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**TRANSURANIUM PROCESSING PLANT
SEMIANNUAL REPORT OF PRODUCTION,
STATUS, AND PLANS
FOR PERIOD ENDING JUNE 30, 1970**

W. D. Burch
J. E. Bigelow
L. J. King

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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CHEMICAL TECHNOLOGY DIVISION

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JANUARY 1971

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SUMMARY

This is the fifth 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 total amounts of transuranium elements recovered during the period January 1, 1970, through June 30, 1970, are: 4.6 g of ^{242}Pu , 1.9 g of ^{243}Am , 34.5 g of ^{244}Cm , 3.8 mg of ^{249}Bk , 40.7 mg of ^{252}Cf , 298 μg of ^{253}Es , and 4×10^8 atoms of ^{257}Fm . We made 63 shipments, which contained the following total amounts of nuclides: 2.3 mg of ^{244}Pu that had been isotopically enriched in a calutron and then irradiated in the HFIR prior to shipment; 26.48 g of ^{243}Am and 14.45 g of ^{244}Cm that had been separated and purified; a mixture of 5.1 g of ^{243}Am and 5.58 g of ^{244}Cm ; 376.3 μg of ^{248}Cm ; 3.6 mg of ^{249}Bk ; 220 μg of isotopically pure ^{249}Cf ; 161 μg of high-purity ^{250}Cf that was produced by irradiating ^{249}Bk in the HFIR hydraulic rabbit facility; 12.3 mg of ^{252}Cf in a mixture of californium isotopes; 259 μg of ^{253}Es in a mixture of einsteinium isotopes; 36 μg of isotopically pure ^{253}Es ; and 3.7×10^8 atoms of ^{257}Fm .

During the next 18 months, we expect to recover 385 mg of ^{252}Cf from 163 americium-curium slugs that are presently being irradiated at the Savannah River Plant and 108 mg of ^{252}Cf from the processing of irradiated HFIR targets. A total of 68 mg of ^{249}Bk and 1.5 mg of ^{253}Es will also be recovered as by-products from these campaigns.

The process steps currently being used at TRU have not been changed since the previous report.

An unused cell in the TURF facility has been equipped for the purification and encapsulation of californium. The primary purpose of this cell is to provide a ^{244}Cm -free environment so that extremely pure ^{248}Cm may be recovered from aged ^{252}Cf neutron sources. A hydraulic rabbit tube has been installed to permit the rapid transfer of small amounts of irradiated materials from the HFIR pool to a shielded cave in an alpha laboratory in TRU.

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Seven neutron sources were fabricated during this report period; to date, 15 neutron sources have been fabricated at TRU. In a special project, we produced about 155 μg of ^{250}Cf (isotopic purity, 87%) for use as a target for transactinide element production in the Berkeley HILAC and about 6 μg of ^{250}Cf (isotopic purity, ~94%), part of which was sent to the Los Alamos Scientific Laboratory for use in fission cross-section studies.

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 fifth report in a series¹⁻⁴ 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 the report period are summarized. Quantities of materials that were recovered and shipped are specified, and proposed processing schedules and anticipated yields of various products are presented. Special processing, fabrication, and irradiation programs are described. The original and current contents of all neutron sources that have been made at TRU, as well as the person to whom each source has been loaned, are tabulated. Values of nuclear parameters which were used as input data for the calculations of production rates for transuranium elements, along with a tabulation of the parameters which were used to calculate the specific activities of the isotopes that are of interest to TRU, are included in the Appendix.

2. PROCESSING SUMMARY AND PRODUCTION ESTIMATE

The isotopic concentrations of the various transuranium elements are not constant, but are functions of irradiation histories and decay times. We have selected one isotope of each element to use in making material balances for the isotopic mixtures normally handled in TRU. Thus we usually trace curium by the isotope ^{244}Cm . Except in special instances, ^{242}Pu , ^{243}Am , ^{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 "isotopically pure."

2.1 Processing Summary

During January-June 1970, we recovered 4.6 g of ^{242}Pu , 1.9 g of ^{243}Am , 34.5 g of ^{244}Cm , 3.8 mg of ^{249}Bk , 40.7 mg of ^{252}Cf , 298 μg of ^{253}Es , and about 4×10^8 atoms of ^{257}Fm as purified products from irradiated HFIR targets. In two campaigns, we processed (1) 7 irradiated plutonium targets and 18 irradiated curium pellets, and (2) 7 irradiated plutonium targets and 2 irradiated curium targets. Individual products of the campaigns are listed in Table 2.1.

Sixty-three shipments (Table 2.2) that were made from TRU during this period included: (1) 2.3 mg of ^{244}Pu (calutron enriched) which was irradiated in the HFIR prior to shipment; (2) 26.48 g of ^{243}Am and 14.45 g of ^{244}Cm that had been separated and purified; (3) a mixture of 5.1 g of ^{243}Am and 5.58 g of ^{244}Cm (to the European Transuranium Institute, Karlsruhe, Germany); (4) 376.3 μg of ^{248}Cm (in curium products containing from 89 to 99.9% ^{248}Cm); (5) 3.6 mg of ^{249}Bk ; (6) 220 μg of isotopically pure ^{249}Cf that had been "milked" from ^{249}Bk ; (7) 161 μg of high-purity (87 to 94%) ^{250}Cf that was produced by irradiating ^{249}Bk in the HFIR hydraulic rabbit facility; (8) 12.3 mg of ^{252}Cf in a mixture of californium isotopes (~85% ^{252}Cf); (9) 259 μg of ^{253}Es containing some ^{254}Es and ^{255}Es ; (10) 36 μg of ^{253}Es (isotopically pure) that had been "milked" from californium; and (11) 3.7×10^8 atoms of ^{257}Fm .

As of June 30, 1970, an inventory of the transuranium materials on hand (exclusive of HFIR targets) showed the following: 9 g of ^{242}Pu , 82 g of ^{243}Am , 162 g of ^{244}Cm , and 26 mg of ^{252}Cf .

