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Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending December 31, 1976

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TRANSURANIUM PROCESSING PLANT SEMIANNUAL REPORT OF PRODUCTION, STATUS, AND PLANS FOR PERIOD ENDING DECEMBER 31, 1976

L. J. King, J. E. Bigelow, and E. D. Collins

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OAK RIDGE NATIONAL LABORATORY
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CONTENTS

SUMMARY

This is the eighteenth report in a series that is being issued semi-annually to inform the heavy-element community of the status and future production plans of the Transuranium Element Production Program at ORNL.

During the period July 1, 1976, through December 31, 1976, we obtained transuranium elements from 11 irradiated HFIR targets; products recovered are listed in Table 2.1 on p. 3. Two batches of high-purity ^{248}Cm were purified chemically for shipment, and another batch containing about 62 mg of ^{248}Cm was separated from ^{252}Cf. Thirty shipments were made from TRU during the period; recipients and the amounts of nuclides are listed in Table 2.2 on pp. 4-5. Nine HFIR targets, each containing 8 to 9 g of curium, were fabricated.

During the next 18 months, we expect to obtain totals of 89 mg of ^{249}Bk, 870 mg of ^{252}Cf, 3.6 mg of ^{253}Es (in a mixture of isotopes), 620 μg of high-purity ^{253}Es, and 1.6 pg of ^{257}Fm; we also expect to make available 250 mg of high-purity ^{248}Cm.

We changed the sequence of chemical processing steps used to purify the californium product; this change yielded a shorter recovery time for high-purity ^{253}Es, which enabled a 50% increase in the amount obtained.

Eight neutron sources were fabricated during this report period, bringing the total fabricated to date to 92. Three sources that had previously been returned to TRU were reassigned; two others are also available for reassignment.

No special projects were undertaken during the current report period.

The values that we are currently using for transuranium element decay data and for cross-section data in planning irradiation-processing cycles, calculating production forecasts, and assaying products are tabulated in the Appendix.

1. INTRODUCTION

This is the eighteenth report in a series that is being issued semi-annually to inform the heavy-element community of the status and the future production plans of the Transuranium Element Production Program at ORNL. The objective of these reports is to provide information that will enable users of the products to obtain maximum service from the production facilities. Production plans and schedules are sharply defined only for the short term; long-range plans can be markedly influenced by feedback from researchers and other users of transuranium elements.

Operations during this report period are summarized, and the amounts of materials obtained and shipped are listed. Proposed processing schedules and anticipated yields of various products in the near future are outlined. An improvement in the processing sequence for "milking" high-purity ^{253}Es from the californium product is described. The original and current contents (^{252}Cf and ^{248}Cm) of existing neutron sources made at TRU, as well as the individuals to whom these sources are currently loaned, are tabulated. Values of nuclear parameters which were used as input data for the calculations of production rates for transuranium elements, along with a listing of the parameters which were used to calculate the specific activities of the isotopes that are of interest to TRU, are included in the Appendix.

Previous reports in this series are:

(1) For period ending June 30, 1968 – ORNL-4376.
(2) For period ending December 31, 1968 – ORNL-4428.
(3) For period ending June 30, 1969 – ORNL-4447.
(4) For period ending December 31, 1969 – ORNL-4540.
(5) For period ending June 30, 1970 – ORNL-4588.
(6) For period ending December 31, 1970 – ORNL-4666.
(7) For period ending June 30, 1971 – ORNL-4718.
(8) For period ending December 31, 1971 – ORNL-4767.
(9) For period ending June 30, 1972 – ORNL-4833.
(10) For period ending December 31, 1972 – ORNL-4884.
(11) For period ending June 30, 1973 – ORNL-4921.
(12) For period ending December 31, 1973 – ORNL-4965.
(13) For period ending June 30, 1974 – ORNL-4991.
(14) For period ending December 31, 1974 – ORNL-5034.
(15) For period ending June 30, 1975 – ORNL-5084.
(16) For period ending December 31, 1975 – ORNL-5146.
(17) For period ending June 30, 1976 – ORNL-5216.

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2. PROCESSING SUMMARY AND PRODUCTION ESTIMATE

The isotopic concentrations of the various transuranium elements are not constant but are functions of irradiation histories and decay times. We have selected one isotope of each element to use in making material balances for the isotopic mixtures normally handled. Except in special instances, ^{242}Pu, ^{243}Am, ^{244}Cm, ^{249}Bk, ^{252}Cf, ^{253}Es, and ^{257}Fm are the isotopes used for tracing the corresponding elements. Throughout this report, we are discussing mixtures of isotopes unless we indicate otherwise.

2.1 Processing Summary

During the period between July 1, 1976, and December 31, 1976, the following operations were accomplished:

(1) One campaign (No. 51) was made to obtain transuranium elements from 11 HFIR-irradiated targets plus rework material. Products from this campaign are listed in Table 2.1.

(2) We made the initial separation (Batch No. 21) of about 62 mg of high-purity ^{248}Cm (curium that typically contains 97% ^{248}Cm, 3% ^{246}Cm, and less than 0.01% ^{244}Cm) from 82 mg of ^{252}Cf, and completed the purification from ^{252}Cf and shipment of two batches (Nos. 19B and 20) of ^{248}Cm that had been separated during previous report periods.[1,2]

(3) Thirty product shipments were made. Recipients and the amounts of nuclides shipped are listed in Table 2.2.

(4) Nine HFIR targets were fabricated. Each contained 8 to 9 g of curium in the form of curium oxide--aluminum pellets that had been pressed to 80% of the theoretical density of the pellet core. The isotopic composition of the curium in these targets was approximately 46.5% ^{244}Cm, 0.5% ^{245}Cm, 45.7% ^{246}Cm, 1.3% ^{247}Cm, and 6% ^{248}Cm.

