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A RE-EVALUATION OF FISSION RATIOS MEASURED IN ZPR-III CRITICAL ASSEMBLIES

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ABSTRACT

A recent comparison of measured and calculated fission ratios for 18 ZPR-III fast critical assemblies showed that the interpretation of these data contained ambiguities that suggested that the intercalibration of the fission chambers should be re-examined. Hence, we have carried out an independent intercalibration in which the relative masses of fissile materials were estimated in terms of the fission rates in a thermal flux and the well-known thermal cross sections of certain fissile isotopes. The original mass calibrations were generally confirmed with corrections being of the order of only 3%, but the U^{234} chambers required corrections of 9 to 12%. Additional small corrections of up to 1% were also established to allow for certain errors in the techniques used for the fission ratio measurements. The original measured data have been corrected and recompared with calculations. These revised experimental data are shown to be in better agreement with calculated values.

INTRODUCTION

Since 1955, more than 50 U^{235} fueled fast critical assemblies have been constructed in the Zero Power Reactor III (ZPR-III). The experimental data obtained constitute a large fraction of the available information on dilute fast reactors, and clearly it is important that this data be firmly established. However, a recent analysis of the ZPR-III data [Davey[1]] indicated there were ambiguities in the fission ratios which rendered interpretation difficult. The experimental ratios of the threshold materials Pu^{240}, U^{236}, and U^{238}, relative to the nonthreshold materials Pu^{239} and U^{233}, were found to be in good agreement with calculation, thus indicating that the calculated spectra were correct. However, the calculated fission rates in U^{235} and U^{234} were, respectively, 6% low and 8% high relative to those of the other five materials. Thus the fission ratios of U^{234}, U^{236}, U^{238}, and Pu^{240}, relative to U^{235}, disagreed with calculation and indicated that the calculated spectra were too hard.

The present investigation was undertaken to examine this discrepancy. It had the objectives of (a) trying to provide a second, independent calibration of the chambers, (b) examining the validity of the experimental techniques, and (c) reassessing the accuracy of the measured fission ratios.

DESCRIPTION OF THE FISSION CHAMBERS AND PREVIOUS MEASURING TECHNIQUES

Fission ratios in ZPR-III have been principally measured with the so-called absolute fission chambers developed by Kirn.[2] The Kirn chambers are of simple construction. The chamber body is a stout-walled steel cylinder, 2 in. in diameter and 1 in. high. The fissile material is deposited on the base of the chamber, and a circular collection plate is mounted about 0.3 in. from the base. The chamber is filled with an argon-methane mixture and sealed. The chamber is calibrated by deposition of an accurately known quantity of fissile material on the chamber base in a thin, adherent film spread over a circle of known diameter. This is accomplished by making the chamber base an electrode in an electrolytic cell containing as the electrolyte a solution of a salt of the fissile material. The strength and volume of the solution are known accurately, and the plating is continued until nearly all the fissile material is deposited. An analysis of the strength of the residual electrolyte gives the amount of material left in solution and hence gives the amount deposited. The second electrode of the cell consists of a rotating paddle which stirs the electrolyte so that the fissile material is deposited in a uniform film. The chambers contain 400 to 800 μg of material deposited over an area about 1 in. in diameter, and in these thin films, the absorption of fission fragments is small.

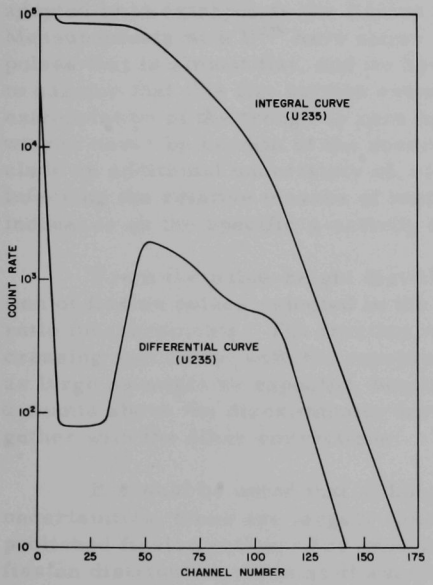
The published fission ratios were measured by integral techniques in which a discrimination level below the midpoint of the flat portion of the integral count rate curve was selected. All pulses greater than this level were counted. The fraction of fission pulses counted was then assumed to be the same for all materials. In addition, the fraction of fission fragments entirely stopped in the fissile film was assumed to be the same for all materials.

