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The Spectral Distribution of Neutrons and Neutron Reaction Cross Sections in an Unreflected Uranium-235 Critical Assembly and the Fission Neutron Spectrum

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Previously reported inconsistencies between activation detector and n,p scattering/time-of-flight (TOF) measurements of the thermal-neutron-induced ^{235}U fission spectrum prompted a comparison of such measurements in the core center and on the surface of a bare ^{235}U assembly, referred to as Godiva. For the present study, TOF measurements and multiple foil measurements of the core and surface spectra of the APFA-III-Godiva are compared. Comparison of the integral fluxes above specified energies for the two methods shows agreement to within ~5% at core center. Results obtained at $\frac{1}{2}$ in. from the core surface, however, show disagreement between the multiple foil and TOF (and previously reported photo-plate data) which is similar to that found for measurements in the fission spectrum. Results for the fission spectrum are re-analyzed using the same evaluated energy-dependent cross sections as used for the Godiva study but with a larger number of foil reactions than previously available. A Monte Carlo error analysis code is used for the assignment of errors for the activation results for the Godiva and fission spectrum studies. It is concluded that if the activation measurements of the Godiva and fission spectrum remain firm, and significant changes in current evaluated reaction cross sections are not effected, then increases up to as much as 10 to 15% in the mean energy of the Godiva leakage and fission spectrum must be considered.

INTRODUCTION

Inconsistencies between activation detector and n-p scattering photoplate (PP)/time-of-flight (TOF) measurements of the thermal-neutron-induced ^{235}U fission spectrum have been reported.[1-3,a] Forms of the fission spectrum previously derived from activation measurements

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[a]References listed at end of paper.

have up to 0.2 to 0.3 MeV higher mean energies and up to 30% greater integral flux above 3 MeV than reported by Watt,[4] Cranberg et al.,[5] and others who used PP and TOF techniques. As recently suggested by Grundl,[6] if the activation measurements of reaction rates and the shape of the fission spectrum determined by differential techniques are accepted, then fission as well as other reaction cross sections must be modified by amounts outside the range of uncertainty of current measurements.

The higher energy forms of the fission spectrum yield calculated values of the Fermi age to indium resonance in water that are higher by up to ~2 to 3 cm^2 than that obtained with the Watt or Cranberg forms.[7,8] For D_2O and graphite systems, however, they appear to give values in close agreement with experiment.[9] These higher energy forms have also been shown to yield higher calculated $^{238}U/^{235}U$ fission ratios for some uranium-H_2O lattices, and to decrease by ~ 1.7% eigenvalues of some homogeneous ^{235}U-H_2O spheres, presently in agreement with experiment[7,10] to better than 0.4%. The implications of many of these discrepancies have been discussed recently by Grundl,[2,6] Fabry,[3,9] Fabry et al.,[8] and Fabry and Vandeplas,[11] Smith,[12] Jaffey,[13] and Lubitz and Stewart.[14] Green[15,16] recently reported integral and differential measurements of the ^{252}Cf fission spectrum which are in serious disagreement with those of Meadows.[17] Leonard and Thomsen have analytically studied the effect of an energy dependent ν value on the high energy part of the fission spectrum for a bare ^{235}U assembly and find a hardening effect,[18] which experimentally has not been reported.

In the study over the last decade of neutron flux and fluence monitors, agreement has not been reached on a fission spectrum averaged cross section ($\bar{\sigma}^f$) for one of the most widely used monitors, $^{54}Fe(n,p)^{54}Mn$. The often recommended value of 68 mb for this reaction is seldom used. Most experimenters use values between 82 and 91 mb, which provide better overall consistency with the results of other monitors or monitoring techniques. Preliminary absolute measurements by Fabry suggest a value[9] of around 89 mb. The harder energy forms of the fission spectrum with current evaluated energy-dependent cross sections [$\sigma(E)$] yield calculated values of $\bar{\sigma}^f$ for this reaction that are in better agreement with the value of 89 than 68. Similarly, for the $^{238}U(n,f)FP$ monitor, recently revised[19-21] $\sigma(E)$'s yield calculated values of $\bar{\sigma}^f$ in the Watt and Cranberg form of the fission spectrum of ~ 278 to ~ 289 mb that are in disagreement with measured absolute values of ~ 304 to ~ 353 mb.[5,22-25] The harder energy forms of the fission spectrum yield calculated values that range from ~ 314 to 335 (see Ref. 1 and the last part of this paper), which are in better agreement with experiment.

Inconsistencies of the types indicated above (~ 10 to 30%) cannot be ignored. Without adequate explanations for them, these inconsistencies cast doubt on the reliability of (a) previous PP/TOF measurements of the fission spectrum, (b) existing measured and evaluated cross-section data, and (c) multiple-foil integral flux measurements.

Previous interlaboratory studies of (a) the multiple foil method and activation detector cross-section and flux spectral data, (b) spectrometry data, and (c) reactor physics calculations for different thermal and fast reactor environments have helped in establishing areas and limits of uncertainty for these three methods of analysis.[26-31]

The present interlaboratory study[32] intercompares results for a bare ^{235}U assembly, designated as Godiva by Frye, Gammel, and Rosen,[33] and others. Neill, Crosbie, and Russell[34] made TOF measurements and we made multiple foil measurements of the core and surface spectra of the APFA-III-Godiva, an unreflected spherical critical assembly composed of uranium metal enriched to 93% in the ^{235}U isotope. The assembly is located at Gulf General Atomic.

An important objective of this test was to determine if the multiple foil method with current evaluated reaction cross sections and reaction rate measurements would yield flux-spectral results that were in as good or better agreement with reactor physics calculations and/or spectrometer measurements than that obtained in more complex environments.[26,29,30] In addition, previously reported[1-3] results for the fission spectrum were re-analyzed using the current evaluated reaction cross sections so that similarities and/or differences in results for the ^{235}U assembly and fission spectrum could be directly compared and used in the study and definition of areas of major uncertainty in the three methods of analysis.

REACTION RATES

The choice of foil material was dictated primarily by the range of neutron energy coverage, the half-life of the product nuclide, and the accuracy of the reaction cross section. Table I lists the foil detectors and pertinent physical and nuclear data that are applicable for this test. The foils were ~ 1/2 in. in diameter for the core center position and were packaged together within a length of ~1/2 in. With this arrangement, spectral perturbation and gradient/attenuation effects for any foil were estimated[2] to be < ~ 3%. Except for

TABLE I

Foil Detector Nuclear and Physical Properties

Foil Form[a]	Foil Reaction	Product Nuclide's Half-Life
^{238}U (0.02 to 5 mil)	$^{238}U(n,\gamma)^{239}U$	[b]
	$^{238}U(n,f)FP$	[b]
^{232}Th (10-mil foil)	$^{232}Th(n,f)FP$	[b]
^{235}U (0.02 to 5 mil)	$^{235}U(n,f)$ FP	[b]
^{239}Pu (0.001 mil)	$^{239}Pu(n,f)FP$	[b]
^{237}Np (0.01 mil)	$^{237}Np(n,f)FP$	[b]
NaCl (50 to 200-mil foil)	$^{23}Na(n,\gamma)^{24}Na$	15.0 h
Au (0.05 and 2-mil foil)	$^{197}Au(n,\gamma)^{198}Au$	2.698 days
Co (0.5-mil foils)	$^{59}Co(n,\gamma)^{60}Co$	5.268 days
Mn (1.29% MnF_2 in LiF, 40 mil)	$^{55}Mn(n,\gamma)^{56}Mn$	2.576 h
Cu (0.5 to 100-mil foils)	$^{63}Cu(n,\gamma)^{64}Cu$	12.84 h
	$^{63}Cu(n,\alpha)^{60}Co$	5.268 yr
In (2 to 10-mil foils)	$^{115}In(n,n')^{115m}In$	4.50 h
	$^{115}In(n,\gamma)^{116m}In$	54.2 h
Fe (20 to 40-mil foils)	$^{54}Fe(n,p)^{54}Mn$	313.5 days
	$^{56}Fe(n,p)^{56}Mn$	2.576 h
Sc (20-mil foil)	$^{45}Sc(n,\gamma)^{46}Sc$	84.0 days
S (70 to 250-mil foils)	$^{32}S(n,p)^{32}P$	14.4 days
Ni (20-mil foil)	$^{58}Ni(n,p)^{58}Co$	71.3 days
Ti (10-mil foil)	$^{46}Ti(n,p)^{46}Sc$	84.0 days
Al (5-mil foil)	$^{27}Al(n,\alpha)^{24}Na$	15.0 h
	$^{27}Al(n,p)^{27}Mg$	9.5 min
Mg (5-mil foil)	$^{24}Mg(n,p)^{24}Na$	15.0 h
KI (50 to 90-mil foils)	$^{127}I(n,2n)^{126}I$	13.1 days

[a]All foils were ~0.5 in. in diameter.

[b]These reactions were analyzed by fission product (^{95}Mo and ^{140}Ba) and/or fission track counting [except for the $^{238}U(n,\gamma)$ reaction which was analyzed by ^{239}Np counting] by Armani,[35] Tochilin,[36] and Zimmer.[37]

the fission foils, the thinner foils in Table I were used for the core center position.

At the surface 14 circumferentially equally spaced positions, 0.500 in. (-0.000, +0.010 in.) from the surface (~ 4.12 in. from the center), were used to obtain a simultaneous irradiation of thick, sandwiched, bare, and cadmium-covered foils. The 1/2-in. position was used to reduce the magnitude of flux gradient corrections for foil position and thickness differences. Except for the fission and for the thickest Cu, NaCl, and S foils, foils were grouped such that the thickness of any one set was $<\sim 0.1$ in. and were carefully packaged so that the distance from the surface of each foil to the 0.5 in. position was known to within ~ 0.010 in.[38] The ^{238}U, ^{235}U, ^{237}Np, ^{232}Th, and ^{239}Pu fission foils were placed separately at 5 of the 14 locations. Except for bare copper and indium foils, all surface foils were covered with ~ 20 mils of cadmium.

Most of the core center and surface foils were irradiated[39] simultaneously for a period of 5.6 h at a constant reactor power of ~130 W. Two separate low power runs were made for the fission track foils. (The track technique was used only for the core surface position because the available foil holders were too large for the central position.) One surface position was used to place sulfur foils for subsequent power level normalization between the low and high power runs. Copper and gold foils on the surface and in the core center were also used to check the sulfur results. Reactor power level instrument readings were used together with the foil results to normalize the fission track results to the ~ 130-W high power run (see Appendix A).

For the high power run, cadmium-covered copper (0.5 mils) foils at vertical distances of ~1, 2, 4, and 8 in. above the sphere gave reaction rate gradient information. A bare copper foil on top of the furthest-out cadmium-covered foil provided a measure of the direct room return equivalent thermal flux. The $^{63}Cu(n,\gamma)^{64}Cu$ measured results together with those obtained from other core center and surface foils, and from reactor physics calculations,[34,40] yielded a reaction rate gradient correction factor of ~0.067%/mil for distances between 0.5 and 0.75 in. from the surface for low and high energy neutron detectors. The equivalent 2200 m/sec direct room return thermal flux was measured to be $\sim 2.7 \times 10^6$ n/(cm^2 sec) at the 1/2-in. distance at the ~ 130-W power level. It was $\sim 2.5 \times 10^6$ n/(cm^2 sec) ~8 in. above the sphere.