Table 2.1. Amounts of Materials Recovered in
Major Campaigns in the Transuranium Processing Plant
During the Period January 1, 1970, through June 30, 1970

	Campaign No.	
	16	19
Completion date	February 1970	May 1970
Material processed	7 plutonium targets; 18 curium pellets	7 plutonium targets; 2 curium targets
Amounts recovered		
^{242}Pu , g	3.5	1.1
^{243}Am , g ^a	1.2	0.7
^{244}Cm , g ^a	18.9	15.6
^{249}Bk , mg	1.2	2.6
^{252}Cf , mg	12.2	28.5
^{253}Es , μg	78	220
^{257}Fm , atoms	8.8×10^7	3.0×10^8

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

Table 2.2. Distribution of Heavy Elements from
the Transuranium Processing Plant
During the Period January 1, 1970, to June 30, 1970

Major Nuclide	Date	TRU File No.	Shipped To	
			Individual	Site
<u>Plutonium-244, mg</u>				
1.0 (irradiated)	2-11-70	238	R. J. Morrow	LRL-L
1.3 (irradiated)	6-02-70	280	R. J. Morrow	LRL-L
2.3				
<u>Americium-243, g</u>				
0.10	1-08-70	166	J. A. Harris	LRL-B
0.11	2-05-70	230	J. A. Harris	LRL-B
2.03	2-05-70	231	R. W. Hoff	LRL-L
10.15	2-05-70	233	F. B. Simpson	INC
1.02	2-19-70	232	R. O. Budd	PNL
6.81	2-26-70	254	P. R. Fields	ANL
0.12	3-12-70	277	W. J. McDowell	ORNL-CTD
5.10 (mixed with Cm)	4-01-70	276	R. Lindner	Karlsruhe
3.07	6-25-70	281	L. J. Nugent	ORNL-TRL
3.07	6-29-70	282	R. O. Budd	PNL
31.58				
<u>Curium-244, g</u>				
0.10	1-08-70	171	J. A. Harris	LRL-B
4.1 ^a	1-27-70	124	R. A. Penneman	LASL
10.25	1-27-70	235	R. W. Hoff	LRL-L
5.58 (mixed with Am, above)	4-01-70	276	R. Lindner	Karlsruhe
20.03				
<u>Curium-248, µg</u>				
120 (97% ²⁴⁸ Cm)	1-16-70	246	R. J. Silva	ORNL-TRL
90 (89% ²⁴⁸ Cm)	1-30-70	244	J. A. Harris	LRL-B
83 (89% ²⁴⁸ Cm)	1-30-70	245	D. M. Barton	LASL
1.3 (97% ²⁴⁸ Cm)	2-10-70	240	M. L. Hyder	SRL
26 (99.9% ²⁴⁸ Cm)	2-19-70	256	J. R. Peterson	Liege
17 (99.9% ²⁴⁸ Cm)	2-19-70	257	P. R. Fields	ANL
17 (99.9% ²⁴⁸ Cm)	2-19-70	258	R. A. Penneman	LASL
17 (99.9% ²⁴⁸ Cm)	2-19-70	259	T. C. Parsons	LRL-B
5 (97% ²⁴⁸ Cm)	6-30-70	288	C. H. Ice	SRL
376.3				

Table 2.2 (continued)

Major Nuclide	Date	TRU File No.	Shipped To	
			Individual	Site
<u>Berkelium-249, μg</u>				
2.25	1-28-70	155	B. Gordon	BNL
1081	3-11-70	241	T. D. Chikalla	PNL
107	3-19-70	278	R. J. Silva	ORNL-TRL
5	4-28-70	309	Prod. Support	ORNL-TRU
5	4-29-70	310	Prod. Support	ORNL-TRU
700	5-20-70	260	P. R. Fields	ANL
700	5-20-70	262	R. W. Hoff	LRL-L
300	6-03-70	261	J. A. Harris	LRL-B
700	6-03-70	263	R. D. Baybarz	ORNL
<u>3600.25</u>				
<u>Californium-249 (isotopically pure), μg</u>				
150	5-26-70	311	A. Ghiorso	LRL-B
70 ^b	5-26-70	312	R. A. Penneman	LASL
<u>220</u>				
<u>Californium-250, μg</u>				
155 (87%)	6-03-70	289	J. A. Harris	LRL-B
3 (94%)	6-03-70	290	R. A. Penneman	LASL
3 (94%)	6-03-70	313	C. E. Bemis	ORNL
<u>161</u>				
<u>Californium-252, μg</u>				
816 (NS-6)	1-07-70	266	R. W. Hoff	LRL-L
0.1	1-15-70	325	W. J. McDowell	ORNL-CTD
185 (NS-2)	1-19-70	237	J. E. Powell	Sandia
820 (NS-7)	1-28-70	228	E. Ricci	ORNL-TRL
34	1-28-70	326	Isotopes Sales	ORNL
(1920) (NS-8) ^c	2-09-70	253	A. R. Boulogne	SRL
1920 (NS-8)	3-03-70	267	H. Berger	ANL
224	4-02-70	269	P. R. Fields	ANL
8 (NS-11) ^a	4-03-70	255	R. R. Fullwood	LASL
1880	5-08-70	268	A. R. Boulogne	SRL
2590	5-28-70	291	A. R. Boulogne	SRL
3820	6-16-70	252	A. R. Boulogne	SRL
<u>12297.1</u>				

Table 2.2 (continued)

Major Nuclide	Date	TRU File No.	Shipped To	
			Individual	Site
<u>Einsteinium-253, μg</u>				
17	2-12-70	272	T. C. Parsons	LRL-B
33	2-20-70	271	C. E. Bemis	ORNL-TRL
7	2-20-70	236	R. A. Penneman	LASL
165	4-29-70	279	A. Ghiorso	LRL-B
37	5-12-70	308	A. Ghiorso	LRL-B
<u>259</u>				
 <u>Einsteinium-253 (isotopically pure), μg</u>				
12	3-18-70	274	T. C. Parsons	LRL-B
1 (irradiated)	3-23-70	273	H. Diamond	ANL
2 (irradiated)	5-11-70	248	H. Diamond	ANL
10	6-05-70	305	R. G. Haire	ORNL
4	6-05-70	306	R. W. Hoff	LRL-L
2 (irradiated)	6-08-70	302	H. Diamond	ANL
5 (irradiated)	6-22-70	303	H. Diamond	ANL
<u>36</u>				
 <u>Fermium-257, atoms</u>				
7×10^7	2-20-70	275	C. E. Bemis	ORNL-TRL
<u>$\sim 3 \times 10^8$</u>	5-12-70	307	D. C. Hoffman	LASL
$\sim 3.7 \times 10^8$				

^aThese shipments were prepared by ORNL Isotopes Sales.

^bReturn of LASL's material.

^cSource NS-8 was loaned to SRL for about one month prior to being shipped to ANL. This source is included in the total for ^{252}Cf only once.

2.2 Irradiation and Processing Proposals

The estimated future production of transcurium elements is given in Table 2.3. During the period July 1970 through May 1971, we will process 163 americium-curium slugs that are being irradiated as part of the Californium-I program at the Savannah River Plant (SRP). In this program, californium is being produced for use in the USAEC program to evaluate the commercial market for ^{252}Cf .⁵ Although the californium that is recovered from the slugs is primarily intended for use in the market evaluation studies, some of it will be made available to satisfy research requirements of the National Transplutonium Program of the USAEC's Research Division. Approximately 450 g of curium, assaying about 28% ^{246}Cm , will be recovered from the slugs. This curium is earmarked for future reirradiation at SRP to produce ^{252}Cf ; however, some of it may also be made available to the research program. The by-products ^{249}Bk and ^{253}Es will be allocated to researchers by the Transplutonium Committee.

