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Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending June 30, 1975

L. J. King
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CHEMICAL TECHNOLOGY DIVISION

TRANSURANIUM PROCESSING PLANT SEMIANNUAL REPORT OF PRODUCTION, STATUS, AND PLANS FOR PERIOD ENDING JUNE 30, 1975

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

MARCH 1976

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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UNION CARBIDE CORPORATION
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SUMMARY

This is the fifteenth 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, 1975, through June 30, 1975, we recovered transuranium elements from 22 irradiated HFIR targets; products recovered are listed in Table 2.1 on p. 3. We separated 45 mg of high-purity ^{248}Cm from ^{252}Cf which had been recovered and purified during earlier periods; in addition, we separated 56 mg of a lower-quality ^{248}Cm from californium purification rework solutions. Fifty-three shipments were made from TRU during the period; recipients and the amounts of nuclides are listed in Table 2.2 on pp. 4-6. Five HFIR targets, each containing approximately 9 g of actinides (predominantly curium), were fabricated.

A new long-term projection showed that ^{252}Cf production in the TRU-HFIR complex could increase to as much as 2.5 g/year. This assumes the availability of adequate feed stocks and would require processing approximately 65 targets per year over a 10 year period. Our present budgeted rate is 25 targets per year.

During the next 18 months, we expect to recover totals of 46 mg of ^{249}Bk, 520 mg of ^{252}Cf, 2.0 mg of ^{253}Es (in a mixture of isotopes), 220 μg of high-purity ^{253}Es, and 1.6 pg of ^{257}Fm. We also expect to obtain 125 mg of high-purity ^{248}Cm from purified californium now in storage. There are no plans to process any of the remaining SRP Pu-Al 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 in the chemical processing flowsheets normally used at TRU during this report period. A new rack was installed in cubicle 4 which contains equipment that will be used for purification of curium by oxalate precipitation and for preparation of curium oxide microspheres by the resin loading--calcination method.[1]

Two neutron sources were fabricated, bringing the total fabricated to 77. Two sources that had been used previously in various projects were

returned to the TRU inventory and are available for reassignment. Two sources from the TRU inventory were assigned to new users during this report period. Accumulated data relating to the calibration of reference standards NSS-19 and NSS-62 were evaluated.

In special projects, we (1) produced about 1 mg of ^{250}Cf by irradiation of ^{249}Bk in HFIR rabbits, and (2) processed some irradiated ^{248}Cm samples and obtained yield and isotopic composition data for use in determining the capture cross section of ^{249}Cm in the HFIR.

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 fifteenth 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 (and are) 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 recovered and shipped are listed. Proposed processing schedules and anticipated yields of various products in the near future are outlined. Revisions made to plant equipment are described. The original and current contents (^{252}Cf and ^{248}Cm) of all neutron sources that have been made at TRU, as well as the individuals to whom these sources are currently loaned, are tabulated. Special processing, fabrication, and irradiation programs are described. Values of nuclear parameters which were used as input data for the calculations of production rates for transuranium elements, along with a listing of the parameters which were used to calculate the specific activities of the isotopes that are of interest to TRU, are included in the Appendix.

Previous reports in this series are:

(1) For period ending June 30, 1968 — ORNL-4376.
(2) For period ending December 31, 1968 — ORNL-4428.
(3) For period ending June 30, 1969 — ORNL-4447.
(4) For period ending December 31, 1969 — ORNL-4540.
(5) For period ending June 30, 1970 — ORNL-4588.
(6) For period ending December 31, 1970 — ORNL-4666.
(7) For period ending June 30, 1971 — ORNL-4718.
(8) For period ending December 31, 1971 — ORNL-4767.
(9) For period ending June 30, 1972 — ORNL-4833.
(10) For period ending December 31, 1972 — ORNL-4884.
(11) For period ending June 30, 1973 — ORNL-4921.

(12) For period ending December 31, 1973 — ORNL-4965.

(13) For period ending June 30, 1974 — ORNL-4991.

(14) For period ending December 31, 1974 — ORNL-5034.

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

During the period January 1, 1975, through June 30, 1975, we made two campaigns (Nos. 48 and 49) to recover the transuranium elements from 22 irradiated HFIR targets; products recovered are listed in Table 2.1. Eighteen of the processed targets had originally contained curium which had been recovered at TRU from materials irradiated at the Savannah River Plant (SRP). This was part of the SRP Californium-I campaign, an irradiation and processing campaign designed to obtain ^{252}Cf for use in the ^{252}Cf market evaluation program being conducted by the ERDA Division of Nuclear Fuel Cycle and Production (NFCP).

During this period, we also separated and purified two batches of ^{248}Cm. The product obtained from the first batch was 45 mg of high-purity ^{248}Cm with an isotopic composition of approximately 97% ^{248}Cm and 3% ^{246}Cm; this material was separated from ^{252}Cf which had been recovered and purified during earlier periods. The second batch product was 56 mg of lower-quality ^{248}Cm, with an isotopic composition of approximately 92% ^{248}Cm, 4% ^{246}Cm, and 4% ^{244}Cm; this material was recovered from rework solutions which had been accumulated in californium purification operations during the past 5 years.

