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Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending December 31, 1977

L. J. King
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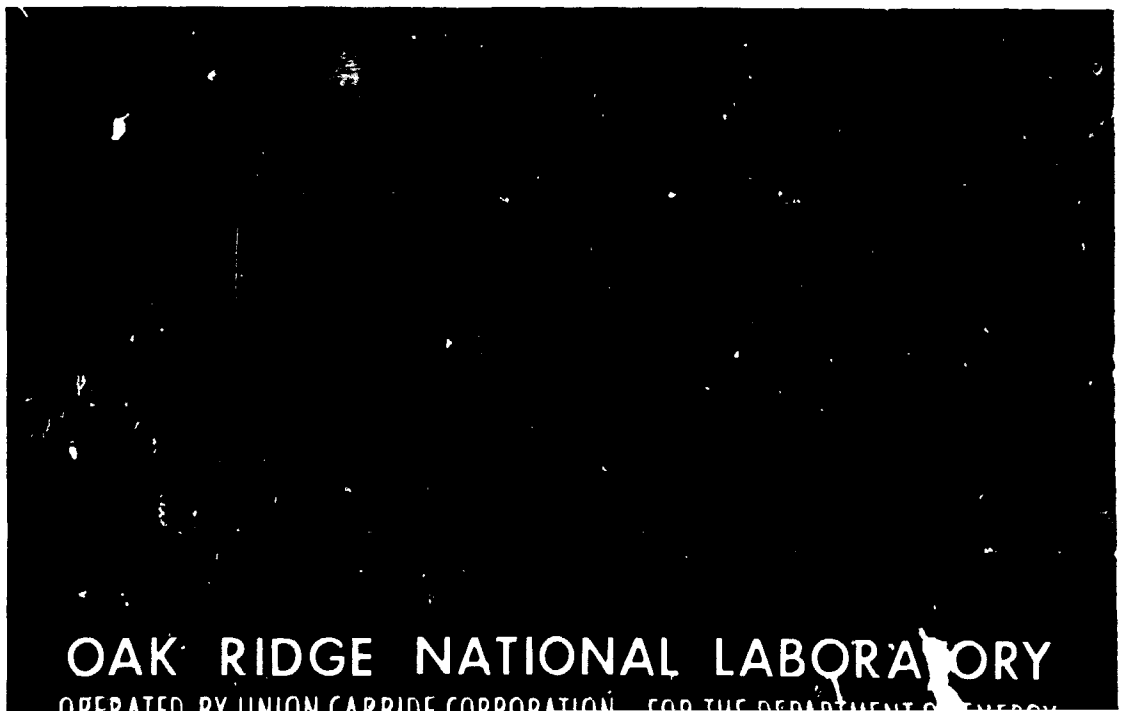

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION FOR THE DEPARTMENT OF ENERGY

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TRANSURANIUM PROCESSING PLANT SEMIANNUAL REPORT OF PRODUCTION, STATUS, AND PLANS FOR PERIOD ENDING DECEMBER 31, 1977

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

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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Reports previously issued in this series are as follows:

ORNL-4376 Period Ending June 30, 1968
ORNL-4428 Period Ending December 31, 1968
ORNL-4447 Period Ending June 30, 1969
ORNL-4540 Period Ending December 31, 1969
ORNL-4588 Period Ending June 30, 1970
ORNL-4666 Period Ending December 31, 1970
ORNL-4718 Period Ending June 30, 1971
ORNL-4767 Period Ending December 31, 1971
ORNL-4833 Period Ending June 30, 1972
ORNL-4884 Period Ending December 31, 1972
ORNL-4921 Period Ending June 30, 1973
ORNL-4965 Period Ending December 31, 1973
ORNL-4991 Period Ending June 30, 1974
ORNL-5024 Period Ending December 31, 1974
ORNL-5084 Period Ending June 30, 1975
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ORNL-5216 Period Ending June 30, 1976
ORNL-5305 Period Ending December 31, 1976
ORNL-5358 Period Ending June 30, 1977

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SUMMARY

This is the twentieth report in a series that is being issued semiannually 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, 1977 through December 31, 1977, we obtained transuranium elements from 13 irradiated HFIR targets; products recovered are listed in Table 2.1 on p. 2. One batch of high-purity ^{248}Cm (~75 mg) was separated from ^{252}Cf. Eighteen shipments were made from TRU during the period; recipients and the amounts of nuclides are listed in Table 2.2 on pp. 3-4. Seven HFIR targets, each containing 8 to 9 g of curium, were fabricated.

During the next 18 months, we expect to obtain totals of 97 mg of ^{249}Bk, 985 mg of ^{252}Cf, 4.2 mg of ^{253}Es (in a mixture of isotopes), 665 μg of high-purity ^{253}Es, and 1.8 pg of ^{257}Fm; we also expect to make available 250 mg of high-purity ^{248}Cm.