It should be noted that the threshold fission ratios must already be corrected before they can be compared with calculated values. This is because the fission ratios are calculated for homogeneous reactors, whereas the measured ratios are for the neutron spectrum inside the fission chambers. If the chamber walls are thin, the spectrum inside will be trivially different from that outside; but the walls of the Kirn chambers are sufficiently thick for inelastic scattering in them to degrade the spectrum

significantly. The experimental fission rates in the U^{238}, U^{236}, U^{234}, and Pu^{240} chambers must be increased by 8, 6, 4, and 4% respectively. These corrections have been discussed fully by Davey.[3]

THE PULSE-HEIGHT DISTRIBUTION OBTAINED FROM THE FISSION CHAMBERS

Before discussing the question of thermal intercalibration, we will examine the pulse-height distribution obtained from Kirn-type fission chambers. All the fissile materials are α-active, and hence the pulse-height distribution arises from both α and fission fragment pulses. Typical integral and differential curves obtained for chambers containing materials of relatively low α-activity (e.g., U^{235}) and high α-activity (e.g., Pu^{240}) are shown in Figs. 1 and 2, respectively. The differential curves were obtained with a 256-channel pulse-height analyzer used for all the present measurements, and the integral curves were obtained by summing the counts above each level.



ID-103-2331

Fig. 1. Differential and Integral Pulse-height Spectra for a U^{235} Fission Chamber

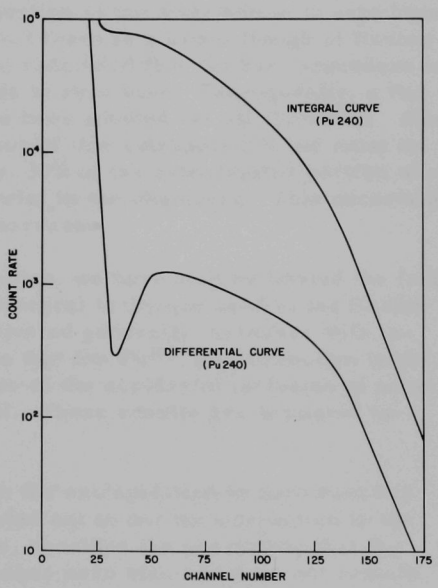


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Fig. 2. Differential and Integral Pulse-height Spectra for a Pu^{240} Fission Chamber

In Fig. 1, the broad trough (Channels 10 to 30) is believed to arise from fission fragments that lose a significant part of their energy in the fissile film. The broad, high-energy peak arises from fission fragments

that lose little of their energy in the fissile film. The double-peaked distribution expected from the known energy distribution of fission fragments does not occur because the path length in the chamber is not large enough to stop all the fragments.

The steeply rising portion at the low-energy end is due to α pulses, and arises largely from the simultaneous detection of several α particles; i.e., this is an α pile-up curve. Consequently, as shown in Figs. 1 and 2, with a higher specific α-activity, the α portion extends further towards the fission fragment peak, and the integral plateau becomes shorter. Hence, the integral operating point rises with increasing α-activity, and a greater fraction of fission pulses are not counted.

