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TRANSURANIUM PROCESSING PLANT  
SEMIANNUAL REPORT OF PRODUCTION,  
STATUS, AND PLANS FOR PERIOD ENDING  
JUNE 30, 1973

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

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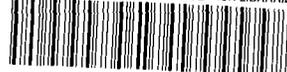
TRANSURANIUM PROCESSING PLANT SEMIANNUAL REPORT OF  
PRODUCTION, STATUS, AND PLANS FOR PERIOD ENDING JUNE 30, 1973

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

MARCH 1974

OAK RIDGE NATIONAL LABORATORY  
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## SUMMARY

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

During the period January 1, 1973, through June 30, 1973, we recovered transuranium elements from 22-1/2 irradiated HFIR targets and from 3 Pu-Al tubes that had been irradiated at the Savannah River Plant (SRP) as part of the Californium-I program to evaluate the commercial market for  $^{252}\text{Cf}$  and to establish an inventory of material for sale. Products recovered are listed in Table 2.1 on page 3. We purified 187 g of Californium-I curium and converted it to oxide for use in HFIR targets. Also, 1.8  $\mu\text{g}$  of  $^{254}\text{Es}$ , 3.24 g of  $^{244}\text{Pu}$ , and 12 mg of  $^{248}\text{Cm}$ , all of high isotopic purity, were recovered from materials previously processed. Sixty-four shipments were made from TRU during the period; recipients and the amounts of nuclides are listed in Table 2.2 on pp. 5-7. Twenty HFIR targets, each containing 7 to 9 g of actinides (predominantly curium), were fabricated.

During the next 18 months, we expect to recover totals of 49 mg of  $^{249}\text{Bk}$ , 575 mg of  $^{252}\text{Cf}$ , 2.3 mg of  $^{253}\text{Es}$  (in a mixture of isotopes), 255  $\mu\text{g}$  of isotopically pure  $^{253}\text{Es}$ , and 1.5  $\mu\text{g}$  of  $^{257}\text{Fm}$ . Also, we expect to obtain 50 mg of high-purity  $^{248}\text{Cm}$  from purified californium now in storage. Currently, we do not plan to process any of the remaining SRP Pu-Al tubes or to irradiate any plutonium targets in the HFIR; thus, we do not expect to recover any  $^{244}\text{Pu}$ .

Work was done during this period to improve one of our processing steps. A new batch solvent extraction process, using 60% TBP as extractant, was tested as an alternative to the Cleanex process.

Three neutron sources were fabricated, bringing the total fabricated to 63; 5 sources that had been used in various projects were returned to TRU for reassignment or reprocessing. Tests were made to determine the containment classification for Zircaloy-2 encapsulated sources, and studies relative to neutron counter dead time were made to improve neutron source calibration.

In special projects, one  $^{253}\text{Es}$  rabbit was encapsulated, irradiated, and shipped to ANL. About 79 mg of  $^{252}\text{Cf}$  was assembled as a neutron source and was used by the ORNL Analytical Chemistry Division to analyze a series of solid and liquid samples by neutron activation; this was done as part of an AEC program to improve interpretation of neutron activation analysis systems.

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 eleventh report in a series that is being issued semi-annually to inform the heavy-element community of the status and the future production plans of the Transuranium Element Production Program at ORNL. The objective of these reports is to provide information that will enable users of the products to obtain maximum service from the production facilities at ORNL. Production plans and schedules are definitely established only for the short term; long-range plans can be (and are) markedly influenced by feedback from researchers and other users of transuranium elements.

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

Previous reports in this series are:

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

## 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

During the period January 1, 1973, through June 30, 1973, we recovered transuranium elements from 22-1/2 irradiated HFIR targets and from 3 Pu-Al tubes that had been irradiated at the Savannah River Plant (SRP) as part of the Californium-I program to evaluate the commercial market for  $^{252}\text{Cf}$  and to establish an inventory of material for sale. Three major campaigns were made: two to process the HFIR targets, and one to process the SRP tubes. Products recovered are listed in Table 2.1. A fourth campaign was made to purify and convert 187 g of Californium-I curium to the oxide form for use in HFIR targets.

Three special-interest isotopes,  $^{254}\text{Es}$ ,  $^{248}\text{Cm}$ , and  $^{244}\text{Pu}$ , were obtained during this report period. Einsteinium and plutonium product fractions recovered from the three SRP Pu-Al tubes were each combined with similar fractions recovered from three tubes processed previously.<sup>1</sup> The  $^{253}\text{Es}$  had decayed for more than one year, and we were able to recover high-purity  $^{254}\text{Es}$  (about 1.8  $\mu\text{g}$  was obtained).

After purification of the composite plutonium, 12.6 g (22.6%  $^{244}\text{Pu}$ ) was converted to the oxide form and shipped to the Y-12 Plant for enrichment of  $^{244}\text{Pu}$  in the calutrons. At Y-12, the plutonium was combined with 24 g of plutonium that had been purified previously at TRU,<sup>2</sup> and the total enriched product obtained from the calutrons consisted of 3.24 g of 98.58%  $^{244}\text{Pu}$ .

Table 2.1. Amounts of Materials Recovered in Major Campaigns in the Transuranium Processing Plant During the Period January 1, 1973, Through June 30, 1973

	Campaign No.			Total
	38	39	40	
Completion date	January	February	March	
Material processed	3 SRP Pu-Al Tubes + Rework	12-1/2 TRU-HFIR Cm Targets + Rework	10 Cf-I Cm- HFIR Targets + Rework	
Amounts recovered				
$^{242}\text{Pu}$ , g	2.1 <sup>a</sup>	None	None	2.1 <sup>a</sup>
$^{243}\text{Am}$ , g <sup>b</sup>	2.4	1.8	None	4.2
$^{244}\text{Cm}$ , g <sup>b</sup>	84.2	36.6	49.3	170.1
$^{249}\text{Bk}$ , mg	9.0	12.8	19.2	41.0
$^{252}\text{Cf}$ , mg	75	83	203	361
$^{253}\text{Es}$ , $\mu\text{g}$	None <sup>c</sup>	555	994	1549
$^{257}\text{Fm}$ , pg	None	0.5 <sup>d</sup>	0.75 <sup>d</sup>	1.25 <sup>d</sup>

<sup>a</sup>The plutonium product also contained 1.3 g of  $^{244}\text{Pu}$ .

<sup>b</sup>Americium and curium are not usually separated from each other.

<sup>c</sup> $^{254}\text{Es}$  was recovered as a product.

<sup>d</sup>Estimated amounts.

Part of the  $^{248}\text{Cm}$  that was initially isolated in September 1972<sup>3</sup> was used for an experiment in the ORELA. On completion of the experiment, this material was returned to TRU, where repurification yielded about 12 mg of high-purity (~97%)  $^{248}\text{Cm}$ .

Sixty-four shipments were made during this period; recipients and the amounts of nuclides are listed in Table 2.2. Nine of the shipments were comprised of materials that had been previously shipped but had been returned for repurification or reirradiation.

Twenty HFIR targets were fabricated from actinide oxide prepared by the resin loading--calcination technique. Each target contained 7 to 9 g of actinide metals (predominantly curium) in the form of actinide oxide--aluminum pellets that had been pressed to 80% of the theoretical density of the pellet core. Isotopic distribution of the curium in the targets was within the range of 62 to 64%  $^{244}\text{Cm}$ , 28 to 30%  $^{246}\text{Cm}$ , and 1.8 to 3.2%  $^{248}\text{Cm}$ . Fifteen of the targets were prepared from Californium-I curium.

## 2.2 Irradiation and Processing Proposals

The amounts of transcurium elements that will be produced at TRU during the next few years will depend on: (1) the needs of researchers for various isotopes, (2) the needs for  $^{252}\text{Cf}$  in the Production and Materials Management (PMM) Division's market evaluation and sales program, and (3) the capabilities of the TRU-HFIR complex to produce the required materials. The long-term capability of the TRU-HFIR complex to produce transuranium elements was described in a previous report<sup>4</sup> in this series. The processing schedule for the next 18 months can be predicted reasonably and is described below.