Comparable capability for measuring the foil activities exists at each of the laboratory sites (ANL,[35] USNRDL,[36] PNL,[41] ARHCO,[37] GGA[42]) involved in this test. Each laboratory measured particular foils or foil sets. Calibrated gamma-ray counting systems were utilized such as NaI(Tl) and Ge(Li) detectors. One laboratory (ARHCO) counted ^{140}Ba[43] directly for the fission foils. The track counting technique[44,45] was used by two laboratories (USNRDL and ANL) while one laboratory (ANL) performed chemical separations for ^{99}Mo.[43,46] Except for the $Pu(n,f)$ result, which is based on two track results, averaged values of fission rates are given based on up to three different measurement techniques. The results of individual laboratories are compared and discussed in Appendix A.

For this work, measured reaction rates with estimated absolute uncertainties of less than ~ 10%, 1 standard deviation or 1 standard error, are given in Table II for ~ 20 reactions for the core center (column 2) and surface (column 6) locations. The relative uncertainty between the core center and surface results is much less than the absolute uncertainty, as indicated by detectors with similar energy response; i.e., the monitors $^{238}U(n,f)$, $^{32}S(n,p)$, $^{54}Fe(n,p)$, and $^{58}Ni(n,p)$ all have a core center-to-surface reaction rate ratio[50] of ~ 6.9. [Problems associated with both the counting and selection of suitable fission yields for the ^{99}Mo and ^{140}Ba reaction products were encountered

TABLE II

APFA-III Core Center and Surface — Absolute Measured Values of Reaction Rates*
($\times 10^{15}$)

Reaction	Core Center				Core Surface[b]	Ratio
	This Work	Grundl Hansen[a]	Hansen[48] Byers[49]	Average of Three Measurements	This Work	
$^{239}Pu(n,f)FP$	-	-	61.9	61.9	9.56 ± 11%†	6.48
$^{235}U(n,f)FP$	40.6 ± 8%	41.6	43.6	41.9 ± 2%	6.02 ± 8%	6.74
$^{237}Np(n,f)FP$	-	34.3	-	34.3	4.85 ± 10%	7.08
$^{238}U(n,f)FP$	6.84 ± 6%	6.67	6.79	6.77 ± 1%	0.993 ± 4%	6.89
$^{232}Th(n,f)FP$	1.93 ± 2%	-	-	1.93 ± 2%	0.230 ± 7%	8.39
$^{238}U(n,\gamma)^{239}U$	3.39 ± 5%	-	3.20	3.30 ± 3%	0.468 ± 5%	7.24
$^{197}Au(n,\gamma)^{198}Au$	4.65 ± 7%[d]	-	4.57	4.61 ± 1%	1.33 ± 7%[e]	3.50
$^{197}Au(n,\gamma)^{198}Au$	4.65 ± 7%	-	-	-	0.669 ± 7%[f]	6.95
$^{59}Co(n,\gamma)^{60}Co$	0.255 ± 7%[g]	-	-	0.255 ± 7%	0.0801 ± 7%[g]	3.18
$^{23}Na(n,\gamma)^{24}Na$	0.0122 ± 7%	-	-	0.0122 ± 7%	0.00164 ± 7%	7.44
$^{63}Cu(n,\gamma)^{64}Cu$	0.468 ± 7%	-	-	0.468 ± 7%	0.0586 ± 7%	7.99
$^{63}Cu(n,\gamma)^{64}Cu$	0.468 ± 7%	-	-	-	0.0708 ± 7%[h†]	6.61
$^{115}In(n,\gamma)^{116m}In$[i]	3.29 ± 30%†	-	5.49	4.39 ± 30%	0.560 ± 10%	5.88
$^{115}In(n,\gamma)^{116m}In$	3.29 ± 30%	-	-	-	0.964 ± 10%[i†]	3.41
$^{58}Fe(n,\gamma)^{59}Fe$	0.125 ± 7%	-	-	0.125 ± 7%	-	-
$^{45}Sc(n,\gamma)^{46}Sc$	0.293 ± 7%	-	-	0.293 ± 7%	0.0449 ± 7%	6.53
$^{55}Mn(n,\gamma)^{56}Mn$	-	-	-	-	0.0252 ± 5%	-
$^{115}In(n,n')^{115m}In$	4.74 ± 5%	-	-	4.74 ± 5%	0.634 ± 5%	7.48
$^{31}P(n,p)^{31}Si$	-	0.780	-	0.780	-	-
$^{32}S(n,p)^{32}P$	1.54 ± 7%	-	-	1.54 ± 7%	0.225 ± 2%	6.84
$^{54}Fe(n,p)^{54}Mn$	1.78 ± 2%	-	-	1.78 ± 2%	0.261 ± 2%	6.82
$^{56}Fe(n,p)^{56}Mn$	0.0287 ± 7%	0.0239	-	0.0263 ± 9%	0.00386 ± 7%	7.43
$^{58}Ni(n,p)^{58}Co$	2.40 ± 2%	-	-	2.40 ± 2%	0.347 ± 2%	6.92
$^{46}Ti(n,p)^{46}Sc$	0.288 ± 7%	-	-	0.288 ± 7%	0.0394 ± 7%	7.31
$^{27}Al(n,p)^{27}Mg$	0.0923 ± 7%	0.0967	-	0.0945 ± 2%	0.0154 ± 7%	5.99
$^{27}Al(n,\alpha)^{24}Na$	0.0163 ± 2%	0.0156	-	0.0160 ± 2%	0.00253 ± 2%	6.44
$^{24}Mg(n,p)^{24}Na$	0.0337 ± 7%	-	-	0.0337 ± 7%	0.00494 ± 7%	6.82
$^{127}I(n,2n)^{126}I$	0.0244 ± 7%	-	-	0.0244 ± 7%	0.00393 ± 7%	6.21
$^{63}Cu(n,\alpha)^{60}Co$	-	-	-	-	0.00172 ± 10%†	-
$^{63}Cu(n,2n)^{62}Cu$	-	0.00256	-	0.00256	-	-

*Units of disintegrations or fissions per second per target nuclei at a stated reactor power of ~130 W; all surface foils are covered with ~20 mils of cadmium unless specified otherwise. (There is, in addition, ~0.5 mils of nickel and copper, and 10 to 15 mils of cadmium covering all internal and external components of the sphere.) A dagger indicates that the result was not used in subsequent SAND-II data analysis because of the uncertainty in the measured reaction rate and/or SAND-II reaction cross section.

[a]Reference 47, relative measurements. These and Hansen's and Byers' results were normalized to those of the present work by minimization of the sum of the squares of the differences between all reactions common to the present work. The activation detector fission reaction rate measurements are compared with fission chamber measurements in Ref. 47. They agree to within ~2%. The $^{115}In(n,\gamma)$ result was not used in establishing this normalization because of excessive deviation in measured reaction rates between laboratories.

[b]At a distance of 0.500 in. (-0.000 in., +0.010 in.) from the core surface; ~10.46 cm from the core center.

[c]Ratio of core center over core surface, this work, except for ^{237}Np and ^{239}Pu, which are compared with Grundl, Hansen, and Byers' values.

[d]0.05-mil foils. (Average value of three sandwiched foils; center foil was <1% lower than average value.)

[e]0.05-mil foils. (Value for middle of three sandwiched foils, center foil was ~2% lower than average value of outer two foils which had equal activities to within ~2%.)

[f]2-mil foils. (Value for middle of three sandwiched foils, center foil was 10% lower than outer two foils, which had equal activities.) There was ~15 mils copper on side of foils away from the core surface.

[g]0.5-mil foils. (Average of three sandwiched foils for core center, no measurable self-shielding effect; the surface foils showed a self-shielding effect, the outer foil was 15% higher than the center foil, which in turn was <1% higher than the foil closest to the sphere. These three results were used to extrapolate to a result for an infinitely dilute foil, an estimated +5% correction for the outer foil.)

[h]Bare foil on top of cadmium. The difference between a cadmium covered and bare 0.5-mil foil yields a thermal flux value of 2.7×10^6 n/(cm^2 sec) based on a 2200 m/sec cross section of 4.51 b for copper.

[i]2- and ~5-mil foils used in the core center and surface, respectively.

[j]Bare foil on top of cadmium. The difference between a cadmium covered and this bare 5-mil foil yields a thermal flux value of 2.6×10^6 n/(cm^2 sec) based on a 2200 m/sec cross section of 155 b for indium.

with the analysis of the ^{232}Th(n,f) reaction, which has a similar response to ^{238}U(n,f), but a higher ratio of 8.39. Consequently, the assigned ± 2% uncertainty appears to be more a measure of precision than of accuracy between the two laboratories reporting values.]

The lack of consistency for the ratios for resonance detectors (in particular gold and cobalt) and thick, thin, sandwiched, and bare foils is not a result of data inaccuracies but indicates the presence of low energy/room return neutrons for the surface position. This conclusion is based on a study of integral flux solutions which includes room return neutrons. It yielded calculated values of reaction rates in agreement with measured values for bare, sandwiched, thick and thin, and cadmium-covered foils.

For the most important reactions, the present core center results are in good agreement with the high precision relative foil and fission chamber measurements of Grundl and Hansen[47] and Hansen,[48] and Byers,[49] columns 3 and 4. This agreement establishes increased confidence in the accuracy of many of the most important Godiva reaction rate measurements, Table II, as well as in Grundl's[2] (and indirectly, Fabry's[3]) previous results for the fission spectrum. It suggests that errors in the more important reaction rate measurements are not a significant cause of inconsistencies between activation, spectrometry, and reactor physics results.

BARE ^{235}U ASSEMBLY FLUX SPECTRUM

Measured

The relative accuracy and consistency of all the present reaction rate measurements and corresponding SAND-II evaluated energy-dependent cross sections are not as firmly established experimentally as those of Grundl's for his fission spectrum study.[2,20] Nevertheless, a set of reactions considered to be reasonably self-consistent was selected from those listed in Table II for subsequent SAND-II analysis. For the central core spectrum, averages of the values listed were obtained for comparison of measured and calculated absolute values of spectral averaged cross sections.

Reaction rates measured in the present test, denoted by entries without a cross in Table II, together with different spectral approximations, were input to the SAND-II code[1,26,27,29] to obtain flux spectral solutions for comparison with the TOF and PP results. In Table III, for core center, the small deviation among results with different input forms indicates that the average solution depends on the accuracy of the measured reaction rates and reaction energy-dependent cross sections, but not on the input spectral form. Thus this average solution provides an essentially independent measurement of the APFA-III central core spectrum for comparison with the TOF data. [Such uniqueness was also found for measurements in the fission spectrum,[1] and more recently for measurements in Experimental Breeder Reactor-II (EBR-II).[28,30]] Comparison of the integral fluxes above specified energies for the average solution with Neill's 0-deg angular TOF results, in the last row of Table III, shows agreement[51] to within ~ 5%. (There are no TOF data for comparison above 11 MeV.)

The uncertainty in this average solution due to errors in measured reaction rates and SAND-II evaluated cross sections was investigated by a Monte Carlo technique.[53] (More details on the procedure, analysis, and error assignments are provided in Appendix B.) Results (one standard deviation) are given under the average solution integral flux values, Table III. Corresponding uncertainties in the best SAND-II differential flux solution, run 8, Table III, are shown in Fig. 1. Neill's TOF measurements are also shown for comparison. There is little effect on the average solution by not using ^{232}Th(n,f) as well as a few other reactions expected to have large uncertainties as shown by run 9, Table III.

