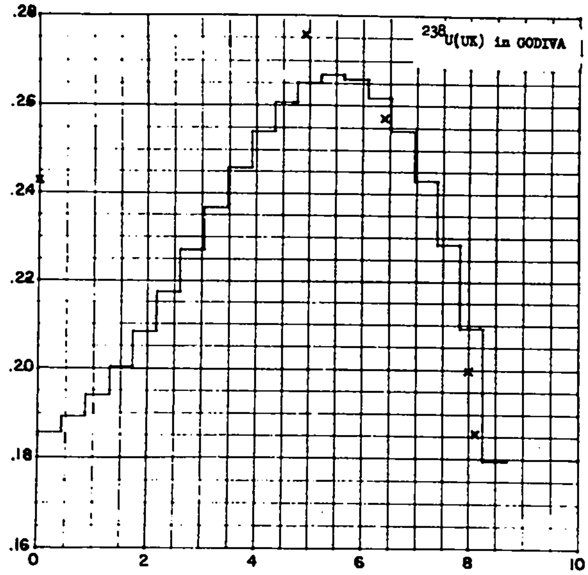

235U(UK) in JEZEBEL
10
8
6
4
2
0
0
2
4
6
8

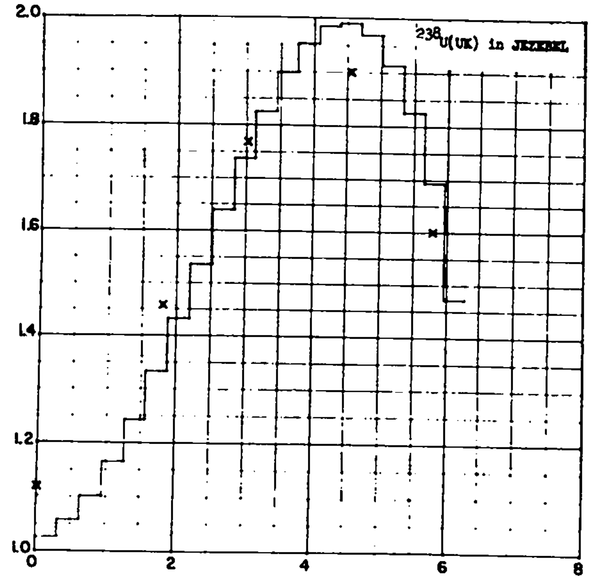

235U(UK) in TOPSY
3
2
1
0
0
10
20
30

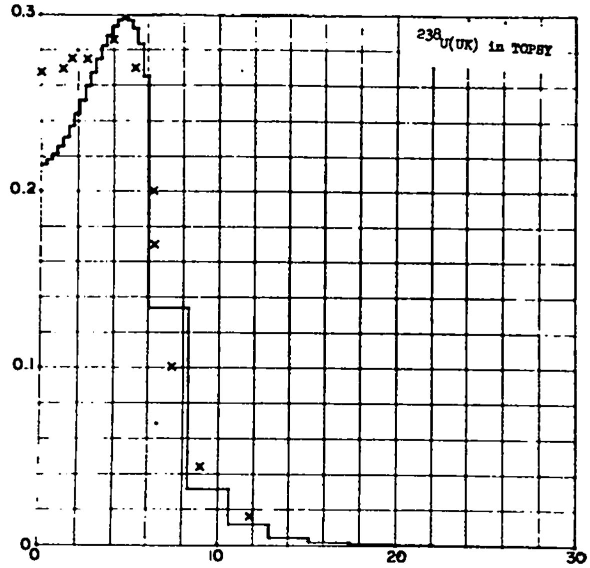

238U(LRL) in GODIVA
.30
.25
.20
.15
0
2
4
6
8
10

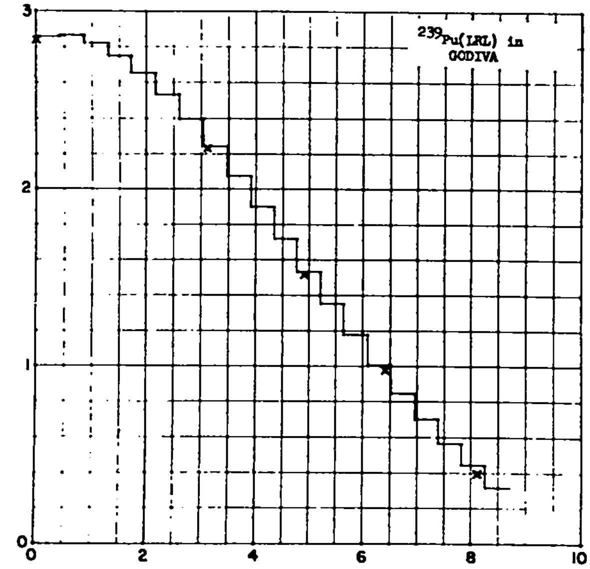

^{238}U(LRL) in JEZEBEL
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0
2
4
6
8