A new scrubber system was installed in the dissolver off-gas (DOG) stream to remove the bulk of the ^{131}I and to reduce the amount sorbed in the Hopcalite--charcoal system. During TRU target Campaign 53, the DOG stream was scrubbed with hyperazeotropic nitric acid (the IODOX process). Both the equipment and the process performed satisfactorily.

Three neutron sources were fabricated during this report period, bringing the total fabricated to date to 100. Six sources were returned to TRU and are available for reassignment.

Special projects included the production of several grams of ultra-high-purity ^{243}Am and the development of a method for purification of the $ZnBr_2$ solution from a shielding window.

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 twentieth report in a series that is being issued semiannually 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. 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. Special projects to produce several grams of ultrahigh-purity ^{243}Am and to purify the $ZnBr_2$ solution from a shielding window are described. Values of nuclear parameters that were used as input data for the calculations of production rates for transuranium elements, along with a listing of the parameters used to calculate the specific activities of the isotopes that are of interest to TRU, are included in the Appendix.

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, 1977 and December 31, 1977, the following operations were accomplished:

(1) One chemical processing campaign (No. 53) was made to obtain transuranium elements from 13 HFIR-irradiated targets plus rework material. Products from this campaign are listed in Table 2.1.

(2) We made the initial separation (Batch No. 23) of about 75 mg of high-purity ^{248}Cm (curium that typically contains 97% ^{248}Cm, 3% ^{246}Cm, and <0.01% ^{244}Cm) from 100 mg of the parent ^{252}Cf.

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

(4) Seven 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 36.0% ^{244}Cm, 0.3% ^{245}Cm, 54.2% ^{246}Cm, 1.4% ^{247}Cm, and 8.1% ^{248}Cm.

Table 2.1. Amounts of materials obtained in the major campaign in the Transuranium Processing Plant during the period July 1, 1977 – December 31, 1977

	Campaign No. 53
Completion date	October 1977
Material processed	7 Cf-I Cm-HFIR targets 6 TRU Cm-HFIR targets plus rework material
Amounts obtained:	
^{243}Am, g[a]	0.4
^{244}Cm, g[a]	22(68)[b]
^{249}Bk, mg	34
^{252}Cf, mg	318
^{253}Es, mg	1.957[c]
^{257}Fm, pg	0.8[d]

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

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

[c]Before final purification.

[d]Estimated.

Table 2.2. Distribution of heavy elements from the Transuranium Processing Plant during the period July 1, 1977 – December 31, 1977

Major nuclide	Date shipped	TRU file No.	Shipped to: Individual	Site
Curium-246 (46%), g				
1.01	8-24-77	837	R. W. Hoff	LLL
Californium-252, mg				
37.054	7-18-77	901	A. R. Boulougne	SRL
0.0078	8-02-77	924	Isotopes Sales for	EG&GI[a]
0.428(NZD-35)	8-10-77	926	N. Clark	UCR[b]
43.250	8-22-77	930	A. R. Boulougne	SRL
9.791(NSD-67)	9-06-77	694A	H. G. Rieck	PNL
16.532(NSD-70)	9-06-77	694A	H. G. Rieck	PNL
12.372(NSD-72)	9-06-77	694A	H. G. Rieck	PNL
4.845(NSD-98)	9-06-77	918	J. L. Fuller	HEDL
12.011(NSD-68)	9-30-77	694B	H. G. Rieck	PNL
11.966(NSD-69)	9-30-77	694B	H. G. Rieck	PNL
15.628(NSD-71)	9-30-77	694B	H. G. Rieck	PNL
0.715(NSD-99)	9-30-77	927	G. P. Gottschalk	HEDL
1.313(NSD-94)	10-28-77	912	F. M. Clikeman	PU[c]
1.307(NSD-95)	10-28-77	912	F. M. Clikeman	PU[c]
1.015(NSD-96)	10-28-77	912	F. M. Clikeman	PU[c]
1.190(NSD-97)	10-28-77	912	F. M. Clikeman	PU[c]
16.539(NSD-101)	11-11-77	932	J. E. Powell	S-NM[d]
5.469(NSD-88)	11-29-77	722	R. L. Ullrich	ORNL-B[e]
0.021	12-15-77	890	IRML[f]	ORNL
191.4538				
Einsteinium-253, μg				
147	10-10-77	935A	R. G. Haire	ORNL
192	11-07-77	935B	R. G. Haire	ORNL
339				

Table 2.2. (continued)

Major nuclide	Date shipped	TRU file No.	Shipped to: Individual	Site
Einsteinium-253 (milked), μg				
164	11-01-77	937	R. G. Haire	ORNL
17	11-03-77	938	D. C. Hoffman	LASL
181				
Fermium-257, pg				
0.8	10-27-77	936	W. T. Carnall	ANL

[a]EG&G - Idaho.

