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Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending June 30, 1976

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

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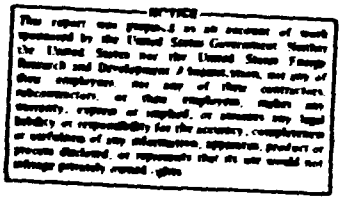

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Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

CONTENTS

SUMMARY

This is the seventeenth 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 January 1, 1976, through June 30, 1976, we obtained transuranium elements from ten irradiated HFIR targets; products recovered are listed in Table 2.1 on p. 3. About 50 mg of high-purity ^{248}Cm was purified chemically for shipment, and another 75 mg of ^{248}Cm was separated from ^{252}Cf. Forty shipments were made from TRU during the period; recipients and the amounts of nuclides are listed in Table 2.2 on pp. 4-5. Nineteen HFIR targets, each containing approximately 9 g of curium, were fabricated.

During the next 18 months, we expect to obtain totals of 70 mg of ^{249}Bk, 815 mg of ^{252}Cf, 3.1 mg of ^{253}Es (in a mixture of isotopes), 360 μg of high-purity ^{253}Es, and 1.7 pg of ^{257}Fm; we also expect to make available 150 mg of high-purity ^{248}Cm. There are no plans to process any of the remaining SRP plutonium-aluminum tubes or to irradiate any plutonium targets in the HFIR; thus, we do not expect to recover any ^{244}Pu.

There have been no changes during this report period in the chemical processing flowsheets normally used at TRU.

Five neutron sources were fabricated, bringing the total fabricated to 34. Six sources that were used previously in various projects have been returned to TRU and are available for reassignment.

Special projects included (1) the continued study of ^{250}Cm production by irradiation of ^{248}Cm; (2) the production of 0.54 mg of ^{250}Cf by irradiation of ^{249}Bk; (3) the separation of approximately 200 pg of ^{254}Cf from 39-hr ^{254m}Es that was produced by irradiation of 5 μg of ^{253}Es; and (4) the determination of process steps needed to obtain rare-earth fission products in an oxide form from LiCl-based anion exchange raffinate 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 seventeenth 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 at ORNL. 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.

TRU 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 that have been 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) study the production of ^{250}Cm by irradiation of ^{248}Cm, (2) produce ^{250}Cf by irradiation of ^{249}Bk, (3) produce enriched ^{254}Cf by irradiation of ^{253}Es, and (4) isolate a portion of the Campaign 50 rare-earth fission products in an oxide form. 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.

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(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.

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 in TRU. Except in special instances, ^{242}Pu, ^{243}Am, ^{244}Cm, ^{249}Bk, ^{252}Cf, and ^{253}Es are the isotopes used for tracing the corresponding elements. Throughout this report section, we are discussing mixtures of isotopes unless we indicate otherwise.

2.1 Processing Summary

One TRU campaign (No. 50) was made between January 1, 1976, and June 30, 1976, to obtain transuranium elements from ten irradiated HFIR targets; products are listed in Table 2.1. These targets originally contained curium that had been recovered from previous HFIR irradiation of Californium-I (Cf-I) curium. Californium-I was 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 Nuclear Fuel Cycle and Production (DNFCP). Much of the curium recovered during the Cf-I campaign has been irradiated in the HFIR to produce transcurium elements.

Two batches of high-purity ^{248}Cm were processed. (High-purity ^{248}Cm typically contains 97% ^{248}Cm, 3% ^{246}Cm, and less than 0.01% ^{244}Cm.) About 50 mg of the first batch, which had been initially separated from ^{252}Cf during an earlier report period,[1] was purified from residual ^{252}Cf and packaged for shipment. The second batch (calculated to contain 75 mg of ^{248}Cm) was separated from 110 mg of ^{252}Cf during this report period. Another small batch (2.5 mg) of ^{248}Cm, obtained during the final purification of the californium product from Campaign 49, was isolated, sampled, and analyzed to determine

Table 2.1. Amounts of materials recovered in the major campaign in the Transuranium Processing Plant during the period January 1, 1976, through June 30, 1976

	Campaign number 50
Completion date	February
Material processed	10 Cf-I Cm-HFIR targets plus rework
Amounts recovered	
^{243}Am, g[a]	2
^{244}Cm, g[a]	50 (107)[b]
^{249}Bk, mg	29
^{252}Cf, mg	277
^{253}Es, mg	1.7
^{257}Fm, pg	0.5

[a]Americium and curium are not usually separated from each other.
[b]The amount shown in parentheses is total curium.

the ^{250}Cm concentration for comparison with a calculated value (see Sect. 5.1). The composition of this batch was approximately 98% ^{248}Cm, 2% ^{246}Cm, and 0.1% ^{244}Cm (this was not considered to be high-purity ^{248}Cm because of the relatively high concentration of ^{244}Cm). This material is now available for allocation.