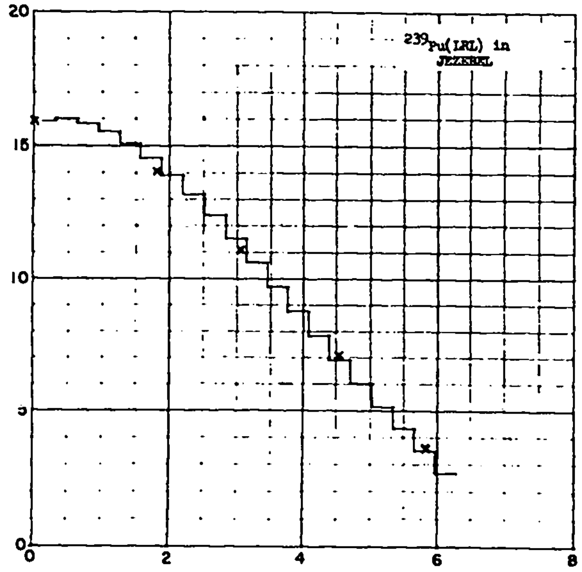

^{238}U(LRL) in TOPSY
0.4
0.3
0.2
0.1
0
0
10
20
30

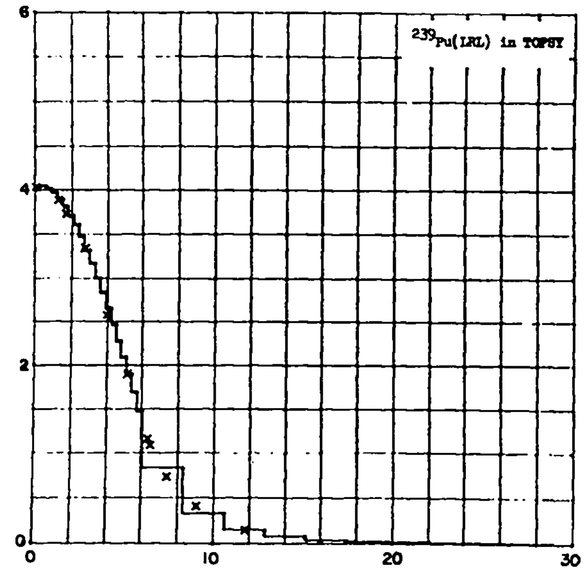

^{238}U(UK) in GODIVA
.28
.26
.24
.22
.20
.18
.16
0
2
4
6
8
10

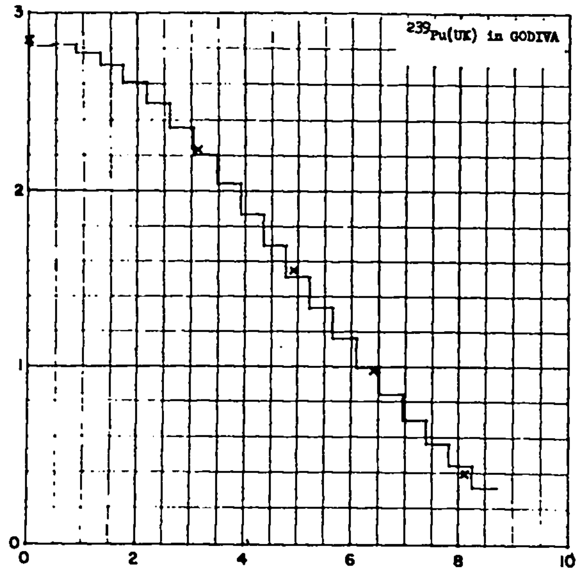

^{238}U(UK) in JEZEBEL
2.0
1.8
1.6
1.4
1.2
1.0
0
2
4
6
8

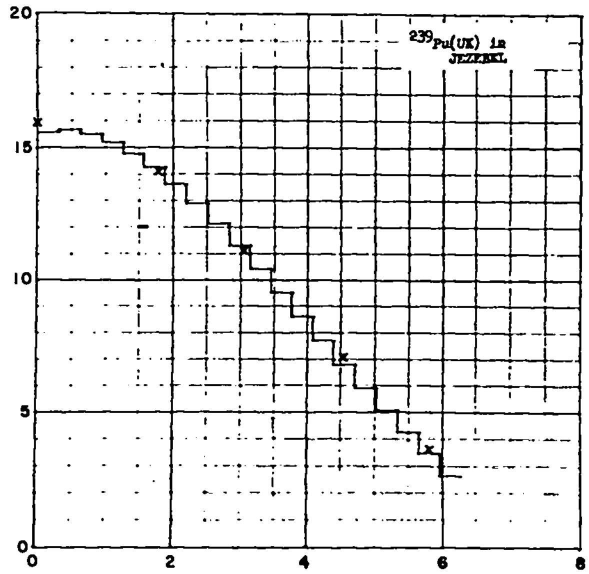

^{238}U(UK) in TOPSY
0.3
0.2
0.1
0
0
10
20
30

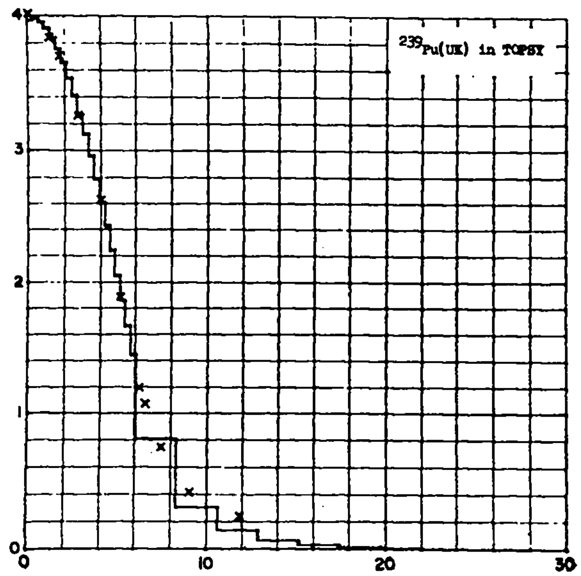

^{239}Pu(LRL) in GODIVA
3
2
1
0
0
2
4
6
8
10


^{239}Pu(LRL) in JEZEBEL


^{239}Pu(LRL) in TOPSY


^{239}Pu(UK) in GODIVA


^{239}Pu(UK) in JEZEBEL


^{239}Pu(UK) in TOPSY

APPENDIX F

GODIVA σ's x 1.1, ALL GROUPS

Act	No Pert	σ_a	$\nu\sigma_f$	$\sigma_{gg'}$	Expt
H	50.462	50.458	50.462	55.514	47.800
D	23.024	23.049	23.024	25.301	17.800
T	3.679	3.679	3.679	4.047	-0.000
HE3	-74.962	-82.953	-74.962	-74.468	-0.000
LI6	-47.135	-52.197	-47.135	-46.787	-0.000
LI7	2.040	2.040	2.040	2.244	-0.000
BE	6.233	6.648	6.233	6.441	7.300
B10	-40.866	-45.171	-40.866	-40.649	-55.300
C	-1.396	-1.396	-1.396	-1.535	2.400
C	1.702	1.701	1.702	1.872	2.400
O	2.043	2.003	2.043	2.285	-0.000
O	2.015	1.969	2.015	2.270	-0.000
NA	.119	.107	.119	.141	-0.000
AL	-.110	-.142	-.110	-.090	.500
MN	4.228	4.186	4.228	4.692	-0.000
FE	-1.679	-1.719	-1.679	-1.809	-.200
NI	-5.627	-6.061	-5.627	-5.757	-4.400