Since we wish to check the original mass calibration, we must ensure that all chambers have the same counting efficiency for fission fragments. Because of the change of pulse-height distribution with the type of material in the chamber, the only single operating point where equal efficiency is achieved for fission pulses is at zero bias. Hence, the procedure we have adopted is to extrapolate the fission portion of the distribution to zero bias. Measurements with U^{235} have shown that there is a broad trough of fission pulses that is almost flat, and we have concluded that the best procedure is to assume that this flat portion extends to zero bias. Consequently, a flat extrapolation of the trough to zero has been adopted for all chambers. Since we can never be certain of the accuracy of this extrapolation, we must include an additional uncertainty of, say, 30% of the extrapolated portion when inferring the relative masses of material in the chambers. This uncertainty increases as the specific α-activity increases.

From the pulse-height distribution, we have also estimated the fraction of fission pulses rejected in the integral technique used in the fission ratio measurements. The fraction rejected generally increases with increasing α-activity, with the exception that for Pu^{240}, the correction is not as large as might be expected, because of the accidental inclusion of some α counts above the discriminator level. These results are tabulated together with the other corrections.

It should be noted that although the extrapolation to zero bias has uncertainties, these are largely canceled out in our net correction to the published fission ratios. For example, consider the possibility that the fission distribution rises as it approaches zero bias and does not remain flat as we have assumed. In this event, by taking a flat extrapolation, we underestimate the mass of material in the chamber, but we also underestimate the fraction of fission pulses rejected by the single-level discrimination used in the fission ratio measurements. Hence, the extrapolation uncertainty cancels out. The same argument holds if the true low-bias fission distribution drops below the assumed flat extrapolation.

This cancellation of errors points out that an advantage of thermal calibration is that what is determined is not the relative masses of material in the chambers, but essentially the product of mass times efficiency for specific counting conditions. Thus, no assumptions as to the relative efficiencies of the fission chambers are necessary.

THERMAL CALIBRATION

Most threshold fission chambers and fissile foils contain some significant fraction of the thermally fissile isotopes U^{233}, U^{235}, and Pu^{239}, and the thermal cross sections of these materials are known to a high degree of accuracy. In a reactor thermal column at distances far from the core, the neutron spectrum is known to correspond closely to a Maxwellian spectrum whose temperature is that of the column. When the Westcott[4] convention is used to define effective cross sections, the cross section averaged over a pure Maxwellian spectrum $\overline{\sigma}$, is

$$\overline{\sigma} = g \sqrt{\frac{\pi T_0}{4T}}\, \sigma_0,$$

where

σ_0 = cross section for 2200-m/sec neutrons,

T_0 = 293.6°K,

T = Maxwellian temperature in °K,

and

g is a parameter that measures the deviation of the cross section from 1/v in the thermal region.

Sjöstrand and Story[5] have made a very thorough analysis of the thermal parameters of U^{233}, U^{235}, and Pu^{239} which includes data measured in thermal column and reactor spectra, as well as measurements in monoenergetic beams. From their final list of recommended, self-consistent parameters, we have, at 2200 m/sec,

$$\sigma_{F_o}U^{233} = 524.5 \pm 2.7 \text{ barns},$$

$$\sigma_{F_o}U^{235} = 579.9 \pm 2.7 \text{ barns},$$

and

$$\sigma_{F_o}Pu^{239} = 740.6 \pm 5.5 \text{ barns};$$

and also,

$$\sigma_{Fo}U^{233}/\sigma_{Fo}U^{235} = 0.9045 \pm 0.0045,$$

and

$$\sigma_{Fo}Pu^{239}/\sigma_{Fo}U^{235} = 1.277 \pm 0.009.$$

In their study, Sjöstrand and Story assumed the data of Westcott[6] in correcting thermal column and reactor measurements to 2200-m/sec values, and for consistency, we also use Westcott's data. The thermal irradiations in the present work were made in the thermal column of the Argonne Fast Source Reactor, AFSR [Brunson[7]], at a temperature of 23°C.