Similar results, Table IV and Fig. 2, were obtained at 1/2 in. above the core surface where fission reaction rate measurements, by track and

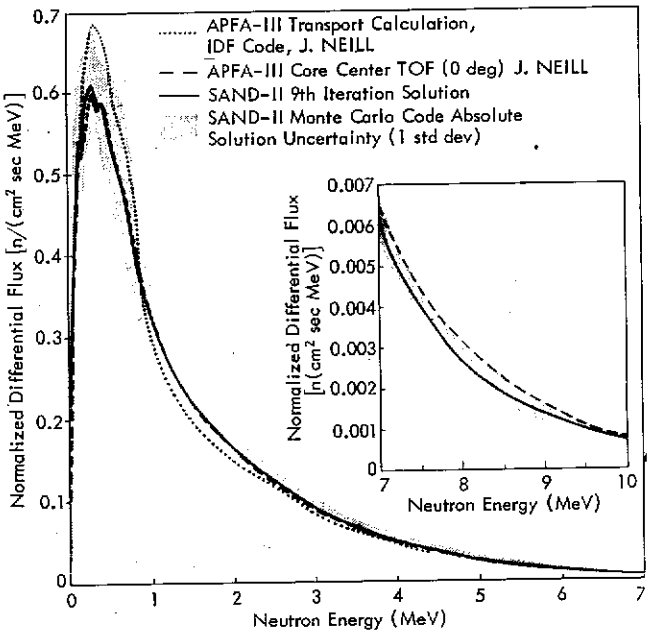

Fig. 1. APFA-III bare ^{235}U assembly central core spectrum.

TABLE III

SAND-II Absolute Integral Flux Solution Comparison — APFA-III Core Center

Run	Input Spectral Form[a]	Foil Reactions Used	Solution[b]		Average[c] Energy (MeV)		Integral Flux Values Above Specified Neutron Energies[d] (MeV) × 10^{-10} [n/(cm^2 sec)]							
			K	*SPD*	>0.01	>0.4	0.01	0.1	0.4	0.9	1.4	3.0	6.0	11.0
1	1	20[e]	41	6.3	1.96*	1.99	2.792*	2.771*	2.751	2.228	1.471	0.5012	0.06531	0.001963
2	2	20	33	5.7	1.54	1.83	3.632	3.576	2.955	1.969	1.406	0.5145	0.06567	0.001947
3	3	20	22	4.2	1.67	1.94	3.248	3.137	2.735	1.969	1.432	0.5099	0.06416	0.001938
4	4	20	12	5.7	1.62	1.93	3.372	3.237	2.755	1.988	1.446	0.5082	0.06319	0.001939
5	4	17[f]	19	5.2	1.61	1.92	3.407	3.277	2.777	1.995	1.449	0.5062	0.06406	0.001939
6	5	20	14	5.4	1.57	1.86	3.526	3.438	2.893	2.005	1.420	0.5164	0.06378	0.002070
7	6	20	9	5.4	1.55	1.87	3.570	3.499	2.856	1.942	1.416	0.5211	0.06261	0.002051
8	7	20	6	5.3	1.56	1.90	3.501	3.402	2.802	1.938	1.409	0.5209	0.06280	0.002040
9	7	14[g]	22	4.0	1.55	1.98	3.362	3.246	2.550	1.800	1.356	0.5161	0.06437	0.002070
Average value*					1.58	1.91	3.452	3.352	2.786	1.982	1.423	0.5127	0.06399	0.001995
Percent standard deviation (Monte Carlo analysis)					±2.5	±4.5	±3.9	±4.5	±7.1	±6.0	±5.1	±6.7	±7.5	±29
Normalized average value (NAV)					1.58	1.91	1.000	0.9710	0.8071	0.5742	0.4122	0.1485	0.01854	0.0005779
Normalized TOF value[34]					1.56	1.88	0.9995	0.9713	0.8033	0.5515	0.3964	0.1457	0.01957	-
Ratio (NAV)/(TOF)					-	-	1.000	0.997	1.005	1.041	1.040	1.019	0.9474	-

*Excluded from average because of excessive deviation from the mean; the extreme form of the input spectral form was the cause of this excessive deviation.

[a]Number 1 is based on a $1/E$ form between 10^{-10} and 18 MeV. Number 2 is based on an E form between 10^{-10} and 18 MeV. Number 3 is based on a constant form between 10^{-10} and 18 MeV. Number 4 is based on a constant form above 10^{-2} MeV and an E form below. Number 5 is a Watt fission form.[4] Number 6 is the Godiva leakage spectrum above 10^{-5}, zero below.[33] Number 7 is Neill's TOF data (0-deg angular flux), Ref. 34.

[b]The convergence criterion used was that the change between the solution standard percent deviation (SPD) between successive iterations had stabilized to less than 1% (see Refs. 26 and 27). The *SPD* is defined as

$$SPD^{(K)} = \left[\frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{A_i^{(K)} - A_i^m}{A_i^{(K)}}\right)^2\right]^{1/2},$$

where n is the number of foil reactions, A_i^m is the measured reaction rate for the i'th foil, and $A_i^{(K)}$ is a calculated value using the solution differential flux at the K'th cycle of iteration and the energy-dependent cross section for the i'th foil. In general, iteration beyond a stability limit of 1% produces little change in integral flux.

[c]Defined as $\bar{E}(>E) \equiv \int_E^\infty E\phi(E)\,dE \Big/ \int_E^\infty \phi(E)\,dE$.

[d]The energy values have been selected to correspond to those used by Grundl[2] and Grundl and Hansen[47] and the magnitudes of the fluxes are for a stated APFA-III reactor power of 130 watts.[39] The fraction of the flux below 10^{-2} MeV is estimated to be <0.05%.

[e]Fission and non fission foils.

[f]Non fission foils only were used.

[g]Run with the more reliable foil reaction cross sections; i.e., $^{235}U(n,f)$, $^{238}U(n,f)$, $^{238}U(n,\gamma)$, $^{197}Au(n,\gamma)$, $^{23}Na(n,\gamma)$, $^{58}Ni(n,p)$, $^{54}Fe(n,p)$, $^{56}Fe(n,p)$, $^{27}Al(n,p)$, $^{32}S(n,p)$, $^{27}Al(n,\alpha)$, $^{24}Mg(n,p)$, $^{127}I(n,2n)$, $^{115}In(n,n')$.

TABLE IV

TABLE IV

SAND-II Absolute Integral Flux Solution Comparison — AFPA-III Core Surface

Run	Input Spectral Form[a]	Foil Reactions Used	Solution[b]		Average[c] Energy (MeV)		Integral Flux Values Above and Below Specified Neutron Energies[d] (MeV) × 10^{-9} [n/(cm² sec)]										
			K	*SPD*	>0.01	>0.4	$<4\times10^{-7}$	<0.0001	<0.01	>0.01	>0.1	>0.4	>0.9	>1.4	>3.0	>6.0	>11.0
1	1	23[e]	26	6.5	2.02	2.08	0.004728	0.01375	0.03043	3.632	3.616	3.518	2.749	1.984	0.7430	0.09040	0.003180
2	2	23	16	20.8	1.43	1.82	0.000000*	0.00004*	0.00252*	5.423	5.324	4.076	2.539	1.852	0.7465	0.09742	0.003230
3	3	23	16	6.9	1.71	2.08	0.000001*	0.00085*	0.01508*	4.277	4.094	3.434	2.555	1.934	0.7529	0.09223	0.003162
4	4	23	12	20.7	1.56	2.04	0.000000*	0.00004*	0.01375*	4.727	4.453	3.485	2.516	1.908	0.7551	0.09377	0.003202
5	5	23	28	7.4	1.60	2.05	0.000000*	0.00078*	0.00595*	4.580	4.420	3.456	2.480	1.896	0.7741	0.09109	0.003386
6	6	23	23	5.4	1.84	2.06	0.004676	0.01034	0.02070	4.014	3.964	3.524	2.663	1.948	0.7563	0.09116	0.003283
7	6	22[f]	25	4.1	1.90	2.12	0.004817	0.01083	0.02341	3.780	3.731	3.344	2.583	1.920	0.7591	0.09106	0.003280
8	6	19[g]	24	4.1	1.95	2.20	0.004930	0.01131	0.02499	3.590	3.537	3.122	2.444	1.900	0.7652	0.09090	0.003277
Average value* (scalar flux)					1.75	2.06	0.004788	0.01156	0.02488	4.253	4.142	3.495	2.566	1.918	0.7565	0.09225	0.003250
Percent standard deviation (Monte Carlo analysis)					±2.9	±3.0	±2.3	±13	±17	±4.4	±4.5	±4.7	±5.5	±5.5	±4.0	±7.4	±19
Normalized average value (NAV)					-	-	0.001119	0.002702	0.005816	0.9942	0.9682	0.8170	0.5998	0.4483	0.1768	0.02156	0.0007597
Normalized TOF corrected to scalar flux (TOFSF)[h]							-	-	-	0.9905	0.9637	0.8168	0.5763	0.4150	0.1548	0.02114	-
Normalized leakage spectrum corrected to scalar flux (LSSF)[i]										0.9934	0.9782	0.8298	0.5571	0.3974	0.1466	0.02041	-
Ratio (NAV)/(LSSF)					-	-	-	-	-	1.001	0.9898	0.9846	1.077	1.128	1.206	1.056	-
Ratio (NAV)/(TOFSF)					-	-	-	-	-	1.003	1.005	1.000	1.041	1.080	1.141	1.020	-

*Excluded from average because the input spectral form was too extreme to allow a proper low energy component to be generated.

[a]Number 1 is based on a 20°C thermal Maxwellian form below 4×10^{-7} MeV and a $1/E$ form between 4×10^{-7} and 18 MeV. Number 2 is based on a 20°C thermal Maxwellian form below 4×10^{-7} MeV and an E form between 4×10^{-7} and 18 MeV. Number 3 is based on a 20°C thermal Maxwellian form below 4×10^{-7} MeV and a constant form between 4×10^{-7} and 18 MeV. Number 4 is based on a constant form above 10^{-2} MeV, an E form between 4×10^{-7} and 10^{-2} MeV, and a 20°C thermal Maxwellian form below 4×10^{-7} MeV. Number 5 is a Watt fission form.[4] Number 6 is Neill's TOF data (0-deg angular flux),[34] extended below $\sim10^{-2}$ MeV with a $1/E$ form matched to a 20°C thermal Maxwellian form below 4×10^{-7} MeV.

[b]The convergence criterion used was that the change between the solution standard percent deviation (SPD) between successive iterations had stabilized to less than 1% (see Refs. 26 and 27). The *SPD* is defined as

$$SPD^{(K)} = \left[\frac{1}{n-1}\sum_{i=1}^{n'}\left(\frac{A_i^{(K)} - A_i^m}{A_i^{(K)}}\right)^2\right]^{1/2},$$

where n is the number of foil reactions, A_i^m is the measured reaction rate for the j'th foil, and $A_i^{(K)}$ is a calculated value using the solution differential flux at the K'th cycle of iteration and the energy-dependent cross section for the i'th foil. In general, iteration beyond a stability limit of 1% produces little change in integral flux.

[c]Defined as $\bar{E}(>E) = \int_E^\infty E\phi(E)\,dE / \int_E^\infty \phi(E)\,dE$.

[d]The energy values have been selected to correspond to those used by Grundl[2] and Grundl and Hansen[47] and the magnitudes of the fluxes are for a stated APFA-III reactor power of 130 watts.[39]

[e]Fission and nonfission foils listed in Table II. The ^{239}Pu(n,f)FP and ^{63}Cu$(n,\alpha)^{60}$Co reactions were not used because of rather large uncertainties in the measured reaction rates.

[f]Repeat of run 6 with ^{235}U(n,f) removed.

[g]Nonfission foils only.

[h]Converted to a scalar flux by using calculated ratios of the 0-deg angular to scalar flux (for a distance of 10.46 cm from core center) obtained from a reactor physics calculation using the 1DF code.[34] (Corrections varied from ~2% at 0.4 MeV up to ~9% at 6 MeV.)