NB	-4.201	-4.440	-4.201	-4.384	-0.000
MO	-3.326	-3.463	-3.326	-3.524	-0.000
TA	-13.833	-15.201	-13.833	-13.851	-0.000
W	.566	.029	.566	1.156	-4.000
TH	-10.019	-11.622	-9.244	-10.194	-1.400
U233	254.838	237.747	297.295	254.953	-0.000
U233	236.966	219.727	277.632	237.233	-0.000
U234	120.746	112.196	141.128	120.985	-0.000
U235	146.259	134.624	172.670	146.106	149.300
ZR	-2.904	-3.005	-2.904	-3.095	-0.000
TA	-13.798	-15.033	-13.798	-13.944	-0.000
U235	152.877	141.620	179.289	153.009	149.300
U236	53.072	49.473	61.187	53.705	-0.000
U238	18.571	16.219	22.726	18.623	24.300
U238	23.653	21.363	27.683	24.293	24.300
PU239	285.852	269.000	330.356	285.792	285.200
PU240	132.681	122.005	156.113	133.102	170.000
PU239	281.227	266.897	323.620	291.283	285.200
PU240	157.624	148.212	182.653	157.767	170.000
PU241	314.782	299.442	360.418	315.963	-0.000
PU241	275.569	259.336	319.444	275.482	-0.000

JEZEBEL

Act	No Pert	σ_a	$\nu\sigma_f$	$\sigma_{gg'}$	Expt
H	45.362	45.343	45.362	49.931	62.800
D	-5.902	-5.664	-5.902	-6.728	-5.300
T	-25.591	-25.599	-25.591	-28.152	-0.000
HE3	-398.266	-436.135	-398.266	-400.223	-0.000
LI6	-210.363	-230.207	-210.363	-211.555	-0.000
LI7	-11.459	-11.459	-11.459	-12.607	-0.000
BE	17.248	20.820	17.248	15.398	15.500
B10	-190.739	-208.822	-190.739	-191.732	-251.000
C	-46.048	-46.048	-46.048	-50.652	-6.900