2.2 Irradiation and Processing Proposals

The level of transuranium element production is expected to continue at two processing campaigns per year. A long-term projection of the capability of the TRU-HFIR complex to produce the "yardstick" isotope ^{252}Cf

Table 2.1. Amounts of materials recovered in the major campaign in the Transuranium Processing Plant during the period July 1, 1976 – December 31, 1976

	Campaign number 51
Completion date	October
Material processed	4 Cf-I Cm-HFIR targets[a]
	7 TRU Cm-HFIR targets
	Rework material
Amounts recovered:	
^{243}Am, g[b]	0.3
^{244}Cm, g[b]	16.6 (41.6)[c]
^{249}Bk, mg	23
^{252}Cf, mg	211
^{253}Es, mg	1.15[d]
^{247}Fm, pg	0.4

[a]The term "Cf-I Cm" designates curium recovered during Californium-I (Cf-I), a Savannah River Plant (SRP) irradiation--TRU processing campaign made to obtain ^{252}Cf for use in a ^{252}Cf market evaluation program conducted by the ERDA Division of Waste Management, Production, and Reprocessing (DWMPR).

[b]Americium and curium are not usually separated from each other.

[c]The amount shown in parentheses is total curium.

[d]Before final purification.

was described in a previous report in this series.[2] Table 2.3 outlines the estimated production of transcurium elements from a series of likely processing campaigns that are scheduled through June 1978. Projected estimates for the remainder of 1978 and for 1979 are based on current trends.

2.3 Estimates of the Availability of Transuranium Elements

The amounts of transcurium elements expected from each campaign are shown in Table 2.3. During the next 18 months, we expect to recover a total of 89 mg of ^{249}Bk, 870 mg of ^{252}Cf, 3.6 mg of ^{253}Es (in a mixture of isotopes),

Table 2.2. Distribution of heavy elements from the Transuranium Processing Plant during the period July 1, 1976 – December 31, 1976

Major nuclide	Date	TRU file number	Shipped to: Individual	Site
Tin-126 (~5%), μg				
8	10-27-76	885	C. J. Orth	LASL
Plutonium-244 (98.5%), mg				
0.1	7-15-76	861	D. M. Robertson	PNL
Curium-243 (56%), μg				
9.07	11-03-76	873	Isotopes Sales for	PNL
Curium-248 (97%), mg				
50	7-07-76	858	Iso. Res. Mat'l. Lab for	LLL
0.688	8-16-76	859	Isotopes Sales for	RI[a]
50	10-13-76	879	W. T. Carnall	ANL
100.688				
Curium-250 (14 ppm), ng				
32	9-02-76	877	C. E. Bemis	ORNL
Berkelium-249, mg				
0.994	9-01-76	841	E. K. Hulet	LLL
4.3	11-29-76	895	W. T. Carnall	ANL
4.3	11-29-76	896	N. M. Edelstein	LBL
4.3	11-29-76	897	R. W. Hoff	LLL
4.3	11-29-76	899	R. G. Haire	ORNL
18.194				
Californium-252, mg				
10.058(NS-82)	7-20-76	718	G. Tessler	BAPL
9.487(NS-83)	7-20-76	718	G. Tessler	BAPL
9.880(NS-84)	7-20-76	718	G. Tessler	BAPL
10.051(NS-85)	7-20-76	718	G. Tessler	BAPL
0.1153(NSD-51)	8-10-76	871	H. Toffer	UNI[b]
0.2153(NSD-30)	8-11-76	874	F. J. Muckenthaler	ORNL
0.379(NSD-40)	8-12-76	872	J. P. Balagna	LASL
0.316(NSD-57)	8-12-76	872	J. P. Balagna	LASL
0.260(NSD-93)	8-12-76	872	J. P. Balagna	LASL
0.0010	8-16-76	867	Isotopes Sales for	SRI[c]
0.0005	8-16-76	868	Isotopes Sales for	IPL[d]
0.010	8-25-76	875	Isotopes Sales for	TX-A&M[e]
0.0005	9-03-76	878	Isotopes Sales for	IPL[d]

Table 2.2. (continued)

Major nuclide	Date	TRU file number	Shipped to: Individual	Site
Californium-252, mg (continued)				
2.870(NS-92)	9-13-76	832	V. Spiegel	NBS
0.010	9-24-76	869	Isotopes Sales for	Belg.[f]
47.182	11-10-76	887	A. R. Boulogne	SRL
90.8356				
Einsteinium-253, µg				
280	10-08-76	882A	R. G. Haire	ORNL
358	10-21-76	883	W. T. Carnall	ANL
66	10-25-76	882B	R. G. Haire	ORNL
704				
Einsteinium-253 (milked), µg				
109	11-09-76	891	R. G. Haire	ORNL
16.3	11-09-76	892	R. W. Hoff	LLL
10.9	11-09-76	893	D. C. Hoffman	LASL
136.2				
Fermium-257, pg				
0.7	10-29-76	886	D. C. Hoffman	LASL

[a]Rockwell International.

[b]United Nuclear Industries.

[c]Stanford Research Institute.

[d]Isotope Product Laboratory.

[e]Texas A&M University.

[f]Geel, Belgium.

Table 2.3. Estimated future production of transcurium elements

Period	Processing campaign	^{249}Bk (mg)	^{252}Cf (mg)	^{253}Es[a] (μg)	^{257}Fm (pg)	^{252}Cf production[b] During the period (mg)	^{252}Cf production[b] Cumul. (mg)	Date products available
Through December 1976							2186[b]	
January-June 1977	{7 Cf-I Cm-HFIR targets, 5 TRU Cm-HFIR targets}	27	250	975(200)	0.5	250	2436	March 1977
July-December 1977	{7 Cf-I Cm-HFIR targets, 6 TRU Cm-HFIR targets}	32	320	1370(220)	0.6	320	2756	October 1977
January-June 1978	13 Cf-I Cm-HFIR targets	30	300	1260(200)	0.5	300	3056	March 1978
July-December 1978						300	3356	
1979						600	3956	

[a]Amounts from initial separation. Amounts "milked" from californium product fraction after decay period are given in parentheses.

[b]Californium produced in SRP irradiations is not included in production totals. A total of 720 mg was recovered from 164 SRP slugs and 21 SRP tubes processed between November 1970 and January 1973.

620 μg of high-purity ^{253}Es, and 1.6 pg of ^{257}Fm. The following steps were used to forecast the amounts: (1) calculation of the amounts of transcurium elements in each group of targets at the time of reactor discharge by means of our computer code, (2) addition of the assumed amounts of rework feed, and (3) application of the assumed chemical yield factors and net decay factors for the assumed recovery times to the amounts of total feed (targets plus rework). The assumed chemical yields and recovery times are based on past performance data, and the most recently revised values are underlined in Table 2.4.

