



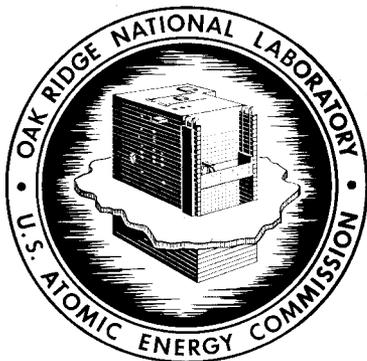
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ORNL-4428
UC-80 – Reactor Technology

TRANSURANIUM PROCESSING PLANT
SEMIANNUAL REPORT OF PRODUCTION,
STATUS, AND PLANS
FOR PERIOD ENDING DECEMBER 31, 1968

W. D. Burch
J. E. Bigelow
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OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

Printed in the United States of America. Available from Clearinghouse for Federal
Scientific and Technical Information, National Bureau of Standards,
U.S. Department of Commerce, Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

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ORNL-4428

Contract No. W-7405-eng-26

CHEMICAL TECHNOLOGY DIVISION

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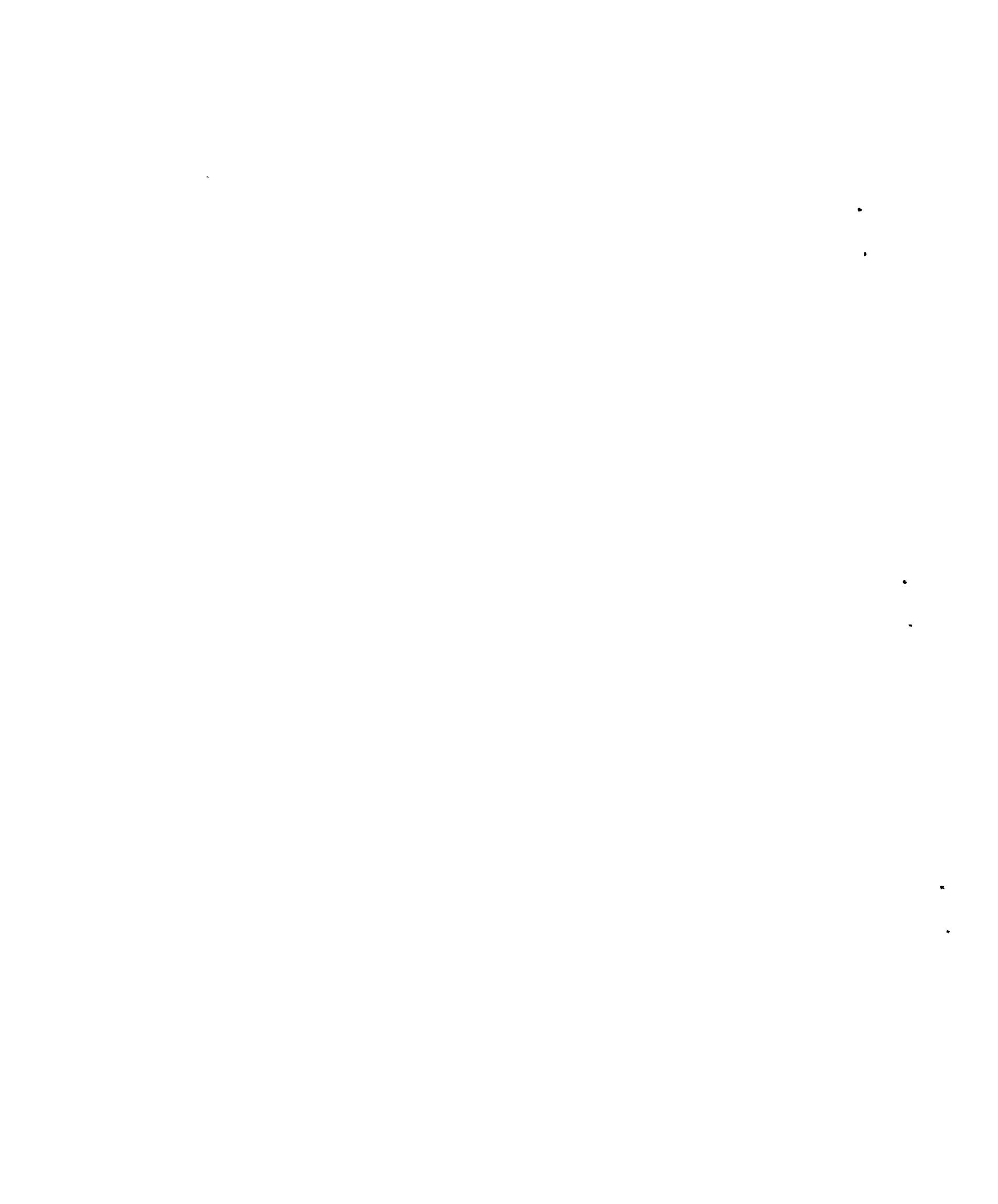
NOVEMBER 1969

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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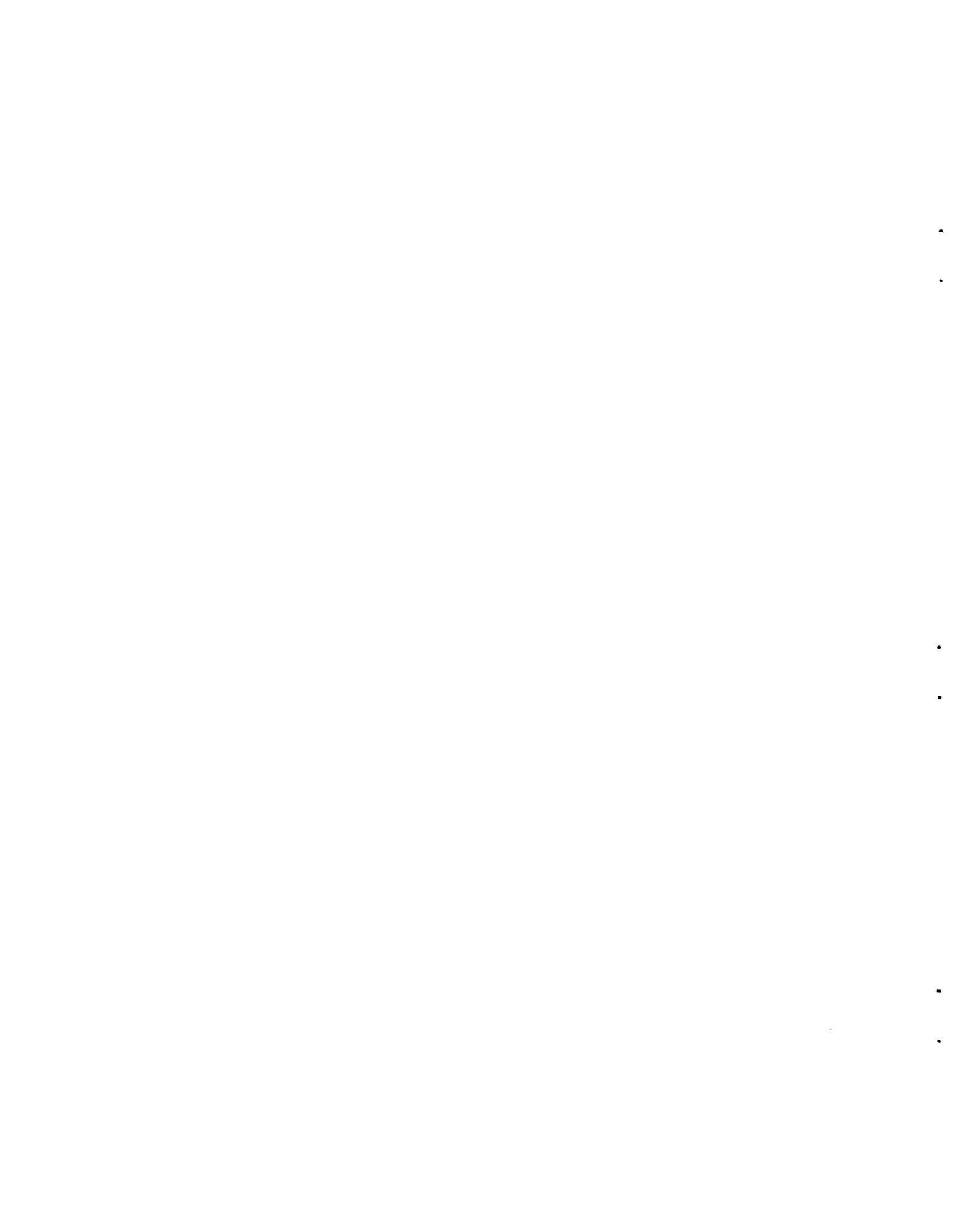