C	-7.285	-7.299	-7.285	-8.013	-6.900
O	-8.778	-9.129	-8.778	-9.313	-9.900
O	-9.989	-10.495	-9.989	-10.489	-9.900
NA	-12.865	-12.962	-12.865	-14.062	-0.000
AL	-14.651	-14.913	-14.651	-15.863	-14.100
MN	-16.097	-16.270	-16.097	-17.544	-0.000
FE	-22.174	-22.387	-22.174	-24.188	-21.500
NI	-54.555	-57.957	-54.555	-56.622	-48.000
NB	-60.153	-61.024	-60.153	-65.314	-0.000
MO	-48.416	-48.965	-48.416	-52.726	-44.000
TA	-112.826	-118.407	-112.826	-118.542	100.500
W	-88.476	-90.641	-88.476	-95.070	-82.300
TH	-85.343	-93.162	-79.337	-92.083	-64.700

U233	1357.589	1270.959	1583.732	1353.824	1359.000
U233	1245.243	1158.412	1459.587	1242.239	1359.000
U234	725.324	674.086	852.947	721.457	-0.000
U235	797.768	738.791	941.827	792.446	804.000
ZR	-36.678	-37.282	-36.678	-39.763	-35.600
TA	-120.284	-125.202	-120.284	-127.408	-100.500
U235	820.612	763.463	963.661	816.758	804.000
U236	297.178	273.497	355.818	291.930	-0.000
U238	102.648	87.983	133.965	96.243	114.000
U238	98.037	83.732	128.252	91.916	114.000
PU239	1591.129	1507.344	1837.537	1587.602	1592.000
PU240	854.868	795.341	1004.129	850.607	1038.000
PU239	1556.809	1480.580	1792.054	1553.458	1592.000
PU240	982.895	926.101	1141.697	979.069	1038.000
PU241	1646.815	1569.221	1891.538	1644.353	-0.000
PU241	1494.808	1412.923	1730.223	1490.745	-0.000

