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Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending December 31, 1973

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

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CHEMICAL TECHNOLOGY DIVISION

TRANSURANIUM PROCESSING PLANT SEMIANNUAL REPORT OF
PRODUCTION, STATUS, AND PLANS FOR PERIOD ENDING DECEMBER 31, 1973

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

NOVEMBER 1974

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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SUMMARY

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

During the period July 1, 1973, through December 31, 1973, we recovered transuranium elements from 10 irradiated HFIR targets; products recovered are listed in Table 2.1 on p. 3. In addition, we repurified 77 g of ^{244}Cm (81 g of curium) for the Heat Source Program at the ORNL Isotopes Division, and began a campaign to recover transuranium elements from accumulated rework materials. In product finishing operations, we processed 2 g of ^{243}Am , 92 g of ^{244}Cm (160 g of curium), 221 mg of ^{252}Cf , 737 μg of ^{253}Es (mixed isotopes), 183 μg of high-purity ^{253}Es , and approximately 0.5 μg of ^{257}Fm . Thirty-five shipments were made from TRU during the period; recipients and the amounts of nuclides are listed in Table 2.2 on pp. 4 and 5. Eleven HFIR targets, each containing 7 to 9 g of actinides (predominantly curium), were fabricated.

During the next 18 months, we expect to recover totals of 50 mg of ^{249}Bk , 555 mg of ^{252}Cf , 2.3 mg of ^{253}Es (in a mixture of isotopes), 255 μg of high-purity ^{253}Es , and 1.5 μg of ^{257}Fm . Also, we expect to obtain 75 mg of high-purity ^{248}Cm from purified californium now in storage. Currently, we do not plan 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. In maintenance operations, one of the three sampler equipment racks (Cubicle 7) was replaced. The new rack contains an improved transfer system that utilizes vacuum tanks in place of pumps. Six of the eight glass windows in the Equipment Decontamination Glove Box were replaced with Rowlex (polycarbonate) windows, each equipped with a new glove system — La Calhene J2L Containment Elements, Type 33 — distributed by Central Research Laboratories, Inc.

Six neutron sources were fabricated, bringing the total fabricated to 69; 4 sources that had been used in various projects were returned to TRU for reassignment or reprocessing.

In special projects, a new experimental facility designed to hold a standard HFIR target in one of the VXF holes of the HFIR beryllium reflector was approved; a special target, ST-8, which contained several samples and flux monitors, was fabricated and irradiated in the VXF facility. A new technique using magnesium diluent was developed and used to fabricate milligram amounts of ^{249}Bk into HFIR hydraulic rabbit capsules for production of ^{250}Cf ; approximately 372 μg of ^{250}Cf was obtained. In addition, a quartz ampul containing 1.8 mg of ^{152}Sm was encapsulated into a standard rabbit capsule, irradiated in HFIR, and shipped to ANL.

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 twelfth 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 definitely established 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. Work done this period toward improvement of plant equipment is 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.

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 when we do not stipulate otherwise.

2.1 Processing Summary

During the period July 1, 1973, through December 31, 1973, we made one campaign (No. 45) to recover the transuranium elements from ten irradiated HFIR targets; products recovered are listed in Table 2.1. In addition, one campaign (No. 44) was made to repurify 77 g of ^{244}Cm (81 g of curium) for the Heat Source Program at the ORNL Isotopes Division; another campaign (No. 41) was begun specifically to recover transuranium elements from accumulated rework materials. The ten HFIR targets processed during TRU Campaign No. 45 had originally contained curium which had been recovered at TRU from materials irradiated at Savannah River; this was part of the Californium-I program, a sales program for ^{252}Cf , sponsored by the AEC Division of Production and Materials Management (PMM).

Product finishing operations normally include: (1) final purification and packaging of the transcurium elements; (2) separation, purification, and packaging of daughter products (high-purity ^{248}Cm , ^{249}Cf , and ^{253}Es); and (3) final purification of the plutonium and americium-curium products (americium and curium are not normally separated) followed by conversion of the actinide elements to the oxide form for use in HFIR targets. During this report period, we purified some of the products from target Campaign No. 45, from previous campaigns, and from various rework materials. The amounts of materials undergoing product finishing operations included 2 g of ^{243}Am , 92 g of ^{244}Cm (160 g of curium), 221 mg of ^{252}Cf , 737 μg ^{253}Es (mixed isotopes), 183 μg of high-purity ^{253}Es , and

Table 2.1 Amounts of Materials Recovered in the Major Campaign
in the Transuranium Processing Plant During the Period
July 1, 1973, Through December 31, 1973

		Campaign Number 45
Completion date		October
Material processed		10 Cf-I Cm- HFIR Targets + Rework
Amounts recovered		
²⁴³ Am, g ^a		0.8
²⁴⁴ Cm, g ^a		43 (81) ^b
²⁴⁹ Bk, mg		21
²⁵² Cf, mg		225
²⁵³ Es, mg		1.2
²⁵⁷ Fm, pg		0.5

^aAmericium and curium are not usually separated from each other.

^bThe amount shown in parentheses is total curium.

about 0.5 pg of ²⁵⁷Fm. We also began the separation of high-purity ²⁴⁸Cm from ²⁵²Cf that had been recovered and purified during earlier periods.

Thirty-five shipments were made during this report period; recipients and the amounts of nuclides are listed in Table 2.2. Three of the shipments were comprised of materials that had been previously shipped, but had been returned for reshipment. Two shipments contained the curium that had been repurified for the ORNL Isotopes Division.

Eleven HFIR targets were fabricated from actinide oxide prepared by the resin loading--calcination technique. Each target contained 7 to 9 g of actinide metals (predominantly curium) in the form of actinide oxide--aluminum pellets that had been pressed to 80% of the theoretical density of the pellet core. Isotopic composition of the curium in the targets

Table 2.2. Distribution of Heavy Elements from the
Transuranium Processing Plant During the Period
July 1, 1973 - December 31, 1973

Major Nuclide	Date	TRU File No.	Shipped To:	
			Individual	Site
Samarium-153, Ci				
200	10-30-73	663	A. M. Friedman	ANL
Curium-244, g				
40.4 ^a	8-02-73	652	T. A. Butler	ORNL
36.6 ^a	8-24-73	653	T. A. Butler	ORNL
0.000135	8-31-73	655	J. R. Peterson	ORNL
<u>77.000135</u>				
Berkelium-249, mg				
4.0	7-02-73	644	T. D. Chikalla	PNL
0.36	7-18-73	651	R. A. Penneman	LASL
0.8 ^b	7-26-73	582C	R. J. Silva	ORNL
<u>4.36</u>				
Californium-249, mg (isotopically pure)				
2.75	7-18-73	590	R. A. Penneman	LASL
Californium-250 (90%), mg				
0.237	9-10-73	641	C. E. Bemis, Jr.	ORNL
0.135	10-12-73	642	W. T. Carnall	ANL
<u>0.372</u>				
Californium-252, mg				
0.114 (NS-65)	7-13-73	624	L. Green	BAPL
0.611 (NSD-63)	7-20-73	623	H. O. Menlove	LASL
0.193 (NSD-64)	7-20-73	623	H. O. Menlove	LASL
0.01	7-30-73	650	Isotopes Sales	ORNL
0.281 (NSD-20) ^c	8-06-73	625	J. E. Powell	Sandia, NM
3.45 (NSD-66)	8-06-73	625	J. E. Powell	Sandia, NM
0.007	8-07-73	637	R. C. Greenwood	ANC
13.54 (NSD-73)	9-17-73	626	G. I. Gleason	ORAU
4.42 (NSD-74)	9-17-73	626	G. I. Gleason	ORAU
30.42	9-26-73	633	A. R. Boulogne	SRL
0.005	10-03-73	646	Isotopes Sales	ORNL

