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Argonne National Laboratory

THE RATIO OF U^{238} CAPTURE
AND U^{235} FISSION CROSS SECTIONS
IN FAST REACTORS

by

William G. Davey

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Idaho Division

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	7
1. INTRODUCTION	7
2. PREVIOUS MEASUREMENTS OF σ_{C8}/σ_{F5} IN ZPR-3 ASSEMBLIES	8
3. INDIRECT EVIDENCE REGARDING σ_{C8}/σ_{F5}	10
3.a. Critical Sizes	10
3.b. The Snell Experiment	11
4. THE PRESENT MEASUREMENTS OF σ_{C8}/σ_{F5}	12
4.a. Experimental Technique	12
4.a.1. Measurements of U^{238} Activation	12
4.a.2. Measurements of U^{235} Fission Rate	17
4.a.3. The Thermal Calibration	18
4.a.4. The Fast-spectrum Measurements	23
4.b. Experimental Results	23
4.b.1. The RAPSODIE Assembly (ZPR-3 Assembly 44)	25
4.b.2. Assembly 45	27
4.b.3. Assembly 45A	28
4.b.4. Assembly 46B (FARET)	28
5. COMPARISON WITH CALCULATED VALUES	29
6. DISCUSSION	30
7. CONCLUSIONS	30
8. ADDENDUM	31
9. ACKNOWLEDGMENTS	31
REFERENCES	32

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Variation of Counter Efficiency with Gamma-ray Energy. . . .	14
2.	Barium-133 Pulse-height Distribution with and without a Platinum Filter	15
3.	Uranium-239 Pulse-height Distribution	15
4.	Pulse-height Distribution of Uranium-235 Thermal-fission Products.	16
5.	Uranium-235 Fission Chamber	17
6.	Fission Chamber Pulse-height Distribution.	18
7.	Pulse-height Distribution from Uranium-238 Irradiated in a Fast Spectrum	19

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Comparison of Experimental Radiochemical Measurements of σ_{C8}/σ_{F5} with Calculated Values.	9
II.	ZPR-3 Assembly Compositions and Computed Values of k. . .	10
III.	Typical Thermal Calibration of Depleted Uranium Foil (D402)	21
IV.	Results of Thermal Calibration.	22
V.	Fission Product Pulse-height Spectra: 23-25 min Irradiation	24
VI.	Core Compositions of the ZPR-3 Assemblies	24
VII.	Activation of Depleted Uranium Foil D402 in RAPSODIE Mock-up	25
VIII.	Irradiation Results with RAPSODIE Mock-up	26
IX.	Calculated and Measured Values of σ_{C8}/σ_{F5}	29
X.	Calculated Central Spectra in the ZPR-3 Assemblies	29

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ABSTRACT

A new activation technique has been developed for the measurement of the ratio of the capture cross section of U^{238} and the fission cross section of U^{235} in zero-energy fast reactors. This work was initiated because of the long-standing discrepancy between calculated values of this ratio and radiochemically measured values. The new technique is a direct counting method which does not involve chemical separation in any way. Measurements have been made in four ZPR-3 fast reactor assemblies, two with hard spectra and two with soft spectra. In all four cases the measured ratio was slightly (4%) higher, on the average, than the calculated value. This is in strong contrast with the past radiochemical measurements in ZPR-3 assemblies, which gave values 16% less than calculation.

The present measurements, therefore, support the general correctness of the calculated ratio, and hence indicate that there are no gross errors in the assumed average microscopic values of the U^{238} capture cross section and the U^{235} fission cross section.

1. INTRODUCTION

Two of the principal constituents of fast reactors and fast critical assemblies are U^{238} and U^{235} , and accurate knowledge of the cross sections of these materials is essential for the understanding of the physics of fast reactors. Consequently, it is a matter of some importance that the calculated and measured values of the ratio of the capture cross section of U^{238} to the fission cross section of U^{235} (namely, σ_{C8}/σ_{F5}) in fast reactors differ systematically and significantly.

This discrepancy could arise from erroneous calculated ratios if the assumed microscopic nuclear data for U^{238} and U^{235} were incorrect; for example, Loewenstein and Okrent⁽¹⁾ have discussed the possibility that

$\sigma_{(n,\gamma)}$ for U^{238} could be in error. However, the necessary changes in nuclear data are sufficiently large to remove the good correlation between other calculated and measured parameters, such as critical size and it is not clear that this solution is acceptable. Consequently, the possibility that the measured σ_{C8}/σ_{F5} ratios are in error has been examined, and to this end a new technique for their measurement has been developed. In the present paper, the new technique and results are described and discussed, together with the previous σ_{C8}/σ_{F5} measurements and other relevant integral data.

The new measurements were made by use of the Argonne National Laboratory Zero Power Reactor 3 (ZPR-3) and the Argonne Fast Source Reactor (AFSR).

ZPR-3 is a split-halves machine of great versatility; during 8 yr of operation, more than 50 different critical assemblies have been built with core volumes ranging in size from 2 to 660 liters and in critical mass from 26 to 580 kg U^{235} . The machine has been described in detail,⁽²⁾ and experimental techniques and results have been largely described by Long *et al.*^(3,4) The experiments performed up to 1958 were analyzed by Loewenstein and Okrent.⁽¹⁾ These and subsequent experiments were analyzed by Davey,⁽⁵⁻⁸⁾ using nuclear data based on the study of Yiftah, Okrent, and Moldauer (YOM).⁽⁹⁾ Details of most of the assemblies mentioned in the present paper will not be given, since these are covered fully in the above references.

AFSR is a reactor which provides both fast and thermal irradiation facilities. The highly enriched uranium core is cylindrical, being about 11 cm in diameter and 11 cm high. It is surrounded by a depleted uranium blanket. A graphite thermal column is provided. A detailed description of AFSR has been given by Brunson.⁽¹⁰⁾

2. PREVIOUS MEASUREMENTS OF σ_{C8}/σ_{F5} IN ZPR-3 ASSEMBLIES

The ratio σ_{C8}/σ_{F5} has been measured in 16 ZPR-3 assemblies by means of a radiochemical method. In this technique enriched and depleted uranium foils are irradiated simultaneously, usually in the center of the reactor core, and the Np^{239} activity per gram of U^{238} and the Mo^{99} activity per gram of U^{235} are determined.

The Np^{239} is separated chemically from the depleted uranium foil and the Np^{239} beta activity is measured with a calibrated counter. The efficiency of the neptunium separation is measured by adding a known quantity of α -active Np^{237} as a tracer and measuring the α activity after separation. The fissions per gram of U^{235} are determined by chemically separating Mo^{99} from the enriched foil, adding molybdenum as a carrier

before the separation process to determine the efficiency of extraction. The Mo^{99} disintegration rate is determined by beta counting, and use of the yield of Mo^{99} in fission gives the fissions per gram.