[b]University of Costa Rica.

[c]Purdue University.

[d]Sandia-New Mexico.

[e]ORNL Biology Division.

[f]Isotopes Research Materials Laboratory, ORNL.

2.2 Irradiation and Processing Proposals

The level of transuranium element production is expected to continue at a rate of two processing campaigns per year. A long-term projection of the capability of the TRU-HFIR complex to produce the "yardstick" isotope ^{252}Cf was described in a previous report in this series.[1] Table 2.3 outlines the estimated production of transcurium elements from a series of likely processing campaigns that are scheduled through June 1979. Projections for the remainder of 1979 and for 1980 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 97 mg of ^{249}Bk, 985 mg of ^{252}Cf, 4.2 mg of ^{253}Es (in a mixture of isotopes), 665 μg of high-purity ^{253}Es, and 1.8 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 2.3 of ref. 2.

Curium-248, a valuable research material, is formed by alpha decay of ^{252}Cf. On December 31, 1977, TRU had the inventory of purified californium shown in Table 2.4. At appropriate times, a group of packages and/or unneeded pellets or neutron sources 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 the decay of ^{250}Cf, which is present in the californium. We expect to make available 150 mg of the high-purity ^{248}Cm in 1978 and 100 mg in early 1979.

Table 2.3. Estimated future production of transcurium elements

Period	Processing campaign	Products of campaigns				^{252}Cf production[b]		
		^{249}Bk (mg)	^{252}Cf (mg)	^{253}Es[a] (μg)	^{257}Fm (pg)	During the period (mg)	Cumul. (mg)	Date products available
Through December 1977							2792[b]	
January-June 1978	13 Cf-I Cm-HFIR targets	30	290	1215(195)	0.5	290	3082	March 1978
July-December 1978	{ 10 Cf-I Cm-HFIR targets 3 TRU Cm-HFIR targets }	32	330	1410(225)	0.6	330	3412	November 1978
January-June 1979	{ 7 Cf-I Cm-HFIR targets 3 TRU Cm-HFIR targets }	35	365	1550(245)	0.7	365	3777	July 1979
July-December 1979						300	4077	
1980						600	4677	

[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.

Table 2.4. Inventory of purified californium-252

Container		Content on December 31, 1977	
Type	Number	^{252}Cf (mg)	^{248}Cm (mg)
Stored packages	24	781	189
^{252}Cf Pellets	10	37	13
Neutron sources	80	190	205
		1008	407

3. PROCESSES AND EQUIPMENT

Cooling periods for irradiated HFIR targets processed at TRU are kept short to enhance the yields of ^{253}Es (half-life = 20.5 days). Because of this short cooling time, the group of targets processed during a TRU campaign typically contains several hundred curies of ^{131}I when the targets are processed. Several methods for removing radioiodine from the off-gas have been tested and used at TRU. For the past 6 years, a Hopcalite--charcoal system has been used in the vessel off-gas system (~450 cfm). (Hopcalite is an MnO_2-CuO mixture used to catalyze the oxidation of organic materials to compounds that are either not sorbed on charcoal or are less strongly sorbed than iodine.) Although this system has worked well and releases of ^{131}I have been low, about 5 to 25 Ci of ^{131}I was sorbed in the system during each campaign; this constituted a potential for accidental release. A scrubber system was installed in the dissolver off-gas system (~0.25 cfm) to remove the bulk of the ^{131}I and reduce the amount sorbed in the Hopcalite--charcoal system.

During TRU Campaign 53, the dissolver off-gas was scrubbed with hyperazeotropic nitric acid (the Iodox process). Equipment performance was satisfactory, and the amount of ^{131}I sorbed in the Hopcalite--charcoal system was significantly less than in previous campaigns. More than 99% of the ^{131}I in the nitric acid dissolver solution was volatilized and then sorbed into either 21 or 23 M HNO_3 in a six-stage bubble-cap column. Iodine

decontamination factors achieved in the column ranged from 1×10^4 to 8×10^4, or about 5 to 7 per stage. These were the first tests made of the Iodox process at high-activity levels, and the results were consistent with the results of tracer-level tests.

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 1977

Three ^{252}Cf neutron sources, NSD-88, -99, and -101, were fabricated during this report period.

4.2 Used Sources Returned to TRU

A number of neutron sources are returned to TRU when the projects for which they were requested are completed or when 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. Six sources were returned during this report period.

