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Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending June 30, 1977

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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
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SUMMARY

This is the nineteenth 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 January 1, 1977, through June 30, 1977, we obtained transuranium elements from 12 irradiated HFIR targets; products recovered are listed in Table 2.1 on p. 2. One batch of high-purity ^{248}Cm (~50 mg) was separated from ^{252}Cf. Twenty-three shipments were made from TRU during the period; recipients and the amounts of nuclides are listed in Table 2.2 on pp. 3-4. Five HFIR targets, each containing 8 to 9 g of curium, were fabricated.

During the next 18 months, we expect to obtain totals of 92 mg of ^{249}Bk, 910 mg of ^{252}Cf, 3.8 mg of ^{253}Es (in a mixture of isotopes), 615 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.

No process or equipment changes were made during this report period.

Five neutron sources were fabricated during this report period, bringing the total fabricated to date to 97. Two sources that had previously been returned to TRU were reassigned.

Special projects included the following: (1) the enrichment of the ^{244}Pu concentration in 100 mg of plutonium by irradiation to burn out the lighter isotopes, (2) the separation of 245 pg of ^{254}Cf from 39-hr ^{254m}Es that was produced by irradiation of 5 μg of ^{253}Es, and (3) an experimental separation of cerium from the other rare-earth elements in a TRU process waste solution.

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 nineteenth 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. 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 are described; these projects were designed to (1) enrich the ^{244}Pu concentration in 100 mg of plutonium, (2) produce enriched ^{254}Cf by irradiation of ^{253}Es, and (3) study methods for separating cerium from process solutions. 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.

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 January 1, 1977, and June 30, 1977, the following operations were accomplished:

(1) One chemical processing campaign (No. 52) was made to obtain transuranium elements from 12 HFIR-irradiated targets plus rework material. Products from this campaign are listed in Table 2.1.

(2) We made the initial separation (Batch No. 22) of about 50 mg of high-purity ^{248}Cm (curium that typically contains 97% ^{248}Cm, 3% ^{246}Cm, and <0.01% ^{244}Cm) from 90 mg of the parent ^{252}Cf.

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

(4) Five 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 40.4% ^{244}Cm, 0.4% ^{245}Cm, 50.4% ^{246}Cm, 1.3% ^{247}Cm, and 7.5% ^{248}Cm.

Table 2.1. Amounts of materials obtained in the major campaign in the Transuranium Processing Plant during the period January 1, 1977 — June 30, 1977

	Campaign number 52
Completion date	March
Material processed	7 Cf-I Cm-HFIR targets 5 TRU Cm-HFIR targets plus rework material
Amounts obtained:	
^{243}Am, g[a]	0.1
^{244}Cm, g[a]	21 (59)[b]
^{249}Bk, mg	29.5
^{252}Cf, mg	288
^{253}Es, mg	1.475[c]
^{257}Fm, pg	0.7[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 January 1, 1977 — June 30, 1977

Major nuclide	Date	TRU file number	Shipped to: Individual	Site
Curium-243 (55%), mg				
0.93	1-04-77	900	Isotopes Sales for	EPA[a]
Berkelium-249, mg				
5.8	3-24-77	913	W. T. Carnall	ANL
5.8	3-24-77	914	N. M. Edelstein	LBL
5.8	3-24-77	915	R. W. Hoff	LLL
0.0001	6-10-77	923	Isotopes Sales for	FSU[b]
17.4001				
Californium-252, mg				
0.0005	2-01-77	904	Isotopes Sales for	IPL[c]
33.372	2-08-77	888	A. R. Boulogne	SRL
0.045	2-11-77	894	W. T. Carnall	ANL
0.030 (NS-2)	2-16-77	905	J. E. Rushton	ORNL
41.459	2-24-77	902	A. R. Boulogne	SRL
0.0005	3-09-77	911	Isotope Sales for	IPL[c]
0.0005	5-06-77	922	Isotopes Sales for	IPL[c]
0.0164	5-27-77	889	IRML[d]	ORNL
74.9239				
Californium-254, pg				
245	2-18-77	906	E. K. Hulet	LLL
Einsteinium-253, μg				
486.5	2-18-77	907	R. G. Haire	ORNL
409	3-01-77	908	W. T. Carnall	ANL
2.5	3-08-77	884	E. K. Hulet	LLL
15.6	5-12-77	909A	W. T. Carnall	ANL
15.6	5-13-77	909B	R. G. Haire	ORNL
929.2				

Table 2.2. (continued)

Major nuclide	Date	TRU file number	Shipped to: Individual	Site
Einsteinium-253 (milked), μg				
20.4	3-25-77	919	R. W. Hoff	LLL
16.3	3-25-77	920	D. C. Hoffman	LASL
167.4	3-30-77	921	R. G. Haire	ORNL
204.1				
Fermium-257, pg				
0.7	3-09-77	910	W. T. Carnall	ANL

[a] Environmental Protection Agency, Nevada.

[b] Florida State University.

[c] Isotope Products Laboratories, Burbank, California.

[d] Isotope 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 December 1978. Projections for 1979 and 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 92 mg of ^{249}Bk, 910 mg of ^{252}Cf, 3.8 mg of ^{253}Es (in a mixture of isotopes), 615 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 2.3 of ref. 2.