The experimental radiochemical values for $\sigma_{\text{C8}}/\sigma_{\text{F5}}$ at the centers of 16 ZPR-3 assemblies are given in Table I together with values calculated⁽⁵⁾ using a cross-section set⁽⁵⁾ based on that of YOM.⁽⁹⁾ The data are listed in order of increasing calculated values of $\sigma_{\text{C8}}/\sigma_{\text{F5}}$, which is a measure of increasing softness of the reactor spectrum.

Table I

COMPARISON OF EXPERIMENTAL RADIOCHEMICAL MEASUREMENTS
OF $\sigma_{\text{C8}}/\sigma_{\text{F5}}$ WITH CALCULATED VALUES

ZPR-3 Assembly Number	Experimental Ratio (Ref.) E ^(a)	Calculated Ratio ⁽⁵⁾ C	Ratio E/C ^(b)	Deviation from Mean of 0.84
5	0.087 (1)	0.102	0.85	+0.01
6F	0.084 (1)	0.103	0.82	-0.02
23	0.089 (4)	0.105	0.85	+0.01
15	0.080 (9)	0.110	0.73	-0.11
10	0.093 (1)	0.110	0.85	+0.01
36	0.097 (11)	0.111	0.87	+0.03
22	0.091 (4)	0.113	0.81	-0.03
24	0.092 (4)	0.116	0.79	-0.05
20	0.100 (12)	0.116	0.86	+0.02
12	0.100 (1)	0.120	0.83	-0.01
17	0.104 (1)	0.122	0.85	+0.01
42	0.103 (13)	0.125	0.82	-0.02
14	0.109 (1)	0.126	0.86	+0.02
35	0.111 (14)	0.126	0.88	+0.04
29	0.115 (15)	0.126	0.91	+0.07
43	0.114 (16)	0.139	0.82	-0.02

(a) Experimental error approximately $\pm 5\%$.

(b) Mean value of E/C = 0.84.

It can be seen that the experimental ratios are, on the average, 16% less than the calculated ratios; with the exception of one case, this discrepancy is the same for all cases within the limits of the experimental error of 5%. This approximately constant discrepancy could be explained by a systematic error or errors in the experimental determinations, or by systematic errors in the assumed cross sections of U^{235} or U^{238} . Since the ratio $\sigma_{\text{C8}}/\sigma_{\text{C5}}$ is not very sensitive to the neutron spectrum, it is unlikely that the discrepancy is due to erroneous calculated reactor spectra. It should also be noted that if the error lay in incorrectly calculated spectra,

then the measurements would indicate that the calculated spectra are all too soft, and this is in conflict with a number of other experimental data which indicate that the calculated spectra are too hard.⁽⁸⁾

3. INDIRECT EVIDENCE REGARDING σ_{C8}/σ_{F5}

Although no measurements of σ_{C8}/σ_{F5} have been made in ZPR-3 assemblies other than those discussed above, other experimental parameters exist which are dependent on these cross sections, and a comparison of measured and calculated values of these data also throws some light on the correctness of the assumed cross sections. The parameters we shall consider here are: (a) critical sizes of ZPR-3 assemblies, and (b) the equilibrium diffusion of fast neutrons in natural uranium, the Snell experiment.

3.a. Critical Sizes

The author has recently⁽⁸⁾ compared a number of measured and calculated parameters of 23 ZPR-3 assemblies using a cross-section set based on that of YOM.⁽⁹⁾ Included in this comparison is the calculated multiplication constant, k , for idealized spherical models of the assemblies. In the absence of any errors in the cross sections and in the experimental data, k should, of course, be unity. Table II gives the results of this analysis, including the ratio of U^{238} to U^{235} atoms in the core and its approximate composition.

Table II
ZPR-3 ASSEMBLY COMPOSITIONS AND COMPUTED VALUES OF k

Assembly Number	Ratio of U^{238} and U^{235} Atoms in Core	Approximate Volume Percentage of Material in Core							Computed k_{eff}	Deviation from Mean k of 1.000	Equivalent Deviation in Critical Mass (%)
		U^{235}	U^{238}	Steel	Al	Na	C	O			
23	0.07	9.3	0.7	9.2	42.8				1.004	+0.004	+1.8
2A	0.07	14.0	1.0	27.8	31.4				1.005	+0.005	+1.7
6F	1.1	14.0	15.9	12.4	31.4				1.003	+0.003	+1.1
5	1.1	14.0	15.9	12.3	31.4				1.005	+0.005	+2.1
29	2.0	5.0	10.0	24.9	24.4			14.5	1.003	+0.003	+1.6
30	1.5	5.9	9.0	24.7	23.4			7.3	1.009	+0.009	+5.1
31	1.6	5.8	9.1	24.8	23.5				1.006	+0.006	+3.4
34	2.2	4.7	10.3	24.8	25.5		9.1		0.997	-0.003	-1.5
9A	3.2	11.7	38.0	14.4	21.5				0.998	-0.002	-0.9
20(a)	3.1	6.1	19.0	14.5	25.1				0.992	-0.008	-4.0
41	4.9	6.0	29.1	14.2	17.9				1.002	+0.002	+1.0
10	4.9	11.9	57.9	19.5					0.999	-0.001	-0.5
11	7.5	9.5	71.7	9.2					0.994	-0.006	-4.2
24	9.6	7.6	72.9	9.4					0.995	-0.005	-4.7
25	10.3	7.2	74.2	9.2					0.991	-0.009	-6.5
35	0.07	4.1	0.3	50.0		35.6		4.2	0.994	-0.006	-2.9
36	5.3	9.4	49.5	12.8		18.2			0.994	-0.006	-2.6
33	0.07	9.3	0.7	64.2		18.2			1.014	+0.014	+5.9
32	0.07	9.3	0.7	81.8					1.015	+0.015	+6.3
16	5.3	9.4	50.1	9.2			18.1		0.999	-0.001	-0.5
12	3.8	9.4	35.4	9.2			32.0		0.998	-0.002	-1.2
17	2.2	9.4	20.6	9.2			45.7		0.998	-0.002	-0.9
14	0.07	9.4	0.7	9.2			63.9		0.995	-0.005	-1.9

(a) Plus 5.0 v/o Mo and 4.3 v/o Zr.

It can be seen that the computed k values are very close to unity. In no case is k more than $1\frac{1}{2}\%$ different from unity, and in 21 of the 23 cases the deviation is less than 1%.

We will now consider the results that would be obtained if the values of σ_{C8} and σ_{F5} were altered so that the calculated values of σ_{C8}/σ_{F5} were in agreement with the experimental radiochemical ratios given in Table I. Since σ_{C8}/σ_{F5} is not very sensitive to the neutron spectrum, the spectrum changes caused by changing cross sections have been ignored, and the changes in k have been estimated on an elementary one-group basis.