Table 1.1. Data for neutron sources prepared at TRI

Source	Date of calibration	^{252}Cf Content at calibration (mg)	Content as of 12/31/77 ^{252}Cf (mg)	^{244}Cm (mg)	On loan to: Individual	Site
NS-1[a]	5-28-68	316	27	b	K. L. Swinth	PNL
NS-2	8-23-68	275	24	b	G. L. Ragan	ORNL
NS-3	5-15-69	490	49	b	G. E. Gleason	ORAU
NS-4	7-09-69	883	90	751	C. F. Masters	LASL
NS-5[c]	8-14-69	981	109	831	d	
NS-6	11-21-69	747	89	627	R. W. Hoff	LLL
NS-7	1-21-70	789	99	658	F. R. Chattin	ORNL-TRU
NS-8	12-17-69	1839	224	1540	H. Berger	ANL
NSD-9	4-17-70	1720	228	1422	S. D. Bogman	PNL
NSS-10	3-11-70	113	15	b	J. P. Balagna	LASL
NS-11	3-10-70	8	1	b	R. R. Fullwood	LASL
NSS-12	6-30-70	1868	262	1532	R. W. Hoff	LLL
NSD-13	5-19-71	3063	706	2664	H. O. Menlove	LASL
NSS-14	6-29-70	4615	646	3785	D. C. Stewart	ANL
NS-15[c]	6-25-71	830	116	681	d	
NSS-17	8-31-71	4886	929	3775	L. W. Dahlke	Sandia-Livermore
NS-18[c]	6-24-70	924	129	758	d	
NSS-19	6-26-70	493	69	404	E. Bigelow	ORNL-TRU
NSD-20	7-01-70	630	88	517	J. E. Powell	Sandia-NM
NSS-21	10-21-70	18	3	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	9	b	F. J. Muckenthaler	ORNL
NSD-26	2-11-71	14	2	b	H. O. Menlove	LASL
NSD-27	1-29-71	2528	412	2017	L. C. Nelson, Jr.	New Brunswick
NSD-28	2-12-71	11	2	b	E. E. Hicks	Rocky Flats
NSD-29	9-10-71	11393	2183	8783	S. G. Snow	Y-12
NSD-30	3-31-71	879	150	695	F. J. Muckenthaler	ORNL
NZD-31	11-23-71	1733	350	1319	J. L. White	HEDL
NZD-34	11-23-71	1924	389	1464	W. G. Spear	HEDL
NZD-35	11-23-71	1896	383	1443	N. Clark	HEDL
NS-36[c]	3-23-71	2070	351	1639	Y. D. Harker	EG&G Idaho
NSD-37	9-04-71	9838	1877	7592	R. W. Perkins	PNL
NSD-38	6-16-71	102	18	b	H. O. Menlove	LASL
NS-39	11-07-71	942	188	719	V. Spiegel	NBS
NSD-40	4-27-72	1154	261	852	J. P. Balagna	LASL
NSD-41	11-08-71	5117	1023	3904	C. J. Emert	BAPL

Table 3.1 (continued)

Source	Date of calibration	^{252}Cf content at calibration (μg)	Content as of 12/31/77 ^{252}Cf (μg)	Content as of 12/31/77 ^{248}Cm (μg)	On loan to: Individual	Site
NSD-42	11-02-71	4434	862	3387	C. J. Emert	BAPL
NSD-43	4-20-72	4639	1086	3577	C. J. Emert	BAPL
NSD-44	5-15-72	10539	2412	7750	d	
NSD-45	8-18-71	1776	335	1374	R. L. Smith	PNL
NSD-46	4-23-72	629	142	465	H. O. Menlove	LASL
NSD-47	7-14-71	209	37	159	P. L. Johnson	Mound
NSD-48	7-14-71	194	36	151	A. C. England	ORNL
NSD-49	7-14-71	199	37	155	L. J. Esch	BAPL
NS-50	8-23-71	138	26	107	S. G. Carpenter	ANL-NRTS
NSD-51	11-02-71	365	73	279	H. Toffer	[illegible][e]
NSD-52	9-02-71	280	53	216	E. D. Clayton	PNL
NSD-53	10-25-71	1051	208	804	L. J. Esch	BAPL
NS-54	1-19-73	3187	872	2208	V. Spiegel	NBS
NSD-55	4-19-72	4	1	b	L. J. Esch	BAPL
NSD-56	4-19-72	124	28	92	M. M. Bretscher	ANL
NSD-57	4-14-72	973	218	720	J. P. Balagna	LASL
NSD-58	5-15-72	10849	2483	7978	d	
NS-59[c]	7-13-72	55	13	b	G. E. Hanson	LASL
NSD-60	4-11-72	20	4	b	E. F. Haywood	ORNL-DOSAR
NSD-61	1-19-73	5225	1430	3619	L. J. Esch	BAPL
NSS-62	3-27-73	3755	1078	2553	J. E. Bigelow	ORNL-TRU
NSD-63	4-21-72	847	191	626	H. O. Menlove	LASL
NSD-64	7-19-73	193	60	127	H. O. Menlove	LASL
NS-65	7-09-73	114	35	75	L. Green	BAPL
NSD-66	8-02-73	3449	1085	2254	J. E. Powell	Sandia-NM
NSD-67	6-07-76	13501	8958	4333	H. G. Rieck	PNL
NSD-68	6-07-76	16838	11172	5404	H. G. Rieck	PNL
NSD-69	6-07-76	16775	11130	5383	H. G. Rieck	PNL
NSD-70	6-10-76	22748	15125	7269	H. G. Rieck	PNL
NSD-71	7-15-76	21819	14536	6469	H. G. Rieck	PNL
NSD-72	7-15-76	16602	11320	5038	H. G. Rieck	PNL
NSD-73	9-11-73	13545	4387	8734	G. I. Gleason	ORAU
NSD-74	9-11-73	4416	1430	2847	G. I. Gleason	ORAU
NS-75	10-01-73	1919	630	1229	R. J. Kloepping	LLL
NSD-76	3-09-74	434	160	261	P. L. Johnson	Mound
NSD-77	3-09-74	433	159	261	P. L. Johnson	Mound
NSD-78	3-09-74	429	158	258	P. L. Johnson	Mound