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CONTENTS

	Page
Summary	v
1. Introduction	1
2. Processing Summary and Production Estimate	1
2.1 Processing Summary	2
2.2 Irradiation and Processing Proposals	7
2.3 Estimates of the Availability of Transuranium Elements	9
3. Processes and Equipment	10
3.1 Target Dissolution	12
3.2 Recovery of Plutonium	13
3.3 First-Cycle Solvent Extraction Process (Tramex)	13
3.4 Partitioning of Actinides	13
3.5 Separation of Transcurium Elements	14
3.6 Preparation of Actinide Oxides	16
3.7 Fabrication of Targets	16
3.8 Irradiation of ^{252}Cf to Produce ^{253}Es	16
3.9 Analysis of ^{252}Cf by Neutron Activation of Aluminum	20
3.10 HFIR Target Rod Failures	21
4. Special Projects	21
4.1 Einsteinium Rabbits	21
4.2 Fabrication of a Neutron Source Using Californium	22
4.3 Curium for Isotope Separation	22
5. References	24
6. Appendix	25



SUMMARY

This report is the second in a series that is being issued semiannually 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.

The total amounts of transuranium elements processed during the period July 1, 1968, to December 31, 1968, are (approximately): 17 g of ^{242}Pu , 90 g of ^{243}Am , 141 g of ^{244}Cm , 7 mg of ^{252}Cf , 1 mg of ^{249}Bk , 49 μg of ^{253}Es , and 10^8 atoms of ^{257}Fm . We made 50 shipments, which totaled: 9.26 g of ^{243}Am , 22 g of ^{244}Cm , 93 μg of ^{248}Cm , 855 μg of ^{249}Bk , 48 μg of isotopically pure ^{249}Cf , 18 μg of ^{250}Cf (72 μg total californium), 3.2 mg of ^{252}Cf , 4.5 μg of isotopically pure ^{253}Es , 31.5 μg of ^{253}Es containing some ^{254}Es and ^{255}Es , and 7×10^7 atoms of ^{257}Fm .

We anticipate the production of about 4.7 mg of ^{249}Bk , 48 mg of ^{252}Cf , 507 μg of ^{253}Es , and 7×10^8 atoms of ^{257}Fm during the next eighteen months. We expect to produce a total of about 1 g of californium by about 1973.

The processes and equipment that are used in TRU are being modified from time to time as our knowledge increases. The current sequence of process steps is as follows: (1) a feed solution is prepared by dissolving irradiated targets; (2) the plutonium is recovered using a batch solvent extraction process (Pubex); (3) the transplutonium elements are decontaminated from fission products by countercurrent solvent extraction (Tramex); (4) the americium and curium are separated from the transcurium elements by ion exchange or solvent extraction; (5) the transcurium elements are separated from each other by chromatographic elution with α -hydroxyisobutyrate from a high-pressure ion exchange column; (6) the plutonium, americium, and curium are converted to oxide microspheres, using

a sol-gel technique; and (7) the microspheres are fabricated into HFIR targets, by remote means, for reirradiation to produce more transcurium elements.

We were able to increase the yield of ^{253}Es from ^{252}Cf irradiations by fabricating the californium into rabbits instead of our usual targets. This type of assembly permits irradiation of any duration while the reactor is at full power. For example, we can irradiate the californium for 2 to 3 days to approach the equilibrium ^{253}Cf content and then withdraw the rabbit for 10 to 18 days to allow the ^{253}Cf to decay to ^{253}Es .

We are developing a nondestructive method for assaying the ^{252}Cf content of neutron sources and californium shipping containers. Weighed aluminum discs are activated by fast neutrons emitted by ^{252}Cf and then assayed by gamma-ray spectrometry for the activation product, ^{24}Na . Although we need to improve the calibration of the method, the precision is excellent for sources containing more than a few hundred micrograms of ^{252}Cf .

No additional target failures have occurred in the HFIR even though a number of targets have been irradiated to higher burnups than we had estimated would be needed to cause failure.

The services available at TRU are used to prepare special materials that are not normally produced in main-line efforts. Four rabbits containing ^{253}Es were prepared and irradiated in the HFIR to produce 39.3-hr $^{254\text{m}}\text{Es}$ for use at ANL in studying the energy level structure of the decay product, ^{250}Bk . A neutron source containing 400 μg of ^{252}Cf was fabricated for the Health Physics Division at ORNL to be used in measuring the gamma and neutron leakage from duplicates of the first atomic bombs exploded in World War II.

The values that we use 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 report is the second in a series¹ that is being issued semiannually 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.

TRU operations during the report period are summarized. Quantities of materials that were produced, processed, and shipped are specified, and proposed processing schedules and anticipated yields of various products are presented. The Appendix contains a tabulation of the values of nuclear parameters which were used as input data for calculations of production rates for transuranium elements; a tabulation of the parameters which were used to calculate the specific activities of the isotopes that are of interest to TRU is also included. Special processing, fabrication, and irradiation programs are described.

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 that we usually handle. Thus we usually trace curium by the isotope ^{244}Cm . Except in special instances, ^{242}Pu , ^{243}Am , ^{249}Bk , ^{252}Cf , and ^{253}Es are the isotopes used for tracing the corresponding elements. Throughout this report, we are discussing mixtures of isotopes when we do not stipulate "isotopically pure."