Table 2.2 (continued)

Major Nuclide	Date	TRU File No.	Shipped To:	
			Individual	Site
Californium-252, mg (continued)				
0.009	10-03-73	654	Isotopes Sales	ORNL
1.919 (NS-75)	10-19-73	628	V. Spiegel	NBS
1.861 (NS-75) ^d	11-13-73	628	V. Spiegel	NBS
0.105 (NS-65) ^d	11-30-73	624	L. Green	BAPL
<u>54.698</u>				
Californium-252 (97%), mg				
0.001	7-26-73	639	Isotopes Sales	ORNL
0.0005	7-26-73	649	Isotopes Sales	ORNL
0.01	7-30-73	638	Isotopes Sales	ORNL
<u>0.0115</u>				
Einsteinium-253, µg				
7.5	10-17-73	602	F. P. Hungate	PNL
200	10-17-73	658	W. T. Carnall	ANL
70	10-17-73	662	K. W. MacMurdo	SRL
186	10-23-73	660	R. G. Haire	ORNL
<u>463.5</u>				
Einsteinium-253, µg (isotopically pure)				
108	11-14-73	665	R. G. Haire	ORNL
75	11-26-73	664	R. W. Hoff	LLL
<u>183</u>				
Fermium-257, pg				
0.43 ^e	10-19-73	610	W. T. Carnall	ANL

^aThis is Heat Source Program material being returned to the ORNL Isotopes Division after repurification at TRU.

^bThis shipment consists of material previously shipped as No. 582B; it was not included in the total.

^cThis source had been previously shipped to another user. The current contents are shown, but are not included in the total.

^dThis source had been returned to correct leakage and/or contamination. The current contents are shown, but are not included in the total.

^eAs measured by recipient.

was within the range of 62 to 68% ^{244}Cm , 28 to 33% ^{246}Cm , and 1.9 to 2.7% ^{248}Cm . Eight of the targets were prepared from Californium-I curium.

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 Production and Materials Management (PMM) Division's market evaluation and sales program, and (3) the capabilities of the TRU-HFIR complex to produce the required materials. The long-term capability of the TRU-HFIR complex to produce transuranium elements was described in a previous report¹ in this series. The processing schedule for the near future can be predicted reasonably and is described below.

The estimated future production of transcurium elements from a series of likely processing campaigns which are scheduled through June 1975 is outlined in Table 2.3. We plan to process three groups of HFIR targets, two of which were prepared from Californium-I curium and the other from regular TRU stock. The quality (isotopic distribution) of curium from the two sources was similar. Estimates for the period of July to December 1975 and for 1976 are projections based on current trends. At present, we do not have plans to process any SRP-irradiated materials.

2.3 Estimates of the Availability of Transuranium Elements

The amounts of transcurium elements expected from each campaign are given in Table 2.3. During the next 18 months, we expect to recover totals of 50 mg of ^{249}Bk , 555 mg of ^{252}Cf , 2.3 mg of ^{253}Es (in a mixture of isotopes), 255 μg of high purity ^{253}Es , and 1.5 pg of ^{257}Fm . These forecasts were made by means of a method which includes estimation of (1) the amounts of transuranium elements in each group of irradiated HFIR targets, (2) the amounts of transuranium elements in rework materials within each processing campaign, and (3) the processing time required for recovery of each product.

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)	$^{253}\text{Es}^a$ (μg)	^{257}Fm (pg)	During the Period (mg)	Cumul. (mg)	
Through December 1973							796 ^b	
January-June 1974	12 Cf-I Cm-HFIR Targets	17	185	750(85)	0.5	185	981	March 1974
July-December 1974	11 TRU-HFIR Targets	16	180	750(85)	0.5	180	1161	October 1974
January-June 1975	10 Cf-I Cm-HFIR Targets	17	190	770(85)	0.5	190	1351	March 1975
July-December 1975						200	1551	
1976						450	2001	

^aAmounts from initial separation. Amounts "milked" from californium product fraction after decay period are given in parentheses.

^bCalifornium 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.

The forecasting method was described in the previous report in this series.²

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 .

In accordance with an agreement between the Physical Research and PMM Divisions, we are maintaining 90 to 100 mg of purified ^{252}Cf , recovered from Californium-I material, for use as a "cow" which can be "milked" periodically to obtain high-purity ($\sim 97\%$) ^{248}Cm . Due to the presence of ^{250}Cf in the cow, the curium contains about 3% ^{246}Cm . More ^{248}Cm will also become available from other purified californium. We expect to obtain 25 mg of ^{248}Cm in March 1974, and an additional 50 mg in September 1974.

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 is continually maintained. When replacements are necessary, modifications are usually included to provide improved capability and performance.

During this report period, one of the three sampler equipment racks (Cubicle 7) was replaced. The new rack contains an improved transfer system that utilizes vacuum tanks in place of pumps. Similar racks for replacement of those in Cubicles 4 and 6 are being constructed. Six of the eight glass windows in the Equipment Decontamination Glove Box were replaced with Rowlex (polycarbonate) windows, each equipped with a new glove system - La Calhene J2L Containment Elements, Type 33 - distributed

by Central Research Laboratories, Inc. The remaining windows were not replaced because the glove ports are not used frequently.

4. CALIFORNIUM NEUTRON SOURCES

Much 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 them were fabricated into one of the four standard models illustrated in Fig. 4.1 of ref. 3, and designated in the table by a three-letter prefix. Nonstandard sources are designated simply "NS- ". The three-letter prefix indicates whether the source is singly or doubly encapsulated, and whether it is fabricated from type 304L stainless steel or Zircaloy-2. The characteristics of standard source capsules are listed in Table 4.2 of ref. 3.

4.1 Sources Fabricated During July-December 1973

Six sources were fabricated during this report period. Four of these, NSD-64, 66, 73, and 74 are standard TRU sources doubly encapsulated in type 304L stainless steel. Sources NS-65 and NS-75 were fabricated in nonstandard forms specified by the users.