Forty shipments were made from TRU. Recipients and the amounts of nuclides shipped are listed in Table 2.2.

Nineteen HFIR targets were fabricated. Each contained approximately 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 curium had been recovered during the Cf-I campaigns at TRU and had an isotopic composition ranging from 57 to 66% ^{244}Cm, 27 to 34% ^{246}Cm, and 1.9 to 2.7% ^{248}Cm.

Table 2.2. Distribution of heavy elements from the Transuranium Processing Plant during the period January 1, 1976 – June 30, 1976

Major nuclide	Date	TRU file No.	Shipped to: Individual	Site
Tin-126 (~5%), μg				
140	6-22-76	866	C. J. Orth	LASL
Americium-243, g				
2.08	3-09-76	836	Iso. Res. Mat'l. Lab.	ORNL
Curium-243 (56%), mg				
0.93	5-19-76	812	Isotopes Sales for USEPA,	Nevada
1.26	6-25-76	863	G. Struble	LLL
5.06	6-25-76	864	J. J. Thompson	Lovelace
7.25				
Curium-248 (97%), mg				
25.0	2-20-76	830	N. M. Edelstein	LBL
25.0	2-20-76	831	R. G. Haire	ORNL
50.0				
Berkelium-249, mg				
2.369	3-31-76	839A	N. M. Edelstein	LBL
5.685	3-31-76	840	R. W. Hoff	LLL
0.0011	3-31-76	843	F. P. Hungate	PNL
2.369	4-02-76	842A	M. M. Abraham	ORNL
2.25	5-13-76	842B	R. G. Haire	ORNL
4.4	6-09-76	838	W. T. Carnall	ANL
0.0018	6-09-76	854	Isotopes Sales for Sandia,	NM
2.132	6-21-76	839B	N. M. Edelstein	LBL
19.2079				
Californium-249, mg				
0.622	6-17-76	850	W. T. Carnall	ANL
0.49	6-17-76	855	Isotopes Sales for Sandia,	NM
0.828	6-17-76	856	N. M. Edelstein	LBL
0.828	6-18-76	857	R. J. Silva	ORNL
2.768				
Californium-250 (89%), mg				
0.54	4-26-76	849	W. T. Carnall	ANL

Table 2.2. (continued)

Major nuclide	Date	TRU file No.	Shipped to: Individual	Site
Californium-252, mg				
44.278	1-08-76	810	A. R. Boulogne	SRL
0.011	1-09-77	821	Isotopes Sales	ORNL
0.0614 (NSD-49)	2-02-76	823	L. J. Esch	KAPL
0.0135 (NSD-91)	2-02-76	823	L. J. Esch	KAPL
0.1153 (NSD-51)	3-08-76	835	F. J. Muckenthaler	ORNL
19.931 (NSD-87)	4-05-76	721	G. I. Gleason	ORAU
0.0816 (NSD-48)	4-12-76	848	A. C. England	ORNL
1.085 (SR-Cf-167)	4-23-76	851	J. E. Rushton	ORNL
0.028	5-19-76	853	R. J. Silva	ORNL
0.0419 (NSD-56)	6-29-76	822	M. M. Bretscher	ANL
65.6467				
Californium-254, pg				
19	6-22-76	865	J. B. Wilhelmy	LASL
Einsteinium-253, µg				
300	2-13-76	825A	R. G. Haire	ORNL
409	2-17-76	824	W. T. Carnall	ANL
60	3-10-76	825B	R. G. Haire	ORNL
22	3-11-76	826B	D. C. Hoffman	LASL
27	3-11-76	827	R. W. Hoff	LLL
5	4-02-76	833	F. P. Hunsate	PNL
10.7	6-21-76	826A	D. C. Hoffman	LASL
833.7				
Einsteinium-253 (milked), µg				
57	4-01-76	847	R. G. Haire	ORNL
11.2	4-02-76	846	R. W. Hoff	LLL
68.2				
Fermium-257, pg				
0.54	3-05-76	829	D. C. Hoffman	LASL

2.2 Irradiation and Processing Proposals

The level of TRU operations is expected to continue at two processing campaigns per year to produce transcurium elements. 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.[2] Table 2.3 outlines the estimated production of transcurium elements from a series of likely processing campaigns that are scheduled through December 1977. Projected estimates for 1978 and 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 70 mg of ^{249}Bk, 815 mg of ^{252}Cf, 3.1 mg of ^{253}Es (in a mixture of isotopes), 360 μg of high-purity ^{253}Es, and 1.7 pg of ^{257}Fm. These estimates were made by means of a method described in a previous report in this series.[3] That method requires the use of assumed values for chemical yields and recovery times for each of the transplutonium elements that are separated at TRU. The assumed values are based on past performance data, and the most recently revised values are listed in Table 2.4 of ref. 4.