2.1 Processing Summary

Two major processing campaigns were carried out during the past six months (Table 2.1): (1) We completed the processing of a raffinate solution that resulted from plutonium recovery processing at the Savannah River Plant (SRP). About 275 μg of californium of unusual isotopic composition (48% ^{249}Cf , 25% ^{250}Cf , 9% ^{251}Cf , and 18% ^{252}Cf) was recovered. A mixture of about 90 g of ^{243}Am and 100 g of ^{244}Cm is being stored for use in fabricating targets for irradiation in the HFIR. (2) We recovered 17 g of ^{242}Pu , 40 g of ^{244}Cm , 1.2 mg of ^{249}Bk , 6 mg of ^{252}Cf , 30 μg of ^{253}Es , and 7×10^7 atoms of ^{257}Fm as purified products from 14 irradiated HFIR targets.²

Fifty shipments, which were made from TRU (see Table 2.2) during this period, included: (1) 9.26 g of ^{243}Am and 18.85 g of ^{244}Cm that had been separated and purified; (2) 1.0 g of ^{244}Cm that contained about 4% ^{245}Cm and 2.32 g of ^{244}Cm that contained about 10% ^{246}Cm (shipped to the Y-12 Plant for separation of the heavy curium isotopes); (3) 93 μg of ^{248}Cm (approximately 35% ^{248}Cm); (4) 855 μg of ^{249}Bk ; (5) 48 μg of ^{249}Cf (isotopically pure) that had been "milked" from ^{249}Bk ; (6) 18 μg of ^{250}Cf (72 μg of total californium) which was recovered from the long-decayed SRP raffinate solution; (7) 2.4 mg of ^{252}Cf in a mixture of californium isotopes (75 to 80% ^{252}Cf); (8) 750 μg of ^{252}Cf that had been irradiated to 99% ^{252}Cf ; (9) 4.5 μg of ^{253}Es (isotopically pure) that had been "milked" from californium; (10) 31.5 μg of ^{253}Es containing some ^{254}Es ; and (11) 7×10^7 atoms of ^{257}Fm .

As of December 31, 1968, our inventory of transuranium materials (exclusive of HFIR targets) was as follows: 103 g of ^{242}Pu , 183 g of ^{243}Am , 222 g of ^{244}Cm , 0.3 mg of ^{249}Bk , 2.5 mg of ^{252}Cf , and 7 μg of ^{253}Es .

Table 2.1. Amounts of Materials Processed During
Major Campaigns in the Transuranium Processing Plant
During the Period July 1, 1968, to December 31, 1968

Listed values are measurements or estimates of feed solutions

Campaign Number	9	10 and 11
Completion date	December 1968	September 1968
Material processed	Remainder of SRP solution	14 HFIR targets
Amounts processed		
^{242}Pu , g ^a	--	17.1
^{243}Am , g ^a	90	--
^{244}Cm , g ^a	100	40.6
^{249}Bk , mg	--	1.4
^{252}Cf , mg	b	6.9
^{253}Es μg	--	49

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

^b275 μg of total californium was recovered (48% ^{249}Cf , 25% ^{250}Cf , 9% ^{251}Cf , and 18% ^{252}Cf).

Table 2.2. Distribution of Heavy Elements from the
Transuranium Processing Plant During the Period July 1, 1968,
to December 31, 1968

Major Nuclide	Date	Shipped To	
		Individual	Site
<u>Americium-243, g</u>			
7.18	12-6-68	L. L. Burger	PNL
2.08	12-6-68	R. W. Hoff	LRL-L
<u>9.26</u>			
<u>Curium-244, g</u>			
4.83	7-12-68	R. W. Hoff	LRL-L
4.10	7-18-68	R. D. Kelsch	SRL
0.02	8-19-68	M. Abraham	ORNL-Solid State
9.90	11-13-68	R. W. Hoff	LRL-L
<u>18.85</u>			
<u>Curium-244 (high ^{245}Cm content), g</u>			
0.10	9-11-68	Stable Isotopes	ORNL
0.18	9-16-68	Stable Isotopes	ORNL
0.18	9-19-68	Stable Isotopes	ORNL
0.18	9-25-68	Stable Isotopes	ORNL
0.18	9-27-68	Stable Isotopes	ORNL
0.18	10-03-68	Stable Isotopes	ORNL
<u>1.00</u>			
<u>Curium-244 (high ^{246}Cm content), g</u>			
0.33	8-28-68	Stable Isotopes	ORNL
0.48	11-05-68	Stable Isotopes	ORNL
0.48	11-07-68	Stable Isotopes	ORNL
1.03	11-19-68	Stable Isotopes	ORNL
<u>2.32</u>			
<u>Curium-248, μg</u>			
93 ($\sim 35\%$ ^{248}Cm)	8-01-68	C. E. Bemis	ORNL-TRL

Table 2.2 (continued)

Major Nuclide	Date	Shipped To	
		Individual	Site
<u>Berkelium-249, μg</u>			
140	8-14-68	P. Fields	ANL
140	8-14-68	M. L. Hyder	SRL
155	8-14-68	R. A. Penneman	LASL
140	8-14-68	R. W. Hoff	LRL-L
140	8-14-68	B. Cunningham	LRL-B
<u>140</u>	8-14-68	R. D. Baybarz	ORNL-Chem. Tech.
855			
<u>Californium-249 (isotopically pure), μg</u>			
48	10-11-68	A. Ghiorso	LRL-B
<u>Californium-250, μg</u>			
18 (72 μg total Cf)	7-12-68	A. Ghiorso	LRL-B
<u>Californium-252, μg</u>			
420	8-27-68	J. A. Auxier	ORNL-HP
10	9-03-68	Isotopes Sales	ORNL
1.5	9-16-68	Production Support	ORNL-TRU
900	9-30-68	A. R. Boulogne	SRL
3.6	10-03-68	M. L. Perlman	BNL
20	10-03-68	E. D. Clayton	PNL
200	10-04-68	P. Fields	ANL
10	10-10-68	Production Support	ORNL
10	10-30-68	Isotopes Sales	ORNL
533	11-13-68	R. A. Latimer	LRL-B
1	11-14-68	R. L. Ferguson	ORNL-Chemistry
319	11-26-68	R. F. Barnes	ANL
0.8	12-07-68	B. Weaver	ORNL-Chem. Tech.
<u>6</u>	12-07-68	Isotopes Sales	ORNL
2434.9			
<u>Californium-252 (irradiated to 99% ^{252}Cf), μg</u>			
750	7-18-68	Production Support	ORNL

Table 2.2 (continued)

