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BURNUP DETERMINATION OF NUCLEAR FUELS
PROJECT REPORT
FOR THE QUARTER APRIL 1-JUNE 30, 1966

Edited by
William J. Maeck and James E. Rein

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

**PHILLIPS
PETROLEUM
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ATOMIC ENERGY DIVISION

**NATIONAL REACTOR TESTING STATION
US ATOMIC ENERGY COMMISSION**

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Atomic Energy Division

Contract A1(10-1)-205

Idaho Operations Office

U. S. ATOMIC ENERGY COMMISSION

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OF NUCLEAR FUELS

PROJECT REPORT

FOR THE QUARTER APRIL 1 - JUNE 30, 1966

Edited by

William J. Maeck and James E. Rein

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SUMMARY

In this continuing program to develop methods for the accurate determination of burnup of nuclear fuels, the main emphasis this period was additional measurements of U-233 fission yields from the third and fourth irradiated capsules of U-233. These capsules contained a weighed quantity of highly enriched U-233. One capsule was irradiated to approximately 8 atom percent fission and the other to approximately 32 atom percent fission. The capsules were separately dissolved and analyzed for the number of atoms of each uranium isotope and for the number of atoms of many stable and long-lived fission product nuclides. The average absolute U-233 thermal fission yield values based on the analysis of these two capsules are given below.

<u>Mass Number</u>	<u>Element</u>	<u>Fission Yield, %</u>
83	Kr	1.07
84	Kr	1.79
85 (10.76 yr)	Kr	0.534
86	Kr	3.01
101	Ru	3.38
102	Ru	2.59
104	Ru	1.08
106	Ru	0.269
131	Xe	3.55
132	Xe	5.00
134	Xe	6.28
137	Cs	6.98
140	Ce	6.62
142	Ce	6.82
143	Nd	5.95
144	Ce	4.78
144	Nd	4.79
144	Nd+Ce	4.79
145	Nd	3.44
146	Nd	2.59
147	Sm	1.97
148	Nd	1.34
149	Sm	0.806
150	Nd	0.509
151	Sm	0.376
152	Sm	0.201

All of the above values are tentative and as additional capsules are analyzed refined data will be reported.

Previous project reports are:

<u>Period</u>	<u>Report</u>
Annual - 1962	TID-17385
Annual - 1963	IDO-14649
Annual - 1964	IDO-14656

<u>Period</u>	<u>Report</u>
Quarter, January - March, 1965	IDO-14660
Quarter, April - June, 1965	IDO-14663
Quarter, July - September, 1965	IDO-14667
Quarter, October - December, 1965	IDO-14676
Quarter, January - March, 1966	IDO-14678

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BURNUP DETERMINATION OF NUCLEAR FUELS

INTRODUCTION

The objective of this project is the development of methods for the accurate determination of burnup of nuclear fuels. The emphasis is on power reactor fuels having long residence time and high burnup rather than on short-term, experimental irradiations. The principal measurement technique under study is chemical analysis for fission products. The use of long-lived, radiochemically determined fission products is not applicable because the errors of the in-pile decay corrections are magnified with long-term irradiations, the nuclear constants are not known with sufficient accuracy, and the few available nuclides, Cs-137 and Sr-90, are volatile. Therefore, the use of stable fission product nuclides, determined by isotope dilution mass spectrometry, has been selected. The degree of reliability of a burnup determination based on stable fission product analyses depends on three factors; the accuracy of the values used for the fission yields, the linearity between the number of fissions and the number of atoms of the fission product present at the end of the irradiation, and the reliability of the analysis methods.

Specific goals of this project are the accurate measurement of the fission yields of selected nuclides for various fissioning isotopes, the selection of fission product nuclides for use as fission monitors for various fuel types, and the development of separation and mass analysis methods for these nuclides. Presently, experiments are in progress to measure the absolute thermal fission yields for U-233, U-235, Pu-239, and Pu-241 to a high degree of accuracy. Later in the program, epithermal and fast fission yields will be measured.

Initial values for many U-235 and U-233 thermal fission yields have been reported in previous quarterly reports IDO-14660, IDO-14663, IDO-14667, IDO-14676, and IDO-14678.