Plutonium, americium, and curium that are separated from the transcurium elements during the processing of irradiated targets are generally considered to be intermediate feed materials. However, two isotopes of these elements, ^{244}Pu and ^{248}Cm, which are valuable research materials, are frequently recovered. Within the next 18 months, we do not plan to process any of the remaining Cf-I materials irradiated at SRP or to irradiate any plutonium targets in the HFIR; thus, we do not expect to recover any ^{244}Pu.

On June 30, 1976, TRU had an inventory of purified californium in several batches, which contained totals of 650 mg of ^{252}Cf and 154 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; 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

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 1976							1951[b]	
July-December 1976	{4 Cf-I Cm-HFIR targets 7 TRU Cm-HFIR targets}	22	270	1060 (120)	0.6	270	2221	October 1976
January-June 1977	{7 Cf-I Cm-HFIR targets 5 TRU Cm-HFIR targets}	24	275	960 (120)	0.5	275	2496	February 1977
July-December 1977	{5 Cf-I Cm-HFIR targets 6 TRU Cm-HFIR targets}	24	270	1060 (120)	0.6	270	2766	October 1977
1978						540	3306	
1979						540	3846	

[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.

in the californium. We expect to make available 50 mg of high-purity ^{248}Cm in July 1976, and an additional 100 mg during 1977.

3. PROCESSES AND EQUIPMENT

There have been no changes in the chemical processing flowsheets or equipment used at TRU during this report period. The condition of processing equipment at TRU is generally good and is continually maintained.

4. CALIFORNIUM NEUTRON SOURCES

Some of the californium recovered at TRU 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 1976

Five sources, NSD-87 and NS-82, -83, -84, and -85 were fabricated during this report period. The latter four were fabricated in a nonstandard form specified by the user.

4.2 Sources Returned

An increasing 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

Table 4.1 Data for neutron sources prepared at TRU

Source	Date of calibration	^{252}Cf Content at calibration (μg)	Content as of 6/30/76 ^{252}Cf (μg)	Content as of 6/30/76 ^{248}Cm (μg)	On loan to: Individual	On loan to: Site
RS-1[a]	8-28-68	316	41	b	K. L. Swinth	PNL
RS-2	8-23-68	254	32	b	c	
RS-3	5-13-69	~90	~14	b	G. I. Gleason	ORAU
RS-4	7-09-69	883	142	707	C. F. Masters	LASL
RS-5[d]	8-14-69	946	156	753	F. B. Simpson	ARC
RS-6	11-21-69	747	132	586	R. W. Hoff	LLL
RS-7	1-21-70	788	146	612	c	
RS-8	12-17-69	1839	332	1437	H. Berger	ANL
RSD-9	4-17-70	1720	339	1317	H. D. Wagnon	PNL
RSS-10	3-11-70	113	22	b	J. P. Balagna	LASL
RS-11	3-10-70	8	2	b	R. R. Fullwood	LASL
RSS-12	6-30-70	1868	388	1412	R. W. Hoff	LLL
RSD-13	3-19-71	4649	1165	3323	H. O. Menlove	LASL
RSS-14	6-29-70	4615	957	3488	D. C. Stewart	ANL
RS-15[d]	6-25-70	931	193	704	F. B. Simpson	ARC
RSS-17	8-31-71	4886	1378	3346	L. W. Dahlke	Sandia-Livermore
RS-18[d]	6-24-70	962	199	728	F. B. Simpson	ARC
RSS-19	6-26-70	493	102	373	J. E. Bigelow	ORNL-TRU
RSD-20	7-01-70	630	131	476	J. E. Powell	Sandia-NM
RSS-21	10-21-70	18	4	b	F. Cross	PNL
RS-22	9-10-70	13	3	b	J. E. Bigelow	ORNL-TRU
RSD-24	10-15-70	6	1	b	J. E. Rushton	ORNL
RS-25	11-09-70	58	13	b	F. J. Muckenthaler	ORNL
RSD-26	2-11-71	14	3	b	H. O. Menlove	LASL
RSD-27	1-29-71	2528	611	1828	L. C. Nelson, Jr.	New Brunswick
RSD-28	2-12-71	11	3	b	E. E. Hicks	Rocky Flats
RSL-29	9-10-71	11393	3236	7779	S. G. Snow	Y-12
RSD-30	3-31-71	879	222	626	c	
RZD-31	11-23-71	1733	519	1158	J. L. White	RFDL
RZD-34	11-23-71	1924	576	1285	W. C. Spear	RFDL
RZD-35	11-23-71	1904	570	1272	c	
RS-36[d]	3-23-71	2070	520	1478	F. B. Simpson	ARC
RSD-37	9-04-71	9838	2783	6729	R. W. Perkins	PNL
RSD-38	6-16-71	102	27	b	H. O. Menlove	LASL
RS-39	11-07-71	942	279	632	V. Spiegel	FRG
RSD-40	4-27-72	1154	387	732	c	
RSD-41	11-08-71	5117	1515	3434	C. J. Emert	BAPL
RSD-42	11-02-71	4434	1308	2981	C. J. Emert	BAPL
RSD-43	4-20-72	4839	1613	3077	C. J. Emert	BAPL
RZD-44	5-15-72	10731	3641	6761	F. B. Simpson	ARC
RS-45	8-18-71	1776	496	1220	K. L. Swinth	PNL
RSD-46	4-23-72	629	210	399	H. O. Menlove	LASL