First, we consider the effect of increasing σ_{F5} by 16%. This will increase the calculated k for all the assemblies, the increase being approximately 10% to 16% depending upon the core considered. Thus, not only will the mean k be increased to about 1.1, but the spread of values will be about $\pm 3\%$ rather than the existing $+1\frac{1}{2}\%$ to -1% .

Next, we consider the effect of decreasing σ_{C8} by 16%. In the six cases for which the U^{238} content is low (ratio U^{238} to U^{235} is 0.07), there will only be small changes in k , the mean value remaining at about 1.00. The effect on the other 17 cases will increase as the U^{238} content increases. The effect is quite complicated since there will be changes in the neutron economy in the core, in the leakage from the core, and in the effectiveness of the blanket as a reflector (since the blankets are largely U^{238}). The calculated k will increase by up to about 7% for Assemblies 24 and 25, for which there were about 10 U^{238} atoms per U^{235} atom, and, crudely, will be proportionately less for the other cases. Thus, if σ_{C8} is decreased by 16%, the computed values of k will range from about 1.00 to 1.07.

Clearly the consistency and accuracy of the calculation of k for the ZPR-3 assemblies is adversely affected by simple changes in cross sections of U^{235} and U^{238} of the magnitude required to give calculated values of σ_{C8}/σ_{F5} which agree with the radiochemical measurements. However, it must be strongly emphasized that this in itself is not sufficient reason for rejecting the possibility that such changes may indeed be correct. The calculated k values depend upon many cross sections, and the possibility of compensating errors can not be overlooked.

3.b. The Snell Experiment

The Snell experiment is an exponential experiment in natural uranium whereby the asymptotic relaxation length L and various spectral indices are measured. Recently, Michael⁽¹⁷⁾ has analyzed the two most recent, carefully executed experiments of Chezem⁽¹⁸⁾ and Campon *et al.*,⁽¹⁹⁾ and has shown that although both sets of experimental data require correction to reduce them to the asymptotic values, the corrected results are in excellent agreement with each other. The two experimental corrected values

of L are 9.23 ± 0.05 cm and 9.02 ± 0.18 cm, giving a weighted mean value of 9.21 ± 0.04 cm. The calculated value obtained by use of the unmodified YOM cross sections is 9.00 cm, and if recent U^{238} inelastic scattering cross sections of Smith⁽²⁰⁾ are used, the calculated value of L is increased to 9.28 cm. Thus the present calculations of L are in excellent agreement with the weighted mean experimental data, but if σ_{C8} is decreased by 16%, the calculated L will increase by about 8% and the agreement will be lost. Again, as with the considerations of critical size, this does not exclude the possibility that σ_{C8} could be in error by 16% since there could be compensating cross-section errors.

4. THE PRESENT MEASUREMENTS OF σ_{C8}/σ_{F5}

4.a. Experimental Technique

The present experimental method is basically the simple technique of measuring the activation of U^{238} relative to fission of U^{235} both in the fast spectrum and in a thermal spectrum. The ratio of fast cross sections can then be simply obtained in terms of the well-known thermal cross sections.

The difficulties that arise in the present work are twofold. First, and most important, is the difficulty of measuring the activity resulting from neutron capture in U^{238} in the presence of the U^{238} fast-fission products. Since, in a fast spectrum, the fission cross section of U^{238} may be larger than the capture cross section, this can be quite difficult. Second is the lesser problem of measuring the U^{235} fission rate in both a fast and a thermal spectrum. If the fission product activity in a U^{235} foil is measured, then the relationship between fast and thermal U^{235} fission product activities and fast and thermal fissions must be determined. Since U^{235} fast and thermal fission product yields are not identical, the activities per fission cannot be identical although they may, of course, be closely similar.

Somewhat novel approaches to both these problems have been developed for the current experiments. These will now be described.

4.a.1. Measurements of U^{238} Activation

The half-lives of nuclides following neutron capture in U^{238} are as follows:

Either the U^{239} or the Np^{239} activity may be measured to determine the capture in U^{238} , but in the past effort has been concentrated on Np^{239} .

Since the activated U^{238} foils must be extracted and counted within about one or two hours at most if the U^{239} activity is to be measured, determination of the Np^{239} activity has marked advantages in reactors where access is not easy, such as power reactors. However, if the counting statistics at the available reactor power are such as to require near-saturation activities, then the long half-life of Np^{239} can be a strong disadvantage, since irradiation times of about 5 days are needed. This is the case with ZPR-3, which normally operates at not more than 50 W. Consequently, in the present experiments the activity of U^{239} has been measured.

In the decay of U^{239} , a single, 74-keV γ ray and a 17-keV X ray are emitted, and a NaI scintillation counting arrangement has been designed to optimize the detection of the 74-keV γ ray and minimize the detection of other γ rays. The design can be considered in four parts:

(a) A NaI crystal, 0.2 cm thick, was chosen so that the efficiency for stopping a 74-keV γ ray is about 92%. The calculated variation of the absorption in a 0.2-cm path length in NaI is given in Fig. 1(a), and it can be seen that only 6% or less of the γ rays above 500 keV are stopped in the crystal. Increase of the crystal thickness to 0.4 cm will give 99.3% absorption at 74 keV, but will also approximately double the absorption at 500 keV and above. Thus, since many fission product γ rays have energies greater than 500 keV, selection of a crystal thickness greater than about 0.2 cm will decrease the discrimination against fission product radiation with only a marginal increase in the detection of U^{239} radiation.

(b) A 0.010-cm-thick lead "filter" was placed between the foil and the NaI crystal. The K-shell and L-shell absorption edges in lead lie at 88 keV and 16 keV, respectively, so that the absorption at 74 keV is much less than it is below 50 keV and between 88 keV and 110 keV. The percentage transmission through 0.010 cm of lead is shown in Fig. 1(b). The product of the lead transmission and NaI absorption curves gives the peaked net efficiency curve shown in Fig. 1(c). (See footnote.)

(c) The depleted uranium foils used in the irradiations were thin. The half-thickness of uranium for absorption of 74-keV γ rays is 0.015 cm and hence, if foils of this thickness were used, there would be significant absorption of U^{239} radiation. However, the higher-energy fission product radiation would suffer less attenuation, and there would in effect be less discrimination against fission product activities. Consequently, the foils used were only 0.002 cm thick (about 35 mgm/cm²).

The effectiveness of the lead filter is diminished but not eliminated by the presence of 72 keV fluorescence x rays that are emitted when K-shell photoelectric absorption occurs in lead. These 72 keV x rays are effectively indistinguishable from the 74 keV U^{239} γ rays, but the present results are not affected since the fluorescence radiation is created by fission product γ rays and is subtracted from the total activity when the fission product correction is made.

