



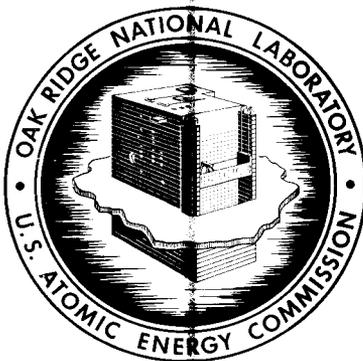
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UC-80 – Reactor Technology

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TRANSURANIUM PROCESSING PLANT  
SEMIANNUAL REPORT OF PRODUCTION,  
STATUS, AND PLANS  
FOR PERIOD ENDING JUNE 30, 1971

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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ORNL-4718

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CHEMICAL TECHNOLOGY DIVISION

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DECEMBER 1971

OAK RIDGE NATIONAL LABORATORY  
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## SUMMARY

This is the seventh 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.

During the period January 1, 1971, through June 30, 1971, we recovered 330 g of  $^{244}\text{Cm}$ , 18 mg of  $^{249}\text{Bk}$ , 131 mg of  $^{252}\text{Cf}$ , and 79  $\mu\text{g}$  of  $^{253}\text{Es}$  as purified products from 129 reactor slugs that had been irradiated as part of the Californium-I program at the Savannah River Plant (SRP) to evaluate the commercial market for  $^{252}\text{Cf}$  and establish an inventory of  $^{252}\text{Cf}$  for sale. We also recovered 9.9 g of  $^{242}\text{Pu}$ , 4 g of  $^{243}\text{Am}$ , 40.2 g of  $^{244}\text{Cm}$ , 6.1 mg of  $^{249}\text{Bk}$ , 62 mg of  $^{252}\text{Cf}$ , 379  $\mu\text{g}$  of  $^{253}\text{Es}$ , and  $9 \times 10^8$  atoms of  $^{257}\text{Fm}$  from 18 irradiated HFIR targets. We made 61 shipments, which contained the following total amounts of nuclides: 1.2 g of  $^{244}\text{Pu}$ , 2.84 g of  $^{243}\text{Am}$ , 2.1 g of  $^{244}\text{Cm}$ , 1.42 mg of  $^{248}\text{Cm}$ , 18.44 mg of  $^{249}\text{Bk}$ , 250  $\mu\text{g}$  of isotopically pure  $^{249}\text{Cf}$ , 174.2 mg of  $^{252}\text{Cf}$  in a mixture of californium isotopes, 330  $\mu\text{g}$  of  $^{253}\text{Es}$  in a mixture of einsteinium isotopes, 20.5  $\mu\text{g}$  of isotopically pure  $^{253}\text{Es}$ , and  $8 \times 10^8$  atoms of  $^{257}\text{Fm}$ .

Predictions of processing for the next 18 months are somewhat uncertain for two reasons. First, we do not know how many SRP reactor tubes we will be asked to process. At present, we expect to process 9 during the period July through December 1971 and have tentative plans to process 11 early in 1972. Second, we are anticipating approval of a proposal to irradiate 200 g of curium from the Californium-I program. This would result in the production of an additional 25 mg of  $^{249}\text{Bk}$ , 1380  $\mu\text{g}$  of  $^{253}\text{Es}$ ,  $3.8 \times 10^9$  atoms of  $^{257}\text{Fm}$ , and 260 mg of  $^{252}\text{Cf}$ . The maximum amounts of transuranium elements that would be produced during this period are as follows: 85 mg of  $^{249}\text{Bk}$ , 970 mg of  $^{252}\text{Cf}$ , 2.4 mg of  $^{253}\text{Es}$ , and  $6.4 \times 10^9$  atoms of  $^{257}\text{Fm}$ .

The processes and equipment used for the SRP reactor slugs were generally the same as those used to process HFIR targets. The curium products met all of the Savannah River Laboratory specifications; the

transcurium products were of usual TRU quality. However, we were unable to establish satisfactory operation of the continuous Tramex solvent extraction equipment and had to use batch Tramex extractions. Also, we experienced catastrophic pitting-type corrosion of a vacuum transfer system as the result of its contact with HCl dissolver solutions. We switched to  $\text{HNO}_3$  dissolutions to minimize this problem.

Tests were made using prototypes of the standard TRU neutron source capsules, and the results were forwarded to the AEC Division of Materials Licensing for cataloging. Seven neutron sources were fabricated during this period; this brings the total fabricated to date to 30. Equipment for assaying californium sources and shipping packages by means of fast-neutron counting has been installed in the source and target decontamination facility. Results of comprehensive tests showed the system to be excellent (reproducible within  $\pm 1\%$ ) for comparing sources and shipping packages with a standard source that is assayed within the same test period.

In special projects, two rabbits containing isotopically pure  $^{253}\text{Es}$  were fabricated, irradiated, and delivered to H. Diamond at ANL for use in studying the energy-level structure of  $^{250}\text{Bk}$ , a decay product of  $^{254}\text{Es}$ . Also, a gamma-ray source was fabricated from 1 g of  $^{242}\text{Pu}$  for use in Mössbauer 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 seventh 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 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 individuals to whom these sources have 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 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.

## 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  $^{244}\text{Cm}$ . Except in special instances,  $^{242}\text{Pu}$ ,  $^{243}\text{Am}$ ,  $^{249}\text{Bk}$ ,  $^{252}\text{Cf}$ , and  $^{253}\text{Es}$  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

We recovered 330 g of  $^{244}\text{Cm}$ , 18 mg of  $^{249}\text{Bk}$ , 131 mg of  $^{252}\text{Cf}$ , and 79  $\mu\text{g}$  of  $^{253}\text{Es}$  as purified products from 129 reactor slugs that had been irradiated as part of the Californium-I program at the Savannah River Plant (SRP) to evaluate the commercial market for  $^{252}\text{Cf}$  and to establish an inventory of material for sale. We also recovered 9.9 g of  $^{242}\text{Pu}$ , 4 g of  $^{243}\text{Am}$ , 40.2 g of  $^{244}\text{Cm}$ , 6.1 mg of  $^{249}\text{Bk}$ , 62 mg of  $^{252}\text{Cf}$ , 379  $\mu\text{g}$  of  $^{253}\text{Es}$ , and  $9 \times 10^8$  atoms of  $^{257}\text{Fm}$  from 18 irradiated HFIR targets.

Sixty-one shipments (Table 2.1) that were made from TRU during this period contained the following amounts of nuclides: (1) 1.2 g of  $^{242}\text{Pu}$ ; (2) 2.84 g of  $^{243}\text{Am}$ ; (3) 2.1 g of  $^{244}\text{Cm}$ ; (4) 1.42 mg of  $^{248}\text{Cm}$  (in products containing 97%  $^{248}\text{Cm}$ ); (5) 18.44 mg of  $^{249}\text{Bk}$ ; (6) 250  $\mu\text{g}$  of isotopically pure  $^{249}\text{Cf}$  that had been "milked" from  $^{249}\text{Bk}$ ; (7) 174.2 mg of  $^{252}\text{Cf}$  in a mixture of californium isotopes (159.5 mg of this  $^{252}\text{Cf}$  was included in shipments of Californium-I material to SRP); (8) 330.1  $\mu\text{g}$  of  $^{253}\text{Es}$ ; (9) 20.5  $\mu\text{g}$  of isotopically pure  $^{253}\text{Es}$ ; and (10)  $8 \times 10^8$  atoms of  $^{257}\text{Fm}$ .

### 2.2 Irradiation and Processing Proposals

The amounts of transcurium elements that will be produced at TRU during the next few years will depend upon: (1) the needs of researchers for various isotopes, (2) the needs for  $^{252}\text{Cf}$  in the Production Division's market evaluation and sales programs, and (3) the capabilities at TRU to produce the required materials. We showed in the previous report in this series<sup>1</sup> that, by 1975, the TRU-HFIR complex could maintain a steady-state production rate of 1.2 g of  $^{252}\text{Cf}$  per year by

Table 2.1. Distribution of Heavy Elements from  
the Transuranium Processing Plant  
During the Period January 1 - June 30, 1971

Major Nuclide	Date	TRU File No.	Shipped To	
			Individual	Site
<u>Plutonium-242, g</u>				
1.168 (GS-3)	5-18-71	447	P. G. Huray	ORNL-TRL
<u>0.0027</u>	6-30-71	435	F. Asaro	LRL-B
1.1707				
<u>Americium-243, g</u>				
0.53	2-01-71	365	Isotopes Sales	ORNL
0.11	2-02-71	364	J. A. Harris	LRL-B
<u>2.20</u>	6-30-71	453	R. D. Baybarz	ORNL-CTD
2.84				
<u>Curium-244, g</u>				
0.074 (isotopically enriched)	1-27-71	366	Target Fabrication	ORNL
2.0	2-26-71	368	F. J. Zelle	PNL
<u>0.026</u>	4-07-71	388	M. M. Abraham	ORNL-TRL
2.100				
<u>Curium-248 (97%), mg</u>				
0.22	1-18-71	389	C. E. Bemis	ORNL-TRL
<u>1.2</u>	6-30-71	403	T. D. Chikalla	PNL
1.42				
<u>Berkelium-249, mg</u>				
3.0	1-14-71	359	P. R. Fields	ANL
2.0	1-14-71	360	R. W. Hoff	LRL-L
4.5	1-14-71	353	O. L. Keller	ORNL-TRL
2.0	3-15-71	354	M. L. Hyder	SRL
2.0	3-15-71	355	R. A. Penneman	LASL
0.2	3-17-71	353	R. D. Baybarz	ORNL-CTD
0.5	6-08-71	448	R. D. Baybarz	ORNL-CTD
0.008	6-14-71	406	Research Pool	ORNL
3.06	6-15-71	407	R. K. Sjoblom	ANL
0.105	6-15-71	408	M. L. Hyder	SRL
0.017	6-15-71	409	F. J. Zelle	PNL
<u>1.05</u>	6-15-71	410	J. A. Harris	LRL-B
18.44				
<u>Californium-249 (isotopically pure), µg</u>				
<u>250</u>	2-12-71	361	D. R. Atherton	Univ. of Utah
250				

Table 2.1 (continued)