Curium-248, a valuable research material, is formed by alpha decay of ^{252}Cf. On June 30, 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 early 1978 and 100 mg in late 1978.

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 June 1977							2474[b]	
July-December 1977	7 Cf-I Cm-HFIR targets 6 TRU Cm-HFIR targets	32	320	1370(230)	0.6	320	2794	October 1977
January-June 1978	13 Cf-I Cm-HFIR targets	30	290	1215(195)	0.5	290	3084	February 1978
July-December 1978	11 Cf-I Cm-HFIR targets 2 TRU Cm-HFIR targets	30	300	1260(200)	0.5	300	3384	November 1978
1979						600	3984	
1980						500	4484	

[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

Type container	Content on June 30, 1977	
	^{252}Cf, mg	^{248}Cm, mg
Stored packages	712	186
^{252}Cf pellets	36	17
Neutron sources	193	171
	941	374

3. PROCESSES AND EQUIPMENT

No process or 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 January-June 1977

Five ^{252}Cf neutron sources, NSD-94, -95, -96, -97, and NS-98 were fabricated during this report period. One of these (NS-98) was fabricated in a nonstandard form specified by the user.

Table 4.1. Data for neutron sources prepared at TRU

Source	Date of calibration	^{252}Cf content at calibration (μg)	Content as of 6/30/77		On loan to:	
			^{252}Cf (μg)	^{248}Cm (μg)	Individual	Site
NS-1[a]	8-28-68	316	31	b	K. L. Swinth	PNL
NS-2	8-23-68	275	27	b	G. L. Ragan	ORNL
NS-3	5-13-69	~90	~11	b	G. I. Gleason	ORAU
NS-4	7-09-69	883	109	738	C. F. Masters	LASL
NS-5[c]	8-14-69	946	120	788	F. B. Simpson	ANC
NS-6	11-21-69	747	102	615	R. W. Hoff	LLL
NS-7	1-21-70	789	112	645	F. R. Chattin	ORNL-TRU
NS-8	12-17-69	1839	255	1510	H. Berger	ANL
NSD-9	4-17-70	1720	261	1392	M. D. Mogman	PNL
NSS-10	3-11-70	113	17	b	J. P. Balagna	LASL
NS-11	3-10-70	8	1	b	R. R. Fullwood	LASL
NSS-12	6-30-70	1868	298	1497	R. W. Hoff	LLL
NSD-13	3-[illegible]-71	4649	896	3579	H. O. Menlove	LASL
NSS-14	6-29-70	4615	737	3698	D. C. Stewart	ANL
NS-15[c]	6-25-70	931	148	746	F. B. Simpson	ANC
NSS-17	8-31-71	4886	1060	3668	L. W. Dahlke	Sandia-Livermore
NS-18[c]	6-24-70	962	153	771	F. B. Simpson	ANC
NSS-19	5-26-70	493	79	395	J. E. Bigelow	ORNL-TRU
NSD-20	7-01-70	630	101	505	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	10	b	F. J. Muckenthaler	ORNL
NSD-26	2-11-71	14	3	b	H. O. Menlove	LASL
NSD-27	1-29-71	2528	471	1962	L. C. Nelson, Jr.	New Brunswick Lab
NSD-28	2-12-71	11	2	b	E. E. Hicks	Rocky Flats
NSD-29	9-10-71	11393	2491	8490	S. G. Snow	Y-12
NSD-30	3-31-71	879	171	675	F. J. Muckenthaler	ORNL
NZD-31	11-23-71	1733	399	1273	J. L. White	HEDL
NZD-34	11-23-71	1924	474	1412	W. G. Spear	HEDL
NZD-35	11-23-71	1904	439	1397	d	
NS-36[c]	3-23-71	2070	400	1592	F. B. Simpson	ANC
NSD-37	9-04-71	9838	2141	7340	R. W. Perkins	PNL
NSD-38	6-16-71	102	21	b	H. O. Menlove	LASL
NS-39	11-07-71	942	215	694	V. Spiegel	NBS
NSD-40	4-27-72	1154	298	817	J. P. Balagna	LASL
NSD-41	11-08-71	5117	1167	3767	C. J. Emert	BAPL

Table 4.1. (continued)