(d) Further energy discrimination was provided by using a 127-channel pulse-height analyzer. An energy region may then be selected in which the U^{239} counts predominate.

The performance of this γ -ray counter is illustrated in Figs. 2, 3, and 4. Figure 2 shows the pulse-height spectrum obtained with a Ba^{133}

FIG. 1
VARIATION OF COUNTER EFFICIENCY WITH GAMMA-RAY ENERGY

FIG. 2
BARIUM-133 PULSE-HEIGHT DISTRIBUTION WITH AND WITHOUT
A PLATINUM FILTER

FIG. 3
URANIUM-239 PULSE-HEIGHT DISTRIBUTION

FIG. 4
PULSE-HEIGHT DISTRIBUTION OF
URANIUM-235 THERMAL-FISSION PRODUCTS

source without any filter between the source and the NaI crystal (i.e., the lead filter described above was removed) and also with a 0.025-cm-thick platinum filter. Ba^{133} emits a 31-keV X ray and γ rays of 70-keV, 81-keV, 292-keV, 360-keV, and 441-keV energies. With the particular gain used, the spectrum is cut off at about 180 keV, and without the platinum filter the peaks due to the 31 keV and 81 keV radiation are most prominent. There is also a small peak at about 53 keV, arising from the 81-keV γ ray due to loss of the 28-keV iodine X ray, and a higher-energy background due to the 292-, 360-, and 441-keV γ rays. However, the 70-keV peak is completely obscured. With the platinum filter, a completely different spectrum is obtained. The K absorption edge in platinum

is at 78.5 keV, so that the 81-keV γ ray is strongly absorbed, as is also the 31-keV X ray. The higher-energy γ rays are slightly absorbed. The 70-keV γ ray is transmitted, and the 70-keV peak (and a peak at about 42 keV, arising from absorption of the 70-keV γ ray but with loss of the iodine K X ray) is very prominent. This illustrates the mechanism of the filtering action obtained with a lead filter and the 74-keV γ ray of U^{239} .

Figure 3 shows the pulse-height spectrum over the range from 0 to 180 keV given by a sample of highly depleted uranium which has been irradiated in a thermal flux. The most prominent peak is at an energy of 74 keV, corresponding to the capture of the 74-keV γ ray and subsequent capture of the 28-keV iodine K X ray. The smaller peak is also due to capture of the 74-keV γ ray, but the iodine K X ray is lost. The small number of counts at energies greater than 74 keV is due to the small number of U^{235} thermal-fission products.

Figure 4 shows the pulse-height spectrum over the range from 0 to 180 keV from U^{235} thermal-fission products. This spectrum arises from γ rays of many energies, so that the spectrum does not contain many

features. The fairly low broad peak obtained centered at about 80 keV arises because of the greater efficiency of the detector at these energies (see Fig. 1).

4.a.2. Measurements of U^{235} Fission Rate

The U^{235} fission rate has been measured directly by the use of a fission chamber in both the thermal and fast irradiations. A section of this counter is shown in Fig. 5.

FIG. 5
URANIUM-235 FISSION CHAMBER
(Dimensions in inches)

The counter is a parallel-plate, gas-flow chamber closely similar in dimensions to the modified Kirn absolute fission chambers used for fission ratio measurements in ZPR-3,⁽²¹⁾ but it is made of aluminum instead of stainless steel and has a recessed plate which holds the depleted uranium foil during irradiation. The U^{235} deposit weighed about $35 \mu\text{g}$ and was plated on one side of a 0.050-cm-thick stainless steel plate. The depleted uranium foil was wrapped in aluminum foil and held against the other side of the steel plate so that the U^{235} and U^{238} were essentially in the same flux during irradiation.

In both thermal and fast irradiations the fission-chamber efficiency is the same and the flux is held at a constant level, so that in each irradiation the count rate on the fission chamber is proportional to the product of flux and the U^{235} fission cross section. This is discussed below in Sect. 4.a.3.

The fission chamber count rates were measured by recording the counts on a 256-channel pulse analyzer. A typical pulse-height spectrum is shown in Fig. 6. It can be seen that the discrimination between

FIG. 6
FISSION CHAMBER PULSE-HEIGHT DISTRIBUTION

the fission pulses and the low-energy amplifier noise and γ ray pulses is excellent. The fission rate is then obtained by summing all counts above the trough between the low-energy pulses and the fission pulses. The same technique is used in both fast and thermal irradiations so that there is a negligibly small error arising from ignoring the contribution of the low-energy tail of the fission counts.

Three to five such fission chamber counts were taken during each irradiation thus monitoring the constancy of the flux.

4.a.3. The Thermal Calibration

The thermal irradiations were carried out in the center of Hole 2 of the AFSR thermal column.⁽¹⁰⁾ There are 3 ft of graphite between this

point and the outer surface of the AFSR reflector, and a well-thermalized flux is obtained. The boron-10 cadmium ratio is approximately 800.

The reactor is first brought to a steady power. The U^{235} counter containing the depleted uranium foil is rapidly inserted and the time noted. The depleted foil and counter are irradiated at the constant power level for either one or two half-lives of U^{239} (i.e., 23.5 or 47.0 min) and then rapidly removed from the reactor. During the irradiation three to five counts are made as described in Sect. 4.a.2 to obtain the U^{235} fission rate.

The depleted uranium foil is then removed from the fission chamber and counted in the scintillation counter described in Sect. 4.a.1. A fixed procedure was used in which 2-min counts were taken at intervals of 5 min, the first count starting 10 min after removal of the foil from the thermal column. The pulse-height spectra so obtained were the sums of curves similar to those of Figs. 3 and 4. A typical spectrum is shown in Fig. 7. The upper energy end of this composite spectrum is entirely due to fission product activity with no contribution from U^{239} decay.

FIG. 7
PULSE-HEIGHT DISTRIBUTION FROM URANIUM-238 IRRADIATED
IN A FAST SPECTRUM

The U^{235} fission product activity must be subtracted. This was accomplished by use of the results of subsidiary experiments. In these experiments highly enriched uranium foils of dimensions similar to those of the depleted foils were irradiated and their activities measured in the scintillation counter under precisely the same conditions as the depleted foil irradiations, that is, the enriched foils were irradiated for 23.5 or 47.0 min and counted for 2 min at 5-min intervals after the end of irradiation. Thus, the U^{235} fission product pulse-height spectrum is known for each occasion when the mixed U^{239} and U^{235} fission product activities were counted. The U^{235} fission product spectrum is then normalized to the upper end of the composite spectrum and subtracted from the total count to give the U^{239} activity alone. This is illustrated in Fig. 7.