Major Nuclide	Date	TRU File No.	Shipped To	
			Individual	Site
<u>Californium-252, mg</u>				
23.39	1-13-71	356	A. R. Boulogne	SRL
26.88	1-22-71	363	A. R. Boulogne	SRL
2.43 (NSD-27)	1-29-71	358	J. E. Powell	Sandia-NM
0.017	2-05-71	449	Isotopes Sales	ORNL
0.0037	2-12-71	362	D. R. Atherton	Univ. of Utah
0.014 (NSD-26) <sup>a</sup>	2-18-71	335	J. R. Engel	ORNL-Reactor
22.02	2-19-71	369	A. R. Boulogne	SRL
0.024	2-26-71	372	F. J. Zelle	PNL
22.25	3-10-71	381	A. R. Boulogne	SRL
0.011 (NSD-28)	3-19-71	370	E. E. Hicks	Rocky Flats
0.201	3-19-71	371	R. K. Sjoblom	ANL
4.87 (NSD-13)	3-24-71	295	H. O. Menlove	LASL
0.014 (NSD-26) <sup>a</sup>	3-24-71	295	H. O. Menlove	LASL
2.17 (NS-36)	3-24-71	383	F. B. Simpson	INC
32.8	4-01-71	385	A. R. Boulogne	SRL
0.857 (NSD-30)	4-07-71	376	E. B. Darden	ORNL-Biology
0.01	5-20-71	433	Isotopes Sales	ORNL
0.025	5-28-71	293	C. E. Bemis	ORNL-TRL
3.80 (SR-Cf-167)	6-10-71	390	H. W. Dickson	ORAU
32.17	6-14-71	392	A. R. Boulogne	SRL
0.10 (NSD-38)	6-16-71	394	H. O. Menlove	LASL
0.165	6-30-71	437	R. K. Sjoblom	ANL
174.2077 <sup>a</sup>				
<u>Einsteinium-253, µg</u>				
16.6	2-19-71	377	P. R. Fields	ANL
20.8	3-31-71	378	D. C. Hoffman	LASL
5.2	3-31-71	379	R. D. Baybarz	ORNL-CTD
5.2	3-31-71	386	P. R. Fields	ANL
100	6-22-71	424	R. W. Hoff	LRL-L
70	6-22-71	425	H. Diamond	ANL
50	6-22-71	426	M. L. Hyder	SRL
10	6-22-71	428	F. J. Zelle	PNL
52.3	6-28-71	427	R. D. Baybarz	ORNL-CTD
330.1				
<u>Einsteinium-253 (isotopically pure), µg</u>				
18	1-08-71	357	R. W. Hoff	LRL-L
1	1-08-71	367	R. G. Haire	ORNL-CTD
0.8 (irradiated)	4-21-71	391	H. Diamond	ANL
0.7 (irradiated)	5-24-71	432	H. Diamond	ANL
20.5				

Table 2.1 (continued)

Major Nuclide	Date	TRU File No.	Shipped To	
			Individual	Site
<u>Fermium-257, atoms</u>				
$\sim 3 \times 10^8$	2-19-71	380	R. W. Hoff	LRL-L
$\sim 3 \times 10^8$	3-29-71	387	R. W. Hoff	LRL-L
$\sim 2 \times 10^8$	4-29-71	393	M. L. Hyder	SRL
$\sim 8 \times 10^8$				

<sup>a</sup>Source NSD-26 was shipped to two users during this period. Its californium content was included only once in the total.

irradiating the curium from the Californium-I program (based on an estimated isotopic content of 24%  $^{246}\text{Cm}$  and 1%  $^{248}\text{Cm}$ ) or could produce about 0.5 g per year by irradiating Curium-II curium (95%  $^{244}\text{Cm}$ ). The amounts of  $^{249}\text{Bk}$  and  $^{253}\text{Es}$  produced would be about 10% and 0.5%, respectively, of the amounts of  $^{252}\text{Cf}$ . Another source of transuranium elements is the SRP Pu-Al tubes, each of which contains about 20 g of  $^{244}\text{Cm}$ , 2 mg of  $^{249}\text{Bk}$ , and 25 mg of  $^{252}\text{Cf}$ , but little  $^{253}\text{Es}$  or  $^{257}\text{Fm}$ .

Assuming that we continue, on a schedule similar to that used in recent report periods, to process SRP materials (slugs and tubes) for the Californium-I program and irradiate and process TRU materials (supplemented by Curium-II curium) in order to provide products for researchers, we would expect to produce about 200 mg of  $^{252}\text{Cf}$ , 20 mg of  $^{249}\text{Bk}$ , and 1000  $\mu\text{g}$  of  $^{253}\text{Es}$  for research use during the next 18 months by processing irradiated TRU-HFIR targets. Processing of up to 20 SRP Pu-Al tubes would yield a maximum of 510 mg of  $^{252}\text{Cf}$  for the Californium-I program, plus 625 g of curium ( $^{246}\text{Cm}$  content is projected to be 31%) and an additional 40 mg of  $^{249}\text{Bk}$ . A proposal has been made, but has not yet been approved, to increase the amount of materials available to both the Research and Production Divisions during the next 18 months by fabricating targets from 200 g of Californium-I curium. This would provide the Research Division with an additional 25 mg of  $^{249}\text{Bk}$ , 1380  $\mu\text{g}$  of  $^{253}\text{Es}$ , and  $3.8 \times 10^9$  atoms of  $^{257}\text{Fm}$ , and would also provide an additional 260 mg of  $^{252}\text{Cf}$ . We expect the proposal to be approved. Table 2.2 lists the proposed campaigns for processing (1) existing TRU-HFIR targets, (2) targets made from 200 g of Californium-I curium, and (3) 20 SRP Pu-Al tubes from the Californium-I program. If we do not irradiate and process targets from Californium-I curium, we will extend the processing of TRU-HFIR targets over the entire period. This would increase the amounts of materials recovered from the TRU-HFIR targets from the sums of values in the table to the amounts listed at the beginning of this paragraph.

We have firm plans to process nine Pu-Al tubes to recover 18 mg of  $^{249}\text{Bk}$  and 230 mg of  $^{252}\text{Cf}$  by November 1971. About 5  $\mu\text{g}$  of  $^{254}\text{Es}$  will be recovered, but because of the long cooling, there will be little  $^{253}\text{Es}$ .

Table 2.2. Estimated Future Production of Transcurium Elements

Period	Processing Campaign	Products of Campaigns			<sup>252</sup> Cf Production		Date Products Available
		<sup>249</sup> Bk (mg)	<sup>252</sup> Cf (mg)	<sup>253</sup> Es <sup>a</sup> (μg)	During the Period (mg)	Cumulative (mg)	
Through June 1971						135	
July - December 1971	9 SRP Cf-I tubes	18	230 <sup>b</sup>	0 <sup>c</sup>	0	135	November 1971
January - June 1972	9 TRU-HFIR targets	6	60	330(60)			January 1972
	11 SRP Cf-I tubes	22	280 <sup>b</sup>	0 <sup>c</sup>			May 1972
	10 TRU-HFIR targets	5	50	275(50)	110	245	June 1972
July - December 1972	10 SRP-Cm targets	15	150	750(150)			September 1972
	5 TRU-HFIR targets	4	50	275(50)			November 1972
	10 SRP-Cm targets	15	150	750(150)	350	595	December 1972
1973					~305	~900	
1974					~400	~1300	

<sup>a</sup>Amounts from initial separation. Amounts "milked" from californium product fraction after decay period are given in parentheses.

<sup>b</sup>Californium produced in the SRP tube campaigns is not included in production totals.

<sup>c</sup><sup>254</sup>Es (~5 μg) can be recovered.

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About 6 mg of  $^{249}\text{Bk}$ , 60 mg of  $^{252}\text{Cf}$ , and 330  $\mu\text{g}$  of  $^{253}\text{Es}$  will be recovered in January 1972 from the processing of nine curium targets that are currently being irradiated in the HFIR. We have tentative plans to process 11 additional Pu-Al tubes during the period February through May 1972 in order to recover 22 mg of  $^{249}\text{Bk}$ , 280 mg of  $^{252}\text{Cf}$ , and 5  $\mu\text{g}$  of  $^{254}\text{Es}$ . The processing of ten irradiated curium TRU-HFIR targets in June 1972 will produce 5 mg of  $^{249}\text{Bk}$ , 50 mg of  $^{252}\text{Cf}$ , and 275 mg of  $^{253}\text{Es}$ . About 15 mg of  $^{249}\text{Bk}$ , 150 mg of  $^{252}\text{Cf}$ , and 750  $\mu\text{g}$  of  $^{253}\text{Es}$  could be recovered in September 1972 from the irradiation in HFIR and processing of ten targets fabricated from 100 g of curium from SRP-slug campaign 21 (27.6%  $^{246}\text{Cm}$ ). We expect to recover 4 mg of  $^{249}\text{Bk}$ , 50 mg of  $^{252}\text{Cf}$ , and 275  $\mu\text{g}$  of  $^{253}\text{Es}$  in November 1972 from the processing of five TRU-HFIR targets that we plan to fabricate from recycle curium recovered during this report period. We could then recover 15 mg of  $^{249}\text{Bk}$ , 150 mg of  $^{252}\text{Cf}$ , and 750  $\mu\text{g}$  of  $^{253}\text{Es}$  in December 1972 from the processing of ten additional targets fabricated from SRP-slug curium.

### 2.3 Estimates of the Availability of Transuranium Elements

Plutonium, americium, and curium are considered to be intermediate feed materials rather than products. Estimates of the availability of berkelium, californium, einsteinium, and fermium during the next 18 months are given below. The proposal for irradiation and processing 200 g of Californium-I curium is included.

#### 2.3.1 Berkelium

As much as 85 mg of  $^{249}\text{Bk}$  could become available during the next 18 months: 18 mg in November 1971 from 9 SRP Pu-Al tubes, 6 mg in January 1972 from 9 TRU-HFIR targets, 22 mg in May 1972 from 11 SRP Pu-Al tubes, 5 mg in June 1972 from 10 TRU-HFIR targets, 15 mg in September 1972 from 10 SRP-Cf-I curium targets irradiated in the HFIR, 4 mg in November 1972 from 5 TRU-HFIR targets, and 15 mg in December 1972 from 10 SRP-Cf-I curium targets irradiated in the HFIR.

### 2.3.2 Californium

The Division of Production will loan the Division of Research 20 mg of  $^{252}\text{Cf}$  to be used in filling existing research requirements. About 100 mg of the  $^{252}\text{Cf}$  that will be recovered from the SRP tubes will be retained for some time at ORNL to permit the daughter product  $^{248}\text{Cm}$  to be collected. This californium will also serve as a stock for supplying various needs that might arise.