Table 2.1. Amounts of materials recovered in the major campaigns in the Transuranium Processing Plant during the period January 1, 1975, through June 30, 1975

	Campaign number 48	Campaign number 49	Total
Completion date	April	June	
Material processed	12 Cf-I Cm-HFIR targets + rework	6 Cf-I Cm-HFIR targets, 4 TRU Cm-HFIR targets + rework	22 HFIR targets + rework
Amounts recovered			
^{243}Am, g[a]	0.7	1.3	2.0
^{244}Cm, g[a]	32(71)[b]	27(62)[b]	59(133)[b]
^{249}Bk, mg	24	27	51
^{252}Cf, mg	225	240	465
^{253}Es, mg	1.2	1.3	2.5
^{257}Fm, pg	0.7	0.7	1.4

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

Fifty-three shipments were made during this report period. Recipients and the amounts of nuclides are listed in Table 2.2.

Five HFIR targets were fabricated from actinide oxide prepared by the resin loading--calcination technique.[1] Each target contained approximately 9 g of actinide metals (predominantly curium) in the form of actinide oxide--aluminum pellets that had been pressed to 80% of theoretical density of the pellet core. This material had been recovered during TRU Campaign 48 and had an isotopic composition of approximately 48% ^{244}Cm, 0.5% ^{245}Cm, 45% ^{246}Cm, 1% ^{247}Cm, and 5.5% ^{248}Cm.

Table 2.2. Distribution of heavy elements from the Transuranium Processing Plant during the period January 1, 1975 — June 30, 1975

Major nuclide	Date	TRU file No.	Shipped to: Individual	Site
Curium-243 (56%), mg				
0.088	6-16-75	753	Isotopes Sales	ORNL
1.76	6-19-75	742	C. E. Bemis	ORNL
1.76	6-25-75	741	N. M. Edelstein	LBL
3.608				
Curium-244, g				
0.0103	2-18-75	744	M. M. Abraham	ORNL
0.238	6-18-75	752	R. P. Turcotte	PNL
0.2483				
Curium--mixed isotopes, mg				
0.362	2-12-75	751	N. M. Edelstein	LBL
Curium-245 (23%), mg				
0.211	2-12-75	745	N. M. Edelstein	LBL
0.191	3-05-75	747	R. Lanier	LLL
0.064	6-12-75	746	R. L. Hahn	ORNL
0.466				
Curium-247 (24%), mg				
0.017	3-05-75	750	R. Lanier	LLL
Curium-248 (97%), mg				
6.76	1-10-75	734	W. T. Carnall	ANL
6.76	1-10-75	735	N. M. Edelstein	LBL
6.76	1-10-75	736	R. W. Hoff	LLL
6.76	1-10-75	737	R. A. Penneman	LASL
6.76	1-22-75	738	R. L. Fellows	ORNL
0.24	4-30-75	757	F. P. Hungate	PNL
34.04				
Curium-248 (92%), mg				
5.0	4-22-75	552	W. T. Carnall	ANL
10.0	4-22-75	553	N. M. Edelstein	LBL
10.0	4-22-75	554	R. J. Silva	ORNL
15.0	4-22-75	767	R. W. Hoff	LLL
40.0				

Table 2.2 (continued)

Major nuclide	Date	TRU file No.	Shipped to: Individual	Site
Berkelium-249				
4.1	5-08-75	777	R. G. Haire	ORNL
4.1	5-09-75	774	W. T. Carnall	ANL
4.1	5-09-75	775	N. M. Edelstein	LBL
2.5	5-09-75	776	R. W. Hoff	LLL
7.83	5-29-75	778	Target Fabrication	ORNL
22.63				
Californium-249, mg				
1.09	6-17-75	786	R. G. Haire	ORNL
0.29	6-17-75	787	R. G. Haire	ORNL
1.09	6-18-75	783	W. T. Carnall	ANL
1.36	6-25-75	784	N. M. Edelstein	LBL
3.83				
Californium-250, mg				
1.1	4-16-75	766	R. Lanier	LLL
Californium-252, mg				
0.012	1-16-75	740	R. J. Silva	ORNL
0.00087(NZS-90)	1-28-75	733	J. R. Smith	Aerojet
0.731(NZD-31)	3-27-75	754	J. L. White	HEDL
35.539	4-08-75	723	A. R. Boulogne	SRL
0.015	4-10-75	765	R. J. Silva	ORNL
0.002	4-14-75	763	Isotopes Sales	ORNL
0.840(NSD-27)	4-16-75	726	L. C. Nelson, Jr.	New Brunswick
0.012	4-18-75	768	Target Fabrication	ORNL
12.687(NSD-89)	4-25-75	724	J. E. Powell	Sandia-NM
31.409	5-14-75	769	A. R. Boulogne	SRL
0.010	5-15-75	779	Target Fabrication	ORNL
31.894	5-29-75	770	A. R. Boulogne	SRL
39.613	6-11-75	771	A. R. Boulogne	SRL
32.238	6-18-75	755	A. R. Boulogne	SRL
185.00287				
Einsteinium-253, μg				
533	3-24-75	758	W. T. Carnall	ANL
350	3-27-75	759	R. G. Haire	ORNL
130	4-09-75	761	W. T. Carnall	ANL
4.3	4-15-75	760	F. P. Hungate	PNL
440	6-26-75	790	R. G. Haire	ORNL
0.04	6-30-75	791	W. J. McDowell	ORNL
1457.34				

Table 2.2 (continued)

Major nuclide	Date	TRU file No.	Shipped to: Individual	Site
Einsteinium-253 (milked), μg				
80	4-30-75	772	W. T. Carnall	ANL
10	4-30-75	773	R. W. Hoff	LLL
90				
Fermium-257, pg				
0.74[a]	4-09-75	762	E. K. Hulet	LLL

[a]Customer's assay.