Major Nuclide	Date	Shipped To	
		Individual	Site
<u>Einsteinium-253</u> (isotopically pure), μg			
1.8	8-12-68	R. D. Baybarz	ORNL-Chem. Tech.
0.9 (irradiated)	9-03-68	H. Diamond	ANL
0.9 (irradiated)	9-23-68	H. Diamond	ANL
0.9 (irradiated)	10-28-68	H. Diamond	ANL
<u>4.5</u>			
<u>Einsteinium-253, μg</u>			
26	7-26-68	R. A. Latimer	LRL-B
2.0	8-12-68	P. Fields	ANL
2.5	8-12-68	B. Silva	ORNL-TRL
1.0	8-12-68	L. Nugent	ORNL-TRL
<u>31.5</u>			
<u>Fermium-257, atoms</u>			
6×10^7	7-25-68	E. K. Hulet	LRL-L
1×10^7	8-01-68	C. E. Bemis	ORNL-TRL
7×10^7			

2.2 Irradiation and Processing Proposals

The estimated future production rates of transcurium elements are given in Table 2.3. The estimate for californium is based on the assumption that 80% of all of the curium isotopes that are recovered during each processing campaign are recycled to the HFIR for transcurium element production. The other 20% has been assumed to be accounted for through product shipments (which include, in some cases, mass separation in the calutrons to concentrate heavy isotopes) and processing losses.

Six americium-curium targets will be processed in March 1969, after an eight-month irradiation period. Each target originally contained 4.4 g of ^{244}Cm , 0.3 g of heavier curium isotopes, and 0.8 g of ^{243}Am . We expect to recover 0.8 mg of ^{249}Bk , 8 mg of ^{252}Cf , and 61 μg of ^{253}Es as purified products.

At about the same time, we expect to obtain about 18 μg of einsteinium from the irradiation of 2.3 mg of ^{252}Cf in the HFIR hydraulic rabbit facility.

In August 1969 we will process six plutonium targets that will have been irradiated for two years. We expect to recover 0.7 mg of ^{249}Bk , 5 mg of ^{252}Cf , and a total of 29 μg of ^{253}Es . About 48 μg of ^{253}Es will also be produced during August 1969 from the irradiation of ^{252}Cf in the HFIR hydraulic rabbit facility. The use of the rabbit facility for making short irradiations is important because the effective half-life of ^{253}Cf (the parent of ^{253}Es) in the reactor is only 2.1 days due to its high fission cross section.

In December 1969 we expect to process nine plutonium targets and recover 0.9 mg of ^{249}Bk , 6 mg of ^{252}Cf , and 35 μg of ^{253}Es . About 75 μg of ^{253}Es will be produced during December 1969 from the irradiation of ^{252}Cf in the HFIR hydraulic rabbit facility.

The curium from six targets that will be processed in March 1969 will be used to fabricate two third-cycle targets. We expect to recover about 1 mg of ^{249}Bk , 15 mg of ^{252}Cf , and 86 μg of ^{253}Es from these targets in April 1970. This particular curium will be a very fertile source of transcurium elements because it will be rich in ^{246}Cm and ^{248}Cm . Also,

Table 2.3. Estimated Future Production of Transcurium Elements

Period	Processing Campaign	Products of Campaigns			252Cf Production		Date Products Available
		249Bk (mg)	252Cf (mg)	253Es ^a (μg)	In Period (mg)	Cumulative (mg)	
Through December 1968						11	
January - June 1969	6 Cm targets (second cycle) Hydraulic rabbits (Cf irradiation)	0.8 --	8 --	49(12) 12(6)			March 1969 March 1969
July - December 1969	6 Pu targets ^b Hydraulic rabbits (Cf irradiation)	0.7 --	5 --	25(4) 32(16)			August 1969 August 1969
	9 Pu targets ^b Hydraulic rabbits (Cf irradiation)	0.9 --	6 --	30(5) 50(25)	11	30	December 1969 December 1969
January - June 1970	2 Cm targets ^c (third recycle) 6 Pu targets ^b Hydraulic rabbits (Cf irradiation)	1.0 1.3 --	15 14 --	75(11) 70(10) 50(25)			April 1970 April 1970 April 1970
July - December 1970					75	134	
1971					150	284	
1972					300	584	
1973					450	1034	
1974					600	1634	

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

^bEach of the targets originally contained 8 g of plutonium (95.7% ²⁴²Pu) as PuO₂.

^cThese targets will contain unburned curium from the 6 Cm targets to be processed in March 1969.

in April 1970, about 1.3 mg of ^{249}Bk , 14 mg of ^{252}Cf , and 80 μg of ^{253}Es will be recovered from six plutonium targets that were specially fabricated in 1967 to determine whether lower amounts of actinides per target, and/or lower pellets densities, would prevent target rupture during irradiation. At the time of their dissolution, the six targets will have been irradiated two full-power years. About 75 μg of ^{253}Es will be produced during April 1970 from the irradiation of ^{252}Cf in the HFIR hydraulic rabbit facility.

2.3 Estimates of the Availability of Transuranium Elements

Although plutonium, americium, and curium are usually considered to be intermediate feed materials rather than products, we routinely purify and distribute isotopes of these elements (primarily ^{242}Pu , ^{243}Am , and ^{244}Cm). We expect to provide only small quantities of the heavy curium isotopes, ^{246}Cm , ^{247}Cm , and ^{248}Cm , for experimental work since these isotopes are very fertile feed materials for the production of transcurium elements. The removal of a large fraction of the available heavy curium isotopes from the production line would result in a drastic reduction in the production rate of transcurium elements.

2.3.1 Berkelium

About 4.7 mg of ^{249}Bk will be available during the next 18 months: 0.8 mg in March 1969, 0.7 mg in August 1969, 0.9 mg in December 1969, and 2.3 mg in April 1970. It would be possible to increase the rate of production of berkelium if irradiation-processing schedules were optimized for the production of berkelium instead of californium. However, this would considerably decrease the availability of californium.

2.3.2 Californium

We expect to produce 48 mg of mixed californium isotopes (about 80% ^{252}Cf) during the next 18 months: 8 mg in March 1969, 11 mg in the last half of 1969, and 29 mg in April 1970.

The production of isotopically pure ^{249}Cf by "milking" ^{249}Bk is not anticipated in the next 18 months because we expect to ship all of the berkelium as soon as it becomes available.

2.3.3 Einsteinium

We expect to recover 61 μg of ^{253}Es (about 0.3% ^{254}Es and 0.06% ^{255}Es) in March 1969, 57 μg in August 1969, 80 μg in December 1969, and 195 μg in April 1970. These amounts will come from both HFIR targets and rabbits irradiated in the HFIR hydraulic rabbit facility.

After the mixture of einsteinium isotopes has been separated from the purified californium, the latter will be stored to allow ^{253}Es to grow in from the decay of ^{253}Cf ; then the second-growth ^{253}Es will be recovered. About 18, 20, 30, and 46 μg of isotopically pure ^{253}Es will be "milked" from the californium that will be isolated in March 1969, August 1969, December 1969, and April 1970 respectively.

2.3.4 Fermium

Approximately 1.5×10^7 atoms of ^{257}Fm per milligram of ^{252}Cf will be present in each batch of californium that will be recovered. Thus, about 7.2×10^8 atoms will be produced during the next 18 months: 1.2×10^8 atoms in March 1969, 1.7×10^8 atoms in the last half of 1969, and 4.3×10^8 atoms in April 1970.

