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A SURVEY AND EVALUATION OF THERMAL FISSION YIELDS FOR U-235, Pu-239, U-233, AND Pu-241

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FOREWORD

An important limitation on the accuracy of nuclear fuel burnup has been the uncertainty in the fission yields of those fission products selected for measurement. Therefore, an effort has been made in recent years to reduce these uncertainties.

This report is one of three which summarize five years of work on accurate nuclear fuel burnup analysis. The other two reports are GEAP-5354, "Determination of Nd-148 in Irradiated Uranium and Plutonium as a Measure of Burnup," and GEAP-5355, "BURNUP: A Fortran IV Code for Computing Uranium and Plutonium Fuel Burnup from U, Pu, and Nd Mass Spectrometric Measurements."

A SURVEY AND EVALUATION OF THERMAL-NEUTRON FISSION
YIELDS FOR U-235, Pu-239, U-233, AND Pu-241

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J. P. Peterson, Jr.
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ABSTRACT

The accurate determination of atom percent fission (burnup) in nuclear fuel by the fission product-to-fuel ratio method requires the use of accurate fission yields in the calculation. Recent measurements of chain yields in thermal-neutron induced fission of U-235, Pu-239, U-233, and Pu-241 have been made to improve the accuracy of fission yields. Fission yield accuracies of several mass chains used for burnup analysis now approach 2% at the 95% confidence level. Thermal fission yields published through June 1967 are compiled and evaluated. From this compilation a set of thermal fission yields is prepared for use in nuclear fuel burnup analysis.

INTRODUCTION

Fission of heavy nuclei induced by thermal neutrons normally results in the formation of two fission products, one with a light mass (95 ± 20) and one with a heavier mass (139 ± 23). The probability, in percent, of any given nuclide being formed in fission is defined as its fission yield. Most fission products are formed with an excess of neutrons and they decay by a chain of successive beta emissions until they reach stability. The independent fission yield of stable or long lived fission products is normally small and most of such fission products which are found in irradiated fuel accumulate from decay of less stable earlier members in their mass chain. For determination of fuel burnup from the fission product to fuel ratio, it is the cumulative chain yield which is of interest.

SURVEY OF PUBLISHED VALUES

The published chain yields in thermal-neutron induced fission have been surveyed and they are tabulated in Appendices A, B, C, and D for U-235, Pu-239, U-233, and Pu-241. Yields for mass chains such as 99, 137, 140, 144, and 148 which are frequently used for determination of fissions are the most accurately known. Their yields are somewhat better known for U-235 than for other fissionable nuclides. Fission yield accuracies for these chains approach 2% for U-235 and range from 2 to 3% for Pu-239 and U-233 but are estimated to be 5 to 7% for Pu-241.

Isotope dilution mass spectrometry is normally used for determination of the absolute number of atoms of stable and long-lived fission products. Radiochemical analysis is usually used for determination of the number of atoms of short-lived fission products. In general, the mass spectrometric results are more accurate than radiochemical results and are preferred where available. Determination of the number of fissions associated with the measured number of atoms of each fission product nuclide contributes a large portion of the error in fission yield measurements. Fissions have been determined by various methods including the use of fission counters, the determination of the difference in the absolute number of fuel atoms before and after irradiation, and the use of neutron flux monitors to measure integrated neutron exposures from which fissions are computed through use of a suitable fission cross section. In some experiments, the number of fissions have not been determined but the yields are expressed relative to Mo-99, Ba-140, or Cs-137. To aid in normalization of such relative yields and to substantiate the validity of absolute yields, use is usually made of the requirement that the light and heavy mass groups of fission products must each sum to 100%.

Earlier evaluations of U-235 thermal yields were made by Steinberg, et al.,¹ in 1958, by Katcoff² in 1960, and by Farrar, et al.,³ in 1962. Many measurements have been made since that time in this and in other laboratories. These measurements are summarized in Appendix A with the values from previous summaries. An attempt was made to cite original measurements and to avoid

secondary references to the same measurements. Estimated values have been assigned to masses for which no measurements have been made. These values were obtained from interpolation or extrapolation by previous compilers. The original data of Anikina, et al.,⁴ were reported relative to Nd-146. For valid comparison, these values have been renormalized to a 2.96% Nd-146 yield which is the mean value for all reported measurements. In a similar manner, the relative yields of Fickel⁵ have been normalized to the average value of 3.58% for mass-88. The relative yields of Baerg and Bartholomew⁶ and Brown⁷ have been normalized to 6.30% for mass-140. In the last column a mean value with its error estimated at the 95% confidence level is given for the measurements listed. The largest uncertainty is in mass-138 where the measurement of Farrar³ is over 16% greater than the value recommended by Katcoff.² Although natural Ba contamination is to be expected at mass-138, the extent of such contamination has been measured and corrected for by Farrar.³ Because measurements in this laboratory⁸ confirm the work of Farrar within 2%, the much lower earlier value has been excluded from the mean. The sums of the yields for the light and heavy peaks are 100.0 and 100.0% as expected for binary fission.