Table 4.1 (continued)

Source	Date of calibration	^{252}Cf Content at calibration (mg)	Content as of 6/30/76 ^{252}Cf (mg)	Content as of 6/30/76 ^{248}Cm (mg)	On loan to: Individual	On loan to: Site
HSD-47	7-14-71	200	54	139	P. L. Johnson	Mound
HSD-48	7-14-71	194	53	135	A. C. England	ORNL
HSD-49	7-14-71	199	54	138	L. J. Koch	KAPL
HS-50	8-23-71	138	39	95	S. G. Carpenter	ANL-HWTS
HSD-51	11-02-71	365	120	245	F. J. Muckenthaler	ORNL
HSD-52	9-02-71	280	79	192	E. D. Clayton	PNL
HSD-53	10-25-71	1051	308	708	L. J. Koch	KAPL
HS-54	1-19-73	3187	1293	1806	V. Spiegel	HRS
HSD-55	4-19-72	4	1	b	L. J. Koch	KAPL
HSD-56	4-19-72	124	45	79	M. M. Bretscher	ANL
HSD-57	4-14-72	973	325	620	c	
HZD-58	5-15-72	11003	3733	6933	F. B. Simpson	ANC
HS-59[d]	7-13-72	53	19	b	G. E. Hansen	LASL
HSD-60	4-11-72	20	7	b	F. F. Haywood	ORNL-DOSAR
HSD-61	1-19-73	5225	2120	2961	L. J. Koch	KAPL
HSE-62	3-27-73	3755	1598	2057	J. E. Biglow	ORNL-TRU
HSD-63	4-21-72	847	282	538	H. O. Menlove	LASL
HSD-64	7-19-73	193	89	99	H. O. Menlove	LASL
HS-65	7-09-73	114	52	59	L. Green	BAPL
HSD-66	8-02-73	3449	1609	1755	J. E. Powell	Sandia-HN
HSD-73	9-11-73	13545	6503	6715	G. I. Gleason	ORAU
HSD-74	9-11-73	4416	2120	2199	G. I. Gleason	ORAU
HS-75	10-01-73	1919	935	939	R. J. Kloepping	LLL
HSD-76	3-09-74	434	237	188	P. L. Johnson	Mound
HSD-77	3-09-74	433	236	188	P. L. Johnson	Mound
HSD-78	3-09-74	429	234	186	P. L. Johnson	Mound
HS-79	10-02-74	1650	1045	577	V. Spiegel	HRS
HSD-80	6-03-74	5966	3464	2386	C. J. Emert	BAPL
HSD-81	6-03-74	6364	3695	2545	C. J. Emert	BAPL
HS-82	5-19-75	14264	10645	3451	e	
HS-83	9-24-75	11783	9639	2044	e	
HS-84	9-30-75	12674	10413	2156	e	
HS-85	10-22-75	12181	10167	1921	e	
HS-86	11-17-75	2620	2228	374	V. Spiegel	HRS
HSD-87	10-15-75	22387	18592	3619	G. I. Gleason	ORAU
HSD-89	4-23-75	12687	9293	3236	J. E. Powell	Sandia-HN
HZS-90	1-16-75	0.87	<1	b	J. R. Smith	ANC
HSD-91	9-26-75	15	12	b	L. J. Koch	KAPL
SR-Cf-167[f]	5-26-71	3975	1046	2794	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 being held for use at BAPL.

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

reprocessing to recover the ingrown ^{248}Cm. Six sources that contain from 32 to 570 μg of ^{252}Cf are now in this category and are so designated in Table 4.1.

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[5] 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. The following special projects were undertaken during the current report period.

5.1 Production of ^{250}Cm

Preparations for a study of the production of ^{250}Cm by irradiation of ^{248}Cm were described in the previous report in this series.[1] Four special HFIR targets, each containing one or two ^{248}Cm pellets located within the targets at positions corresponding to a specific flux region within the reactor, were fabricated and scheduled for irradiation for varying lengths of time. Irradiation and processing of two of the targets have now been completed. The results are summarized in Table 5.1.

The ^{250}Cm content of these pellets is so low that it cannot be measured with high precision. However, the results imply that the ^{249}Cm capture cross section is in the range of 10 to 22b, nearly an order of magnitude higher than previously supposed. This information, in conjunction with data obtained previously[2] for long exposures, leads to the conclusion that the burnout cross section of the ^{250}Cm is about 90 to 180 b, much higher than previously supposed.