We can produce up to 970 mg of  $^{252}\text{Cf}$  during the next 18 months. As much as 510 mg will be recovered from SRP feed materials primarily for the Californium-I program (230 mg during the period July through November 1971, and 280 mg during the period February through May 1972). Approximately 160 mg will be recovered from TRU-HFIR targets for the Trans-uranium Element Production Program (60 mg in January 1972, 50 mg in June 1972, and 50 mg in November 1972). The processing of two groups of ten irradiated HFIR targets fabricated from SRP Californium-I curium could produce a total of 300 mg of  $^{252}\text{Cf}$ , that is, 150 mg in September 1972 and 150 mg in December 1972.

### 2.3.3 Einsteinium

We can recover about 2380  $\mu\text{g}$  of  $^{253}\text{Es}$  in a mixture of einsteinium isotopes during the next 18 months: 330  $\mu\text{g}$  in January 1972, 275  $\mu\text{g}$  in June 1972, and 275  $\mu\text{g}$  in November 1972 from TRU-HFIR targets; and 750  $\mu\text{g}$  in September 1972 and 750  $\mu\text{g}$  in December 1972 from irradiation and processing of HFIR targets containing SRP curium.

Some "second-growth" einsteinium will be recovered from the 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  $^{253}\text{Es}$  to "grow in" from the decay of  $^{253}\text{Cf}$ ; then this second-growth  $^{253}\text{Es}$  will be recovered. About 60  $\mu\text{g}$ , 50  $\mu\text{g}$ , and 50  $\mu\text{g}$  of isotopically pure  $^{253}\text{Es}$  will be "milked" from the californium that will be isolated in January 1972, June 1972, and November 1972, respectively. About 150  $\mu\text{g}$  would be milked from each of the SRP-curium target campaigns in September 1972 and December 1972.

#### 2.3.4 Fermium

Each batch of californium that is recovered from the processing of HFIR targets will contain about  $1.5 \times 10^7$  atoms of  $^{257}\text{Fm}$  per milligram of  $^{252}\text{Cf}$ . Thus, about  $9 \times 10^8$  atoms,  $7.5 \times 10^8$  atoms, and  $7.5 \times 10^8$  atoms will become available in January 1972, in June 1972, and in November 1972, respectively. About  $2 \times 10^9$  atoms would be produced in each of the SRP-curium target campaigns in September 1972 and December 1972.

### 3. PROCESSES AND EQUIPMENT

Most of the processes and equipment that were used to process the SRP slugs were the ones normally used in processing HFIR targets. All of the products were satisfactory. The transcurium products were of the usual TRU quality, and the curium products met Savannah River Laboratory's specifications with regard to limits of impurities and penetrating radiation. However, we did experience difficulty in using the Tramex solvent extraction process to decontaminate the actinides from fission products. We were scarcely able to operate the continuous solvent extraction equipment during the first SRP slug campaign and failed altogether to establish satisfactory column operation in subsequent campaigns. Therefore, most of the Tramex processing had to be done by batch extractions. Although the decontamination factors obtained with this alternative technique were high enough to permit us to complete the processing of the slugs and produce satisfactory products, they were poor — about a factor of 10 lower than was anticipated.

#### 3.1 Corrosion of Zircaloy-2

A vacuum-actuated solution transfer system constructed of Zircaloy-2 failed during the third SRP slug campaign because of corrosion of the transfer lines. The corrosion was apparently caused by the radioactive HCl dissolver solutions that had been transferred via this equipment during previous slug campaigns. Examination of a Zircaloy-2 test specimen that had been exposed to a sample of HCl dissolver solution from

the second slug campaign revealed evidences of a severe, nonuniform pitting attack and indicated a corrosion rate of about 180 mils/year. This was surprising since results of tests<sup>2</sup> made several years ago showed the corrosion rate of Zircaloy-2 to be only 60 mils/year in chloride solutions having the same solution power density (10 W/liter) as the dissolver solution, and no pitting was observed.

Because of the pitting attack, we suspected that the corrosion of the transfer lines was caused by the presence of HNO<sub>3</sub> (from residual dejacketing solution) in the HCl; however, the dissolver solution used in the test had a nitrate concentration of only 0.02 M, which we consider too low to be the cause of the catastrophic corrosion.

We decided to use HNO<sub>3</sub> to dissolve the actinides because (1) HNO<sub>3</sub> solutions do not corrode Zircaloy-2 catastrophically even when they have very high power densities, and (2) conversion from a nitrate to a chloride medium (required for the Tramex process) could be readily accomplished during the Cleanex batch extraction steps that were already planned.

#### 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 fabricated in one of two standard TRU models shown in Fig. 4.1. Those that are standard models, NSS (singly encapsulated) and NSD (doubly encapsulated), are indicated in the table. The characteristics of these models are listed in Table 4.2.

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

Table 4.1. Data for Neutron Sources Prepared at TRU

Source	Date of Calibration	<sup>252</sup> Cf Content at Calibration (μg)	<sup>252</sup> Cf Content as of 6-30-71 (μg)	<sup>248</sup> Cm Content as of 6-30-71 (μg)	On Loan To	
					Individual	Site
NS-1 <sup>a</sup>	8-28-68	311	148	b	J. L. Cason	PNL
NS-2	8-23-68	268	127	b	J. E. Powell	Sandia
NS-3	5-13-69	~90	~52	b	H. E. Banta	ORAU
NS-4	7-09-69	925	552	356	C. F. Masters	LASL
NS-5 <sup>c</sup>	8-14-69	992	607	367	F. B. Simpson	INC
NS-6	11-21-69	783	515	256	R. W. Hoff	LRL-L
NS-7	1-21-70	807	554	241	T. F. Handley	ORNL
NS-8	12-17-69	1927	1289	608	H. Berger	ANL
NSD-9	4-17-70	1802	1315	465	N. D. Wogman	PNL
NSS-10	3-11-70	118	83	b	J. P. Balagna	LASL
NS-11	3-10-70	8	5	b	R. R. Fullwood	LASL
NSS-12	6-30-70	1957	1506	430	R. W. Hoff	LRL-L
NSD-13	3-24-71	4870	4539	316	H. O. Menlove	LASL
NSS-14	6-29-70	4833	3718	1063	D. C. Stewart	ANL
NS-15 <sup>c</sup>	6-25-70	975	748	216	F. B. Simpson	INC
NSD-16	10-08-70	1736	1438	284	R. Yoshimura	Sandia-NM
NS-18 <sup>c</sup>	6-24-70	1008	773	224	F. B. Simpson	INC
NSS-19	6-26-70	469	360	104	J. E. Bigelow	ORNL-TRU
NSS-20	7-01-70	605	466	133	J. E. Bigelow	ORNL-TRU
NSS-21	10-21-70	18	15	b	F. Cross	PNL
NS-22	9-10-70	13	11	b	W. S. Lyon	ORNL
NSD-24	10-15-70	8	7	b	J. B. Davidson	ORNL
NS-25	11-09-70	56	47	b	F. J. Muckenthaler	ORNL
NSD-26	3-24-71	14	13	b	H. O. Menlove	LASL
NSD-27	1-29-71	2430	2179	239	J. E. Powell	Sandia-NM
NSD-28	2-12-71	11	10	b	E. E. Hicks	Rocky Flats
NSD-30	3-31-71	857	803	51	E. B. Darden	ORNL
NS-36 <sup>c</sup>	3-23-71	2169	2020	142	F. B. Simpson	INC
NSD-38	6-16-71	100	99	b	H. O. Menlove	LASL
SR-Cf-167 <sup>d</sup>	5-26-71	3796	3702	89	H. W. Dickson	ORAU

<sup>a</sup>This source is encapsulated in aluminum.

<sup>b</sup>This source is not suitable for recovery of <sup>248</sup>Cm.

<sup>c</sup>This source is encapsulated in type 405 stainless steel.

<sup>d</sup>This source was fabricated at TRU in standard Savannah River SR-Cf-100 series hardware.

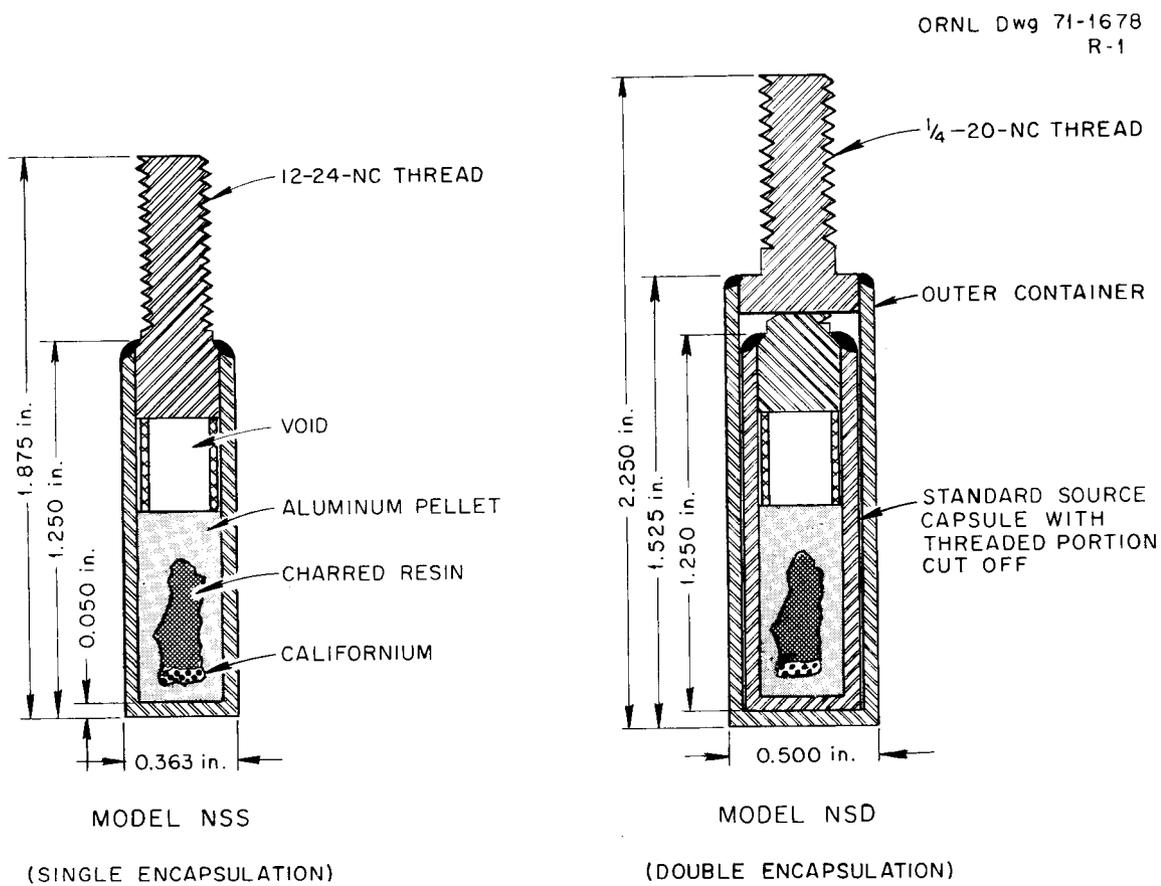


Fig. 4.1. Standard TRU Models for  $^{252}\text{Cf}$  Neutron Sources Encapsulated in Stainless Steel.