3. PROCESSES AND EQUIPMENT

The processes and equipment that are used in TRU are modified from time to time as our knowledge increases. These modifications range from trivial changes (i.e., changing the concentration of a process stream) to significant ones (i.e., using a completely new process to perform one of the processing steps).

Figure 3.1 is a block diagram showing the processing steps that are required for transuranium element production. These steps are: (1) the

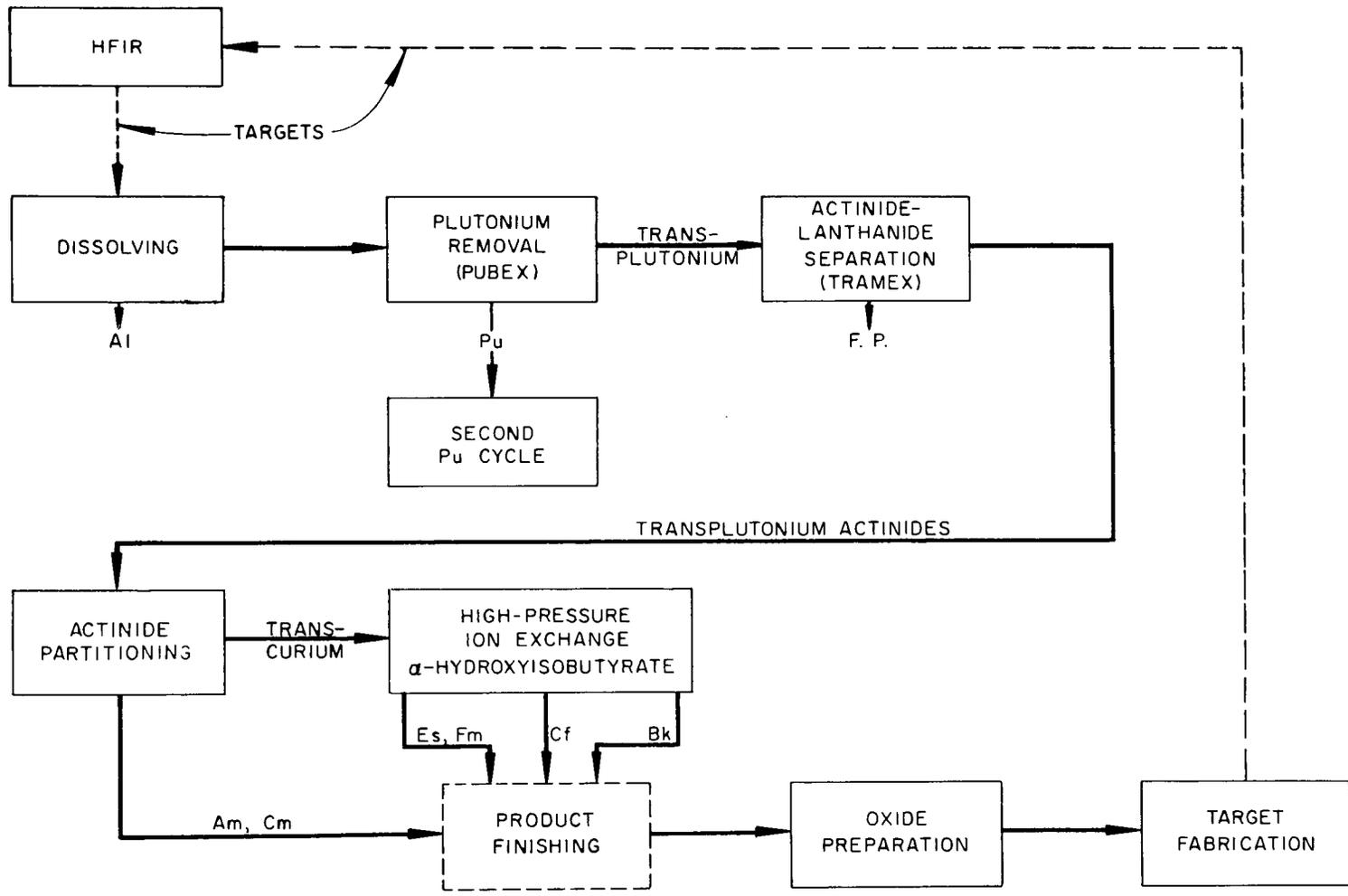


Fig. 3.1. Processing Steps Used for Transuranium Element Production.

preparation of a feed solution by dissolving irradiated targets; (2) the recovery of plutonium; (3) the decontamination of the transplutonium elements; (4) the separation of americium and curium from the transcurium elements; (5) the separation and purification of berkelium, californium, einsteinium, and fermium; (6) the preparation of americium-curium oxide microspheres by a sol-gel process; and (7) the fabrication of targets to be irradiated in the HFIR.

The first four processing steps, plus target fabrication, are being performed routinely in the main TRU operating facilities. Plant-scale equipment for making americium-curium oxide microspheres has been installed and is ready for in-cell testing. The separation and purification of the transcurium elements are being carried out in equipment that is installed in the chemical development cell (cell 5) in TRU. Product finishing operations and special separations are being performed in cell 5 and in supporting shielded cave facilities.

3.1 Target Dissolution

The target dissolution procedure was modified slightly to prevent corrosion of the Zircaloy-2 dissolver, T-70, by the radioactive HCl solutions. Measurements that were made during campaigns, plus laboratory tests, had indicated that Zircaloy-2 corrosion rates were as high as 60 mils/year in 6 M HCl at a solution power density (from alpha decay) of 37 w/liter, which is typical for dissolver solutions.

In the new dissolution procedure, the aluminum (jackets and matrix material) was dissolved as usual in T-70 using 6 M NaOH--3 M NaNO₃ solution. Then, instead of dissolving the residue of actinide oxides by adding 6 M HCl to T-70, which is made of Zircaloy-2, we slurried the oxides in water by vigorous air sparging and subsequently transferred them to a tantalum-lined tank for the acid dissolution step.

Fourteen targets, each of which originally contained 8 g of PuO₂ (95.7% ²⁴²Pu), were dissolved during this reporting period by using this new procedure.

3.2 Recovery of Plutonium

No further changes have been made in the Pubex extraction process, which is used for recovering plutonium. The plutonium is extracted into 1 M di(2-ethylhexyl)phosphoric acid (HDEHP) in diethylbenzene (DEB). Then di-tert-butylhydroquinone is used to reduce the plutonium in the organic phase so that it can be stripped into concentrated HCl.

3.3 First-Cycle Solvent Extraction Process (Tramex)

The Tramex continuous solvent extraction process is used to decontaminate the transplutonium elements from the lanthanide rare-earth elements and other major fission products. In this process, the transplutonium elements are extracted from 11 M LiCl--0.2 M HCl solution into a solution of Adogen 364-HP (a high-purity tertiary amine) in DEB diluent and are back-extracted into concentrated HCl.