Table 2.4. Assumptions for forecasts of transplutonium element recoveries

	Cm	Bk	Cf	Es	Fm
Chemical yield factors					
Product recovery	0.78	0.96	0.89	0.85	0.85
Rework	0.15	0.01	0.09	0	0
Recovery time,[a] weeks	17	11	16[b]	8	9
Net decay factors during recovery time	0.99	0.84	0.92	0.72	0.63
Total product recovery factor (chemical yield x net decay)	0.77	0.81	0.82	0.61	0.54

[a]Recovery time is considered to be the interval between reactor discharge and shipment of the product. Within the recovery time, cooling and main-line processing are assumed to require 3 weeks each.

[b]This time includes a 4-week growing period for ^{253}Es after initial isolation of the californium. Total recovery factor for high-purity ^{253}Es is 0.06% of the ^{252}Cf in the HFIR targets at discharge.

Curium-248, a valuable research material, is formed by alpha decay of ^{252}Cf. On December 31, 1976, TRU had an inventory of purified californium in several batches, which contained totals of 687 mg of ^{252}Cf and 169 mg of ^{248}Cm. At appropriate times, each batch will be processed to separate the californium and curium. The curium thus obtained is considered to be high-purity ^{248}Cm; the typical isotopic composition is 97% ^{248}Cm, 3% ^{246}Cm, and <0.01% ^{244}Cm. The ^{246}Cm is produced by decay of ^{250}Cf, which is present in the californium. We expect to make available 100 mg of the high-purity ^{248}Cm in mid-1977, 100 mg in late 1977, and 50 mg in early 1978.

3. PROCESSES AND EQUIPMENT

During this report period, we changed the sequence of steps used to purify the californium product. This change yielded a shorter recovery time for high-purity ^{253}Es, which enabled a 50% increase in the amount obtained. After initial isolation of the californium, the previous purification steps included: (1) preparation of californium oxysulfate, (2) packaging and transfer of the californium oxysulfate to the TURF Californium Facility, (3) stripping the californium from the package with HNO_3, and (4) separation of the high-purity ^{253}Es and the ^{244}Cm impurity from the californium by means of a high-pressure ion exchange run. Because of limitations of the equipment and shielding at TURF, the californium product from a typical campaign had to be divided into three batches for processing; thus, by the time the last batch was completed, a significant portion of the high-purity ^{253}Es had decayed. In the new procedure, the californium product solution is: (1) stored in Cell 5 at TRU during the 4-week growing period for ^{253}Es, (2) processed by means of two cycles of high-pressure ion exchange to obtain the high-purity ^{253}Es, and (3) treated as before to transfer the californium to TURF where the final purification from ^{244}Cm is made.

No equipment changes were made during this report period. The processing equipment at TRU is in generally good condition and is continually maintained.

4. CALIFORNIUM NEUTRON SOURCES

Some of the recovered californium is incorporated into neutron sources, which are subsequently loaned to researchers. Data for existing neutron sources that have been fabricated at TRU are listed in Table 4.1. Most of the sources were fabricated into one of the four standard models illustrated in Fig. 4.1 of ref. 3, and are designated in the table by a three-letter prefix. Nonstandard sources are designated simply NS-. The three-letter prefix indicates whether the source is singly or doubly encapsulated, and whether it is fabricated from type 304L stainless steel or Zircaloy-2. The characteristics of standard source capsules are listed in Table 4.2 of ref. 3.

4.1 Sources Fabricated During July-December 1976

Eight sources, NSD-67, -68, -69, -70, -71, -72, -93, and NS-92, were fabricated during this report period. One of these (NS-92) was fabricated in a nonstandard form specified by the user.

4.2 Sources Returned

A number of neutron sources are being returned as the projects for which they were requested are completed or as replacement sources are ordered to make up for decay of the ^{252}Cf. The returned sources are available for reassignment until the appropriate time for reprocessing to recover the ingrown ^{248}Cm. Three of these sources were reassigned during this report period; two other sources, which contain 28 and 500 μg of ^{252}Cf, respectively, remain in the "available" category and are so designated in Table 4.1.

Table 4.1. Data for neutron sources prepared at TRU

Source	Date of calibration	^{252}Cf content at calibration (mg)	Content as of 12/31/76 ^{252}Cf (mg)	Content as of 12/31/76 ^{244}Cm (mg)	On loan to: Individual	On loan to: Site
NS-1[a]	8-20-68	316	36	b	K. L. Swinth	PNL
NS-2	8-23-68	254	28	b	c	
NS-3	5-13-69	~80	~12	b	G. I. Gleason	ORNL
NS-4	7-08-69	883	124	723	C. F. Masters	LASL
NS-5[d]	8-14-69	946	137	772	F. B. Simpson	ANC
NS-6	11-21-69	747	116	602	R. W. Hoff	LLL
NS-7	1-21-70	780	128	630	F. R. Chattin	ORNL-TRU
NS-8	12-17-69	1830	291	1476	M. Berger	ANL
NSD-9	4-17-70	1720	297	1357	[illegible]. D. Vaughan	PNL
NSS-10	3-11-70	113	19	b	J. P. Balagna	LASL
NS-11	3-10-70	8	1	b	R. R. Fullwood	LASL
NSS-12	6-30-70	1868	340	1457	R. W. Hoff	LLL
NSD-13	3-19-71	4649	1021	3460	H. O. Menlove	LASL
NSS-14	6-29-70	15	839	3601	J. C. Stewart	ANL
NS-15[d]	6-25-70	931	160	727	F. B. Simpson	ANC
NSS-17	8-31-71	4886	1207	3508	L. W. Dahlke	Sandia-Livermore
NS-18[d]	6-24-70	962	174	751	F. B. Simpson	ANC
NSS-19	6-26-70	493	89	385	J. E. Bigelow	ORNL-TRU
NSD-20	7-01-70	630	115	491	J. E. Powell	Sandia-NM
NSS-21	10-21-70	18	4	b	F. Cross	PNL
NS-22	9-10-70	13	2	b	J. E. Bigelow	ORNL-TRU
NSD-24	10-15-70	6	1	b	J. E. Rushton	ORNL
NS-25	11-09-70	58	12	b	F. J. Muckenthaler	ORNL
NSD-26	2-11-71	14	3	b	H O. Menlove	LASL
NSD-27	1-29-71	2528	536	1900	L. C. Nelson, Jr.	New Brunswick
NSD-28	2-12-71	11	2	b	E. E. Hicks	Rocky Flats
NSD-29	9-10-71	11303	2836	8160	S. G. Snow	Y-12
NSD-30	3-31-71	879	195	663	F. J. Muckenthaler	ORNL
NSD-31	11-23-71	1733	455	1219	J. L. White	MEDL
NSD-34	11-23-71	1924	505	1363	W. G. Spear	MEDL
NSD-35	11-23-71	1904	500	1339	c	
NS-36[d]	5-25-71	2070	456	1530	F. B. Simpson	ANC
NSD-37	9-04-71	9838	2438	7057	R. W. Perkins	PNL
NSD-38	6-16-71	102	24	b	H. O. Menlove	LASL
NS-39	11-07-71	942	244	665	V. Spiegel	NBS
NSD-40	4-27-72	1154	339	777	J. P. Balagna	LASL
NSD-41	11-08-71	5117	1329	3613	C. J. Emert	BAPL
NSD-42	11-02-71	4434	1146	3135	C. J. Emert	BAPL
NSD-43	4-20-72	4839	1413	3267	C. J. Emert	BAPL
NSD-44	5-15-72	10731	3191	7190	F. B. Simpson	ANC
NSD-45	8-18-71	1776	435	1279	K. L. Swinth	PNL
NSD-46	4-23-72	629	184	424	H. O. Menlove	LASL
NSD-47	7-14-71	200	48	145	P. L. Johnson	Mound
NSD-48	7-14-71	194	46	141	A. C. England	ORNL
NSD-49	7-14-71	199	48	144	L. J. Esch	BAPL
NS-50	8-23-71	138	34	99	S. G. Carpenter	ANL-NRTS