Another possible method for producing ^{250}Cm is by the alpha-branching decay of ^{254}Cf (0.31%). To investigate this possibility, we recovered about 2.5 mg of ^{248}Cm from the ^{252}Cf product of Campaign 49. The decay

Table 5.1. Summary of data obtained from the irradiation of ^{248}Cm pellets to produce ^{250}Cm

Pellet number	P1	P2	P3	P4
Cycles of irradiation	1	1	2	2
Neutron flux	3×10^{15}	1.5×10^{15}	3×10^{15}	1.5×10^{15}
Isotopic analysis of curium products, at. %				
^{244}Cm	1.416	1.263	2.14	0.847
^{245}Cm	0.020	0.018	0.028	0.013
^{246}Cm	3.44	3.29	4.14	3.19
^{247}Cm	0.082	0.064	0.119	0.078
^{248}Cm	95.04	95.37	93.57	95.87
^{250}Cm	0.0007	0.0003	0.0015	0.0005

history of this material was well-known. Using the mass-spectrometer data for the composition of the initial californium and the known decay properties of the californium isotopes, it was calculated that the recovered curium would contain 12.9 ppm of ^{250}Cm. The sample was carefully purified from californium (to avoid interference by ^{250}Cf) and analyzed on the mass spectrometer. The results showed a ^{250}Cm content of 14 ppm, which was excellent confirmation of the instrumentally derived branching ratio. Calculations to optimize this technique suggest that a curium product containing 0.5 mg of ^{248}Cm with 25 ppm of ^{250}Cm might be obtained by irradiating 100 mg of ^{252}Cf followed by short-cooled processing of the target(s).

5.2 Production of ^{250}Cf

Argonne National Laboratory (ANL) requested that 0.5 mg of ^{250}Cf be produced from a portion of their share of the ^{249}Bk from Campaign 50.

The calculated amount of ^{249}Bk required for irradiation was 3.0 mg (about 53% of ANL's share). The ^{249}Bk was purified to remove the ^{249}Cf daughter and miscellaneous cationic impurities; nine aluminum pellets, each containing 0.33 mg of ^{249}Bk, were then prepared by means of the resin loading--magnesium-diluent technique.[6] Three HFIR rabbits, each containing three pellets, were fabricated and transferred to the HFIR for a planned 16-hr irradiation at a thermal flux of 3×10^{15} neutrons·cm^{-2}·sec^{-1}. After an irradiation period of 9.5 hr, a leak was detected from one of the rabbits, and it was discharged. Irradiation of the other two rabbits was completed as planned, and all three were transferred to TRU for chemical processing. Approximately 0.54 mg of ^{250}Cf and 2.3 mg of residual ^{249}Bk were obtained. Isotopic composition of the ^{250}Cf product is shown in Table 5.2.

Table 5.2. Composition of ^{250}Cf product

Batch identification code	4H40-Cf-prod.
Date of analysis	April 22, 1976
Nuclide	Isotopic composition (at. %)
^{249}Cf	6.68
^{250}Cf	87.18
^{251}Cf	5.57
^{252}Cf	0.566
^{253}Cf	<0.002
^{254}Cf	<0.002

5.3 Production of ^{254}Cf

Californium-254 was produced experimentally by the electron-capture decay (0.078% branching) of 39-hr ^{254m}Es. For this experiment, a HFIR rabbit containing approximately 5 μg of ^{253}Es was fabricated, irradiated for 32 hr at a flux of 3×10^{15} neutron·cm^{-2}·sec^{-1}, cooled for 2 hr, and then chemically processed at TRU to isolate the irradiated einsteinium ($^{253-254m}Es$) from other actinide, fission product, and activation product elements. The isolated einsteinium, containing 2.75 μg of ^{253}Es, was transferred to a glove box and processed at a micro level by means of ion exchange runs to separate the californium daughters. One run was made as soon as possible after isolating the einsteinium, and a second run was made after a 5-day interval. The isotopic compositions of the californium products recovered in the glove box are listed in Table 5.3. These compositions are similar to that predicted by calculation except that there was somewhat more ^{252}Cf than expected. The glove-box facility had been chosen for this purpose in order to minimize contamination by ^{252}Cf, which is omnipresent in our cells. During the processing, we discovered that a rather high-gamma background was associated with the ^{254m}Es content of this sample, and the radiation levels were about twice what we would normally accept for routine handling. Thus, the amount of ^{254}Cf produced in this manner and processed in the shielded cave and glove-box facilities at TRU should be limited to about 50 pg. Additional shielding would be required for handling larger amounts of ^{254}Cf. It is estimated that as much as 5 ng could be produced by irradiation of ^{253}Es fabricated into HFIR targets which would be processed in the main cell bank at TRU. However, processing in the main cell bank would increase the possibility of ^{252}Cf contamination of the product.