The U^{239} activities are then corrected for decay and for the finite irradiation time to give the saturation activity of U^{239} . With the nomenclature

$F = U^{235}$ fission-chamber count rate

$C = U^{239}$ saturation activity

E_A = efficiency of fission chamber

E_B = efficiency of scintillation counter for U^{239} γ rays

ϕ = flux

N = number of atoms

σ = cross section

and using the subscripts

F = fission

C = capture

$5 = U^{235}$

$8 = U^{238}$,

we have in any flux, fast or thermal,

$$F = E_A \phi N_5 \sigma_{F5}; \quad (1)$$

$$C = E_B \phi N_8 \sigma_{C8}. \quad (2)$$

Hence,

$$\frac{C}{F} = \left(\frac{E_B N_8}{E_A N_5} \right) \left(\frac{\sigma_{C8}}{\sigma_{F5}} \right), \quad (3)$$

and from the thermal irradiation we obtain

$$\left(\frac{E_B N_8}{E_A N_5} \right) = \left(\frac{C \sigma_{F5}}{F \sigma_{C8}} \right)_{\text{Thermal}} \quad (4)$$

the quantity on the right-hand side of Eq. 4 can be obtained in terms of the experimentally determined values of C and F and the well-known thermal cross sections of U^{235} and U^{238} .

We will now examine the calibration in more detail.

Each pulse-height spectrum obtained with the scintillation counter is divided into 127 equal channels extending from 0 to about 160 keV. To reduce the amount of data handled, the 127 channels were grouped into five energy intervals: channels 1 through 23 (0 to 28 keV), 24 through 47 (28 to 58 keV), 48 through 71 (58 to 88 keV), 72 through 95 (88 to 117 keV), and 96 through 127 (117 to 157 keV). The energy limits of these groups are shown in Figs. 3, 4, and 7. The bulk of the U^{239} activity lies in groups 2 and 3, and there is negligible U^{239} activity in group 5. The fission product spectra were, therefore, normalized at group 5.

The procedure involved in a typical calibration is given in detail in Table III. First the foil background, i.e., the natural activity of the uranium, is subtracted group by group to give the U^{239} plus fission product activity in each group. Next, the enriched uranium pulse-height spectrum obtained with the same irradiation and decay time is normalized to the group-5 count, giving the fission product count. The U^{239} activity is obtained by subtraction and is then corrected to give the count rate at the instant when the foil was removed from the reactor, i.e., at zero time. It can be seen from Table III that the zero-time count rates (which were corrected assuming a 23.5-min half-life) are in good agreement with each other, thus indicating that the fission product counts have been correctly estimated. The sum of the U^{239} counts in groups 2 and 3 is taken as the U^{239} activity. A weighted mean of the counts at different decay times is taken to obtain the best measure of the U^{239} activity at zero time. These are then corrected for length of irradiation to give the saturated activity.

Table III
TYPICAL THERMAL CALIBRATION OF DEPLETED URANIUM FOIL (D402)

Time after Irradiation Ends (min)	Energy Group	Total Counts(a)	Foil Background(a)	Counts for U^{239} Plus Fission Products	Counts for Fission Products	Counts for U^{239}	Counts for U^{239} at Zero Time
10	1	1,479	172	1,307	1,002	305	410
	2	4,775	391	4,384	1,564	2,820	3,787
	3	18,610	1,022	17,588	3,217	14,371	19,300
	4	2,493	782	1,711	1,712	-1	-1
	5	1,869	174	1,695	1,695	0	0
20	1	993	172	821	662	159	287
	2	3,332	391	2,941	1,032	1,909	3,444
	3	13,994	1,022	12,972	2,225	10,747	19,388
	4	2,132	782	1,350	1,218	132	238
	5	1,378	174	1,204	1,204	0	0
30	1	802	172	630	454	176	426
	2	2,519	391	2,128	709	1,419	3,438
	3	10,439	1,022	9,417	1,574	7,843	19,004
	4	1,757	782	975	877	98	237
	5	1,033	174	859	859	0	0

(a) All counts are per 2-min period.

Fission Chamber counts/2 min = 61,971.

61,772

61,480

Altogether, three depleted uranium foils were calibrated, one of which was run twice at two different reactor powers. To relate counts taken at different power levels, the saturation U^{239} counts in groups 2 and 3 were normalized to 10^6 counts per minute on the U^{235} fission chamber. The three foils were of somewhat different weights, and in each case the count/mg of depleted uranium was obtained.

The results of the calibration are given in Table IV, and it can be seen that there is good agreement between the counts/mg of foil. The four measurements were of different statistical weights because of different count rates, and a weighted mean was taken to give the best value for the thermal ratio C/F defined by Eqs. 1 through 4. We have
 $(C/F)_{\text{Thermal}} = 2.67 \times 10^4 U^{239}$ counts per min/mg/ 10^6 cpm on the fission chamber.

Table IV
RESULTS OF THERMAL CALIBRATION

Foil Number	Reactor Power (W)	U^{239} cpm(a) at Zero Time/ 10^6 Fission Counts	Foil Weight (mg)	U^{239} cpm(b)/ mg U/ 10^6 Fission Counts	Weight of Result
D401	100	7.34×10^5	27.5	2.67×10^4	6.4
D401	50	7.31×10^5	27.5	2.66×10^4	1.7
D403	50	9.30×10^5	34.6	2.69×10^4	1.5
D404	50	9.16×10^5	33.8	2.71×10^4	0.6

(a) Sum of counts in groups 2 and 3.

(b) Corrected to saturation activities.

Weighted Mean of Column 5 = 2.67×10^4 .

To complete the thermal calibration, we need the ratio σ_{C8}/σ_{F5} in a thermal flux. At a neutron velocity of 2200 m/sec, we have $\sigma_{C8} = 2.71 \pm 0.02$ b⁽²²⁾ and $\sigma_{F5} = 579.9 \pm 2.7$ b.⁽²³⁾ We require the ratio of these cross sections averaged over a Maxwellian spectrum and not at 2200 m/sec, and thus, in terms of the Westcott convention,⁽²⁴⁾ each cross section must be multiplied by the appropriate g factor. At 20°C, the temperature of the AFSR thermal column, we have for σ_{C8} and σ_{F5} , g values of 1.002 and 0.978, respectively.⁽²⁴⁾ Since we are only concerned with the ratios of cross sections, we only require the ratio of the g factors and do not actually need the cross sections averaged over a Maxwellian spectrum. Thus we find

$$\left(\frac{\sigma_{C8}}{\sigma_{F5}} \right)_{\text{Thermal}} = \frac{2.71 \times 1.002}{579.9 \times 0.978} = 4.788 \times 10^{-3}$$

It should be noted that, since the two cross sections have nearly the same energy dependence in the thermal region (they are both almost $1/v$ cross sections), the ratio of cross sections is not sensitive to the Maxwellian temperature assumed. The assumption of a temperature of 40°C instead of 20°C would only change the ratio of g values by about 0.5%.