Table 4.1 (continued)

Source	Date of calibration	^{252}Cf content at calibration (μg)	Content as of 12/31/76 ^{252}Cf (μg)	Content as of 12/31/76 ^{248}Cm (μg)	On loan to: Individual	On loan to: Site
NSD-51	11-02-71	365	94	258	H. Toffer	UNI
NSD-52	9-02-71	280	89	201	E. D. Clayton	PNL
NSD-53	10-25-71	1051	270	745	L. J. Esch	KAPL
NS-54	1-19-73	3187	1133	1959	V. Spiegel	NBS
NSD-55	4-19-72	4	1	b	L. J. Esch	KAPL
NSD-56	4-19-72	124	36	84	M. M. Bretscher	ANL
NSD-57	4-14-72	973	283	658	J. P. Balagna	LASL
NSD-58	5-15-72	11003	3272	7373	F. B. Simpson	ANL
NS-59[d]	7-13-72	53	16	b	G. E. Hanson	LASL
NSD-60	4-11-72	20	6	b	F. F. Haywood	ORNL-DOSAR
NSD-61	1-[illegible]-73	5225	1857	3211	L. J. Esch	KAPL
NSS-62	3-27-73	3755	1401	2245	J. E. Bigelow	ORNL-TRU
NSD-63	4-21-72	847	248	572	H. O. Menlove	LASL
NSD-64	7-19-73	195	78	110	H. O. Menlove	LASL
NS-65	7-09-73	114	46	65	L. Green	BAPL
NSD-66	8-02-73	3449	1410	1944	J. E. Powell	Sandia-NM
NSD-67	6-07-76	13522	11656	1779	e	
NSD-68	6-07-76	16825	14504	2274	e	
NSD-69	6-07-76	16681	14580	2195	e	
NSD-70	6-10-76	22694	19605	2946	e	
NSD-71	7-15-76	21336	18900	2323	e	
NSD-72	7-15-76	16742	14831	1823	e	
NSD-73	9-11-73	13545	5699	7482	G. I. Gleason	ORAU
NSD-74	9-11-73	4416	1858	2439	G. I. Gleason	ORAU
NS-75	10-01-73	1919	819	1049	R. J. Kloepping	LLL
NSD-76	3-09-74	434	208	216	P. L. Johnson	Mound
NSD-77	3-09-74	433	207	215	P. L. Johnson	Mound
NSD-78	3-09-74	429	205	213	P. L. Johnson	Mound
NS-79	10-02-74	1650	916	700	V. Spiegel	NBS
NSD-80	6-03-74	5966	3036	2794	C. J. Emert	BAPL
NSD-81	6-03-74	6364	3238	2981	C. J. Emert	BAPL
NS-82	5-19-75	14264	9329	4706	G. Tessler	BAPL
NS-83	9-24-75	11783	8447	3181	G. Tessler	BAPL
NS-84	9-30-75	12674	9125	3384	G. Tessler	BAPL
NS-85	10-22-75	12181	9910	3119	G. Tessler	BAPL
NS-86	11-17-75	2620	1953	637	V. Spiegel	NBS
NSD-87	10-15-75	22387	16293	5811	G. I. Gleason	ORAU
NSD-89	4-23-75	12687	8344	4332	J. E. Powell	Sandia-NM
NCS-90	1-16-75	0.87	<1	b	J. R. Smith	ANL
NSD-91	9-26-75	15	11	b	L. J. Esch	KAPL
NS-92	6-24-76	2960	2583	360	V. Spiegel	NBS
NSD-93	1-29-74	500	233	255	J. P. Balagna	LASL
SR-Cf-167[f]	5-26-71	3975	916	2917	J. E. Rushton	ORNL

[a] This source is encapsulated in aluminum.

[b] This source is not suitable for recovery of ^{248}Cm.

[c] This source is held at ORNL and is available for reissue.

[d] This source is encapsulated in type 405 stainless steel.

[e] This source is being held for use at PNL.

[f] This source was fabricated at TRU in standard Savannah River SR-Cf-100 series hardware.

5. SPECIAL PROJECTS

The primary functions of TRU are: (1) to fabricate targets for irradiation in the HFIR to produce transuranium elements, and (2) to isolate and purify transuranium elements for use by research workers. However, the facilities that are available[4] are also used for a variety of other purposes such as nonroutine production, special preparations, and special irradiations in HFIR; in each case, a unique service can be provided to assist a research program at ORNL or another site. No special projects were undertaken during the current report period.

