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BURNUP DETERMINATION OF NUCLEAR FUELS

PROJECT REPORT
FOR THE QUARTER APRIL 1 - JUNE 30, 1965

Edited By
W. J. Maeck and J. E. Rein

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**PHILLIPS
PETROLEUM
COMPANY**

ATOMIC ENERGY DIVISION

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

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OF NUCLEAR FUELS

PROJECT REPORT
FOR THE QUARTER APRIL 1 - JUNE 30, 1965

Edited By

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BURNUP DETERMINATION
OF NUCLEAR FUELS

PROJECT REPORT
FOR THE QUARTER APRIL 1 - JUNE 30, 1965

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 the burnup of nuclear fuels, the main emphasis this period was the measurement of U-233 thermal fission yields for many stable and long-lived fission products. A capsule containing a weighed quantity of highly enriched U-233, irradiated to 11.4 atom percent fission, was dissolved and analyzed for the number of atoms of each uranium isotope and for the number of atoms of various stable and long-lived fission product nuclides. From these data the capture-to-fission ratio (α) and absolute fission yields were determined. The value for α_0 is 0.0986 ± 0.0015 . The fission yield values are:

<u>Mass</u> <u>Number</u>	<u>Element</u>	<u>Fission</u> <u>Yield</u>	<u>Mass</u> <u>Number</u>	<u>Element</u>	<u>Fission</u> <u>Yield</u>
83	Kr	1.02 ± 0.02	144	Ce	4.63 ± 0.08
84	Kr	1.68 ± 0.04	144	Nd+Ce	4.69 ± 0.08
85(10.76y)	Kr	0.497 ± 0.011	145	Nd	3.40 ± 0.06
86	Kr	2.84 ± 0.06	146	Nd	2.54 ± 0.04
131	Xe	3.56 ± 0.07	147	Sm	1.82 ± 0.06
132	Xe	4.86 ± 0.10	148	Nd	1.31 ± 0.02
134	Xe	6.10 ± 0.13	149	Sm	0.751 ± 0.013
137(30.3y)	Cs	6.69 ± 0.17	150	Nd	0.498 ± 0.008
140	Ce	6.54 ± 0.10	151	Sm	0.364 ± 0.012
142	Ce	6.66 ± 0.11	152	Sm	0.193 ± 0.007
143	Nd	5.87 ± 0.10	154	Sm	0.020 ± 0.006
144	Nd	4.74 ± 0.09			

These values are tentative. Additional capsules will be similarly handled to produce refined data.

Previous project reports are:

<u>Period</u>	<u>Report</u>
Annual - 1962	TID-17385
Annual - 1963	IDO-14649
Annual - 1964	IDO-14656
Quarter, Jan-March, 1965	IDO-14660

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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 two available nuclides, Cs-137 and Sr-90, are volatile. The use of stable fission product nuclides, determined by isotope dilution mass spectrometry, has therefore 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 products 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 it is planned to determine the fast fission yields for the heavy element isotopes, from Th-232 through Pu-242.

Initial values for many U-235 thermal fission yields have been reported in the previous quarterly report, IDO-14660.

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 period a U-233 capsule was dissolved and the absolute fission yields were measured for many lanthanides, krypton, xenon, and Cs-137. Also measured was α_0 , the thermal capture-to-fission ratio.

Irradiation History of Capsule

Standard burnup capsule CPP-6-4-2, which contained 152.4 mg of U-233 enriched U₃O₈, was irradiated for 3 cycles (1850 Mwd) in the MTR at an estimated unperturbed flux of 6×10^{13} n/cm² sec (accumulated nvt = 2.4×10^{20}). The cadmium ratio for cobalt for this irradiation was 15. The capsule was discharged from the reactor June 8, 1964, allowed to cool in the MTR canal, and was dissolved April 12, 1965.

Dissolution of Capsule, R. E. Foster, S. F. Marsh

The dissolution of the 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 dissolution proceeded smoothly and was complete in 3.5 hr. The fission gases, krypton and xenon, appeared 1.5 hr after the start of the dissolution and their evolution continued for 2 hr.

After cooling, the dissolver solution was quantitatively transferred to a 250-ml, class "A" volumetric flask with the aid of 6M HCl-1.6M HNO₃ rinses. The 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 Fissions, R. M. Abernathey, L. W. Buttars, M. E. Kussy, W. J. Maeck, R. A. Nielsen, F. W. Sprakles

The accuracy of the absolute fission yield measurements directly depends on the accuracy of the determined number of fissions in the irradiated U-233 capsule. For this reason, a large effort was placed on the pre- and postirradiation analyses for the atoms of the various uranium isotopes from which the number of fissions was calculated.