The thermal fission yields for Pu-239 are summarized in Appendix B. In the last column a mean value with its error estimated at the 95% confidence is given for the measurements listed. Agreement of the yields for Pu-239 has not been so good as for U-235, principally because two sets of absolute yields by Fickel and Tomlinson⁹ and by Anikina, et al.,⁴ have not been in agreement at mass-142 and above. Walker¹⁰ has pointed out that the much higher yields of Anikina result in a peak yield of about 106%. The more reasonable peak yield of Fickel and Tomlinson is also supported in the very high mass region by Bunney, et al.¹¹ The values of Anikina have been renormalized to the average value of 2.50% for Nd-146, the same isotope used by Anikina to normalize his U-235 yields. Radiochemical measurements^{1,12} of the Cs-137 yield from Pu-239 fission have been lower than mass spectrometric measurements by as much as 17%. Because recent measurements^{13,14} support the higher mass spectrometric values, the lower radiochemical values for Cs-137 have been excluded from the mean value. The sums of the yields for the light and heavy peaks are 99.7 and 99.6%, respectively.

The thermal fission yields for U-233 are summarized in Appendix C. In the last column is listed the mean value with its error estimated at the 95% confidence level. An excellent survey of U-233 fission yield data up to 1962 was given by Ferguson, et al.¹⁵ Because of the discrepancies he noted in the published yield values, he selected what he considered to be the most reliable measurements. Recent measurements made here¹⁶ and other laboratories^{11,13,17} support his selections. The sums of the light and heavy mass peaks are 100.6 and 99.5%, respectively.

The thermal fission yields of Pu-241 are summarized in Appendix D. Very little work has been done on Pu-241 fission yields. The light mass peak has been estimated by Walker¹⁰ who averaged the values for U-233, U-235, and Pu-239 fission yield curves after he had shifted them to the right by 8, 6, and 2 mass units, respectively. The heavy mass peak has been measured by Farrar, et al.,¹⁸ by mass spectrometry. Measurements made by Okazaki¹⁹ and in this laboratory are also included. The sums of the light and heavy mass peaks are 100.7 and 100.0%, respectively.

Thirty-six capsules containing the fissionable nuclides, U-233, U-235, Pu-239, and Pu-241 were prepared by and irradiated by Idaho Nuclear Corporation in the Materials Testing Reactor (MTR).²⁰ Many of these are still being analyzed by Idaho Nuclear Corporation to determine thermal fission yields. No final averages can be derived from these measurements until work on these capsules is completed in FY 1968 at which time Idaho Nuclear Corporation will issue a separate final report.

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APPENDIX A

PER CENT CHAIN YIELDS IN THERMAL NEUTRON FISSION OF U-235

TABLE 1. Per Cent Chain Yields in Thermal Neutron Fission of U-235

Mass	Element	Measurements	Mean Value ^a
72	Zn	0.000016(1,2)	0.000017 ^c
73	Ga	0.00010(2)	0.00010
74	Ga	0.00035(64)	0.00035
75	As	0.0012 ^b (67)	0.0012
76	Ge	0.0035 ^b (67)	0.0035
77	As	0.0083(3,4)	0.0083
78	As	0.020(3,4)	0.020
79	As	0.056(5)	0.056
80	Se	0.09 ^b (67)	0.09
81	Se	0.22(93)	0.22
82	Se	0.24 ^b (67)	0.24
83	Kr	0.544(7-11), 0.548(70), 0.496(71), 0.499(72)	0.52 ± 0.02
84	Kr	1.00(9-12,63), 1.01(70), 0.953(71), 0.936(72)	0.97 ± 0.04
85	Rb	1.30(9-11,63), 1.31(70)	1.30 ± 0.05
86	Kr	2.02(9-11), 2.04(70), 1.84(71), 1.82(72)	1.93 ± 0.10
87	Rb	2.50(70), 2.49(9,15,63)	2.50 ± 0.07
88	Sr	3.57(9,13), 3.58(70)	3.58 ± 0.15
89	Sr	4.79(14,16,17), 4.73(70)	4.76 ± 0.30
90	Sr	5.77(70), 5.77(9,13,14,18,19)	5.77 ± 0.35
91	Y(Zr)	5.97(70), 5.84(13,14,17,18,19)	5.90 ± 0.40
92	Zr	6.03(13,14,20), 6.03(70)	6.03 ± 0.25
93	Zr	6.40(13,14,62), 6.51(70)	6.48 ± 0.25
94	Zr	6.40(13,14,21), 6.55(70)	6.48 ± 0.30
95	Zr(Nb,Mo)	6.27(13,14,22), 6.55(70)	6.41 ± 0.30
96	Zr	6.33(13), 6.41(70)	6.37 ± 0.30
97	Mo	6.09(13,14,16,22), 6.33(70)	6.21 ± 0.30
98	Mo	5.78(13), 5.93(70)	5.86 ± 0.30
99	Mo(Tc)	6.25(76), 6.06(16,23), 6.20(77), 6.37(78), 6.06(79)	6.19 ± 0.16
100	Mo	6.30(13), 6.58(70)	6.44 ± 0.35
101	Ru	5.0(13,24), 5.03(80), 5.02(81)	5.02 ± 0.40
102	Ru	4.1(13,24), 4.18(80), 4.17(81)	4.15 ± 0.30
103	Ru(Rh)	3.0(25)	3.0 ± 0.2
104	Ru	1.8(13), 1.81(80), 1.81(81)	1.81 ± 0.12
105	Ru(Rh)	0.9(24,26)	0.9 ± 0.2