The estimated future production of transcurium elements from a series of likely processing campaigns which are scheduled through December 1974 is outlined in Table 2.3. We plan to process three groups of HFIR targets, two of which were prepared from Californium-I curium and the other from regular TRU stock. The quality (isotopic distribution) of curium from the two sources was similar. At present, we do not have plans to process any SRP-irradiated materials.

Table 2.2. Distribution of Heavy Elements from the  
Transuranium Processing Plant During the Period  
January 1, 1973 - June 30, 1973

Major Nuclide	Date	TRU File No.	Shipped To:	
			Individual	Site
Plutonium-242, g				
13.0	6-01-73	636	W. T. Carnall	ANL
Plutonium-244 (22%), g				
2.85	4-16-73	631	Isotope Separation	ORNL
Curium-243 (55%), mg				
0.021	1-12-73	578	W. Stevens	U. of Utah
1.67	2-09-73	618	W. T. Carnall	ANL
<u>1.691</u>				
Curium-244, g				
0.27	4-19-73	494	T. D. Chikalla	PNL
Curium-245 (35%), mg				
0.09	1-19-73	576	W. T. Carnall	ANL
Curium-246 (50%), mg				
0.10	1-19-73	577	W. T. Carnall	ANL
0.08	6-15-73	643	W. T. Carnall	ANL
<u>0.18</u>				
Curium-248 (97%), mg <sup>a</sup>				
2.60	5-01-73	579	R. W. Hoff	LLL
0.30	6-04-73	475A	R. J. Silva	ORNL
0.90	6-04-73	475B	N. R. Johnson, Jr.	ORNL
2.23	6-05-73	472	W. T. Carnall	ANL
2.23	6-05-73	473	R. A. Penneman	LASL
2.21	6-05-73	474	J. A. Harris	LBL
0.55	6-05-73	580	K. W. MacMurdo	SRL
0.70	6-29-73	475C	J. R. Peterson	ORNL
<u>11.72</u>				

Table 2.2 (continued)

Major Nuclide	Date	TRU File No.	Shipped To:	
			Individual	Site
Berkelium-249, mg				
0.3	6-04-73	614	R. J. Silva	ORNL
1.0	6-05-73	582A	C. J. Orth	LASL
0.01	6-05-73	584	W. Stevens	U. of Utah
5.0	6-05-73	585	W. T. Carnall	ANL
0.5	6-08-73	635	R. D. Baybarz	Karlsruhe
4.2	6-13-73	583	J. R. Peterson	ORNL
4.0	6-22-73	581	J. A. Harris	LBL
4.0	6-22-73	586	R. W. Hoff	LLL
4.0	6-22-73	587	K. W. MacMurdo	SRL
3.0	6-29-73	582B	R. G. Haire	ORNL
<u>26.01</u>				
Californium-249, mg (isotopically pure)				
1.51	6-29-73	588	J. A. Harris	LBL
1.51	6-29-73	589	R. W. Hoff	LLL
1.51	6-29-73	591A	R. G. Haire	ORNL
0.10	6-29-73	591B	Production Support	ORNL
1.01	6-29-73	592	K. W. MacMurdo	SRL
0.93	6-29-73	645	W. T. Carnall	ANL
<u>6.57</u>				
Californium-252, mg				
3.98 (NSS-62)	1-05-73	595	J. E. Bigelow	ORNL
3.19 (NS-54)	1-22-73	504	V. Spiegel	NBS
5.23 (NSD-61)	1-22-73	537	L. J. Esch	KAPL
0.012	1-24-73	612	Isotopes Sales	ORNL
0.012	1-24-73	613	Isotopes Sales	ORNL
0.012	2-01-73	617	Isotopes Sales	ORNL
34.49	5-25-73	615	A. R. Boulogne	SRL
<u>46.926</u>				
Californium-252 (97%), mg				
0.0108	1-09-73	445	J. J. Thompson	Lovelace
0.0019	1-18-73	531	Isotopes Sales	ORNL
<u>0.0127</u>				

Table 2.2 (continued)

Major Nuclide	Date	TRU File No.	Shipped To:	
			Individual	Site
Einsteinium-253, $\mu\text{g}$				
10	2-16-73	597	J. A. Harris	LBL
310	2-16-73	598	M. M. Abraham	ORNL
5	2-16-73	599	F. P. Hungate	PNL
25	2-16-73	601	R. G. Haire	ORNL
200	2-23-73	596	W. T. Carnall	ANL
24	2-27-73	620	R. G. Haire	ORNL
0.0001	3-02-73	622	R. L. Hayes	ORAU
220	3-23-73	600	W. T. Carnall	ANL
130	3-23-73	627-1	R. G. Haire	ORNL
74	3-29-73	627-2	R. G. Haire	ORNL
106	3-30-73	621	R. D. Baybarz	Karlsruhe
127	3-30-73	-	$^{254}\text{Es}$ Production	ORNL
5 (irradiated) <sup>b</sup>	4-23-73	632	R. K. Sjoblom	ANL
<u>1231.0001</u>				
Einsteinium-253, $\mu\text{g}$ (isotopically pure)				
33	4-13-73	603	W. T. Carnall	ANL
0.005	4-13-73	629	R. L. Hayes	ORAU
0.5	5-11-73	605	W. Stevens	U. of Utah
50	5-11-73	606	R. W. Hoff	LLL
50	5-11-73	607	R. G. Haire	ORNL
<u>133.505</u>				
Einsteinium-254, $\mu\text{g}$				
0.5	2-13-73	556	J. A. Harris	LBL
0.3	2-13-73	558	W. T. Carnall	ANL
0.5	2-13-73	619	R. A. Penneman	LASL
0.5	2-16-73	608	R. J. Silva	ORNL
<u>1.8</u>				
Fermium-257, pg				
1.25	3-23-73	609	D. C. Hoffman	LASL
c	4-17-73	630	D. C. Hoffman	LASL

<sup>a</sup>All of the  $^{248}\text{Cm}$  shipments consisted of material previously shipped as No. 545.

<sup>b</sup>This shipment consists of material previously shipped as No. 600; it was not included in the total.

<sup>c</sup>The estimated total  $^{257}\text{Fm}$  available was 1.25 pg, as indicated for shipment No. 609. As the customer indicated poor yield, a second attempt was made to recover the same batch of material.

Table 2.3. Estimated Future Production of Transcurium Elements

Period	Processing Campaign	Products of Campaigns				<sup>252</sup> Cf Production <sup>b</sup>		Date Products Available
		<sup>249</sup> Bk (mg)	<sup>252</sup> Cf (mg)	<sup>253</sup> Es <sup>a</sup> (μg)	<sup>257</sup> Fm (pg)	During the Period (mg)	Cumul. (mg)	
Through June 1973							571 <sup>b</sup>	
July-December 1973	10 Cf-I Cm-HFIR Targets	16	210	780(85)	0.5	210	781	October 1973
January-June 1974	12 Cf-I Cm-HFIR Targets	17	185	750(85)	0.5	185	966	March 1974
July-December 1974	11 TRU-HFIR Targets	16	180	750(85)	0.5	180	1146	October 1974
1975						400	1546	
1976						450	1996	

<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 irradiations is not included in production totals. A total of 720 mg has been recovered from 164 SRP slugs and 21 SRP tubes processed through June 1973.

### 2.3 Estimates of the Availability of Transuranium Elements

The amounts of transcurium elements expected from each campaign are given in Table 2.3. During the next 18 months, we expect to recover totals of 49 mg of  $^{249}\text{Bk}$ , 575 mg of  $^{252}\text{Cf}$ , 2.3 mg of  $^{253}\text{Es}$  (in a mixture of isotopes), 255  $\mu\text{g}$  of isotopically pure  $^{253}\text{Es}$ , and 1.5  $\mu\text{g}$  of  $^{257}\text{Fm}$ . These forecasts were made by beginning with the usual calculation of amounts of transcurium elements in each group of targets at the time of reactor discharge by means of our computer code, then adding the assumed amounts of rework feed, and applying assumed chemical yield factors and net decay factors for the assumed recovery times to the amounts of total feed (targets plus rework). Assumed chemical yields and recovery times were based on past performance, with appropriate adjustments for current levels of manpower at TRU. The assumptions are summarized in Table 2.4.