Table 4.2. Characteristics of Standard TRU  
 $^{252}\text{Cf}$  Neutron Sources

	Model NSS	Model NSD
Degree of encapsulation	Single	Double
Material of outer container	304L SS	304L SS
Source classification	III D	IV D
Diameter, in.		
Nominal	0.363	0.500
Maximum	0.364	0.500
Minimum	0.360	0.495
Length of body, in.		
Nominal	1.250	1.525
Maximum	1.260	1.535
Minimum	0.800	1.025
Overall length, in.		
Nominal	1.875	2.175
Maximum	1.885	2.185
Minimum	1.000	1.400
Maximum diameter at weld, in.	0.375	0.500
Maximum $^{252}\text{Cf}$ Loading, mg	25	25

#### 4.1 Tests of Prototype $^{252}\text{Cf}$ Neutron Sources

Tests were made using prototypes of the standard TRU source capsules, and the results were forwarded to the AEC Division of Materials Licensing for cataloging. The tests were conducted in accordance with the "Source Application Guide Based on the ORNL Source Classification System."<sup>3</sup> A singly encapsulated source (model NSS) meets the requirements of a class III D capsule, and a doubly encapsulated source (model NSD) is a class IV D capsule. Summaries of the tests are given in Tables 4.3 and 4.4.

#### 4.2 Sources Fabricated During January-June 1971

Seven sources were fabricated during this report period. Of these, NSD-13, NSD-27, NSD-28, NSD-30, and NSD-38 are standard doubly encapsulated sources. Source NS-36 is doubly encapsulated in type 405 stainless steel.

Source SR-Cf-167 was fabricated to demonstrate the capability at TRU for fabricating sources in the SRL standard SR-Cf-100 series<sup>4</sup> configuration. We had no difficulty in welding the platinum inner container or the 304L stainless steel outer container. Because of the small volume available in the source pellet for resin, we were able to load only 3.8 mg of  $^{252}\text{Cf}$  using our usual technique; however, by modifying the procedure slightly, we believe that we could easily load 5 mg of  $^{252}\text{Cf}$  into an SR-Cf-100 series source.

Source NSD-26, which was fabricated during the last report period, was returned from J. R. Engel at ORNL and shipped to H. O. Menlove at LASL.

#### 4.3 Calibration of $^{252}\text{Cf}$ Sources Using a Fast-Neutron Detector

Equipment for assaying californium sources and shipping packages by means of fast-neutron counting has been installed in the source and target decontamination facility. Fast-neutron counting appeared to be an attractive method for us. It is preferable to thermal-neutron counting or the manganese sulfate method because of the smaller shielded space required.

Table 4.3. Classification Test Summary for Standard TRU  
Singly Encapsulated Sources

Manufacturer: Chemical Technology Division,  
Oak Ridge National Laboratory

Reference drawing: ORNL 70-4580 (also ORNL 71-1678)

Description: Singly encapsulated  $^{252}\text{Cf}$  source; type 304L stainless  
steel; 0.050-in. wall thickness; 0.363 in. OD by 1.25 in.  
long exclusive of handling attachment

Previous testing: None

Test results:

<u>Conditions</u>	<u>Leak Test</u>	<u>Class</u>
2400°F for 1 hr	Negative	D
-70°F for 24 hr; 1700°F for 24 hr from 1700°F preheat into -70°F chamber within 1 sec	Negative	D
weight in free fall at 44 fps onto capsule positioned on a 1/8-in.-diam pin	Negative	D
120 ft-lb impact	Negative	IV
10,000-lb shear force	Positive	-
1000-lb shear force	Negative	III
2000-lb crushing force load	Negative	III
1000-psi external hydrostatic press	Negative	III

Classification assigned: III D

Investigators: R. G. Niemeyer, E. L. Ryan

Date completed: March 11, 1971

Comments: Failure during Class IV (10,000-lb) shear test occurred at  
~8400 lb shear force; four capsules used for test series

Table 4.4. Classification Test Summary for Standard TRU  
Doubly Encapsulated Source

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Manufacturer: Chemical Technology Division,  
Oak Ridge National Laboratory

Reference drawing: ORNL 70-12449R1 (also ORNL 71-1678)

Description: Doubly encapsulated  $^{252}\text{Cf}$  source; 0.50 in.OD by 1.48 in.  
long exclusive of handling attachment; type 304L stainless  
steel, 0.050-in.-wall inner and outer capsules

Previous testing: Inner capsule is made according to ORNL Dwg. 70-4580  
and has been previously classified as a class III D  
capsule.

Test results:

<u>Conditions</u>	<u>Leak Test</u>	<u>Class</u>
2400°F for 1 hr	Negative	D
20,000-lb crushing force load	Negative	IV
10,000-lb shear force	Negative	IV

Class IV impact, puncture, and pressure resistance and  
Class D operating temperature and thermal shock tests are  
assumed, based on previous tests of the inner capsule alone.

Classification assigned: IV D

Investigators: R. G. Niemeyer, E. L. Ryan

Date completed: March 12, 1971

Comments: One capsule used for test series

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Two (parallel) detectors located in a box in the water shield just outside the target and source decontamination cubicle measure fission events in  $^{238}\text{U}$  caused by absorption of fast neutrons that are emitted from a californium source located on a measuring bar inside the cubicle. Capture of thermal neutrons is discriminated against by minimizing the  $^{235}\text{U}$  content of the uranium and by wrapping each detector in a cadmium sheath.

In a series of evaluation tests (discussed below), we found that the system is excellent (reproducible within  $\pm 1\%$ ) for comparing sources and shipping packages with a standard source assayed during the same test period.

Geometry Factors. — There are five positions at which source holders can be placed on a positioning bar inside the cubicle. Each position is approximately twice as far from the detectors as the previous one. Virgin  $^{252}\text{Cf}$  fission neutrons can be scattered once by the water shield or the steel liner of the cell and still have sufficient energy to cause fission in the  $^{238}\text{U}$  detector. This scattering effect was measured by counting the same neutron source in the different positions. As the table below shows, scattered neutrons make up more than half of the count rate for position E (relative to the extrapolated value at the detector); however, this should not be a problem as long as the source and detectors maintain a fixed geometry within the source and target decontamination facility.

Position	Distance to Detectors (mm)	$\pi r^2$	Source Count Rate (counts/sec)	Count Rate $\times \pi r^2$	% of Count Rate due to Scattering
B	138	$5.97 \times 10^4$	706.7	$4.22 \times 10^7$	
C	288	$2.60 \times 10^5$	214.4	$5.58 \times 10^7$	$\geq 22.4$
D	592	$1.01 \times 10^6$	62.74	$6.90 \times 10^7$	$\geq 37.2$
E	1200	$4.53 \times 10^6$	21.11	$9.56 \times 10^7$	$\geq 54.7$

A special holder that would support the source at varying heights above the position bar was constructed, and counts were taken in positions B and C. Analysis of the data showed that the count rate reached a maximum 0.32 in.

below the geometric midplane at position B, and 0.25 in. above the midplane at position C. If the source were actually misplaced 0.125 in. (the maximum permitted by TRU source geometry) within the source capsule in the worst direction, it would cause errors of 0.52% and 0.13% in positions B and C respectively.

Background. — One important consideration of the usefulness of the neutron counter system is that other sources may be stored within the facility without appreciably affecting the counter. When the source that was counted in the tests described above was lowered about 18 in. down into a well in the center of the facility, the count rate decreased to 0.161 counts/sec, which is only 0.7% of the count rate for position E. Thus, small corrections made for backgrounds caused by sources stored in the well have very little effect on overall precision.

Scattering due to Miscellaneous Items in the Facility. — It was necessary to check the importance of scattering from casual items within the facility. One such item that is always present is the manipulator hand. A test was made with the hand nearly in the line of sight, as compared with the hand raised and extended as far as possible. The count rate was increased 1.1% with the hand near the line of sight; however, since this increase was approximately equal to the standard deviation of the total counts, it could have occurred randomly. Keeping the manipulators away from the line of sight should prevent difficulties.

Two experiments were made to evaluate the effects of scattering from hydrogenous materials. The count rate fell 32% in one test in which a 1-in.-diam plastic bottle filled with water was placed between the source and detector. This shows that even a thin film of water seeping into the gap between the face of the detector box and the liner of the cubicle could affect the count rate. Hence, the importance of using a standard source for comparison in all measurements cannot be overemphasized.

In the other experiment, three large paraffin blocks were placed just behind the line of sight. The count rate was increased 9.6% by the additional scattering. Thus, bottles of reagents and paraffin-block shadow shields must be kept well away from the counting area.

Scattering due to Source Containers. — In a series of experiments, cylindrical shells of aluminum and stainless steel having various thicknesses were placed over a standard neutron source and the neutron count rate was measured. Shells 1/16 and 1/8 in. thick had almost no effect on the count rate; a 1/4-in.-thick shell caused a change that coincided with the limit of the statistical fluctuations of the count rate. The best fit to the data was a net scattering coefficient ( $\Sigma_S$ ) of  $0.01 \text{ cm}^{-1}$  for aluminum and  $0.02 \text{ cm}^{-1}$  for stainless steel. These numbers are an order of magnitude smaller than the theoretical values, showing that the scattering of neutrons out of the beam of neutrons heading toward the detector is almost completely compensated for by the scattering of additional neutrons into the beam from the outer layers of the cylindrical shells. Thus it appears that small variations in the cladding thickness of two sources will not affect the calibration, and that major differences (such as single or double encapsulation) can be easily compensated for by calculation or by mockups.