For T = 23°C (316.6°K), Westcott[6] gives $g_F U^{233} = 1.0003$, $g_F U^{235} = 0.9752$, and $g_F Pu^{239} = 1.0507$. Using the above data, we find that at 23°C,

$$\overline{\sigma}_F U^{233}/\overline{\sigma}_F U^{235} = 0.9277 \pm 0.0046,$$

and

$$\overline{\sigma}_F Pu^{239}/\overline{\sigma}_F U^{235} = 1.376 \pm 0.010,$$

if we assume no errors in Westcott's g factors.

The boron-10 cadmium ratio in the measuring position is approximately 800, indicating a well-thermalized spectrum, and thus Westcott's g factors are applicable.

The procedure used in the present work was first to compare the thermal fission rates for U^{233}, U^{235}, and Pu^{239} films plated on stainless steel discs of 0.0025-in. thickness. This was done by mounting the discs in turn in a thin aluminum-walled, gas-flow, fission chamber (similar in design to the Kirn chamber), which was placed in a highly reproducible position in the AFSR thermal column. A 256-channel pulse-height analyzer was used to measure the pulse-height distributions, and the fission rates to zero bias were obtained by flat extrapolation as discussed above. Next, for example, the U^{235} foils were mounted in a thick steel-walled, gas-flow chamber, closely similar to the Kirn chambers and compared with the U^{235}-loaded Kirn chambers in the fast flux in the beam hole of AFSR. The same procedure was repeated with the U^{233} and Pu^{239} foils and chambers. The same procedure of extrapolation to zero bias was also used in the beam hole irradiations.

That the 0.0025-in. steel backings did not significantly affect the relative fission rates in the U^{233}, U^{235}, and Pu^{239} foils was checked by adding an additional 0.010-in. steel foil and again comparing thermal fission rates. No significant difference was found.

Thus, the relative effective masses of fissile material in the U^{233}, U^{235}, and Pu^{239} Kirn chambers could be determined in terms of the thermal cross sections of U^{233}, U^{235}, and Pu^{239} by using the foils on thin stainless steel backings as intermediate standards.

These relative masses were normalized to the mass of 804 μg of uranium, which was believed to be plated on the Kirn U^{235} chamber No. 5 (which has been used as a standard in the fission ratio measurements).

This technique gives no cross-check on the calibration of the threshold Kirn chambers, and this calibration has been carried out using the less accurate technique of comparing the fission rates of the Kirn chambers themselves in the AFSR thermal column. Although the Kirn chambers are massive (200 g) and thus introduce a thermal flux depression measured at about 25%, the chamber weights do not differ by more than about 4%, so that the fluxes inside each chamber should not differ by more than a few percent. It was only feasible to compare the U^{234} chambers (containing 4.87% U^{235}) and the Pu^{240} chambers (containing 20.17% Pu^{239}) with the Kirn U^{233}, U^{235}, and Pu^{239} chambers. The isotopic composition of the U^{236} chambers is too uncertain, and the U^{235} content of the U^{238} chambers is too low, to permit adequate measurements.

Since the Maxwellian spectrum is distorted by absorption in the steel walls, the average cross sections are not quite those for the pure Maxwellian spectrum. However, the shape of the distorted spectrum was estimated, and the U^{233}, U^{235}, and Pu^{239} fission cross sections were averaged over this modified spectrum. The relative fission cross sections were within about 3/4% of those for the undistorted spectrum. This is not surprising since all three fission cross sections have roughly the same energy dependence over the region of importance in a Maxwellian spectrum at 23°C. This is shown by the closely similar g factors for these three materials.

The deduced masses from this less exact calibration were also normalized to a mass of 804 μg for Kirn chamber No. 5.

Details of the results are presented in Appendices A, B, and C and are summarized in Table I, together with the masses that are believed to have been plated on the chambers. These data show that there is good agreement between the two thermal calibrations, the greatest difference being 3 to 4% (for the Pu^{239} chambers 20 and 21).