Source	Date of calibration	^{252}Cf content at calibration (µg)	Content as of 6/30/77 ^{252}Cf (µg)	Content as of 6/30/77 ^{248}Cm (µg)	On loan to: Individual	On loan to: Site
NSD-42	11-02-71	4434	1007	3268	C. J. Emert	BAPL
NSD-43	4-20-72	4839	1241	3431	C. J. Emert	BAPL
NZD-44	5-15-72	10731	2802	7561	F. B. Simpson	ANC
NSD-45	8-18-71	1776	382	1329	K. L. Swinth	PNL
NSD-46	4-23-72	629	162	446	H. O. Menlove	LASL
NSD-47	7-14-71	200	42	151	P. L. Johnson	Mound
NSD-48	7-14-71	194	41	146	A. C. England	ORNL
NSD-49	7-14-71	199	42	150	L. J. Esch	KAPL
NS-50	8-23-71	138	36	103	S. G. Carpenter	ANL-NRTS
NSD-51	11-02-71	365	83	269	H. Toffer	Un. Nucl. Ind.
NSD-52	9-02-71	280	61	209	E. D. Clayton	PNL
NSD-53	10-25-71	1051	237	776	L. J. Esch	KAPL
NS-54	1-19-73	3187	995	2090	V. Spiegel	NBS
NSD-55	4-19-72	4	a	b	L. J. Esch	KAPL
NSD-56	4-19-72	124	32	88	M. M. Bretscher	ANL
NSD-57	4-14-72	973	249	691	J. P. Balagna	LASL
NZD-58	5-15-72	11003	2874	7753	F. B. Simpson	ANC
NS-59[c]	7-13-72	53	14	b	G. E. Hanson	LASL
NSD-60	4-11-72	20	5	b	F. F. Haywood	ORNL-DOSAR
NSD-61	1-19-73	5225	1631	3427	L. J. Esch	KAPL
NSS-62	3-27-73	3755	1230	2408	J. E. Bigelow	ORNL-TRU
NSD-63	4-21-72	847	217	600	H. O. Menlove	LASL
NSD-64	7-19-73	193	69	119	H. O. Menlove	LASL
NS-65	7-09-73	114	40	70	L. Green	BAPL
NSD-66	8-02-73	3449	1238	2108	J. E. Powell	Sandia-NM
NSD-67	6-07-76	13522	10237	3132	e	
NSD-68	6-07-76	16625	12738	3898	e	
NSD-69	6-07-76	16681	12629	3864	e	
NSD-70	6-10-76	22694	17218	5222	e	
NSD-71	7-15-76	21336	16599	4517	e	
NSD-72	7-15-76	16742	13025	3544	e	
NSD-73	9-11-73	13545	5005	8144	G. I. Gleason	ORAU
NSD-74	9-11-73	4416	1632	2655	G. I. Gleason	ORAU
NS-75	10-01-73	1919	719	1144	R. J. Kloepping	LLL
NSD-76	3-09-74	434	182	240	P. L. Johnson	Mound
NSD-77	3-09-74	433	182	239	P. L. Johnson	Mound
NSD-78	3-09-74	429	180	237	P. L. Johnson	Mound
NS-79	10-02-74	1650	804	807	V. Spiegel	NBS

Table 4.1. (continued)

Source	Date of calibration	^{252}Cf content at calibration (μg)	Content as of 6/30/77 ^{252}Cf (μg)	Content as of 6/30/77 ^{248}Cm (μg)	On loan to: Individual	On loan to: Site
NSD-80	6-05-74	5966	2666	3147	C. J. Emert	BAPL
NSD-81	6-03-74	6365	2844	3357	C. J. Emert	BAPL
NS-82	5-19-75	14264	8193	5789	G. Tessler	BAPL
NS-83	9-24-75	11783	7419	4162	G. Tessler	BAPL
NS-84	9-30-75	12674	8014	4443	G. Tessler	BAPL
NS-85	10-22-75	12181	7825	4154	G. Tessler	BAPL
NS-86	11-17-75	2620	1715	863	V. Spiegel	MBS
NSD-87	10-15-75	22387	14310	7703	G. I. Gleason	ORAU
NSD-89	4-23-75	12687	7153	5277	J. E. Powell	Sandia-NM
NZS-90	1-16-75	0.87	<1	b	J. R. Smith	AMC
NSD-91	9-26-75	15	9	b	L. J. Esch	KAPL
NS-92	6-24-76	2960	2268	659	V. Spiegel	MBS
NSD-93	1-29-74	509	204	282	J. P. Balagna	LASL
NSD-94	3-09-77	1528	1405	113	f	
NSD-95	3-09-77	1549	1428	115	f	
NSD-96	3-09-77	1397	1288	104	f	
NSD-97	3-09-77	1176	1084	87	f	
NS-98	9-30-75	8143	5149	2855	g	
SR-Cf-167[h]	5-26-71	3975	805	3023	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 405 stainless steel.

[d]This source is being held for use at the University of Costa Rica.

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

[f]This source is being held for use at Purdue University.

[g]This source is being held for use at MEDL.

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

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. Two of these sources were reassigned during this report period; currently, there are no sources in the "available" category.

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 Enrichment of Plutonium-244

The purpose of this project was to enrich the ^{244}Pu concentration in ~100 mg of plutonium by irradiating it in the HFIR to burn out the lighter isotopes. The isotopic composition of plutonium in the feed material is shown in Table 5.1. Starting with about 150 mg in the oxide form, the feed material was prepared for irradiation by (1) dissolving the oxide in fluoride-catalyzed nitric acid, (2) removing miscellaneous impurities by means of an anion exchange run, (3) preparing oxysulfate microspheres by the cation resin loading--calcination technique,[5] (4) blending the microspheres with aluminum powder and dispersing the mixture into four pellets, and (5) fabricating a special HFIR target containing the four pellets.

The target was irradiated for two cycles in the HFIR and then returned to TRU where it was chemically processed to recover the enriched plutonium-244. The processing included a caustic dissolution of the sections of the

Table 5.1. Enrichment of plutonium-244

Nuclide	Feed plutonium (at. %)	Irradiated plutonium (at. %)
^{238}Pu	0.001	0.00004[a]
^{239}Pu	0.003	0.0076[b]
^{240}Pu	0.305	0.0016
^{241}Pu	0.074	0.0013
^{242}Pu	1.050	0.572
^{244}Pu	98.57	99.41
^{246}Pu	--	0.0098

[a]Determined by alpha counting.