The slugs will be processed in three groups: 35, beginning about October 15, 1970; 64, beginning January 1, 1971; and 64, beginning March 1, 1971. The processing of each group of slugs, designated as a campaign, will require 6 weeks.

There is some uncertainty about how long the irradiation of the slugs will be continued after October 1, 1970. Naturally, a revision in the irradiation schedule would change the amounts of transuranium materials that would be produced. According to present irradiation-processing plans, we expect to recover about 100 g of ^{244}Cm (150 g of total curium) and 300 μg of ^{253}Es in each of the three campaigns. The successive campaigns are expected to yield 125, 120, and 140 mg of ^{252}Cf , and 17, 18, and 21 mg of ^{249}Bk .

If the second and third groups of slugs (64 each) are not irradiated after October 1, the yields in each of the corresponding processing campaigns will be about 200 g of ^{244}Cm (containing 16% ^{246}Cm), 10 mg of ^{249}Bk , 60 mg of ^{252}Cf , and 15 μg of ^{253}Es .

Table 2.3. Estimated Future Production of Transcurium Elements

Period	Processing Campaign	Products of Campaigns			252Cf Production ^a		Date Products Available
		249Bk (mg)	252Cf (mg)	253Es (μg)	Period (mg)	Cumulative (mg)	
Through June 1970						73	
July - December 1970	35 SRP Cf-I slugs	17	125 ^a	300		73	January 1971
January - June 1971	Irradiation of 100 mg of Cf ^b	--	--	500			
	64 SRP Cf-I slugs	18	120 ^a	300			March 1971
	64 SRP Cf-I slugs	21	140 ^a	300			May 1971
	7 Pu targets	1	12	55(10)			June 1971
	5 Cm targets	5	40	220(40)	52	125	June 1971
July - December 1971	6 Pu targets	1	11	60(11)			September 1971
	5 Cm targets	5	45	250(45)	56	181	November 1971
1972					~400 ^c	~600 ^c	
1973					~500 ^c	~1100 ^c	
1974					~500 ^c	~1600 ^c	

^aCalifornium produced in the SRP-slug campaigns is not included in production totals.

^bIt is possible that, concurrently with one of the other campaigns planned for this period, up to 100 mg of californium will be made available for reirradiation in the HFIR to produce 500 μg of ²⁵³Es.

^cEstimates of californium production rates during 1972, 1973, and 1974 assume that additional curium will be available for fabrication of targets.

After the SRP-slug campaigns have been completed, we will resume the processing of HFIR targets. Five irradiated curium targets and seven irradiated plutonium targets will be processed in June 1971 to produce 6 mg of ^{249}Bk , 52 mg of ^{252}Cf , and 275 μg of ^{253}Es . Six irradiated plutonium targets will be processed in September 1971 to produce 1 mg of ^{249}Bk , 11 mg of ^{252}Cf , and 60 μg of ^{253}Es . Five irradiated curium targets will be processed in November 1971 to produce 5 mg of ^{249}Bk , 45 mg of ^{252}Cf , and 250 μg of ^{253}Es .

2.3 Estimates of the Availability of Transuranium Elements

Plutonium, americium, and curium are usually considered to be intermediate feed materials rather than products. Estimates of the availability of berkelium, californium, einsteinium, and fermium are given below. The estimates of the amounts to be recovered from the three SRP-slug campaigns are based on present plans, which are somewhat uncertain.

2.3.1 Berkelium

About 68 mg of ^{249}Bk is expected to become available during the next 18 months: 17 mg in January 1971, 18 mg in March 1971, 21 mg in May 1971, 6 mg in June 1971, 1 mg in September 1971, and 5 mg in November 1971.

2.3.2 Californium

We expect to produce about 493 mg of ^{252}Cf contained in a mixture of californium isotopes (about 85% ^{252}Cf) during the next 18 months. About 385 mg will be recovered in the SRP-slug campaigns (125 mg in January 1971, 120 mg in March 1971, and 140 mg in May 1971), and 108 mg will be recovered from HFIR targets (52 mg in June 1971, 11 mg in September 1971, and 45 mg in November 1971).

2.3.3 Einsteinium

We expect to recover about 1.5 mg of ^{253}Es in a mixture of einsteinium isotopes during the next 18 months: 300 μg in each of the SRP-slug campaigns in January 1971, March 1971, and May 1971; 275 μg in June 1971; 60 μg in September 1971; and 250 μg in November 1971. If more einsteinium is needed, an additional 500 μg of ^{253}Es (in a mixture of isotopes) could be produced by irradiating 100 mg of ^{252}Cf , assuming that this operation would not interfere with the processing schedule and the needs dictated by the californium market evaluation program. Such an irradiation could be scheduled so that it would coincide with one of the processing campaigns during the period January-June 1971.

Some "second-growth" einsteinium will be recovered from the HFIR target campaigns. That is, after the mixture of einsteinium isotopes has been separated from the californium, the latter will be stored about one month to allow ^{253}Es to "grow in" from the decay of ^{253}Cf ; then this second-growth ^{253}Es will be recovered. About 50 μg , 11 μg , and 45 μg of isotopically pure ^{253}Es will be "milked" from the californium that will be isolated in June 1971, September 1971, and November 1971, respectively.

About 40 μg of isotopically pure ^{253}Es can be recovered from the californium product from each of the SRP-slug campaigns if the californium products can be held for one month to permit the growth of ^{253}Es .

2.3.4 Fermium

Each batch of californium that is recovered from the processing of HFIR targets will contain about 1×10^7 atoms of ^{257}Fm per milligram of ^{252}Cf . Thus, about 5.2×10^8 atoms, 1.1×10^8 atoms, and 4.5×10^9 atoms will be available in June 1971, September 1971, and November 1971, respectively. Data that would permit us to predict the yields in the SRP reactor are not currently available; however, we estimate that each of the SRP-slug campaigns will produce on the order of 10^9 atoms.

3. PROCESSES AND EQUIPMENT

Figure 3.1 is a block diagram showing the processing steps that are required for transuranium element production. These steps are: (1) the preparation of a feed solution by dissolving irradiated targets; (2) the recovery of plutonium; (3) the decontamination of the transplutonium elements from fission products; (4) the separation of americium-curium from the transcurium elements; (5) the separation and purification of berkelium, californium, einsteinium, and fermium; (6) the preparation of americium-curium oxide; and (7) the fabrication of targets to be irradiated in the HFIR.