5.4 Separation of Rare-Earth Elements from Anion Exchange Raffinate

A portion of the LiCl-based anion exchange raffinate (10 M LiCl) obtained during Campaign 50 was processed to determine the steps that would be required to obtain the rare-earth fission products in a purified solid form. The solution was processed by means of a Tramex batch solvent

Table 5.3. Isotopic composition of californium separated from irradiated ^{253}Es

	First separation (at. %)	Second separation (at. %)
^{249}Cf	≤6.0[a]	≤6.4[a]
^{250}Cf	83.33	88.60
^{251}Cf	8.38	3.95
^{252}Cf	2.25	1.03
^{253}Cf	≤0.05[b]	≤0.45[b]
^{254}Cf	0.032[c]	0.054[c]
Total ^{254}Cf recovered	113 pg	79 pg

[a]Determination is difficult due to residue of ^{249}Bk.

[b]Determination is difficult due to residue of ^{253}Es.

[c]These values were derived from the results of neutron counting, alpha counting, and mass spectrographic analyses.

extraction to remove LiCl and two cycles of oxalate precipitation to remove aluminum and other miscellaneous impurities. The oxalate precipitate was then calcined to convert the rare earths to the oxide form. An aliquot of the oxide product was dissolved in nitric acid and processed by means of a Berkex batch solvent-extraction run in glass equipment to separate cerium from the other rare earths. No significant difficulties were encountered during any of the processing steps.

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[7-13] which 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]	60Dr12, 61Dr04
^{238}Np	2.10 ± 0.01 d					50Fr53
^{239}Np	2.359 ± 0.010 d					59Co03
^{240}Np	63 ± 2 m					60Le03
^{240m}Np	7.3 ± 0.3 m					48Hy01
^{241}Np	16 m					60Le03
^{241m}Np	3.4 h					60Le03
^{238}Pu	87.404 ± 0.041 y			(5 ± 0.6) × 10^{10} y	2.33 ± 0.08	61Dr04, 68Ja15, 56Mi01
^{239}Pu		(2.4413 ± 0.003) × 10^4 y		5.5 × 10^{15} y	2.24[d]	52Se67, 59Ma26
^{240}Pu		6580 ± 4[illegible] y		(1.340 ± 0.015) × 10^{11} y	2.177 ± 0.009	51In03, 67Ma13, 68Ba54
^{241}Pu	14.98 ± 0.33 y	(5.72 ± 0.3) × 10^5 y				60Cu19, 60Dr15
^{242}Pu		(3.869 ± 0.016) × 10^5 y		(7.45 ± 0.17) × 10^{10} y	2.166 ± 0.009	63Ma50, 69Ba06, 68Ba54
^{243}Pu	4.955 ± 0.003 h					60Bi09
^{244}Pu		(8.28 ± 0.10) × 10^7 y		(6.55 ± 0.32) × 10^{10} y	2.04[d]	66Fl07, 69Ba06
^{245}Pu	10.6 ± 0.4 h					56Ba02
^{246}Pu	10.85 ± 0.02 d					56Ma23
^{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 ± 0.15) × 10^4 y				59Ba21[c]
^{243}Am		7370 ± 40 y				60Dr22
^{244}Am	10.1 ± 0.1 h					67Ve08
^{244m}Am	26 m					56Ga24
^{245}Am	2.07 ± 0.02 h					56Ba02
^{246}Am	25.0 ± 0.2 m					55En16
^{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	51Ha07, 57Po52, 56Mi01
^{243}Cm		32 y				57As78
^{244}Cm	18.099 ± 0.015 y		α/SF = (7.43 ± 0.01) × 10^5		2.84 ± 0.09	61Mo02, 68Ba26, 56Mi01
^{245}Cm		8265 ± 100 y				68Mo01
^{246}Cm		4655 ± 60 y	α/SF = 3822 ± 10		3.00[d]	68Mo01, 71Mc19
^{247}Cm		(1.56 ± 0.05) × 10^7y				71Fi01
^{248}Cm		(3.703 ± 0.0321 × 10^5 y		(4.115 ± 0.034) × 10^6 y	3.32[d]	71Mc19
^{249}Cm	64 ± 3 m					58Le04
^{250}Cm				(1.74 ± 0.24) × 10^4 y	3.56[d]	68Bo01