GODIVA σ's x 1.1 g 1-12

H	50.462	50.460	50.462	50.627	47.800
D	23.024	23.049	23.024	22.959	17.800
T	3.679	3.679	3.679	3.386	-0.000
HE3	-74.962	-77.748	-74.962	-75.200	-0.000
LI6	-47.135	-47.899	-47.135	-47.301	-0.000
LI7	2.040	2.040	2.040	1.889	-0.000
BE	6.233	6.648	6.233	5.991	7.300
B10	-40.866	-41.708	-40.866	-41.003	-55.300
C	-1.396	-1.396	-1.396	-1.808	2.400
C	1.702	1.701	1.702	1.594	2.400
O	2.043	2.003	2.043	1.980	-0.000
O	2.015	1.960	2.015	1.957	-0.000
NA	.119	.109	.119	-.021	-0.000
AL	-.110	-.136	-.110	-.241	.500
MN	4.228	4.221	4.228	4.037	-0.000
FE	-1.679	-1.696	-1.679	-1.865	-.200
NI	-5.627	-6.026	-5.627	-5.827	-4.400
NB	-4.201	-4.212	-4.201	-4.459	-0.000
MO	-3.326	-3.348	-3.326	-3.711	-0.000
TA	-13.833	-14.077	-13.833	-14.378	-0.000
W	.566	.449	.566	.635	-4.000
TH	-10.019	-10.660	-9.244	-10.441	-1.400
U233	254.838	247.557	274.439	254.804	-0.000
U233	236.966	229.734	255.202	236.812	-0.000
U234	120.746	115.130	135.622	120.753	-0.000
U235	146.259	141.312	159.182	145.877	149.300
ZR	-2.904	-2.954	-2.904	-3.151	-0.000
TA	-13.798	-14.001	-13.798	-14.195	-0.000
U235	152.877	148.023	165.727	152.688	149.300
U236	53.022	50.027	61.013	53.113	-0.000
U238	18.571	16.905	22.715	18.415	24.300
U238	23.653	22.027	27.617	23.712	24.300
PU239	285.852	278.205	309.290	285.578	285.200
PU240	132.681	126.583	150.831	132.731	170.000
PU239	281.227	274.121	303.857	281.149	285.200
PU240	157.624	151.136	177.168	157.590	170.000
PU241	314.782	308.241	336.236	314.820	-0.000
PU241	275.569	268.740	296.111	275.307	-0.000

JEZEBEL σ's x 1.1 g 1-12

H	45.362	45.350	45.362	41.758	62.800
D	-5.902	-5.664	-5.902	-9.678	-5.300
T	-25.591	-25.589	-25.591	-28.793	-0.000
HE3	-398.266	-417.136	-398.266	-400.937	-0.000
LI6	-210.363	-215.451	-210.363	-211.883	-0.000
LI7	-11.459	-11.459	-11.459	-12.786	-0.000
BE	17.248	20.820	17.248	15.021	15.500
B10	-190.739	-196.559	-190.739	-192.021	-251.000
C	-46.048	-46.048	-46.048	-50.788	-6.900
C	-7.285	-7.289	-7.285	-8.237	-6.900