During this last quarter, third and fourth sets of values for the thermal fission yields of U-233 were obtained and are given in this report.

ABSOLUTE U-233 THERMAL FISSION YIELDS OF LONG-LIVED AND STABLE FISSION PRODUCTS

A major goal of the burnup project is the accurate determination of the thermal fission yields of long-lived and stable fission products. A series of capsules containing weighed amounts of the oxides of highly enriched U-233, U-235, Pu-239, and Pu-241 was prepared and irradiated in the MTR⁽¹⁾. During this quarter the third and fourth U-233 capsules were dissolved and the absolute fission yields were measured for many lanthanides, krypton, ruthenium, xenon, and Cs-137.

Irradiation History of U-233 Capsules

Standard burnup capsule CPP-6-2-4, which contained 58.8 ± 0.2 mg of highly enriched U_3O_8 , and capsule CPP-6-5-1, which contained 144.4 ± 0.2 mg of highly enriched U_3O_8 , were irradiated for eight cycles (1994 Mwd) and two cycles (1290 Mwd) respectively in the MTR at an estimated unperturbed flux of 6×10^{13} n/cm² sec. The cadmium ratio for cobalt for these irradiations was 15 ± 3 . The cooling time for these capsules was approximately 20 months.

Dissolution of U-233 Capsules - R. E. Foster, S. F. Marsh

The dissolution of each capsule was carried out in a 4-in. lead-shielded facility. The dissolution apparatus has been previously described^(1,2). The dissolver flask and reflux condenser were fabricated from high-purity quartz and an acid mixture of 6M HCl-1.6M HNO₃, prepared from quartz-distilled reagents, was used for the dissolution⁽¹⁾.

The dissolutions proceeded smoothly and each were complete in 3.5 hr. The fission gases, krypton and xenon, appeared 1.5 hr after the start of each dissolution and their evolution continued for 2 hr. The final solutions (about 200 ml) were water clear and contained no residue.

After cooling, each dissolver solution was quantitatively transferred to a 250-ml, class "A" volumetric flask with the aid of 6M HCl-1.6M HNO₃ rinses. Each solution was cooled and diluted to volume with quartz-distilled water. A Teflon-coated stirring bar was admitted and the contents were stirred for 1 hr.

Determination of Number of U-233 Fissions - R. M. Abernathey, L. W. Buttars, M. E. Kussy, F. L. Lisman, W. J. Maeck, R. A. Nielsen, F. W. Sprakes

The U_3O_8 (obtained from ORNL) that was weighed into the capsules was analyzed both for weight-percent uranium content and isotopic distribution. For the former, samples of the U_3O_8 were weighed on a micro balance and dissolved in nitric acid, weight aliquots were mixed with weight aliquots of a standard U-235 solution, and the mixtures were analyzed by isotope dilution mass spectrometry. Isotopic distribution was determined on unspiked samples. The calculated atoms of each uranium isotope are summarized in Table I. Of interest was the finding that the uranium content of the U_3O_8 corresponded to 99.525% of theoretical.

The postirradiation atoms of each uranium isotope for each capsule were determined in a similar manner with unspiked and U-235 spiked aliquots of the dissolver solution. The aliquots of the dissolver solution were delivered with calibrated 1000- μ l pipets. The calculated atoms are presented in Table I.

To accurately compute the number of U-233 fissions by the relationship:

$$F_3 = U^0 - U$$

in which:

F_3 = number of U-233 fissions
 U^0 = total preirradiated atoms of uranium
 U = total postirradiated atoms of uranium

one must account for those atoms of U-235 and U-238 lost by fission and capture. This was done with data obtained from a computer program which simulated the history of the irradiation. The cross sections were selected from the latest literature. The loss of U-235 and U-238 during the irradiation amounted to less than 0.002% of the total uranium measured at the end of the irradiation.

The number of fissions and the atom percent U-233 fissioned (defined as atoms of U-233 fissioned per 100 initial atoms of U-233) for the two capsules are given in Table II. The quoted error is the propagated standard deviation.

Capture-To-Fission Ratio for U-233 - F. L. Lisman, W. J. Maeck, F. W. Spraktes

Detailed discussion and calculation of the effective and 2200m/sec capture-to-fission ratio, α_3 , for these capsules have been previously⁽³⁾ reported.