6. REFERENCES

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7. APPENDIX

We have traditionally used the Appendix in this series of semiannual reports to tabulate decay data and cross-section data of interest to the transplutonium community. In the first few issues, rapid changes occurred as a result of the publication of much new data. Sometimes, by virtue of personal contacts with some of the investigators, we were able to incorporate new data in our tables even before formal publication. In more recent issues, the press of other work has prevented us from revising the tables; as a result, they are no longer current. In the meantime, the Nuclear Data Project at ORNL has issued revised and updated Nuclear Data Sheets[5-11] that cover the mass region of interest (A>237) and which are considered the definitive source of all types of nuclear data relating to decay modes, half-lives, etc. However, because these Appendix tables have proven to be a convenient reference to us at TRU, we will continue to publish them with each issue. It is our expectation that, as time permits, we will bring the decay data in these tables in line with the latest revisions of the Nuclear Data Sheets.

7.1 Decay Data

Table A-1 is a list of all nuclides of interest to the Transplutonium Element Production Program (i.e., all that can be produced by neutron bombardment of ^{238}U). The list includes values for half-lives and branching ratios or partial decay half-lives, along with literature references where available. In many cases, the half-life of an isotope was determined by relating that isotope's half-life to the half-life of some other reference isotope. In a few of these cases, a newer value has been accepted for the half-life of the reference isotope, and the values of the half-lives that were dependent upon it have been recalculated. Such cases are footnoted because the half-life value in our table no longer agrees with the value given in the reference. However, we did use the relationship given in the referenced work.

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Table A-1. Half-life values[a] for isotopes of transuranium elements

Nuclide	Total Half-Life	Partial Half-Life for α Decay	Branching Ratios	Partial Half-Life for Spontaneous Fission	Neutrons per Fission	References[b]
^{237}Np		$(2.14 \pm 0.01) \times 10^{6}$ y		$>10^{18}$ y	2.00[d]	60Dr12, 61Dr04
^{238}Np	2.10 ± 0.01 d					50Py53
^{239}Np	2.355 ± 0.010 d					50Co03
^{240}Np	63 ± 2 m					60Le03
^{240m}Np	7.3 ± 0.3 m					48Hy61
^{241}Np	16 m					60Le03
^{242}Np	3.4 h					60Le03
^{238}Pu	87.404 ± 0.041 y			$(5 \pm 0.6) \times 10^{10}$ y	2.33 ± 0.08	61Dr04, 64Jo15, 56Hi01
^{239}Pu		$(2.4413 \pm 0.003) \times 10^{4}$ y		5.5×10^{15} y	2.24[d]	52Se67, 58Wa26
^{240}Pu		6580 ± 40 y		$(1.340 \pm 0.015) \times 10^{11}$ y	2.177 ± 0.008	51Ig03, 62Ma13, 65Bo54
^{241}Pu	14.98 ± 0.33 y	$(5.72 \pm 0.1) \times 10^{5}$ y				48Ca19, 60Br15
^{242}Pu		$(3.869 \pm 0.016) \times 10^{5}$ y		$(7.45 \pm 0.17) \times 10^{10}$ y	2.166 ± 0.009	63Mo50, 60Be06, 65Bo54
^{243}Pu	4.953 ± 0.003 h					68D109
^{244}Pu		$(8.28 \pm 0.10) \times 10^{7}$ y		$(6.55 \pm 0.32) \times 10^{10}$ y	2.84[d]	66F107, 60Be06
^{245}Pu	10.6 ± 0.4 h					56Bu03
^{246}Pu	10.85 ± 0.02 d					56Ho23
^{241}Am		432.7 ± 0.7 y		$(2.3 \pm 0.8) \times 10^{14}$ y	2.48[d]	61Dr04, 67Ca01
^{242}Am	16.01 ± 0.02 h		EC/β = 0.19			53Ke38
^{242m}Am	144 ± 7 y	$(2.92 \pm 0.15) \times 10^{4}$ y				59Ba31[c]
^{243}Am		7370 ± 40 y				68Br22
^{244}Am	10.1 ± 0.1 h					62Va08
^{244m}Am	26 m					54Ga24
^{245}Am	2.07 ± 0.02 h					56Bu03
^{246}Am	25.0 ± 0.2 m					55En16
^{246m}Am	40 ± 7 m					67Or02
^{247}Am	24 ± 3 m					67Or03
^{242}Cm	162.7 ± 0.1 d			7.2×10^{6} y	2.65 ± 0.09	51Ha87, 57Pe52, 56Hi01
^{243}Cm		32 y				57As70
^{244}Cm	18.099 ± 0.015 y		α/SF = $(7.43 \pm 0.01) \times 10^{5}$		2.84 ± 0.09	65Me02, 68Be26, 56Hi01
^{245}Cm		8265 ± 180 y				68Me01
^{246}Cm		4655 ± 40 y	α/SF = 3822 ± 10		3.00[d]	68Me01, 71Me19
^{247}Cm		$(1.56 \pm 0.05) \times 10^{7}$ y				71F101
^{248}Cm		$(3.703 \pm 0.032) \times 10^{5}$ y		$(4.115 \pm 0.034) \times 10^{6}$ y	3.32[d]	71Me19
^{249}Cm	64 ± 3 m					38Ea06
^{250}Cm				$(1.74 \pm 0.24) \times 10^{4}$ y	3.56[d]	66Ha01

Table A-1. (continued)