The equipment used for Tramex was replaced; it was becoming increasingly difficult to operate because of corrosion, wear, and damage. The new equipment is different from the old equipment in that it is designed to operate with the organic phase continuous. The primary advantage of having Tramex equipment that will operate with the organic phase continuous is that the Hepex process (see next section) can be run in the same equipment with only minor modifications. In the case of the Tramex process, very little difference was noted between the two modes of operation. It was easier to control the interfaces in the organic-continuous equipment, and we corrected the difficulty associated with the organic overflow to the off-gas header from the columns. However, these operational improvements could have also been designed into new aqueous-continuous equipment.

3.4 Partitioning of Actinides

The transcurium elements are separated from americium and curium by means of an anion exchange process in which the actinides and some impurities are sorbed on Dowex 1-X10 resin from a 12 M LiCl--0.1 M HCl

solution. Nickel and rare earths are eluted from the resin with 10 M LiCl--0.1 M NH₂OH·HCl--5 vol % CH₃OH; americium and curium are eluted with 9 M LiCl--0.1 M HCl; and the transcurium elements are eluted with 8 M HCl. No changes have been made in this process since the last semiannual report.

The Hepex solvent extraction process for partitioning actinides was tested in-cell, using the new Tramex equipment (modified slightly), and was found to be satisfactory for use in TRU. A test made to demonstrate this process showed that it was well suited for batches containing large amounts (more than 100 g) of americium and curium. [We do not expect it to be used very often at TRU because the LiCl-based anion exchange process is better suited for handling our usual batch sizes (10 to 30 g of americium plus curium).] About 275 μ g of californium was separated from 100 g of curium and 90 g of americium. Material balances for californium and curium were 104% and 100.6% respectively. Two process upsets, which resulted from our lack of experience in operation, caused the californium product to be contaminated with curium and americium. However, in the early part of the run, prior to the upsets, the californium decontamination factor was 7000 (the ratio of curium to californium in the feed was 7000 times the ratio in the californium product).

The flowsheet for the Hepex process is given in Fig. 3.2. In this process, Tramex product solution is adjusted to Hepex feed (0.15 M HCl--1 M LiCl), which is fed to the top of the extraction column. The transcurium actinides are extracted into a solution of 0.8 M HDEHP in Amsco 125-82 diluent, which is fed to the bottom of the extraction column. The americium-curium--bearing aqueous phase flows out the bottom of the extraction column to a product catch tank. The solvent is pumped to the scrub column, where small amounts of americium and curium are removed with 0.5 M HCl; then, in the strip column, the transcurium actinides are stripped into 5 M HCl.

3.5 Separation of Transcurium Elements

Procedures that were described previously are still being used to separate and purify the transcurium elements. The transcurium elements are separated from one another on a high-pressure ion exchange column (Dowex

ORNL DWG. 69-4894

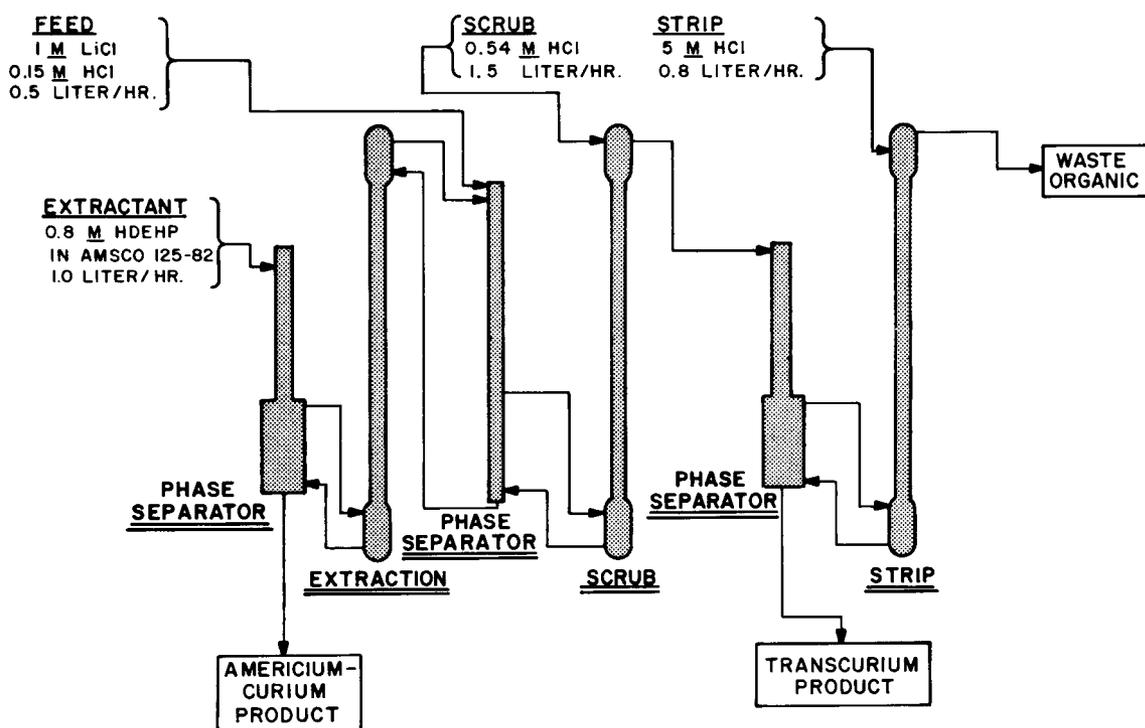


Fig. 3.2. Flowsheet for the Hepex Process for Partitioning Actinides.

50-X8 resin) by chromatographic elution with α -hydroxyisobutyrate. The californium and berkelium product fractions are converted to 8 M HNO_3 solutions by cation exchange. The einsteinium and fermium are separated and purified by using additional cycles of high-pressure ion exchange treatment, and the final product fractions, which are in α -hydroxyisobutyrate solution, are converted to HNO_3 solutions by using a cation exchange method.

3.6 Preparation of Actinide Oxides

Figure 3.3 is a photograph of a new equipment rack, which was installed in cell 4 in TRU, for preparing americium and curium oxides by the sol-gel technique. Out-of-cell tests, in which europium was used as a stand-in for americium and curium, have shown the equipment to be satisfactory.

3.7 Fabrication of Targets

No targets of usual geometry for insertion into the HFIR flux trap were fabricated. However, nine targets (rabbits) were fabricated for irradiation in the HFIR hydraulic rabbit facility; five contained ^{252}Cf (Sect. 3.8), and four contained ^{253}Es (Sect. 4.1). A rabbit for the HFIR (Fig. 3.4) consists of target material (actinides on some sort of matrix material or in a quartz capsule) encapsulated in one or more aluminum pellets that are sealed in a support tube by welded end plugs. The support tube is fabricated from tubing similar to that used for TRU-HFIR targets.