[b]This is an unexpectedly high number and may be due to sample contamination.

target rod containing the pellets, a HNO_3-HF dissolution of the plutonium oxide microspheres, and an anion exchange purification run. Residual solids from the plutonium dissolution procedure were given a second treatment with HNO_3-HF, and the resulting plutonium solution was also purified by anion exchange. The two plutonium product solutions contained 60 and 10 mg of ^{244}Pu, respectively, and rework solutions contained ~6 mg of ^{244}Pu. The specific activity of the irradiated plutonium was reduced to ~6.2×10^4 alpha counts per min per mg of ^{244}Pu; this activity is about seventeen times lower than that of the feed plutonium. Isotopic analyses of the plutonium before and after irradiation are shown in Table 5.1.

5.2 Production of Californium-254

Californium-254 was produced by the electron-capture decay (0.078% branching) of 39-hr ^{254m}Es. In a manner similar to a previous operation,[6] a HFIR rabbit containing ~5 μg of ^{253}Es was fabricated and irradiated.

The irradiated rabbit was returned to TRU in the Curium-Americium Slug Transfer (CAST) cask and chemically processed in Cave B to isolate the irradiated einsteinium ($^{253-254m}$Es) from other actinide, fission product, and activation product elements. Following a decay period of 5 days, the isolated einsteinium, containing 3.3 μg of ^{253}Es, was transferred to a glove box and processed at a micro level by means of ion exchange runs to separate and purify the californium daughters as a product. This product contained 1.24 μg of ^{250}Cf and 245 pg of ^{254}Cf. The isotopic composition of the product, shown in Table 5.2, indicated a contamination by ^{249}Cf. The presence of ^{249}Cf was probably caused by incomplete chemical separation and/or contamination during handling in the glove box.

Table 5.2. Isotopic composition of californium separated from irradiated ^{253}Es

Nuclide	At. %
^{249}Cf	71.80
^{250}Cf	23.30
^{251}Cf	3.41
^{252}Cf	1.44
^{253}Cf	0.037[a]
^{254}Cf	0.0046[b]
Total ^{254}Cf recovered, pg	245

[a]Mass 253 component is probably some residual ^{253}Es.

[b]Determined by neutron counting.

5.3 Separation of Cerium from Rare-Earth Elements

We have started a long-range study of methods for separating cerium from other materials. Our interest is twofold -- first, to recover cerium as a product, and second, to reduce the cerium content in other products.

During this report period, an experiment was made, using as feed material, the bulk of the raffinate from the LiCl-based anion exchange runs made during Campaign 52. This material was processed in TRU process equipment to study cerium separation methods. Previous tests in glassware had been successful. The composited feed solution contained approximately 65% of the rare-earth fission products from the campaign and 100 moles of LiCl. Most of the LiCl was removed by means of a Tramex batch extraction and the product solution was converted to the nitrate form. Then a Berkex-type batch extraction was made to separate the cerium from the other rare-earth elements. This run included: (1) adjusting the feed solution to 8 M HNO_3--0.25 M $NaBrO_3$, (2) contacting the solution with Berkex extractant (0.7 M HDEHP in n-paraffin) to extract Ce^{+4}, (3) scrubbing with 8 M HNO_3--0.25 M $NaBrO_3$, and (4) reducing and stripping the cerium as Ce^{+3} with 8 M HNO_3--1.0 M H_2O_2. Results from the run showed that the separation factor between ^{144}Ce and ^{156}Eu was greater than 10^4.

6. REFERENCES

1. L. J. King, J. E. Bigelow, and E. D. Collins, Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending December 31, 1975, ORNL-5146.

2. L. J. King, J. E. Bigelow, and E. D. Collins, Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending December 31, 1976, ORNL-5305.

3. L. J. King, J. E. Bigelow, and E. D. Collins, Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending June 30, 1973, ORNL-4921.

4. L. J. King, J. E. Bigelow, and E. D. Collins, Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending June 30, 1972, ORNL-4833.

5. W. D. Burch, J. E. Bigelow, and L. J. King, Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending December 31, 1971, ORNL-4767.

6. L. J. King, J. E. Bigelow, and E. D. Collins, Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending June 30, 1976, ORNL-5216.

7. Y. A. Ellis and A. H. Wapstra, Nucl. Data Sheets 3(2), 1 (1969) (A = 243-251).

8. Y. A. Ellis, Nucl. Data Sheets 4, 635 (1970) (A = 238).

9. M. R. Schmorak, Nucl. Data Sheets 4, 661 (1970) (A = 240).

10. Y. A. Ellis, Nucl. Data Sheets 4, 683 (1970) (A = 242).

11. Y. A. Ellis, Nucl. Data Sheets 6, 539 (1971) (A = 237).

12. A. Artna-Cohen, Nucl. Data Sheets 6, 577 (1971) (A = 239).

13. Y. A. Ellis, Nucl. Data Sheets 6, 621 (1971) (A = 241).

14. M. R. Schmorak, Nucl. Data Sheets 17, 391 (1976) (A = 244-262).

15. M. R. Schmorak, Nucl. Data Sheets 18, 389 (1976) (A = 249-263).

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[7-15] 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.