Nuclide	Total Half-Life	Partial Half-Life for α Decay	Branching Ratios	Partial Half-Life for Spontaneous Fission	Neutrons per Fission	References[b]
^{249}Bk	314 ± 8 d		α/β = (1.45 ± 0.08) × 10^{-5}	(1.87 ± 0.09) × 10^{9} y	3.72 ± 0.16	57Es01, 68Hi08, 64Py02
^{250}Bk	3.222 ± 0.005 h					59Va02
^{251}Bk	57 ± 1.7 m					66RG04
^{249}Cf		352 ± 6 y	α/SF = (1.992 ± 0.040) × 10^{8}		3.44[d]	68Me01, 68Hi08
^{250}Cf		13.08 ± 0.09 y	α/SF = 1260 ± 40		3.54[d]	63Ph01, 68Me01
^{251}Cf		900 ± 50 y				68Me01
^{252}Cf	2.644 ± 0.004 y		α/SF = 31.3 ± 0.2		3.796 ± 0.031	61Me02, 68Mh04
^{253}Cf	17.812 ± 0.082 d		α/β = (3.1 ± 0.4) × 10^{-3}			68Dr02, 66RG01
^{254}Cf	60.5 ± 0.2 d		α/SF = (3.10 ± 0.16) × 10^{-3}		3.90 ± 0.14	63Ph01, 64Py02, 68Be21
^{255}Cf	1.5 ± 0.5 h					70Lo19
^{253}Es	20.467 ± 0.024 d		α/SF = (1.15 ± 0.03) × 10^{7}		3.82[d]	61Me03, 68Dr02
^{254}Es	276 d			~2.5 × 10^{7} y	4.04[d]	67Fi03, 67Un01
^{254m}Es	39.3 ± 0.2 h		β/α = 382 ± 30 E.C./β = 0.00078 ± 0.00006			62Un01, 63Ph01
^{255}Es	39.8 ± 1.2 d		α/β = 0.0866 ± 0.0043 α/SF = (2.22 ± 0.10) × 10^{4}		4.16[d]	66RG01, 67Fi03
^{256}Es	25 ± 3 m					68Lo11
^{254}Fm	3.24 ± 0.01 h		α/SF = 1695 ± 8		4.05 ± 0.18	56Jo09, 67Fi03, 56Ch03
^{255}Fm	20.07 ± 0.07 h		SF/α = (2.4 ± 1.1) × 10^{-7}		4.16[d]	63Ph01, 64As01
^{256}Fm	2.62 ± 0.03 h		~100% SF		4.27[d]	68Me13
^{257}Fm	94 ± 10 d					66RG01
^{258}Fm	380 ± 60 μs		~100% SF			71Hu03

[a]The half-life values used in this table were being used at TRU at the end of the report period.

[b]References are decoded in Table A-2.

[c]Published values are adjusted for ^{241}Am half-life of 432.7 y.

[d]Value estimated by linear interpolation of the values for ^{244}Cm and ^{252}Cf, based on nuclidic mass.

The references used in Table A-1 are decoded in Table A-2. The system of references is that used in the Nuclear Data Sheets. Table A-3 lists derived data, such as specific activities, along with information concerning the hazard associated with handling these nuclides.

7.2 Neutron Cross-Section Data

The values of neutron cross sections used to compute transmutations in HFIR target irradiations are listed in Table A-4. This table shows six parameters describing the neutron interactions. The first is the thermal-neutron capture cross section, σ^{c}_{2200}, and the third is the neutron capture resonance integral, RI. The second parameter, C, is a constant that is a function of the target geometry; it is used to estimate the resonance self-shielding effect. The effective capture cross section, σ^{c}_{eff}, would be:

$$\sigma^{c}_{eff} = \sigma^{c}_{2200} + \frac{\phi_{res}}{\phi_{2200}} \frac{RI}{\sqrt{1 + CN}} ,$$

where N is the number of grams of the particular nuclide in one target rod, ϕ_{res} is the average flux per unit lethargy width in the resonance region, and ϕ_{2200} is the equivalent flux of 2200-m/sec neutrons that would give the same reaction rate with a 1/v absorber as would the actual reactor flux. In the HFIR, the ratio ϕ_{res}/ϕ_{2200} ranges from 0.042 to 0.051. The effective cross section for fission is computed by a similar relationship among the last three parameters.

These cross sections are to be regarded as a self-consistent set whereby one can compute overall transmutation effects and as a set of arbitrary constants to be used to obtain the best fit to our data. Hopefully, these numbers and the cross sections experimentally measured on pure isotopes will agree; however, we will not allow the possibility of a discrepancy to confine us.

It should be pointed out that ^{244c}Am is a fictitious isotope which is used to simplify the calculation of the main transmutation chain involving ^{244}Am. The properties of ^{244c}Am were calculated from the properties of the

Table A-2. References for Table A-1

Code	Reference
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Table A-3. Properties[a] of transuranium nuclides