The pellet for NS-65 was fabricated previously,⁴ but was encapsulated during this period. The original encapsulation appeared to leak at a very small rate (approximately 75 pg of ^{252}Cf per day). Attempted repair by rewelding reduced the measured leak rate to about 25 pg per day. After reencapsulation and extensive testing, the measured leak rate was equal to or less than 0.1 pg per day, which was acceptable to the user. We reached the tentative conclusion that the capsule did not leak, but that a region of the weld was contaminated with ^{252}Cf , some of which was incorporated into the oxide film that formed over the surface of the capsule.

Table 4.1. Data for Neutron Sources Prepared at TRU

Source	Date of Calibration	^{252}Cf Content at Calibration (μg)	^{252}Cf Content as of 12-31-73 (μg)	^{248}Cm Content as of 12-31-73 (μg)	On Loan To:	
					Individual	Site
NS-1 ^a	8-28-68	316	78	b	K. L. Swinth	PNL
NS-2	8-23-68	254	62	b	c	
NS-3	5-13-69	~90	~27	b	G. I. Gleason	ORAU
NS-4	7-09-69	883	273	582	C. F. Masters	LASL
NS-5 ^d	8-14-69	946	300	616	F. B. Simpson	ANC
NS-6	11-21-69	747	255	470	R. W. Hoff	LLL
NS-7	1-21-70	788	281	484	c	
NS-8	12-17-69	1839	639	1145	H. Berger	ANL
NSD-9	4-17-70	1720	651	1019	N. A. Wogman	PNL
NSS-10	3-11-70	113	42	b	J. P. Balagna	LASL
NS-11	3-10-70	8	3	b	R. R. Fullwood	LASL
NSS-12	6-30-70	1868	746	1070	R. W. Hoff	LLL
NSD-13	3-19-71	4649	2240	2297	H. O. Menlove	LASL
NSS-14	6-29-70	4615	1842	2645	D. C. Stewart	ANL
NS-15 ^d	6-25-70	931	370	535	F. B. Simpson	ANC
NSD-16	10-08-70	1657	711	902	c	
NSS-17	8-31-71	4886	2650	2132	L. W. Dahlke	Sandia-Liv.
NS-18 ^d	6-24-70	962	383	553	F. B. Simpson	ANC
NSS-19	6-26-70	493	196	283	J. E. Bigelow	ORNL-TRU
NSD-20	7-01-70	630	252	361	J. E. Powell	Sandia-NM
NSS-21	10-21-70	18	8	b	F. Cross	PNL
NS-22	9-10-70	13	5	b	J. E. Bigelow	ORNL-TRU
NSD-24	10-15-70	8	3	b	J. B. Davidson	ORNL
NS-25	11-09-70	58	25	b	F. J. Muckenthaler	ORNL
NSD-26	2-11-71	14	7	b	H. O. Menlove	LASL
NSD-27	1-29-71	2467	1148	1258	c	
NSD-28	2-12-71	11	5	b	E. E. Hicks	Rocky Flats
NSD-29	9-10-71	11393	6224	4929	J. D. White	Y-12
NSD-30	3-31-71	879	427	431	F. F. Haywood	ORNL-DOSAR
NZD-31	11-23-71	1756	1012	710	c	
NZD-32	11-23-71	1800	1037	728	c	
NZD-33	11-23-71	1888	1088	763	c	
NZD-34	11-23-71	1924	1108	778	W. G. Spear	Westinghouse-Han.
NZD-35	11-23-71	1904	1097	770	c	
NS-36 ^d	3-23-71	2070	1000	1020	F. B. Simpson	ANC
NSD-37	9-04-71	9838	5352	4278	R. W. Perkins	PNL
NSD-38	6-16-71	102	52	b	H. O. Menlove	LASL
NS-39	11-07-71	942	536	387	V. Spiegel	NBS
NSD-40	4-27-72	1161	748	394	E. B. Darden	ORNL-Biology

Table 4.1. (continued)

Source	Date of Calibration	^{252}Cf Content at Calibration (μg)	^{252}Cf Content as of 12-31-73 (μg)	^{248}Cm Content as of 12-31-73 (μg)	On Loan To:	
					Individual	Site
NSD-41	11-08-71	5117	2916	2099	C. J. Emert	BAPL
NSD-42	11-02-71	4434	2516	1829	C. J. Emert	BAPL
NSD-43	4-20-72	4839	3102	1656	C. J. Emert	BAPL
NZD-44	5-15-72	10731	7004	3554	F. B. Simpson	ANC
NSD-45	8-18-71	1776	954	784	K. L. Swinth	PNL
NSD-46	4-23-72	629	404	214	H. O. Menlove	LASL
NSD-47	7-14-71	200	105	91	P. L. Johnson	Mound
NSD-48	7-14-71	194	102	88	P. L. Johnson	Mound
NSD-49	7-14-71	199	104	90	P. L. Johnson	Mound
NS-50	8-23-71	138	74	61	S. G. Carpenter	ANL-NRTS
NSD-51	11-02-71	365	207	151	L. C. Nelson, Jr.	New Brunswick
NSD-52	9-02-71	280	152	122	E. D. Clayton	PNL
NSD-53	10-25-71	1051	593	437	L. J. Esch	KAPL
NS-54	1-19-73	3187	2487	668	V. Spiegel	NBS
NSD-55	4-19-72	4	3	b	L. J. Esch	KAPL
NSD-56	4-19-72	121	78	41	L. J. Esch	KAPL
NSD-57	4-14-72	973	621	336	c	
NZD-58	5-15-72	11003	7181	3644	F. B. Simpson	ANC
NS-59	7-13-72	53	36	b	G. E. Hanson	LASL
NSD-60	4-11-72	20	13	b	J. S. Cheka	ORNL
NSD-61	1-19-73	5225	4077	1095	L. J. Esch	KAPL
NSS-62	3-27-73	3765	3082	651	J. E. Bigelow	ORNL-TRU
NSD-63	4-21-72	847	543	290	H. O. Menlove	LASL
NSD-64	7-19-73	193	171	21	H. O. Menlove	LASL
NS-65	7-09-73	114	101	13	L. Green	BAPL
NSD-66	8-02-73	3449	3095	337	J. E. Powell	Sandia-NM
NSD-73	9-11-73	13545	12509	988	G. I. Gleason	ORAU
NSD-74	9-11-73	4416	4078	322	G. I. Gleason	ORAU
NS-75	10-01-73	1919	1798	116	R. J. Kloepping	LLL
SR-Cf-167 ^e	5-26-71	3975	2011	1873	c	

^aThis source is encapsulated in aluminum.

^bThis source is not suitable for recovery of ^{248}Cm .

^cThis source is available for reissue.

^dThis source is encapsulated in type 405 stainless steel.

^eThis source was fabricated at TRU in standard Savannah River SR-Cf-100 series hardware.

4.2 Sources Returned

An increasing number of 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. The returned sources are available for re-assignment until the appropriate time for reprocessing to recover the ingrown ^{248}Cm . Ten sources that contain from 62 to 2011 μg of ^{252}Cf are now in this category and are so designated in Table 4.1. The following sources were returned during this report period: NS-2, NSD-16, NSD-27, and SR-Cf-167.