Table 2.4. Assumptions for Forecasts of Transcurium Product Recoveries

	Bk	Cf	Es	Fm
Chemical Yield Factors				
Product Recovery	0.75	0.90	0.85	0.85
Rework	0.15	0.05	0	0
Recovery Time, <sup>a</sup> weeks	15	13 <sup>b</sup>	9	10
Net decay factors during recovery time	0.79	0.937	0.704	0.58
Total Product Recovery Factor (chemical yield x net decay)	0.59	0.84	0.60	0.5

<sup>a</sup>Recovery time is considered to be the interval between reactor discharge and shipment of the product. Within the recovery time, cooling and main-line processing are assumed to require 3 and 5 weeks, respectively.

<sup>b</sup>This time includes a 4-week growing period for  $^{253}\text{Es}$  after final purification of the californium. Total recovery factor for isotopically pure  $^{253}\text{Es}$  is 0.04% of the  $^{252}\text{Cf}$  in the HFIR targets at discharge.

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

In accordance with an agreement between the Physical Research and PMM Divisions, we are maintaining 90 to 100 mg of purified  $^{252}\text{Cf}$ , recovered from Californium-I material, for use as a "cow" which can be "milked" periodically to obtain high-purity ( $\sim 97\%$ )  $^{248}\text{Cm}$ . Due to the presence of  $^{250}\text{Cf}$  in the cow, the curium contains about 3%  $^{246}\text{Cm}$ . Some  $^{248}\text{Cm}$  will also become available from other purified californium. We expect to obtain 25 mg of  $^{248}\text{Cm}$  in October 1973, and an additional 25 mg in April 1974.

### 3. PROCESSES AND EQUIPMENT

There have been no changes in the chemical processing flowsheets or equipment normally used at TRU during this report period. However, efforts were made to improve one of the processing steps. The results are described below.

In the Cleanex process (a batch solvent extraction process), trivalent actinides are extracted into 1 M HDEHP from solutions having low acid concentrations (less than 0.1 N  $\text{H}^+$ ). However, hydrolysis and the buffering action of impurities often cause difficulties in this process. In an attempt to circumvent such difficulties, we developed an alternative method, also a batch solvent extraction, in which acidities as high as 0.2 N can be used. The new method consists of extracting the actinides from a concentrated solution of mixed nitrate and chloride salts into 60% TBP in an aliphatic hydrocarbon diluent. In a typical application, one-tenth to five-tenths volume of 12 M LiCl is added to one volume of 2 M  $\text{Al}(\text{NO}_3)_3$ . If a large quantity of sodium is present, actinide extraction is decreased considerably, and the addition of chloride (or total salt concentration)

must be limited to prevent precipitation of NaCl. If the ratio of 12 M LiCl added to 2 M Al(NO<sub>3</sub>)<sub>3</sub> is greater than approximately 3, AlCl<sub>3</sub> will precipitate. Some of the LiNO<sub>3</sub> and essentially all of the acid are extracted; however, chloride extraction is minimal. Tests of this process in TRU were made with rework solutions but were only partially successful. Difficulties were encountered in determining the feed composition needed to give satisfactory actinide extraction.

#### 4. CALIFORNIUM NEUTRON SOURCES

Much of the californium recovered at TRU is incorporated into neutron sources, which are subsequently loaned to researchers. Data for all of the neutron sources that have been fabricated at TRU are listed in Table 4.1. Most of them were fabricated into one of the four standard models illustrated in Fig. 4.1 and designated in the table by a three-letter prefix. Nonstandard sources are designated simply "NS-". The three-letter prefix indicates whether the source is singly or doubly encapsulated, and whether it is fabricated from type 304L stainless steel or Zircaloy-2. The characteristics of these source capsules are listed in Table 4.2. During this report period, prototypes of the Zircaloy-2-clad sources were subjected to a series of classification tests by the ORNL Isotopes Division,<sup>5</sup> as was done earlier for the stainless-steel-clad sources.<sup>6</sup> The results of these tests, shown in Tables 4.3 and 4.4, place both the singly and doubly encapsulated Zircaloy-2-clad sources in the classification III-C. We plan to request cataloging of Zircaloy-2 encapsulated sources of this source design by the AEC Directorate of Licensing. Thus far, only sources fabricated from type 304L stainless steel have been cataloged.

##### 4.1 Sources Fabricated During January-June 1973

Three standard sources were completed during this report period. One of these, NSS-62, was fabricated toward the end of the previous period; however, calibration was delayed. It is our intent to use NSS-62 as an in-house reference standard for calibrating other sources, since the source

Table 4.1. Data for Neutron Sources Prepared at TRU

Source	Date of Calibration	$^{252}\text{Cf}$	$^{252}\text{Cf}$	$^{248}\text{Cm}$	On Loan To:	
		Content at Calibration ( $\mu\text{g}$ )	Content as of 6-30-73 ( $\mu\text{g}$ )	Content as of 6-30-73 ( $\mu\text{g}$ )	Individual	Site
NS-1 <sup>a</sup>	8-28-68	316	89	b	K. L. Swinth	PNL
NS-2	8-23-68	254	71	b	J. E. Powell	Sandia-NM
NS-3	5-13-69	~90	~30	b	G. I. Gleason	ORAU
NS-4	7-09-69	883	312	545	C. F. Masters	LASL
NS-5 <sup>c</sup>	8-14-69	946	343	575	F. B. Simpson	ANC
NS-6	11-21-69	747	291	435	R. W. Hoff	LLL
NS-7	1-21-70	788	320	446	d	
NS-8	12-17-69	1839	729	1059	H. Berger	ANL
NSD-9	4-17-70	1720	743	931	N. D. Wogman	PNL
NSS-10	3-11-70	113	48	b	J. P. Balagna	LASL
NS-11	3-10-70	8	3	b	R. R. Fullwood	LASL
NSS-12	6-30-70	1868	851	970	R. W. Hoff	LLL
NSD-13	3-19-71	4649	2556	1996	H. O. Menlove	LASL
NSS-14	6-29-70	4615	2102	2397	D. C. Stewart	ANL
NS-15 <sup>c</sup>	6-25-70	931	423	485	F. B. Simpson	ANC
NSD-16	10-08-70	1657	811	807	R. Yoshimura	Sandia-NM
NSS-17	8-31-71	4886	3024	1776	L. W. Dahlke	Sandia-Liv.
NS-18 <sup>c</sup>	6-24-70	962	437	501	F. B. Simpson	ANC
NSS-19	6-26-70	493	224	257	J. E. Bigelow	ORNL-TRU
NSD-20	7-01-70	630	287	327	J. E. Bigelow	ORNL-TRU
NSS-21	10-21-70	18	9	b	F. Cross	PNL
NS-22	9-10-70	13	6	b	d	
NSD-24	10-15-70	8	4	b	J. B. Davidson	ORNL
NS-25	11-09-70	58	29	b	F. J. Muckenthaler	ORNL
NSD-26	2-11-71	14	8	b	H. O. Menlove	LASL
NSD-27	1-29-71	2467	1310	1104	J. E. Powell	Sandia-NM
NSD-28	2-12-71	11	6	b	E. E. Hicks	Rocky Flats
NSD-29	9-10-71	11393	7102	4092	J. D. White	Y-12
NSD-30	3-31-71	879	488	373	F. F. Haywood	ORNL
NZD-31	11-23-71	1756	1154	574	d	
NZD-32	11-23-71	1800	1183	588	d	
NZD-33	11-23-71	1888	1241	617	d	
NZD-34	11-23-71	1924	1265	629	W. G. Spear	Westinghouse-Hanf.
NZD-35	11-23-71	1904	1252	622	d	
NS-36 <sup>c</sup>	3-23-71	2070	1142	885	F. B. Simpson	ANC
NSD-37	9-04-71	9838	6107	3558	R. W. Perkins	PNL
NSD-38	6-16-71	102	60	b	H. O. Menlove	LASL
NS-39	11-07-71	942	612	315	V. Spiegel	NBS
NSD-40	4-27-72	1161	854	293	E. B. Darden	ORNL-Biology

Table 4.1 (continued)