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) × 10^6 y		>10^{18} y	2.00[d]	60Br12, 61Dr04
^{238}Np	2.10 ± 0.01 d					50Pr53
^{239}Np	2.359 ± 0.010 d					59Co93
^{240}Np	63 ± 2 m					60Lo03
^{240m}Np	7.3 ± 0.3 m					48Wy61
^{241}Np	16 m					60Lo03
^{241m}Np	3.4 h					60Lo03
^{238}Pu	87.404 ± 0.041 y			(5 ± 0.6) × 10^{10} y	2.33 ± 0.08	61Dr04, 66Je15, 56Hi01
^{239}Pu		(2.4413 ± 0.003) × 10^4 y		5.5 × 10^{15} y	2.24[d]	52Se67, 59Ne36
^{240}Pu		6580 ± 40 y		(1.340 ± 0.015) × 10^{11} y	2.177 ± 0.009	51In03, 67Wa11, 68Be34
^{241}Pu	14.98 ± 0.33 y	(5.72 ± 0.1) × 10^3 y				60Ca19, 60Dr15
^{242}Pu		(3.869 ± 0.06) × 10^5 y		(7.45 ± 0.17) × 10^{10} y	2.166 ± 0.009	62Ma30, 69Be06, 68Be34
^{243}Pu	4.955 ± 0.003 h					68D109
^{244}Pu		(8.09 ± 0.10) × 10^7 y		(6.55 ± 0.32) × 10^{10} y	2.34[d]	66F107, 69Be06
^{245}Pu	10.6 ± 0.4 h					56Mu92
^{246}Pu	10.85 ± 0.02 d					56Ne23
^{241}Am		432.7 ± 0.7 y		(2.3 ± 0.8) × 10^{14} y	3.48[d]	61Dr04, 67Oe01
^{242}Am	16.01 ± 0.02 h		EC/β = 0.19			53Ke38
^{242m}Am	144 ± 7 y	(2.92 ± 0.13) × 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					56Mu92
^{246}Am	25.0 ± 0.2 m					55Ea16
^{246m}Am	40 ± 7 m					67Dr02
^{247}Am	24 ± 3 m					67Dr02
^{242}Cm	162.7 ± 0.1 d			7.2 × 10^6 y	2.65 ± 0.09	51Ha87, 57Po52, 56Hi01
^{243}Cm		32 y				57Ab70
^{244}Cm	18.099 ± 0.015 y		α/SF = (7.43 ± 0.01) × 10^3		2.84 ± 0.09	61Ne02, 68Be26, 56Hi01
^{245}Cm		8265 ± 180 y				69Ne01
^{246}Cm		4655 ± 40 y	α/SF = 3822 ± 10		3.08[d]	66Ne01, 71Ne19
^{247}Cm		(1.56 ± 0.05) × 10^7 y				71F101
^{248}Cm		(3.703 ± 0.032) × 10^5 y		(4.115 ± 0.034) × 10^6 y	3.32[d]	71Ne19
^{249}Cm	64 ± 3 m					58Es06
^{250}Cm				(1.74 ± 0.24) × 10^4 y	3.56[d]	68Ab01

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^{-3}	(1.87 ± 0.08) × 10^{9} y	3.72 ± 0.16	87Ls01, 68Mi08, 64Py02
^{250}Bk	3.222 ± 0.005 h					59Ve02
^{251}Bk	57 ± 1.7 m					66Gi04
^{249}Cf		352 ± 6 y	α/SF = (1.792 ± 0.040) × 10^{8}		3.44[d]	68Me01, 67Mi08
^{251}Cf		13.08 ± 0.03 y	α/SF = 1260 ± 40		3.56[d]	63Ph01, 68Me01
^{252}Cf		900 ± 50 y				68Me01
^{253}Cf	2.646 ± 0.004 y		α/SF = 31.3 ± 0.2		3.796 ± 0.031	68Me02, 68Bh04
^{253}Cf	17.812 ± 0.002 d		α/β = (3.1 ± 0.4) × 10^{-3}			68Gr02, 66Gi01
^{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]	68Me02, 68Gr02
^{254}Es	276 d			≥2.5 × 10^{7} y	4.04[d]	67Fi03, 67Un01
^{254m}Es	39.3 ± 0.2 h		α/α = 382 ± 30 E.C./β = 0.00078 ± 0.00006			67Ur01, 63Ph01
^{255}Es	39.8 ± 1.2 d		α/β = 0.084 ± 0.0043 β/SF = (2.22 ± 0.10) × 10^{4}		4.16[d]	66Gi01, 67Fi03
^{256}Es	25 ± 1 m					68Lo11
^{254}Fm	3.24 ± 0.01 h		α/SF = 1685 ± 8		4.03 ± 0.19	56Je09, 67Fi05, 56Ch83
^{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]	68Ha15
^{257}Fm	94 ± 10 d					66Gi01
^{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:

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

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 properties of the

Table A-2. References for Table A-1

Code	Reference
48Hy01	E. K. Hyde, M. H. Studier, and A. M. Manning, ANL-4143 (April 15, 1948) and ANL-4182 (August 4, 1948).
50Fr53	M. S. Freedman, A. H. Jaffey, and F. Wagner, Jr., Phys. Rev., 79, 410-411 (1950).
51Ha67	G. C. Hanna, B. G. Harvey, N. Moss, and P. R. Tunnicliffe, Phys. Rev., 81, 466-467 (1951).
51In03	M. G. Inghram, D. C. Hess, P. R. Fields, and G. L. Pyle, Phys. Rev., 83, 1250 (1951).
52Se67	E. Segrè, Phys. Rev., 86, 21-28 (1952).
53Ke38	T. K. Keenan, R. A. Penneman, and B. B. McInteer, J. Chem. Phys., 21, 1802-1803 (1953).
54Gh24	A. Ghiorso, S. G. Thompson, G. R. Choppin, and B. G. Harvey, Phys. Rev., 94, 1081 (1954).
55En16	D. Engelkemeir, P. R. Fields, S. Fried, G. L. Pyle, C. M. Stevens, L. B. Asprey, C. I. Browne, H. Louise Smith, and R. W. Spence, J. Inorg. Nucl. Chem., 1, 345-351 (1955).
56Bu02	J. P. Butler, T. A. Eastwood, T. L. Collins, M. E. Jones, F. M. Rourke, and R. P. Schuman, Phys. Rev., 103, 634 (1956).
56Ch03	G. R. Choppin, B. G. Harvey, D. A. Hicks, J. Ise, Jr., and R. V. Pyle, Phys. Rev., 102, 766 (1956).
56Hi01	D. A. Hicks, J. Ise, Jr., and R. V. Pyle, Phys. Rev., 101, 1016-1020 (1956).
56Ho23	D. C. Hoffman and C. I. Browne, J. Inorg. Nucl. Chem., 2, 209 (1956).
56Jo00	M. Jones, R. P. Schuman, J. P. Butler, G. Cowper, T. A. Eastwood, and H. G. Jackson, Phys. Rev., 102, 203-207 (1956).
57As70	F. Asaro, S. G. Thompson, F. S. Stephens, Jr., and I. Perlman, Bull. Am. Phys. Soc., 8, 393 (1957).
57Ea01	T. A. Eastwood, J. P. Butler, M. J. Cabell, H. G. Jackson, R. P. Schuman, F. M. Rourke, and T. L. Collins, Phys. Rev., 107, 1635-1638 (1957).
57Pe52	R. A. Penneman, L. H. Treiman, and B. Bevan, as reported by D. C. Hoffman, G. P. Ford, and F. O. Lawrence, J. Inorg. Nucl. Chem., 5, 6-11 (1957).
58Ea00	T. A. Eastwood and R. P. Schuman, J. Inorg. Nucl. Chem., 6, 261-262 (1958).
59Ba21	R. F. Barnes, D. J. Henderson, A. L. Harkness, and H. Diamond, J. Inorg. Nucl. Chem., 9, 105-107 (1959).
59Co03	D. Cohen, J. C. Sullivan, and A. J. Zielen, J. Inorg. Nucl. Chem., 11, 159-161 (1959).
59Ma26	T. L. Markin, J. Inorg. Nucl. Chem., 9, 320-322 (1959).
59Va02	S. E. Vandenbosch, H. Diamond, R. K. Sjoblom, and P. R. Fields, Phys. Rev., 115, 115-121 (1959).
60Br12	F. P. Brauer, R. W. Stromatt, J. D. Ludwick, F. P. Roberts, and W. L. Lyon, J. Inorg. Nucl. Chem., 12, 234-235 (1960).
60Br15	F. Brown, G. G. George, D. E. Green, and D. E. Watt, J. Inorg. Nucl. Chem., 13, 192-195 (1960).
60Le03	R. M. Lessler and M. C. Michel, Phys. Rev., 118, 263-264 (1960).
61Dr04	V. A. Druin, V. P. Perelygin, and G. I. Khlebnikov, Sov. Phys. JETP, 13, 913-914 (1961).
62Un06	J. Unik, P. Day, and S. Vandenbosch, Nucl. Phys., 36, 284-300 (1962).
62Va00	S. E. Vandenbosch and P. Day, Nucl. Phys., 30, 177-196 (1962).
62Wa13	D. E. Watt, F. J. Bannister, J. B. Laidler, and F. Brown, Phys. Rev., 126, 264-265 (1962).
63Ma50	L. Z. Malkin, I. D. Alkhazov, A. S. Krivokhatskii, and K. A. Petrzhak, At. Energ. (USSR), 15, 158-159 (1963).
63Ph01	L. Phillips, R. Gatti, A. Brandt, and S. G. Thompson, J. Inorg. Nucl. Chem., 25, 1085-1087 (1963).
64As01	F. Asaro, S. Bjørnholm, and I. Perlman, Phys. Rev., 133, B291-B300 (1964).
64Py02	R. V. Pyle, Unpublished results as reported in E. K. Hyde, "Fission Phenomena," Prentice Hall, Inc. (1964).
65Me02	D. Metta, H. Diamond, R. F. Barnes, J. Milsted, J. Gray, Jr., D. J. Henderson, and C. M. Stevens, J. Inorg. Nucl. Chem., 27, 33-35 (1965).
66Fi07	P. R. Fields, A. M. Friedman, J. Milsted, J. Lerner, C. M. Stevens, D. Metta, and W. K. Sabine, Nature, 212, 131 (1966).
66RC01	Combined Radiochemistry Group, LRL, LASL, and ANL, Phys. Rev., 148, No. 3, 1192-1198 (1966).
66RC04	Argonne Heavy Element Group (unpublished data).
67Fi05	P. R. Fields, H. Diamond, A. M. Friedman, J. Milsted, J. L. Lerner, R. F. Barnes, R. K. Sjoblom, D. N. Metta, and E. P. Horwitz, Nucl. Phys., A96, 440-448 (1967).
67Oe01	F. L. Oetting and S. R. Gunn, J. Inorg. Nucl. Chem., 29, 2659-2664 (1967).
67Or02	C. J. Orth, W. R. Daniels, B. H. Erkkila, F. O. Lawrence, and D. C. Hoffman, Phys. Rev. Letters, 19, No. 3, 128-131 (1967).
67Un01	J. Unik, private communication to P. Fields (1967).
68Be21	C. E. Bemis, Jr. and J. Halperin, Nucl. Phys., A121, 433-439 (1968).
68Be26	W. C. Bentley, J. Inorg. Nucl. Chem., 30, 2007-2009 (1968).
68Bo54	J. W. Boldeman, J. Nucl. Energy, 22, 63-72 (1968).
68Br22	L. C. Brown and R. C. Propst, J. Inorg. Nucl. Chem., 30, 2591-2594 (1968).
68Ca19	M. J. Cabell, J. Inorg. Nucl. Chem., 30, 2583-2589 (1968).
68Di09	H. Diamond, J. J. Hines, R. K. Sjoblom, R. F. Barnes, D. N. Metta, J. L. Lerner, and P. R. Fields, J. Inorg. Nucl. Chem., 30, 2553-2559 (1968).
68Ho13	R. W. Hoff, J. E. Evans, E. K. Hulet, R. J. Dupzyk, and B. J. Qualheim, Nucl. Phys., A115, 225-233 (1968).
68Jo15	K. C. Jordan, MLM-1443, 11-30 (1968).
68Lo11	R. W. Lougheed, private communication to J. E. Bigelow (1968).
68Wh04	P. H. White and E. J. Axton, J. Nucl. Energy, 22, 73-77 (1968).
69Be06	C. E. Bemis, Jr., J. Halperin, and R. Eby, J. Inorg. Nucl. Chem., 31, 599-604 (1969).
69Dr02	R. E. Druschel, J. Halperin, and C. E. Bemis, Jr., ORNL-4437, 28-29 (1969).
69Me01	D. N. Metta, H. Diamond, and F. R. Kelly, J. Inorg. Nucl. Chem., 31, 1245-1250 (1969).
69Mi08	J. Milsted, E. P. Horwitz, A. M. Friedman, and D. N. Metta, J. Inorg. Nucl. Chem., 31, 1561-1569 (1969).
70Lo19	R. W. Lougheed, J. E. Evans, and E. K. Hulet, private communication to J. E. Bigelow (1970).
71Fi01	P. R. Fields, I. Ahmad, A. M. Friedman, J. Lerner, and D. N. Metta, Nucl. Phys., A160, 460-470 (1971).
71Hu03	E. K. Hulet, J. F. Wild, R. W. Lougheed, J. E. Evans, B. J. Qualheim, M. Nurmia, and A. Ghiorso, Phys. Rev. Letters, 26, 523 (1971).
71Mc19	J. E. McCracken, J. R. Stokely, R. D. Baybarz, C. E. Bemis, Jr., and R. Eby, J. Inorg. Nucl. Chem., 33, 3251-3259 (1971).