Table 3.1 (continued)

Source	Date of calibration	Curies at calibration (mCi)	Content as of 12/31/77 ^{252}Cf (mg)	^{250}Cm (mg)	On loan to: Individual	Site
NS-79	10-02-74	1650	705	901	V. Spiegel	NBS
NSD-80	6-05-74	5960	2337	3461	C. J. Emert	BAPL
NSD-81	6-05-74	6364	2432	3692	C. J. Emert	BAPL
NS-82	5-19-75	14264	7180	6755	G. Tessler	BAPL
NS-83	9-24-75	11783	6502	5036	G. Tessler	BAPL
NS-84	9-30-75	12674	7024	5388	G. Tessler	BAPL
NS-85	10-22-75	12181	6858	5076	G. Tessler	BAPL
NS-86	11-17-75	2620	1503	1065	V. Spiegel	NBS
NSD-87	10-15-75	22387	12541	9590	G. I. Gleason	ORNL
NSD-88	8-26-75	9528	5157	4169	R. L. Ulrich	ORNL
NSD-89	4-25-75	12721	6[illegible]	[illegible]137	d	
NCS-90	1-16-75	0.87	<1	b	J. R. Smith	ANC
NSD-91	9-26-75	15	8	b	L. J. Esch	KAPL
NS-92	6-24-76	2960	1968	927	V. Spiegel	NBS
NSD-93	1-29-74	500	179	306	J. P. Pizzagna	LASL
NSD-94	5-09-77	1544	1248	282	F. M. Clikeman	Purdue
NSD-95	5-09-77	1537	1242	281	F. M. Clikeman	Purdue
NSD-96	5-09-77	1194	965	218	F. M. Clikeman	Purdue
NSD-97	5-09-77	1399	1131	256	F. M. Clikeman	Purdue
NSD-98	9-30-75	8000	4433	3401	J. L. Fuller	HEDL
NSD-99	9-21-77	715	665	46	C. A. Strand	HEDL
NSD-101	5-24-76	24136	15854	7896	J. E. Powell	Sandia-NM
SR-Cf-167[g]	5-26-71	3975	705	3118	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 encapsulated in Type-305 stainless steel.

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

[e] University of Costa Rica.

[f] United Nuclear Industries.

[g] This source was fabricated at TRL 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.

5.1 Purification of Americium-243

Many requests have been received through the years for highly purified ^{243}Am, to be used for neutron cross-section studies, for capture gamma studies, and as an analytical standard. A quantity of excellent feedstock that contained 120 ppm of ^{241}Am and 0.4% ^{244}Cm (by weight), was available from earlier programs at the Savannah River Laboratory; we were asked to reduce the curium concentration in some of this material to less than 5 ppm. The corresponding ^{252}Cf content that will yield a comparable neutron emission rate is 25 parts per trillion of americium. Hence it is necessary to have an ultraclean facility in which to do this work. A suitable facility was not available until recently when a new liner was installed in Cave A of Laboratory 111 at TRU.

We have prepared about 10 g of ^{243}Am averaging less than 1 ppm of ^{244}Cm using ion exchange techniques. This is sufficient to meet current requests. We anticipate preparing a similar amount for future needs before allowing Cave A or the equipment to be used for any other purpose.

5.2 Purification of Zinc Bromide from Cave-A Shielding Window

During replacement of the Cave-A liner, the zinc bromide solution in the shielding window was drained and the window was disassembled to replace leaking gaskets. The zinc bromide solution was filtered through a medium of glass fiber covered with a diatomaceous-earth filter aid to remove some of the yellow-colored matter, and the filtered solution was put back into

the repaired window. Several weeks after the filtration, the solution again became cloudy and yellow. We were unable to locate a supply of fresh optical-grade zinc bromide solution nor could we find anyone (at several other DOE sites and shielding window firms) who could offer a solution to our problem. The cloudiness in the Cave A window appeared to stabilize at a condition in which the window was useable. Thus we have resumed operations in Cave A but are continuing to search for a way to improve the situation, either by locating a supply of new zinc bromide at some reasonable cost or by developing a method for clarifying our present supply of zinc bromide.