TABLE 1. Per Cent Chain Yields in Thermal Neutron Fission of U-235
(Continued)

Mass	Element	Measurements	Mean Value ^a
106	Ru(Rh)	0.38(13,25), 0.382(82), 0.412(83), 0.373(80), 0.398(81)	0.39 ± 0.05
107	Rh	0.19(27)	0.19 ± 0.04
108	Pd	0.070 ^b (67)	0.070
109	Pd	0.030(28)	0.030
110	Pd	0.018 ^b (67)	0.018
111	Ag	0.019(28)	0.019
112	Pd	0.010(28,29)	0.010
113	Ag	0.016 ^b (61)	0.016
114	Cd	0.014 ^b (61)	0.014
115	Total Cd	0.0104(30)	0.0104
116	Cd	0.018 ^b (67)	0.018
117	Cd	0.010 ^b (69), 0.011 ^b (67)	0.011

a. Mean cumulative chain yield.

b. Estimated value.

c. Zn-72 is assumed to be 93% of the chain yield.⁶⁷

TABLE 2. Per Cent Chain Yields in Thermal Neutron Fission of U-235

Mass	Element	Measurements	Mean Value ^a
118	Sn	0.0014 ^b (67)	0.014
119	Sn	0.014 ^b (67)	0.014
120	Sn	0.014 ^b (67)	0.014
121	Sn	0.015(32), 0.012(91)	0.014
122	Te	0.015 ^b (67)	0.015
123	Sb	0.016 ^b (67)	0.016
124	Sn	0.018 ^b (67)	0.018
125	Sb	0.021(34-36)	0.021
126	Total Sn+Sb+Te	0.032 ^b (67)	0.032
127	Sb	0.13(28, 37, 38)	0.13
128	Sn	0.37(27)	0.58 ^c
129	Te(I, Xe)	0.8(37, 39)	0.8 ± 0.2
130	Sn	2.0(40)	2.0 ± 0.5
131	I(Xe)	2.93(11, 28, 37, 40, 41, 44), 2.92(9), 2.93(70), 2.90(71), 2.87(72)	2.91 ± 0.12
132	I(Xe)	4.38(44, 11, 37), 4.37(9), 4.38(70), 4.22(71), 4.28(72)	4.33 ± 0.16
133	I(Xe, Cs)	6.62(9, 37, 42, 44), 6.75(86), 6.75(87), 6.62(70), 6.59(84)	6.67 ± 0.20
134	Xe	8.03(9), 8.06(43, 84), 7.74(71), 7.73(72), 8.06(70)	7.92 ± 0.40
135	Xe(Cs)	6.41(9, 37, 42, 45-47), 6.45(70)	6.43 ± 0.30
136	Xe	6.46(11, 48), 6.44(9), 6.47(70)	6.46 ± 0.30
137	Cs	6.15(9), 6.22(49), 6.17(70), 6.13(17), 6.22(71), 6.20(72), 6.05(86), 6.19(87), 6.22(88), 6.28(79)	6.18 ± 0.13
138	Ba	6.68(70), 5.74(13, 50) ^d , 6.52(92)	6.60 ± 0.40
139	Ba	5.87(89), 6.55(14, 16, 17), 6.42(70)	6.28 ± 0.35
140	Ce	6.44(84), 6.18(65), 6.56(13), 6.33(9), 6.25(70), 6.24(71), 6.41(72), 6.31(79), 5.87(89), 6.36(17, 49)	6.30 ± 0.12
141	Ce	6.30(17), 5.22(89), 5.73(70), 6.0(14, 17, 53, 54)	5.81 ± 0.36
142	Ce	6.01(84), 6.03(9), 5.80(70), 5.40(89), 5.92(72), 5.88(79), 5.84(71), 5.89(65)	5.84 ± 0.13
143	Ce(Pr, Nd)	5.88(75), 5.40(89), 5.71(70), 5.90(79), 5.91(72), 5.88(71), 5.96(85), 6.04(86), 5.98(87), 5.89(65), 6.03(55, 84)	5.87 ± 0.11
144	Ce(Pr, Nd)	5.22(89), 5.30(70), 5.36(71), 5.48(72), 5.43(79), 5.29(87), 5.31(86), 5.33(85), 5.30(65), 5.62(84)	5.34 ± 0.12
145	Nd	4.04(68), 3.86(9), 3.80(70), 3.87(70), 3.89(72), 3.85(79), 3.94(86), 3.91(87), 3.89(85), 3.88(65), 3.73(80)	3.88 ± 0.08

TABLE 2. Per Cent Chain Yields in Thermal Neutron Fission of U-235
(Continued)