Source	Date of Calibration	$^{252}\text{Cf}$ Content at Calibration ( $\mu\text{g}$ )	$^{252}\text{Cf}$ Content as of 6-30-73 ( $\mu\text{g}$ )	$^{248}\text{Cm}$ Content as of 6-30-73 ( $\mu\text{g}$ )	On Loan To:	
					Individual	Site
NSD-41	11-08-71	5117	3328	1706	C. J. Emert	BAPL
NSD-42	11-02-71	4434	2871	1490	C. J. Emert	BAPL
NSD-43	4-20-72	4839	3540	1239	C. J. Emert	BAPL
NZD-44	5-15-72	10731	7992	2612	F. B. Simpson	ANC
NSD-45	8-18-71	1776	1089	655	K. L. Swinth	PNL
NSD-46	4-23-72	629	461	160	H. O. Menlove	LASL
NSD-47	7-14-71	200	120	77	P. L. Johnson	Mound
NSD-48	7-14-71	194	116	74	P. L. Johnson	Mound
NSD-49	7-14-71	199	119	76	P. L. Johnson	Mound
NS-50	8-23-71	138	85	51	S. G. Carpenter	ANL-NRTS
NSD-51	11-02-71	365	236	123	L. C. Nelson, Jr.	New Brunswick
NSD-52	9-02-71	280	174	102	E. D. Clayton	PNL
NSD-53	10-25-71	1051	677	357	L. J. Esch	KAPL
NS-54	1-19-73	3187	2837	333	V. Spiegel	NBS
NSD-55	4-19-72	4	3	b	L. J. Esch	KAPL
NSD-56	4-19-72	121	88	31	L. J. Esch	KAPL
NSD-57	4-14-72	973	709	252	d	
NZD-58	5-15-72	11003	8194	2679	F. B. Simpson	ANC
NS-59	7-13-72	53	41	b	G. E. Hanson	LASL
NSD-60	4-11-72	20	15	b	J. S. Cheka	ORNL
NSD-61	1-19-73	5225	4652	547	L. J. Esch	KAPL
NSS-62	3-27-73	3765	3517	237	J. E. Bigelow	ORNL-TRU
NSD-63	4-21-72	847	620	227	J. E. Bigelow	ORNL-TRU
SR-Cf-167 <sup>e</sup>	5-26-71	3975	2295	1602	G. I. Gleason	ORAU

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

<sup>b</sup>This source is not suitable for recovery of  $^{248}\text{Cm}$ .

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

<sup>d</sup>This source is available for reissue.

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

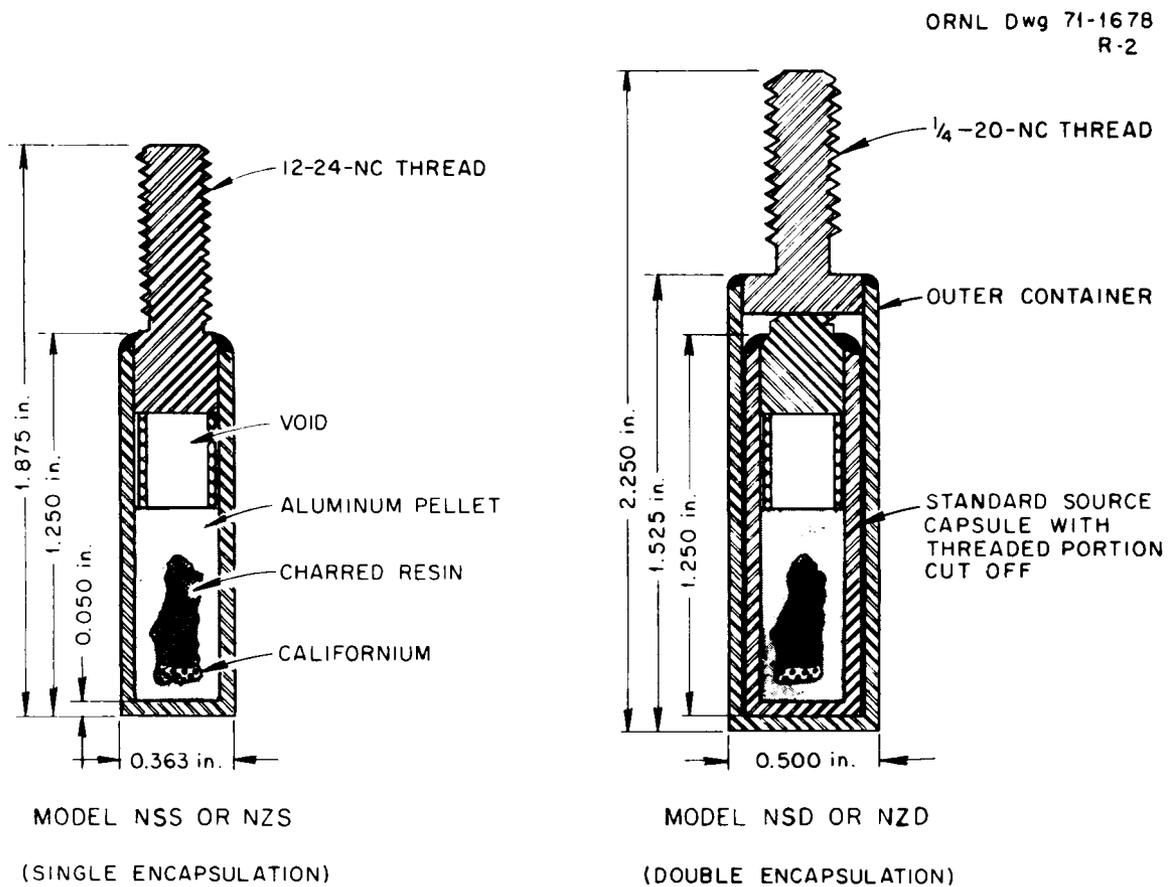


Fig. 4.1. Standard TRU Models for  $^{252}\text{Cf}$  Neutron Sources Encapsulated in Stainless Steel or Zircaloy-2.

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

	Model NSS or NZS	Model NSD or NZD
Degree of encapsulation	Single	Double
Material of outer container	304L SS or Zircaloy-2	304L SS or Zircaloy-2
Source classification		
Stainless steel	III-D	IV-D
Zircaloy-2	III-C	III-C
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

Table 4.3. Classification Test Summary for TRU  
<sup>252</sup>Cf Source Capsule with Single Zircaloy-2 Encapsulation

Manufacturer: Chemical Technology Division,  
 Oak Ridge National Laboratory

Reference drawing: ORNL Dwg. 71-1678 R2

Description: Singly encapsulated <sup>252</sup>Cf source; Zircaloy-2;  
 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	Positive	-
1700°F for 1 hr	Negative	C
-70°F for 24 hr, 500°F for 24 hr	Negative	C
500°F preheat to -32°F chamber in 1 sec, then to -70°F within 15 min	Negative	C
31 fps onto 1/8-in.-diam pin	Negative	III
60 ft-lb impact	Negative	III
10,000-lb shear force	Positive	-
1000-lb shear force	Negative	III
2000-lb crushing force	Negative	III
1000-psi external hydrostatic pressure	Negative	III

Classification assigned: III-C

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

Comments: Failure during Class IV (10,000 lb) shear test occurred at  
 ~7,500-lb force; four capsules used for test series

Table 4.4. Classification Test Summary for TRU  
 $^{252}\text{Cf}$  Source Capsule with Double Zircaloy-2 Encapsulation

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Manufacturer: Chemical Technology Division,  
Oak Ridge National Laboratory

Reference drawing: ORNL Dwg. 71-1678 R2

Description: Doubly encapsulated  $^{252}\text{Cf}$  source; Zircaloy-2;  
0.050-in. wall thickness inner and outer capsule;  
0.50 in. OD by 1.525 in. long exclusive of handling  
attachment

Previous testing: Inner capsule made according to ORNL Dwg. 71-1678 R2  
(single encapsulation) and previously classified as  
Class III-C

Test results:

<u>Conditions</u>	<u>Leak Test</u>	<u>Class</u>
2400°F for 1 hr	Positive	-
10,000-lb shear force	Positive	-

Class III impact, pressure, crushing, and shear tests and Class C maximum temperature, operating temperature, and thermal shock tests are assumed; based on previous tests of the inner capsule alone.