3.8 Irradiation of ^{252}Cf to Produce ^{253}Es

When targets containing ^{252}Cf were irradiated for three to five reactor cycles in the HFIR target island in order to produce ^{253}Es , we found that the disappearance cross section of ^{252}Cf was much higher than we had previously estimated. Thus, the irradiation times that we had

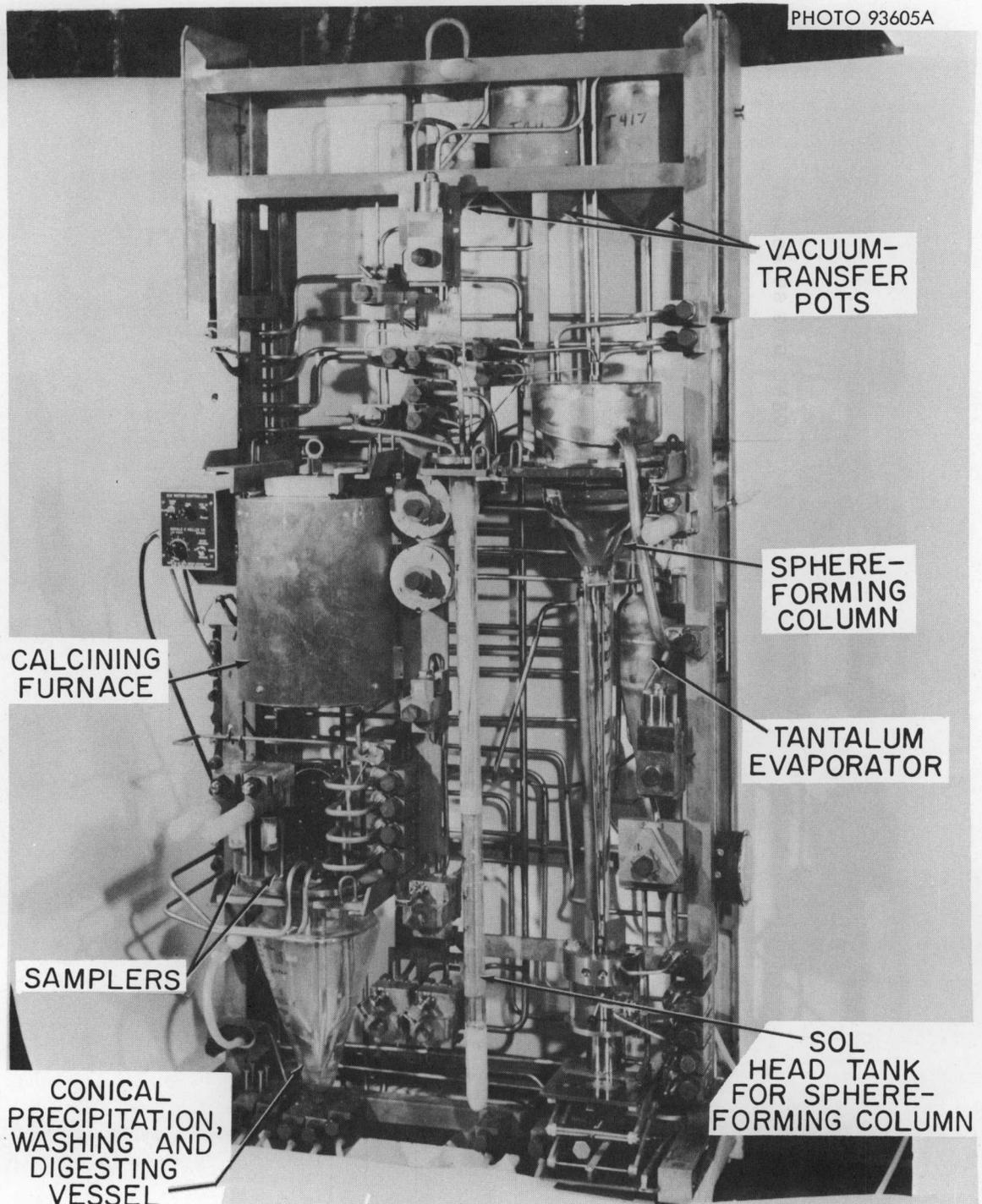


Fig. 3.3. Sol-Gel Equipment for Producing Actinide Oxide Microspheres.

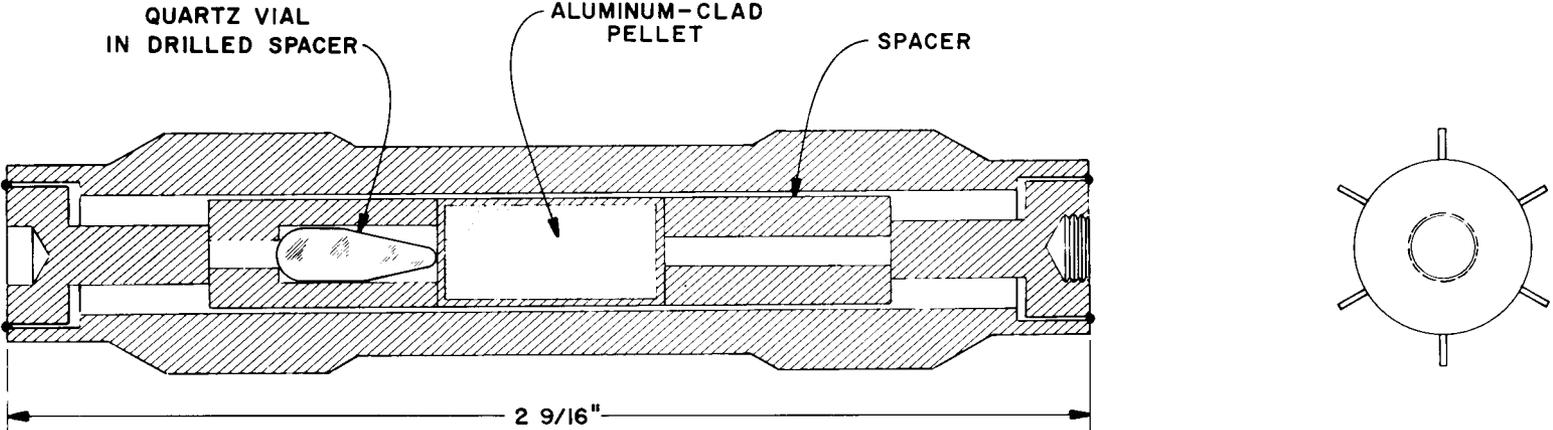


Fig. 3.4. TRU-HFIR Hydraulic Rabbit.

been using were much too long for optimum einsteinium production, causing a significant fraction of the californium to be consumed in nonproductive reactions.