2.2 Irradiation and Processing Proposals

The amounts of transcurium elements that will be produced at TRU during the next few years will depend on: (1) the needs of researchers for various isotopes, (2) the needs for ^{252}Cf in the NFCP Division's ^{252}Cf market evaluation and sales program, and (3) the capabilities of the TRU-HFIR complex to produce the required materials. In general, reasonable predictions can be made of the processing schedule for the near future. Table 2.3 outlines the estimated production of transcurium elements from a series of likely processing campaigns which are scheduled through 1976. Estimates for 1977 and 1978 are projections based on current trends. Normally, we would have scheduled one campaign during each of the three 6-month periods. However, the campaign which would have been scheduled for July to December 1975 was moved forward to June 1975, because the HFIR was shut down in June to replace the permanent beryllium reflector. The reactor was expected to be down for as long as 4 months.

A long-term projection of the capability of the TRU-HFIR complex to produce the "yardstick" isotope ^{252}Cf is illustrated in Fig. 2.1. Such long-term projections can only be made on an idealized basis in which carefully defined, irradiation-processing cycles are combined in a straightforward way.

The present projection is an improvement over previous projections[2] because the individual irradiation-processing cycles are separately optimized. The basis of optimization is the amount of californium produced per unit of potential californium consumed, both in the irradiation and in the processing steps. (The concept of potential californium refers to the amount of californium that could ultimately be produced from a given starting material by the most efficient scheme imaginable.) The results of the individual optimized cycle calculations are then combined into an overall recycle-reprocessing scheme that is flexible enough to accommodate variations in cycle length, and yet is sufficiently idealized to be calculable. Note that the concept of potential californium is used only to select the optimum length of an irradiation cycle. It does not enter into the calculation of product yield once that cycle length has been chosen.

Table 2.3. Estimated future production of transcurium elements

Period	Processing campaign	Products of campaigns				^{252}Cf production[b]		Date products available
		^{249}Bk (mg)	^{252}Cf (mg)	^{253}Es[a] (μg)	^{257}Fm (pg)	During the period (mg)	Cumul. (mg)	
Through June 1975							1674[b]	
July-December 1975						0	1674	
January-June 1976	10 Cf-I Cm-HFIR Targets	22	260	1000(110)	0.8	260	1934	February 1976
July-December 1976	{5 Cf-I Cm-HFIR Targets, 5 TRU Cm-HFIR Targets}	24	260	1000(110)	0.8	260	2194	October 1976
1977						500	2694	
1978						500	3194	

[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.