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 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 Special HFIR Targets

A new experimental facility designed to hold one standard HFIR target (of the type used for transplutonium element production) has been approved for use in the HFIR reflector. The purpose for locating the holder in one of the VXF holes of the beryllium reflector is to provide a flux significantly different from that in the target island. The contrast between the well-thermalized spectrum in the outer part of the reflector to the relatively hard spectrum in the target island will provide an opportunity to explore the relative importance of resonance and thermal absorptions in a number of key isotopes of the transplutonium production chain. The facility has been approved as suitable for the irradiation of a HFIR target, and

subsequent approval of individual target assemblies can be made on the basis of adherence to the established criteria that pertain to HFIR target irradiations.

The initial experiment inserted into the VXF-target holder was special target ST-8, which contained several samples and flux monitors. The samples and the purposes for which they were irradiated were as follows:

(1) Two curium oxide pellets from pellet batch TRU-36, each containing 271 mg of curium. These pellets were used to study the production of ^{249}Bk and ^{250}Cf from ^{248}Cm .

(2) Two pellets, each containing approximately 1 μg of ^{252}Cf . These were old pellets, and were also used to study the production of ^{249}Bk from ^{248}Cm , as well as the burn-out of lighter californium isotopes. This pellet also afforded a check on the production of ^{253}Es and ^{254}Es .

(3) Two special containers each containing about 1 mg of ^{241}Am fixed on a bed of zeolite. These samples were used to test the Szilard-Chalmers type of enrichment of $^{242\text{m}}\text{Am}$ from the target isotope ^{241}Am .

(4) Three similar containers with ^{141}Pr on zeolite were used to check the procedures for the above tests. The ^{141}Pr process had worked well in ORR irradiations. One of the capsules had a standard substrate. The other two tested different formulations.

(5) Three flux monitor assemblies containing 6-mg pieces of niobium wire and cobalt-aluminum alloy wire in small quartz ampuls.

The remaining space in the target was filled with dummy pellets and aluminum spacers.

The target was loaded into the reactor on July 22, and was irradiated for 1 cycle in position VXF-19. After discharge on August 15, 1973, it was returned to TRU for disassembly and analysis of the experiment.

Results show that while the thermal flux, as measured by the cobalt monitors, was roughly what was anticipated, the burnup of the actinides suggested a much higher flux (about a factor of 2). Reconciliation of these data apparently involves the resonance spectrum; probably, the

location of some fission sources (the curium pellets) in this part of the reflector increased the resonance flux appreciably above the calculated (unperturbed) value.

5.2 Irradiation of ^{249}Bk to Produce ^{250}Cf

A new technique was developed and used to fabricate approximately 1.2 mg of ^{249}Bk into a target for production of ^{250}Cf . The main problem was that of obtaining an even distribution of approximately 0.4 mg of ^{249}Bk through each of three aluminum pellets to avoid local overheating. This problem and that of handling such a small amount of ^{249}Bk were overcome by the development of a resin-loading technique with an added diluent.

Both magnesium and neodymium were tested as possible diluents because of their minimal production of induced radioactivity, and the promise of ease of separation from berkelium and californium by ion exchange techniques. Magnesium was especially attractive because of its extremely low neutron cross section. In each test, 2 meq of the diluent were loaded onto a 10% excess (1.4 ml) of Bio-Rad 50W-8X resin. The loaded resin was then calcined to remove all volatile components; the resulting microspheres were blended with 1.2 g of aluminum powder and dispensed equally into three aluminum target liners. Each liner was then pressed into pellets with approximately 80% of the theoretical density of aluminum metal. X-rays of the neodymium pellets showed equal distribution of microspheres. We could not determine the distribution of the magnesium because it is nearly the same density as the matrix aluminum.

The magnesium pellets were tested further using the chemical processes necessary for separation of californium from berkelium (in the case of neodymium, the necessary separations were well known). The pellets were dissolved by caustic dissolution, the oxide was dissolved in 1 M HNO_3 , the feed was adjusted to 0.2 M HNO_3 , and a high pressure ion exchange run was made. No difficulties arose during any of these operations. The elution position of the magnesium from the high pressure column was determined to be between the 12th and 16th column volume of 0.5 M alpha-hydroxyisobutyrate, which is well after the elution positions of californium and

berkelium. Because of its lower cross section and its elution position after the actinide products, we decided to use magnesium as the diluent.

A sample containing an estimated 1.2 mg of ^{249}Bk was purified, a HFIR hydraulic rabbit capsule prepared, the capsule irradiated for 16 hr and then processed, all within a 5-day time interval. A speedy schedule is necessary to minimize the contamination of the ^{250}Cf product with ^{249}Cf which continually forms from the ^{249}Bk , regardless of whether the sample is in the reactor or out. The procedure went very much as planned, and the measured ^{250}Cf product was 237 μg of ^{250}Cf . The isotopic composition on September 6, 1973, was:

<u>Nuclide</u>	<u>Atom %</u>
^{249}Cf	3.28
^{250}Cf	89.07
^{251}Cf	6.82
^{252}Cf	0.823
^{253}Cf	<0.002
^{254}Cf	<0.002

Approximately 1 mg of residual ^{249}Bk was recovered, purified, and again fabricated into a HFIR rabbit by the resin-loading technique. The ^{250}Cf isolated from the second run amounted to 135 μg .

5.3 ^{152}Sm Rabbit

A special irradiation of 1.8 mg of ^{152}Sm was performed for A. M. Friedman of ANL. Dr. Friedman originally asked for a 5-day irradiation, but we scaled it back to 20 hr to produce an estimated 20 Ci of ^{153}Sm , based on a cross-section of 140 b. The rabbit, upon discharge, was hotter than anticipated, and was given an additional day to cool before shipment to ANL. Dr. Friedman estimates he received about 150 Ci, implying that the true activation cross section in the HFIR is an order of magnitude higher than the literature value.

6. REFERENCES

1. W. D. Burch, J. E. Bigelow, and L. J. King, Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending December 31, 1971, ORNL-4767, pp. 8-11.
2. L. J. King, J. E. Bigelow, and E. D. Collins, Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending June 30, 1973, ORNL-4921, p. 9.
3. Ibid., pp. 14-15.
4. Ibid., p. 18.
5. C. M. Lederer, J. M. Hollander, and I. Perlman, Table of Isotopes, 6th ed., Wiley, New York, 1967.
6. A. H. Wapstra, "Actinide Fingerprints," Actinides Rev. 1, 39-53 (1967).

7. APPENDIX

We have tabulated the decay data and the cross-section data that we use in planning irradiation-processing cycles, calculating production forecasts, and assaying products. The tables will be reproduced completely in each of these semiannual reports, and changes made since the preceding report will be indicated. We wish to state clearly that these data merely represent numbers being used in our calculations and that the data are presented on a "best efforts" basis. Although the information is intended to be definitive, it has not been checked and cross-checked sufficiently to be considered "publishable."