The Tramex feed system was modified during this report period. The other processes (and equipment) have remained essentially the same since the previous report.

3.1 Tramex Feed System

In the original Tramex feed system, the feed solution was pumped to a pressurized feed pot, which overflowed through a jackleg to the feed tank; from this tank, the feed was introduced to the solvent extraction columns through an orifice. Feed line plugging problems had plagued us in nearly every Tramex run made with this system. During the previous report period, we replaced the orifice with a metering pump in an effort to eliminate these problems; no difficulties were encountered with the feed system during a subsequent Tramex run.

In the first of the two processing campaigns made during this report period, the pump that is used to transfer feed from the tank in the tank pit to the pressurized pot on the Tramex equipment rack in the cubicle became plugged. A temporary (plastic) vacuum system was installed to transfer the feed solution from the cell tank, through a filter, to a feed pot from which the clear solution was pumped into the solvent extraction equipment. This system had the additional advantage of reducing the amount of solution required to flush the system free of feed solution. Following this campaign, a permanent (metal)

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Fig. 3.1. Processing Steps Used for Transuranium Element Production.

feed system was installed on the Tramex equipment rack.

Operation of the new system was satisfactory during the second campaign.

3.2 Fabrication of Targets

Four HFIR targets were fabricated during this report period. Each target contained 9.4 g of actinides (from 72 to 92% ^{244}Cm) in the form of actinide oxide--aluminum pellets that were pressed to 80% of the theoretical density of the pellet core.

Nine targets (rabbits) were fabricated for irradiation in the HFIR hydraulic rabbit facility; three contained ^{249}Bk (Sect. 5.1), four contained ^{253}Es (Sect. 5.2), and two contained ^{244}Pu (Sect. 5.3).

3.3 Iodine Studies

A large iodine removal unit for treating the entire vessel and cubicle off-gas system (450 cfm) at TRU is being fabricated. During the two processing campaigns in this report period, we continued to perform iodine experiments in conjunction with the LMFBR program, using small-scale equipment to treat off-gas from the dissolver vessel. The targets that were processed in these campaigns contained 306 Ci and 572 Ci of ^{131}I , respectively, when processing was started. Of these initial quantities, only 52 mCi and 60 mCi were released to the atmosphere.

Small-scale iodine experiments have been terminated. Future iodine studies will be concerned with the performance of the large system, which will be installed before the first SRP-slug campaign commences.

3.4 Californium Facility at TURF

Cell G in TURF, which is located across the street from TRU, has been equipped to provide space for the purification and encapsulation of californium. It was placed in service in March 1970. The primary purpose of this cell is to provide a ^{244}Cm -clean environment in which

to prepare extremely pure ^{248}Cm , the alpha decay product of ^{252}Cf . Curium-248 is of special interest because it has a very low specific activity (half-life, 3.52×10^5 years) and it can be recovered in relatively pure form. The ^{252}Cf product from each processing campaign can be purified and held to permit decay, during which ^{248}Cm "grows in" and can be recovered. Previously, the purity of ^{248}Cm had been limited by the massive contamination levels of ^{244}Cm in the TRU production cells.

About 10 g of ^{244}Cm and 10 mg of ^{252}Cf are processed in a typical processing campaign. To obtain high-quality ^{248}Cm , the ^{252}Cf must be purified until it contains only 1 nanogram of ^{244}Cm prior to the decay period for ^{248}Cm production. This degree of purity requires a curium DF of 10^{10} . (Another contaminant isotope, ^{246}Cm , is formed by the alpha decay of ^{250}Cf . If our usual mixture of californium isotopes contains no curium initially, the curium recovered following the usual decay period is sufficiently contaminated with ^{246}Cm that the alpha emission rate of this isotope is about equal to the emission rate from ^{248}Cm . Therefore, the highest-purity ^{248}Cm can be recovered only if the ^{250}Cf is burned out of our normal californium product by a short neutron irradiation.)

The plan view of the californium facility in TURF (Fig. 3.2) shows the three work stations located adjacent to three viewing windows in the single large cell. The three stations are used for: (1) final purification of the californium product from TRU; (2) "milking" of ^{248}Cm from used sources or stored solutions; and (3) source fabrication and packaging operations. The processing steps and techniques used in the facility duplicate those used in TRU; they have been described in previous reports or are discussed in other sections of this report.

Cell G in TURF was originally intended to be used as a high-level gamma-shielded cell; thus no particular consideration was given to neutron shielding in the design of the facility. The zinc bromide shielding windows, instead of the concrete cell walls, are the weak points in the neutron shielding. These windows are built of heavy steel sections, which permit streaming of neutrons when sources are aligned with the steel. In addition, activation of the zinc bromide

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Fig. 3.2. Plan View of the Californium Facility at TURF.

near the inside of the cell can cause problems as the solution is circulated slowly to the cold side of the window by action of the argon sparge and purge system or by simple thermal convection.

To date, 35 mg of ^{252}Cf has been handled in the facility; no shielding problems have been encountered. Based on this experience and other considerations, we estimate that 100 mg could be handled without difficulty.

3.5 Hydraulic Rabbit Tube from HFIR Pool

A hydraulic rabbit tube has been installed to permit the rapid transfer of small hydraulic rabbits from the HFIR pool to a shielded cave in an alpha laboratory in TRU. Previously, all HFIR-irradiated materials have been brought to TRU in carriers. In many cases, experiments were seriously limited because the time required for transfer by carrier was long as compared with the half-life of the material of interest. The 700-ft-long hydraulic tube (1-in. stainless steel pipe) permits transfer of a rabbit from the core of the HFIR to the shielded cave in about 10 min. For safety reasons, an irradiated rabbit cannot be transferred directly from the core to TRU. Instead, it must be removed from the normal rabbit core-tube unloading station (which is located under water in the HFIR pool) and transferred manually to the new rabbit transfer tube. From here, it is sent by hydraulic means to TRU. A cooling time of 10 min is required to permit short-lived nuclides, which are formed by activation of the aluminum rabbit, to decay sufficiently to make the 2 ft of concrete shielding in the cave adequate. The actual transit time is about 5 min.

3.6 HFIR Target Rod Failures

The first targets that failed during irradiation in the HFIR (in February and March 1967)¹ had been irradiated for about one year in an SRP reactor prior to the HFIR irradiation. Each of them had originally contained 10 g of plutonium (9.57 g of ^{242}Pu), in the form of PuO_2 , in aluminum pellets that had been pressed to 90% of theoretical density.

This left 10% void space in the pellets. The ruptured targets were examined, and an engineering model was developed to guide the development of a new target design. Hot-cell measurements showed that the exposure of the aluminum alloy cladding material to the high fast-neutron flux in the HFIR had caused a rapid decrease in ductility. Apparently, fission products had accumulated and filled the void volume in the pellets, and the fission gases had increased the pressure in the remaining voids. These effects then undoubtedly resulted in a gradual increase in the stresses in the cladding. When these stresses reached the yield point of the cladding, the embrittled cladding fractured instead of yielding.