[i]Based on photo-plate measurements between 0.3 and 8.8 MeV.[33] For comparison, an E form below 0.3 MeV and a fission form above 8.8 MeV has been used to extend these data down to 10^{-10} MeV and up to 18 MeV, respectively. (The use of the E form below 0.3 MeV adds 9.5% more flux to the pp data; this compares closely with the multiple foil results which place ~9% of the flux below 0.3 MeV for runs 6, 7, and 8.) These results were converted to a scalar flux by using calculated ratios of the neutron current to scalar flux.[33] See footnote h. Corrections varied from ~1% at 0.4 MeV up to ~3% at 6 MeV.

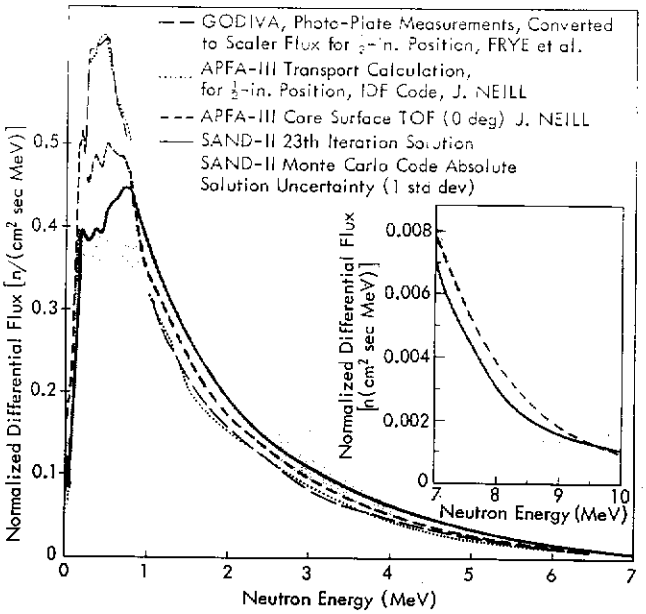

Fig. 2. APFA-III bare ^{235}U assembly core surface spectrum.

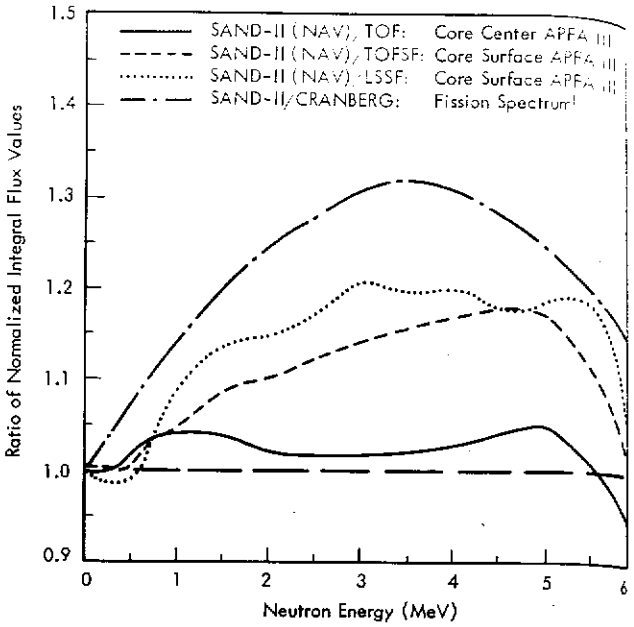

Fig. 3. Comparison of SAND-II, TOF, and PP integral flux values vs neutron energy.

radiochemistry counting, provided further validation of the estimated accuracy of the measured reaction rates (see Appendix A). Neill's TOF (0-deg angular surface flux) and Frye et al.'s[33] PP data (a measurement of the leakage neutron current ~ 42 in. from core center) were converted[54] to scalar fluxes for the 1/2-in. position for comparison with the multiple foil results using conversion factors from reactor physics calculations.[34,55] Neill's and Frye et al.'s converted results agree to within ~ 5% at all energies specified in Table IV but disagree up to ~ 21% with the multiple foil results. The difference between the best SAND-II differential flux solution, run 6 of Table IV, and Neill's 0-deg angular TOF and Frye's scalar corrected PP results is shown in Fig. 2.

One of the more serious and unexplained discrepancies for the core surface comparison, Fig. 2 and Table IV, is that the 0-deg angular TOF results yield a softer spectrum than that derived from the activation detectors. The reverse should be true. It is tempting to attribute this to experimental uncertainties and to the effect of room return neutrons; however, they should have little effect on the TOF measurement because of collimation and they exert a softening effect on the activation measurements.

In Fig. 3, the ratios given in Tables III and IV are plotted and compared with results previously reported for the fission spectrum.[1] The similarity of the disagreement for the Godiva leakage and fission spectrum is apparent. It is noted that the Cranberg et al.[5] form of the fission spectrum (which has a mean energy of 1.93 MeV) which agrees fairly well with the Watt[4] form (with a mean energy of 2.00 MeV), is based on Cranberg's TOF measurements and Frye et al.'s PP measurements; that is, the ~ 42-in. Godiva PP leakage spectrum and Cranberg form of the fission spectrum result from measurements using the same experimental apparatus.[33] If there is disagreement between activation and PP measurements of the fission spectrum, similar disagreement should exist for the Godiva leakage spectrum, as has been found for the present study.

A comparison of the average energies of measured and calculated core and surface spectra is provided in Table V. Reactor physics calculations, Neill's converted TOF data, and the multiple foil results show an expected core-to-surface hardening of the spectrum ($E > 0.4$ MeV, Table V) of 0.05, 0.05, and 0.15 MeV, respectively. (The comparison is made for the flux above 0.4 MeV to include the PP data which cover only the range from 0.3 to 8.8 MeV.) Calculations yielded scalar flux averaged energies for the core center and 1/2-in. surface locations of 1.78 and 1.83 MeV, respectively, which are too low in comparison with the PP, TOF, and multiple foil results, and raise questions about the validity of the calculations for the bare assembly. These differences in mean energy manifest themselves as significant differences in integral fluxes.

Frye et al.'s PP results (converted or unconverted) yield a value of ~ 1.86 MeV for the surface

TABLE V

Comparison of Measured and Calculated Neutron Average Energies

Source	Average Energy $\bar{E}$[a] (MeV)				$\Delta\bar{E}$	
	Surface		Center		Surface-Center	
	$E > 0.01$	$E > 0.4$	$E > 0.01$	$E > 0.4$	$E > 0.01$	$E > 0.4$
Photo-plate[b] (current)	1.61	1.87	-	-	-	-
Photo-plate[c] (scalar flux)	1.60	1.86	-	-	-	-
TOF[d] (0-deg angular)	1.68	1.97	1.56	1.88	0.12	0.09
TOF[e] (scalar flux)	1.63	1.93	1.56	1.88	0.07	0.05
Calculation[f] (scalar flux)	1.54	1.83	1.45	1.78	0.09	0.05
Multiple foils[g] (scalar flux)	1.75	2.06	1.58	1.91	0.17	0.15

[a]Defined as $\bar{E}(>E) = \int_E^{18} E\ \phi(E)\,dE \Big/ \int_E^{18} \phi(E)\,dE$.

[b]Reference 33, measured at a distance of ~42 in. from core center; for this comparison, an E form was fit below 0.3 MeV and a fission form above 8.8 MeV.

[c]Photo-plate data converted to a scalar flux; see footnote i, Table IV.

[d]Reference 34; see footnote a, Table IV.

[e]TOF data converted to a scalar flux; see footnote h, Table IV.

[f]Reactor physics calculation; see footnote h, Table IV.

[g]Results from Tables III and IV.

leakage spectrum. Since this value does not agree with the higher TOF and multiple foil values of 1.93 to 2.06 MeV, and shows no hardening relative to the measured central core values of 1.88 to 1.91, Table V, the PP results appear to have underestimated the mean energy of the Godiva leakage spectrum by 0.07 to 0.2 MeV.

The upper limit of 0.2 MeV is subject to some question since the new TOF 0-deg angular flux value of 1.97 MeV is less than the foils scalar flux value of 2.06 MeV; the reverse should be true with a calculated difference of ~0.04 MeV, Table V. The uncertainty associated with the multiple foil absolute value of average energy (>0.4 MeV, Table IV) may be partly responsible for this reversal; however, the uncertainties (percent standard deviations) given in Tables III and IV are mainly a measure of the absolute rather than the relative uncertainties in energy between the core center and surface results. That is, the relative uncertainty associated with this difference is dependent mainly on relative accuracy of the difference in core to surface measured reaction rates for the foil reactions, Table II. Consequently, the best multiple foil estimate of the difference in mean energy between the core center and surface spectra would be obtained by using the solutions based on the best (TOF) input spectral forms. These solutions are listed as run 8 (Table III) and run 6 (Table IV) and provide mean energies of 1.90 and 2.06 MeV, respectively, with a relative difference of 0.16 MeV, which is in good agreement with the average value of 0.15 MeV given in Table V. Adding the value of 0.16 MeV to the measured central core absolute values of 1.88 to 1.91 MeV gives absolute values of 2.04 to 2.07 MeV for the surface leakage spectrum.

In summary, multiple foils appear to yield a mean energy for the Godiva surface leakage spectrum that is ~0.1 to 0.2 MeV harder than that obtained by PP and TOF measurements and calculations. In core center, multiple foils and TOF results appear to agree, but yield a value that is ~0.1 MeV harder than that calculated. In the fission spectrum the difference is ~0.2 to 0.3 MeV between multiple foil and PP/TOF measurements.[1] If the activation detector results were to remain firm, it then appears that previous PP results have underestimated the mean energies of both the Godiva leakage and fission spectrum.

Calculated

Multiple foil and reactor physics calculations are compared in Fig. 4. The core center (solid line) and surface (dashed line) ratio of the multiple foil average integral flux values (NAV, Tables III and IV) to those from the 1DF code,[55] which is the Gulf General Atomic version of the DTF-IV code,[60] are given.[61] For a few core center points, Grundl provided results from calculations performed at Los Alamos Scientific Laboratory.[40] These results are represented by the circles and diamonds.

There is strikingly similar disagreement between the multiple foil results and the reactor physics calculations, Fig. 4, and between the

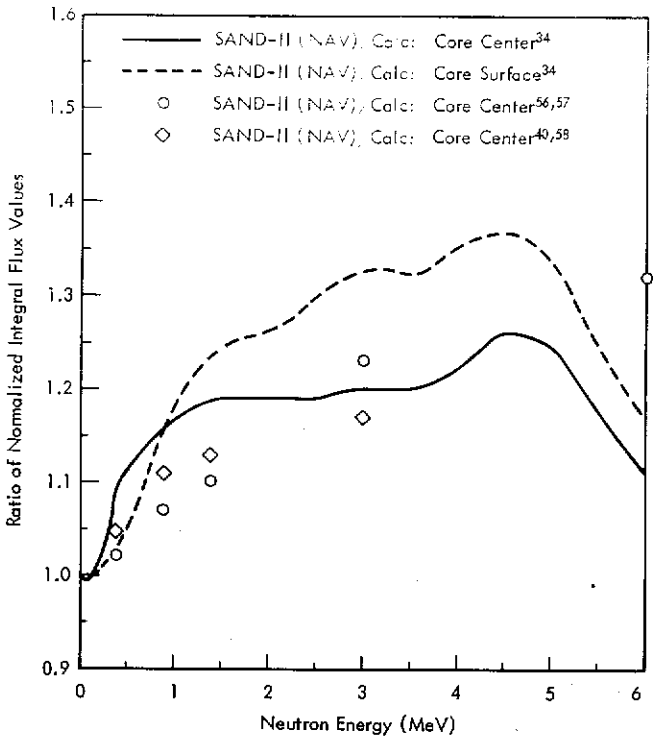

Fig. 4. Comparison of SAND-II and calculated integral flux values vs neutron energy.

multiple foil and the TOF/PP results for both the Godiva leakage spectrum and the fission spectrum, Fig. 3. These, together with previous results, indicate the existence of problems with the method of computation for a bare ^{235}U assembly and/or possibly the scattering and/or capture cross sections for ^{235}U and ^{238}U. Fabry has studied this problem and has reported on similar difficulties for a ^{238}U assembly.[8,11]

In comparison to the rather large ~35% disagreement found for the APFA-III test, Fig. 4, multiple foil results and reactor physics calculations for central core positions for much more complex reactors, such as ECEL[26] and EBR-II[30] have been obtained that do not disagree by more than ~12 and ~15%, respectively. Further study is required, therefore, to determine why better agreement can be obtained in the more complex environments.