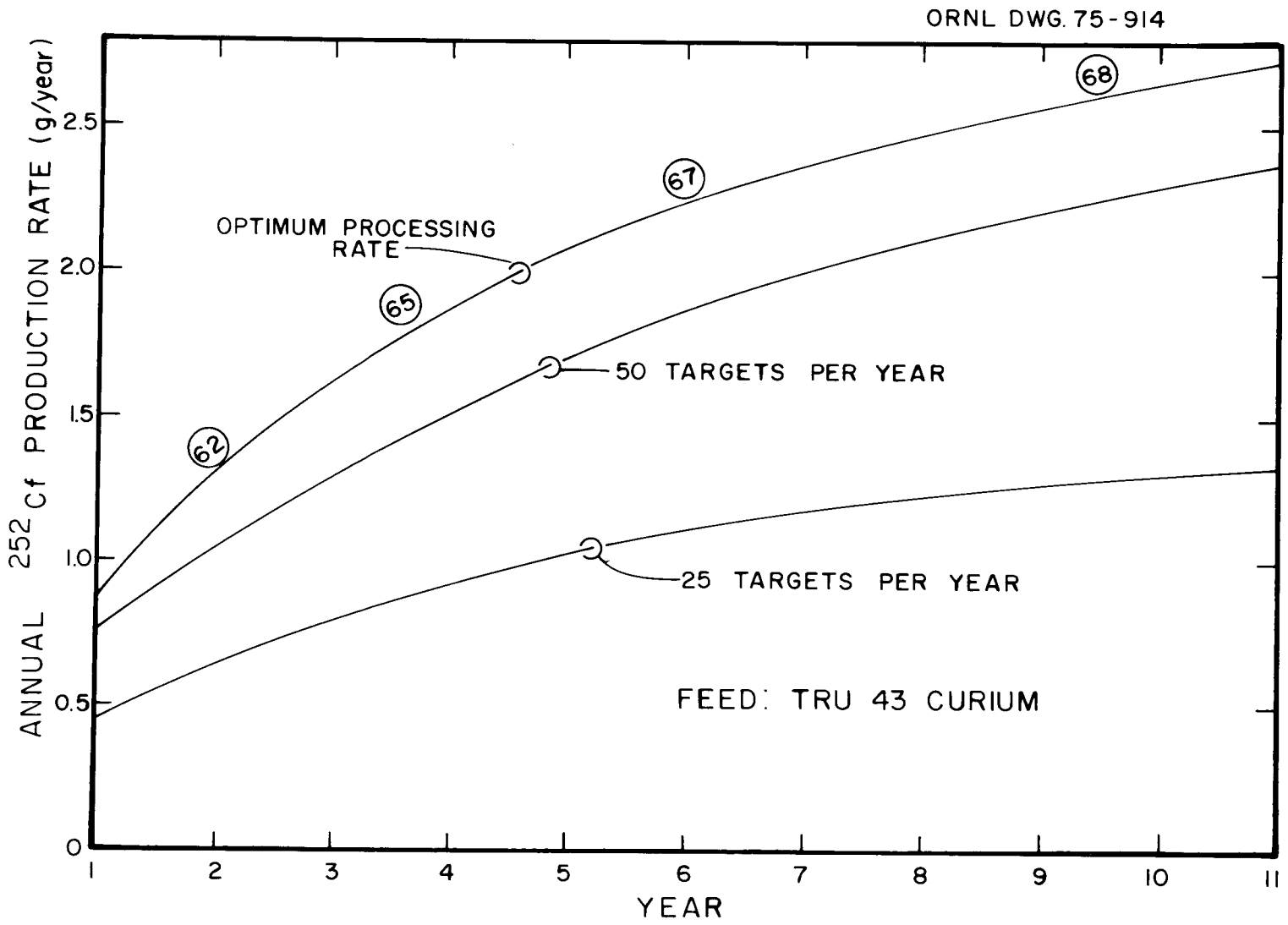

Fig. 2.1. Projected californium production rate.

Evidence to date suggests that this basis for optimizing individual cycles results in a projection of californium production that probably represents very closely the maximum amount of ^{252}Cf that can be produced from feed of a given quality.

The upper curve in Fig. 2.1 shows such a maximum output for a curium feed quality which is roughly equivalent to that resulting from the Cf-I program at SRP. However, the amount of feed that is available could not sustain such a program for more than a few years. The numbers in circles at the top curve indicate the annual target processing rate that would be required to reach the optimum production level. The two lower curves show the production rate attainable when the throughput is limited to 25 or 50 targets per year. At the present time, we are operating at the level of 25 targets per year.

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 46 mg of ^{249}Bk, 520 mg of ^{252}Cf, 2.0 mg of ^{253}Es (in a mixture of isotopes), 220 μg of high-purity ^{253}Es, and 1.6 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 Californium-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, 1975, TRU had an inventory of purified californium in several batches, which contained totals of 608 mg of ^{252}Cf and 177 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 and 3% ^{246}Cm. The ^{246}Cm "impurity" is produced by decay of ^{250}Cf, which is present in the californium. We expect to obtain 50 mg of high-purity ^{248}Cm in November 1975, and an additional 75 mg during 1976.

3. PROCESSES AND EQUIPMENT

There have been no changes in the chemical processing flowsheets normally used at TRU during this report period. The condition of chemical processing equipment at TRU is generally good, and the equipment is continually maintained. When replacements are necessary, modifications are usually included to provide improved capability and performance.

During this report period, we installed a new rack in cubicle 4 containing equipment that will be used for both the purification of curium by oxalate precipitation and the preparation of curium oxide microspheres by the resin loading--calcination method.[1]

4. CALIFORNIUM NEUTRON SOURCES

Some of the californium recovered at TRU is incorporated into neutron sources, which are subsequently loaned to researchers. Data for all of the 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. 5, 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. 5.