The Transplutonium Element Production Program is now making nuclides available in increasing abundance and purity; therefore, in the next few years, we anticipate a burgeoning literature concerning nuclear constants for the transuranium nuclides. However, since we need such data at the present time, it will not be feasible for us to wait until highly reliable sources, such as Lederer⁵ and Wapstra,⁶ can publish data that have been fully evaluated.

We welcome telephone calls to point out errors or indicate additional sources of information. Please contact John Bigelow, FTS 615-483-1872 or, by commercial telephone service, 615-483-8611, ext. 3-1872.

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 \pm 0.01 d					50Fr53
²³⁹ Np	2.359 \pm 0.010 d					59Co93
²⁴⁰ Np	63 \pm 2 m					60Le03
^{240m} Np	7.3 \pm 0.3 m					48Hy61
²⁴¹ Np	16 m					60Le03
^{241m} Np	3.4 h					60Le03
²³⁸ Pu	87.404 \pm 0.041 y			$(5 \pm 0.6) \times 10^{10}$ y	2.33 \pm 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 \pm 40 y		$(1.340 \pm 0.015) \times 10^{11}$ y	2.177 \pm 0.009	51In03, 62Wa13, 68Bo54
²⁴¹ Pu	14.98 \pm 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 \pm 0.009	63Ma50, 69Be06, 68Bo54
²⁴³ Pu	4.955 \pm 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 \pm 0.4 h					56Bu92
²⁴⁶ Pu	10.85 \pm 0.02 d					56Ho23
²⁴¹ Am		432.7 \pm 0.7 y		$(2.3 \pm 0.8) \times 10^{14}$ y	2.48 ^d	61Dr04, 670e01
²⁴² Am	16.01 \pm 0.02 h		EC/B = 0.19			53Ke38
^{242m} Am	144 \pm 7 y	$(2.92 \pm 0.15) \times 10^4$ y				59Ba21 ^c
²⁴³ Am		7370 \pm 40 y				68Br22
²⁴⁴ Am	10.1 \pm 0.1 h					62Va08
^{244m} Am	26 m					54Ga24
²⁴⁵ Am	2.07 \pm 0.02 h					56Bu92
²⁴⁶ Am	25.0 \pm 0.2 m					55En16
^{246m} Am	40 \pm 7 m					67Or02
²⁴⁷ Am	24 \pm 3 m					67Or02
²⁴² Cm	162.7 \pm 0.1 d			7.2×10^6 y	2.65 \pm 0.09	51Ha87, 57Pe52, 56Hi01
²⁴³ Cm		32 y				57As70
²⁴⁴ Cm	18.099 \pm 0.015 y		α /SF = $(7.43 \pm 0.01) \times 10^5$		2.84 \pm 0.09	65Me02, 68Be26, 56Hi01
²⁴⁵ Cm		8265 \pm 180 y				69Me01
²⁴⁶ Cm		4655 \pm 40 y	α /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 \pm 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 \pm 8 d		$\alpha/\beta = (1.45 \pm 0.08) \times 10^{-5}$	$(1.87 \pm 0.09) \times 10^9$ y	3.72 \pm 0.16	57Ea01, 69Mi08, 64Py02
²⁵⁰ Bk	3.222 \pm 0.005 h					59Va02
²⁵¹ Bk	57 \pm 1.7 m					66RG04
²⁴⁹ Cf		352 \pm 6 y	$\alpha/\text{SF} = (1.992 \pm 0.040) \times 10^8$		3.44 ^d	69Me01, 69Mi08
²⁵⁰ Cf		13.08 \pm 0.09 y	$\alpha/\text{SF} = 1260 \pm 40$		3.56 ^d	63Ph01, 69Me01
²⁵¹ Cf		900 \pm 50 y				69Me01
²⁵² Cf	2.646 \pm 0.004 y		$\alpha/\text{SF} = 31.3 \pm 0.2$		3.796 \pm 0.031	65Me02, 68Wh04
²⁵³ Cf	17.812 \pm 0.082 d		$\alpha/\beta = (3.1 \pm 0.4) \times 10^{-3}$			69Dr02, 66RG01
²⁵⁴ Cf	60.5 \pm 0.2 d		$\alpha/\text{SF} = (3.10 \pm 0.16) \times 10^{-3}$		3.90 \pm 0.14	63Ph01, 64Py02, 68Be21
²⁵⁵ Cf	1.5 \pm 0.5 h					70Lo19
²⁵³ Es	20.467 \pm 0.024 d		$\alpha/\text{SF} = (1.15 \pm 0.03) \times 10^7$		3.92 ^d	65Me02, 69Dr02
²⁵⁴ Es	276 d			$>2.5 \times 10^7$ y	4.04 ^d	67Fi03, 67Un01
^{254m} Es	39.3 \pm 0.2 h		$\beta/\alpha = 382 \pm 30$ E.C./ $\beta = 0.00078 \pm 0.00006$			62Un01, 63Ph01
²⁵⁵ Es	39.8 \pm 1.2 d		$\alpha/\beta = 0.0866 \pm 0.0043$ $\beta/\text{SF} = (2.22 \pm 0.10) \times 10^4$		4.16 ^d	66RG01, 67Fi03
²⁵⁶ Es	25 \pm 3 m					68Lo11
²⁵⁴ Fm	3.24 \pm 0.01 h		$\alpha/\text{SF} = 1695 \pm 8$		4.05 \pm 0.19	56Jo09, 67Fi03, 56Ch83
²⁵⁵ Fm	20.07 \pm 0.07 h		$\text{SF}/\alpha = (2.4 \pm 1.1) \times 10^{-7}$		4.16 ^d	63Ph01, 64As01
²⁵⁶ Fm	2.62 \pm 0.03 h		$\sim 100\%$ SF		4.27 ^d	68Ho13
²⁵⁷ Fm	94 \pm 10 d					66RG01
²⁵⁸ Fm	380 \pm 60 μ s		$\sim 100\%$ SF			71Hu03

^aThe half-life values used in this table were being used at TRU at the end of the report period.

^bReferences are decoded in Table A-2.

^cPublished values are adjusted for ²⁴¹Am half-life of 432.7 y.

^dValue estimated by linear interpolation of the values for ²⁴⁴Cm and ²⁵²Cf, based on nuclidic mass.