The U_3O_8 (obtained from ORNL) that was weighed into the capsule 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 (in the capsule charge of 152.4 ± 0.2 mg U_3O_8) 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 was 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 a calibrated 1000- μ l pipet. 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:

$$F_3 = \text{number of U-233 fissions}$$

$$U^0 = \text{total preirradiated atoms of uranium}$$

$$U = \text{total postirradiated atoms of uranium}$$

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.

From the results:

$$U^0 = (3.31308 \pm 0.00536) \times 10^{20}$$

$$U = (2.93445 \pm 0.00240) \times 10^{20}$$

$$\text{The number of fissions} = F_3 = (3.7863 \pm 0.0588) \times 10^{19}$$

The propagated standard deviation error of 0.0588×10^{19} for the computed number of fissions corresponds to a relative error of 1.55%. The atom percent U-233 fissioned (defined as atoms of U-233 fissioned per 100 initial atoms of U-233) is:

$$\begin{aligned} \% F_3 &= 100 \left[\frac{(3.7863 \pm 0.0588) \times 10^{19}}{(3.3101 \pm 0.0054) \times 10^{20}} \right] \\ &= (11.44 \pm 0.18) \end{aligned}$$

in which the value of 0.18 is the propagated standard deviation error and corresponds to a relative error of 1.55%.

Table I. ANALYSIS RESULTS OF IRRADIATED U-233 CAPSULE
AND CALCULATED NUMBERS OF ATOMS

<u>Preirradiation Data</u>					
Initial Loading	152.4±0.2 mg U ₃ O ₈				
mg U-233/mg U ₃ O ₈	0.84046±0.00079				
mg U-233 in capsule	128.086±0.147(0.162%)				
	<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 _{ind}	0.004	0.002	0.0014	0.003	
std dev _{avg} (n=4)	0.002	0.001	0.0007	0.0015	
number of atoms	3.3101x10 ²⁰	8.5809x10 ¹⁶	1.0602x10 ¹⁶	2.0110x10 ¹⁷	
std dev	0.0054x10 ²⁰	0.3306x10 ¹⁶	0.2326x10 ¹⁶	0.0496x10 ¹⁷	
Total atoms of uranium	(3.31308±0.00536)x10 ²⁰ (0.162%)				
<u>Postirradiation Data</u>					
mg U determined in dissolved sample (n=4)					
111.975±0.091(0.082%)					
	<u>U-233</u>	<u>U-234</u>	<u>U-235</u>	<u>U-236</u>	<u>U-238</u>
Isotopic distribution, wt%	98.614	1.283	0.030	0.0013	0.071
std dev _{ind}	0.011	0.0017	0.0065	0.0015	0.002
std dev _{avg} (n=3)	0.006	0.001	0.004	0.0009	0.001
number of atoms	2.8938x10 ²⁰	3.7646x10 ¹⁸	8.8026x10 ¹⁶	3.8145x10 ¹⁵	2.0833x10 ¹⁷
std dev	0.0024x10 ²⁰	0.0043x10 ¹⁸	1.1708x10 ¹⁶	2.6702x10 ¹⁵	0.0294x10 ¹⁷
Total atoms of uranium	(2.93440±0.00240)x10 ²⁰ (0.082%)				
Total atoms of uranium corrected for loss by processes other than U-233 fission	(2.93445±0.00240)x10 ²⁰ (0.082%)				

Capture-To-Fission Ratio, F. L. Lisman, W. J. Maeck, F. W. Sprakes

The effective capture-to-fission ratio α is calculated from the data in Table I by the method of Okazaki, Lounsbury, and Durham(3). In the relationship

$$\frac{\alpha}{1+\alpha} = \frac{\text{Number of captures}}{\text{Number of absorptions}},$$

the number of absorptions is equal to the loss of U-233 during the irradiation and the number of captures is equal to

$$(N_4 + N_5 + N_6 + \beta + f_5^0) - (N_4^0 + N_5^0) \quad \text{where}$$

N = number of atoms in postirradiated sample

N^0 = preirradiated number of atoms (the subscripts 4, 5, 6 refer to U-234, U-235, and U-236 respectively)