These values are:

<u>Capsule</u>	<u>$\hat{\alpha}$ effective</u>	<u>$\hat{\alpha}$ 2200m/sec</u>
6-2-4	0.1010 $\pm$ 0.0010	0.0997 $\pm$ 0.0016
6-5-1	0.1028 $\pm$ 0.0017	0.1015 $\pm$ 0.0020

Lanthanide Fission Yields of U-233 - F. L. Lisman, S. F. Marsh, W. J. Maeck, F. W. Spraktes

The absolute fission yields of cerium, neodymium, and samarium were determined on capsule 6-5-1 and the yields of cerium and neodymium were determined on capsule 6-2-4. Because of an unusually large amount of natural samarium contamination, accurate samarium yield data could not be obtained for capsule 6-2-4. The source of this contamination is not known. It is believed to have occurred during the separation procedure rather than having been originally present in the capsule dissolver solution. Another aliquot of the capsule 6-2-4 dissolver solution will be analyzed for samarium.

TABLE I. ANALYSIS RESULTS OF IRRADIATED U-233 CAPSULES AND
CALCULATED NUMBER OF ATOMS

CAPSULE 6-2-4

	<u>Preirradiated Data</u>			
Initial Loading	58.8±0.2 mg U ₃ O ₈			
mg U-233/mg U ₃ O ₈	0.84046±0.00079			
mg U-233 in capsule	49.419±0.173 (0.35%)			
	<u>U-233</u>	<u>U-234</u>	<u>U-235</u>	<u>U-238</u>
Isotopic distribution, wt%	99.908	0.026	0.0032	0.062
std dev _{avg} (n = 4)	0.002	0.001	0.0007	0.0015
number of atoms	1.27715x10 ²⁰	3.3107x10 ¹⁶	4.0906x10 ⁻⁵	7.7593x10 ¹⁶
std dev _{avg} (n = 4)	0.00447x10 ²⁰	0.1281x10 ¹⁶	0.8918x10 ⁻⁵	0.1916x10 ¹⁶
Total atoms of uranium	(1.27850±0.00447)x10 ²⁰			
	<u>Postirradiated Data</u>			
mg U-233 in Capsule	31.775±0.018 (0.057%)			
	<u>U-233</u>	<u>U-234</u>	<u>U-235</u>	<u>U-236</u>
Isotopic distribution, wt%	94.9968	4.6450	0.2233	0.0038
std dev _{avg} (n = 4)	0.0368	0.0033	0.0026	0.0012
number of atoms	8.2117x10 ¹⁹	3.9977x10 ¹⁸	1.9133x10 ¹⁷	4.7531x10 ¹⁵
std dev _{avg} (n = 4)	0.0049x10 ¹⁹	0.0036x10 ¹⁸	0.0226x10 ¹⁷	0.5838x10 ¹⁵
Total atoms of uranium	(8.64198±0.00519)x10 ¹⁹			
Total atoms of uranium corrected for loss by processes other than U-233 fission	(8.64491±0.00519)x10 ¹⁹			

CAPSULE 6-5-1

	<u>Preirradiated Data</u>			
	144.4±0.2 mg U ₃ O ₈			
	0.84046±0.00079			
	121.36±0.19 (0.16%)			
	<u>U-234</u>	<u>U-235</u>	<u>U-238</u>	
	0.026	0.0032	0.062	
	0.001	0.0007	0.0015	
	8.1304x10 ¹⁶	1.0045x10 ¹⁶	1.9055x10 ¹⁷	
	0.3138x10 ¹⁶	0.2190x10 ¹⁶	0.0472x10 ¹⁷	
	(3.13915±0.00502)x10 ²⁰			
	<u>Postirradiated Data</u>			
	110.208±0.088 (0.08%)			
	<u>U-233</u>	<u>U-234</u>	<u>U-235</u>	<u>U-236</u>
	98.9561	0.9506	0.0190	Not measured
	0.0025	0.0009	0.0016	0.0006
	2.8431x10 ²⁰	2.7242x10 ¹⁸	5.4388x10 ¹⁶	1.8040x10 ¹⁷
	0.0023x10 ²⁰	0.0022x10 ¹⁸	0.4579x10 ¹⁶	0.0374x10 ¹⁷
	(2.87772±0.00230)x10 ²⁰			
	(2.87774±0.00230)x10 ²⁰			