Nuclide	Half-Life	Energies of Prin. Emissions (MeV) α	β	Specific Activity (Ci/g)	(W/g)	(α cps/mg)	(β dpm/mg)	(Neutrons min^{-1} mg^{-1})	Hazard[b] MPC$_{a(40)}$ (μCi/cm^3)	Body Burden (μCi)	(μg)
^{237}Np	2.14 x 10^6 y	4.78		7.07 x 10^{-4}	2.07 x 10^{-5}	8.01 x 10^5		<7 x 10^{-6}	4 x 10^{-12}	0.06	84.0
^{238}Np	2.14 d		0.25 1.24	2.61 x 10^5	2.27 x 10^3		5.80 x 10^{14}				
^{239}Np	2.359 d		0.332 0.427	2.32 x 10^5	5.06 x 10^2		5.14 x 10^{14}		7 x 10^{-7}	30	1.20 x 10^{-4}
^{240}Np	63 m		0.80	1.24 x 10^7	1.03 x 10^5		2.76 x 10^{16}				
^{240m}Np	7.3 m		2.18 1.6	1.07 x 10^8	5.33 x 10^5		2.38 x 10^{17}				
^{241}Np	16 m			4.86 x 10^7			1.08 x 10^{17}				
^{241m}Np	3.4 h			3.82 x 10^6			8.49 x 10^{15}				
^{238}Pu	87.404 y	5.49		17.2	0.570	1.94 x 10^{10}		155	2 x 10^{-12}	0.04	2.32 x 10^{-3}
^{239}Pu	2.4413 x 10^4 y	5.15		6.13 x 10^{-2}	1.913 x 10^{-3}	6.94 x 10^7		1.35 x 10^{-3}	2 x 10^{-12}	0.04	0.653
^{240}Pu	6580 y	5.16		0.227	7.087 x 10^{-3}	2.57 x 10^8		53.7	2 x 10^{-12}	0.04	0.176
^{241}Pu	14.98 y	4.9	0.02	99.1	4.06 x 10^{-3}	2.94 x 10^6	2.20 x 10^{11}		9 x 10^{-11}	0.9	9.68 x 10^{-3}
^{242}Pu	3.869 x 10^5 y	4.90		3.82 x 10^{-3}	1.13 x 10^{-4}	4.32 x 10^6		95.3	2 x 10^{-12}	0.05	13
^{243}Pu	4.955 h		0.49 0.58	2.60 x 10^6	3.74 x 10^3		5.78 x 10^{15}		2 x 10^{-6}	7.0	2.84 x 10^{-6}
^{244}Pu	8.28 x 10^7 y	4.58		1.77 x 10^{-5}	4.93 x 10^{-7}	2.00 x 10^4		141	2 x 10^{-12}	0.04	3.26 x 10^3
^{245}Pu	10.6 h			1.21 x 10^6			2.68 x 10^{15}		2 x 10^{-7}	3.0	2.48 x 10^{-6}
^{246}Pu	10.85 d		0.15	4.91 x 10^6	66.9		1.09 x 10^{14}				
^{241}Am	432.7 y	5.48		3.43	0.1145	3.88 x 10^9		3.55 x 10^{-2}	6 x 10^{-12}	0.1	0.0292
^{242}Am	16.01 h		0.63 0.67	8.11 x 10^5	2.06 x 10^3		1.80 x 10^{13}[d]		4 x 10^{-8}	0.06	7.39 x 10^{-8}
^{242m}Am	144 y	5.407	I.T.	10.3	3.08 x 10^{-2}	5.53 x 10^7	2.28 x 10^{10}[e]		6 x 10^{-12}	0.07	6.80 x 10^{-3}
^{243}Am	7370 y	5.27		0.200	6.42 x 10^{-3}	2.26 x 10^8			6 x 10^{-12}	0.05	0.25
^{244}Am	10.1		0.387	1.27 x 10^6	8.74 x 10^3		2.82 x 10^{15}				
^{244m}Am	26 m		1.5	2.96 x 10^7	8.98 x 10^4		6.68 x 10^{16}[f]		4 x 10^{-6}	0.2	6.76 x 10^{-9}
^{245}Am	2.07 h		0.91	6.17 x 10^6	1.20 x 10^4		1.37 x 10^{15}				
^{246}Am	25.0 m		1.31	3.06 x 10^7	2.48 x 10^5		6.79 x 10^{16}				
^{246m}Am	40 m			1.91 x 10^7			4.24 x 10^{16}				
^{247}Am	24 m			3.17 x 10^7			7.04 x 10^{16}				
^{242}Cm	162.7 d	6.11		3.32 x 10^3	122	3.76 x 10^{12}		1.21 x 10^6	1 x 10^{-10}	0.05	1.81 x 10^{-5}
^{243}Cm	32 y	5.79		45.9	1.677	5.20 x 10^{10}	3.27 x 10^8		6 x 10^{-12}	0.09	1.96 x 10^{-3}
^{244}Cm	18.099 y	5.81		80.94	2.832	9.16 x 10^{10}		6.87 x 10^5	9 x 10^{-12}	0.1	1.24 x 10^{-3}
^{245}Cm	8265 y	5.36		0.177	5.89 x 10^{-3}	2.00 x 10^8			5 x 10^{-12}	0.04	0.226
^{246}Cm	4655 y	5.39		0.312	1.01 x 10^{-2}	3.52 x 10^8		5.58 x 10^5	5 x 10^{-12}	0.05	0.160
^{247}Cm	1.56 x 10^7 y	4.87		9.48 x 10^{-5}	2.94 x 10^{-6}	1.05 x 10^5			5 x 10^{-12}	0.04	431
^{248}Cm	3.397 x 10^5 y	5.05		4.24 x 10^{-3}	5.34 x 10^{-4}	4.39 x 10^6		2.58 x 10^6	6 x 10^{-13}	0.006	1.38
^{249}Cm	64 m		0.9	1.18 x 10^7	2.06 x 10^4		2.62 x 10^{16}		1 x 10^{-5}	1.0	0.47 x 10^{-6}
^{250}Cm	1.74 x 10^4 y			8.20 x 10^{-2}	~0.1			6.49 x 10^8			

Table A-3. (continued)

Nuclide	Half-life	Energies of Prin. Emissions (MeV) α	β	Specific Activity (Ci/g)	(W/g)	(α cps/mg[c])	(β dps/mg)	(Neutrons min⁻¹ mg⁻¹)	Hazard[b] MPC α(40) (μCi/cm³)	Body Burden (μCi)	(μg)
^{249}Bk	314 d	5.4	0.125	1.67×10^{3}	0.359	2.74×10^{7}	3.71×10^{12}	6.34×10^{3}	9×10^{-10}	0.7	4.19×10^{-4}
^{250}Bk	3.222 h		0.23	3.80×10^{6}	4.75×10^{4}		8.62×10^{15}		1×10^{-7}	0.05	1.20×10^{-8}
^{251}Bk	57 m			1.32×10^{7}			2.92×10^{16}				
^{249}Cf	352 y	5.81		4.08	0.152	4.62×10^{9}		156	2×10^{-12}	0.04	9.80×10^{-3}
^{250}Cf	13.08 y	6.03		109	4.06	1.23×10^{11}		6.85×10^{8}	5×10^{-12}	0.04	3.70×10^{-4}
^{251}Cf	900 y			1.59	5.79×10^{-2}	1.78×10^{9}			2×10^{-12}	0.04	2.50×10^{-2}
^{252}Cf	2.646 y	6.11		536	19.0	5.88×10^{11}		1.40×10^{11}	6×10^{-12}	0.01	1.87×10^{-5}
^{253}Cf	17.812 d	5.96	0.27	2.90×10^{4}	13.89	1.02×10^{11}	6.41×10^{13}		8×10^{-10}	0.04	1.40×10^{-4}
^{254}Cf	60.5 d	5.84		8.49×10^{3}	1.06×10^{4}	2.89×10^{10}		7.35×10^{13}	5×10^{-12}	0.0007	8.24×10^{-8}
^{255}Cf	1.5 h			$\sim 8 \times 10^{6}$							
^{253}Es	20.467 d	6.63		2.52×10^{4}	1.01×10^{3}	2.86×10^{15}		1.91×10^{7}	6×10^{-10}	0.04	1.50×10^{-6}
^{254}Es	276 d	6.42		3.86×10^{3}	71.9	2.11×10^{12}		$\sim 5.04 \times 10^{5}$	7×10^{-11}	0.02	1.00×10^{-5}
^{254m}Es	39.3 h		0.48	3.14×10^{5}	1.10×10^{3}		6.97×10^{14}		5×10^{-9}	0.02	6.37×10^{-8}
^{255}Es	39.8 d			1.29×10^{4}			2.86×10^{13}	$4.. : \times 10^{9}$	4×10^{-10}	0.04	5.10×10^{-6}
^{256}Es	25 m			2.94×10^{7}			6.52×10^{16}				
^{254}Fm	3.24 h	7.20		3.85×10^{6}	1.68×10^{5}	4.31×10^{15}		2.02×10^{13}	6×10^{-8}	0.02	5.25×10^{-9}
^{255}Fm	20.07 h	7.03		6.13×10^{5}	2.79×10^{4}	6.94×10^{14}		1.36×10^{9}	1×10^{-8}	0.04	6.53×10^{-8}
^{256}Fm	2.62 h			4.67×10^{6}	5.85×10^{6}			4.43×10^{16}	2×10^{-9}	0.0008	1.71×10^{-10}
^{257}Fm	94 d			5.41×10^{3}	~ 200	6.12×10^{12}					
^{258}Fm	380 us			1.15×10^{11}							