Reproducibility. — The reproducibility of the system was checked with a series of six counts made in position C without moving the source. The observed standard deviation was 0.29%, which is in excellent agreement with a theoretical value of 0.31% for that size of count. The source was then rotated  $180^\circ$ , presenting the opposite face to the detectors. The standard deviation of the new series of counts was also 0.28%, but the two means differed by 3% (or ten times the standard deviation). A comparison of these count rates with the geometry factors determined earlier shows that the californium is off-center by 0.12 in., which would put it at the edge of the inner capsule. Part of the difference may be due to looseness in the fit of the source parts and holder parts. As a result of this test, the standard procedure now includes rotating the source  $90^\circ$  between each of 4 counting sequences. This will compensate for variability in the location of the source and minimize errors due to this factor.

Long-Term Stability. — A check of long-term stability was made by comparing the counts obtained for sources NSS-19 and NSS-20 in position C over a 121-day period with the calculated source strengths. The average was 460.4 counts per second per milligram of  $^{252}\text{Cf}$ , with a standard deviation of 0.98%. While this standard deviation is larger than the standard

deviations for the counts made on individual days, it is quite satisfactory considering that the counter had been turned off overnight and that the source and source holder were removed from the positioning bar at the end of each day. However, the best results can be obtained only by direct comparison of the source to be measured with a standard or reference source positioned in the same geometry and counted during the same testing period.

## 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 Rabbits Containing $^{253}\text{Es}$

Two rabbits containing isotopically pure  $^{253}\text{Es}$  were fabricated, irradiated, and delivered to H. Diamond at Argonne National Laboratory. These rabbits will be used in studying the energy-level structure of  $^{250}\text{Bk}$ , a decay product of  $^{254\text{m}}\text{Es}$ .

### 5.2 Preparation of a Gamma-Ray Source for Mössbauer Studies

An interesting gamma-ray source (GS-3) was fabricated from approximately 1 g of  $^{242}\text{Pu}$  for use in Mössbauer studies. The gamma ray involved is only a 44-keV emission, which is easily attenuated. In order to obtain adequate intensity, the plutonium had to be deposited in a thin layer over a large area (about 1 in. in diameter) and the container walls had to be very thin. To meet this requirement, we designed a doubly encapsulated container with a 10-mil-thick aluminum window. This window is so soft that a 0.030-in. beryllium shim was placed between the inner and outer containers for protection. Beryllium would have been an ideal container material except

that we have no means of welding beryllium at TRU. The plutonium was loaded into the inner container as  $\text{PuO}_2$ , formed by calcining the oxalate. The powder was spread out into a nearly uniform layer by rotating a close-fitting, thin aluminum disc inside the cup. This disc was backed up by a large Teflon plunger, which was carefully removed, leaving the aluminum disc. The void space was filled with aluminum powder, and an aluminum cover was pressed into place. This pressed the aluminum powder and the disc against the  $\text{PuO}_2$ , thus locking it into place. The cover was then seal-welded around the edge. Leak-checks showed no obvious leaks in the seal weld; however, an X-ray showed it to be rather porous. Therefore, when the inner can was assembled into the outer can, a layer of epoxy cement was added to permanently seal the inner container. The outer container was welded outside the cell bank, resulting in an excellent-quality weld.

The experimenter hopes to obtain two additional sources containing  $^{240}\text{Pu}$  and  $^{238}\text{Pu}$  at a later date.

## 6. REFERENCES

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3. R. G. Niemeyer, Source Application Guide Based on the ORNL Source Capsule Classification System, ORNL-4427 (July 1969).
4. Guide for Fabricating and Handling  $^{252}\text{Cf}$  Sources, SRO-153 (January 1971).
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 Lederer<sup>5</sup> and Wapstra,<sup>6</sup> 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  $^{238}\text{U}$ ). 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

Table A-1. Half-Life Values<sup>a</sup> for Isotopes of Transuranium Elements

Underlines indicate new values since the previous report.

Nuclide	Total Half-Life	Partial Half-Life for $\alpha$ Decay	Branching Ratios	Partial Half-Life for Spontaneous Fission	Neutrons per Fission	References <sup>b</sup>
<u><math>^{237}\text{Np}</math></u>		$(2.14 \pm 0.01) \times 10^6$ y		$>10^{18}$ y	2.00 <sup>d</sup>	60Br12, 61Dr04
$^{238}\text{Np}$	$2.10 \pm 0.01$ d					50Fr53
$^{239}\text{Np}$	$2.359 \pm 0.010$ d					59Co93
$^{240}\text{Np}$	$63 \pm 2$ m					60Le03
$^{240m}\text{Np}$	$7.3 \pm 0.3$ m					48Hy61
$^{241}\text{Np}$	16 m					60Le03
$^{241m}\text{Np}$	3.4 h					60Le03
$^{238}\text{Pu}$	$87.404 \pm 0.041$ y			$(5 \pm 0.6) \times 10^{10}$ y	$2.33 \pm 0.08$	61Dr04, 68Jo15, 56Hi101
$^{239}\text{Pu}$		$(2.4413 \pm 0.003) \times 10^4$ y		$5.5 \times 10^{15}$ y	2.24 <sup>d</sup>	52Se67, 59Ma26
$^{240}\text{Pu}$		$6580 \pm 40$ y		$(1.340 \pm 0.015) \times 10^{11}$ y	$2.257 \pm 0.046$	51In03, 62Wa13, 56Di162
$^{241}\text{Pu}$	$14.98 \pm 0.33$ y	$(5.72 \pm 0.1) \times 10^5$ y				68Ca19, 60Br15
$^{242}\text{Pu}$		$(3.869 \pm 0.016) \times 10^5$ y		$(7.45 \pm 0.17) \times 10^{10}$ y	$2.18 \pm 0.09$	63Ma50, 69Be06, 56Hi101
$^{243}\text{Pu}$	$4.955 \pm 0.003$ h					68Di09
$^{244}\text{Pu}$		$(8.28 \pm 0.10) \times 10^7$ y		$(6.55 \pm 0.32) \times 10^{10}$ y	2.84 <sup>d</sup>	66Fi07, 69Be06
$^{245}\text{Pu}$	$10.6 \pm 0.4$ h					56Bu92
$^{246}\text{Pu}$	$10.85 \pm 0.02$ d					56Ho23
$^{241}\text{Am}$		$432.7 \pm 0.7$ y		$(2.3 \pm 0.8) \times 10^{14}$ y	2.48 <sup>d</sup>	61Dr04, 670e01
$^{242}\text{Am}$	$16.01 \pm 0.02$ h		EC/B = 0.19			53Ke38
$^{242m}\text{Am}$	$144 \pm 7$ y	$(2.92 \pm 0.15) \times 10^4$ y				59Ba21 <sup>c</sup>
$^{243}\text{Am}$		$7370 \pm 40$ y				68Br22
$^{244}\text{Am}$	$10.1 \pm 0.1$ h					62Va08
$^{244m}\text{Am}$	26 m					54Ch24
$^{245}\text{Am}$	$2.07 \pm 0.02$ h					56Bu92
$^{246}\text{Am}$	$25.0 \pm 0.2$ m					55En16
$^{246m}\text{Am}$	$40 \pm 7$ m					670r02
$^{247}\text{Am}$	$24 \pm 3$ m					670r02
$^{242}\text{Cm}$	$162.7 \pm 0.1$ d			$7.2 \times 10^6$ y	$2.65 \pm 0.09$	51Ha87, 57Pe52, 56Hi101
$^{243}\text{Cm}$		32 y				57As70
$^{244}\text{Cm}$	$18.099 \pm 0.015$ y		$\alpha/\text{SF} = (7.43 \pm 0.01) \times 10^5$		$2.84 \pm 0.09$	65Me02, 68Be26, 56Hi101
$^{245}\text{Cm}$		$8265 \pm 180$ y				69Me01
$^{246}\text{Cm}$		$4711 \pm 22$ y	$\alpha/\text{SF} = 3822 \pm 10$		3.08 <sup>d</sup>	69Me01
$^{247}\text{Cm}$		$(1.64 \pm 0.20) \times 10^7$ y				63Fi08
$^{248}\text{Cm}$		$(3.84 \pm 0.04) \times 10^5$ y	$\alpha/\text{SF} = 11.0 \pm 3$		3.32 <sup>d</sup>	69Me01
$^{249}\text{Cm}$	$64 \pm 3$ m					58Ea06
$^{250}\text{Cm}$				$(1.74 \pm 0.24) \times 10^4$ y	3.56 <sup>d</sup>	66RG01

Table A-1 (continued)

Nuclide	Total Half-Life	Partial Half-Life for $\alpha$ Decay	Branching Ratios	Partial Half-Life for Spontaneous Fission	Neutrons per Fission	References <sup>b</sup>
<sup>249</sup> 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
<sup>250</sup> Bk	3.222 $\pm$ 0.005 h					59Va02
<sup>251</sup> Bk	57 $\pm$ 1.7 m					66RG04
<sup>249</sup> Cf		352 $\pm$ 6 y	$\alpha/\text{SF} = (1.992 \pm 0.040) \times 10^8$		3.44 <sup>d</sup>	69Me01, 69Mi08
<sup>250</sup> Cf		13.08 $\pm$ 0.09 y	$\alpha/\text{SF} = 1260 \pm 40$		3.56 <sup>d</sup>	63Ph01, 69Me01
<sup>251</sup> Cf		900 $\pm$ 50 y				69Me01
<sup>252</sup> Cf	2.646 $\pm$ 0.004 y		$\alpha/\text{SF} = 31.3 \pm 0.2$		3.796 $\pm$ 0.031	65Me02, 68Wh04
<sup>253</sup> Cf	17.812 $\pm$ 0.082 d		$\alpha/\beta = (3.1 \pm 0.4) \times 10^{-3}$			69Dr02, 66RG01
<sup>254</sup> 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
<sup>255</sup> Cf	1.5 $\pm$ 0.5 h					70Lo19
<sup>253</sup> Es	20.467 $\pm$ 0.024 d		$\alpha/\text{SF} = (1.15 \pm 0.03) \times 10^7$		3.92 <sup>d</sup>	65Me02, 69Dr02
<sup>254</sup> Es	276 d			$>2.5 \times 10^7$ y	4.04 <sup>d</sup>	67Fi03, 67Un01
<sup>254m</sup> Es	39.3 $\pm$ 0.2 h		$\left\{ \begin{array}{l} B/\alpha = 382 \pm 30 \\ \text{E.C./B} = 0.00078 \pm 0.00006 \end{array} \right.$			62Un01, 63Ph01
<sup>255</sup> Es	39.8 $\pm$ 1.2 d		$\left\{ \begin{array}{l} \alpha/\beta = 0.0866 \pm 0.0043 \\ B/\text{SF} = (2.22 \pm 0.10) \times 10^4 \end{array} \right.$		4.16 <sup>d</sup>	66RG01, 67Fi03
<sup>256</sup> Es	25 $\pm$ 5 m					68Lo11
<sup>254</sup> Fm	3.24 $\pm$ 0.01 h		$\alpha/\text{SF} = 1695 \pm 8$		4.05 $\pm$ 0.19	56Jo09, 67Fi03, 56Ch83
<sup>255</sup> Fm	20.07 $\pm$ 0.07 h		$\text{SF}/\alpha = (2.4 \pm 1.1) \times 10^{-7}$		4.16 <sup>d</sup>	63Ph01, 64As01
<sup>256</sup> Fm	2.62 $\pm$ 0.03 h		$\sim 100\%$ SF		4.27 <sup>d</sup>	68Ho13
<sup>257</sup> Fm	94 $\pm$ 10 d					66RG01
<sup>258</sup> Fm	380 $\pm$ 60 ms		$\sim 100\%$ SF			70Hu17

<sup>a</sup>The half-life values used in this table were being used at TRU at the end of the report period.