TABLE II. NUMBER OF FISSIONS AND ATOM PERCENT FISSION
FOR U-233 CAPSULES

	<u>Capsule 6-2-4</u>	<u>Capsule 6-5-1</u>
1. Initial total uranium (U^0)	$(1.27830 \pm 0.00447) \times 10^{20}$	$(3.13915 \pm 0.00502) \times 10^{20}$
2. Post total uranium corrected for losses other than U-233 fission (U).	$(0.86449 \pm 0.00052) \times 10^{20}$	$(2.87774 \pm 0.00230) \times 10^{20}$
3. Number of fissions (1-2)	$(4.1381 \pm 0.0450) \times 10^{19}$	$(2.6141 \pm 0.0552) \times 10^{19}$
4. Initial U-233 atoms	$(1.27715 \pm 0.00447) \times 10^{20}$	$(3.13634 \pm 0.00502) \times 10^{20}$
5. Atom % U-233 fission $(\frac{3+4}{3+4}) \times 100$	32.40 ± 0.37	8.33 ± 0.17

Details of the separation procedure have been previously reported⁽²⁾. Briefly the procedure used for these capsules is as follows: Four 1000- μ l aliquots of each of the irradiated U-233 dissolver solutions were spiked with known amounts of Ce-136, Nd-150, and Sm-144. The preparation and standardization of the spike solutions has been described previously^(1,2). A three-column sequential procedure was used for the separation of the individual lanthanides. The first column separated the lanthanides from the actinides and most fission products. Cerium is separated from the other lanthanides on a second column. On the third column, the lanthanides are chromatographically separated with α -hydroxyisobutyric acid at controlled pH as the elutrient.

The analysis results and calculated U-233 thermal fission yields for neodymium, cerium, and samarium are summarized in Tables III, IV, and V respectively.

To accurately calculate the fission yields of the lanthanide isotopes, the atoms of each nuclide must be corrected for buildup and burnout due to neutron capture. These corrections were obtained from a computer program which simulated the actual irradiation conditions of the experimental capsule. A detailed discussion of the determination of these correction factors has been previously reported⁽⁴⁾.

The yield of the mass 144 chain was calculated by summing the determined atoms of Ce-144 and Nd-144.

The determined number of atoms of each samarium isotope in capsule 6-5-1, the computer-corrected number of atoms, and the calculated fission yields are summarized in Table V. Due to the large capture cross sections on some of the samarium isotopes, corrections for neutron capture buildup and burnout are much greater than for cerium and neodymium and hence the errors associated with the fission yields are larger.

Most of the Sm-149, due to its very large cross section, is converted to Sm-150. Rather than apply a large correction factor, it is possible to sum the determined atoms of Sm-149 and Sm-150 because Sm-150 is a shielded nuclide and is not directly formed in fission. Small corrections were required however for the loss of Sm-150 by neutron capture. This correction factor was determined from the computer program.

Cs-137 Fission Yield of U-233 - M. E. Kussy, W. J. Maeck

The number of atoms of Cs-137 in the capsule dissolver solution was determined by gamma counting after radiochemistry separation. An additional measurement of the number of atoms of Cs-137 by isotope dilution mass spectrometry is planned.

Three 1000- μ l aliquots of each of the dissolved capsule solutions were diluted to 50.00-ml volumes. Duplicate 1000- μ l aliquots from each dilution then were analyzed by a modified ASTM cesium perchlorate procedure⁽¹⁾. Two different gamma counting techniques were used. One was based on using the 3x3 in. NaI(Tl) crystal as the standard with the crystal parameters recommended by Heath⁽⁵⁾. The other was a comparison method in which the area under the 661-keV photopeak, after correction