The last column, which gives the corrections that we believe should be applied, shows that generally the plated masses are quite accurate, with the exception of U^{234}, where corrections of 9 to 12% are indicated. Examination of past ZPR-III data supports some of these corrections. Specifically a +1% difference between 4 and 5, a -2% difference between 19 and 21, and a +3% difference between 8 and 11 have been observed in fission ratio measurements where both chambers were used.

Table I

FISSILE MASSES DEDUCED FROM IRRADIATIONS

Kirn Chamber Number	Principal Isotope	Plated Mass (μg)	Effective Masses from Irradiations (μg)			Correction to Plated Masses
			Thermal Plus Beam Hole Values	Kirn Thermal Irradiation Values	Selected Best Masses	
5	U^{235}	804	804[a]	804[a]	804[a]	0.0
4	U^{235}	802	811	818	811	+1.1%
16	U^{233}	498	497	498	497	-0.2%
17	U^{233}	500	488	494	488	-2.5%
18	U^{233}	499	494	494	494	-1.0%
19	Pu^{239}	493	477	483	477	-3.4%
20	Pu^{239}	460	454	473	454	-1.3%
21	Pu^{239}	490	490	504	490	0.0
6	Pu^{240}	401	(b)	407	407	+1%(c)
12	Pu^{240}	398	(b)	402	402	+1%(c)
8	U^{234}	497	(b)	453	453	-9%
9	U^{234}	494	(b)	446	446	-10%
11	U^{234}	496	(b)	437	437	-12%

[a] Normalized to this value.

[b] Not measured.

[c] Well within the experimental accuracy of about 4%.

The accuracies of the corrections are difficult to assess. We estimate that the relative values between chambers of the same type are accurate to about 1/2%, and the relative values of the U^{233}, U^{235}, and Pu^{239} chambers are accurate to about 1%. The errors on the Pu^{240} and U^{234} calibrations are estimated to be about 4 and 2% respectively, if the given isotopic compositions are assumed to be correct.

CORRECTIONS TO THE MEASURED FISSION RATIOS

The measured fission ratios can now be corrected both for mass errors and for the errors incurred by differences in the fraction of fission pulses rejected by the integral counting technique.

The fraction rejected is estimated to be 1% for the U^{234}, U^{235}, U^{236}, and U^{238} chambers, and 2% for the U^{233}, Pu^{239}, and Pu^{240} chambers. The size of this correction is a measure of the quality of the plating and of the increase in the discrimination level as the specific α-activity increases. As has been mentioned previously, the Pu^{240} correction is somewhat diminished because of the accidental inclusion of some α pulses above the discrimination level. The Pu^{240} correction of 2% is also somewhat uncertain. Since all fission ratio measurements were made relative to U^{235} chambers, corrections need only be applied to the measurements that include U^{233}, Pu^{239}, and Pu^{240}. These fission ratios are, therefore, to be increased by 1%.

Thermal calibration has shown that there are significant errors in the effective masses of some of the Kirn chambers. However, most of the U^{233}, U^{235}, and Pu^{239} measurements were made with chambers 16, 5, and 21, respectively, and Table I shows that the relative masses we deduce for these chambers differ trivially from the assumed masses. Chamber 11 was used principally for the U^{234} measurement, and hence a correction of -12% is required. The apparent Pu^{240} correction is well within the limits of error and can be ignored. We have no estimate of corrections to the U^{236} and U^{238} chamber masses.

All corrections, including the inelastic scattering correction, are listed in Table II. Also listed in this table are the comparisons of the uncorrected and corrected experimental ratios with the calculated values. It is sufficient to list mean values of the ratio of calculation and experiment since the analysis by Davey[1,3] has shown that these values are independent, within experimental errors, of the reactor spectrum. The corrected and uncorrected fission ratios for each assembly are listed in Appendix D.