The references used in Table A-1 are decoded in Table A-2. The system of references is that used by the Nuclear Data Project here at ORNL in their widely distributed "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_{2200}^c , 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_{eff}^c , would be:

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

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 $\phi_{\text{res}}/\phi_{2200}$ 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 $^{244\text{c}}\text{Am}$ is a fictitious isotope which is used to simplify the calculation of the main transmutation chain involving ^{244}Am . The properties of $^{244\text{c}}\text{Am}$ were calculated from the properties of the

Table A-2. References for Table A-1

Code	Reference	Code	Reference
48Hy61	E. K. Hyde, M. H. Studier, and W. M. Manning, ANL-4143 (April 15, 1948) and ANL-4182 (August 4, 1948).	63Ma50	L. Z. Malkin, I. D. Alkhozov, A. S. Krivokhatskii, and K. A. Petrzhak, <u>At. Energ. (USSR)</u> , 15 , 158-159 (1963).
50Fr53	M. S. Freedman, A. H. Jaffey, and F. Wagner, Jr., <u>Phys. Rev.</u> , 79 , 410-411 (1950).	63Ph01	L. Phillips, R. Gatti, R. Brandt, and S. G. Thompson, <u>J. Inorg. Nucl. Chem.</u> , 25 , 1085-1087 (1963).
51Ha87	G. C. Hanna, B. G. Harvey, N. Moss, and P. R. Tunnicliffe, <u>Phys. Rev.</u> , 81 , 466-467 (1951).	64As01	F. Asaro, S. Bjrnholm, and I. Perlman, <u>Phys. Rev.</u> , 133 , B291-B300 (1964).
51In03	M. G. Inghram, D. C. Hess, P. R. Fields, and G. L. Pyle, <u>Phys. Rev.</u> , 83 , 1250 (1951).	64Py02	R. V. Pyle, Unpublished results as reported in E. K. Hyde, "Fission Phenomena," Prentice Hall, Inc. (1964).
52Se67	L. Segrè, <u>Phys. Rev.</u> , 86 , 21-28 (1952).	65Me02	D. Metta, H. Diamond, R. F. Barnes, J. Milsted, J. Gray, Jr., D. J. Henderson, and C. M. Stevens, <u>J. Inorg. Nucl. Chem.</u> , 27 , 33-35 (1965).
53Ke38	T. K. Keenan, R. A. Penneman, and B. B. McInteer, <u>J. Chem. Phys.</u> , 21 , 1802-1803 (1953).	66Fi07	P. R. Fields, A. M. Friedman, J. Milsted, J. Lerner, C. M. Stevens, D. Metta, and W. K. Sabine, <u>Nature</u> , 212 , 131 (1966).
54Gh24	A. Ghiorso, S. G. Thompson, G. R. Choppin, and B. G. Harvey, <u>Phys. Rev.</u> , 94 , 1081 (1954).	66RG01	Combined Radiochemistry Group, LRL, LASL, and ANL, <u>Phys. Rev.</u> , 148 , No. 3, 1192-1198 (1966).
55En16	D. Engelkemeir, P. R. Fields, T. Fried, G. L. Pyle, C. M. Stevens, L. B. Asprey, C. I. Browne, H. Louise Smith, and R. W. Spence, <u>J. Inorg. Nucl. Chem.</u> , 1 , 345-351 (1955).	66RG04	Argonne Heavy Element Group (unpublished data).
56Bu92	J. P. Butler, T. A. Eastwood, T. L. Collins, M. E. Jones, F. M. Rourke, and R. P. Schuman, <u>Phys. Rev.</u> , 103 , 634 (1956).	67Fi03	P. R. Fields, H. Diamond, A. M. Friedman, J. Milsted, J. L. Lerner, R. F. Barnes, R. K. Sjolom, D. N. Metta, and E. P. Horwitz, <u>Nucl. Phys.</u> , A96 , 440-448 (1967).
56Ch83	G. R. Choppin, B. G. Harvey, D. A. Hicks, J. Ise, Jr., and R. V. Pyle, <u>Phys. Rev.</u> , 102 , 766 (1956).	670e01	F. L. Oetting and S. R. Gunn, <u>J. Inorg. Nucl. Chem.</u> , 29 , 2659-2664 (1967).
56Hi01	D. A. Hicks, J. Ise, Jr., and R. V. Pyle, <u>Phys. Rev.</u> , 101 , 1016-1020 (1956).	670r02	C. J. Orth, W. R. Daniels, B. H. Erkkila, F. O. Lawrence, and D. C. Hoffman, <u>Phys. Rev. Letters</u> , 19 , No. 3, 128-131 (1967).
56Ho23	D. C. Hoffman and C. I. Browne, <u>J. Inorg. Nucl. Chem.</u> , 2 , 209 (1956).	67Un01	J. Unik, private communication to P. Fields (1967).
56Jo09	M. Jones, R. P. Schuman, J. P. Butler, G. Cowper, T. A. Eastwood, and H. G. Jackson, <u>Phys. Rev.</u> , 102 , 203-207 (1956).	68Be21	C. E. Bemis, Jr. and J. Halperin, <u>Nucl. Phys.</u> , A121 , 433-439 (1968).
57As70	F. Asaro, S. G. Thompson, F. S. Stephens, Jr., and I. Perlman, <u>Bull. Am. Phys. Soc.</u> , 8 , 393 (1957).	68Be26	W. C. Bentley, <u>J. Inorg. Nucl. Chem.</u> , 30 , 2007-2009 (1968).
57Ea01	T. A. Eastwood, J. P. Butler, M. J. Cabell, H. G. Jackson, R. P. Schuman, F. M. Rourke, and T. L. Collins, <u>Phys. Rev.</u> , 107 , 1635-1638 (1957).	68Bo54	J. W. Boldeman, <u>J. Nucl. Energy</u> , 22 , 63-72 (1968).
57Pe52	R. A. Penneman, L. H. Treiman, and B. Bevan, as reported by D. C. Hoffman, G. P. Ford, and F. O. Lawrence, <u>J. Inorg. Nucl. Chem.</u> , 5 , 6-11 (1957).	68Br22	L. C. Brown and R. C. Propst, <u>J. Inorg. Nucl. Chem.</u> , 30 , 2591-2594 (1968).
58Ea06	T. A. Eastwood and R. P. Schuman, <u>J. Inorg. Nucl. Chem.</u> , 6 , 261-262 (1958).	68Ca19	M. J. Cabell, <u>J. Inorg. Nucl. Chem.</u> , 30 , 2583-2589 (1968).
59Ba21	R. F. Barnes, D. J. Henderson, A. L. Harkness, and H. Diamond, <u>J. Inorg. Nucl. Chem.</u> , 9 , 105-107 (1959).	68Di09	H. Diamond, J. J. Hines, R. K. Sjolom, R. F. Barnes, D. N. Metta, J. L. Lerner, and P. R. Fields, <u>J. Inorg. Nucl. Chem.</u> , 30 , 2553-2559 (1968).
59Co93	D. Cohen, J. C. Sullivan, and A. J. Zielen, <u>J. Inorg. Nucl. Chem.</u> , 11 , 159-161 (1959).	68Ho13	R. W. Hoff, J. E. Evans, E. K. Hulet, R. J. Dupzyk, and B. J. Qualheim, <u>Nucl. Phys.</u> , A115 , 225-233 (1968).
59Ma26	T. L. Markin, <u>J. Inorg. Nucl. Chem.</u> , 9 , 320-322 (1959).	68Jo15	K. C. Jordan, MLM-1443, 11-30 (1968).
59Va02	S. E. Vandenbosch, H. Diamond, R. K. Sjolom, and P. R. Fields, <u>Phys. Rev.</u> , 115 , 115-121 (1959).	68Lo11	R. W. Loughheed, private communication to J. E. Bigelow (1968).
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60Br15	F. Brown, G. G. George, D. E. Green, and D. E. Watt, <u>J. Inorg. Nucl. Chem.</u> , 13 , 192-195 (1960).	69Be06	C. E. Bemis, Jr., J. Halperin, and R. Eby, <u>J. Inorg. Nucl. Chem.</u> , 31 , 599-604 (1969).
60Le03	R. M. Lessler and M. C. Michel, <u>Phys. Rev.</u> , 118 , 263-264 (1960).	69Dr02	R. E. Drushel, J. Halperin, and C. E. Bemis, Jr., ORNL-4437, 28-29 (1969).
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62Un01	J. Unik, P. Day, and S. Vandenbosch, <u>Nucl. Phys.</u> , 36 , 284-304 (1962).	69Mi08	J. Milsted, E. P. Horwitz, A. M. Friedman, and D. N. Metta, <u>J. Inorg. Nucl. Chem.</u> , 31 , 1561-1569 (1969).
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Table A-3. Properties^a of Transuranium Nuclides