Analysis of the solution in the Cave A window indicated that the cloudiness was probably caused by a high concentration of iron. Therefore, a procedure was developed and demonstrated in the laboratory to remove iron from the zinc bromide solution and then to reconstitute the solution characteristics to those necessary for use in the shielding window. The treatment procedure included (1) dilution by a factor of 2 to reduce the solution viscosity prior to filtration; (2) oxidation with bromine to precipitate the iron; (3) filtration through a 1.6-μm glass-fiber filter to remove the precipitate; (4) reconcentration of the filtrate by means of evaporation; (5) addition of hydroxylamine hydrochloride to prevent further precipitation of iron; and (6) adjustment of the solution alkalinity to 0.3 N by addition of NH_4OH. The feasibility of using the procedure in engineering-scale equipment is being considered.

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[5-13] 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 TKU, 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.

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 ± 0.01) x 10^6 y		>10^{18} y	2.00[d]	60Br12, 61Dr04
^{238}Np	2.10 ± 0.01 d					50Fr53
^{239}Np	2.359 ± 0.010 d					59Ce03
^{240}Np	63 ± 2 m					60Le03
^{240m}Np	7.3 ± 0.3 m					48Hy01
^{241}Np	16 m					60Le03
^{241m}Np	5.4 h					60Le03
^{238}Pu	87.404 ± 0.041 y			(5 ± 0.6) x 10^{10} y	2.33 ± 0.08	61Dr04, 68Je15, 56Hi01
^{239}Pu		(2.4413 ± 0.003) x 10^4 y		5.5 x 10^{15} y	2.24[d]	52Be67, 59Ma26
^{240}Pu		6580 ± 40 y		(1.340 ± 0.015) x 10^{11} y	2.177 ± 0.009	51In03, 62Wa13, 68Be54
^{241}Pu	14.98 ± 0.33 y	(5.72 ± 0.1) x 10^3 y				60Ca19, 60Br15
^{242}Pu		(3.869 ± 0.016) x 10^5 y		(7.41 ± 0.17) x 10^{10} y	2.166 ± 0.009	63Ma50, 68Be06, 68Be54
^{243}Pu	4.955 ± 0.003 h					68Di09
^{244}Pu		(8.28 ± 0.10) x 10^7 y		(6.5 ± 0.32) x 10^{10} y	2.64[d]	66Fi07, 68Be06
^{245}Pu	10.6 ± 0.4 h					56Bu92
^{246}Pu	10.85 ± 0.02 d					56Mo23
^{241}Am		432.7 ± 0.7 y		(3.3 ± 0.8) x 10^{14} y	3.48[d]	61Dr04, 67De01
^{242}Am	16.01 ± 0.02 h		EC/β = 0.19			53Ke38
^{242m}Am	144 ± 7 y	(2.92 ± 0.15) x 10^4 y				59Ba21[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					56Bu92
^{246}Am	25.0 ± 0.2 m					55En10
^{246m}Am	40 ± 7 m					67Dr02
^{247}Am	24 ± 3 m					67Dr02
^{242}Cm	162.7 ± 0.1 d			7.2 x 10^6 y	2.65 ± 0.09	51Ma87, 57Pe52, 56Hi01
^{243}Cm		32 y				57As70
^{244}Cm	18.099 ± 0.015 y		α/SF = (7.43 ± 0.01) x 10^3		2.84 ± 0.09	65Ma02, 68Be26, 56Hi01
^{245}Cm		8265 ± 180 y				69Ma01
^{246}Cm		4655 ± 40 y	α/SF = 3822 ± 10		3.08[d]	69Ma01, 71Ma19
^{247}Cm		(1.56 ± 0.05) x 10^7 y				71Fi01
^{248}Cm		(3.703 ± 0.032) x 10^5 y		(4.15 ± 0.034) x 10^6 y	3.32[d]	71Ma19
^{249}Cm	64 ± 3 m					58Ba06
^{250}Cm				(1.74 ± 0.24) x 10^4 y	3.56[d]	66Ri01