O	-8.776	-9.129	-8.778	-9.567	-9.900
O	-9.989	-10.495	-9.989	-10.755	-9.900
NA	-12.865	-12.954	-12.865	-14.134	-0.000
AL	-14.651	-14.891	-14.651	-15.960	-14.100
MN	-16.097	-16.147	-16.097	-18.932	-0.000
FE	-22.174	-22.304	-22.174	-24.231	-21.500
NI	-54.555	-57.828	-54.555	-56.698	-48.000
NB	-60.153	-60.213	-60.153	-65.384	-0.000
MO	-48.416	-48.553	-48.416	-52.845	-44.000
TA	-112.826	-114.336	-112.826	-118.911	-100.500
W	-88.426	-89.134	-88.426	-95.689	-82.300
TH	-85.343	-89.592	-79.337	-92.343	-64.700
U233	1357.589	1306.724	1493.318	1353.665	1359.000
U233	1245.243	1194.889	1370.795	1241.744	1359.000
U234	725.324	685.560	829.868	721.205	-0.000
U235	797.768	763.127	888.127	792.155	804.000
ZR	-36.678	-37.092	-36.678	-39.797	-35.600
TA	-120.284	-121.481	-120.284	-127.591	-100.500
U235	820.612	786.757	909.838	816.439	804.000
U236	297.178	275.556	354.970	291.204	-0.000
U238	102.648	90.523	133.914	96.076	114.000
U238	98.037	86.271	127.957	91.109	114.000
PU239	1591.129	1537.493	1753.821	1587.303	1592.000
PU240	854.868	811.875	981.758	850.186	1038.000
PU239	1556.809	1507.125	1713.608	1553.346	1592.000
PU240	982.895	937.652	1118.470	978.895	1038.000
PU241	1646.815	1601.225	1795.157	1642.663	-0.000
PU241	1494.808	1447.054	1637.286	1490.609	-0.000

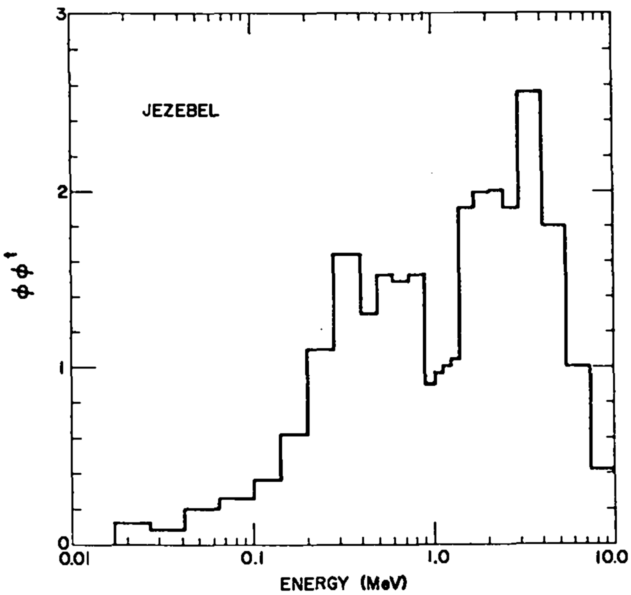


Fig. F-1. Reactivity weighing function $\phi\phi^+(r = 0)$ in JEZEBEL.

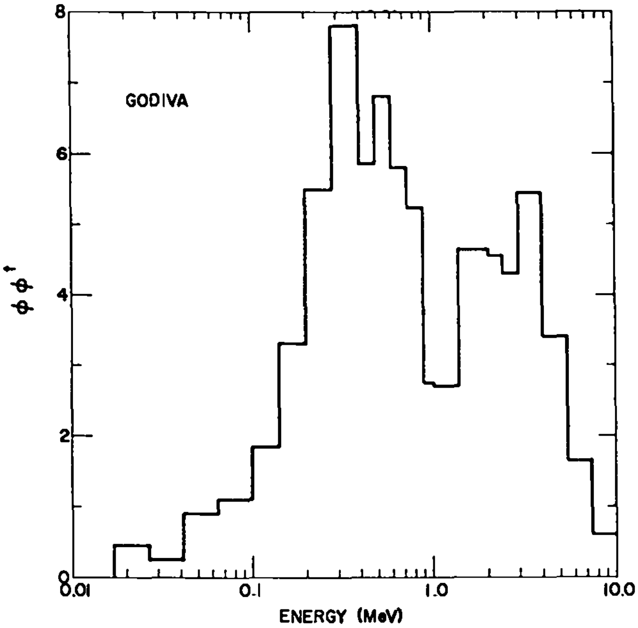


Fig. F-2. Reactivity weighing function $\phi\phi^+(r = 0)$ in GODIVA.