NEUTRON REACTION SPECTRAL AVERAGED CROSS SECTIONS IN AN UNREFLECTED ^{235}U ASSEMBLY

Measured values of spectral averaged cross sections, σ_m, were obtained by use of the expression

$$\bar{\sigma}_m = A_m/\Phi \ , \qquad (1)$$

where A_m is the measured reaction rate and Φ is the absolute value of total flux.[52] Values of A_m for the core center and surface locations with assigned error limits are given in Table II. Φ was set equal to 3.45×10^{10} and 4.28×10^{9} n/(cm^2 sec), respectively, to obtain the measured values of $\bar{\sigma}_m$, Table VI. The absolute uncertainty associated with these $\bar{\sigma}_m$'s is estimated at ± 10 to 15%, or less (1 standard deviation), i.e., the combined absolute uncertainties in Φ and A_m. The relative uncertainty of one $\bar{\sigma}_m$ to another is smaller and dependent only on the estimated uncertainties in the A_m's, Table II.

Calculated values, $\bar{\sigma}_c$, were obtained from the expression

$$\bar{\sigma}_c = \int_0^\infty \sigma(E)\ \phi(E)\,dE \Big/ \int_0^\infty \phi(E)\,dE \ , \qquad (2)$$

where $\sigma(E)$ is the energy-dependent cross section[63] and $\phi(E)$ is the TOF or PP spectrum. Calculated values and the ratio of measured to calculated values are given in Table VI. In core center, relatively good agreement is obtained between these measured and calculated values, column 4, in contrast to findings for the core surface, the last column of Table VI.

The rather large disagreement (and relative differences) for $^{27}Al(n,\alpha)$, $^{24}Mg(n,p)$, $^{127}I(n,2n)$, and $^{63}Cu(n,2n)$- between the measured and calculated core center values suggests that the TOF spectrum may not be entirely correct above ~6 to 7 MeV. Certainly some of the disagreement may be attributed to uncertainties in cross sections; however, the cross section for the $^{27}Al(n,\alpha)$ reaction is considered to be reasonably well known. Because the measured values, $\bar{\sigma}_m$, are only subject to uncertainties in total flux, Φ, and measured reaction rates, A_m, they are considered more reliable and are preferred over the calculated values, $\bar{\sigma}_c$.

From Table II, the average value of the core center measured $^{235}U/^{238}U$ fission ratio is 6.20 ± 0.14 (1 standard error) and the TOF spectrum-calculated value is 6.16. The 1DF code reactor physics spectrum-calculated value is 6.76, which is ~10% higher. Using an earlier 1DF reactor physics calculated spectrum and the same TOF spectrum, Neill has reported values of 7.35 and 6.58, respectively,[64] based on ENDF/B cross sections for ^{235}U and ^{238}U. Here again, the reactor physics calculated spectrum yields a value that is ~10% higher. Fabry has reported similar results for a ^{238}U assembly which show a very large discrepancy in the same direction between calculated and measured fission ratios for ^{235}U and ^{238}U.[11] The lack of agreement between measured, TOF calculated, and reactor physics spectrum calculated values for APFA-III is in contradiction to

TABLE VI

Comparison of Core Center and Surface Measured ($\bar{\sigma}_m$) and Calculated ($\bar{\sigma}_c$) Spectral Averaged Cross Sections for APFA-III*

Reaction	Core Center			Core Surface			
	$\bar{\sigma}_m$(mb)[a]	$\bar{\sigma}_c$(mb)[b]	Ratio[c]	$\bar{\sigma}_m$(mb)	$\bar{\sigma}_c$(mb)[b]	$\bar{\sigma}_c$ (mb)[d]	Ratio[e]
$^{239}Pu(n,f)FP$	1794	1713	1.05	2235	1716	1704	1.30
$^{235}U(n,f)FP$	1214	1251	0.970	1407	1275	1245	1.10
$^{237}Np(n,f)FP$	994	1068	0.931	1134	1088	1077	1.04
$^{238}U(n,f)FP$	196	203	0.966	232	211	202	1.10
$^{232}Th(n,f)FP$	55.9	50.4	1.11	53.8	52.4	50.2	1.03
$^{238}U(n,\gamma)^{239}U$	95.7	107	0.894	109	115	110	0.948
$^{197}Au(n,\gamma)^{198}Au$	134	122	1.10	311	170	144	1.83
$^{59}Co(n,\gamma)^{60}Co$	7.39	7.59	0.974	18.7	12.9	10.5	1.45
$^{23}Na(n,\gamma)^{24}Na$	0.353	0.338	1.04	0.383	0.550	0.494	0.696
$^{63}Cu(n,\gamma)^{64}Cu$	13.6	13.4	1.01	13.7	18.8	16.3	0.729
$^{58}Fe(n,\gamma)^{59}Fe$	3.62	3.47	1.04	-	3.69	3.63	-
$^{45}Sc(n,\gamma)^{46}Sc$	8.49	8.73	0.973	10.5	9.42	8.79	1.11
$^{55}Mn(n,\gamma)^{56}Mn$	-	4.72	-	5.89	8.76	6.44	0.672
$^{115}In(n,n')^{115m}In$	137	135	1.01	148	139	134	1.07
$^{31}P(n,p)^{31}Si$	22.6	22.7	0.996	-	23.8	22.8	-
$^{32}S(n,p)^{32}P$	44.6	42.1	1.06	52.6	44.3	42.3	1.19
$^{54}Fe(n,p)^{54}Mn$	51.6	53.2	0.970	61.0	56.3	54.3	1.08
$^{56}Fe(n,p)^{56}Mn$	0.762	0.830	0.918	0.902	0.885	0.879	1.02
$^{58}Ni(n,p)^{58}Co$	69.5	71.0	0.979	81.1	74.8	72.0	1.08
$^{46}Ti(n,p)^{46}Sc$	8.34	8.01	1.04	9.21	8.53	8.31	1.08
$^{27}Al(n,p)^{27}Mg$	2.74	2.76	0.993	3.60	2.95	2.87	1.22
$^{27}Al(n,\alpha)^{24}Na$	0.464	0.529	0.877	0.591	0.557	0.575	1.06
$^{24}Mg(n,p)^{24}Na$	0.077	1.18	0.828	1.15	1.25	1.29	0.92
$^{127}I(n,2n)^{126}I$	0.707	0.658	1.07	0.919	0.654	0.667	1.41
$^{63}Cu(n,\alpha)^{60}Co$	-	0.279	-	0.402	0.296	0.301	1.36
$^{63}Cu(n,2n)^{62}Cu$	0.0742	0.0915	0.811	-	0.0911	0.0928	-

*Values are given for core center (bare) and surface (cadmium covered) foils for which self-shielding is considered negligible or small.

[a]Measured values based on the average of this work, Grundl's, Hansen's, and Byers' results, column 5, Table II.

[b]Calculated values based on Neill's 0-deg angular TOF data for core center and his scalar corrected 0-deg angular TOF data for the surface.

[c]Ratio of $\bar{\sigma}_m$ divided by $\bar{\sigma}_c$.

[d]Calculated values based on Frye et al.,[33] photo-plate measurements of the leakage spectrum (42 in. from core center) converted to a scalar flux for a distance of $\frac{1}{2}$ in. from the surface. An E form was fit below 0.3 MeV and a fission form was fit above 8.8 MeV for these comparisons.

[e]Ratio of $\bar{\sigma}_m$ divided by the $\bar{\sigma}_c$ values based on Neill's scalar converted TOF data.

the apparent good agreement of calculations for more complex environments as reported by Hardy,[7] who also used ENDF/B cross sections and indicates the complexity of the problem of understanding existing inconsistencies.

Results for the fission spectrum,[1-3] presented in Table VII, show a disagreement (Table VIII) similar to that found for the core surface for the higher energy reactions. [Direct comparison for the (n,γ) reactions is somewhat complicated because of flux-spectral perturbations due to differences in scattered low energy neutron effects in the two environments.]

SPECTRUM OF ^{235}U FISSION NEUTRONS

To complete and update the comparison for the fission spectrum, a multiple foil form of the fission spectrum, Fig. 5 and Table IX, was derived based on a selected set of Grundl's,[2] Fabry's,[3,8,11] Bresesti's,[65] and Boldman's[66] reaction rate measurements, current evaluated reaction cross sections,[31] and a SAND-II solution using the Cranberg[5] form as input.[67]

The selected set of reaction rates (spectral averaged cross sections $\bar{\sigma}^f$) is given in the next to last column of Table VII. To obtain this set, Bresesti's,[65] Boldeman's,[66] and Grundl's[2] results were normalized to Fabry's[3,8,11] by minimizing the sum of the squares of the differences between all the reactions common to Fabry's and each of the other complete sets of data. The set of 12 values used in a previous study is listed in the last column of Table VII for comparison to the present set. The most significant changes are in the $^{197}Au(n,\gamma)$ value which was increased by Fabry[8]

TABLE VII

Uranium-235 Fission Cavity Measured Spectral Averaged Cross Sections $\bar{\sigma}^{f}$ (mb)

(Reaction rates per unit flux)

Reaction	Refs. 3,8,9,11,25	Ref. 65	Ref. 66	Ref. 2[a]	Averaged Values[b]	Ref. 1
$^{115}In(n,\gamma)$	156 (±6)				156* (±6)	-
$^{92}Mo(n,p)$	7.7 (±0.5)				7.7* (±0.5)	-
$^{93}Nb(n,2n)$	0.52 (±0.03)				0.52* (±0.03)	-
$^{46}Ti(n,p)$	13 (±0.6)				13* (±0.6)	-
$^{55}Mn(n,2n)$	0.27 (±0.015)				0.27* (±0.015)	-
$^{64}Zn(n,p)$	32 (±1.7)				32* (±1.7)	-
$^{54}Fe(n,p)$	89 (±5)				89 (±5)	-
$^{58}Ni(n,p)$	120 (±6)	118	133		124 (±4.8)	-
$^{24}Mg(n,p)$	1.62 (±0.07)				1.62 (±0.07)	-
$^{235}U(n,f)$	1335 (±130)			1262 (±76)	1298 (±37)	1294
$^{237}Np(n,f)$	-			1377 (±48)	1377 (±58)[c]	1367
$^{238}U(n,f)$	353 (±30)	347		328	343 (±8)	340
$^{197}Au(n,\gamma)$	94 (±5)				94 (±5)	74
$^{63}Cu(n,\gamma)$	10.8 (±2.5)				10.8* (±2.5)	10.8
$^{115}In(n,n')$	200 (±10)	199			199.5 (±0.5)	200
$^{32}S(n,p)$	74 (±3)		76		75 (±1.0)	74
$^{27}Al(n,p)$	4.35 (±0.20)		3.7	4.74 (±0.2)	4.26 (±0.30)	4.71
$^{27}Al(n,\alpha)$	0.78 (±0.03)	0.782	0.76	0.758 (±0.03)	0.770 (±0.006)	0.767
$^{56}Fe(n,p)$	1.15 (±0.04)	1.19	1.14	1.20 (±0.05)	1.17 (±0.015)	1.19
$^{31}P(n,p)$	-		38.8	39.1 (±2)	39 (±0.15)	38.8
$^{63}Cu(n,2n)$	-			0.125 (±0.008)	0.124 (±0.009)[c]	0.123
$^{63}Cu(n,\alpha)$	0.66 (±0.06)				0.66* (±0.06)	-
$^{232}Th(n,f)$	87.5 (±3.5)				87.5 (±3.5)	-
$^{239}Pu(n,f)$	1985 (±100)				1985 (±100)	-

*Indicates the reaction was not used for the SAND-II unfolding because of excessive error in the measured reaction rate, lack of a cross section, or the uncertainty of the evaluated $\sigma(E)$ on the SAND-II reference cross section tape was considered to be too large.