Mass	Element	Measurements	Mean Value ^a
146	Nd	3.07(84), 2.89(70), 2.94(71), 2.96(72), 2.95(79), 2.96(86), 2.95(87), 2.94(85), 2.95(65), 2.96(89)	2.96 ± 0.06
147	Nd(Pr, Sm)	2.36(84), 2.16(70), 2.03(71), 2.16(72), 2.15(79), 2.70(89), 2.21(75), 2.24(65)	2.25 ± 0.14
148	Nd	1.71(84), 1.58(89), 1.61(70), 1.68(71), 1.69(72), 1.70(79), 1.67(86), 1.67(87), 1.67(85), 1.66(65)	1.66 ± 0.03
149	Pm(Sm)	1.13(9,56), 1.40(89), 1.02(70), 1.0(71), 1.01(72), 1.02(79), 1.04(75), 1.10(65)	1.09 ± 0.10
150	Nd	0.67(84), 0.628(70), 0.634(71), 0.646(72), 0.637(79), 0.65(65), 0.65(86), 0.633(87), 0.64(85)	0.64 ± 0.02
151	Sm	0.45(9), 0.399(70), 0.398(71), 0.436(72), 0.456(79), 0.41(65)	0.42 ± 0.02
152	Sm	0.285(9), 0.260(70), 0.236(71), 0.228(72), 0.231(79), 0.26(65)	0.25 ± 0.02
153	Sm(Eu)	0.169(84), 0.148(70), 0.159(75), 0.163(65), 0.15(51)	0.16 ± 0.012
154	Sm	0.077(9), 0.0724(70), 0.050(71), 0.056(72), 0.074(65)	0.06 ± 0.01
155	Sm(Eu)	0.033(58,59,84), 0.0291(70), 0.032(65)	0.031 ± 0.002
156	Eu	0.014(28,57,59), 0.0125(90), 0.0137(75)	0.0134
157	Eu	0.002(60), 0.0060(90), 0.00614(75)	0.0066
158	Eu	0.002(60), 0.0031(90)	0.0026
159	Gd	0.00107(57,61), 0.0011(90), 0.00993(75)	0.00105
160	Gd	0.00033(67)	0.00033
161	Tb	0.000076(57,61), 0.0000876(75)	0.000082

a. Mean cumulative chain yield.

b. Estimated value.

c. Sn-128 is assumed to be 63.5% of the chain yield.⁶⁷
Ba-140 is assumed to be 99.4% of the chain yield.⁶⁷

d. Not included in the mean.

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APPENDIX B

PER CENT CHAIN YIELDS IN THERMAL NEUTRON FISSION OF Pu-239.

TABLE 1. Per Cent Chain Yields in Thermal Neutron Fission of Pu-239.

Mass	Element	Measurements	Mean Value ^a
72	Zn	$1.1 \times 10^{-4}(2,11)$	0.00011
73	Ga	$0.00025^b(6)$	0.00025
74	Ga	$0.00062^b(6)$	0.00062
75	As	$0.0014^b(6)$	0.0014
76	Ge	$0.0031^b(6)$	0.0031
77	As	$0.0073(20)$	0.0073
78	As	$0.025(20)$	0.025
79	As	$0.025^b(6)$	0.025
80	Se	$0.048^b(6)$	0.048
81	Se	$0.182^d(110)$	0.182
82	Se	$0.17^b(6)$	0.17
83	Br(Kr)	$0.29(3), 0.303(10)$	0.30
84	Kr	$0.47(3), 0.407(10)$	0.44
85	Rb	$0.535(3)$	0.53
86	Kr	$0.75(3)$	0.75
87	Rb	$0.912(3)$	0.91
88	Sr	$1.43(3), 1.39(4)$	1.41 ± 0.06
89	Sr	$1.71(3), 1.8(2,11), 1.74(7), 1.68(14)$	1.73 ± 0.07
90	Sr	$2.16(3), 2.31(4), 2.05(7)$	2.2 ± 0.1
91	Sr(Y,Zr)	$2.9(1), 2.8(2,11), 2.59(3), 2.41(7)$	2.7 ± 0.3
92	Zr	$3.12(3)$	3.12 ± 0.28
93	Zr	$3.94(3)$	3.94 ± 0.32
94	Zr	$4.45(3)$	4.45 ± 0.35
95	Zr(Nb,Mo)	$5.6(2,11), 5.06(7), 4.99(3)$	5.2 ± 0.3
96	Zr	$5.13(3)$	5.13 ± 0.38
97	Mo	$5.61(3), 6.13^c(2,11)$	5.9 ± 0.3
98	Mo	$5.84(3)$	5.84 ± 0.45
99	Mo(Tc)	$6.1(2,11), 6.02(15), 5.61(7)$	5.9 ± 0.2
100	Mo	$7.05(3)$	7.05 ± 0.55
101	Ru	$5.86(3)$	5.86 ± 0.44
102	Ru	$5.94(3)$	5.94 ± 0.44
103	Ru(Rh)	$5.5(2,11), 5.63(3), 5.79(7)$	5.6 ± 0.2
104	Ru	$5.88(3)$	5.88 ± 0.45
105	Ru(Rh)	$5.47(7)$	5.47 ± 0.60
106	Ru(Rh)	$4.7(2,11), 4.53(3), 4.04(7)$	4.4 ± 0.4

TABLE 1. Per Cent Chain Yields in Thermal Neutron Fission of Pu-239
(Continued)

Mass	Element	Measurements	Mean Value ^a
107	Rh	3.4 ^b (6)	3.4 ± 0.3
108	Pd	2.6 ^b (6)	2.6 ± 0.3
109	Pd	1.0(2,11), 1.13(7), 1.56(15)	1.2 ± 0.3
110	Pd	0.74 ^b (6)	0.74 ± 0.07
111	Ag	0.27(2,11), 0.20(15), 0.28(7)	0.25 ± 0.04
112	Pd	0.10(2,11), 0.093(7), 0.12(15)	0.10 ± 0.01
113	Ag	0.065(20)	0.065 ± 0.005
114	Cd	0.055 ^b (6)	0.055 ± 0.03
115	Total Cd	0.048(2,11), 0.036(7), 0.034(15)	0.039
116	Cd	0.037 ^b (6)	0.037
117	Cd	0.036 ^b (6)	0.036
118	Cd	0.035 ^b (6)	0.035

a. Mean cumulative chain yield.

b. Estimated value.

c. Zr-97 is assumed⁶ to be 86.4% of the chain yield.

d. Total for both isomers.