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) x 10^{-5}	(1.17 ± 0.09) x 10^{9} y	3.72 ± 0.16	57Ha01, 68Mi08, 64Fy02
^{250}Bk	3.222 ± 0.005 h					59Va02
^{251}Bk	57 ± 1.7 m					66RG04
^{249}Cf		352 ± 6 y	α/SF = (1.92 ± 0.040) x 10^{8}		3.44[d]	68Me01, 68Mi08
^{250}Cf		13.08 ± 0.09 y	α/SF = 1260 ± 40		3.56[d]	63Ph01, 68Me01
^{251}Cf		900 ± 50 y				68Me01
^{252}Cf	2.646 ± 0.004 y		α/SF = 31.3 ± 0.2		3.786 ± 0.031	68Me02, 68Wh04
^{253}Cf	17.812 ± 0.082 d		α/β = (5.1 ± 0.4) x 10^{-3}			69Dr02, 66RG01
^{254}Cf	60.5 ± 0.2 d		α/SF = (3.10 ± 0.16) x 10^{-3}		3.90 ± 0.14	63Ph01, 64Fy02, 68Be21
^{255}Cf	1.5 ± 0.5 h					70Le19
^{253}Es	20.467 ± 0.024 d		α/SF = (1.15 ± 0.03) x 10^{7}		3.82[d]	68Me02, 69Dr02
^{254}Es	276 d			~2.1 x 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 = 0.0366 ± 0.0043 β/SF = (2.22 ± 0.10) x 10^{4}		4.16[d]	66RG01, 67Fi03
^{256}Es	25 ± 3 m					68Le11
^{254}Fm	3.24 ± 0.01 h		α/SF = 1695 ± 8		4.05 ± 0.18	56Je09, 67Fi03, 56Ch83
^{255}Fm	20.07 ± 0.07 h		SF/α = (2.4 ± 1.1) x 10^{-7}		4.16[d]	63Ph01, 64As01
^{256}Fm	2.62 ± 0.03 h		~100% SF		4.27[d]	68Ho13
^{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:

$$\sigma^{c}_{eff} - \sigma^{c}_{2200} : \frac{\phi_{res}}{\phi_{2200}} \frac{RI}{\sqrt{1 + C\sigma}} ,$$

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	Energies of Prin. Emissions (MeV) β	Specific Activity (Ci/g)	Specific Activity (N/g)	Specific Activity (α dpm/mg[c])	Specific Activity (β dpm/mg)	(Neutrons min^{-1} mg^{-1})	Hazard[b] MPC a(40) ($\mu Ci/cm^3$)	Hazard[b] Body Burden (μCi)	Hazard[b] Body Burden (μg)
^{237}Np	2.14×10^6 y	4.78		7.07×10^{-4}	2.07×10^{-5}	8.01×10^5		<7 x 10^{-6}	4×10^{-12}	0.06	84.9
^{238}Np	2.10 d		0.25 1.24	2.61×10^5	1.27×10^{-3}		5.80×10^{14}				
^{239}Np	2.359 d		0.332 0.427	2.32×10^5	9.86×10^{-3}		5.14×10^{14}		7×10^{-7}	30	$1.[illegible] \times 10^{-4}$
^{240}Np	63 m		0.89	1.24×10^7	1.05×10^{-5}		2.76×10^{16}				
^{240m}Np	7.3 m		2.18 1.6	1.07×10^8	5.35×10^{-5}		2.38×10^{17}				
^{241}Np	16 m			4.86×10^7			1.08×10^{17}				
^{241m}Np	5.4 h			3.82×10^6			8.49×10^{15}				
^{238}Pu	87.404 y	5.49		17.2	0.570	1.94×10^{10}		155	2×10^{-12}	0.04	2.33×10^{-3}
^{239}Pu	2.4413×10^4 y	5.15		6.13×10^{-2}	1.913×10^{-3}	6.94×10^7		1.35×10^{-3}	2×10^{-12}	0.04	0.653
^{240}Pu	6580 y	5.16		0.227	7.087×10^{-3}	2.57×10^8		53.7	2×10^{-12}	0.04	0.176
^{241}Pu	14.98 y	4.9	0.02	99.1	4.06×10^{-3}	2.94×10^6	2.20×10^{11}		9×10^{-11}	0.9	9.08×10^{-3}
^{242}Pu	3.869×10^5 y	4.90		3.82×10^{-5}	1.13×10^{-4}	4.32×10^6		95.3	2×10^{-12}	0.05	13.1
^{243}Pu	4.955 h		0.49 0.58	2.60×10^6	3.34×10^{-3}		5.78×10^{15}		2×10^{-6}	7.0	2.69×10^{-6}
^{244}Pu	8.28×10^7 y	4.587		1.77×10^{-5}	4.93×10^{-7}	2.00×10^4		141	2×10^{-12}	0.04	2.26×10^3
^{245}Pu	10.6 h			1.21×10^6			2.68×10^{15}		2×10^{-7}	3.0	2.48×10^{-6}
^{246}Pu	10.85 d		0.15	4.91×10^6	66.9		1.09×10^{14}				
^{241}Am	433.7 y	5.48		3.43	0.1145	3.88×10^9		3.55×10^{-2}	6×10^{-12}	0.1	0.0293
^{242}Am	16.01 h		0.63 0.67	8.11×10^5	2.08×10^{-3}		1.80×10^{15}[d]		4×10^{-8}	0.06	7.39×10^{-8}
^{242m}Am	144 y	5.20,	1.7,	10.3	3.08×10^{-2}	5.53×10^7	2.28×10^{10}[e]		6×10^{-12}	0.07	6.80×10^{-3}
^{243}Am	7370 y	5.27		0.200	6.42×10^{-3}	2.26×10^8			6×10^{-12}	0.05	0.25
^{244}Am	10.1 h		0.587	1.27×10^6	8.74×10^{-3}		2.82×10^{15}				
^{244m}Am	26 m		1.5	2.96×10^7	8.98×10^{-4}		6.58×10^{16}[f]		4×10^{-6}	0.2	6.76×10^{-9}
^{245}Am	2.07 h		0.9[illegible]	6.17×10^6	1.20×10^{-4}		1.37×10^{16}				
^{246}Am	25.0 m		1.31	3.36×10^7	2.48×10^{-5}		6.79×10^{16}				
^{246m}Am	40 m			1.91×10^7			4.24×10^{16}				
^{247}Am	24 m			3.17×10^7			7.04×10^{16}				
^{242}Cm	162.7 d	6.11		3.32×10^5	122	3.76×10^{12}		1.21×10^6	1×10^{-10}	0.05	1.61×10^{-5}
^{243}Cm	32 [illegible]	5.79		45.9	1.677	5.20×10^{10}	3.27×10^8		6×10^{-12}	0.09	1.06×10^{-3}
^{244}Cm	18.099 y	5.81		80.94	2.832	9.16×10^{10}		6.87×10^7	9×10^{-12}	0.1	1.24×10^{-5}
^{245}Cm	8265 y	5.36		0.177	5.89×10^{-3}	2.00×10^8			5×10^{-12}	0.04	0.226
^{246}Cm	4655 y	5.39		0.312	1.01×10^{-2}	3.52×10^8		5.58×10^5	5×10^{-12}	0.05	0.160
^{247}Cm	1.56×10^7 y	4.87		9.28×10^{-5}	2.94×10^{-6}	1.05×10^3			5×10^{-12}	0.04	431
^{248}Cm	3.397×10^5 y	5.05		4.24×10^{-3}	5.34×10^{-4}	4.39×10^6		2.58×10^6	6×10^{-13}	0.005	1.18
^{249}Cm	64 m		0.9	1.18×10^7	2.06×10^{-4}		2.62×10^{16}		1×10^{-5}	1.0	8.47×10^{-8}
^{250}Cm	1.74×10^4 y			8.20×10^{-2}	>0.1			6.49×10^8			