[a]These values are from excitation ratio measurements; cross section scales have been assigned from the literature in Ref. 2. As explained in the text, the value for the normalizing reaction ^{238}U has been changed from that chosen in Ref. 2.

[b]The assigned errors are taken as one standard percent deviation or one standard percent error if more than one laboratory is reporting. For the SAND-II Monte Carlo error study, a 2% error was used if only two laboratories reported values and the standard error was <2%.

[c]The percent error of the ^{238}U average value was combined with Grundl's assigned relative error to obtain this value.

and the $^{27}Al(n,p)$ value of Grundl's which was reduced by inclusion of the two values of Fabry and Boldeman. Using the average values of $\bar{\sigma}^{f}$ and the assigned errors, column 6 of Table VII, a ratio of 3.78 ± 0.14 (1σ) for $^{235}U/^{238}U$ is obtained; this is consistent with values of 3.81 ± 0.17 to 3.85 ± 0.23 reported by Grundl and 3.78 ± 0.18 reported by Fabry.[6,40] This check on the data set normalization procedure and subsequent error assignment is important because it is a difference of ~15 to 20% between measured and calculated values of this ratio that primarily results in a harder activation foil derived fission spectrum.

Using a selected set of 16 reaction rates, those without an asterisk in Table VII, the multiple foil derived form of the fission spectrum, Fig. 5, is qualitatively the same as that given in Ref. 1, but with a lower mean energy of 2.14 ± 0.07 (2σ) MeV as compared with a previous value of 2.24 MeV.

Another difference is the appearance of a dip in the spectrum just below 1 MeV. The shaded bars in Fig. 5, which designate the 90% energy response range for those detectors that are primarily responsible for this structure, show excellent foil coverage at the dip. However, although the multiple foil technique can detect the existence of such structure, uncertainties in reaction rates and reaction cross section are too large for precise shape definition. In a recent review paper, Grundl[6] brought attention to such structure in the PP and TOF measurements of Cranberg and Rosen (see Ref. 5) and Barnard.[68] Also, Zamyatin et al.[69] have reported observations of structure in fission spectra below ~1 MeV. Using Grundl's[6] presentation of the differential experimental results, curves have been drawn through the data of Cranberg and Rosen to show this structure. It is apparent that the multiple foil results support the

TABLE VIII

Comparison of Measured ($\bar{\sigma}_m$) and Calculated ($\bar{\sigma}_c$) Spectral Averaged Cross Sections for the Fission Spectrum

Reaction	$\bar{\sigma}_m$(mb)[a]	$\bar{\sigma}_c$(mb)[b]	$\bar{\sigma}_c$(mb)[c]	Ratio[d]
$^{235}U(n,f)FP$	1298	1233	1259	1.05
$^{237}Np(n,f)FP$	1377	1276	1269	1.08
$^{238}U(n,f)FP$	343	278	277	1.23
$^{197}Au(n,\gamma)^{198}Au$	94	102	101	0.92
$^{63}Cu(n,\gamma)^{64}Cu$	10.8	11.1	11.5	0.97
$^{115}In(n,n')^{115m}In$	200	180	178	1.11
$^{32}S(n,p)^{32}P$	75	58.2	57.3	1.29
$^{27}Al(n,p)^{27}Mg$	4.26	3.73	3.66	1.14
$^{27}Al(n,\alpha)^{24}Na$	0.77	0.696	0.683	1.11
$^{56}Fe(n,p)^{56}Mn$	1.17	1.10	1.08	1.06
$^{31}P(n,p)^{31}Si$	39	31.6	31.1	1.23
$^{63}Cu(n,2n)^{64}Cu$	0.124	0.118	0.116	1.05

[a]The assigned errors are taken as one standard percent deviation or one standard percent error if more than one laboratory is reporting. For the SAND-II Monte Carlo error study, a 2% error was used if only two laboratories reported values and the standard error was <2%.

[b]Calculated values using Eq. (2), the Cranberg form of the fission spectrum, and the current SAND-II evaluated $\sigma(E)$ library tape[31] but with subsequent updating for $^{197}Au(n,\gamma)$.

[c]Taken from Ref. 1, same calculation as b above, but using previous SAND-II evaluated cross section library tape.

[d]Ratio measured divided by calculated, columns 2 and 3.

TABLE IX

Five-Group Representation of Observations of the ^{235}U Fission-Neutron Spectrum

Energy Groups (MeV)	Maxwellian Description	Activation Detectors	
		Grundl[a] (8 reactions)	Present Work (16 reactions)
0 - 1.4	0.4621	0.373 ± 22%[b]	0.383 ± 17%[b]
1.4- 3.0	0.3386	0.360 ± 21%	0.372 ± 13%
3.0- 6.0	0.1737	0.241 ± 28%	0.219 ± 10%
6.0-11.0	0.0249	0.0257 ± 11%	0.0256 ± 11%
11.0-∞	0.00070	0.00069 ± 18%	0.00075 ± 13%
Average Energy	1.935	2.20 ± 0.16	2.14 ± 0.07

[a]See Ref. 2.
[b]95% confidence level.

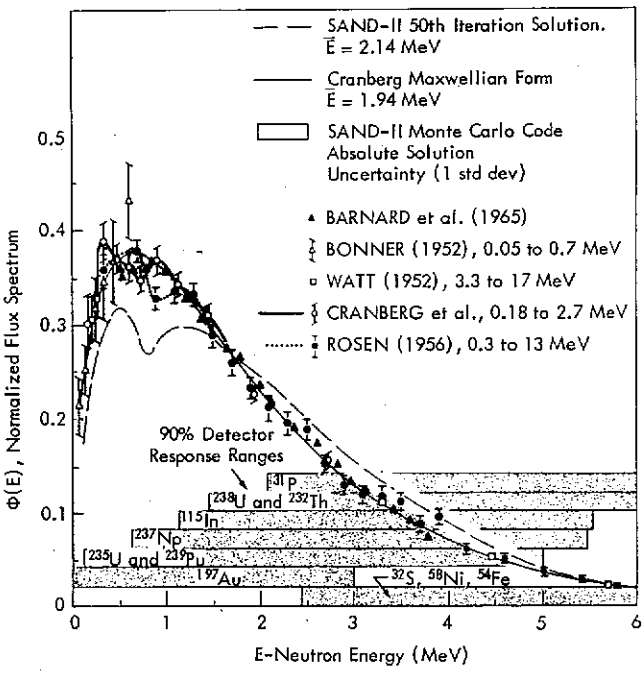

Fig. 5. Fission spectrum comparisons.

previous spectrometer measurements of the possible existence of structure in the peak of the fission spectrum.

This structure may contribute, but only in a secondary manner, to existing discrepancies between activation and spectrometer results because of possible structure in fission and nonfission reaction cross sections in this same region. In this same context, another contributing factor to inconsistencies for some detector reactions may be associated with subthreshold cross sections for exoergic reactions.[70,71]

The absolute uncertainty associated with the multiple foil results is shown by the shaded area in Fig. 5. Uncertainties assigned to the activation measurements and the evaluated cross sections for the SAND-II Monte Carlo analysis are those given in Table VII, column 6, and Appendix B, respectively. Group averaged uncertainties from the same analysis are compared in Table VIII with values previously reported by Grundl.[2] The present work, column 4 of Table IX, provides confirmation of Grundl's earlier findings and error assignments.

The effect of changes in SAND-II evaluated cross sections since the last study[1] is shown in Table VIII by a comparison of previous with present calculated values of fission averaged cross sections using the Cranberg fission spectrum. The set of average measured values from Table VII and the ratio to calculated values are also shown to illustrate the dilemma that exists in establishing agreement between measurement and calculation.

Fabry[8] has further studied the fission spectrum problem with a view toward establishing better consistency between integral and differential data by effecting rather significant changes in evaluated

energy-dependent cross sections. For instance, for $^{238}U(n,f)$, he shifts all of Lamphere's[72] points about 100 keV toward lower energies. In addition, he imposes the constraint of a three parameter fit (in a least squares sense) for a more complicated but theoretically based analytical expression for the fission spectrum which considers scission neutrons. Using a selected set of 11 of the reaction rates given in Table VII, Fabry then derives an activation foil form of the fission spectrum that is in much better agreement with the Watt form for energies below ~ 11 MeV.

Qualitatively, this result is not inconsistent with the results of Grundl's and those of the present study. That is, it shows how changes in energy-dependent cross sections and the acceptance of some distortion in the fission spectrum shape (resulting from the use of a three parameter analytical representation of the fission spectrum) may, at least partially, reconcile conflicting integral and differential data. Fabry's use of the $^{115}In(n,\gamma)$ reaction, omission of the $^{31}P(n,p)$ reaction, and use of different evaluated energy-dependent cross sections for the other as well as the $^{238}U(n,f)$ reaction does not permit a direct quantitative assessment to be made of his results relative to those of the present study.

CONCLUSIONS

The Introduction stated that inconsistencies between integral and differential quantities continue to cast doubt on the reliability of (a) the fission spectral form, (b) evaluated activation reaction cross-section data, and (c) the multiple foil method. The APFA-III test results together with those of previous tests indicate that measurements of reaction rates and lack of solution uniqueness are unlikely sources of significant error for the multiple foil method. This suggests that uncertainties in evaluated energy-dependent reaction cross sections are the major source of error for the multiple foil technique.

Relative to (a) and (b) above, the use of a larger number of foil reactions and updated evaluated cross sections[31] reduced the mean energy of the SAND-II derived multiple foil form[1] of the fission spectrum from 2.24 to 2.14 (±0.07) MeV. However, the relative uncertainties of one cross section to another for the larger set of reactions used in this study are not as firmly established as those used by Grundl in defining a fission spectrum with a mean energy[2,6] of 2.2 ± 0.16 MeV by the activation technique. The values of ± 2.1 to 2.2 MeV based on integral measurements are to be compared with values of 1.93 to 2.00 MeV based on analysis of differential measurements by Cranberg et al.,[5] Frye,[33] and Watt.[4]

Specific results of this study are:

1. Within the limits of experimental uncertainty, good agreement was obtained between multiple foil and TOF results for an irradiation in core of a bare ^{235}U assembly.

2. For an irradiation ~ 1/2 in. above the core surface where a leakage spectrum is measured, however, the multiple foil results are in poor agreement with the present and past TOF/PP measurements. The disagreement is similar to that found for measurements in the fission spectrum.[1-3]

3. If the activation results remain firm, and significant changes in current evaluated reaction cross sections are not effected, then increases up to as much as 10 to 15% in the mean energy of the Godiva leakage and fission spectrum must be considered.

4. The disagreement of reactor physics calculations with all of the present results and the similarity of this disagreement to that found between multiple foils and TOF/PP measurements for the Godiva leakage spectrum, suggests the existence of problems with the method of computation for a bare ^{235}U assembly, and/or possibly the scattering and/or capture cross sections of ^{238}U and ^{235}U.