TABLE 2. Per Cent Chain Yields in Thermal Neutron Fission of Pu-239

Mass	Element	Measurements	Mean Value ^a
119	Sn	0.036 ^b (6)	0.036
120	Sn	0.037 ^b (6)	0.037
121	Sn	0.41(2,11)	0.041
122	Te	0.047 ^b (6)	0.047
123	Sb	0.056 ^b (6)	0.056
124	Sb	0.088(7)	0.088
125	Sb	0.075 ^c (2,11)	0.075
126	Total Sn+Sb+Te	0.16 ^b (6)	0.16
127	Sb	0.37(2,11), 0.55(7)	0.49 ^c ± 0.11
128	Te	0.845 ^b (6)	0.85 ± 0.09
129	Te(I,Xe)	1.7 ^b (6)	1.7 ± 0.2
130	Te	2.7 ^b (6)	2.7 ± 0.3
131	Xe(I)	3.77(3), 3.79(16), 3.80(7)	3.79 ± 0.14
132	Te(I,Xe)	5.26(3), 5.29(16), 5.51(7)	5.35 ± 0.27
133	Xe(Cs)	6.90(3), 5.26(4), 6.95(16), 6.80(8)	6.5 ± 0.8
134	Xe	7.46(3), 7.48(16)	7.47 ± 0.37
135	Cs	7.25(3), 6.95(4), 7.43(19)	7.21 ± 0.34
136	Xe	6.62(3), 6.70(16)	6.66 ± 0.33
137	Cs	5.8 ^e (2,13), 6.48(3), 6.50(4), 5.40 ^e (7), 6.72(8), 6.56(18)	6.56 ± 0.20
138	Ba	6.31(3), 6.26(4), 5.15(18)	5.91 ± 0.75
139	Ba	5.4(2,11), 5.97(14)	5.69 ± 0.55
140	Ce	5.58(3), 5.52(4), 5.38(17), 5.57 ^c (7), 5.46 ^c (2,11)	5.50 ± 0.22
141	Ce	5.64(14), 6.11(7), 6.02(4), 5.23(3), 4.9 ^e (2,11)	5.75 ± 0.42
142	Ce	4.97(3), 4.72 ^d (4), 4.93(8)	4.87 ± 0.19
143	Ce(Pr,Nd)	5.1(2,11), 4.56(3), 4.32 ^d (4), 4.28(7), 4.51(8)	4.55 ± 0.30
144	Ce(Pr,Nd)	3.7(2,11), 3.84(3), 3.90 ^d (4), 3.6(5), 4.09(7), 3.77(8)	3.82 ± 0.14
145	Nd	3.12(3), 2.97 ^d (4), 3.04(8), 2.84(18)	2.99 ± 0.12
146	Nd	2.60(1), 2.57(3), 2.50 ^d (4), 2.49(8), 2.34(18)	2.50 ± 0.09
147	Nd(Pm,Sm)	1.99(19), 1.83 ^d (4), 2.2(5), 1.46(7),	1.87 ± 0.19
148	Nd	1.71(3), 1.63 ^d (4), 1.67(8)	1.65 ± 0.05
149	Pm(Sm)	1.30(3), 1.19 ^d (4), 1.4(5)	1.30 ± 0.10
150	Nd	1.02(3), 0.975 ^d (4), 0.96(8), 0.91(18)	0.96 ± 0.07
151	Sm	0.80(3), 0.71 ^d (4)	0.76 ± 0.06
152	Sm	0.616(3), 0.53 ^d (4)	0.57 ± 0.05

TABLE 2. Per Cent Chain Yields in Thermal Neutron Fission of Pu-239
(Continued)

Mass	Element	Measurements	Mean Value ^a
153	Sm(Eu)	0.39(2,11), 0.33(5)	0.36 ± 0.04
154	Sm	0.25 ^d (4)	0.25 ± 0.02
155	Sm(Eu)	0.23(1)	0.23
156	Eu	0.12(2,11), 0.10(5), 0.062(7), 0.08(3)	0.09
157	Eu	0.076 ^b (6)	0.076
158	Eu	0.042 ^b (6)	0.042
159	Gd	0.021 ^b (6)	0.021
160	Gd	0.0098 ^b (6)	0.0098
161	Tb	0.0039(9)	0.0039
162	Dy	0.0024 ^b (6)	0.0024
163	Dy	0.0010 ^b (6)	0.0010
164	Dy	0.00037 ^b (6)	0.00037
165	Ho	0.00014 ^b (6)	0.00014
166	Dy	0.000068(1)	0.000068

a. Mean cumulative chain yield.

b. Estimated value.

c. Sn-125 is assumed⁶ to be 91.0% of the chain yield.
Sb-127 is assumed⁶ to be 93.9% of the chain yield
Ba-140 is assumed⁶ to be 98.2% of the chain yield.

d. Normalized to 2.50% for Nd-146

e. Not included in mean.