Classification assigned: III-C

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

Comments: Three capsules used for test series

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previously used for this purpose (NSS-19) is getting rather weak. The other two, NSD-61 and NSD-63, were made for others.

Also, we began fabrication of a special californium neutron source, containing 100  $\mu\text{g}$  (nominal) of  $^{252}\text{Cf}$ , for Bettis Atomic Power Laboratory. Two attempts were necessary to make the pellet because it was difficult to load the correct amount of californium into this small source by means of equipment which had been used previously to process hundreds of milligrams of californium. The first attempt yielded a source containing too much  $^{252}\text{Cf}$  (236  $\mu\text{g}$ ); also, the californium was found to be in the wrong position within the pellet. The second attempt produced a pellet which was usable after mechanical alterations were made. This pellet contained 118  $\mu\text{g}$  of  $^{252}\text{Cf}$ . The final configuration of the  $^{252}\text{Cf}$  within the source (as shown by X-radiographs) was an axially centered cylinder, about 0.05 in. in diameter by about 0.15 in. tall.

#### 4.2 Sources Returned

An increasing number of sources are being returned as the projects for which they were requested are completed or as replacement sources are ordered to make up for decay. The returned sources are available for reassignment until the appropriate time for reprocessing to recover the ingrown  $^{248}\text{Cm}$ . Sources that fall in this category are so designated in Table 4.1. The following sources were returned during this report period: NS-7, NZD-31, NZD-32, NZD-33, and NZD-35.

#### 4.3 Neutron Source Calibration

Results obtained in studies relative to the dead time of the neutron counter have convinced us of the validity of the following expression, at least over the range of count rates of interest:

$$A = \frac{C}{1 - \tau C},$$

where  $A$  is the count rate that would be detected by a system with an infinitely fast response,  $C$  is the observed count rate, and  $\tau$  is the effective dead time (i.e., the time required to process an incoming pulse and reset the system so that it is ready to receive another pulse). During the dead time, the counter is not "open for business."

The dead time is conventionally determined by the two-source method<sup>7</sup> in which two sources of nearly equal intensity are counted both individually and together. This method has the disadvantages that (1) the difference between two large numbers is calculated with a great loss of precision, (2) the precision or uncertainty will vary greatly from one determination to the next, thus making it difficult to combine the results of a number of dead-time measurements in a meaningful way, and (3) no suitable way could be found in our work to position two sources in essentially the same location simultaneously.

To circumvent these difficulties, a new method of determining the dead time<sup>8</sup> was devised by Dr. D. M. Levins,\* who is presently a guest scientist at ORNL. Dr. Levins counted a series of different neutron sources containing quantities of  $^{252}\text{Cf}$  ranging from about 200  $\mu\text{g}$  to 40 mg. In each case he determined the count rate in two well-defined source-detector geometries. He then derived a linear relationship between the dead time and the ratio of the count rates in the two geometries, as follows:

in position 1,

$$A_1 = \frac{C_1}{1 - \tau C_1} ;$$

in position 2,

$$A_2 = \frac{C_2}{1 - \tau C_2} .$$

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\* Australian Atomic Energy Commission.

Now, for a given neutron source,  $A_1$  and  $A_2$  are dependent only on the geometry factors associated with the two different positions. Let

$$\frac{A_1}{A_2} = Z .$$

Since  $A_1$  and  $A_2$  are independent of dead time, the ratio  $Z$  will be constant for any source strength or count rate, assuming that the dead-time corrections are made properly. Hence

$$Z = \frac{\frac{C_1}{1 - \tau C_1}}{\frac{C_2}{1 - \tau C_2}}$$

$$\frac{C_1}{1 - \tau C_1} = \frac{Z C_2}{1 - \tau C_2}$$

$$C_1(1 - \tau C_2) = Z C_2(1 - \tau C_1)$$

$$C_1 - \tau C_1 C_2 = Z C_2 - \tau Z C_1 C_2$$

$$C_1 = -\tau Z C_1 C_2 + \tau C_1 C_2 + Z C_2$$

$$\frac{C_1}{C_2} = -\tau Z C_1 + \tau C_1 + Z$$

$$\frac{C_1}{C_2} = -\tau C_1(Z - 1) + Z .$$

Therefore, if our assumptions are good, a plot of  $C_1/C_2$  vs  $C_1$  should yield a straight line with intercept  $Z$  and slope  $-\tau(Z - 1)$ . Such a plot is shown in Fig. 4.2. On this type of plot, all the different determinations of  $C_1/C_2$  were made with about the same standard deviation, and a simple regression analysis yields the result:  $\tau = 9.3 \pm 0.3 \mu\text{sec}$ .

The above dead time was observed for the neutron counters utilized in the Target Decontamination Facility (TDF) when the pulse-shaping time was set to 2  $\mu\text{sec}$ , as it has been throughout our prior use of these counters. However, when the pulse-shaping time was reduced to 1  $\mu\text{sec}$ , the dead time was reduced almost 50%. A shaping time of 1  $\mu\text{sec}$  appears to be about the best compromise in our system between the need to maintain a low dead time at the count rates of interest and the need to provide noise-free amplification of the detector signal. We now routinely use the counters with a shaping time of 1  $\mu\text{sec}$ , which results in a currently measured dead time of  $5.42 \pm 0.76 \mu\text{sec}$ .

The Levins method of determining dead time is a departure from previous procedure.<sup>9</sup> So far, of the calibrations shown in Table 4.1, only those of NSS-62 and NSD-63 have been performed in this manner. We hope to be able to review older data and revise most of the other calibration data for future issues of Table 4.1.

## 5. SPECIAL PROJECTS

The primary functions of TRU are: (1) to fabricate targets for irradiation in the HFIR to produce transuranium elements, and (2) to isolate and purify transuranium elements for use by research workers. However, the facilities that are available 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. The following special projects were undertaken during the current report period.