β = number of U-235 fissions resulting from the U-235 formed by capture on U-233 and U-234 (equal to N_6/α_5 where $\alpha_5 = 0.1770$)

f_5^0 = U-235 fissions from U-235 initially present

CALCULATION OF $\hat{\alpha}$

(1) Atoms U_3^O	=	$(3.3101 \pm 0.0054) \times 10^{20}$
(2) Atoms U_3	=	$(2.8938 \pm 0.0024) \times 10^{20}$
(3) $1 + \hat{\alpha}$ (Total absorptions), (1)-(2)	=	$(0.4163 \pm 0.0059) \times 10^{20}$ (1.42%)
(4) Atoms N_4	=	$(3.7646 \pm 0.0043) \times 10^{18}$
(5) Atoms N_5	=	$(0.0880 \pm 0.0117) \times 10^{18}$
(6) Atoms N_6^O less N_6 formed from N_5^O	=	$(0.0036 \pm 0.0027) \times 10^{18}$
(7) $\beta = (6)/0.1770$	=	$(0.0215 \pm 0.0153) \times 10^{18}$
(8) r_5^O	=	$(0.0012) \times 10^{18}$
(9) Sum (4) thru (8)	=	$(3.8789 \pm 0.0199) \times 10^{18}$ (0.53%)
(10) N_4^O	=	$(0.0858 \pm 0.0033) \times 10^{18}$
(11) N_5^O	=	$(0.0106 \pm 0.0023) \times 10^{18}$
(12) Sum (10) and (11)	=	$(0.0964 \pm 0.0041) \times 10^{18}$ (4.25%)
(13) Number of captures, (9)-(12)	=	$(3.7825 \pm 0.0206) \times 10^{18}$ (0.56%)
(14) $\frac{\hat{\alpha}}{1 + \hat{\alpha}} = \frac{(13)}{(3)}$	=	0.09086 ± 0.0014 (1.54%)
(15) $\hat{\alpha}$	=	0.0999 ± 0.0015 (1.54%)

The propagated standard deviation value of 0.0015 corresponds to a relative error of 1.54%.

The capsule was irradiated in the MTR in a location near the beryllium reflector where the cadmium ratio for cobalt is 15. The Wescott "r" value corresponding to $R_{Cd}^{Co} = 15$ is 0.031(2).

To convert $\hat{\alpha}$ to α_o , the 2200 m/sec value, the relationship:

$$1 + \alpha_o = (1 + \hat{\alpha})(g_f + r s_f)/(g_a + r s_a)$$

applies. For a neutron temperature of 40°C (313°K) the values are:

$g_f = 1.0005$ (ref 4)	$s_a = 1.287$ (ref 3)
$s_f = 1.165$ (ref 3)	$r^a = 0.031$
$g_a = 0.9979$ (ref 4)	$\hat{\alpha} = 0.0999$

The computed value of α is 0.0986 ± 0.0015 . The error (standard deviation) of 0.0015 was computed assuming no uncertainty in the r, g, and s factors.

Lanthanide Fission Yields, S. F. Marsh, W. J. Maeck, F. W. Spraktes

The absolute fission yields of neodymium, samarium, and cerium were determined on the same sample aliquots. Four 1000- μ l aliquots of the irradiated U-233 dissolver solution were spiked with known amounts of Nd-150, Sm-144, and Ce-136. The preparation and standardization of the spike solutions has been described previously(1,2).

A three-column sequential procedure is used for the separation of the individual lanthanides. The first column separates 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. Details of the procedure have been previously reported(2).

The analysis results for neodymium, cerium, and samarium are summarized in Tables II, IV, and VI 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.

For cerium and neodymium, these corrections were 3% or less for each isotope. The determined number of atoms of each isotope in the capsule, the computer-corrected number of atoms, and the calculated fission yields for neodymium and cerium are summarized in Tables III and V respectively.

The yield of the mass 144 chain was calculated three different ways; from the neodymium analysis, the cerium analysis, and the combination of the two. In the case of the neodymium analysis, the atoms of undecayed Ce-144, calculated from the computer program, were added to the determined atoms of Nd-144 giving a percent thermal fission yield of 4.74 ± 0.09 . The yield of the 144 chain calculated only from the mass spectrometrically determined number of atoms of Ce-144, with the appropriate decay corrections applied, was 4.63 ± 0.08 . A statistical "t" test of these two values showed no significant difference. The most accurate fission yield value is considered to be the sum of the determined atoms of Nd-144 and Ce-144. This value is 4.69 ± 0.08 .