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APPENDIX C

PER CENT CHAIN YIELDS IN THERMAL NEUTRON FISSION OF U-233

TABLE 1. Per Cent Chain Yields in Thermal Neutron Fission of U-233

Mass	Element	Measurements	Mean Value ^a
72	Zn	0.000099 ^b (3)	0.000099
73	Ga	0.00033 ^b (3)	0.00033
74	Ga	0.00090 ^b (3)	0.00090
75	As	0.0023 ^b (3)	0.0023
76	Ge	0.0068 ^b (3)	0.0068
77	As	0.019(6)	0.019
78	As	0.10 ^b (3)	0.10
79	As	0.19 ^b (3)	0.19
80	Se	0.28 ^b (3)	0.28
81	Se	0.46 ^b (3)	0.46
82	Se	0.69 ^b (3)	0.69
83	Kr	1.14(1), 1.02(10), 0.985(11), 1.06(7), 1.08(8), 1.04(9)	1.05 ± 0.05
84	Kr	1.91(1), 1.68(10), 1.63(11), 1.79(7), 1.78(8)	1.76 ± 0.08
85	Rb	2.46(1), 2.37(4)	2.42 ± 0.12
86	Kr	3.20(1), 2.84(10), 2.74(11), 3.01(7), 3.02(8)	2.96 ± 0.16
87	Rb	4.47(1)	4.47 ± 0.23
88	Sr	5.36(1), 5.37(2)	5.37 ± 0.22
89	Sr	5.96(1), 6.60(2), 6.5(6), 5.50(5)	6.10 ± 0.50
90	Sr	6.55(1), 5.80(2), 6.40(5)	6.30 ± 0.46
91	Y(Zr)	6.45(1), 6.72(2), 6.48 ^d (23), 6.40(4), 6.94(12), 6.60(20)	6.60 ± 0.34
92	Zr	6.72(1), 6.52(2), 6.65(23)	6.63 ± 0.33
93	Zr	7.01(1), 7.01(2), 7.05(23)	7.02 ± 0.40
94	Zr	6.68(1), 6.67(2), 6.76(23)	6.70 ± 0.33
95	Zr(Nb,Mo)	6.23(1), 6.02(5), 6.21(23), 6.07(4)	6.13 ± 0.30
96	Zr	5.67(1), 5.68(2), 5.56(23)	5.64 ± 0.28
97	Mo	5.51(1), 5.45(23), 5.80 ^c (4)	5.59 ± 0.28
98	Mo	5.22(1), 5.28(23)	5.25 ± 0.26
99	Mo(Tc)	4.96(13), 5.35(14), 5.03(14), 5.23(14), 5.05(14)	5.12 ± 0.14
100	Mo	4.49(23), 4.49(1)	4.49 ± 0.22
101	Ru	2.80(23), 2.87(1), 3.25(10), 3.13(11), 3.29(7), 3.48(8)	3.10 ± 0.22
102	Ru	2.22(23), 2.10(1), 2.44(10), 2.35(11), 2.52(7), 2.65(8)	2.38 ± 0.16
103	Ru(Rh)	1.60(6), 1.55(4), 1.75(5)	1.63 ± 0.15
104	Ru	0.90(23), 0.94(1), 1.02(10), 0.976(11), 1.06(7), 1.11(8)	1.00 ± 0.06
105	Ru(Rh)	0.50 ^b (3)	0.50 ± 0.10
106	Ru(Rh)	0.22(1), 0.28(6), 0.258(10), 0.252(11), 0.267(7), 0.273(8), 0.23(5)	0.25 ± 0.02

TABLE 1. Per Cent Chain Yields in Thermal Neutron Fission of U-233
(Continued)

Mass	Element	Measurements	Mean Value ^a
107	Rh	0.12 ^b (3)	0.12
108	Pd	0.07 ^b (3)	0.07
109	Pd	0.040(6)	0.04
110	Pd	0.03 ^b (3)	0.03
111	Ag	0.025(6), 0.02(5)	0.023
112	Pd	0.016(6,21)	0.016
113	Ag	0.02 ^b (3)	0.02
114	Cd	0.02 ^b (3)	0.02
115	Cd Total	0.020(6,21)	0.02
116	Cd	0.01 ^b (3)	0.01

a. Mean cumulative chain yield.

b. Estimated value.

c. Nb-97 is assumed to be 98.8% of the chain yield.³

d. O'Kelly's error in transcribing Steinberg's yield is here corrected.