Table 4.1 Data for neutron sources prepared at TRU

Source	Date of calibration	^{252}Cf Content at calibration (μg)	Content as of 6/30/75 ^{252}Cf (μg)	Content as of 6/30/75 ^{248}Cm (μg)	On loan to: Individual	On loan to: Site
NS-1[a]	8-28-68	316	53	b	K. L. Swinth	PNL
NS-2	8-23-68	254	42	b	c	
NS-3	5-13-69	∿90	∿18	b	G. I. Gleason	ORAU
NS-4	7-09-69	883	185	666	C. F. Masters	LASL
NS-5[d]	8-14-69	946	203	709	F. B. Simpson	ANC
NS-6	11-21-69	747	172	548	R. W. Hoff	LLL
NS-7	1-21-70	788	190	571	c	
NS-8	12-17-69	1839	432	1342	H. Berger	ANL
NSD-9	4-17-70	1720	440	1220	N. D. Wogman	PNL
NSS-10	3-11-70	113	28	b	J. P. Balagna	LASL
NS-11	3-10-70	8	2	b	R. R. Fullwood	LASL
NSS-12	6-30-70	1868	504	1301	R. W. Hoff	LLL
NSD-13	3-19-71	4649	1514	2989	H. O. Menlove	LASL
NSS-14	6-29-70	4615	1245	3214	D. C. Stewart	ANL
NS-15[d]	6-25-70	931	250	649	F. B. Simpson	ANC
NSD-16	10-08-70	1657	481	1122	c	
NSS-17	8-31-71	4886	1791	2951	L. W. Dahlke	Sandia-Livermore
NS-18[d]	6-24-70	962	259	671	F. B. Simpson	ANC
NSS-19	6-26-70	493	133	344	J. E. Bigelow	ORNL-TRU
NSD-20	7-01-70	630	170	439	J. E. Powell	Sandia-NM
NSS-21	10-21-70	18	5	b	F. Cross	PNL
NS-22	9-10-70	13	4	b	J. E. Bigelow	ORNL-TRU
NSD-24	10-15-70	6	2	b	J. E. Rushton	ORNL
NS-25	11-09-70	58	17	b	F. J. Muckenthaler	ORNL
NSD-26	2-11-71	14	4	b	H. O. Menlove	LASL
NSD-27	1-29-71	2528	795	1653	L. C. Nelson, Jr.	New Brunswick
NSD-28	2-12-71	11	3	b	E. E. Hicks	Rocky Flats
NSD-29	9-10-71	11393	4207	6853	S. G. Snow	Y-12
NSD-30	3-31-71	879	289	563	c	
NZD-31	11-23-71	1733	675	1009	J. L. White	HEDL
NZD-32	11-23-71	1800	701	1048	c	
NZD-33	11-23-71	1888	735	1099	c	
NZD-34	11-23-71	1924	749	1120	W. G. Spear	HEDL
NZD-35	11-23-71	1904	741	1109	c	
NS-36[d]	3-23-71	2070	676	1329	F. B. Simpson	ANC
NSD-37	9-04-71	9838	3617	5932	R. W. Perkins	PNL
NSD-38	6-16-71	102	35	b	H. O. Menlove	LASL
NS-39	11-07-71	942	363	553	V. Spiegel	NBS
NSD-40	4-27-72	1161	506	625	J. B. Storer	ORNL-Biology
NSD-41	11-08-71	5117	1971	3000	C. J. Emert	BAPL
NSD-42	11-02-71	4434	1701	2606	C. J. Emert	BAPL
NSD-43	4-20-72	4839	2097	2615	C. J. Emert	BAPL
NZD-44	5-15-72	10731	4734	5719	F. B. Simpson	ANC

Table 4.1 (continued)

Source	Date of calibration	^{252}Cf Content at calibration (μg)	Content as of 6/30/75 ^{252}Cf (μg)	Content as of 6/30/75 ^{248}Cm (μg)	On loan to: Individual	On loan to: Site
NSD-45	8-18-71	1776	645	1078	K. L. Swinth	PNL
NSD-46	4-23-72	629	273	339	H. O. Menlove	LASL
NSD-47	7-14-71	200	71	123	P. L. Johnson	Mound
NSD-48	7-14-71	194	69	119	J. E. Rushton	ORNL
NSD-49	7-14-71	199	70	123	c	
NS-50	8-23-71	138	50	84	S. G. Carpenter	ANL-NRTS
NSD-51	11-02-71	365	140	215	c	
NSD-52	9-02-71	280	103	169	E. D. Clayton	PNL
NSD-53	10-25-71	1051	401	620	L. J. Esch	KAPL
NS-54	1-19-73	3187	1681	1436	V. Spiegel	NBS
NSD-55	4-19-72	4	2	b	L. J. Esch	KAPL
NSD-56	4-19-72	121	52	65	L. J. Esch	KAPL
NSD-57	4-14-72	973	420	528	c	
NZD-58	5-15-72	11003	4854	5864	F. B. Simpson	ANC
NS-59	7-13-72	53	24	b	G. E. Hanson	LASL
NSD-60	4-11-72	20	9	b	F. F. Haywood	ORNL-DOSAR
NSD-61	1-19-73	5225	2756	2355	L. J. Esch	KAPL
NSS-62	3-27-73	3755	2078	1599	J. E. Bigelow	ORNL-TRU
NSD-63	4-21-72	847	367	457	H. O. Menlove	LASL
NSD-64	7-19-73	193	116	74	H. O. Menlove	LASL
NS-65	7-09-73	114	68	44	L. Green	BAPL
NSD-66	8-02-73	3449	2092	1294	J. E. Powell	Sandia-NM
NSD-73	9-11-73	13545	8455	4854	G. I. Gleason	ORAU
NSD-74	9-11-73	4416	2757	1582	G. I. Gleason	ORAU
NS-75	10-01-73	1919	1215	671	R. J. Kloepping	LLL
NSD-76	3-09-74	434	308	120	P. L. Johnson	Mound
NSD-77	3-09-74	433	307	120	P. L. Johnson	Mound
NSD-78	3-09-74	429	304	119	P. L. Johnson	Mound
NS-79	10-02-74	1650	1359	278	V. Spiegel	NBS
NSD-80	6-03-74	5966	4504	1394	C. J. Emert	BAPL
NSD-81	6-03-74	6364	4804	1487	C. J. Emert	BAPL
NSD-89	4-23-75	12687	12083	576	J. E. Powell	Sandia-NM
NZS-90	1-16-75	0.87	<1	b	J. R. Smith	ANC
SR-Cf-167[e]	5-26-71	3975	1359	2494	c	

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

4.1 Sources Fabricated During January-June 1975

Two standard TRU sources, NSD-89 and NZS-90, were fabricated during this report period. In addition, a quartz-bead type neutron source containing 0.15 μg of ^{252}Cf was prepared; we did not assign an identification number to this source because the bead was not encapsulated.