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	57To01, 68Wi08, 64Py02
^{250}Bk	3.222 ± 0.005 h					59Ke02
^{251}Bk	57 ± 1.7 m					66BG04
^{249}Cf		352 ± 6 y	α/SF = (1.092 ± 0.040) × 10^{8}		3.44[d]	68Me01, 68Wi08
^{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		3.796 ± 0.031	61Me02, 68Bh04
^{253}Cf	17.812 ± 0.082 d		α/β = (3.1 ± 0.4) × 10^{-5}			68Br02, 66BG01
^{254}Cf	60.5 ± 0.2 d		α/SF = (3.10 ± 0.16) × 10^{-3}		3.90 ± 0.14	63Ph01, 64Py02, 68De21
^{255}Cf	1.5 ± 0.5 h					70La10
^{253}Es	20.467 ± 0.024 d		α/SF = (1.15 ± 0.03) × 10^{7}		3.83[d]	65Me02, 68Dr02
^{254}Es	276 d			(2.5 ± 0.5) × 10^{7} y	4.04[d]	67Fi03, 67Um01
^{254m}Es	39.3 ± 0.2 h		α/β = 382 ± 30 E.C./β = 0.00078 ± 0.00006			67Um01, 63Ph01
^{255}Es	39.8 ± 1.2 d		α/β = 0.0066 ± 0.0043 β/SF = (2.22 ± 0.18) × 10^{4}		4.16[d]	66BG01, 67Fi03
^{256}Es	25 ± 3 m					68Le11
^{254}Fm	3.24 ± 0.01 h		α/SF = 1695 ± 6		4.05 ± 0.18	56Ja09, 67Fi03, 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]	68Me13
^{257}Fm	94 ± 10 d					66BG01
^{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 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 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 (W/g)	Specific Activity (α dps/mg)	Specific Activity (β dps/mg)	(Neutron min^{-1} mg^{-1})	Hazard[b] MPC α(40) (μCi/cm^3)	Hazard[b] Body Burden (μCi)	Hazard[b] Body Burden (μg)
^{237}Np	2.14 × 10^6 y	4.78		7.07 × 10^{-6}	2.07 × 10^{-5}	8.01 × 10^5		<7 × 10^{-6}	6 × 10^{-12}	0.06	84.0
^{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 0.427	2.32 × 10^5	5.86 × 10^{-1}		5.14 × 10^{14}		7 × 10^{-7}	30	1.20 × 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 1.4	1.07 × 10^8	5.33 × 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 × 10^9			8.49 × 10^{15}				
^{238}Pu	87.404 y	5.48		17.2	0.57W	1.94 × 10^{10}		155	2 × 10^{-12}	0.04	2.32 × 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	7.097 × 10^{-3}	2.57 × 10^8		53.7	2 × 10^{-12}	0.04	0.176
^{241}Pu	14.96 y	4.9	0.02	99.1	4.06 × 10^{-3}	2.94 × 10^9	2.20 × 10^{11}		8 × 10^{-11}	0.9	9.00 × 10^{-3}
^{242}Pu	3.869 × 10^5 y	4.90		3.82 × 10^{-3}	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	2.60 × 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	2.36 × 10^3
^{245}Pu	10.6 h			1.21 × 10^6			2.60 × 10^{15}		2 × 10^{-7}	3.0	2.40 × 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	0.1165	3.08 × 10^9		3.55 × 10^{-2}	6 × 10^{-12}	0.1	0.0202
^{242}Am	16.01 h		0.63 0.67	8.31 × 10^5	2.96 × 10^3		1.80 × 10^{15}[d]		4 × 10^{-8}	1.00	7.30 × 10^{-6}
^{242m}Am	144 y	5.207	1.7.	10.3	3.68 × 10^{-2}	5.53 × 10^7	2.20 × 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	8.96 × 10^4		6.58 × 10^{16}[f]		4 × 10^{-6}	0.2	6.76 × 10^{-6}
^{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			1.01 × 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}		1.31 × 10^6	1 × 10^{-10}	0.05	1.51 × 10^{-3}
^{243}Cm	32 y	5.79		45.0	1.677	5.26 × 10^{10}	3.27 × 10^8		6 × 10^{-12}	0.09	1.96 × 10^{-3}
^{244}Cm	18.099 y	5.81		80.94	2.832	9.16 × 10^{10}		6.07 × 10^5	8 × 10^{-12}	0.1	1.24 × 10^{-3}
^{245}Cm	8265 y	5.36		0.177	6.00 × 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		9.20 × 10^{-5}	2.94 × 10^{-6}	1.05 × 10^5			5 × 10^{-12}	0.04	481
^{248}Cm	3.387 × 10^5 y	5.05		4.24 × 10^{-3}	5.34 × 10^{-4}	4.38 × 10^6		2.58 × 10^6	9 × 10^{-13}	0.006	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	0.47 × 10^{-6}
^{250}Cm	1.74 × 10^4 y			5.20 × 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)	MPC α(46) (μCi/cm³)	Hazard[b] Body Burden (μCi)	(mg)
^{249}Bk	314 d	5.4	0.125	1.07×10^{3}	0.350	2.74×10^{7}	3.71×10^{12}	6.34×10^{3}	9×10^{-10}	0.7	4.19×10^{-6}
^{250}Bk	3.222 h		0.23	3.09×10^{6}	2.75×10^{4}		8.02×10^{15}		1×10^{-7}	0.05	1.70×10^{-8}
^{251}Bk	57 m			1.32×10^{7}			2.92×10^{16}				
^{248}Cf	352 y	5.81		4.08	0.152	4.62×10^{9}		156	2×10^{-12}	0.04	0.00×10^{-3}
^{250}Cf	13.08 y	6.03		100	4.04	1.33×10^{11}		0.85×10^{0}	5×10^{-12}	0.04	3.70×10^{-6}
^{251}Cf	900 y			1.59	5.79×10^{-2}	1.70×10^{9}			2×10^{-12}	0.04	2.50×10^{-7}
^{252}Cf	2.646 y	6.11		536	30.0	5.68×10^{11}		1.40×10^{11}	0×10^{-12}	0.01	1.07×10^{-5}
^{253}Cf	17.81 d	5.96	0.27	2.90×10^{4}	13.00	1.02×10^{13}	6.41×10^{15}		0×10^{-10}	0.04	1.40×10^{-6}
^{254}Cf	60.5 d	5.84		0.49×10^{3}	1.06×10^{4}	2.00×10^{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	20.007 d	6.63		2.52×10^{6}	1.01×10^{3}	2.86×10^{15}		1.01×10^{7}	6×10^{-10}	0.04	1.59×10^{-6}
^{254}Es	276 d	6.42		1.08×10^{5}	71.9	2.11×10^{12}		5.84×10^{5}	2×10^{-11}	0.02	1.08×10^{-5}
^{254m}Es	39.3 h		0.60	3.14×10^{5}	1.18×10^{3}		6.07×10^{14}		5×10^{-9}	0.02	6.37×10^{-8}
^{255}Es	39.8 d			1.20×10^{6}			7.06×10^{13}	4.92×10^{9}	4×10^{-10}	0.04	3.10×10^{-6}
^{256}Es	25 m			2.04×10^{7}			6.57×10^{16}				
^{254}Fm	3.24 h	7.20		3.81×10^{6}	1.68×10^{5}	4.31×10^{15}		2.03×10^{13}	0×10^{-6}	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}	5.05×10^{4}			6.43×10^{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] ^{241}Am decays by α emission (84%) and orbital capture (16%).