<sup>b</sup>References are decoded in Table A-2.

<sup>c</sup>Published values are adjusted for <sup>241</sup>Am half-life of 432.7 y.

<sup>d</sup>Value estimated by linear interpolation of the values for <sup>244</sup>Cm and <sup>252</sup>Cf, based on nuclidic mass.

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.

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:

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

where  $\sigma_{2200}^{\text{C}}$  is the thermal-neutron capture cross section,  $N$  is the number of grams of the particular nuclide in one target rod,  $\phi_{\text{res}}$  is the average flux per unit lethargy width in the resonance region, and  $\phi_{2200}$  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
48Hy61	E. K. Hyde, M. H. Studier, and W. M. Manning, ANL-4143 (April 15, 1948) and ANL-4182 (August 4, 1948).	62Wa13	D. E. Watt, F. J. Bannister, J. B. Laidler, and F. Brown, <i>Phys. Rev.</i> , <b>126</b> , 264-265 (1962).
50Fr53	M. S. Freedman, A. H. Jaffey, and F. Wagner, Jr., <i>Phys. Rev.</i> , <b>79</b> , 410-411 (1950).	63Fi08	P. R. Fields, A. M. Friedman, J. Lerner, D. Metta, and R. Sjoblom, <i>Phys. Rev.</i> , <b>131</b> , 1249-1250 (1963).
51Ha87	G. C. Hanna, B. G. Harvey, N. Moss, and P. R. Tunncliffe, <i>Phys. Rev.</i> , <b>81</b> , 466-467 (1951).	63Ma50	L. Z. Malkin, I. D. Alkhazov, A. S. Krivokhatskii, and K. A. Petrzhak, <i>At. Energ. (USSR)</i> , <b>15</b> , 158-159 (1963).
51In03	M. G. Inghram, D. C. Hess, P. R. Fields, and G. L. Pyle, <i>Phys. Rev.</i> , <b>83</b> , 1250 (1951).	63Ph01	L. Phillips, R. Gatti, R. Brandt, and S. G. Thompson, <i>J. Inorg. Nucl. Chem.</i> , <b>25</b> , 1085-1087 (1963).
52Se67	E. Segrè, <i>Phys. Rev.</i> , <b>86</b> , 21-28 (1952).	64As01	F. Asaro, S. Bjørnholm, and I. Perlman, <i>Phys. Rev.</i> , <b>133</b> , B291-B300 (1964).
53Ke38	T. K. Keenan, R. A. Penneman, and B. B. McInteer, <i>J. Chem. Phys.</i> , <b>21</b> , 1802-1803 (1953).	64Py02	R. V. Pyle, Unpublished results as reported in E. K. Hyde, "Fission Phenomena", Prentice Hall, Inc., (1964).
54Gh24	A. Ghiorso, S. G. Thompson, G. R. Choppin, and B. G. Harvey, <i>Phys. Rev.</i> , <b>94</b> , 1081 (1954).	65Me02	D. Metta, H. Diamond, R. F. Barnes, J. Milsted, J. Gray, Jr., D. J. Henderson, and C. M. Stevens, <i>J. Inorg. Nucl. Chem.</i> , <b>27</b> , 33-35 (1965).
55En16	D. Engelkeir, P. R. Fields, T. Fried, G. L. Pyle, C. M. Stevens, L. B. Asprey, C. I. Browne, H. Louise Smith, and R. W. Spence, <i>J. Inorg. Nucl. Chem.</i> , <b>1</b> , 345-351 (1955).	66Fi07	P. R. Fields, A. M. Friedman, J. Milsted, J. Lerner, C. M. Stevens, D. Metta, and W. K. Sabine, <i>Nature</i> , <b>212</b> , 131 (1966).
56Bu92	J. P. Butler, T. A. Eastwood, T. L. Collins, M. E. Jones, F. M. Rourke, and R. P. Schuman, <i>Phys. Rev.</i> , <b>103</b> , 634 (1956).	66RG01	Combined Radiochemistry Group, LRL, LASL, and ANL. <i>Phys. Rev.</i> , <b>148</b> , No. 3, 1192-1198 (1966).
56Ch83	G. R. Choppin, B. G. Harvey, D. A. Hicks, J. Ise, Jr., and R. V. Pyle, <i>Phys. Rev.</i> , <b>102</b> , 766 (1956).	66RG04	Argonne Heavy Element Group (unpublished data).
56Di62	B. C. Diven, H. C. Martin, R. F. Taschek, and J. Terrell, <i>Phys. Rev.</i> , <b>101</b> , 1012-1015 (1956).	67Fi03	P. R. Fields, H. Diamond, A. M. Friedman, J. Milsted, J. L. Lerner, R. F. Barnes, R. K. Sjoblom, D. N. Metta, and E. P. Horwitz, <i>Nucl. Phys.</i> , <b>A96</b> , 440-448 (1967).
56Hi01	D. A. Hicks, J. Ise, Jr., and R. V. Pyle, <i>Phys. Rev.</i> , <b>101</b> , 1016-1020 (1956).	67Oe01	F. L. Oetting and S. R. Gunn, <i>J. Inorg. Nucl. Chem.</i> , <b>29</b> , 2659-2664 (1967).
56Ho23	D. C. Hoffman and C. I. Browne, <i>J. Inorg. Nucl. Chem.</i> , <b>2</b> , 209 (1956).	67Or02	C. J. Orth, W. R. Daniels, B. H. Erkkila, F. O. Lawrence, and D. C. Hoffman, <i>Phys. Rev. Letters</i> , <b>19</b> , No. 3, 128-131 (1967).
56Jo09	M. Jones, R. P. Schuman, J. P. Butler, G. Cowper, T. A. Eastwood, and H. G. Jackson, <i>Phys. Rev.</i> , <b>102</b> , 203-207 (1956).	67Un01	J. Unik, private communication to P. Fields (1967).
57As70	F. Asaro, S. G. Thompson, F. S. Stephens, Jr., and I. Perlman, <i>Bull. Am. Phys. Soc.</i> , <b>8</b> , 393 (1957).	68Be21	C. E. Bemis, Jr. and J. Halperin, <i>Nucl. Phys.</i> , <b>A121</b> , 433-439 (1968).
57Ea01	T. A. Eastwood, J. P. Butler, M. J. Cabell, H. G. Jackson, R. P. Schuman, F. M. Rourke, and T. L. Collins, <i>Phys. Rev.</i> , <b>107</b> , 1635-1638 (1957).	68Be26	W. C. Bentley, <i>J. Inorg. Nucl. Chem.</i> , <b>30</b> , 2007-2009 (1968).
57Pe52	R. A. Penneman, L. H. Treiman, and B. Bevan, as reported by D. C. Hoffman, G. P. Ford, and F. O. Lawrence, <i>J. Inorg. Nucl. Chem.</i> , <b>5</b> , 6-11 (1957).	68Br22	L. C. Brown and R. C. Propst, <i>J. Inorg. Nucl. Chem.</i> , <b>30</b> , 2591-2594 (1968).
58Ea06	T. A. Eastwood and R. P. Schuman, <i>J. Inorg. Nucl. Chem.</i> , <b>6</b> , 261-262 (1958).	68Ca19	M. J. Cabell, <i>J. Inorg. Nucl. Chem.</i> , <b>30</b> , 2583-2589 (1968).
59Ba21	R. F. Barnes, D. J. Henderson, A. L. Harkness, and H. Diamond, <i>J. Inorg. Nucl. Chem.</i> , <b>9</b> , 105-107 (1959).	68Di09	H. Diamond, J. J. Hines, R. K. Sjoblom, R. F. Barnes, D. N. Metta, J. L. Lerner, and P. R. Fields, <i>J. Inorg. Nucl. Chem.</i> , <b>30</b> , 2553-2559 (1968).
59Co93	D. Cohen, J. C. Sullivan, and A. J. Zielen, <i>J. Inorg. Nucl. Chem.</i> , <b>11</b> , 159-161 (1959).	68Ho13	R. W. Hoff, J. E. Evans, E. K. Hulet, R. J. Dupzyk, and B. J. Qualheim, <i>Nucl. Phys.</i> , <b>A115</b> , 225-233 (1968).
59Ma26	T. L. Markin, <i>J. Inorg. Nucl. Chem.</i> , <b>9</b> , 320-322 (1959).	68Jo15	K. C. Jordan, <i>MLM-1443</i> , 11-30 (1968).
59Va02	S. E. Vandenbosch, H. Diamond, R. K. Sjoblom, and P. R. Fields, <i>Phys. Rev.</i> , <b>115</b> , 115-121 (1959).	68Lo11	R. W. Loughheed, private communication to J. E. Bigelow (1968).
60Br12	F. P. Brauer, R. W. Stromatt, J. D. Ludwick, F. P. Roberts, and W. L. Lyon, <i>J. Inorg. Nucl. Chem.</i> , <b>12</b> , 234-235 (1960).	68Wh04	P. H. White and E. J. Axton, <i>J. Nucl. Energy</i> , <b>22</b> , 73-77 (1968).
60Br15	F. Brown, G. G. George, D. E. Green, and D. E. Watt, <i>J. Inorg. Nucl. Chem.</i> , <b>13</b> , 192-195 (1960).	69Be06	C. E. Bemis, Jr., J. Halperin, and R. Eby, <i>J. Inorg. Nucl. Chem.</i> , <b>31</b> , 599-604 (1969).
60Le03	R. M. Lessler and M. C. Michel, <i>Phys. Rev.</i> , <b>118</b> , 263-264 (1960).	69Dr02	R. E. Drushel, J. Halperin, and C. E. Bemis, Jr., ORNL-4437, 28-29 (1969).
61Dr04	V. A. Druin, V. P. Pereygin, and G. I. Khebnikov, <i>Sov. Phys. JETP</i> , <b>13</b> , 913-914 (1961).	69Me01	D. N. Metta, H. Diamond, and F. R. Kelly, <i>J. Inorg. Nucl. Chem.</i> , <b>31</b> , 1245-1250 (1969).
62Un01	J. Unik, P. Day, and S. Vandenbosch, <i>Nucl. Phys.</i> , <b>36</b> , 284-304 (1962).	69Mi08	J. Milsted, E. P. Horwitz, A. M. Friedman, and D. N. Metta, <i>J. Inorg. Nucl. Chem.</i> , <b>31</b> , 1561-1569 (1969).
62Va08	S. E. Vandenbosch and P. Day, <i>Nucl. Phys.</i> , <b>30</b> , 177-190 (1962).	70Hu17	E. K. Hulet, J. F. Wild, R. W. Loughheed, J. E. Evans, B. J. Qualheim, M. Nurmi, and A. Ghiorso, UCRL-72858 (1970). To be published in <i>Phys. Rev. Letters</i> .
		70Lo19	R. W. Loughheed, J. E. Evans, and E. K. Hulet, private communication to J. E. Bigelow (1970).