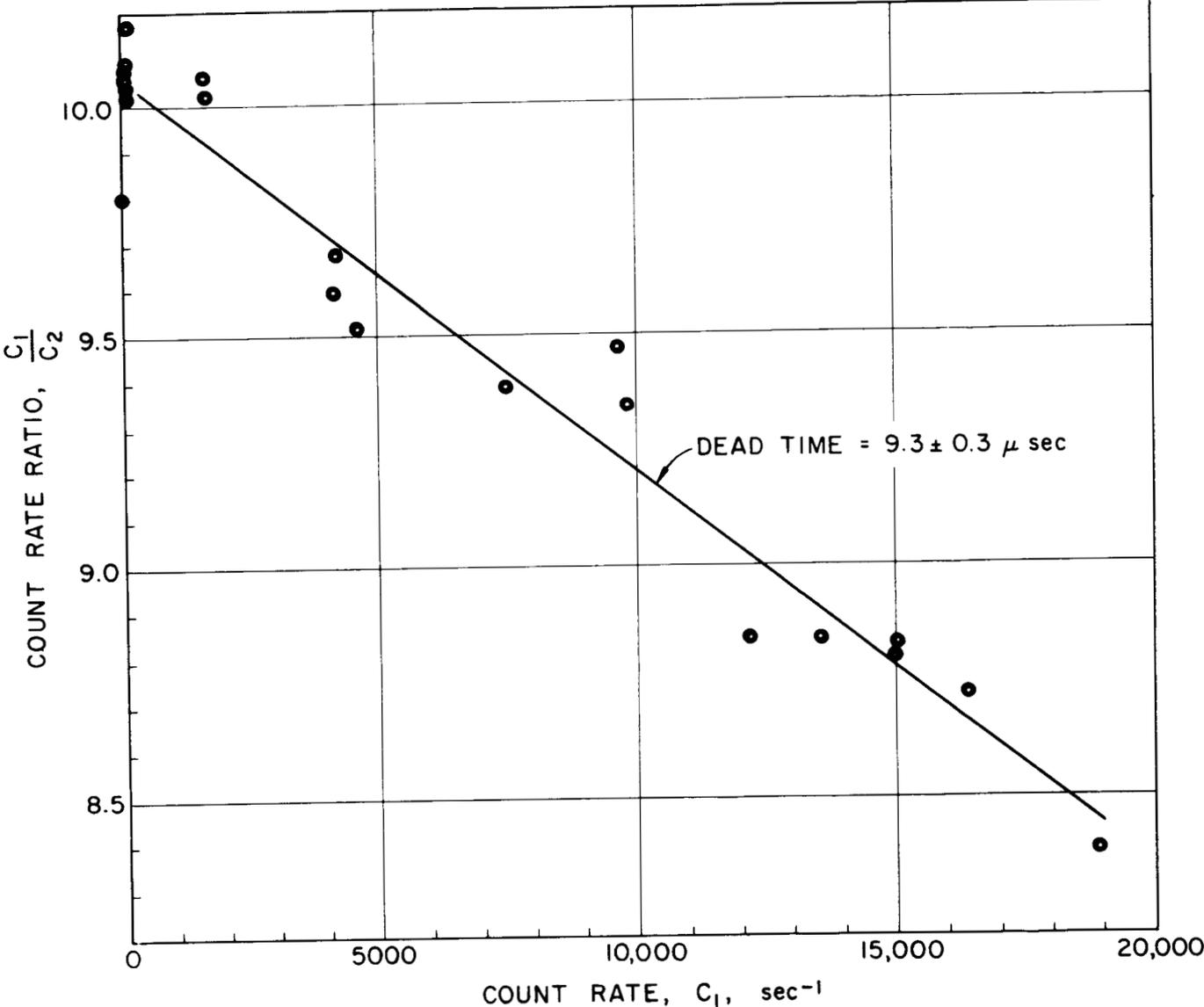


Fig. 4.2. Dead-Time Correlation.

### 5.1 Rabbit Containing $^{253}\text{Es}$

Another einsteinium rabbit was irradiated for ANL. This time approximately 5  $\mu\text{g}$  of  $^{253}\text{Es}$  was sealed in a quartz ampul at ANL and shipped to ORNL. We encapsulated the ampul in a standard aluminum HFIR hydraulic rabbit can, using the glove-box facility at TURF. After it had been irradiated for 24 hr, the capsule was returned by the hydraulic transfer system to TRU, where it was disassembled in Cave B and loaded into a Benelex-lined 6M shipping container. The shipment was routed via Pittsburgh on United Airlines, arriving in Chicago at 7:00 a.m. the following day. The routing that we had used for previous shipments is no longer available for shipping irradiated  $^{253}\text{Es}$  to Chicago because that airline (Delta) will no longer accept Type B packages (such as the 6M container).

### 5.2 Neutron Activation Analysis

The AEC has established a "cooperative californium analytical measurement program" to provide the basis for a more consistent and realistic interpretation of neutron activation analysis systems using  $^{252}\text{Cf}$ . ORNL is one of several AEC laboratories that have set up californium neutron sources to analyze a series of standard solid and liquid samples by neutron activation. The results will be correlated and published by the New Brunswick Laboratory.

The ORNL Analytical Chemistry Division made use of a portion of the  $^{252}\text{Cf}$  inventory that is part of the cow for production of  $^{248}\text{Cm}$ . Three packages containing  $^{252}\text{Cf}$  were seal-welded, decontaminated, and then transferred to the HFIR pool, where they were loaded into a polyethylene block 280 mm in diameter and 280 mm high. A central hole in the block permitted the introduction of a sample for neutron activation. After irradiation, the sample was transported by hand to the counting facility on the experimental floor of the HFIR building.

Calibration data on the packages are:

<u>Package</u>	<u><sup>252</sup>Cf Content (mg)</u>	<u>Date Calibrated</u>
No. 574	34.6	1-30-73
No. 575	24.9	1-30-73
Cow 3	19.5	1-30-73
Total	79.0	

Measurements made with gold and manganese monitors showed the thermal flux in the central hole to be  $1.1 \times 10^9$  neutrons  $\text{cm}^{-2} \text{sec}^{-1}$ ; the thermal-to-resonance ratio was 15.4. This ratio is similar to the value found in <sup>235</sup>U-H<sub>2</sub>O-moderated reactors. Preliminary data for solid samples (0.3 to 0.4 g) showed sensitivities of 11 elements ranging from 0.06  $\mu\text{g}$  for manganese to 150  $\mu\text{g}$  for selenium. These results involved activation times ranging up to 72 hr and counting times up to 2 hr. A substantial portion of the data reduction was performed by an on-line computer.

## 6. REFERENCES

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10. C. M. Lederer, J. M. Hollander, and I. Perlman, Table of Isotopes, 6th ed., Wiley, New York, 1967.
11. 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>10</sup> and Wapstra,<sup>11</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 are footnoted because the half-life value in our table no longer agrees with the value given in the reference. However, we did use the relationship given in the referenced work.

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

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>237</sup> Np		$(2.14 \pm 0.01) \times 10^6$ y		$>10^{18}$ y	2.00 <sup>d</sup>	60Br12, 61Dr04
<sup>238</sup> Np	$2.10 \pm 0.01$ d					50Fr53
<sup>239</sup> Np	$2.359 \pm 0.010$ d					59Co93
<sup>240</sup> Np	$63 \pm 2$ m					60Le03
<sup>240m</sup> Np	$7.3 \pm 0.3$ m					48Hy61
<sup>241</sup> Np	16 m					60Le03
<sup>241m</sup> Np	3.4 h					60Le03
<sup>238</sup> Pu	$87.404 \pm 0.041$ y			$(5 \pm 0.6) \times 10^{10}$ y	$2.33 \pm 0.08$	61Dr04, 68Jo15, 56Hi01
<sup>239</sup> Pu		$(2.4413 \pm 0.003) \times 10^4$ y		$5.5 \times 10^{15}$ y	2.24 <sup>d</sup>	52Se67, 59Ma26
<sup>240</sup> Pu		$6580 \pm 40$ y		$(1.340 \pm 0.015) \times 10^{11}$ y	$2.177 \pm 0.009$	51In03, 62Wa13, 68Bo54
<sup>241</sup> Pu	$14.98 \pm 0.33$ y	$(5.72 \pm 0.1) \times 10^5$ y				68Ca19, 60Br15
<sup>242</sup> Pu		$(3.869 \pm 0.016) \times 10^5$ y		$(7.45 \pm 0.17) \times 10^{10}$ y	$2.166 \pm 0.009$	63Ma50, 69Be06, 68Bo54
<sup>243</sup> Pu	$4.955 \pm 0.003$ h					68Di09
<sup>244</sup> 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
<sup>245</sup> Pu	$10.6 \pm 0.4$ h					56Bu92
<sup>246</sup> Pu	$10.85 \pm 0.02$ d					56Ho23
<sup>241</sup> Am		$432.7 \pm 0.7$ y		$(2.3 \pm 0.8) \times 10^{14}$ y	2.48 <sup>d</sup>	61Dr04, 670e01
<sup>242</sup> Am	$16.01 \pm 0.02$ h		EC/B = 0.19			53Ke38
<sup>242m</sup> Am	$144 \pm 7$ y	$(2.92 \pm 0.15) \times 10^4$ y				59Ba21 <sup>c</sup>
<sup>243</sup> Am		$7370 \pm 40$ y				68Br22
<sup>244</sup> Am	$10.1 \pm 0.1$ h					62Va08
<sup>244m</sup> Am	26 m					54Ga24
<sup>245</sup> Am	$2.07 \pm 0.02$ h					56Bu92
<sup>246</sup> Am	$25.0 \pm 0.2$ m					55En16
<sup>246m</sup> Am	$40 \pm 7$ m					670r02
<sup>247</sup> Am	$24 \pm 3$ m					670r02
<sup>242</sup> Cm	$162.7 \pm 0.1$ d			$7.2 \times 10^6$ y	$2.65 \pm 0.09$	51Ha87, 57Pe52, 56Hi01
<sup>243</sup> Cm		52 y				57As70
<sup>244</sup> Cm	$18.099 \pm 0.015$ y		$\alpha/SF = (7.43 \pm 0.01) \times 10^5$		$2.84 \pm 0.09$	65Me02, 68Be26, 56Hi01
<sup>245</sup> Cm		$8265 \pm 180$ y				69Me01
<sup>246</sup> Cm		$4655 \pm 40$ y	$\alpha/SF = 3822 \pm 10$		3.08 <sup>d</sup>	69Me01, 71Mc19
<sup>247</sup> Cm		$(1.56 \pm 0.05) \times 10^7$ y				71Fi01
<sup>248</sup> Cm		$(3.703 \pm 0.032) \times 10^5$ y		$(4.115 \pm 0.034) \times 10^6$ y	3.32 <sup>d</sup>	71Mc19
<sup>249</sup> Cm	$64 \pm 3$ m					58Ea06
<sup>250</sup> 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		$\left\{ \begin{array}{l} \beta/\alpha = 382 \pm 30 \\ \text{E.C.}/\beta = 0.00078 \pm 0.00006 \end{array} \right.$			62Un01, 63Ph01
<sup>255</sup> Es	39.8 $\pm$ 1.2 d		$\left\{ \begin{array}{l} \alpha/\beta = 0.0866 \pm 0.0043 \\ \beta/\text{SF} = (2.22 \pm 0.10) \times 10^4 \end{array} \right.$		4.16 <sup>d</sup>	66RG01, 67Fi03
<sup>256</sup> Es	25 $\pm$ 3 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 $\mu$ s		$\sim 100\%$ SF			71Hu03

<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.