[e] ^{243}Am decays almost entirely by isomeric transition to the 10-hr ground state, ^{241}Am.

[f] ^{244m}Am decays primarily by α emission, but 0.030% 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	742.6	0	324
^{240}Pu	6580 y	290	0	8053	0.05	0	0
^{241}Pu	14.98 y	360	0	500	1011	0	541
^{242}Pu	3.869×10^{5} y	19.5	6.20	1200	0	0	0
^{243}Pu	4.955 h	80	0	0	220	0	0
^{244}Pu	0.28×10^{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
^{241}Am	7370 y	585	0	1500	0	0	0
^{242}Am	16.1 h	0	0	0	2700	0	0
^{242m}Am	26 m	0	0	0	0	0	0
$^{242c}Am^{a}$	49 m	0	9	0	1120	0	0
^{243}Am	2.07 h	0	0	0	0	0	0
^{244}Am	25.0 m	0	0	0	0	0	0
^{242}Cm	18.099 y	10.0	4.0	650	1.2	4.0	12.5
^{243}Cm	8385 y	343	2.4	120	1727	2.4	1140
^{244}Cm	4655 y	1.25	0	121	0	0	0
^{245}Cm	1.56×10^{7} y	60	0	500	120	0	1000
^{246}Cm	3.307×10^{5} y	3.56	2.0	170	0	0	0
^{247}Cm	64 m	2.0	0	0	50	0	0
^{248}Cm	1.74×10^{6} y	2	0	0	0	0	0
^{249}Bk	314 d	1451	2.4	1240	0	0	0
^{250}Bk	3.222 h	250	0	0	2000	0	0
^{251}Bk	57 m	0	0	0	0	0	0
^{249}Cf	352 y	450	1.46	750	1600	1.0	2920
^{250}Cf	13.08 y	1900	20	11460	0	0	0
^{251}Cf	900 y	2850	14	1600	3750	14	5400
^{252}Cf	2.646 y	19.0	0	44	32	0	110
^{253}Cf	17.812 d	12.6	0	0	1300	0	0
^{254}Cf	60.5 d	50	9	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	2060	0	0
^{254m}Es	39.3 h	1.26	0	0	1040	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	70	0	0	0	0	0
^{255}Fm	20.07 h	25	0	0	100	0	0
^{256}Fm	2.62 h		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, ^{242c}Am, which combines the properties of ^{242m}Am and ^{242}Am according to their relative rates of production from ^{241}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 $f_c = f_g + f_m = 1$.