[a] The values for properties included in this table are those in use at TRU at the end of the report period.

[b] From ICRP Publication 2, "Report of Committee II on Permissible Dose for Internal Radiation" (1959) and ICRP Publication 6, "Recommendations of the International Commission on Radiological Protection" (1964).

[c] Counting geometry, 53%.

[d] ^{242}Am decays by β emission (84%) and orbital capture (16%).

[e] ^{242m}Am decays almost entirely by isomeric transition to the 16-hr ground state, ^{242}Am.

[f] ^{244m}Am decays primarily by β emission, but 0.038% decays by electron capture to ^{244}Pu.

Table A-4. Neutron cross sections used to compute transmutations in HFIR target irradiations

Nuclide	Half-Life	Capture			Fission		
		2200-m/s Cross Section (barns)	Resonance Self-Shielding Constant	Resonance Integral (barns)	2200-m/s Cross Section (barns)	Resonance Self-Shielding Constant	Resonance Integral (barns)
^{238}Pu	87.486 y	560	0	150	16.5	0	25
^{239}Pu	2.4113×10^4 y	265.7	0	195	742.4	0	324
^{240}Pu	6580 y	290	0	8453	0.05	0	0
^{241}Pu	14.98 y	360	0	166	1011	0	561
^{242}Pu	3.869×10^5 y	19.5	6.20	1280	0	0	0
^{243}Pu	4.955 h	80	0	0	210	0	0
^{244}Pu	8.28×10^7 y	1.6	0	0	0	0	0
^{245}Pu	10.6 h	277	0	0	0	0	0
^{246}Pu	10.85 d	0	0	0	0	0	0
^{243}Am	7370 y	105	0	1500	0	0	0
^{244}Am	10.1 h	0	0	0	2300	0	0
^{244m}Am	26 m	0	0	0	0	0	0
$^{244c}Am^a$	49 h	0	0	0	1128	0	0
^{245}Am	2.07 h	0	0	0	0	0	0
^{246}Am	25.0 m	0	0	0	0	0	0
^{244}Cm	18.099 y	1	4.0	650	1.2	4.0	12.5
^{245}Cm	8265 y	36	2.4	120	1727	2.4	1140
^{246}Cm	4655 y	1.25	0	121	0	0	0
^{247}Cm	1.56×10^7 y	60	0	500	120	0	1060
^{248}Cm	3.397×10^5 y	3.50	2.0	170	0	0	0
^{249}Cm	64 m	2.8	0	0	50	0	0
^{250}Cm	1.74×10^4 y	2	0	0	0	0	0
^{249}Bk	314 d	1451	2.4	1240	0	0	0
^{250}Bk	3.222 h	350	0	0	3000	0	0
^{251}Bk	57 m	0	0	0	0	0	0
^{248}Cf	352 y	450	1.46	790	1690	5.8	2920
^{250}Cf	13.08 y	1900	20	11600	0	0	0
^{251}Cf	900 y	2850	14	1600	3750	14	5400
^{252}Cf	2.646 y	19.8	0	44	32	0	110
^{253}Cf	17.812 d	12.6	0	0	1300	0	0
^{254}Cf	60.5 d	50	0	1650	0	0	0
^{255}Cf	1.5 h	0	0	0	0	0	0
^{253}Es	20.467 d	345	0	0	0	0	0
^{254}Es	276 d	20	0	0	3060	0	0
^{254m}Es	39.3 h	1.26	0	0	1840	0	0
^{255}Es	39.8 d	60	0	0	0	0	0
^{256}Es	25 m	0	0	0	0	0	0
^{254}Fm	3.24 h	76	0	0	0	0	0
^{255}Fm	20.07 h	26	0	0	100	0	0
^{256}Fm	2.62 h	45	0	0	0	0	0
^{257}Fm	96 d	10	0	0	5500	0	0
^{258}Fm	380 μs	0	0	0	0	0	0

[a] To simplify calculations we use a fictitious isotope, ^{244c}Am, which combines the properties of ^{244m}Am and ^{244}Am according to their relative rates of production from ^{243}Am.

real isomers ^{244g}Am and ^{244m}Am by assuming that: (1) the number of atoms of ^{244c}Am present equals the total number of atoms of the real isomers; (2) the β decay from ^{244c}Am equals the total β decay from the real isomers; (3) the fissions from ^{244c}Am equal the total fissions from the real isomers; (4) the isomers are in equilibrium with their common parent ^{243}Am while the reactor is operating; and (5) the only significant production and removal factors are the removal of the isomers by decay and neutron absorption and the production of the isomers by transmutation from ^{243}Am. Thus,

$$(1)\quad N_c = N_g + N_m ,$$

$$(2)\quad \lambda_c N_c = \lambda_g N_g + \lambda_m N_m ,$$

$$(3)\quad \sigma_c^f N_c = \sigma_g^f N_g + \sigma_m^f N_m ,$$

$$(4)\quad \frac{dN_c}{dt} = \frac{dN_g}{dt} = \frac{dN_m}{dt} = 0, \text{ and}$$

$$(5)\quad (\lambda_i + \sigma_i^a \phi) N_i = f_i \sigma_i^c N_{243} ,$$

where superscripts f, a, and c refer to fission, neutron absorption, and neutron capture; subscript i refers to the ith isomer, c, g, or m; and f_i is the fraction of neutron captures in ^{243}Am resulting in the ith isomer, such that $f_c = f_g + f_m = 1$.