Table II

FISSION RATIO CORRECTIONS AND COMPARISONS WITH CALCULATIONS

Fission Ratio	Correction Relative to U^{235}(b)				Mean Uncorrected Calc. Ratio / Expt. Ratio (a)	Corrected Calc. Ratio / Expt. Ratio
	Inelastic Scattering	Effective(c) Mass	Operating Conditions	Net Correction		
$\frac{Pu^{239}}{U^{235}}$	0	0	+1%	+1%	1.06	1.05
$\frac{U^{233}}{U^{235}}$	0	0	+1%	+1%	1.05	1.04
$\frac{U^{234}}{U^{235}}$	+4% ±1%	+12%	0	+16%	1.18	1.02
$\frac{Pu^{240}}{U^{235}}$	+4% ±1%	0	+1%	+5%	1.10	1.05
$\frac{U^{236}}{U^{235}}$	+6% ±1½%	Not estimated	0	+6%	1.13	1.07
$\frac{U^{238}}{U^{235}}$	+8% ±2%	Not estimated	0	+8%	1.16	1.08

(a) From Table VIII, Davey[3].

(b) A positive correction indicates an increase in the experimental ratio.

(c) A decrease in the assumed mass increases the experimental ratio.

RESULTS

The data in Table II show that considerable corrections must be applied to the measured ZPR-III fission ratios. The largest corrections are those for inelastic scattering, which have been discussed previously [Davey[1,3]]. The major correction which arises from the present work

is for the fissile masses in the U^{234} chambers. Small corrections are also indicated for errors arising from the integral counting techniques.

Comparison of the last two columns of Table II shows that the calculated fission ratios are in better agreement with the experimental values after the corrections have been applied.

Comparing the corrected, experimental data with calculated values, we see that

(a) The calculated fission rates in U^{235} are too small relative to those in all six materials (U^{233}, U^{234}, U^{236}, U^{238}, Pu^{239}, and Pu^{240}). This indicates that the assumed U^{235} fission cross section is too small, relative to those of the other materials.

(b) There is general agreement between calculation and experiment for Pu^{239}, Pu^{240}, U^{233}, U^{234}, U^{236}, and U^{238}, which indicates that the calculated spectra, as defined by the fission ratios, are not greatly in error.

These observations should be treated with some reserve since real trends may be masked by the experimental errors. In view of the questions raised in these discussions, we believe that the corrected experimental ratios have, in general, an accuracy no better than 2%. For Pu^{240}, the uncertainty may be as large as 5%.

CONCLUSIONS

(a) The relative masses of fissile materials in fission chambers has been determined with an accuracy of the order of 1% by calibrating the chambers in terms of their fission rates in a thermal spectrum and the well-known thermal cross sections of U^{233}, U^{235}, and Pu^{239}. Even chambers of fairly massive construction may be compared in this manner, particularly if a combination of thermal and fast irradiations is used.

(b) Using thermal calibration, the original mass calibrations of the ZPR-III fission chambers have been largely confirmed, the discrepancies generally being no more than about 3%. For U^{234}, discrepancies of 9 to 12% were found.

(c) Errors in the fission ratios arising because of differences in the fraction of fissions rejected when the integral counting technique was used, have been estimated to be no more than about 1%.

(d) These results have been used to correct the original experimental data. The corrected data are in closer agreement with the calculated values. There is some evidence that the calculated spectra are not greatly in error. There is also evidence that the assumed U^{235} fission cross section is too small, relative to those of the other six materials.

(e) The accuracy of the fission ratios is considered to be generally not better than about 2%. For Pu^{240}, the uncertainty may be as large as 5%.