The determined number of atoms of each samarium isotope in the capsule, the computer-corrected number of atoms, and the calculated fission yields are summarized in Table VII. 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, because of 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 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, 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 the dissolved capsule solution were diluted to 50.00-ml volumes. Duplicate 1000- μ l aliquots then were analyzed by a modified ASTM cesium perchlorate procedure(1). Two different gamma counting techniques were used. One was based on using the 3 x 3 in. NaI(Tl) crystal as the standard with the crystal parameters recommended by Heath(7). The other was a comparison method in which the area under the 661-kev photopeak, after correction for Cs-134, was compared to that of a certified standard (RC-137-ASTM, Nuclear Chicago Corp.). This certified standard contained $(1.72 \pm 0.05) \times 10^{14}$ atoms Cs-137/ml on August 8, 1962. The details of the analyses are given in Table VIII. The computation of the fission yield is given in Table IX. The results of the two counting techniques agreed to within 1.5%.

Krypton and Xenon Fission Yields, R. E. Foster, W. J. Maeck, F. W. Sprakles

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 X. The error associated with each value is the standard deviation.

Table II. FISSION PRODUCT NEODYMIUM ANALYSIS RESULTS

<u>Total Neodymium</u>	
<u>Sample</u>	<u>μg Nd/ml</u>
1	5.932
2	5.943
3	5.948
4	5.908
$\bar{X}$	5.933
std dev _{avg} (measurement error only)	+0.009 (0.15%)
std dev _{avg} (including spike uncertainty)	+0.023 (0.39%)

Total micrograms neodymium in postirradiated sample

$$= (5.933 \pm 0.023 \text{ } \mu\text{g Nd/ml})(250 \pm 0.06 \text{ ml}) = 1483.25 \pm 5.80 (0.39\%)$$

<u>Isotopic Analysis</u>							
<u>Wt %^a</u>							
	<u>Nd-142</u>	<u>Nd-143</u>	<u>Nd-144</u>	<u>Nd-145</u>	<u>Nd-146</u>	<u>Nd-148</u>	<u>Nd-150</u>
$\bar{X}_6$	0.010	34.781	17.250	20.744	15.825	8.215	3.169
std dev _{ind}	-	0.040	0.083	0.040	0.038	0.044	0.011
std dev _{avg}	-	0.016	0.034	0.016	0.016	0.018	0.004
% std dev _{avg}	-	0.046	0.197	0.077	0.101	0.219	0.126

^a

All isotopic data have been corrected for natural contamination by that amount of Nd-142 in excess of 0.010%. Uncorrected Nd-142 usually was about 0.3% in raw sample.

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

$$\text{Number of fissions} = (3.7863 \pm 0.0588) \times 10^{19} \quad (1.55\%)$$

	Nd-143	Nd-144	Nd-145	Nd-146	Nd-148	Nd-150
Determined number of atoms	2.174×10^{18}	1.0707×10^{18}	1.279×10^{18}	9.688×10^{17}	4.961×10^{17}	1.888×10^{17}
std dev	0.009×10^{18}	0.005×10^{17}	0.005×10^{18}	0.040×10^{17}	0.023×10^{17}	0.008×10^{17}
Atoms after correction for neutron capture	2.223×10^{18}	$1.7934 \times 10^{18}{}^a$	1.287×10^{18}	9.613×10^{17}	4.941×10^{17}	1.888×10^{17}
std dev	0.010×10^{18}	0.018×10^{18}	0.005×10^{18}	0.040×10^{17}	0.023×10^{17}	0.008×10^{17}
std dev, %	0.50	1.0	0.41	0.41	0.46	0.42
Percent fission yield	5.87	4.74	3.40	2.51	1.31	0.498
std dev	0.10	0.09	0.06	0.04	0.02	0.008
std dev, %	1.65	1.9	1.65	1.65	1.65	1.62

^a

Includes correction for holdup by Ce-144.