The engineering model indicated that target life could be increased by decreasing the amount of target material, which would result in lower temperatures (and thereby limit the internal pressure during irradiation), or by increasing the void space (which would also limit the internal pressure). With such modifications in mind, we fabricated three pairs of special targets, which contained: (1) 8 g of plutonium (95.82% ^{242}Pu) and 20% voids, (2) 8 g of plutonium and 25% voids, and (3) 6 g of plutonium and 20% voids. These targets were placed in the HFIR in June 1967. At the same time, we continued to irradiate our existing HFIR targets, which contained 8 g of plutonium per target and only 10% voids.

The model had predicted that the targets containing 8 g of plutonium and 10% voids would have lifetimes approximately equal to the lifetime required for the desired irradiation-processing cycle. The validity of the model was confirmed when some of these targets failed prior to scheduled processing times and some of them were processed before they ruptured. On the other hand, the engineering model had predicted that all of the special test targets could be irradiated much longer than our specified period, based on production considerations. This prediction also proved to be valid since the special targets were processed (campaign 19) after having been irradiated for about two full-power years in the HFIR (equivalent to about 0.82 fission per original plutonium atom) without failure. In the usual irradiation-processing

cycle, a typical target would be dissolved and processed after being irradiated for a period equivalent to only 0.6 fission per original actinide atom.

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 thus far are listed in Table 4.1. Most of them have been encapsulated in type 304L stainless steel in the typical configuration (not identical dimensions) shown in Fig. 4.1.

Recently, sources have been fabricated from californium that had been highly purified from curium in the new californium facility in TURF (see Sect. 3.4). This ultrapurification step makes the californium suitable for future reprocessing to recover ^{248}Cm (the alpha decay product of ^{252}Cf) that is free from ^{244}Cm contamination. The current ^{248}Cm contents of the californium sources are listed in Table 4.1.

4.1 Sources Fabricated During January-June 1970

Seven sources were fabricated during this report period. Source NS-11 (Table 4.1) is not a typical source; it consists of a quartz bead, originally containing 8 μg of ^{252}Cf , that is sealed in a 1/8-in.-OD stainless steel container. Source NS-9, which contained 1.8 mg of ^{252}Cf when calibrated, was doubly encapsulated to provide sufficient containment to permit off-site use by the recipient. Sources NS-15 and -18, which contained 0.975 mg and 1.008 mg of ^{252}Cf at calibration, were encapsulated in a low-nickel stainless steel (type 405) because nickel would interfere with some of the experiments for which the sources will be used. The other sources, NS-10, -12 and -14, which contained 0.118, 1.96, and 4.83 mg of ^{252}Cf , respectively, were standard sources singly encapsulated in type 304L stainless steel.

Table 4.1. Data for Neutron Sources Prepared at TRU

Source (NS-)	Date of Calibration	²⁵² Cf Content at Calibration (μg)	²⁵² Cf Content as of 6-30-70 (μg)	²⁴⁸ Cm Content as of 6-30-70 (μg)	On Loan To	
					Individual	Site
1 ^a	8-28-68	311	192	b	J. L. Cason	PNL
2	8-23-68	268	165	b	J. E. Powell	Sandia
3	5-13-69	~90	~67	b	H. E. Banta	ORAU
4	7-09-69	925	716	203	C. F. Masters	LASL
5 ^c	8-14-69	992	789	197	F. B. Simpson	INC
6	11-21-69	783	668	112	R. W. Hoff	LRL-L
7	1-21-70	807	720	84	T. F. Handley	ORNL
8	12-17-69	1927	1675	244	H. Berger	ANL
9	4-17-70	1802	1709	90	N. D. Wogman	PNL
10	3-11-70	118	109	b	J. P. Balagna	LASL
11		8			R. R. Fullwood	LASL
12	6-30-70	1957	1957	0	R. W. Hoff	LRL-L
14	6-29-70	4833	4830	3	D. C. Stewart	ANL
15 ^c	6-25-70	975	972	3	F. B. Simpson	INC
18 ^c	6-24-70	1008	1004	4	F. B. Simpson	INC

^aThis source is encapsulated in aluminum.

^bThe californium in this source is not sufficiently decontaminated from ²⁴⁴Cm to be a suitable source of ²⁴⁸Cm.

^cThis source is encapsulated in type 405 stainless steel.

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Fig. 4.1. Standard Neutron Source Using ^{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. The facilities that are available at TRU are also used for a variety of other purposes such as nonroutine productions, special preparations, and special irradiations in HFIR; in each case, a unique service can be provided to assist a research program at ORNL or another site.

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

Two batches of ^{250}Cf were prepared by irradiating ^{249}Bk in HFIR rabbits. This method permitted recovery of ^{250}Cf after a short irradiation, thereby minimizing the production of (and contamination with) higher isotopes of californium. Two test irradiations were made, for 5 and 29 hr respectively, to determine the optimum irradiation time to obtain the highest yield of good-quality product. For each of these irradiations, 5 μg of ^{249}Bk was sealed in a quartz ampul and welded into a standard rabbit. The results allowed us to recalculate cross sections in this region. The best values are given in Table 5.1.

Table 5.1. Effective Cross Sections in HFIR
for ^{250}Cf Production

Nuclide	σ_c	σ_f
^{249}Bk	1260	
^{250}Bk	294	2520
^{249}Cf	262	1430
^{250}Cf	1830	
^{251}Cf	2220	4410
^{252}Cf	18.2	

In the production irradiation, nearly 1.5 mg of ^{249}Bk was irradiated for 15.5 hr in a rabbit containing three pressed pellets made by the resin-loading technique. Forty-five minutes after discharge, the rabbit was transferred to TRU, using our new rabbit transfer line that connects directly to the shielded cave in laboratory 111 (Sect. 3.5). The initial separation was completed within 3 hr of discharge. About 155 μg of ^{250}Cf (isotopic purity, 87%) was recovered from the rabbit and shipped to Lawrence Radiation Laboratory at Berkeley. The ^{250}Cf is to be used as a target for transactinide element production in the Berkeley HILAC.

Four and one-half hours after the initial separation, the ^{250}Cf that had grown in from the ^{250}Bk ($t_{1/2} = 3.72$ hr) was "milked." Nearly 6 μg of ^{250}Cf (isotopic purity, 93.6%) was obtained. A portion of this material was shipped to the Los Alamos Scientific Laboratory for fission cross-section studies; the remainder was retained at ORNL.