TABLE III. U-233 THERMAL FISSION YIELDS OF THE STABLE NEODYMIUM ISOTOPES

CAPSULE 6-2-4		Number of fissions = $(4.1381 \pm 0.0450) \times 10^{19}$ (1.09%)				
	<u>Nd-143</u>	<u>Nd-144</u>	<u>Nd-145</u>	<u>Nd-146</u>	<u>Nd-148</u>	<u>Nd-150</u>
Determined number of atoms	2.1893×10^{18}	1.8696×10^{18}	1.3739×10^{18}	1.0861×10^{18}	5.5034×10^{17}	2.1353×10^{17}
Std dev _{avg} (n = 4)	0.0075×10^{18}	0.0059×10^{18}	0.0039×10^{18}	0.0031×10^{18}	0.0127×10^{17}	0.0021×10^{17}
Atoms after correction for neutron capture	2.4338×10^{18}	$1.9442 \times 10^{18}^a$	1.4006×10^{18}	1.0592×10^{18}	5.4836×10^{17}	2.1366×10^{17}
Std dev(%)	0.60	1.0	0.30	0.30	0.24	0.10
Percent fission yield	5.88	4.70	3.38	2.56	1.32	0.516
Std dev(%)	0.07(1.25%)	0.07(1.48%)	0.04(1.12%)	0.03(1.12%)	0.01(1.1%)	0.006(1.1%)
CAPSULE 6-5-1		Number of fissions = $(2.6141 \pm 0.0552) \times 10^{19}$ (2.1%)				
	<u>Nd-143</u>	<u>Nd-144</u>	<u>Nd-145</u>	<u>Nd-146</u>	<u>Nd-148</u>	<u>Nd-150</u>
Determined number of atoms	1.5550×10^{18}	1.0671×10^{18}	9.1276×10^{17}	6.9160×10^{17}	3.5611×10^{17}	1.3114×10^{17}
Std dev _{avg} (n = 4)	0.0050×10^{18}	0.0023×10^{18}	0.0312×10^{17}	0.0236×10^{17}	0.0072×10^{17}	0.0102×10^{17}
Atoms after correction for neutron capture	1.5766×10^{18}	$1.2765 \times 10^{18}^a$	9.1641×10^{17}	9.5650×10^{17}	3.5515×10^{17}	1.3114×10^{17}
Std dev(%)	0.44	1.0	0.45	0.45	0.36	0.80
Percent fission yield	6.03	4.88	3.51	2.63	1.36	0.502
Std dev(1%)	0.13(2.1%)	0.11(2.3%)	0.07(2.1%)	0.06(2.1%)	0.03(2.1%)	0.011(2.2%)

^aIncludes correction for holdup by Ce-144

TABLE IV. U-233 THERMAL FISSION YIELDS OF LONG-LIVED
AND STABLE CERIUM ISOTOPES

CAPSULE 6-2-4 Number of fissions = $(4.1381 \pm 0.0450) \times 10^{19}$ (1.09%)

	<u>Ce-140</u>	<u>Ce-142</u>	<u>Ce-144</u>
Determined number of atoms	2.6843×10^{18}	2.7886×10^{18}	3.3999×10^{17}
Std dev _{avg} (n = 4)	0.0045×10^{18}	0.0040×10^{18}	0.0063×10^{17}
Atoms after correction for neutron capture and decay	2.7173×10^{18}	2.7774×10^{18}	$1.9661 \times 10^{18}{}^a$
Std dev(%)	0.35	0.33	1.0
Percent fission yield	6.57	6.71	4.75
Std dev(%)	0.08(1.1%)	0.08(1.1%)	0.07(1.5%)

CAPSULE 6-5-1 Number of fissions = $(2.6141 \pm 0.0552) \times 10^{19}$ (2.1%)

	<u>Ce-140</u>	<u>Ce-142</u>	<u>Ce-144</u>
Determined number of atoms	1.7474×10^{18}	1.8153×10^{18}	2.2928×10^{17}
Std dev _{avg} (n = 4)	0.0021×10^{18}	0.0027×10^{18}	0.0039×10^{17}
Atoms after correction for neutron capture and decay	1.7462×10^{18}	1.8124×10^{18}	$1.2594 \times 10^{18}{}^a$
Std dev(%)	0.32	0.34	1.0
Percent fission yield	6.68	6.93	4.82
Std dev(%)	0.14(2.1%)	0.14(2.1%)	0.11(2.3%)

^aIncludes both in-pile and out-pile decay corrections.