Table A-3. (continued)

Nuclide	Half-Life	Energies of Prin. Emissions (MeV) α	β	Specific Activity (Ci/g)	(W/g)	(α cpm/mg[c])	(β dpm/mg)	(Neutrons min⁻¹ mg⁻¹)	Hazard[b] MPC_a(40) (μCi/cm³)	Body Burden (μCi)	Body Burden (μg)
^{249}Bk	314 d	5.4	0.125	1.67×10^{3}	0.358	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	3.89×10^{6}	2.75×10^{4}		8.62×10^{15}		1×10^{-7}	0.05	1.29×10^{-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	8.80×10^{-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	19.9	5.88×10^{11}		1.40×10^{11}	6×10^{-12}	0.01	1.87×10^{-5}
^{253}Cf	17.812 d	5.98	0.27	2.90×10^{4}	13.89	1.02×10^{11}	6.41×10^{13}		8×10^{-10}	0.04	1.40×10^{-6}
^{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^{11}		1.91×10^{7}	6×10^{-10}	0.04	1.59×10^{-6}
^{254}Es	276 d	6.42		1.86×10^{3}	71.9	2.11×10^{12}		5.04×10^{5}	2×10^{-11}	0.02	1.08×10^{-5}
^{254m}Es	39.3 h		0.48	3.14×10^{5}	1.18×10^{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}	4.82×10^{9}	4×10^{-10}	0.04	3.10×10^{-6}
^{256}Es	25 m			2.94×10^{7}			6.52×10^{16}				
^{254}Fm	3.24 h	7.20		3.81×10^{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}		1.56×10^{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, 51%.

[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 α emission, but 0.035% 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	87.404 y	560	0	150	16.5	0	25
^{239}Pu	2.4413×10^{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	541
^{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 m	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	10.0	4.0	650	1.2	4.0	12.5
^{245}Cm	8265 y	343	2.4	120	1727	2.4	1160
^{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	3.56	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
^{249}Cf	352 y	450	1.46	750	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	1340	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	94 d	10	0	0	5500	0	0
^{258}Fm	380 us	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 $f_c = f_g + f_m = 1$.