APPENDIX A

Reaction Rate Measurements

A comparison of core surface fission rate results based on fission track (Mica and Lexan) and radioactive fission product (^{140}Ba and ^{99}Mo) counting is presented followed by a summary of the core surface and center results of participating laboratories. (The ^{140}La daughter of ^{140}Ba was counted after transient equilibrium was established, approximately two weeks after the irradiations.) These results are the detailed data used to generate the core center and surface reaction rate values given in Table II of the text.

The various fission and nonfission foils were irradiated in two low power and one high power reactor runs ~ 1/2 in. from the core surface and in the center of the core. Errors introduced by changing reactor power are considered to be small. The average ratios of integrated neutron exposures for the three reactor runs used to convert foil results to a common basis are given in Table A-I. Corrections (up to ~ 8%) have been made for differences in foil placement. Neutron scattering in the aluminum fission track foil holders (~ 1-in. diam × 1/8-in.-thick edges) is a source of some difference (estimated as less than

TABLE A-I

Comparison of Normalizing Foils and Reactor Power Instrument Integrated Neutron Exposures

Reactor Run	Normalized Foil Results[a] (total number of reactions)					Power Instrument[b] Results (W-min)		Average
	$^{197}Au(n,\gamma)^{c}$		$^{63}Cu(n,\gamma)^{c}$		$^{32}S(n,p)^{c}$			
	Core Center	Core Surface	Core Center	Core Surface	Core Surface	Absolute[d]	Normalized[c]	
1	-	-	-	-	9.93×10^{-5}	4.01	9.21×10^{-5}	9.57×10^{-5} ±2.7% (1 std error)
2	1.49×10^{-3}	1.66×10^{-3}	1.52×10^{-3}	1.51×10^{-3}	1.63×10^{-3}	68.7	1.58×10^{-3}	1.57×10^{-3} ±1.8% (1 std error)
3	1.00	1.00	1.00	1.00	1.00	4.35×10^{4}	1.00	Ref. Power Level

[a]The $^{32}S(n,p)$ results are based on measurements by USNRDL, and the $^{197}Au(n,\gamma)$ and $^{63}Cu(n,\gamma)$ results are based on measurements by PNL. Core center foils were different in thickness between low and high power and this may account for difference in gold core surface and core center results.

[b]The power instrument results are based on APFA-III averaged recorder #1 readings, time of irradiation, and the subsequent calibration of the Keithley recorder with known input currents equal (approximately) to the values observed during the foil irradiations. The experimental data were provided by Crosbie[39] of GGA and were analyzed and interpreted at PNL.

[c]Normalized to the #3 run.

[d]Based on an assumed calibration factor of 1.589×10^{8} W/A for the #1 Recorder-Keithley.

2 to 3% for this work) between track and radiochemistry results (holders were not used with the fission foils analyzed by the radiochemistry technique).

The fission yield values for ^{140}Ba and ^{99}Mo used for the present analysis are based on values for a fission spectrum inferred from irradiations in thermal and fast reactors.[29,73,74] These values and half-lives are listed in Table A-II.

A recent study of ^{140}Ba yields for ^{235}U and ^{238}U by Krappel, Seufert, and Stegemann[75] (based on a comparison of radiochemistry with absolute fission rate measurements using a parallel-plate fission chamber) gave values of (6.10 ± 0.15)% and (6.34 ± 0.41)%, respectively, for measurements in a fast reactor spectrum with a mean energy of ~1.0 MeV (the proton-recoil spectrum in their paper was used to derive this value). A similar study by Armani, Gold, Larsen, and Roberts using track recorders yielded preliminary values for ^{140}Ba of (5.7 ± .3)% for ^{235}U and (5.00 ± 0.08)% for ^{239}Pu in a fast reactor spectrum with a mean energy of ~0.7 MeV.[35,45,74] A value of (5.80 ± 0.05)% for ^{99}Mo for ^{239}Pu was also reported.[74] Since the change in ^{140}Ba yield with energy between these two fast reactor spectra (and the Godiva or fission spectrum) should be small, such a large difference (~7%) between these two essentially identical measurements for ^{140}Ba for ^{235}U is unexpected. Consequently, the present uncertainty associated with ^{140}Ba yield for ^{235}U and possibly other reactions in Table A-II must be placed as high as 5 to 10%.

TABLE A-II

Fission Yield and Half-Life Values Utilized to Interpret Radiochemistry Data

Reaction	Fission Product Yield %		Half-Life Used	
	^{140}Ba	^{99}Mo	^{140}Ba	^{99}Mo
$^{235}U(n,f)$	6.1	6.1	12.8 days	66.7 h
$^{238}U(n,f)$	6.0	6.3	12.8 days	66.7 h
$^{232}Th(n,f)$	7.6	2.7	12.8 days	66.7 h
$^{237}Np(n,f)$	5.8	-	12.8 days	66.7 h
$^{239}Pu(n,f)$	5.1	5.9	12.8 days	66.7 h

The fissions per second per nuclei at a reactor power of 130 W are given in Table A-III. For each reaction, the variation from the mean value results from laboratory imprecision, bias, uncertainty in fission yields, gradient and scattering effects, and power normalization uncertainties.

The measured fission reaction rates given in Table A-III are included with those of other reactions (based on radiochemistry analysis) for both

TABLE A-III

Comparison of Fission Rate Measurements for APFA-III Core Surface

Reaction	Fission[a] / sec nuclei	Method Used	Reactor Run	Source
$^{238}U(n,f)$[b]	10.9×10^{-16}	Track	2	USNRDL[c]
	10.4×10^{-16}	Track	1	ANL[d]
	9.76×10^{-16}	Track	2	ANL[d]
	9.78×10^{-16}	^{99}Mo	3	ANL[d]
	8.98×10^{-16}	^{140}Ba	3	ARHCO[f]
Average	9.93×10^{-16} (±3.9% 1 std error)			
$^{235}U(n,f)$[e]	6.01×10^{-15}	Track	2	ARHCO[c]
	7.16×10^{-15}	Track	2	ANL[d]
	6.05×10^{-15}	^{99}Mo	3	ANL[d]
	4.88×10^{-15}	^{140}Ba	3	ARHCO[f]
Average	6.02×10^{-15} (±7.7% 1 std error)			
$^{232}Th(nf)$	2.33×10^{-16}	Track	2	USNRDL[c]
	2.01×10^{-16}	Track	2	ANL[d]
	2.56×10^{-16}	^{99}Mo	3	ANL[d]
Average	2.03×10^{-16} (±6.9% 1 std error)			
$^{239}Pu(nf)$	8.07×10^{-15}	Track	2	USNRDL[c]
	11.0×10^{-15}	Track	2	ANL[d]
Average	9.56×10^{-15} (±11% 1 std error)			
$^{237}Np(nf)$	4.85×10^{-15} (±10% 1 std deviation, estimated)	Track	2	USNRDL[c]

[a]For a reactor power of 130 W for run 3. The normalization factors given in Table A-I were used for reactor runs 1 and 2.

[b]The ^{238}U results have been corrected for fission of the ^{235}U isotope present. The correction was 0.2% for USNRDL results and 0.1% to 1.3% for ANL (ANL ^{238}U had 170 ppm and 2200 ppm ^{235}U and USNRDL had 360 ppm).

[c]See Ref. 36.

[d]See Ref. 35.

[e]The ^{235}U (93% enriched) results have been corrected for fission of the ^{238}U isotope present. The correction was 1.2%.

[f]See Ref. 37.

the core center and surface positions in Tables A-IV and A-V, respectively. For the core center and surface positions, mean values (with assigned one standard error values) are given when there are measurements from more than one laboratory. For subsequent SAND-II error analysis, a value of at least 2%, one standard error, has been assigned (in Table II of the text) to all results less than 2% because of estimated systematic errors and/or laboratory bias which could not be properly assessed with the limited number of measurements of this work. For a single laboratory result, estimated one standard deviation error assignments are given.

TABLE A-IV

APFA-III Core Center Measured Reaction Rates [10^{-16} Reactions/(sec nuclei) at a 130-W Reactor Power]

Reaction	Laboratory[a] ARHCO or PNL	Laboratory[a] ANL	Laboratory[a] GGA	Average Value
$^{235}U(n,f)FP$	37.2(^{140}Ba)	44.0(^{99}Mo)	-	40.6±8%
$^{238}U(n,f)FP$	6.45(^{140}Ba)	7.23(^{99}Mo)	-	6.84±6%
$^{232}Th(n,f)FP$	1.98(^{140}Ba)	1.88(^{99}Mo)	-	1.93±2%
$^{238}U(n,\gamma)^{239}U$	-	3.39	-	3.39±5%
$^{197}Au(n,\gamma)^{198}Au$	4.65	-	-	4.65±7%
$^{59}Co(n,\gamma)^{60}Co$	0.255	-	-	0.255±7%
$^{23}Na(n,\gamma)^{24}Na$	0.0122	-	-	0.0122±7%
$^{63}Cu(n,\gamma)^{64}Cu$	0.468	-	-	0.468±7%
$^{115}In(n,\gamma)^{116m}In$	-	-	3.29	3.29±30%
$^{58}Fe(n,\gamma)^{59}Fe$	0.125	-	-	0.125±7%
$^{45}Sc(n,\gamma)^{46}Sc$	0.293	-	-	0.293±7%
$^{115}In(n,n')^{115m}In$	4.78	-	4.71	4.74±1%
$^{32}S(n,p)^{32}P$	1.54	-	-	1.54±7%
$^{54}Fe(n,p)^{54}Mn$	1.78	1.78	-	1.78±0%
$^{56}Fe(n,p)^{56}Mn$	-	-	0.0287	0.0287±7%
$^{58}Ni(n,p)^{58}Co$	2.37	2.43	-	2.40±1%
$^{46}Ti(n,p)^{46}Sc$	0.288	-	-	0.288±7%
$^{27}Al(n,p)^{27}Mg$	-	-	0.0923	0.0923±7%
$^{27}Al(n,\alpha)^{24}Na$	0.0161	-	0.0165	0.0163±1%
$^{24}Mg(n,p)^{24}Na$	0.0337	-	-	0.0337±7%
$^{127}I(n,2n)^{126}I$	0.0244	-	-	0.0244±7%

[a]The laboratories are Pacific Northwest Laboratory (PNL), Argonne National Laboratory (ANL), Atlantic Richfield Hanford Company (ARHCO), and Gulf General Atomic (GGA). The fission product used to determine the fission reaction rate follows the measured value.