4.a.4. The Fast-spectrum Measurements

The procedure in the fast irradiations is exactly as in the thermal irradiations, both fission chamber and depleted foil being irradiated and counted as already described. Equations 1 and 2 also hold for the fast irradiation; hence we have

$$\left(\frac{\sigma_{C8}}{\sigma_{F5}}\right)_{\text{Fast}} = \left(\frac{E_{AN_5}}{E_{BN_8}}\right) \left(\frac{C}{F}\right)_{\text{Fast}} \quad (5)$$

The term (E_{AN_5}/E_{BN_8}) in Eq. 5 is identical to that in the thermal irradiation and is given in Eq. 4 in terms of the known thermal value of σ_{C8}/σ_{F5} and the thermal calibration measurements. Hence the value of σ_{C8}/σ_{F5} in the fast spectrum can be obtained.

The only drawback to this simple procedure arises because the fissions in the depleted foil in the fast spectrum are principally in U^{238} and the pulse-height spectrum of U^{238} fission products has not been determined. Consequently, the U^{235} thermal-fission product spectra were assumed to be the same as the U^{238} fission product spectra and were used in the fast-irradiation correction. The correctness of this assumption has been examined by comparing pulse-height spectra of the U^{235} and U^{238} fission products recoiling from the surfaces of uranium foils. Aluminum catcher foils were placed against an enriched foil in a thermal flux and a depleted foil in a fast flux. The catcher pulse-height spectra and the spectra given with an enriched uranium foil in a thermal flux are compared in Table V. All spectra are normalized to 100 in Group 5. Of greatest importance is Group 3, since nearly all the U^{239} counts are located here. Clearly the catcher spectrum from U^{235} thermal fission differs from the uranium foil spectrum, presumably because the range of all fission products in uranium is not the same and some recoil from a greater depth in the foil than others. However, the catcher spectra from U^{235} thermal fission and U^{238} fast fission do not differ by more than about 10%, thus implying that the spectra from the U^{235} and U^{238} fission products retained in the uranium foils do not differ greatly. We therefore use the U^{235} thermal data but assume a possible error of about 10% in the fission product correction in the fast irradiations.

4.b. Experimental Results

Measurements have been made with four fast ZPR-3 assemblies, two with fairly hard central spectra and two with soft spectra.

Table V

FISSION PRODUCT PULSE-HEIGHT SPECTRA: 23.5-min IRRADIATION^(a)

Time after Irradiation (min)	Counts in Group ^(b)				
	1	2	3	4	5
20	55	86	185	101	100
	57	78	150	78	100
	52	79	145	75	100
30	53	82	183	102	100
	55	74	147	76	100
	51	70	143	78	100
40	52	82	185	105	100
	54	72	144	76	100
	56	71	150	82	100
50	51	80	185	106	100
	52	69	138	74	100
	52	71	150	80	100

(a) At each time the upper spectrum is from a U^{235} foil in a thermal spectrum, the central spectrum is from an aluminum catcher placed against the U^{235} foil in a thermal spectrum, and the lower spectrum is from an aluminum catcher and a depleted foil in a fast spectrum.

(b) Normalized to 100 in Group 5.

The first measurements, which were also the most extensive, were made with Assembly 44, a mock-up of a proposed French reactor, RAPSODIE. The measurements with this system have, therefore, been presented in some detail to illustrate the procedure.

The results for other assemblies are only presented in summary. The compositions of the cores of the four assemblies are given in Table VI.

Table VI
CORE COMPOSITIONS OF THE ZPR-3 ASSEMBLIES

Assembly	Ref.	Composition (Atoms per $cm^3 \times 10^{24}$)									
		Pu ^(a)	U235	U238	Fe	Ni	Cr	Al	Na	O	C
44 (RAPSODIE)	25	0.00225	0.00448	0.00273	0.01467	0.00092	0.00197	0.01027	-	0.01958	-
45	26	0.001121	0.000015	0.00723	0.00928	0.00123	0.00249	-	0.00635	-	0.02497
45A	27	0.001121	0.000015	0.00723	0.00757	0.00100	0.00203	-	0.01058	-	0.00833
46B (FARET)	28	0.00170	0.00338	0.00568	0.01057	0.00140	0.00284	-	0.00846	- - -	0.01114

(a) Isotopic composition: 95.03 w/o Pu^{239} , 4.56 w/o Pu^{240} + Pu^{242} , 0.42 w/o Pu^{241} .

4.b.1. The RAPSODIE Assembly (ZPR-3, Assembly 44)

Assembly 44 in ZPR-3 was a mock-up of RAPSODIE. The fuel for this reactor is intended to be a mixture of uranium and plutonium oxides; the critical core volume was about 34 liters.

The procedure used in the experiments with the fission chamber was to load it together with a depleted uranium foil close to the center of the core and then bring the reactor to criticality at a low power of about 0.1 W. The reactor was then set on a 1-min positive period until the power reached 50 W and the power leveled off. The reactor was then held at 50 W for 22.5 or 46.0 min, during which time fission-chamber count rates were measured, and then shut down rapidly. The integrated power during the rise to 50 W was 50 W-min, and the overall irradiation was, therefore, closely equivalent to 23.5 or 47.0 min at a constant power of 50 W.

The U^{239} activity was measured as described in Sect. 4.a.4.

Three separate irradiations were performed, one of 23.5 min and two of 47.0 min, using the three depleted uranium foils used in the thermal calibrations.

The results for foil D402 are given in detail in Table VII. It can be seen that the U^{239} activities when corrected to zero time are in good agreement, which gives some confidence that the fission product activity has been correctly estimated. The fission product count rate in Group 3 is about 20% of the U^{239} count rate.

Table VII
ACTIVATION OF DEPLETED URANIUM FOIL D402 IN RAPSODIE MOCK-UP

Time after Irradiation Ends (min)	Energy Group	Total Counts (per 2 min)	Foil Background (per 2 min)	Counts for U^{239} Plus Fission Products	Counts for Fission Products	Counts for U^{239}	Counts for U^{239} at Zero Time
20	1	7,887	118	7,769	5,388	2,381	4,295
	2	27,293	212	27,081	8,396	18,685	33,708
	3	104,660	430	104,230	18,105	86,125	155,370
	4	10,101	170	9,931	9,915	16	29
	5	9,866	69	9,797	9,797	0	0
30	1	5,090	118	4,972	3,757	1,215	2,944
	2	17,334	212	17,122	5,870	11,252	27,264
	3	77,426	430	76,996	13,035	63,961	154,978
	4	8,641	170	8,471	7,264	1,207	2,925
	5	7,184	69	7,115	7,115	0	0
40	1	3,933	118	3,815	2,774	1,041	3,387
	2	13,432	212	13,220	4,390	8,830	28,733
	3	58,955	430	58,525	9,852	48,673	158,382
	4	6,449	170	6,279	5,617	662	2,154
	5	5,403	69	5,334	5,334	0	0
50	1	3,057	118	2,939	2,180	759	3,318
	2	10,589	212	10,377	3,450	6,927	30,278
	3	44,247	430	43,817	7,930	35,887	156,862
	4	5,338	170	5,168	4,540	628	2,745
	5	4,360	69	4,291	4,291	0	0

Fission Chamber Counts/2 min = 22,706.
22,635
22,529.