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 reprocessing to recover the ingrown ^{248}Cm. Eleven sources that contain from 42 to 1359 μg of ^{252}Cf are now in this category and are so designated in Table 4.1. Sources NSD-30 and NSD-51 were returned, and sources NSD-27 and NZD-31 were reloaned during this report period.

Before shipping NZD-31, we modified the source housing to meet the requirements of the new user. The source as originally prepared had a tang on the bottom (like a screw driver blade). This tang was removed, the source was attached to a handling rod furnished by the customer, and was loaded into the customer's DOT Specification 7A container. Initially, the radiation readings did not meet levels for unrestricted shipment, but after the addition of a tungsten shell around the source, the limit was met.

4.3 Calibration of Neutron Source Reference Standards NSS-19 and NSS-62

Data relating to the calibration of NSS-19 (344 μg of ^{252}Cf) and NSS-62 (1599 μg of ^{252}Cf) were evaluated. We have received calibration data on three TRU neutron sources which we had sent to the National Bureau of Standards. These sources are NS-39, NS-54, and NS-75. Each of these had been compared with NSS-19 at the time they were shipped from TRU. Using the most recent techniques, we recalculated the corrections for dead-time and background found in the earlier results. Three values, based on NBS

counting data on NS-39, NS-54, and NS-75, were then determined for the ^{252}Cf content of NSS-19. These three values corresponded to source strengths of 4.7068×10^8, 4.7177×10^8, and 4.7137×10^8 neutrons/sec, respectively. The average and standard deviation of these numbers are $4.7127 \times 10^8 \pm 0.12\%$, and the standard deviation on the estimation of the mean is only 0.068%. This new calibration differed from the old calibration (which had been based on a preliminary value for only NS-39) by only 0.047%, a fortuitously small amount. Californium assays made in the future will be based on this new standard, but no effort will be made to systematically update old assays.

Following the readjustment of NSS-19 calibration, we examined the records for 21 intercomparisons of NSS-19 and NSS-62 that dated back to March 24, 1973. These data were also recalculated (where necessary) using the best techniques for dead-time and background corrections. After consideration of the statistics, we discarded the four points in which the counts were made in position E on the bar used to position sources relative to the fast-neutron detectors because the count rate for NSS-19 was too low in this position.

The means for count rate ratios in positions C and D on the bar differed by only 0.13%, so these results were pooled. The average ratio of source strengths of NSS-62/NSS-19 was then found to be 15.6275, with a standard deviation of 0.55%. The standard deviation of the estimate of the mean was 0.13%.

With these excellent results, we can now regard NSS-62 as being well calibrated, and it will take its place as the "workhorse" reference standard at TRU. However, we will still use NSS-19 for calibration of sources containing less than about 0.5 mg of ^{252}Cf.

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[6] 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 Irradiation of ^{249}Bk to Produce ^{250}Cf

Approximately 1 mg of ^{250}Cf was prepared for LASL in two cycles of fabrication, irradiation, and processing of HFIR rabbits containing ^{249}Bk. The preparation of BkO_2-MgO microspheres for these rabbits and the processing of the irradiated materials were accomplished with techniques which have been described previously.[7] In the present series of runs, we encountered some difficulties with plugging of the high pressure ion exchange column during the stripping operation. This plugging was attributed to the larger quantity of magnesium present from processing more than one rabbit at a time.

In the first cycle, three rabbits were irradiated 16 hr at a thermal flux of 3×10^{15} neutrons cm^{-2} sec^{-1}. The ^{250}Cf produced (690 μg) was separated from the residual ^{249}Bk (3.3 mg) by means of a high pressure ion exchange run which was made within 30 hr after discharge of the rabbits from the reactor. After purification of the residual ^{249}Bk, two second-cycle rabbits, containing a total of 2.9 mg of ^{249}Bk, were fabricated, irradiated, and processed. The ^{250}Cf products from both cycles of production were combined, purified, packaged, and shipped. The final product consisted of 1.14 mg of ^{250}Cf with the isotopic composition shown in Table 5.1. The amount of residual ^{249}Bk recovered from processing the second-cycle rabbits was 1.6 mg.

Table 5.1. Composition of ^{250}Cf product

Batch identification code	3H12-Cf-prod.
Date of analysis	March 26, 1975
Nuclide	Isotopic composition (atom %)
^{249}Cf	3.62
^{250}Cf	89.22
^{251}Cf	6.48
^{252}Cf	0.678
^{253}Cf	<0.002
^{254}Cf	<0.002

5.2 Phoenix Capsule Processing

Two small containers, called "Phoenix" capsules, were built several years ago to house some ^{248}Cm for an experimental irradiation in the HFIR. The purpose of the experiment was to determine the capture cross section of ^{249}Cm. Each "Phoenix" capsule was a Zircaloy-2 cylinder (0.25-in.-diam by 1-in. long with threaded end plugs) which contained a quartz ampul. A solution containing a total of 150 μg of ^{248}Cm had been dried and flamed into the quartz ampuls. After fabrication, the "Phoenix" capsules were enclosed within a standard-sized HFIR target rod and irradiated in the HFIR core at a flux of 3×10^{15} neutrons cm^{-2} sec^{-1}. After removal of the target rod from the reactor, the "Phoenix" capsules were physically removed from the rod and encapsulated into a new rod for further irradiation. The capsules were irradiated in three different target rods for a total irradiation period of about 1 year. During this report period, the capsules were opened and the quartz ampuls were removed and chemically processed to obtain yield and isotopic composition data.