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 cpm/mg[c])	(β dpm/mg)	(Neutrons min⁻¹ mg⁻¹)	Hazard[b] MPC a(40) (μCi/cm³)	Body Burden (μCi)	(μg)
^{237}Np	2.14×10^{6} y	4.78		7.07×10^{-4}	2.07×10^{-5}	8.01×10^{5}		$<7 \times 10^{-6}$	4×10^{-12}	0.06	94.0
^{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 0.437	2.32×10^{5}	5.89×10^{2}		5.14×10^{14}		7×10^{-7}	30	1.29×10^{-4}
^{240}Np	63 m		0.89	1.24×10^{7}	1.03×10^{5}		2.76×10^{16}				
^{240m}Np	7.3 m		2.18 1.6	1.07×10^{8}	5.33×10^{5}		2.38×10^{17}				
^{241}Np	16 m			4.06×10^{7}			1.08×10^{17}				
^{241m}Np	3.4 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}	6.84×10^{7}		1.35×10^{-3}	2×10^{-12}	0.04	0.653
^{240}Pu	6580 y	5.16		0.227	7.097×10^{-3}	2.57×10^{8}		53.7	2×10^{-12}	0.04	0.176
^{241}Pu	14.98 y	4.9	0.02	99.4	4.06×10^{-3}	2.94×10^{6}	2.20×10^{11}		9×10^{-11}	0.9	9.09×10^{-3}
^{242}Pu	3.869×10^{5} y	4.90		3.82×10^{-3}	1.15×10^{-4}	4.32×10^{6}		85.3	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	8.26×10^{7} y	4.58?		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}	1.0	2.48×10^{-6}
^{246}Pu	10.85 d		0.15	4.91×10^{4}	66.9		1.09×10^{14}				
^{241}Am	432.7 y	5.48		3.43	0.1145	7.60×10^{9}		3.55×10^{-2}	6×10^{-12}	0.1	0.0292
^{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	5.207	1.1	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		0.387	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		0.91	6.17×10^{6}	1.20×10^{4}		1.37×10^{16}				
^{246}Am	25.0 m		1.31	3.06×10^{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^{3}	122	3.76×10^{12}		1.21×10^{6}	1×10^{-10}	0.05	1.51×10^{-5}
^{243}Cm	32 y	5.79		45.9	1.677	5.20×10^{10}	1.27×10^{9}		6×10^{-12}	0.09	1.96×10^{-3}
^{244}Cm	18.099 y	5.81		80.94	2.832	9.16×10^{10}		6.87×10^{5}	9×10^{-12}	0.1	1.24×10^{-3}
^{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}		3.58×10^{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^{5}			5×10^{-12}	0.04	431
^{248}Cm	3.397×10^{5} y	5.05		4.24×10^{-3}	1.34×10^{-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			$8.20 \times 10^{-[illegible]}$	~0.3			$6.49 \times 10^{[illegible]}$			