Table IV. FISSION PRODUCT CERIUM ANALYSIS RESULTS

<u>Total Cerium</u>	
<u>Sample</u>	<u>μg Ce/ml</u>
1	5.399
2	5.392
3	5.377
4	5.409
$\bar{X}$	5.394
std dev _{avg} (measurement error only)	0.007 (0.13%)
std dev _{avg} (includes spike uncertainty)	0.011 (0.34%)
Total micrograms cerium in postirradiated sample	
= $(5.394 \pm 0.011 \text{ μg Ce/ml})(250 \pm 0.06 \text{ ml}) = 1348.5 \pm 4.7 (0.35\%)$	

<u>Isotopic Analysis</u>			
	<u>Wt %</u>		
	<u>Ce-140</u>	<u>Ce-142</u>	<u>Ce-144</u>
$\bar{X}_6$	42.675	44.171	13.179
std dev _{ind}	0.094	0.111	0.104
std dev _{avg}	0.038	0.045	0.042
% std dev _{avg}	0.09	0.10	0.32

Table V. U-233 THERMAL FISSION YIELDS OF LONG-LIVED AND STABLE CERIUM ISOTOPIES

Number of fissions = $(3.7863 \pm 0.0588) \times 10^{19}$ (1.55%)

	Ce-140	Ce-142	Ce-144
Determined number of atoms	2.477×10^{18}	2.528×10^{18}	7.437×10^{17}
std dev	0.009×10^{18}	0.009×10^{18}	0.035×10^{17}
Atoms after correction for neutron capture and decay	2.474×10^{18}	2.522×10^{18}	$1.754 \times 10^{18}{}^a$
std dev	0.009×10^{18}	0.009×10^{18}	0.013×10^{18}
Percent fission yield	6.54	6.66	4.63
std dev	0.10	0.11	0.08
std dev, %	1.6	1.6	1.7

a

Includes in-pile and out-pile decay corrections.

Table VI. FISSION PRODUCT SAMARIUM ANALYSIS RESULTS

<u>Total Samarium</u>	
<u>Sample</u>	<u>μg Sm/ml</u>
1	0.6239
2	0.6356
3	0.6163
4	0.6347
$\bar{X}$	0.6275
std dev _{avg} (measurement error only)	0.0046 (0.73%)
std dev _{avg} (including spike uncertainty)	0.0047 (0.76%)
Total micrograms samarium in postirradiated sample	
= (0.6275 ± 0.0046 μg Sm/ml)(250 ± 0.06 ml) = 156.88 ± 1.19 (0.76%)	

<u>Isotopic Analysis</u>							
Wt % ^a							
	<u>Sm-147</u>	<u>Sm-148</u>	<u>Sm-149</u>	<u>Sm-150</u>	<u>Sm-151</u>	<u>Sm-152</u>	<u>Sm-154</u>
$\bar{X}_5$	21.356	1.000	4.495	40.397	7.207	24.096	1.447
std dev _{ind}	0.083	-	0.058	0.136	0.029	0.098	0.085
std dev _{avg}	0.037	-	0.026	0.056	0.013	0.040	0.038
% std dev _{avg}	0.17	-	0.58	0.14	0.18	0.17	2.63

^aAll isotopic data have been corrected for natural contamination by that amount of Sm-148 in excess of 1.00%. Uncorrected Sm-148 ranged from 1.40 to 1.50% in raw sample.

Table VII. U-233 THERMAL FISSION YIELDS OF STABLE SAMARIUM ISOTOPES

Number of fissions = $(3.7863 \pm 0.0588) \times 10^{16}$ (1.55%)

	Sm-147	Sm-148	Sm-149	Sm-150	Sm-151	Sm-152	Sm-154
Determined number of atoms	1.374×10^{17}	0.063×10^{17}	0.2852×10^{17}	2.546×10^{17}	6.451×10^{17}	1.499×10^{17}	0.888×10^{16}
std dev	0.011×10^{17}	0.001×10^{17}	0.0027×10^{17}	0.019×10^{17}	0.0036×10^{17}	0.012×10^{17}	0.024×10^{16}
Atoms after correction for neutron capture	6.870×10^{17a}	none	2.842×10^{17}	none	1.378×10^{17}	0.730×10^{17}	0.729×10^{16}
std dev	0.206×10^{17}		0.020		0.042	0.022	0.025×10^{16}
Percent fission yield	1.82		0.751		0.364	0.193	0.020
std dev	0.06		0.013		0.012	0.007	0.006
std dev, %	3.4		1.72		3.4	3.4	3.2

^a Includes correction for holdup by Em-147.