The quartz ampuls were jointly crushed and ground to a small particle size and were then leached with nitric acid to dissolve the actinide elements.

The leach solution was processed by means of a high-pressure ion exchange run to separate curium from californium. The curium product contained 2.6 μg of ^{244}Cm, as determined by alpha counting techniques. A mass spectrographic analysis showed that the curium contained 6.7 μg of ^{248}Cm and 125 pg of ^{250}Cm.

Using the exact irradiation history of the capsules, a series of calculations was made to determine the best value for the ^{249}Cm capture cross section. Most of the ^{249}Cm decays to ^{249}Bk with a 64-min half-life; thus, only a small fraction (about 5×10^{-5}) captures a neutron and becomes long-lived ^{250}Cm. In a long irradiation such as the approximately 1-year period used in this experiment, one must consider the possibility that the ^{250}Cm absorbs a neutron and is destroyed. Therefore, the calculations were made over a range of assumed absorption cross sections for ^{250}Cm. The assumed values of σ_a (^{250}Cm) and the corresponding values of σ_c (^{249}Cm) which yielded the observed composition are tabulated below. It will be necessary to make other irradiations to determine these two values separately.

σ_a(^{250}Cm), b (assumed)	σ_c(^{249}Cm), b (calculated)
2	1.25
8	1.59
20	2.43
50	5.27
200	24.0

These results are rather remarkable when compared with the analogous cross sections of other curium isotopes shown in Table 5.2.

Table 5.2. HFIR Effective capture cross sections

Even isotopes	Barns	Odd isotopes	Barns
^{242}Cm	20	^{243}Cm	225
^{244}Cm	43	^{245}Cm	349
^{246}Cm	7.4	^{247}Cm	85
^{248}Cm	12.2	^{249}Cm	1.6[b]
^{250}Cm	8[a]		

[a]Assumed value comparable to other even isotopes.

[b]Resulting value significantly lower than that for other odd isotopes.

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[8-14] 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		$(2.14 \pm 0.01) \times 10^{6}$ y		$>10^{18}$ y	2.00[d]	60Br12, 61Dr04
^{238}Np	2.10 ± 0.01 d					50Fr53
^{239}Np	2.359 ± 0.010 d					59Co93
^{240}Np	63 ± 2 m					60Le03
^{240m}Np	7.3 ± 0.3 m					48Hy61
^{241}Np	16 m					60Le03
^{241m}Np	3.4 h					60Le03
^{238}Pu	87.404 ± 0.041 y			$(5 \pm 0.6) \times 10^{10}$ y	2.33 ± 0.08	61Dr04, 68Jo15, 56Hi01
^{239}Pu		$(2.4413 \pm 0.003) \times 10^{4}$ y		5.5×10^{15} y	2.24[d]	52Se67, 59Ma26
^{240}Pu		6580 ± 40 y		$(1.340 \pm 0.015) \times 10^{11}$ y	$2.177 \bullet 0.009$	51In03, 62Wa13, 68Bo54
^{241}Pu	14.98 ± 0.33 y	$(5.72 \pm 0.1) \times 10^{5}$ y				68Ca19, 60Br15
^{242}Pu		$(3.869 \pm 0.016) \times 10^{5}$ y		$(7.45 \pm 0.17) \times 10^{10}$ y	2.166 ± 0.009	63Ma50, 69Be06, 68Bo54
^{243}Pu	4.955 ± 0.003 h					68Di09
^{244}Pu		$(8.28 \pm 0.10) \times 10^{7}$ y		$(6.55 \pm 0.32) \times 10^{10}$ y	2.84[d]	66Fi07, 69Be06
^{245}Pu	10.6 ± 0.4 h					56Bu92
^{246}Pu	10.85 ± 0.02 d					56Ho23
^{241}Am		432.7 ± 0.7 y		$(2.3 \pm 0.8) \times 10^{14}$ y	2.48[d]	61Dr04, 67Oe01
^{242}Am	16.01 ± 0.02 h		$EC/\beta = 0.19$			53Ke38
^{242m}Am	144 ± 7 y	$(2.92 \pm 0.15) \times 10^{4}$ 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					55En16
^{246m}Am	40 ± 7 m					67Or02
^{247}Am	24 ± 3 m					67Or02
^{242}Cm	162.7 ± 0.1 d			7.2×10^{6} y	2.65 ± 0.09	51Ha87, 57Pe52, 56Hi01
^{243}Cm		32 y				57As70
^{244}Cm	18.099 ± 0.015 y		$\alpha/SF = (7.43 \pm 0.01) \times 10^{5}$		2.84 ± 0.09	65Me02, 68Be26, 56Hi01
^{245}Cm		8265 ± 180 y				69Me01
^{246}Cm		4655 ± 40 y	$\alpha/SF = 3822 \pm 10$		3.08[d]	69Me01, 71Mc19
^{247}Cm		$(1.56 \pm 0.05) \times 10^{7}$ y				71Fi01
^{248}Cm		$(3.703 \pm 0.032) \times 10^{5}$ y		$(4.115 \pm 0.034) \times 10^{6}$ y	3.32[d]	71Mc19
^{249}Cm	64 ± 3 m					58Ea06
^{250}Cm				$(1.74 \pm 0.24) \times 10^{4}$ y	3.56[d]	66RG01