5.2 Einsteinium Rabbits

Four einsteinium rabbits (originally containing 1 to 5 μg of isotopically pure ^{253}Es) were fabricated, irradiated, and delivered to H. Diamond at Argonne National Laboratory (ANL) for use in studying the energy level structure of ^{250}Bk , the decay product of ^{254}Es . The irradiation, handling, and shipping were scheduled in such a manner that the rabbits were available at ANL about 28 hr after they had been removed from the HFIR. Since the half-life of ^{254}Es is 39.3 hr, Diamond received about 60% of the amount of this isotope that was present when each rabbit was removed from the reactor.

5.3 Rabbits Containing ^{244}Pu

At the request of R. J. Morrow of the Lawrence Radiation Laboratory at Livermore, we prepared two ^{244}Pu -containing rabbits, using the quartz ampul technique. The first rabbit contained 1 mg of 99% ^{244}Pu and was

irradiated for 5.5 days in the HFIR. The second contained 1.3 mg of 75% ^{244}Pu and was irradiated for 25 days. After irradiation, the rabbits were transferred to TRU in the new hydraulic transfer tube (Sect. 3.5); they were decanned and then shipped to Livermore via air express.

6. REFERENCES

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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 Lederer⁶ and Wapstra⁷, 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

Table A-1. Half-Life Values^a for Isotopes of Transuranium Elements

Underlines indicate new values since the previous report.

Isotope	Total half-life	Partial half-life for α Decay	Branching Ratios	Partial half-life for Spontaneous Fission	Neutrons per Fission	References ^b
^{237}Np		$(2.14 \pm 0.01) \times 10^6 \text{ y}$		$>10^{18} \text{ y}$	2.00^d	60Br12, 60Br4
^{238}Np	$2.10 \pm 0.01 \text{ d}$					50F53
^{239}Np	$2.350 \pm 0.009 \text{ d}$					50C95
^{240}Np	$63 \pm 2 \text{ m}$					60La3
^{240m}Np	$7.3 \pm 0.3 \text{ m}$					60La1
^{241}Np	16 m					60La3
^{241m}Np	3.4 h					60La3
^{238}Pu	$87.004 \pm 0.041 \text{ y}$			$(5 \pm 0.6) \times 10^{10} \text{ y}$	2.33 ± 0.08	60Br4, 60Ja15, 50a001
^{239}Pu		$(2.4413 \pm 0.003) \times 10^4 \text{ y}$		$5.5 \times 10^{15} \text{ y}$	2.24^d	52Se7, 50Br26
^{240}Pu		$6592 \pm 40 \text{ y}$		$(1.340 \pm 0.015) \times 10^{11} \text{ y}$	2.257 ± 0.006	51J3, 60Br13, 50a012
^{241}Pu	$14.90 \pm 0.33 \text{ y}$	$(5.72 \pm 0.1) \times 10^5 \text{ y}$				60Ca19, 60Br15
^{242}Pu		$(3.800 \pm 0.006) \times 10^5 \text{ y}$		$(7.45 \pm 0.17) \times 10^{10} \text{ y}$	2.10 ± 0.00	60Br10, 60Br06, 50a001
^{243}Pu	$4.955 \pm 0.003 \text{ h}$					60Br09
^{244}Pu		$(8.26 \pm 0.10) \times 10^7 \text{ y}$		$(0.55 \pm 0.32) \times 10^{10} \text{ y}$	2.04^d	60F107, 60Br04
^{245}Pu	$10.6 \pm 0.4 \text{ h}$					50Br2
^{246}Pu	$10.05 \pm 0.02 \text{ d}$					50Br23
^{241}Am		$432.7 \pm 0.7 \text{ y}$		$(2.3 \pm 0.8) \times 10^{14} \text{ y}$	2.00^d	60Br4, 60Br01
^{242}Am	$1.21 \pm 0.02 \text{ h}$		$\alpha/\text{SF} = 0.10$			50Br38
^{243m}Am	$144 \pm 7 \text{ y}$	$(2.92 \pm 0.15) \times 10^4 \text{ y}$				50Br271 ^c
^{243}Am		$7300 \pm 50 \text{ y}$				
^{244}Am	$10.1 \pm 0.1 \text{ h}$					60Br08
^{244m}Am	26 m					50C24
^{245}Am	$2.07 \pm 0.02 \text{ h}$					50Br02
^{246}Am	$25.0 \pm 0.2 \text{ m}$					55E16
^{246m}Am	$40 \pm 7 \text{ m}$					60Br02
^{247}Am	$24 \pm 3 \text{ m}$					60Br02
^{242}Cm	$162.7 \pm 0.1 \text{ d}$			$7.2 \times 10^6 \text{ y}$	2.65 ± 0.00	50Br07, 57F52, 50a001
^{243}Cm		32 y				57Br70
^{244}Cm	$18.000 \pm 0.015 \text{ y}$		$\alpha/\text{SF} = (7.43 \pm 0.01) \times 10^5$		2.04 ± 0.00	60Br02, 60Br26, 50a001
^{245}Cm		$8265 \pm 100 \text{ y}$				60Br01
^{246}Cm		$4711 \pm 22 \text{ y}$	$\alpha/\text{SF} = 3522 \pm 10$		3.00^d	60Br01
^{247}Cm		$(1.64 \pm 0.20) \times 10^7 \text{ y}$				60F100
^{248}Cm		$(3.04 \pm 0.04) \times 10^5 \text{ y}$	$\alpha/\text{SF} = 11.0 \pm 3$		3.32^d	60Br01
^{249}Cm	$64 \pm 3 \text{ m}$					50Br06
^{250}Cm				$(1.74 \pm 0.24) \times 10^6 \text{ y}$	3.56^d	60Br01

Table A-1 (continued)