Nuclide	Half-Life	Energies of Prin. Emissions (MeV)		Specific Activity				(Neutrons min ⁻¹ mg ⁻¹)	Hazard ^b		
		α	β	(Ci/g)	(W/g)	(α cpm/mg ^c)	(B dpm/mg)		MPC α(40) (μCi/cm ³)	Body Burden (μCi) (μg)	
²³⁷ Np	2.14 x 10 ⁶ y	4.78		7.07 x 10 ⁻⁴	2.07 x 10 ⁻⁵	8.01 x 10 ⁵		<7 x 10 ⁻⁶	4 x 10 ⁻¹²	0.06	84.9
²³⁸ Np	2.10 d		0.25 1.24	2.61 x 10 ⁵	1.27 x 10 ³			5.80 x 10 ¹⁴			
²³⁹ Np	2.359 d		0.332 0.427	2.32 x 10 ⁵	5.86 x 10 ²			5.14 x 10 ¹⁴	7 x 10 ⁻⁷	30	1.29 x 10 ⁻⁴
²⁴⁰ Np	63 m		0.89	1.24 x 10 ⁷	1.03 x 10 ⁵			2.76 x 10 ¹⁶			
^{240m} Np	7.3 m		2.18 1.6	1.07 x 10 ⁸	5.33 x 10 ⁵			2.38 x 10 ¹⁷			
²⁴¹ Np	16 m			4.86 x 10 ⁷				1.08 x 10 ¹⁷			
^{241m} Np	3.4 h			3.82 x 10 ⁶				8.49 x 10 ¹⁵			
²³⁸ Pu	87.404 y	5.49		17.2	0.570	1.94 x 10 ¹⁰		155	2 x 10 ⁻¹²	0.04	2.32 x 10 ⁻³
²³⁹ Pu	2.4413 x 10 ⁴ y	5.15		6.13 x 10 ⁻²	1.913 x 10 ⁻³	6.94 x 10 ⁷		1.35 x 10 ⁻³	2 x 10 ⁻¹²	0.04	0.653
²⁴⁰ Pu	6580 y	5.16		0.227	7.097 x 10 ⁻³	2.57 x 10 ⁸		53.7	2 x 10 ⁻¹²	0.04	0.176
²⁴¹ Pu	14.98 y	4.9	0.02	99.1	4.06 x 10 ⁻³	2.94 x 10 ⁶		2.20 x 10 ¹¹	9 x 10 ⁻¹¹	0.9	9.08 x 10 ⁻³
²⁴² Pu	3.869 x 10 ⁵ y	4.90		3.82 x 10 ⁻³	1.13 x 10 ⁻⁴	4.32 x 10 ⁶		95.3	2 x 10 ⁻¹²	0.05	13.1
²⁴³ Pu	4.955 h		0.49 0.58	2.60 x 10 ⁶	3.34 x 10 ³			5.78 x 10 ¹⁵	2 x 10 ⁻⁶	7.0	2.69 x 10 ⁻⁶
²⁴⁴ Pu	8.28 x 10 ⁷ y	4.587		1.77 x 10 ⁻⁵	4.93 x 10 ⁻⁷	2.00 x 10 ⁴		141	2 x 10 ⁻¹²	0.04	2.26 x 10 ³
²⁴⁵ Pu	10.6 h			1.21 x 10 ⁶				2.68 x 10 ¹⁵	2 x 10 ⁻⁷	3.0	2.48 x 10 ⁻⁶
²⁴⁶ Pu	10.85 d		0.15	4.91 x 10 ⁴	66.9			1.09 x 10 ¹⁴			
²⁴¹ Am	432.7 y	5.48		3.43	0.1145	3.88 x 10 ⁹		3.55 x 10 ⁻²	6 x 10 ⁻¹²	0.1	0.0292
²⁴² Am	16.01 h		0.63 0.67	8.11 x 10 ⁵	2.08 x 10 ³			1.80 x 10 ^{15d}	4 x 10 ⁻⁸	0.06	7.39 x 10 ⁻⁸
^{242m} Am	144 y	5.207	I.T.	10.3	3.08 x 10 ⁻²	5.53 x 10 ⁷		2.28 x 10 ^{10e}	6 x 10 ⁻¹²	0.07	6.80 x 10 ⁻³
²⁴³ Am	7370 y	5.27		0.200	6.42 x 10 ⁻³	2.26 x 10 ⁸			6 x 10 ⁻¹²	0.05	0.25
²⁴⁴ Am	10.1 h		0.387	1.27 x 10 ⁶	8.74 x 10 ³			2.82 x 10 ¹⁵			
^{244m} Am	26 m		1.5	2.96 x 10 ⁷	8.98 x 10 ⁴			6.58 x 10 ^{16f}	4 x 10 ⁻⁶	0.2	6.76 x 10 ⁻⁹
²⁴⁵ Am	2.07 h		0.91	6.17 x 10 ⁶	1.20 x 10 ⁴			1.37 x 10 ¹⁶			
²⁴⁶ Am	25.0 m		1.31	3.06 x 10 ⁷	2.48 x 10 ⁵			6.79 x 10 ¹⁶			
^{246m} Am	40 m			1.91 x 10 ⁷				4.24 x 10 ¹⁶			
²⁴⁷ Am	24 m			3.17 x 10 ⁷				7.04 x 10 ¹⁶			
²⁴² Cm	162.7 d	6.11		3.32 x 10 ³	122	3.76 x 10 ¹²		1.21 x 10 ⁶	1 x 10 ⁻¹⁰	0.05	1.51 x 10 ⁻⁵
²⁴³ Cm	32 y	5.79		45.9	1.677	5.20 x 10 ¹⁰		3.27 x 10 ⁸	6 x 10 ⁻¹²	0.09	1.96 x 10 ⁻³
²⁴⁴ Cm	18.099 y	5.81		80.94	2.832	9.16 x 10 ¹⁰		6.87 x 10 ⁵	9 x 10 ⁻¹²	0.1	1.24 x 10 ⁻³
²⁴⁵ Cm	8265 y	5.36		0.177	5.89 x 10 ⁻³	2.00 x 10 ⁸			5 x 10 ⁻¹²	0.04	0.226
²⁴⁶ Cm	4655 y	5.39		0.312	1.01 x 10 ⁻²	3.52 x 10 ⁸		5.58 x 10 ⁵	5 x 10 ⁻¹²	0.05	0.160
²⁴⁷ Cm	1.56 x 10 ⁷ y	4.87		9.28 x 10 ⁻⁵	2.94 x 10 ⁻⁶	1.05 x 10 ⁵			5 x 10 ⁻¹²	0.04	431
²⁴⁸ Cm	3.397 x 10 ⁵ y	5.05		4.24 x 10 ⁻³	5.34 x 10 ⁻⁴	4.39 x 10 ⁶		2.58 x 10 ⁶	6 x 10 ⁻¹³	0.005	1.18
²⁴⁹ Cm	64 m		0.9	1.18 x 10 ⁷	2.06 x 10 ⁴			2.62 x 10 ¹⁶	1 x 10 ⁻⁵	1.0	8.47 x 10 ⁻⁸
²⁵⁰ Cm	1.74 x 10 ⁴ y			8.20 x 10 ⁻²	~0.1			6.49 x 10 ⁸			