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,  $\sigma_{2200}^c$ , and the third is the neutron capture resonance integral, RI. The second parameter, C, is a constant that is a function of the target geometry; it is used to estimate the resonance self-shielding effect. The effective capture cross section,  $\sigma_{\text{eff}}^c$ , would be:

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

where N is the number of grams of the particular nuclide in one target rod,  $\phi_{\text{res}}$  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. In the HFIR, the ratio  $\phi_{\text{res}}/\phi_{2200}$  ranges from 0.042 to 0.051. The effective cross section for fission is computed by a similar relationship among the last three parameters.

These cross sections are to be regarded as a self-consistent set whereby one can compute overall transmutation effects, and as a set of arbitrary constants to be used to obtain the best fit to our data. Hopefully, these numbers and the cross sections experimentally measured on pure isotopes will agree; however, we will not allow the possibility of a discrepancy to confine us.

It should be pointed out that  $^{244c}\text{Am}$  is a fictitious isotope which is used to simplify the calculation of the main transmutation chain involving  $^{244}\text{Am}$ . The properties of  $^{244c}\text{Am}$  were calculated from the properties of the

Table A-2. References for Table A-1

Code	Reference	Code	Reference
48Hy01	E. K. Hyde, M. H. Studier, and W. M. Manning, ANL-4143 (April 15, 1948) and ANL-4182 (August 4, 1948).	63Ma50	L. Z. Malkin, I. D. Alkhozov, A. S. Krivokhatskii, and K. A. Petrzhak, <u>At. Energ. (USSR)</u> , <b>15</b> , 158-159 (1963).
50Fr53	M. S. Freedman, A. H. Jaffey, and F. Wagner, Jr., <u>Phys. Rev.</u> , <b>79</b> , 410-411 (1950).	63Ph01	L. Phillips, R. Gatti, R. Brandt, and S. G. Thompson, <u>J. Inorg. Nucl. Chem.</u> , <b>25</b> , 1085-1087 (1963).
51Ha87	G. C. Hanna, B. G. Harvey, N. Moss, and P. R. Tunnicliffe, <u>Phys. Rev.</u> , <b>81</b> , 466-467 (1951).	64As01	F. Asaro, S. Bjornholm, and I. Perlman, <u>Phys. Rev.</u> , <b>133</b> , B291-B300 (1964).
51In03	M. G. Inghram, D. C. Hess, P. R. Fields, and G. L. Pyle, <u>Phys. Rev.</u> , <b>83</b> , 1250 (1951).	64Py02	R. V. Pyle, Unpublished results as reported in E. K. Hyde, "Fission Phenomena," Prentice Hall, Inc. (1964).
52Se67	L. Segrè, <u>Phys. Rev.</u> , <b>86</b> , 21-28 (1952).	65Me02	D. Metta, H. Diamond, R. F. Barnes, J. Milsted, J. Gray, Jr., D. J. Henderson, and C. M. Stevens, <u>J. Inorg. Nucl. Chem.</u> , <b>27</b> , 33-35 (1965).
53Ke38	T. K. Keenan, R. A. Penneman, and B. B. McInteer, <u>J. Chem. Phys.</u> , <b>21</b> , 1802-1803 (1953).	66Fi07	P. R. Fields, A. M. Friedman, J. Milsted, J. Lerner, C. M. Stevens, D. Metta, and W. K. Sabine, <u>Nature</u> , <b>212</b> , 131 (1966).
54Gh24	A. Ghiorso, S. G. Thompson, G. R. Choppin, and B. G. Harvey, <u>Phys. Rev.</u> , <b>94</b> , 1081 (1954).	66RG01	Combined Radiochemistry Group, LRL, LASL, and ANL, <u>Phys. Rev.</u> , <b>148</b> , No. 3, 1192-1198 (1966).
55En16	D. Engelkemeir, P. R. Fields, T. Fried, G. L. Pyle, C. M. Stevens, L. B. Asprey, C. I. Browne, H. Louise Smith, and R. W. Spence, <u>J. Inorg. Nucl. Chem.</u> , <b>1</b> , 345-351 (1955).	66RG04	Argonne Heavy Element Group (unpublished data).
56Bu92	J. P. Butler, T. A. Lastwood, T. L. Collins, M. E. Jones, F. M. Rourke, and R. P. Schuman, <u>Phys. Rev.</u> , <b>103</b> , 634 (1956).	67Fi03	P. R. Fields, H. Diamond, A. M. Friedman, J. Milsted, J. L. Lerner, R. F. Barnes, R. K. Sjolom, D. N. Metta, and E. P. Horwitz, <u>Nucl. Phys.</u> , <b>A96</b> , 440-448 (1967).
56Ch83	G. R. Choppin, B. G. Harvey, D. A. Hicks, J. Ise, Jr., and R. V. Pyle, <u>Phys. Rev.</u> , <b>102</b> , 766 (1956).	670e01	F. L. Oetting and S. R. Gunn, <u>J. Inorg. Nucl. Chem.</u> , <b>29</b> , 2659-2664 (1967).
56Hi01	D. A. Hicks, J. Ise, Jr., and R. V. Pyle, <u>Phys. Rev.</u> , <b>101</b> , 1016-1020 (1956).	670r02	C. J. Orth, W. R. Daniels, B. H. Erkkila, F. O. Lawrence, and D. C. Hoffman, <u>Phys. Rev. Letters</u> , <b>19</b> , No. 3, 128-131 (1967).
56Ho23	D. C. Hoffman and C. I. Browne, <u>J. Inorg. Nucl. Chem.</u> , <b>2</b> , 209 (1956).	67Un01	J. Unik, private communication to P. Fields (1967).
56Jo09	M. Jones, R. P. Schuman, J. P. Butler, G. Cowper, T. A. Lastwood, and H. G. Jackson, <u>Phys. Rev.</u> , <b>102</b> , 203-207 (1956).	68Be21	C. E. Bemis, Jr. and J. Halperin, <u>Nucl. Phys.</u> , <b>A121</b> , 435-439 (1968).
57As70	F. Asaro, S. G. Thompson, F. S. Stephens, Jr., and I. Perlman, <u>Bull. Am. Phys. Soc.</u> , <b>8</b> , 393 (1957).	68Be26	W. C. Bentley, <u>J. Inorg. Nucl. Chem.</u> , <b>30</b> , 2007-2009 (1968).
57Ea01	T. A. Lastwood, J. P. Butler, M. J. Cabell, H. G. Jackson, R. P. Schuman, F. M. Rourke, and T. L. Collins, <u>Phys. Rev.</u> , <b>107</b> , 1635-1638 (1957).	68Bo54	J. W. Boldeman, <u>J. Nucl. Energy</u> , <b>22</b> , 63-72 (1968).
57Pe52	R. A. Penneman, L. H. Treiman, and B. Bevan, as reported by D. C. Hoffman, G. P. Ford, and F. O. Lawrence, <u>J. Inorg. Nucl. Chem.</u> , <b>5</b> , 6-11 (1957).	68Br22	L. C. Brown and R. C. Propst, <u>J. Inorg. Nucl. Chem.</u> , <b>30</b> , 2591-2594 (1968).
58Ea06	T. A. Lastwood and R. P. Schuman, <u>J. Inorg. Nucl. Chem.</u> , <b>6</b> , 261-262 (1958).	68Ca19	M. J. Cabell, <u>J. Inorg. Nucl. Chem.</u> , <b>30</b> , 2583-2589 (1968).
59Ba21	R. F. Barnes, D. J. Henderson, A. L. Harkness, and H. Diamond, <u>J. Inorg. Nucl. Chem.</u> , <b>9</b> , 105-107 (1959).	68Di09	H. Diamond, J. J. Hines, R. K. Sjolom, R. F. Barnes, D. N. Metta, J. L. Lerner, and P. R. Fields, <u>J. Inorg. Nucl. Chem.</u> , <b>30</b> , 2553-2559 (1968).
59Co93	D. Cohen, J. C. Sullivan, and A. J. Zielen, <u>J. Inorg. Nucl. Chem.</u> , <b>11</b> , 159-161 (1959).	68Ho13	R. W. Hoff, J. E. Evans, E. K. Hulet, R. J. Dupzyk, and B. J. Qualheim, <u>Nucl. Phys.</u> , <b>A115</b> , 225-233 (1968).
59Ma26	T. L. Markin, <u>J. Inorg. Nucl. Chem.</u> , <b>9</b> , 320-322 (1959).	68Jo15	K. C. Jordan, MLM-1443, 11-30 (1968).
59Va02	S. E. Vandenbosch, H. Diamond, R. K. Sjolom, and P. R. Fields, <u>Phys. Rev.</u> , <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, <u>J. Inorg. Nucl. Chem.</u> , <b>12</b> , 234-235 (1960).	68Wh04	P. H. White and E. J. Axton, <u>J. Nucl. Energy</u> , <b>22</b> , 73-77 (1968).
60Br15	F. Brown, G. G. George, D. E. Green, and D. E. Watt, <u>J. Inorg. Nucl. Chem.</u> , <b>13</b> , 192-195 (1960).	69Be06	C. E. Bemis, Jr., J. Halperin, and R. Eby, <u>J. Inorg. Nucl. Chem.</u> , <b>31</b> , 599-604 (1969).
60Le03	R. M. Lessler and M. C. Michel, <u>Phys. Rev.</u> , <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. Perelygin, and G. I. Khibnikov, <u>Sov. Phys. JETP</u> , <b>13</b> , 913-914 (1961).	69Me01	D. N. Metta, H. Diamond, and F. R. Kelly, <u>J. Inorg. Nucl. Chem.</u> , <b>31</b> , 1245-1250 (1969).
62Un01	J. Unik, P. Day, and S. Vandenbosch, <u>Nucl. Phys.</u> , <b>36</b> , 284-304 (1962).	69Mi08	J. Milsted, E. P. Horwitz, A. M. Friedman, and D. N. Metta, <u>J. Inorg. Nucl. Chem.</u> , <b>31</b> , 1561-1569 (1969).
62Va08	S. E. Vandenbosch and P. Day, <u>Nucl. Phys.</u> , <b>30</b> , 177-190 (1962).	70Lo19	R. W. Loughheed, J. E. Evans, and E. K. Hulet, private communication to J. E. Bigelow (1970).
62Wa13	D. E. Watt, F. J. Bannister, J. B. Laidler, and F. Brown, <u>Phys. Rev.</u> , <b>126</b> , 264-265 (1962).	71Fi01	P. R. Fields, I. Ahmad, A. M. Friedman, J. Lerner, and D. N. Metta, <u>Nucl. Phys.</u> , <b>A160</b> , 460-770 (1971).
		71Hu03	E. K. Hulet, J. F. Wild, R. W. Loughheed, J. E. Evans, B. J. Qualheim, M. Nurmia, and A. Ghiorso, <u>Phys. Rev. Letters</u> , <b>26</b> , 523 (1971).
		71Mc19	J. E. McCracken, J. R. Stokely, R. D. Baybarz, C. E. Bemis, Jr., and R. Eby, <u>J. Inorg. Nucl. Chem.</u> , <b>33</b> , 3251-3259 (1971).