Isotope	Total half-life	Partial half-life for α decay	Branching Ratio	Partial half-life for Spontaneous Fission	Neutrons per fission	References ^b
²¹⁰ Pb	134 ± 4 d		$\alpha/\beta = (1.45 \pm 0.08) \times 10^{-5}$	$(1.67 \pm 1.00) \times 10^3$ y	3.72 ± 0.16	57b01, 68b06, 68p02
²¹⁰ Bi	3.222 ± 0.006 h					58b02
²¹¹ Pb	17 ± 1.7 d					68b04
²¹⁰ Bi		35.2 ± 0.7 y	$\alpha/\beta = (1.102 \pm 0.009) \times 10^8$		3.44 ^d	68b01, 68b06
²¹⁰ Po		13.00 ± 0.09 y	$\alpha/\beta = 1.260 \pm 40$		3.56 ^d	63p01, 68b01
²¹¹ Bi		900 ± 50 y				68b01
²¹² Bi	2.040 ± 0.024 y		$\alpha/\beta = 34.3 \pm 0.2$		3.796 ± 0.031	68b02, 68b04
²¹² Po	17.812 ± 0.082 d					68b02
²¹⁴ Bi	60.5 ± 0.2 d			61.5 ± 0.2 d	3.90 ± 0.14	63p01, 68p02
²¹¹ Pb	20.467 ± 0.034 d		$\alpha/\beta = (1.15 \pm 0.03) \times 10^7$		3.92 ^d	68b02, 68b02
²¹⁴ Pb	270 d			$>2.1 \times 10^7$ y	4.00 ^d	67f03, 67b01
²¹⁴ Bi	19.9 ± 0.2 h		$\alpha/\beta = 352 \pm 37$ $\beta/\beta = 0.00170 \pm .00006$			63b01, 63p01
²¹⁴ Pb	20.8 ± 1.2 d		$\alpha/\beta = 0.0006 \pm 0.0003$ $\alpha/\beta = (2.22 \pm .10) \times 10^6$		4.16 ^d	68b01, 67f03
²¹⁴ Bi	25 ± 3 d					68b01
²¹⁴ Pb	1.24 ± 0.04 h		$\alpha/\beta = 1495 \pm 8$		4.05 ± 0.19	56f00, 67f03, 56C33
²¹⁴ Pb	20.67 ± 0.07 h		$\beta/\alpha = (2.6 \pm 1.1) \times 10^{-7}$		4.16 ^d	63p01, 68b01
²¹⁴ Pb	2.62 ± 0.05 h			2.61 ± 0.03 h	4.27 ^d	68b03
²¹⁷ Pb	94 ± 10 d					68b01

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

^bReferences are denoted in Table A-2.

^cPublished values are adjusted for ²¹⁴Pb half-life of 432.7 y.

^dValues estimated by linear interpolation of the values for ²¹⁴Pb and ²¹²Bi, based on periodic mass.

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.

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, and the third is the neutron capture resonance integral. The second parameter 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, $\sigma_{\text{eff}}^{\text{C}}$, would be:

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

where σ_{2200}^{C} is the thermal-neutron capture cross section, 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. 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.

Table A-2. References for Table A-1

Code	Reference	Code	Reference
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Table A-3. Properties^a of Transuranium Nuclides

Underlines indicate new values since the previous report.

Nuclide	Half-life	Range of Prim. Emissions (MeV)		Specific Activity				Based ^b on $\frac{dN}{dV \cdot dt}$ (atoms/cm ³)		Density (g/cm ³)	Atomic Weight
				(Ci/g)	(W/g)	(atoms/g)	(atoms/g)	(atoms/cm ³)	(atoms/cm ³)		
²³⁸ U	2.34×10^8 y	4.70		7.07×10^{-4}	2.07×10^{-5}	8.02×10^5		$<7 \times 10^{-6}$	4×10^{-12}	0.26	238.0
²³⁹ U	2.30 d	0.25 1.24		2.62×10^5	1.27×10^3		5.00×10^{14}				
²³⁹ U	2.330 d	0.332 0.407		2.32×10^5	5.06×10^2		5.14×10^{14}		8×10^{-7}	30	1.29×10^{-4}
²⁴⁰ U	63 m	0.40		1.24×10^7	1.03×10^5		2.75×10^{16}				
²⁴⁰ U	7.3 m	2.20 1.6		1.07×10^8	5.33×10^5		2.30×10^{17}				
²⁴¹ U	26 m			4.06×10^7			1.00×10^{17}				
²⁴² U	3.4 h			3.02×10^8			8.49×10^{15}				
²³⁸ Pu	87.400 y	5.40		17.2	0.570	1.94×10^{10}		195	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	0.050
²⁴⁰ Pu	6580 y	5.26		0.007	7.007×10^{-3}	2.57×10^8		55.7	2×10^{-12}	0.04	0.176
²⁴¹ Pu	14.30 y	4.9	0.02	99.1	4.06×10^{-3}	2.94×10^6	2.20×10^{11}		9×10^{-11}	0.9	9.00×10^{-3}
²⁴² Pu	2.70×10^5 y	4.90		3.02×10^{-3}	1.13×10^{-4}	4.32×10^6		95.9	2×10^{-12}	0.05	13.0
²⁴³ Pu	4.955 h	0.40 0.50		2.60×10^6	3.34×10^3		5.70×10^{15}		2×10^{-6}	7.2	2.70×10^{-6}
²⁴⁴ Pu	8.00×10^7 y	4.907		1.77×10^{-5}	4.93×10^{-7}	2.00×10^8		241	2×10^{-12}	0.04	2.23×10^3
²⁴⁵ Pu	10.6 h			1.23×10^6			2.00×10^{15}		2×10^{-7}	3.0	4.03×10^3
²⁴⁶ Pu	10.85 d	0.15		4.98×10^5	66.9		1.00×10^{14}				
²⁴¹ Am	432.7 y	5.40		3.43	0.1145	3.00×10^9		3.55×10^{-5}	6×10^{-12}	0.1	0.0002
²⁴² Am	16.02 h	0.63 0.67		8.11×10^5	2.00×10^3		1.00×10^{15}		1×10^{-8}	0.06	7.30×10^{-8}
²⁴³ Am	11.4 y	5.207	1.7	10.3	3.00×10^{-2}	5.33×10^7	2.20×10^{10}		6×10^{-12}	0.07	6.00×10^{-3}
²⁴⁴ Am	7540 y	5.27		0.000	6.45×10^{-3}	2.27×10^8			6×10^{-12}	0.05	0.25
²⁴⁵ Am	10.1 h	0.307		1.27×10^6	8.74×10^3		2.00×10^{15}		2×10^{-7}	0.10	1.40×10^{-7}
²⁴⁶ Am	26 m	1.5		2.06×10^7	8.00×10^4		6.90×10^{16}		1×10^{-6}	0.10	6.00×10^{-9}
²⁴⁷ Am	2.07 h	0.98		6.17×10^6	1.00×10^4		1.71×10^{16}		3×10^{-6}	12	1.94×10^{-6}
²⁴⁸ Am	25.0 m	1.38		3.06×10^7	2.40×10^5		6.79×10^{16}				
²⁴⁹ Am	16 m			1.98×10^7			4.34×10^{16}				
²⁵⁰ Am	26 m			3.17×10^7			7.04×10^{16}				
²⁴² Cm	166.7 d	6.11		3.30×10^3	1.02	3.76×10^{12}		1.21×10^6	1×10^{-10}	0.05	6.27×10^{-7}
²⁴³ Cm	30 y	5.70		45.9	1.077	5.30×10^{10}	3.27×10^8		6×10^{-12}	0.09	1.96×10^{-3}
²⁴⁴ Cm	18.400 y	5.00		80.94	2.070	9.16×10^{10}		6.07×10^5	9×10^{-12}	0.1	1.24×10^{-3}
²⁴⁵ Cm	8500 y	5.36		0.177	5.00×10^{-3}	2.00×10^8			5×10^{-12}	0.04	0.263
²⁴⁶ Cm	4711 y	5.4		0.379	1.01×10^{-2}	3.97×10^8		5.34×10^5	5×10^{-12}	0.07	2.194
²⁴⁷ Cm	1.64×10^7 y			8.03×10^{-3}	4.03×10^{-6}	1.00×10^5			5×10^{-12}	0.04	453
²⁴⁸ Cm	3.30×10^5 y	5.05		4.00×10^{-3}	3.70×10^{-6}	4.25×10^6		2.54×10^6	6×10^{-13}	0.04	2.90
²⁴⁹ Cm	62 m	0.9		1.10×10^7	2.06×10^5		2.40×10^{16}		8×10^{-6}	0.8	6.70×10^{-8}
²⁵⁰ Cm	1.74×10^4 y			8.00×10^{-2}	40.1			6.44×10^8			
²⁵⁰ Bk	324 d	5.4	0.105	1.07×10^3	0.398	2.74×10^7	3.71×10^{12}	6.34×10^3	9×10^{-10}	0.7	4.10×10^{-4}
²⁵¹ Bk	3.200 h	0.73		3.00×10^6	2.75×10^4		8.40×10^{15}		1×10^{-7}	0.04	1.03×10^{-7}
²⁵² Bk	97 m			1.30×10^7			2.00×10^{16}				