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)	(μg)
^{249}Bk	314 d	5.4	0.125	1.67 x [illegible]	0.358	2.74 x 10^{7}	3.71 x 10^{12}	6.34 x 10^{3}	9 x 10^{-10}	0.7	4.19 x 10^{-4}
^{250}Bk	3.222 h		0.23	3.89 x 10^{6}	2.75 x 10^{4}		8.62 x 10^{15}		1 x 10^{-7}	0.05	1.[illegible] 10^{-8}
^{251}Bk	57 m			1.32 x 10^{7}			2.92 x 10^{16}				
^{248}Cf	352 y	5.81		4.08	0.152	4.62 x 10^{9}		156	2 x 10^{-12}	0.04	9.00 x 10^{-3}
^{250}Cf	13.08 y	6.03		109	4.06	1.23 x 10^{11}		6.85 x 10^{8}	5 x 10^{-12}	0.04	3.70 x 10^{-4}
^{251}Cf	900 y			1.59	5.79 x 10^{-2}	1.78 x 10^{9}			3 x 10^{-12}	0.04	2.50 x 10^{-2}
^{252}Cf	2.646 y	6.11		536	58.0	5.88 x 10^{11}		1.40 x 10^{11}	6 x 10^{-12}	0.01	1.87 x 10^{-5}
^{253}Cf	17.812 d	5.98	0.27	2.90 x 10^{4}	13.00	1.02 x 10^{11}	6.41 x 10^{13}		8 x 10^{-10}	0.04	1.40 x 10^{-6}
^{254}Cf	60.5 d	5.84		8.49 x 10^{3}	1.06 x 10^{4}	2.89 x 10^{10}		7.35 x 10^{13}	5 x 10^{-12}	0.0007	8.26 x 10^{-8}
^{255}Cf	1.5 h			~8 x 10^{6}							
^{253}Es	20.4±7 d	6.63		2.52 x 10^{4}	1.01 x 10^{3}	2.86 x 10^{13}		1.91 x 10^{7}	6 x 10^{-10}	0.04	1.80 x 10^{-6}
^{254}Es	276 d	6.42		1.86 x 10^{3}	71.9	2.11 x 10^{12}		~5.04 x 10^{5}	2 x 10^{-11}	0.02	1.08 x 10^{-5}
^{254m}Es	38.5 h		0.48	3.14 x 10^{5}	1.18 x 10^{3}		6.97 x 10^{14}		5 x 10^{-9}	0.02	6.37 x 10^{-8}
^{255}Es	38.8 d			1.29 x 10^{4}			2.86 x 10^{13}	4.92 x 10^{9}	4 x 10^{-10}	0.04	3.10 x 10^{-6}
^{255}Es	25 m			2.94 x 10^{7}			6.52 x 10^{16}				
^{254}Fm	3.24 h	7.20		3.81 x 10^{6}	1.68 x 10^{3}	4.31 x 10^{15}		2.02 x 10^{13}	6 x 10^{-8}	0.02	5.25 x 10^{-9}
^{255}Fm	20.07 h	7.03		6.13 x 10^{5}	2.79 x 10^{4}	6.94 x 10^{14}		1.36 x 10^{9}	1 x 10^{-8}	0.04	6.83 x 10^{-8}
^{256}Fm	2.62 h			4.67 x 10^{6}	5.85 x 10^{6}			4.45 x 10^{16}	2 x 10^{-9}	0.0008	1.71 x 10^{-10}
^{257}Fm	94 d			5.41 x 10^{3}	~200	6.12 x 10^{12}					
^{258}Fm	380 μs			1.15 x 10^{11}							

[a] The values for properties included in this table are those in use at YBU 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 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	87.404 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	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	3.56	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	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	1400	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 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 $f_c = f_g + f_m = 1$.

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