TABLE 2. Per Cent Chain Yields in Thermal Neutron Fission of U-233

Mass	Element	Measurements	Mean Value ^a
117	Cd	0.01 ^b (3)	0.01
118	Sn	0.02 ^b (3)	0.02
119	Sn	0.02 ^b (3)	0.02
120	Sn	0.02 ^b (3)	0.02
121	Sn	0.018(6,21)	0.018
122	Te	0.03 ^b (3)	0.03
123	Sb	0.04 ^b (3)	0.04
124	Sn	0.05 ^b (3)	0.05
125	Sb	0.050(6)	0.050
126	Sb	0.26 ^b (3)	0.26
127	Sb	0.61 ^b (3)	0.61
128	Te	1.05 ^b (3)	1.05
129	Te(I, Xe)	1.70 ^b (3)	1.70
130	Te	2.33 ^b (3)	2.33
131	I(Xe)	3.41(1), 3.65(4), 3.40(6), 3.08(5), 3.56(10), 3.44(11), 3.42(7), 3.68(8)	3.46 ± 0.14
132	I(Xe)	4.68(1), 4.91(4), 4.64(6), 4.10(5), 4.86(10), 4.71(11), 4.97(7), 5.04(8)	4.74 ± 0.20
133	I(Xe, Cs)	6.15(2), 5.99 ^c (4), 5.60(1), 6.50(5), 5.62(6), 5.85(15), 5.88(16), 6.11(17), 5.97(4)	5.96 ± 0.20
134	Xe	5.99(1), 6.10(10), 5.93(11), 6.10(5), 5.95(6), 6.19(7), 6.37(8)	6.09 ± 0.30
135	Cs	5.84(1), 4.55(5)	5.2 ± 0.6
136	Xe	6.68(1)	6.68 ± 0.40
137	Cs	6.90(2), 6.38(1), 6.02(18), 6.51(6), 6.94(7), 7.03(8), 6.69(10), 6.60(11), 6.13(19), 6.63(15), 6.60(16), 6.58(17)	6.58 ± 0.20
138	Ba	7.10(2), 6.17(4), 5.74(22)	6.3 ± 0.7
139	Ba	6.61(2), 6.58(20)	6.64 ± 0.33
140	Ce	6.90(2), 6.52(1), 6.57(7), 6.68(8), 6.54(10), 6.30(11)	6.59 ± 0.20
141	Ce	6.24(2), 6.39(4), 7.58(12), 6.10(5), 7.26(20), 6.92(1)	6.77 ± 0.50
142	Ce	6.79(2), 6.79(1), 6.66(10), 6.35(11), 6.71(7), 6.93(8), 6.83(22)	6.72 ± 0.20
143	Ce(Pr, Nd)	5.80(2), 6.03(1), 5.57(4), 5.92(12), 5.98(15), 5.90(16), 5.90(17), 5.88(7), 6.03(8), 5.87(10), 5.57(11)	5.86 ± 0.17
144	Ce(Pr, Nd)	4.30(2), 4.72(1), 4.54(5), 4.69(10), 4.62(15), 4.72(16), 4.51(17), 4.48(11), 4.74(12), 4.70(7), 4.88(8), 4.53(4)	4.62 ± 0.14

C-4

GEAP-5356

TABLE 2. Per Cent Chain Yields in Thermal Neutron Fission of U-233
(Continued)

Mass	Element	Measurements	Mean Value ^a
145	Nd	3.22(2), 3.55(1), 3.40(10), 3.22(11), 3.51(8), 3.38(7), 3.39(15), 3.40(17), 3.39(16)	3.38 ± 0.10
146	Nd	2.50(2), 2.66(1), 2.54(10), 2.41(11), 2.63(8), 2.56(7), 2.52(15), 2.52(16), 2.51(17)	2.54 ± 0.08
147	Nd(Pm, Sm)	1.71(2), 2.15(1), 1.89(12), 1.75(4), 1.97(8), 1.79(10), 1.78(11)	1.86 ± 0.10
148	Nd	1.20(2), 1.36(1), 1.31(10), 1.25(11), 1.36(8), 1.32(7), 1.30(15), 1.27(16), 1.27(17)	1.29 ± 0.04
149	Sm	0.78(2), 0.766(1), 0.815(12), 0.806(8), 0.746(10), 0.710(11)	0.77 ± 0.04
150	Nd	0.55(2), 0.550(1), 0.498(10), 0.484(15), 0.491(16), 0.491(17), 0.471(11), 0.502(8), 0.516(7)	0.51 ± 0.06
151	Sm	0.37(2), 0.324(1), 0.366(10), 0.363(11), 0.376(8), 0.337(12)	0.36 ± 0.02
152	Sm	0.23(2), 0.215(1), 0.201(8), 0.177(10), 0.166(11)	0.20 ± 0.02
153	Sm(Eu)	0.15(2), 0.108(12), 0.122(1), 0.095(6)	0.12 ± 0.02
154	Sm	0.047(1), 0.023(10), 0.024(11)	0.03 ± 0.02
155	Sm(Eu)	0.03 ^b (3)	0.03
156	Eu	0.011(21), 0.0121(12)	0.0116
157	Eu	0.0063 ^c (12)	0.00635
158	Eu	0.0024 ^b (3)	0.0024
159	Gd	0.000905(12)	0.000905
160	Gd	0.0003 ^b (3)	0.0003
161	Tb	0.000117(12)	0.000117

a. Mean cumulative chain yield.

b. Estimated value.