Table A-3 (continued)

Nuclide	Half-Life	Energies of Prin. Emissions (MeV)		Specific Activity				(Neutrons min ⁻¹ mg ⁻¹)	Hazard ^b		
		α	β	(Ci/g)	(W/g)	(α cpm/mg ^c)	(β dpm/mg)		MPC ^a (40) (μCi/cm ³)	Body Burden (μCi)	(μg)
²⁴⁹ Bk	314 d	5.4	0.125	1.67 x 10 ³	0.358	2.74 x 10 ⁷	3.71 x 10 ¹²	6.34 x 10 ³	9 x 10 ⁻¹⁰	0.7	4.19 x 10 ⁻⁴
²⁵⁰ Bk	3.222 h		0.23	3.89 x 10 ⁶		2.75 x 10 ⁴	8.62 x 10 ¹⁵		1 x 10 ⁻⁷	0.05	1.29 x 10 ⁻⁸
²⁵¹ Bk	57 m			1.32 x 10 ⁷			2.92 x 10 ¹⁶				
²⁴⁹ Cf	352 y	5.81		4.08	0.152	4.62 x 10 ⁹		156	2 x 10 ⁻¹²	0.04	9.80 x 10 ⁻³
²⁵⁰ Cf	13.08 y	6.03		109	4.06	1.23 x 10 ¹¹		6.85 x 10 ⁸	5 x 10 ⁻¹²	0.04	3.70 x 10 ⁻⁴
²⁵¹ Cf	900 y			1.59		5.79 x 10 ⁻²		1.78 x 10 ⁹	2 x 10 ⁻¹²	0.04	2.50 x 10 ⁻²
²⁵² Cf	2.646 y	6.11		536	39.0	5.88 x 10 ¹¹		1.40 x 10 ¹¹	6 x 10 ⁻¹²	0.01	1.87 x 10 ⁻⁵
²⁵³ Cf	17.812 d	5.98	0.27	2.90 x 10 ⁴	13.89	1.02 x 10 ¹¹	6.41 x 10 ¹³		8 x 10 ⁻¹⁰	0.04	1.40 x 10 ⁻⁶
²⁵⁴ Cf	60.5 d	5.84		8.49 x 10 ³	1.06 x 10 ⁴	2.89 x 10 ¹⁰		7.35 x 10 ¹³	5 x 10 ⁻¹²	0.0007	8.24 x 10 ⁻⁸
²⁵⁵ Cf	1.5 h			~8 x 10 ⁶							
²⁵³ Es	20.467 d	6.63		2.52 x 10 ⁴	1.01 x 10 ³	2.86 x 10 ¹³		1.91 x 10 ⁷	6 x 10 ⁻¹⁰	0.04	1.59 x 10 ⁻⁶
²⁵⁴ Es	276 d	6.42		1.86 x 10 ³	71.9	2.11 x 10 ¹²		<5.04 x 10 ⁵	2 x 10 ⁻¹¹	0.02	1.08 x 10 ⁻⁵
^{254m} Es	39.3 h		0.48	3.14 x 10 ⁵	1.18 x 10 ³		6.97 x 10 ¹⁴		5 x 10 ⁻⁹	0.02	6.37 x 10 ⁻⁸
²⁵⁵ Es	39.8 d			1.29 x 10 ⁴			2.86 x 10 ¹³	4.92 x 10 ⁹	4 x 10 ⁻¹⁰	0.04	3.10 x 10 ⁻⁶
²⁵⁶ Es	25 m			2.94 x 10 ⁷			6.52 x 10 ¹⁶				
²⁵⁴ Fm	3.24 h	7.20		3.81 x 10 ⁶	1.68 x 10 ⁵	4.31 x 10 ¹⁵		2.02 x 10 ¹³	6 x 10 ⁻⁸	0.02	5.25 x 10 ⁻⁹
²⁵⁵ Fm	20.07 h	7.03		6.13 x 10 ⁵	2.79 x 10 ⁴	6.94 x 10 ¹⁴		1.36 x 10 ⁹	1 x 10 ⁻⁸	0.04	6.53 x 10 ⁻⁸
²⁵⁶ Fm	2.62 h			4.67 x 10 ⁶	5.85 x 10 ⁶			4.43 x 10 ¹⁶	2 x 10 ⁻⁹	0.0008	1.71 x 10 ⁻¹⁰
²⁵⁷ Fm	94 d			5.41 x 10 ³	~200	6.12 x 10 ¹²					
²⁵⁸ Fm	380 μs			1.15 x 10 ¹¹							

^aThe values for properties included in this table are those in use at TRU at the end of the report period.

^bFrom 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).

^cCounting geometry, 51%.

^d²⁴²Am decays by β emission (84%) and orbital capture (16%).

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

^f^{244m}Am decays primarily by β emission, but 0.039% decays by electron capture to ²⁴⁴Pu.

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 x 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 x 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 x 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 x 10 ⁷ y	60	0	500	120	0	1060
²⁴⁸ Cm	3.397 x 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 x 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 μ s	0	0	0	0	0	0

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

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 i th isomer, c, g, or m; and f_i is the fraction of neutron captures in ^{243}Am resulting in the i th isomer, such that $f_c = f_g + f_m = 1$.



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