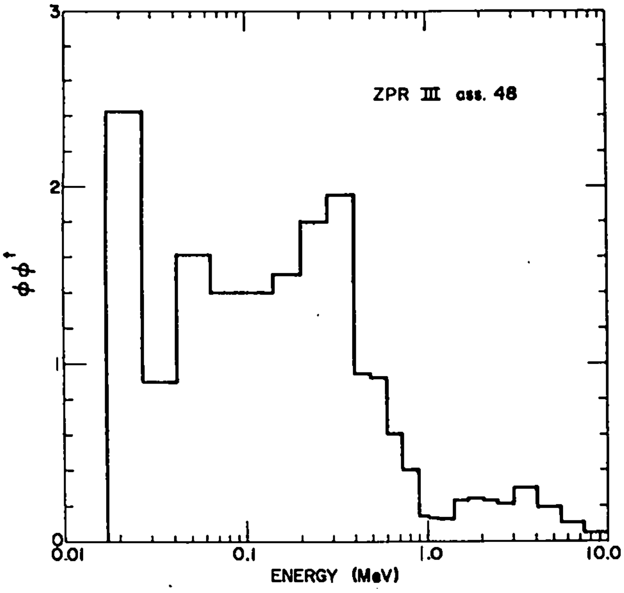


Fig. F-3. Reactivity weighing function $\phi\phi^+(r = 0)$ in ASSEMBLY 48.

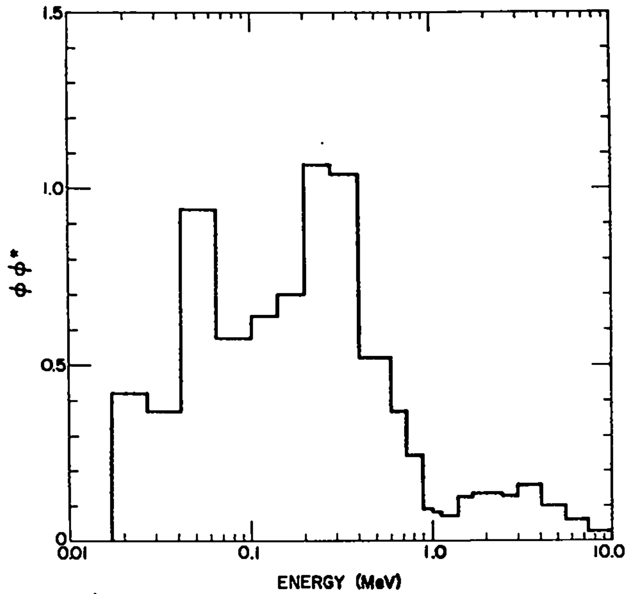


Fig. F-4.

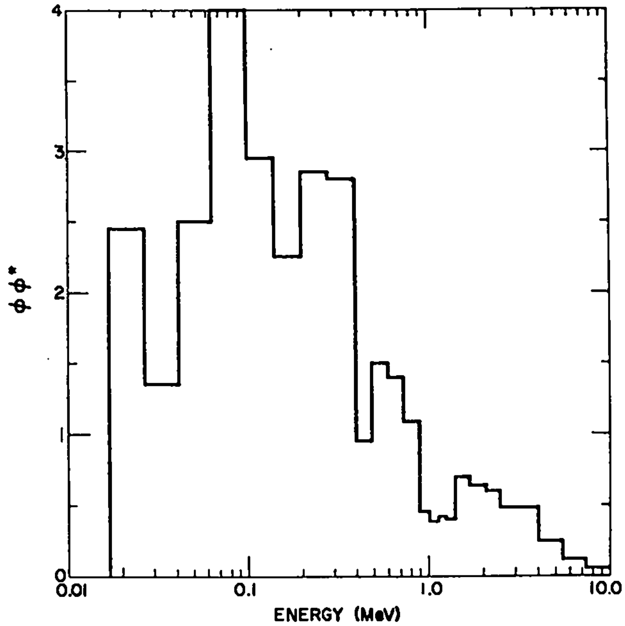


Fig. F-5.