APPENDIX A

Thermal Intercalibration of U^{233}, U^{235}, and Pu^{239} Foils, Plated on 0.0025-in.-thick Stainless Steel

Foil Number	Type	Thermal Cross Section of Fissile Isotope, $\bar{\sigma}$ (barns)	Total Counts to Zero Bias (C)	Relative Masses of Fissile Isotopes, $C/\bar{\sigma}$
F3	U^{235}	565.5	58,516	103.5
F8	U^{235}	565.5	60,516	105.6
F21	U^{233}	524.7	127,807	243.6
F22	U^{233}	524.7	130,017	244.9
F34	Pu^{239}	778.1	77,204	99.2

APPENDIX B

Beam Hole Intercalibrations of the U^{233}, U^{235}, and Pu^{239} Kirn Chambers and the Foils Plated on 0.0025-in.-thick Stainless Steel

Chamber or Foil Number	Type	Total Counts to Zero Bias	Mass of Principal Isotope (μg)	Total Mass (μg)
Kirn 5	U^{235}	126,868	751[a]	804[a]
Kirn 4	U^{235}	127,896	758	811
Foil 3	U^{235}	66,135	391	420
Foil 8	U^{235}	67,772	401	430
Foil 21	U^{233}	247,884	925[b]	941
Foil 22	U^{233}	248,275	926[b]	942
Kirn 16	U^{233}	130,845	489	497
Kirn 17	U^{233}	128,804	480	488
Kirn 18	U^{233}	130,341	486	494
Foil 34	Pu^{239}	49,062	375[b]	375
Kirn 19	Pu^{239}	62,292	477	477
Kirn 20	Pu^{239}	59,358	454	454
Kirn 21	Pu^{239}	64,074	490	490

[a] Normalized to these masses.

[b] From the relative masses of Appendix A, and the normalized masses of U^{235} Foils 3 and 8.

APPENDIX C

Thermal Intercalibration of the Kirn Counters

Chamber Number	Type	Cross Section of Thermally Fissile Isotope ($\bar{\sigma}$)	Total Counts to Zero Bias (C)	Mass[a] of Thermally Fissile Isotopes (μg)	Total Mass (μg)
5	U^{235}	565.5	85,380	751[b]	804[b]
4	U^{235}	565.5	86,942	764	818
16	U^{233}	524.7	51,697	490	498
17	U^{233}	524.7	51,283	486	494
18	U^{233}	524.7	51,242	486	494
19	Pu^{239}	778.1	75,560	483	483
20	Pu^{239}	778.1	73,928	473	473
21	Pu^{239}	778.1	78,935	504	504
6	Pu^{240}	778.1	12,870	82.1	407
12	Pu^{240}	778.1	12,710	81.1	402
8	U^{234}	565.5	2,509	22.1	453
9	U^{234}	565.5	2,472	21.7	446
11	U^{234}	565.5	2,423	21.3	437

[a]The masses of the thermally fissile isotopes are the values of $C/\bar{\sigma}$ normalized to the assumed mass of Chamber 5.

[b]Normalized to these values.