APPENDIX B

Multiple Foil Technique Error Analysis

A SAND-II Monte Carlo Error Analysis Code[53] was used for the assignment of errors to multiple foil flux-spectral results. One of the more difficult aspects of this work is the proper assignment of errors for the current SAND-II energy-dependent evaluated cross sections.[31]

Two methods of error assignment have been studied to date. First, assuming no separation in shape and magnitude, as discussed below, individual errors were assigned to each of the 620 SAND-II energy groups based on a review of literature evaluations. However, a constraint was imposed that over certain fixed regions such as thermal, resonance, and fast, the total integrated error from the individual assignments must be consistent with anticipated experimental errors in the measured 2200 m/sec, resonance integral, and fission averaged cross sections, respectively.[29,31] This procedure has been used primarily for analytical studies directed toward the general problem of understanding error propagation for the multiple foil technique. The Monte Carlo code is designed to permit the individual or simultan-

TABLE A-V

APFA-III Core Surface Measured Reaction Rates [10^{-15} Reactions (sec nuclei) at a 130-W Reactor Power]

Reaction	Laboratory[a]				Average Value
	ARHCO or PNL	ANL	USNRDL	GGA	
$^{239}Pu(n,f)FP$	-	-	-	-	9.56[b] ± 11%
$^{235}U(n,f)FP$	-	-	-	-	6.02[b] ± 8%
$^{237}Np(n,f)FP$	-	-	-	-	4.85[b] ± 10%
$^{238}U(n,f)FP$	-	-	-	-	0.993[b] ± 4%
$^{232}Th(n,f)FP$	-	-	-	-	0.230[b] ± 7%
$^{239}U(n,\gamma)^{239}U$	-	0.468	-	-	0.468 ± 5%
$^{197}Au(n,\gamma)^{198}Au$	1.33[c]	-	-	-	1.33 ± 7%
$^{197}Au(n,\gamma)^{198}Au$	0.669[c]	-	-	-	0.669 ± 7%
$^{59}Co(n,\gamma)^{60}Co$	0.0801[c]	-	-	-	0.0801 ± 7%
$^{23}Na(n,\gamma)^{24}Na$	0.00164	-	-	-	0.00164 ± 7%
$^{63}Cu(n,\gamma)^{64}Cu$	0.0586	-	-	-	0.0586 ± 7%
$^{63}Cu(n,\gamma)^{64}Cu$	0.0708	-	-	-	0.0708 ± 7%
$^{115}In(n,\gamma)^{116m}In$	-	-	-	0.560[c]	0.560 ± 10%
$^{115}In(n,\gamma)^{116m}In$	-	-	-	0.964[c]	0.964 ± 10%
$^{45}Sc(n,\gamma)^{46}Sc$	0.0449	-	-	-	0.0449 ± 7%
$^{55}Mn(n,\gamma)^{56}Mn$	-	-	-	0.0252	0.0252 ± 5%
$^{115}In(n,n')^{115m}In$	0.668	-	-	0.600	0.634 ± 5%
$^{32}S(n,p)^{32}P$	0.228	-	0.222	-	0.225 ± 1%
$^{54}Fe(n,p)^{54}Mn$	0.265	0.257	-	-	0.261 ± 1%
$^{56}Fe(n,p)^{56}Mn$	-	-	-	0.00386	0.00386 ± 7%
$^{58}Ni(n,p)^{58}Co$	0.346	0.347	-	-	0.347 ± 1%
$^{46}Ti(n,p)^{46}Sc$	0.0394	-	-	-	0.0394 ± 7%
$^{27}Al(n,p)^{27}Mg$	-	-	-	0.0154	0.0154 ± 7%
$^{27}Al(n,\alpha)^{24}Na$	0.00254	-	-	0.00252	0.00253 ± 1%
$^{24}Mg(n,p)^{24}Na$	0.00494	-	-	-	0.00494 ± 7%
$^{127}I(n,2n)^{126}I$	0.00393	-	-	-	0.00393 ± 7%
$^{63}Cu(n,\alpha)^{60}Co$	0.00172	-	-	-	0.00172 ± 10%

[a]The laboratories are Pacific Northwest Laboratory (PNL), Argonne National Laboratory (ANL), Atlantic Richfield Hanford Company (ARHCO), U.S. Naval Radiology Defense Laboratory (USNRDL), and Gulf General Atomic (GGA).

[b]See Table A-III for individual laboratory results.

[c]See Table II of the text for information on foil thickness, covering, etc.

eous application of the two types of cross-section errors and to combine these errors with those due to uncertainties in measured reaction rates (saturated activities). Thus the effect of a single type of error can be studied independently or combined with other errors.

A second approach to cross-section error assignment is considered more realistic and practical in terms of present applied problems. The second approach assumes that over certain regions the relative uncertainty in the shape of a cross section is much smaller than in its magnitude, and a set of energy regions (based mainly on intervals where individual or consistent cross section measurements have been made) was selected within which the cross-section shape was held constant but its magnitude was allowed to independently vary, again with certain constraints based on integral consistency requirements. The regions and tentative error assignments used in the second approach to derive a SAND-II error matrix are presented in Table B-1. Grundl's,[2,20] Fabry et al.'s[76] and McElroy et al.'s[29,70,71] works were primarily used as the guide in the selection of both the energy regions and subsequent assignment of these cross section errors.

Two types of significant errors which propagate in spectral unfolding are contained in the matrix of Table B-I. The first is related to the uncertainties in the shape of each reaction cross section. The second is associated with the magnitude of all reaction cross sections in each of the energy intervals. Both of these may be considered as absolute errors in the sense that they are quantitative uncertainties associated with each particular cross section magnitude. However, if the analysis is concerned only with establishing spectral shapes, only the relative errors should be considered. That is, shape errors should be assigned relative to a reference cross section in an

TABLE B-I

SAND-II Evaluated Cross Section Error Assignment* (%)

Reaction	1-162[a]	162-226	226-361	361-406	406-440	440-455	455-463	463-471	471-481	481-491	491-501	501-521	521-551	551-571	571-621
	1^{-10}-4^{-7}[b]	4^{-7}-1^{-5}	1^{-5}-1^{-2}	1^{-2}-1^{-1}	1^{-1}-6^{-1}	6^{-1}-1.4	1.4-2.2	2.2-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-8.0	8.0-11.0	11.0-13.0	13.0-18.0
$^{58}Ni(n,p)$	0	0	0	0	0	250	30	10	10	5	5	4	6	10	10
$^{54}Fe(n,p)$	0	0	0	0	1000	500	50	10	10	8	8	7	5	10	10
$^{27}Al(n,\alpha)$	0	0	0	0	0	0	0	0	0	30	20	6	6	10	10
$^{59}Co(n,\alpha)$	0	0	0	0	0	0	0	0	0	1000	15	8	8	10	10
$^{60}Ni(n,p)$	0	0	0	0	0	0	1000	500	250	50	15	8	8	8	8
$^{45}Sc(n,\gamma)$	2	5	5	6	10	10	11	11	11	11	11	11	11	11	11
$^{232}Th(n,\gamma)$	1.4	5	5	5	5	8	8	8	8	8	8	8	8	8	8
$^{237}Np(n,f)$	16	10	10	10	20	5	3	2	5	5	5	10	10	10	10
$^{238}Pu(n,f)$	0.5	8	8	8	7	6	5	5	6	6	6	6	6	10	10
$^{232}Th(n,f)$	0	0	0	0	0	100	25	20	10	10	10	10	10	10	10
$^{235}U(n,f)$	2	8	8	8	7	6	5	3	6	6	6	6	6	10	10
$^{238}U(n,\gamma)$	1.5	5	5	5	5	5	5	5	5	5	5	5	5	10	10
$^{238}U(n,f)$	0	0	0	0	1000	30	4	2	3	3	3	4	4	10	10
$^{115}In(n,\gamma)$	2.5	5	5	5	5	10	17	17	17	17	17	17	17	17	17
$^{55}Mn(n,\gamma)$	0.8	5	5	5	5	5	5	8	8	8	8	8	10	10	10
$^{64}Zn(n,p)$	0	0	0	0	1000	750	100	50	15	15	15	15	15	15	15
$^{32}S(n,p)$	0	0	0	0	0	0	100	20	5	5	5	5	5	8	8
$^{28}Si(n,p)$	0	0	0	0	0	0	0	0	0	250	50	15	15	15	15
$^{34}S(n,\alpha)$	0	0	0	0	0	0	0	0	0	1000	50	25	15	10	10
$^{24}Mg(n,p)$	0	0	0	0	0	0	0	0	0	100	50	10	10	10	10
$^{35}Cl(n,\alpha)$	0	0	0	0	0	0	0	500	20	20	30	30	30	30	30
$^{58}Ni(n,2n)$	0	0	0	0	0	0	0	0	0	0	0	0	0	30	20
$^{127}I(n,2n)$	0	0	0	0	0	0	0	0	0	0	0	0	30	30	15
$^{90}Zr(n,2n)$	0	0	0	0	0	0	0	0	0	0	0	0	0	30	15
$^{63}Cu(n,2n)$	0	0	0	0	0	0	0	0	0	0	0	0	0	8	8
$^{31}P(n,p)$	0	0	0	0	0	0	50	6	12	12	12	10	10	10	10
$^{56}Fe(n,p)$	0	0	0	0	0	0	0	0	8	8	8	6	6	15	15
$^{27}Al(n,p)$	0	0	0	0	0	0	0	50	10	8	8	8	8	20	20
$^{115}In(n,n')$	0	0	0	0	250	20	10	10	10	5	5	5	5	10	10
$^{239}Pu(n,f)$	10	10	10	10	12	10	10	10	10	10	10	10	10	10	10
$^{58}Fe(n,\gamma)$	8	8	28	12	12	12	12	12	12	12	12	12	12	12	12
$^{63}Cu(n,\alpha)$	1000	1000	1000	1000	1000	1000	500	400	200	50	25	8	8	10	10
$^{23}Na(n,\gamma)$	1	5	5	5	5	5	5	5	5	5	5	5	5	10	10
$^{197}Au(n,\gamma)$	0.5	4	5	5	5	5	5	5	5	5	5	5	5	7	7
$^{59}Co(n,\gamma)$	4	5	5	5	6	7	7	7	7	7	7	7	7	10	10
$^{63}Cu(n,\gamma)$	5	5	5	5	5	5	5	5	7	7	7	7	7	7	7
$^{46}Ti(n,p)$	0	0	0	0	0	0	1000	150	25	20	20	10	10	20	20
$^{47}Ti(n,p)$	0	0	0	0	1000	500	100	50	15	15	15	15	15	15	15
$^{48}Ti(n,p)$	0	0	0	0	0	0	0	0	1000	200	25	15	15	15	15

Note: It is recognized that the group structure selected for the error matrix will have an effect on the propagation of errors. The group energy bounds have been set up as a variable, therefore, so that changes in group structure can be easily accommodated for the study of this effect.

*One standard deviation in percent.

[a]SAND-II group numbers.

[b]SAND-II group energy bounds. Note: $1^{-10} = 1 \times 10^{-10}$, etc.

1 W
2 J
3 A
4 R
5 T
ROSE
6 J
scopic
Neutr
70100
7 J
Grund
sented
at the
8 A
integra
Reacti
9 A
tional
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10 A
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energy interval which is taken to be known exactly. Relative errors between reactions in each energy region should be assigned with respect to selected reference reaction cross sections and the larger overall absolute error on the barn scale ignored.

Thus the cross-section error assignment in each energy region was guided both by recognizing the relative error reduction resulting from shape and magnitude cross-section adjustment for all the reactions (accomplished by demanding integral consistency for a variety of spectra) and also from previous detailed investigations.[2,20,70,71,76] For example, Grundl has effectively accomplished a separation of absolute and relative errors for a few of the fission and short half-life reactions listed in Table B-I based on an extensive set of relative cross section measurements performed at the Los Alamos Van de Graaff.[20] It is very difficult at present to assign such relative errors precisely for all reactions of interest in terms of the two-dimensional input matrix to the Monte Carlo analysis; however, Table B-I is considered to contain conservative estimates reflecting both major sources of relative uncertainty.

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[a]SAND-II group numbers.
[b]SAND-II group energy bounds. Note: $1^{-10} = 1 \times 10^{-10}$, etc.

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[51]The 0-deg angular and scalar fluxes are equal at core center. After completion of this study, Jenkins and Kam[52] reported on the results of a similar investigation for the core center position, but they did not find the good agreement reported here. A study was therefore made of their activation results compared with those of the present study, Hansen's and Byers',[48,49] and Grundl's and Hansen's.[47] Multiple foil solutions were obtained which used averaged (equal weight) values of the reaction rates based on the four separate sets of measurements. The combined results gave a solution that was in good agreement with the present findings. A solution was also obtained using just Jenkins' and Kam's results which yielded a disagreement similar to that reported by them. Since error assignments are not given for their activation results, a proper assessment of the accuracy of their findings relative to those of the present study cannot be made.

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