Table VIII. SUMMARY OF Cs-137 ANALYSIS DATA

Constants for Cs-137 counting

Source	=	3/4-in. disk	
Distance	=	10 cm	
T	=	detector efficiency = 0.02012	} Estimated std dev = 1.5%
P	=	photopeak efficiency = 0.536	
A	=	absorber (1.18 mg/cm ² Be = 0.934)	
q	=	$\gamma/\text{dis} = 0.857 \pm 0.010$	
$t_{1/2}$	=	30.3 ± 0.5 yr (1.7%)	
Cooling time	=	316 days	

Results based on 3 x 3 in. NaI(Tl) crystal as the standard

cpm under 661-keV photopeak (corrected for chemical yield)

$\bar{X}_6$	=	74,093	
std dev _{ind}	=	1343	(1.81%)
std dev _{avg}	=	$1343/\sqrt{6} = 548$	(0.74%) measurement error only
std dev _{avg}	=	622	(0.84%) includes uncertainty in carrier value
atoms Cs-137 per capsule	=	$(2.517 \pm 0.064) \times 10^{18}$	(2.56%)

Results from comparison method

ratio, $\frac{\text{sample activity}}{\text{standard activity}}$	=	12.374 ± 0.110	(0.84%)
atoms Cs-137 per capsule	=	$(2.555 \pm 0.079) \times 10^{18}$	(3.1%) includes 3% uncertainty in certified value of the standard

Table IX. U-233 THERMAL FISSION YIELD OF Cs-137

Atoms Cs-137 using crystal as standard

$$= (2.517 \pm 0.064) \times 10^{18} \quad (2.56\%)$$

Atoms Cs-137 by comparison method

$$= (2.555 \pm 0.079) \times 10^{18} \quad (3.1\%)$$

Weighted value, atoms Cs-137^a

$$= (2.532 \pm 0.050) \times 10^{18} \quad (1.96\%)$$

Number of fissions

$$= (3.7863 \pm 0.0588) \times 10^{19} \quad (1.55\%)$$

Fission yield Cs-137

$$= 6.69 \pm 0.17 \quad (2.51\%)$$

^a Values were averaged by weighting the reciprocals of the variances.

Table X. U-233 THERMAL FISSION YIELDS OF
STABLE KRYPTON AND XENON ISOTOPES

<u>Isotope</u>	<u>Percent Fission Yield</u>
Kr-83	1.02±0.02
Kr-84	1.68±0.04
Kr-85 (10.76 yr)	0.497±0.011
Kr-86	2.84±0.06
Xe-131	3.56±0.07
Xe-132	4.86±0.10
Xe-134	6.10±0.13

SUMMARY OF FISSION YIELDS

Summarized in Table XI from the preceding sections are the U-233 thermal fission yield values for the stable and long-lived isotopes of krypton, xenon, Cs-137, neodymium, cerium, and samarium. For comparison purposes, literature values for U-233 thermal fission are also given. Additional capsules containing U-233 have been irradiated over a range of burnup levels and also will be analyzed for fission yield data to produce refined data.

Table XI. SUMMARY OF THE U-233 THERMAL FISSION YIELDS OF THE STABLE AND LONG-LIVED ISOTOPES OF KRYPTON, XENON, CERIUM, NEODYMIUM, SAMARIUM, AND Cs-137

<u>Mass No.</u>	<u>Element</u>	<u>Ferguson and O'Kelley(6)</u>	<u>This Work</u>
83	Kr	1.14	1.02±0.02
84	Kr	1.91	1.68±0.04
85(10.76y)	Kr		0.497±0.011
86	Kr	3.20	2.84±0.06
131	Xe	3.41	3.56±0.07
132	Xe	4.68	4.86±0.10
134	Xe	5.99	6.10±0.13
137(30.3y)	Cs	6.64	6.69±0.17
140	Ce	6.71	6.54±0.10
142	Ce	6.79	6.66±0.11
143	Nd	5.91	5.87±0.10
144	Nd	4.51	4.74±0.09
144	Ce		4.63±0.08
144	Nd+Ce		4.69±0.08
145	Nd	3.38	3.40±0.06
146	Nd	2.58	2.54±0.04
147	Sm	1.93	1.82±0.06
148	Nd	1.28	1.31±0.02
149	Sm	0.77	0.751±0.013
150	Nd	0.55	0.498±0.008
151	Sm	0.35	0.364±0.012
152	Sm	0.22	0.193±0.007
154	Sm	0.047	0.020±0.006

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