TABLE V. U-233 THERMAL FISSION YIELDS OF
STABLE SAMARIUM ISOTOPES

<u>CAPSULE 6-5-1</u>		Number of fissions = $(2.6141 \pm 0.0552) \times 10^{19}$ (2.1%)				
	<u>Sm-147</u>	<u>Sm-148</u>	<u>Sm-149</u>	<u>Sm-150</u>	<u>Sm-151</u>	<u>Sm-152</u>
Determined number of atoms	1.9167×10^{17}	4.9980×10^{15}	3.3049×10^{16}	1.7762×10^{17}	4.1421×10^{16}	1.0859×10^{17}
Std dev _{avg} (n = 4)	0.0136×10^{17}	0.0050×10^{15}	0.0236×10^{16}	0.0078×10^{17}	0.0257×10^{16}	0.0052×10^{17}
Atoms after correction for neutron capture	$5.1412 \times 10^{17}{}^a$	None	2.1067×10^{17}	None	9.8445×10^{16}	5.2439×10^{16}
Std dev(%)	3.1		0.40		5.0	3.0
Percent fission yield	1.97		0.806		0.376	0.201
Std dev(%)	0.07(3.7%)		0.017(2.1%)		0.021(5.5%)	0.007(3.7%)

^aIncludes corrections for holdup by Pm-147

of Cs-134, was compared to that of a certified standard (RC-137-ASTM, Nuclear Chicago Corporation). The details of the analyses and computations for the two methods have been previously discussed⁽²⁾.

The determined number of Cs-137 atoms by both methods and the U-233 thermal fission yield are given in Table VI.

Krypton and Xenon Fission Yields for U-233 - R. E. Foster, W. J. Maeck, F. W. Spraktes

These two gases were trapped from the capsule dissolver off-gas on Molecular Sieve 5A at -190°C. The concentration of each gas was determined by temperature-programmed gas chromatography. The separated gas fractions from the chromatographic column were collected on charcoal at -80°C and were transferred to the mass laboratory for isotopic distribution analysis. Details of the apparatus and the procedure for the collection and analysis have been reported^(1,2).

The computed fission yields of the stable krypton and xenon isotopes and of 10.76-yr Kr-85 are given in Table VII. The error associated with each value is the standard deviation.

Ruthenium Fission Yields of U-233 - R. E. Foster, F. L. Idsman, W. J. Maeck, F. W. Spraktes

The absolute thermal fission yields of ruthenium were determined on each of the two, dissolved, U-233 standard burnup capsules (6-2-4 and 6-5-1). Four 1000- μ l aliquots from each dissolver solution were spiked with known amounts of Ru-106 and carried through the separation and analysis procedure. The preparation and calibration of the spike and the detailed separation procedure have been previously described⁽⁶⁾. The analysis results and the calculated fission yields for ruthenium are summarized in Table VIII.

Corrections for the buildup and burnout of the ruthenium isotopes are based on a series of computer programs which simulate the irradiation history of the samples. These programs give the number of individual fission product atoms formed during the irradiation and their manner of formation. Details of these programs have been previously reported⁽⁴⁾.

In the case of ruthenium, corrections for the buildup and burnout of the stable isotopes are small (<1%), because of the small capture cross sections.

TABLE VI. DETERMINED ATOMS OF Cs-137 AND CALCULATED
U-233 FISSION YIELD

	<u>Capsule 6-2-4</u>		<u>Capsule 6-5-1</u>	
Atoms Cs-137 using crystal as standard	$(2.880 \pm 0.075) \times 10^{18}$	(2.60%)	$(1.8588 \pm 0.045) \times 10^{18}$	(2.43%)
Atoms Cs-137 by comparison method	$(2.884 \pm 0.088) \times 10^{18}$	(3.05%)	$(1.8540 \pm 0.056) \times 10^{18}$	(3.05%)
Weighted value, atoms Cs-137 ^a	$(2.882 \pm 0.058) \times 10^{18}$	(2.00%)	$(1.857 \pm 0.037) \times 10^{18}$	(2.00%)
Number of fissions	$(4.1381 \pm 0.0450) \times 10^{19}$	(1.09%)	$(2.6141 \pm 0.0552) \times 10^{19}$	(2.1%)
Fission yield Cs-137	6.94 ± 0.16	(2.3%)	7.03 ± 0.20	(2.9%)

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^aValues were averaged by weighting the reciprocals of the variances.