The sum of the U^{239} activities in Groups 2 and 3 were corrected to give the counts/mg of foil for 10^6 cpm on the fission chamber. The three values obtained for D402, D403, and D404 were, respectively, 6.00, 6.07, and 6.07×10^5 cpm. The detailed results are given in Table VIII, and the weighted mean is

$$(C/F)_{Fast} = 6.05 \times 10^5 U^{239} \text{ cpm/mgm}/10^6 \text{ fission chamber counts.}$$

Using the thermal calibration data (see Sect. 4.a.3), we obtain

$$\left(\frac{\sigma_{C8}}{\sigma_{F9}}\right) = \frac{6.05 \times 10^5}{2.67 \times 10^4} \times 4.788 \times 10^{-3} = 0.108.$$

Table VIII
IRRADIATION RESULTS WITH RAPSODIE MOCK-UP

Foil Number	Irradiation Time (min)	U^{239} cpm(a) at Zero Time/ 10^6 Fission Counts	Foil Weight (mg)	U^{239} cpm(b)/ mg U/ 10^6 Fission Counts	Weight of Result
D402	23.5	1.649×10^7	27.5	6.00×10^5	1.0
D403	47.0	2.100×10^7	34.6	6.07×10^5	1.5
D404	47.0	2.051×10^7	33.8	6.07×10^5	1.5

(a)Sum of counts in Groups 2 and 3.

(b)Corrected to saturation activities.

Weighted Mean of Column 5 = 6.05×10^5 .

In assigning an error to this ratio we see that the statistical errors for the thermal and fast irradiations were less than 1%, and measurements for the three different foils are certainly consistent with this figure. If we accept the quoted errors for the thermal cross sections of U^{235} and U^{238} , then the ratio of these is known to about 1%. As has already been noted, both σ_{C8} and σ_{F5} are close to $1/v$ cross sections in the thermal region and the ratio of the cross sections alters by only 0.5% if the neutron temperature is altered by 20°C, so that the uncertainties in the thermal spectrum should be small. The greatest region of uncertainty lies in the accuracy of the assessment of the 20% U^{238} fission product correction in the fast irradiation. Since the U^{238} fast and U^{235} thermal catcher pulse-height spectra differed at most by about 10%, it appears reasonable to assign a 10% uncertainty to the fission product correction. This gives a 2% uncertainty in the final result. Compounding these errors quadratically gives an overall error of approximately 3%. This appears to be the best estimate of error, but we note that even if the uncertainty in the U^{238} fission product correction is doubled, i.e., is 20%, the overall error only increases to about 5%.

We have, therefore, for the RAPSODIE mock-up,

$$(\sigma_{C8}/\sigma_{F5})_{Fast} = 0.108 \pm 0.003.$$

4.b.2. Assembly 45

Assembly 45⁽²⁶⁾ was a multizoned reactor in which the composition of the central zone simulated a large, carbon-rich, PuC-UC-fueled reactor core. The core was primarily designed to investigate the Doppler effect in fast reactors, and a very soft fast reactor spectrum was obtained.

Measurements with this core differed in two important respects from those in the harder RAPSODIE-mock-up spectrum. First, there was the beneficial effect of reduced U^{238} fission in this core. In the RAPSODIE mock-up, the U^{238} fission product count in the depleted uranium foil was about 20% of the U^{239} count, but in Assembly 45 the corresponding figure was only 5%. Hence, the uncertainty due to the correction for U^{238} fission was greatly reduced.

Second, a complication arose from the fact that in this very soft spectrum the usual fast reactor assumption that the reactor is essentially homogeneous was not valid. The ZPR-3 assemblies are constructed using fuel plates and U^{238} plates which are usually $1/8$ in. thick. The other materials, such as sodium and carbon, are interleaved with the fissile and fertile materials in the correct numbers to give the required average composition. Clearly, the neutron spectrum inside a graphite plate will be softer than in a fuel plate, but with an index such as σ_{C8}/σ_{F5} , which is not very sensitive to spectral hardness, the variations of spectrum are usually not important. This was not the case with Assembly 45, and the measured values of σ_{C8}/σ_{F5} varied with the local arrangement of fuel and diluent materials.

ZPR-3 drawers are normally loaded so that all fuel and diluent pieces are vertical in the reactor. Some pieces must be removed from the core to allow the insertion of a counter; hence, the pieces on either side (i.e., in a horizontal direction) of the counter may be fuel, U^{238} , Na, C, or some other diluent depending upon the size of counter. Hence, the neutron spectrum impinging on the counter may be harder or softer than the average spectrum, depending upon the size of counter. Within practical limitations provided by the materials available, the best that could be done was to lay the drawers on either side of the measuring position on their sides so that the plates in these two drawers were horizontal. The counter was placed in an approximately cubical void, 2-in. in size, created in this way so that the fuel and diluent plates on all six faces presented their edges to the counter. Thus, since the core position was repeated in each drawer, the counter was faced on all six

sides with the average reactor composition. A measurement made with this arrangement gave $\sigma_{C_8}/\sigma_{F_5} = 0.189$, and this must be considered to be the preferred value for Assembly 45.

However, a measurement in which the two drawers on either side of the measuring position were left with the plates in their normal vertical position gave a value of 0.177, and a third arrangement in which the U^{238} pieces in the core were withdrawn about 1/2 in. from the measuring position gave 0.207. These two values, which are, respectively, $6\frac{1}{2}\%$ lower and $9\frac{1}{2}\%$ higher than the preferred value, give some indication of the ambiguities involved in this measurement in a soft spectrum. It should be noted that the arithmetic mean of the three measurements is 0.191, which is close to the preferred value.

In view of these uncertainties a 5% error is assigned to the measurement, even though counting statistics, etc., would indicate a smaller error. Thus, we have $\sigma_{C_8}/\sigma_{F_5} = 0.189 \pm 0.010$ for Assembly 45.

4.b.3. Assembly 45A

Assembly 45A⁽²⁷⁾ was similar in certain respects to Assembly 45, the major difference being that a large fraction of the graphite in the central zone was replaced by sodium. Thus, Assembly 45A more nearly represents a monocarbide-fueled reactor and the neutron spectrum is harder than in Assembly 45. As in Assembly 45, the U^{238} fission product count was about 5% of the U^{239} count.