c. I-133 is assumed to be 98.3% of the chain yield.³

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APPENDIX D

PER CENT CHAIN YIELDS IN THERMAL FISSION OF Pu-241

TABLE 1. Per Cent Chain Yields in Thermal Fission of Pu-241

<u>Mass</u>	<u>Element</u>	<u>Measurements</u> ^b	<u>Mean Value</u> ^a
77	As	0.000465(5)	0.00047
78	As	0.0082(5)	0.0082
82	Se	0.07 ^b (2)	0.07
83	Br(Kr)	0.208(5)	0.20
84	Br	0.341(5)	0.30
85	Rb	0.30 ^b (2)	0.30
86	Kr	0.40 ^b (2)	0.40
87	Rb	0.50 ^b (2)	0.50
88	Sr	0.70 ^b (2)	0.70
89	Sr	0.90 ^b (2)	0.90
90	Sr	1.4 ^b (2)	1.4
91	Sr(Y, Zr)	1.7 ^b (2)	1.7
92	Zr	2.1 ^b (2)	2.1
93	Zr	2.5 ^b (2)	2.5
94	Zr	3.2 ^b (2)	3.2
95	Zr(Nb, Mo)	5.03(5)	5.0
96	Zr	5.0 ^b (2)	5.0
97	Zr	5.31(5)	5.3
98	Mo	6.0 ^b (2)	6.0
99	Mo(Tc)	6.0(5)	6.0
100	Mo	6.3 ^b (2)	6.3
101	Ru	6.4 ^b (2)	6.4
102	Ru	6.3 ^b (2)	6.3
103	Ru(Rh)	6.2 ^b (2)	6.2
104	Ru	6.0 ^b (2)	6.0
105	Ru(Rh)	5.8 ^b (2)	5.8
106	Ru(Rh)	5.5 ^b (2)	5.5
107	Rh	5.0 ^b (2)	5.0
108	Pd	4.0 ^b (2)	4.0
109	Pd	3.1 ^b (2)	3.1
110	Pd	2.2 ^b (2)	2.2
111	Ag	0.513(5)	0.5
112	Pd	0.7 ^b (2)	0.7
113	Ag	0.142(5)	0.1
114	Cd	0.2 ^b (2)	0.2
115	Total Cd	0.1 ^b (2)	0.1

TABLE 1. Per Cent Chain Yields in Thermal Fission of Pu-241
(Continued)

<u>Mass</u>	<u>Element</u>	<u>Measurements</u>	<u>Mean Value</u> ^a
116	Cd	0.06 ^b (2)	0.06
117	Cd	0.05 ^b (2)	0.05
118	Cd	0.05 ^b (2)	0.05
119	Sn	0.05 ^b (2)	0.05

a. Mean cumulative chain yield.

b. Estimated value.

TABLE 2. Per Cent Chain Yields in Thermal Fission of Pu-241

<u>Mass</u>	<u>Element</u>	<u>Measurements</u>	<u>Mean Value</u> ^a
120	Sn	0.025 ^b (1)	0.025
121	Sn	0.025 ^b (1)	0.025
122	Te	0.025 ^b (1)	0.025
123	Sb	0.036 ^b (1)	0.036
124	Sn	0.043 ^b (1)	0.043
125	Sb	0.065 ^b (1)	0.065
126	Sb	0.128 ^b (1)	0.128
127	Sb	0.25 ^b (1)	0.25
128	Te	0.50 ^b (1)	0.50
129	Te(I, Xe)	1.02 ^b (1)	1.02
130	Te	1.84 ^b (1)	1.84
131	I(Xe)	3.01 (1)	3.01
132	I(Xe)	4.47 (1)	4.47
133	Xe(Cs)	6.56 (1), 6.52 (4)	6.54
134	Xe	7.81 (1)	7.81
135	I(Xe, Cs)	7.08 (1), 7.53 (3)	7.30
136	Xe	7.04 (1)	7.04
137	Cs	6.62 (1), 6.14 (4), 6.62 (5)	6.46
138	Ba	6.83 (1), 6.75 (5)	6.79
139	Ba	6.30 ^b (1)	6.30
140	Ba(La, Ce)	5.78 (1), 6.21 (3)	6.00
141	Ce	4.84 (1), 5.2 (5)	5.02
142	Ce	4.70 (1)	4.70
143	Ce(Pr, Nd)	4.44 (1), 4.38 (4), 4.70 (5)	4.51
144	Ce(Pr, Nd)	4.07 (1), 4.08 (4)	4.08
145	Nd	3.16 (1), 3.11 (4)	3.14
146	Nd	2.71 (1), 2.60 (4)	2.66
147	Nd(Pm, Sm)	2.33 (1)	2.33
148	Nd	1.91 (1), 1.84 (4)	1.88
149	Pm(Sm)	1.55 (1)	1.55
150	Nd	1.24 (1), 1.10 (4)	1.17
151	Sm	0.959 (1)	0.959
152	Sm	0.757 (1)	0.757
153	Sm(Eu)	0.559 ^b (1)	0.559

TABLE 2. Per Cent Chain Yields in Thermal Fission of Pu-241
(Continued)

<u>Mass</u>	<u>Element</u>	<u>Measurements</u>	<u>Mean Value</u> ^a
154	Sm	0.408 (1)	0.408
155	Sm(Eu)	0.293 ^b (1)	0.293
156	Eu	0.209 ^b (1)	0.209
157	Eu	0.146 ^b (1)	0.146
158	Eu	0.101 ^b (1)	0.101
159	Gd	0.068 (1)	0.068
160	Gd	0.045 (1)	0.045
161-164	Tb(Dy, Ho)	0.065 (1)	0.065

a. Mean cumulative chain yield.

b. Estimated value.

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