Table A-3. Properties<sup>a</sup> of Transuranium Nuclides  
 Underlines indicate new values since the previous report.

Nuclide	Half-Life	Energies of Prin. Emissions (MeV)		Specific Activity				Hazard <sup>b</sup>		
		$\alpha$	$\beta$	(Ci/g)	(W/g)	( $\alpha$ cpm/mg <sup>c</sup> )	( $\beta$ dpm/mg)	(Neutrons min <sup>-1</sup> mg <sup>-1</sup> )	MPC <sub>a</sub> (40) ( $\mu$ Ci/cm <sup>3</sup> )	Body Burden ( $\mu$ Ci) (ug)
<sup>237</sup> Np	2.14 x 10 <sup>6</sup> y	4.78		7.07 x 10 <sup>-4</sup>	2.07 x 10 <sup>-5</sup>	8.01 x 10 <sup>5</sup>		<7 x 10 <sup>-6</sup>	4 x 10 <sup>-12</sup>	0.06 84.9
<sup>238</sup> Np	2.10 d		0.25 1.24	2.61 x 10 <sup>5</sup>	1.27 x 10 <sup>3</sup>		5.80 x 10 <sup>14</sup>			
<sup>239</sup> Np	2.359 d		0.332 0.427	2.32 x 10 <sup>5</sup>	5.86 x 10 <sup>2</sup>		5.14 x 10 <sup>14</sup>		8 x 10 <sup>-7</sup>	30 1.29 x 10 <sup>-4</sup>
<sup>240</sup> Np	63 m		0.89	1.24 x 10 <sup>7</sup>	1.03 x 10 <sup>5</sup>		2.76 x 10 <sup>16</sup>			
<sup>240m</sup> Np	7.3 m		2.18 1.6	1.07 x 10 <sup>8</sup>	5.33 x 10 <sup>5</sup>		2.38 x 10 <sup>17</sup>			
<sup>241</sup> Np	16 m			4.86 x 10 <sup>7</sup>			1.08 x 10 <sup>17</sup>			
<sup>241m</sup> Np	3.4 h			3.82 x 10 <sup>6</sup>			8.49 x 10 <sup>15</sup>			
<sup>238</sup> Pu	87.404 y	5.49		17.2	0.570	1.94 x 10 <sup>10</sup>		155	2 x 10 <sup>-12</sup>	0.04 2.32 x 10 <sup>-3</sup>
<sup>239</sup> Pu	2.4413 x 10 <sup>4</sup> y	5.15		6.13 x 10 <sup>-2</sup>	1.913 x 10 <sup>-3</sup>	6.94 x 10 <sup>7</sup>		1.35 x 10 <sup>-3</sup>	2 x 10 <sup>-12</sup>	0.04 0.654
<sup>240</sup> Pu	<u>6580 y</u>	5.16		0.227	<u>7.097 x 10<sup>-3</sup></u>	2.57 x 10 <sup>8</sup>		55.7	2 x 10 <sup>-12</sup>	0.04 0.176
<sup>241</sup> Pu	14.98 y	4.9	0.02	99.1	4.06 x 10 <sup>-3</sup>	2.94 x 10 <sup>6</sup>	2.20 x 10 <sup>11</sup>		9 x 10 <sup>-11</sup>	0.9 9.08 x 10 <sup>-3</sup>
<sup>242</sup> Pu	3.869 x 10 <sup>5</sup> y	4.90		3.82 x 10 <sup>-3</sup>	1.13 x 10 <sup>-4</sup>	4.32 x 10 <sup>6</sup>		95.9	2 x 10 <sup>-12</sup>	0.05 13.0
<sup>243</sup> Pu	4.955 h		0.49 0.58	2.60 x 10 <sup>6</sup>	3.34 x 10 <sup>3</sup>		5.78 x 10 <sup>15</sup>		2 x 10 <sup>-6</sup>	7.2 2.78 x 10 <sup>-6</sup>
<sup>244</sup> Pu	8.28 x 10 <sup>7</sup> y	4.587		1.77 x 10 <sup>-5</sup>	4.93 x 10 <sup>-7</sup>	2.00 x 10 <sup>4</sup>		141	2 x 10 <sup>-12</sup>	0.04 2.23 x 10 <sup>3</sup>
<sup>245</sup> Pu	10.6 h			1.21 x 10 <sup>6</sup>			2.68 x 10 <sup>15</sup>		2 x 10 <sup>-7</sup>	3.0 4.03 x 10 <sup>5</sup>
<sup>246</sup> Pu	10.85 d		0.15	4.91 x 10 <sup>4</sup>	66.9		1.09 x 10 <sup>14</sup>			
<sup>241</sup> Am	432.7 y	5.48		3.43	0.1145	3.88 x 10 <sup>9</sup>		3.55 x 10 <sup>-2</sup>	6 x 10 <sup>-12</sup>	0.1 0.0292
<sup>242</sup> Am	16.01 h		0.63 0.67	8.11 x 10 <sup>5</sup>	2.08 x 10 <sup>3</sup>		1.80 x 10 <sup>15d</sup>		4 x 10 <sup>-8</sup>	0.06 7.39 x 10 <sup>-8</sup>
<sup>242m</sup> Am	144 y	5.207	I.T.	10.3	3.08 x 10 <sup>-2</sup>	5.53 x 10 <sup>7</sup>	2.28 x 10 <sup>10e</sup>		6 x 10 <sup>-12</sup>	0.07 6.80 x 10 <sup>-3</sup>
<sup>243</sup> Am	7370 y	5.27		0.200	6.42 x 10 <sup>-3</sup>	2.26 x 10 <sup>8</sup>			6 x 10 <sup>-12</sup>	0.05 0.25
<sup>244</sup> Am	10.1 h		0.387	1.27 x 10 <sup>6</sup>	8.74 x 10 <sup>3</sup>		2.82 x 10 <sup>15</sup>		2 x 10 <sup>-7</sup>	0.18 1.42 x 10 <sup>-7</sup>
<sup>244m</sup> Am	26 m		1.5	2.96 x 10 <sup>7</sup>	8.98 x 10 <sup>4</sup>		6.58 x 10 <sup>16f</sup>		4 x 10 <sup>-6</sup>	0.18 6.08 x 10 <sup>-9</sup>
<sup>245</sup> Am	2.07 h		0.91	6.17 x 10 <sup>6</sup>	1.20 x 10 <sup>4</sup>		1.37 x 10 <sup>16</sup>		3 x 10 <sup>-6</sup>	12 1.94 x 10 <sup>-6</sup>
<sup>246</sup> Am	25.0 m		1.31	3.06 x 10 <sup>7</sup>	2.48 x 10 <sup>5</sup>		6.79 x 10 <sup>16</sup>			
<sup>246m</sup> Am	40 m			1.91 x 10 <sup>7</sup>			4.24 x 10 <sup>16</sup>			
<sup>247</sup> Am	24 m			3.17 x 10 <sup>7</sup>			7.04 x 10 <sup>16</sup>			
<sup>242</sup> Cm	162.7 d	6.11		3.32 x 10 <sup>3</sup>	122	3.76 x 10 <sup>12</sup>		1.21 x 10 <sup>6</sup>	1 x 10 <sup>-10</sup>	0.05 6.27 x 10 <sup>-7</sup>
<sup>243</sup> Cm	32 y	5.79		45.9	1.677	5.20 x 10 <sup>10</sup>	3.27 x 10 <sup>8</sup>		6 x 10 <sup>-12</sup>	0.09 1.96 x 10 <sup>-3</sup>
<sup>244</sup> Cm	18.099 y	5.80		80.94	2.832	9.16 x 10 <sup>10</sup>		6.87 x 10 <sup>5</sup>	9 x 10 <sup>-12</sup>	0.1 1.24 x 10 <sup>-3</sup>
<sup>245</sup> Cm	8265 y	5.36		0.177	5.89 x 10 <sup>-3</sup>	2.00 x 10 <sup>8</sup>			5 x 10 <sup>-12</sup>	0.04 0.263
<sup>246</sup> Cm	4711 y	5.4		<u>0.409</u>	1.01 x 10 <sup>-2</sup>	3.50 x 10 <sup>8</sup>		5.52 x 10 <sup>5</sup>	5 x 10 <sup>-12</sup>	0.05 0.194
<sup>247</sup> Cm	1.64 x 10 <sup>7</sup> y			8.83 x 10 <sup>-5</sup>	~2.8 x 10 <sup>-6</sup>	1.00 x 10 <sup>5</sup>			5 x 10 <sup>-12</sup>	0.04 453
<sup>248</sup> Cm	3.52 x 10 <sup>5</sup> y	5.05		4.09 x 10 <sup>-3</sup>	5.72 x 10 <sup>-4</sup>	4.25 x 10 <sup>6</sup>		2.51 x 10 <sup>6</sup>	6 x 10 <sup>-13</sup>	0.01 2.91
<sup>249</sup> Cm	64 m		0.9	1.18 x 10 <sup>7</sup>	2.06 x 10 <sup>4</sup>		2.62 x 10 <sup>16</sup>		8 x 10 <sup>-6</sup>	0.8 6.78 x 10 <sup>-8</sup>
<sup>250</sup> Cm	1.74 x 10 <sup>4</sup> y			8.20 x 10 <sup>-2</sup>	~0.1			6.49 x 10 <sup>8</sup>		
<sup>249</sup> Bk	314 d	5.4	0.125	1.67 x 10 <sup>3</sup>	0.358	2.74 x 10 <sup>7</sup>	3.71 x 10 <sup>12</sup>	6.34 x 10 <sup>3</sup>	9 x 10 <sup>-10</sup>	0.7 4.19 x 10 <sup>-4</sup>
<sup>250</sup> Bk	3.222 h		0.23	3.89 x 10 <sup>6</sup>	2.75 x 10 <sup>4</sup>		8.62 x 10 <sup>15</sup>		1 x 10 <sup>-7</sup>	0.04 1.03 x 10 <sup>-7</sup>
<sup>251</sup> Bk	57 m			1.32 x 10 <sup>7</sup>			2.92 x 10 <sup>16</sup>			