TABLE VII. U-233 THERMAL FISSION YIELDS OF STABLE
KRYPTON AND XENON ISOTOPES

	<u>Percent Fission Yield</u>	
	<u>Capsule 6-2-4</u>	<u>Capsule 6-5-1</u>
Kr-83	1.06±0.02	1.08±0.03
Kr-84	1.79±0.03	1.78±0.05
Kr-85 (10.76yr)	0.534±0.010	0.534±0.014
Kr-86	3.01±0.05	3.02±0.08
Xe-131	3.42±0.07	3.68±0.10
Xe-132	4.97±0.00	5.04±0.14
Xe-134	6.19±0.14	6.37±0.18

TABLE VIII. U-233 THERMAL FISSION YIELDS OF LONG-LIVED
AND STABLE RUTHENIUM ISOTOPES

<u>CAPSULE 6-2-4</u>		Number of fissions = $(4.1381 \pm 0.0450) \times 10^{19}$ (1.09%)			
		<u>Ru-101</u>	<u>Ru-102</u>	<u>Ru-104</u>	<u>Ru-106</u>
Determined number of atoms		1.3587×10^{18}	1.0441×10^{18}	4.4040×10^{17}	2.9550×10^{16}
Std dev _{avg} (n = 4)		0.0026×10^{18}	0.0021×10^{18}	0.0122×10^{17}	0.0122×10^{16}
Atoms after correction for neutron capture and decay		1.3592×10^{18}	1.0441×10^{18}	4.4022×10^{17}	1.1050×10^{17a}
Std dev(%)		0.20	0.20	0.28	1.1
Percent fission yield		3.29	2.52	1.06	0.267
Std dev(%)		0.04(1.1%)	0.03(1.1%)	0.01(1.1%)	0.004(1.5%)

<u>CAPSULE 6-5-1</u>		Number of fissions = $(2.6141 \pm 0.0062) \times 10^{19}$ (2.1%)			
		<u>Ru-101</u>	<u>Ru-102</u>	<u>Ru-104</u>	<u>Ru-106</u>
Determined number of atoms		9.1026×10^{17}	6.9159×10^{17}	2.9113×10^{17}	2.0242×10^{16}
Std dev _{avg} (n = 4)		0.0062×10^{17}	0.0062×10^{17}	0.0072×10^{17}	0.0020×10^{16}
Atoms after correction for neutron capture and decay		9.1035×10^{17}	6.9159×10^{17}	2.9107×10^{17}	7.1426×10^{16a}
Std dev(%)		0.08	0.10	0.24	1.4
Percent fission yield		3.48	2.65	1.11	0.273
Std dev(%)		0.07(2.1%)	0.06(2.1%)	0.02(2.1%)	0.007(2.5%)

^aIncludes in-pile and out-pile decay corrections.

REFERENCES

1. Maeck, W. J., Rein, J. E., Editors, Burnup Determination of Nuclear Fuels: 1964 Annual Report, IDO-14656 (1965).
2. Maeck, W. J., Rein, J. E., Editors, Burnup Determination of Nuclear Fuels: Project Report for the Quarter January 1 - March 31, 1965, IDO-14660 (1965).
3. Maeck, W. J., Lisman, F. L., Rein, J. E., Editors, Burnup Determination of Nuclear Fuels: Project Report for the Quarter January 1 - March 31, 1966, IDO-14678 (1966).
4. Maeck, W. J., Rein, J. E., Editors, Burnup Determination of Nuclear Fuels: Project Report for the Quarter July 1 - September 30, 1965, IDO-14667 (1965).
5. Heath, R. L., Scintillation Spectrometry Gamma Ray Spectrum Catalogue, 2nd Ed., Vol. 1 of 2, IDO-16880 (1964).
6. Maeck, W. J., Abernathey, R. M., Rein, J. E., Editors, Burnup Determination of Nuclear Fuels: Project Report for the Quarter October 1 - December 31, 1965, IDO-14676 (1966).

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