Table A-3 (continued)

Radionuclide	Half-life	Sample of Prim. Standard		Specific Activity				Dose ^b	
		a	b	(Ci/g)	(u/g)	(u gpmg ⁻¹)	(d gpmg)	(Röntgen cm ⁻² hr ⁻¹)	(mCi/cm ²)
²³⁸ U	380 y	5.81		4.88	0.140	1.60×10^9		2×10^{-12}	0.01
²³⁸ U	37.05 y	6.33		525	1.55	1.25×10^{11}		5×10^{-12}	0.01
²³² Th	900 y			1.50	5.79×10^{-2}	1.70×10^9		2×10^{-12}	0.01
²³² Th	2.046 y	6.11		535	39.0	5.00×10^{11}		1.00×10^{11}	0.01
²³² Th	17.82 d		0.27	2.90×10^4	13.80		6.42×10^{13}	8×10^{-10}	0.01
²³² Th	68.5 d	5.85		8.51×10^3	1.05×10^4		7.35×10^{13}	5×10^{-10}	0.01
²³³ Pa	30.147 d	6.43		2.57×10^4	1.01×10^4	1.05×10^{13}		1.91×10^7	0.01
²³³ Pa	276 d	6.40		1.85×10^3	71.9	2.11×10^{12}		5.04×10^5	0.01
²³³ Pa	39.3 h		0.10	3.35×10^5	1.15×10^5		6.97×10^{14}	5×10^{-9}	0.01
²³³ Pa	39.8 d			1.39×10^4			2.85×10^{13}	4.92×10^9	0.01
²³³ Pa	25 h			2.00×10^7			6.32×10^{16}		
²³⁴ Pa	3.28 h	7.30		1.81×10^6	1.00×10^5	1.31×10^{15}		2.02×10^{13}	0.01
²³⁴ Pa	30.07 h	7.03		6.13×10^5	2.79×10^4	6.05×10^{14}		1.30×10^9	0.01
²³⁴ Pa	2.68 h			1.07×10^6	5.05×10^5			1.43×10^{16}	0.01
²³⁷ Pa	94 d			5.11×10^3	1000	6.12×10^{12}			

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

^bFrom IAEA Publication 2, "Report of Committee II on Radioactive Dose for Internal Radiation (1979)" and the 1982 Supplement.

^cAssuming geometry, 50%.

^dSee decay by β emission (100%) and orbital electron capture (100%).

^eSee decay almost entirely by isomeric transition to the 26-hr ground state, ^{234m}Pa.

^fSee decay primarily by β emission, but 0.020% decay by electron capture to ^{234g}Pa.

Table A-4. Neutron Cross Sections Used to Compute Transmutations in HFIR Target Irradiation

Nuclide	Half-Life	Cadmium			Plutonium		
		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)
²³⁷ Pu	87.464 y	560	0	150	16.5	0	25
²³⁹ Pu	24,413 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	385,900 y	18.5	7.409	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	7340 y	75	2.126	1500	0	0	0
²⁴⁴ Am ^a	27.3 m	0	0	0	130	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	6.9	650	2.7	6.9	72
²⁴⁵ Cm	8265 y	445.3	1.4	90	1544	1.4	600
²⁴⁶ Cm	47 y	5	0.866	170	0	0	0
²⁴⁷ Cm	1.54 x 10 ⁷ y	77.63	0	200	281.33	0	1000
²⁴⁸ Cm	352,000 y	5.2	1.477	250	0	0	0
²⁴⁹ Cm	64 m	2.8	0	0	50	0	0
²⁵⁰ Cm	17,400 y	2	0	0	0	0	0
²⁴⁹ Bk	314 d	1786	0	1850	553.5	0	0
²⁵⁰ Bk	3.722 h	350	0	0	960	0	0
²⁴⁹ Cf	352 y	330	0	0	1735	0	0
²⁵⁰ Cf	13.08 y	2000	0	0	0	0	0
²⁵¹ Cf	900 y	1948	0	0	5126	0	0
²⁵² Cf	2.646 y	19.8	0	44	0	0	0
²⁵³ Cf	17.812 d	12.6	0	0	1300	0	0
²⁵⁴ Cf	60.5 d	75	0	1650	0	0	0
²⁵³ Ba	20.467 d	345	0	0	0	0	0
²⁵⁴ Ba	276 d	20	0	0	3060	0	0
^{254m} Ba	39.3 h	1.26	0	0	1840	0	0
²⁵⁵ Ba	39.8 d	60	0	0	0	0	0
²⁵⁶ Ba	25 m	0	0	0	0	0	0
²⁵⁴ Pu	3.24 h	76	0	0	0	0	0
²⁵⁵ Pu	20.07 h	26	0	0	100	0	0
²⁵⁶ Pu	2.62 h	20	0	0	0	0	0
²⁵⁷ Pu	94 d	10	0	0	100	0	0

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

It should be pointed out that $^{244}\text{C}_{\text{Am}}$ is a fictitious isotope that combines the properties of $^{244\text{m}}\text{Am}$ and $^{244\text{g}}\text{Am}$ according to their relative rates of production from ^{243}Am . The use of this isotope simplifies the calculations of the main transmutation chain involving ^{244}Am .