Table A-3 (continued)

Nuclide	Half-Life	Energies of Prin. Emissions (MeV)		Specific Activity				Hazard <sup>b</sup>			
		$\alpha$	$\beta$	(Ci/g)	(N/g)	( $\alpha$ cpm/mg <sup>c</sup> )	( $\beta$ dpm/mg)	(Neutrons min <sup>-1</sup> mg <sup>-1</sup> )	MPC <sup>a</sup> (40) (uCi/cm <sup>3</sup> )	Body Burden (uCi) (ug)	
<sup>249</sup> Cf	352 y	5.81		4.08	0.152	$4.62 \times 10^9$		156	$2 \times 10^{-12}$	0.04 $8.98 \times 10^{-3}$	
<sup>250</sup> Cf	13.08 y	6.03		109	4.06	$1.23 \times 10^{11}$		$6.85 \times 10^8$	$5 \times 10^{-12}$	0.04 $3.70 \times 10^{-4}$	
<sup>251</sup> Cf	900 y			1.59	$5.79 \times 10^{-2}$	$1.78 \times 10^9$			$2 \times 10^{-12}$	0.04 $2.50 \times 10^{-2}$	
<sup>252</sup> Cf	2.646 y	6.11		536	39.0	$5.88 \times 10^{11}$		$1.40 \times 10^{11}$	$6 \times 10^{-12}$	0.01 $1.87 \times 10^{-5}$	
<sup>253</sup> Cf	17.812 d	5.98	0.27	$2.90 \times 10^4$	13.89	$1.02 \times 10^{11}$	$6.41 \times 10^{13}$		$8 \times 10^{-10}$	0.04 $1.40 \times 10^{-6}$	
<sup>254</sup> Cf	60.5 d	5.84		$8.49 \times 10^3$	$1.06 \times 10^4$	$2.89 \times 10^{10}$		$7.35 \times 10^{13}$	$5 \times 10^{-12}$	0.01 $1.18 \times 10^{-6}$	
<sup>255</sup> Cf	1.5 h			$\sim 8 \times 10^6$							
<sup>253</sup> Es	20.467 d	6.63		$2.52 \times 10^4$	$1.01 \times 10^3$	$2.86 \times 10^{13}$		$1.91 \times 10^7$	$7 \times 10^{-10}$	0.04 $1.59 \times 10^{-6}$	
<sup>254</sup> Es	276 d	6.42		$1.86 \times 10^3$	71.9	$2.11 \times 10^{12}$		$< 5.04 \times 10^5$	$2 \times 10^{-11}$	0.02 $1.08 \times 10^{-5}$	
<sup>254m</sup> Es	39.3 h		0.48	$3.14 \times 10^5$	$1.18 \times 10^3$			$6.97 \times 10^{14}$	$5 \times 10^{-9}$	0.02 $6.37 \times 10^{-8}$	
<sup>255</sup> Es	39.8 d			$1.29 \times 10^4$				$2.86 \times 10^{13}$	$4.92 \times 10^9$	$6 \times 10^{-10}$	0.04 $3.10 \times 10^{-6}$
<sup>256</sup> Es	25 m			$2.94 \times 10^7$				$6.52 \times 10^{16}$			
<sup>254</sup> Fm	3.24 h	7.20		$3.81 \times 10^6$	$1.68 \times 10^5$	$4.31 \times 10^{15}$		$2.02 \times 10^{13}$	$6 \times 10^{-8}$	0.02 $5.25 \times 10^{-9}$	
<sup>255</sup> Fm	20.07 h	7.03		$6.13 \times 10^5$	$2.79 \times 10^4$	$6.94 \times 10^{14}$		$1.36 \times 10^9$	$2 \times 10^{-8}$	0.04 $6.53 \times 10^{-8}$	
<sup>256</sup> Fm	2.62 h			$4.67 \times 10^6$	$5.85 \times 10^6$			$4.43 \times 10^{16}$	$2 \times 10^{-9}$	0.01 $2.14 \times 10^{-9}$	
<sup>257</sup> Fm	94 d			$5.41 \times 10^3$	$\sim 200$	$6.12 \times 10^{12}$					
<sup>258</sup> Fm	380 ms			$1.15 \times 10^{11}$							

<sup>a</sup>The values for properties included in this table are those in use at TRU at the end of the report period.

<sup>b</sup>From ICRP Publication 2, "Report of Committee II on Permissible Dose for Internal Radiation (1959)" and the 1962 Supplement.

<sup>c</sup>Counting geometry, 51%.

<sup>d</sup><sup>242</sup>Am decays by  $\beta$  emission (84%) and orbital electron capture (16%).

<sup>e</sup><sup>242m</sup>Am decays almost entirely by isomeric transition to the 16-hr ground state, <sup>242</sup>Am.

<sup>f</sup><sup>244m</sup>Am decays primarily by  $\beta$  emission, but 0.039% decays by electron capture to <sup>244</sup>Pu.

Table A-4. Neutron Cross Sections Used to Compute Translations 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)
<sup>238</sup> Pu	87.404 y	560	0	150	16.5	0	25
<sup>239</sup> Pu	2.4413 x 10 <sup>4</sup> y	265.7	0	195	742.4	0	324
<sup>240</sup> Pu	6580 y	290	0	8453	0.05	0	0
<sup>241</sup> Pu	14.98 y	360	0	166	1011	0	541
<sup>242</sup> Pu	3.869 x 10 <sup>5</sup> y	18.5	7.409	1280	0	0	0
<sup>243</sup> Pu	4.955 h	80	0	0	210	0	0
<sup>244</sup> Pu	8.28 x 10 <sup>7</sup> y	1.6	0	0	0	0	0
<sup>245</sup> Pu	10.6 h	277	0	0	0	0	0
<sup>246</sup> Pu	10.85 d	0	0	0	0	0	0
<sup>243</sup> Am	7370 y	75	2.126	1500	0	0	0
<sup>244</sup> Am	10.1 h	0	0	0	2300	0	0
<sup>244m</sup> Am	26 m	0	0	0	0	0	0
<sup>244c</sup> Am <sup>a</sup>	49 m	0	0	0	1128	0	0
<sup>245</sup> Am	2.07 h	0	0	0	0	0	0
<sup>246</sup> Am	25.0 m	0	0	0	0	0	0
<sup>244</sup> Cm	18.099 y	12.0	6.9	650	1.2	6.9	12.5
<sup>245</sup> Cm	8265 y	340	2.4	100	1920	2.4	1140
<sup>246</sup> Cm	4711 y	1.25	2.4	121	0	0	0
<sup>247</sup> Cm	1.64 x 10 <sup>7</sup> y	60	0	500	120	0	1060
<sup>248</sup> Cm	3.52 x 10 <sup>5</sup> y	5.2	1.477	250	0	0	0
<sup>249</sup> Cm	64 m	2.8	0	0	50	0	0
<sup>250</sup> Cm	1.74 x 10 <sup>4</sup> y	2	0	0	0	0	0
<sup>249</sup> Bk	314 d	1451	2.4	1240	0	0	0
<sup>250</sup> Bk	3.222 h	350	0	0	3000	0	0
<sup>249</sup> Cf	352 y	450	1.46	750	1690	5.8	2920
<sup>250</sup> Cf	13.08 y	1900	13.3	6670	0	0	0
<sup>251</sup> Cf	900 y	2360	14	7000	3280	94	47,000
<sup>252</sup> Cf	2.646 y	19.8	0	44	0	0	56
<sup>253</sup> Cf	17.812 d	12.6	0	0	1300	0	0
<sup>254</sup> Cf	60.5 d	50	0	1650	0	0	0
<sup>255</sup> Cf	1.5 h	0	0	0	0	0	0
<sup>253</sup> Es	20.467 d	345	0	0	0	0	0
<sup>254</sup> Es	276 d	20	0	0	3060	0	0
<sup>254m</sup> Es	39.3 h	1.26	0	0	1840	0	0
<sup>255</sup> Es	39.8 d	60	0	0	0	0	0
<sup>256</sup> Es	25 m	0	0	0	0	0	0
<sup>254</sup> Fm	3.24 h	76	0	0	0	0	0
<sup>255</sup> Fm	20.07 h	26	0	0	100	0	0
<sup>256</sup> Fm	2.62 h	45	0	0	0	0	0
<sup>257</sup> Fm	94 d	10	0	0	5500	0	0
<sup>258</sup> Fm	380 ms	0	0	0	0	0	0

<sup>a</sup>To simplify calculations we use a fictitious isotope, <sup>244c</sup>Am, which combines the properties of <sup>244m</sup>Am and <sup>244</sup>Am according to their relative rates of production from <sup>243</sup>Am.

It should be pointed out that  $^{244}\text{CAm}$  is a fictitious isotope which is used to simplify the calculation of the main transmutation chain involving  $^{244}\text{Am}$ . The properties of  $^{244}\text{CAm}$  were calculated from the properties of the real isomers  $^{244}\text{gAm}$  and  $^{244}\text{mAm}$  by assuming that: (1) the number of atoms of  $^{244}\text{CAm}$  present equals the total number of atoms of the real isomers; (2) the  $\beta$  decay from  $^{244}\text{CAm}$  equals the total  $\beta$  decay from the real isomers; (3) the fissions from  $^{244}\text{CAm}$  equal the total fissions from the real isomers; (4) the isomers are in equilibrium with their common parent  $^{243}\text{Am}$  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  $^{243}\text{Am}$ . 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  $^{243}\text{Am}$  resulting in the  $i$ th isomer, such that  $f_c = f_g + f_m = 1$ .

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