APPENDIX D

Corrected Experimental Fission Ratios in ZPR-III Assemblies

Assembly Number	Uncorrected Ratio	Chamber(s) Used	Corrected Ratio	Uncorrected Ratio	Chamber(s) Used	Corrected Ratio	Uncorrected Ratio	Chamber(s) Used	Corrected Ratio
	U^{233}/U^{235}			U^{234}/U^{235}			U^{236}/U^{235}		
10	1.52	16	1.535	0.332, 0.330	8, 11	0.378	(c)		
11[a]	1.51	16	1.525	0.299, 0.293	8, 11	0.339	(c)		
12	1.46	16	1.475	0.297, 0.288	8, 11	0.335	(c)		
14	1.45	16	1.465	0.306, 0.304	8, 11	0.348	(c)		
16	(c)			0.297	8	0.336	(c)		
17	1.46	16	1.475	0.296, 0.299	8, 11	0.340	(c)		
20	1.52	16	1.535	0.304, 0.292	8, 11	0.342	(c)		
23	1.48	16	1.495	0.408, 0.396	8, 11	0.460	(c)		
24[b]	1.44	16, 18	1.462	0.268	11	0.311	(c)		
25	(c)			0.253	11	0.293	(c)		
29	1.47	16	1.485	0.259	11	0.300	0.082	24	0.087
30	1.49	16	1.505	0.301	11	0.349	0.099	25	0.105
31	1.52	16	1.535	0.334	11	0.387	0.106	24, 25	0.112
32	1.51	16	1.525	0.367	11	0.426	0.110	24	0.117
33	1.51	16	1.525	0.370	11	0.429	0.119	24	0.126
34	1.45	16	1.465	0.247	11	0.287	0.076	24	0.081
35	1.41	18	1.437	0.232	11	0.269	(c)		
36	1.47	16	1.485	0.312	11	0.362	0.094	24	0.100
41	1.454	18	1.483	0.286	11	0.332	0.085	24	0.090
	U^{238}/U^{235}			Pu^{239}/U^{235}			Pu^{240}/U^{235}		
10	0.0440	2, 3	0.0475	1.21, 1.23	20, 21	1.24	(c)		
11[a]	0.0355	2, 3	0.0383	1.18, 1.18	20, 21	1.19	(c)		
12	0.0444	2, 3	0.0480	1.10	20	1.12	(c)		
14	0.0550	2, 3	0.0594	1.05, 1.05	20, 21	1.06	(c)		
16	0.0414	2	0.0447	(c)			(c)		
17	0.0490	2, 3	0.0529	1.07, 1.09	20, 21	1.10	(c)		
20	0.0381	2, 3	0.0411	1.15, 1.14	20, 21	1.17	0.332	12	0.349
23	0.0678	2, 3	0.0732	1.19	21	1.20	(c)		
24[b]	0.0308	2, 3	0.0333	1.17	21	1.18	(c)		
25	0.0292	3	0.0315	1.17	21	1.18	(c)		
29	0.0356	2, 3	0.0384	1.06	21	1.07	0.289	6, 12	0.303
30	0.0427	2	0.0461	1.12	21	1.13	(c)		
31	0.0440	2	0.0475	1.17, 1.19	19, 21	1.21	0.313	6, 12	0.329
32	0.0451	2	0.0487	1.20	21	1.21	0.382	12	0.401
33	0.0480	2	0.0518	1.21	21	1.22	0.400	12	0.420
34	0.0339	2	0.0366	1.07	21	1.08	0.271	6, 12	0.285
35	0.0301	3	0.0325	1.09	21	1.10	0.250	12	0.262
36	0.0410	2	0.0443	1.19	21	1.20	0.337	6, 12	0.354
41	0.0395	2	0.0427	1.16	21	1.17	(c)		

[a] Mean values for Assemblies 11 and 22, which are nearly identical in composition.

[b] Mean values for Assemblies 24 and 38, which are nearly identical in composition.

[c] Not measured.

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REFERENCES

1. W. G. Davey, Nucl. Sci. Eng. 19, pp. 259-273 (1964).

2. F. S. Kirn, Neutron Dosimetry, Vol. II, pp. 497-512, IAEA, Vienna, 1963.

3. W. G. Davey, A Critical Comparison of Measured and Calculated Fission Ratios for ZPR-III Assemblies, ANL-6617 (1962).

4. C. H. Westcott, W. H. Walker, and T. K. Alexander, Proc. 2nd Intern. Conf. Peaceful Uses of Atomic Energy, Geneva, Paper 202 (1958).

5. N. G. Sjöstrand and J. S. Story, Neutron Cross Sections and Fission Parameters of U^{233}, U^{235}, and Pu^{239} at 2200 m/sec, AEEW-M125 (1961).

6. C. H. Westcott, Effective Cross Section Values for Well-Moderated Thermal Reactor Spectra (3rd Edition, Corrected), AECL-1101 (1960).

7. G. S. Brunson, Design and Hazards Report for the Argonne Fast Source Reactor (AFSR), ANL-6204 (1959).