Only one measurement was made in which the drawers were arranged in the preferred orientation described in Sect. 4.b.2, i.e., in the two drawers on each side of the measuring position the plates were laid horizontally. The result was $\sigma_{C_8}/\sigma_{F_5} = 0.152 \pm 0.007$.

As in Assembly 45, a 5% error was assigned to the measurement, even though the local drawer arrangement will be less important since the spectrum is harder.

4.b.4. Assembly 46B (FARET)

Assembly 46B⁽²⁸⁾ was a mock-up of a possible core for the FARET reactor. The fuel density in the core was fairly high, and the central spectrum was hard, although not quite as hard as in the RAPSODIE assembly. As in the RAPSODIE mock-up, the U^{238} fast fission count was about 20% of the U^{239} count. Also, as in the RAPSODIE Assembly, the ambiguities due to the heterogeneity of the core that were found in Assemblies 45 and 45A would not be expected to occur.

Two measurements were made, both with the plates in the preferred orientation discussed in Sects. 4.b.2 and 4.b.3. Both measurements gave a value of 0.111.

Thus, for Assembly 46B we have $\sigma_{C8}/\sigma_{F5} = 0.111 \pm 0.005$.

5. COMPARISON WITH CALCULATED VALUES

The present four measurements are compared with calculated values in Table IX. The calculated neutron spectra for the centers of the four assemblies are given in Table X.

Table IX
CALCULATED AND MEASURED VALUES OF σ_{C8}/σ_{F5}

Assembly	Experiment (E)	Calculation (C)	Ratio E/C
44	0.108 ± 0.003	0.104	1.04 ± 0.03
45	0.189 ± 0.010	0.181	1.04 ± 0.05
45A	0.152 ± 0.007	0.149	1.02 ± 0.05
46B	0.111 ± 0.005	0.106	1.05 ± 0.05

Average value of E/C = 1.04.

Table X
CALCULATED CENTRAL SPECTRA IN THE ZPR-3 ASSEMBLIES

Using ANL 635 Set				Using APDA 24 Set			
Group	Lower Energy Limit	Group Flux		Group	Lower Energy Limit	Group Flux	
		Assembly 44	Assembly 46B			Assembly 45	Assembly 45A
1	3.668 MeV	0.039	0.036	1	3.668 MeV	0.016	0.016
2	2.225 MeV	0.077	0.069	2	2.225 MeV	0.033	0.031
3	1.35 MeV	0.116	0.107	3	1.35 MeV	0.055	0.055
4	0.825 MeV	0.138	0.136	4	0.825 MeV	0.077	0.079
5	0.50 MeV	0.164	0.165	5	0.50 MeV	0.106	0.122
6	0.30 MeV	0.145	0.160	6	0.30 MeV	0.112	0.137
7	0.18 MeV	0.123	0.121	7	0.18 MeV	0.104	0.125
8	0.11 MeV	0.084	0.087	8	0.11 MeV	0.094	0.112
9	67.0 keV	0.057	0.056	9	67.0 keV	0.080	0.082
10	40.7 keV	0.033	0.033	10	40.7 keV	0.077	0.079
11	25.0 keV	0.013	0.016	11	25.0 keV	0.053	0.041
12	15.0 keV	0.008	0.009	12	15.0 keV	0.055	0.048
13	9.1 keV	0.002	0.003	13	9.1 keV	0.039	0.027
14	5.5 keV	0.001	0.001	14	5.5 keV	0.026	0.014
15	2.1 keV	0.000	0.001	15	3.36 keV	0.020	0.007
16	0.5 keV	0.000	0.000	16	2.04 keV	0.010	0.005
				17	1.01 keV	0.021	0.012
				18	502.0 eV	0.013	0.005
				19	249.0 eV	0.006	0.002
				20	55.6 eV	0.003	0.001
				21	12.4 eV	0.000	0.000
				22	2.77 eV	0.000	0.000
				23	0.625	0.000	0.000
				24	Thermal	0.000	0.000

The central spectra of Assemblies 44 and 46B were calculated by use of the same cross-section set [ANL Set 635(5)] that was used for the calculations compared with the radiochemical measurements (see Sect. 2). However, this set terminates at a lower energy limit of 500 eV and was

inadequate for the calculation of the very soft spectra in Assemblies 45 and 45A. Hence, for these two assemblies an extended cross section set was used, designated APDA 24, developed by Fischer⁽²⁹⁾ of Atomic Power Development Associates from the YOM set. The group structure is identical down to Group 14 of YOM, i.e., down to 5.5 keV, but the remaining two groups of YOM have been replaced by ten groups extending to thermal energies. The top 14 groups of the two sets do not have identical cross sections but they are quite similar.

The central spectrum of Assembly 44 was obtained from a transport-theory criticality calculation using the DSN code. The spectra for the other assemblies were obtained using a fundamental mode calculation.

6. DISCUSSION

The data in Table IX show that the present experimental results are in quite good agreement with the calculated values. However, there is a tendency for the experimental data to be slightly higher than calculated values. On the average, the experimental results are 4% higher than those calculated.

This is in strong disagreement with the comparison of radiochemical measurements and calculated values discussed in Sect. 2 and detailed in Table I. The radiochemical measurements, on the average, are 16% lower than calculated values and, hence, are about 20% lower than the present measurements.

The discussion in Sect. 2 shows that it is legitimate to compare discrepancies between experiment and calculation in different reactors because the ratio σ_{C8}/σ_{F5} is not very sensitive to reactor spectrum. Thus, we have a clear, strong disagreement between the results given by the radiochemical technique used and the present technique.

7. CONCLUSIONS

The present measurements of σ_{C8}/σ_{F5} in four fast reactor assemblies are in quite good agreement with calculated values. On the average, the present measurements are 4% higher than those calculated. This is in strong disagreement with the radiochemical measurements where the experimental results are about 16% lower than those calculated.

We conclude, therefore, that the present measurements support the general correctness of the calculated values of the ratio σ_{C8}/σ_{F5} and, hence, indicate that there are no gross errors in the assumed average microscopic values of the capture cross section of U^{238} and fission cross section of U^{235} .

8. ADDENDUM

Since the completion of the present work, a recalibration of the Np^{239} counter used in the radiochemical measurements has been made (see Reactor Development Program Progress Report for April 1965, ANL-7045). It was discovered that the calibration of the Np^{239} counter was in error; as a consequence, all U^{239} capture measurements made since 1958 should be multiplied by a factor of 1.227.

Multiplication of the experimental radiochemical data in Table I by 1.227 gives a revised ratio of experiment to calculation of 1.03. This is excellent confirmation of the value of 1.04 obtained with the present activation technique and supports the correctness of the present conclusions.

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