Table A-3. Properties<sup>a</sup> of Transuranium Nuclides

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)	( $\mu$ g)
<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>5</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>		7 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	0.653
<sup>240</sup> Pu	6580 y	5.16		0.227	7.097 x 10 <sup>-3</sup>	2.57 x 10 <sup>8</sup>		53.7	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>		95.3	2 x 10 <sup>-12</sup>	0.05	13.1
<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>	7.0	2.69 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	2.26 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	2.48 x 10 <sup>-6</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	1.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>				
<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>	0.2	6.76 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>				
<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	1.51 x 10 <sup>-5</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	5.81		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	0.226
<sup>246</sup> Cm	4655 y	5.39		0.312	1.01 x 10 <sup>-2</sup>	3.52 x 10 <sup>8</sup>		5.58 x 10 <sup>5</sup>	5 x 10 <sup>-12</sup>	0.05	0.160
<sup>247</sup> Cm	1.56 x 10 <sup>7</sup> y	4.87		9.28 x 10 <sup>-5</sup>	2.94 x 10 <sup>-6</sup>	1.05 x 10 <sup>5</sup>			5 x 10 <sup>-12</sup>	0.04	431
<sup>248</sup> Cm	3.397 x 10 <sup>5</sup> y	5.05		4.24 x 10 <sup>-3</sup>	5.34 x 10 <sup>-4</sup>	4.39 x 10 <sup>6</sup>		2.58 x 10 <sup>6</sup>	6 x 10 <sup>-13</sup>	0.005	1.18
<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>		1 x 10 <sup>-5</sup>	1.0	8.47 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>			

Table A-3 (continued)

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

<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 ICRP Publication 6, "Recommendations of the International Commission on Radiological Protection" (1964).

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

<sup>d</sup><sup>242</sup>Am decays by β emission (84%) and orbital 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 β emission, but 0.039% decays by electron capture to <sup>244</sup>Pu.

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

Nuclide	Half-Life	Capture			Fission		
		2200-m/s Cross Section (barns)	Resonance Self-Shielding Constant	Resonance Integral (barns)	2200-m/s Cross Section (barns)	Resonance Self-Shielding Constant	Resonance Integral (barns)
<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	19.5	6.20	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	105	0	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	10.0	4.0	650	1.2	4.0	12.5
<sup>245</sup> Cm	8265 y	343	2.4	120	1727	2.4	1140
<sup>246</sup> Cm	4655 y	1.25	0	121	0	0	0
<sup>247</sup> Cm	1.56 x 10 <sup>7</sup> y	60	0	500	120	0	1060
<sup>248</sup> Cm	3.397 x 10 <sup>5</sup> y	3.56	2.0	170	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>251</sup> Bk	57 m	0	0	0	0	0	0
<sup>249</sup> Cf	352 y	450	1.46	750	1690	5.8	2920
<sup>250</sup> Cf	13.08 y	1900	20	11600	0	0	0
<sup>251</sup> Cf	900 y	2850	14	1600	3750	14	5400
<sup>252</sup> Cf	2.646 y	19.8	0	44	32	0	110
<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 $\mu$ s	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.

real isomers  $^{244g}\text{Am}$  and  $^{244m}\text{Am}$  by assuming that: (1) the number of atoms of  $^{244c}\text{Am}$  present equals the total number of atoms of the real isomers; (2) the  $\beta$  decay from  $^{244c}\text{Am}$  equals the total  $\beta$  decay from the real isomers; (3) the fissions from  $^{244c}\text{Am}$  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,

$$\begin{aligned}
 (1) \quad N_c &= N_g + N_m, \\
 (2) \quad \lambda_c N_c &= \lambda_g N_g + \lambda_m N_m, \\
 (3) \quad \sigma_c^f N_c &= \sigma_g^f N_g + \sigma_m^f N_m, \\
 (4) \quad \frac{dN_c}{dt} &= \frac{dN_g}{dt} = \frac{dN_m}{dt} = 0, \text{ and} \\
 (5) \quad (\lambda_i + \sigma_i^a \phi) N_i &= f_i \sigma_i^c N_{243},
 \end{aligned}$$

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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