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		$\alpha/\beta = (1.45 \pm 0.08) \times 10^{-5}$	$(1.87 \pm 0.09) \times 10^{9}$ y	3.72 ± 0.16	57Ea01, 69Mi08, 64Py02
^{250}Bk	3.222 ± 0.005 h					59Va02
^{251}Bk	57 ± 1.7 m					66RG04
^{249}Cf		352 ± 6 y	$\alpha/SF = (1.992 \pm 0.040) \times 10^{8}$		3.44[d]	69Me01, 69Mi08
^{250}Cf		13.08 ± 0.09 y	$\alpha/SF = 1260 \pm 40$		3.56[d]	63Ph01, 69Me01
^{251}Cf		900 ± 50 y				69Me01
^{252}Cf	2.646 ± 0.004 y		$\alpha/SF = 31.3 \pm 0.2$		3.796 ± 0.031	65Me02, 68Wh04
^{253}Cf	17.812 ± 0.082 d		$\alpha/\beta = (3.1 \pm 0.4) \times 10^{-3}$			69Dr02, 66RG01
^{254}Cf	60.5 ± 0.2 d		$\alpha/SF = (3.10 \pm 0.16) \times 10^{-3}$		3.90 ± 0.14	63Ph01, 64Py02, 68Be21
^{255}Cf	1.5 ± 0.5 h					70Lo19
^{253}Es	20.467 ± 0.024 d		$\alpha/SF = (1.15 \pm 0.03) \times 10^{7}$		3.92[d]	65Me02, 69Dr02
^{254}Es	276 d			$>2.5 \times 10^{7}$ y	4.04[d]	67Fi03, 67Un01
^{254m}Es	39.3 ± 0.2 h		$\beta/\alpha = 382 \pm 30$ $E.C./\beta = 0.00078 \pm 0.00006$			62Un01, 63Ph01
^{255}Es	39.8 ± 1.2 d		$\alpha/\beta = 0.0866 \pm 0.0043$ $\beta/SF = (2.22 \pm 0.10) \times 10^{4}$		4.16[d]	66RG01, 67Fi03
^{256}Es	25 ± 3 m					68Lo11
^{254}Fm	3.24 ± 0.01 h		$\alpha/SF = 1695 \pm 8$		4.05 ± 0.19	56Jo09, 67Fi03, 56Ch83
^{255}Fm	20.07 ± 0.07 h		$SF/\alpha = (2.4 \pm 1.1) \times 10^{-7}$		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:

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

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)		Specific Activity					Hazard[b]		
		α	β	(Ci/g)	(W/g)	(α cpm/mg[c])	(β dpm/mg)	(Neutrons min^{-1} mg^{-1})	$MPC_a(40)$ ($\mu Ci/cm^3$)	Body Burden (μCi)	Body Burden (μg)
^{237}Np	2.14×10^6 y	4.78		7.07×10^{-4}	2.07×10^{-5}	8.01×10^5		$<7 \times 10^{-6}$	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	5.86×10^2		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			4.86×10^7			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	2.32×10^{-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	14.98 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^{-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	2.69×10^{-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	4.91×10^4	66.9		1.09×10^{14}				
^{241}Am	432.7 y	5.48		3.43	0.1145	3.88×10^9		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	I.T.	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}	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}		6.87×10^5	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		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}	1.05×10^5			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 [redacted]		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	Energies of Prin. Emissions (MeV) β	Specific Activity (Ci/g)	Specific Activity (W/g)	Specific Activity (α cpm/mg[c])	Specific Activity (β dpm/mg)	(Neutrons min^{-1} mg^{-1})	Hazard[b] MPC[a](40) (μCi/cm^3)	Hazard[b] Body Burden (μCi)	Hazard[b] 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	9.80×10^{-3}
^{250}Cf	13.08 y	6.03		109	4.06	1.23×10^{11}		6.85×10^8	5×10^{-12}	0.04	3.70×10^{-4}
^{251}Cf	900 y			1.59	5.79×10^{-2}	1.78×10^9			2×10^{-12}	0.04	2.50×10^{-2}
^{252}Cf	2.646 y	6.11		536	39.0	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^{13}		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}		$<5.04 \times 10^5$	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}	4.92×10^9	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}		1.36×10^9	1×10^{-8}	0.04	6.53×10^{-8}
^{256}Fm	2.62 h			4.67×10^6	5.85×10^6			4.43×10^{16}	2×10^{-9}	0.0008	1.71×10^{-10}
^{257}Fm	94 d			5.41×10^3	~200	6.12×10^{12}					
^{258}Fm	380 μs			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 β emission, but 0.039% 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	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 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) $N_c = N_g + N_m$,

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

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

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

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

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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