A rabbit containing 1.5 μg of ^{252}Cf was irradiated in the hydraulic rabbit facility for three days to obtain data on the capture cross section of ^{252}Cf . The activation cross section of ^{252}Cf (to ^{253}Cf) appeared to be about 20 barns, which is in good agreement with the values measured recently in the Oak Ridge Research Reactor (ORR) by Bemis and Halperin.³ The value of 20 barns is roughly one-half of the total disappearance cross section (40-50 barns), as measured in special targets early this year.¹ We are not sure whether the earlier value is in error, or whether there is loss by fissioning. Taking the steady-state ratios of ^{253}Cf to ^{252}Cf determined in previous experiments, we calculated a ^{253}Cf fission cross section of 1450 barns; this value indicates that, during irradiation in the HFIR, more than 90% of the ^{253}Cf fissions before it decays to ^{253}Es .

These studies have shown that the optimum irradiation period for producing ^{253}Es is much shorter than the three to five cycles used for the special californium targets; in fact, it appears to be less than one reactor cycle. Therefore, we experimented with methods for loading significant amounts of ^{252}Cf into pellets for short-term rabbit irradiations. A method using CeO_2 microspheres as a carrier was developed, and a rabbit containing 10 μg of ^{252}Cf was fabricated and irradiated 16 days to test this concept. Processing of the irradiated rabbit revealed no difficulties; consequently, we prepared our remaining ^{252}Cf (approximately 2.3 mg) in a similar form for irradiation to produce ^{253}Es and heavier isotopes.

In the method mentioned above, the californium was precipitated, then dissolved in a small volume of 1 M HNO_3 , and finally blended with 6 ml of $\text{Ce}(\text{OH})_3$ hydrosol. The sol was formed into gel microspheres by injecting it from a syringe into a beaker of stirred 2-ethylhexanol. The gel microspheres were calcined at 800°C , blended with aluminum powder, and formed into four standard-size HFIR target pellets. These four pellets, containing a total of 2.3 mg ^{252}Cf , were fabricated into two HFIR rabbits, which were loaded into the hydraulic tube on December 29 for the first irradiation period. The rabbits will be irradiated two to three days to

produce ^{253}Cf and will then be withdrawn from the reactor for 10 to 18 days to allow the ^{253}Cf to decay to ^{253}Es . This cycle will be repeated throughout January and February 1969 with the objective of producing einsteinium that is rich in the heavy isotopes ^{254}Es and ^{255}Es and contains some ^{257}Fm . Final discharge is scheduled for February 20, 1969.

A fifth rabbit, which contained 10 μg of ^{252}Cf , was fabricated using a pellet prepared by the earlier technique. This rabbit will be irradiated about seven days to obtain additional data on cross sections of californium isotopes.

3.9 Analysis of ^{252}Cf by Neutron Activation of Aluminum

We are developing a nondestructive method for assaying the ^{252}Cf content of neutron sources and californium shipping containers. At present, we have to depend on measurements of product and waste solutions to estimate the amount of ^{252}Cf in a source or a shipping capsule. The non-destructive method consists in activating weighed discs of aluminum by the fast-neutron emissions from ^{252}Cf and then assaying the discs by gamma-ray spectrometry for the activation product, ^{24}Na . Uncertainties, which we hope to resolve, or bypass, by calibration procedures are: (1) uncertainty of the detailed neutron energy spectrum of ^{252}Cf fission, (2) uncertainty in the fine structure of energy-dependence of the aluminum activation cross section, and (3) uncertainty of the geometry and efficiency of counting the gamma-ray emissions from ^{24}Na .

Four pellets containing ^{252}Cf (which were made into HFIR rabbits) were tested, in-cell, to determine the neutron source strength by aluminum activation. Six discs were exposed to each pellet, at distances of 1, 2, and 4 in. on either side. Each disc was counted twice. The inferred loadings of the pellets (in μg of ^{252}Cf), and the standard deviations, are tabulated below.

<u>Pellet No.</u>	<u>First Counting</u>	<u>Second Counting</u>
CE-1	576 \pm 1.1%	584 \pm 4.7%
CE-2	697 \pm 1.7%	681 \pm 1.5%
CE-3	659 \pm 2.0%	631 \pm 3.0%
CE-4	<u>1038</u> \pm 1.1%	<u>1019</u> \pm 1.1%
Total	2970	Total 2915

Although subsequent measurements of solutions of the dissolved pellets showed the actual content was somewhat lower, the precision is excellent for sources containing a few hundred micrograms of ^{252}Cf .

3.10 HFIR Target Rod Failures

No further target failures have been observed since the first group of targets, which had been irradiated for about one year in a Savannah River Plant reactor, failed after 125 to 175 days of additional irradiation in the HFIR.

The engineering model formulated to predict target failures, which was discussed in the previous semiannual report,¹ indicated that 13 of the 14 targets subsequently processed in campaign 11 should fail at a burnup of 0.46 fission per original plutonium atom. However, inspection of the targets, after irradiation to burnups of from 0.48 to 0.52 fission per original plutonium atom, disclosed no failures. A similar target has now been irradiated to 0.57 fission per original plutonium atom without failure. We plan to continue irradiating this target until the spring of 1970 (about 0.77 fission per original plutonium atom) or until the cladding ruptures.

4. SPECIAL PROJECTS

Numerous projects that are being carried out by various groups at ORNL and at other sites require the services available at TRU for the preparation of special materials that are not normally produced in the mainline efforts. The phases of these projects involving activities at TRU are reported here; the end results of the research are reported elsewhere.

4.1 Einsteinium Rabbits

Four rabbits containing from 0.04 to 0.9 μg of ^{253}Es were prepared for irradiation in the HFIR. Our objective was to produce 39.3-hr $^{254\text{m}}\text{Es}$ for use at ANL in studying the energy level structure of the alpha-decay

product, ^{250}Bk . The rabbits were irradiated for 2- to 3-day intervals in the HFIR during July, September (two intervals), and October.

After each rabbit was irradiated, it was moved to TRU, dejacketed, and repackaged for air-freight shipment to Chicago. It reached its destination about 24 hr after it had been discharged from the HFIR.

4.2 Fabrication of a Neutron Source Using Californium

A special neutron source, containing 400 μg of ^{252}Cf , was fabricated for the Health Physics Division at ORNL for use in measuring the gamma and neutron leakage from duplicates of the first atomic bombs exploded during World War II. By using the ^{252}Cf source, these spectra could be obtained without actually detonating the bombs.

The source was in the form of a doubly encapsulated 1/4-in. pellet; the first encapsulation was a 3/8-in.-diam aluminum tube, and the second was a 5/8-in.-diam stainless steel capsule.

4.3 Curium for Isotope Separation

Portions of two batches of curium, CMP-10B and CMP-11 (see Table 4.1), were set aside for separation of isotopes in the calutrons at the Y-12 Plant. The source of CMP-10B was the curium recovered at PNL from the blanket of the Shippingport Reactor. The curium in CMP-11 was recovered at TRU during campaign 11. These materials were purified by carbonate precipitation (to separate the americium from the curium), followed by three successive oxalate precipitations to purify the curium from most metallic contaminants. The oxalate was fired to oxide (believed to be $\text{CmO}_{1.72}$) at 800°C for 4 hr and was then loaded into graphite charging bottles preparatory to insertion into the calutron. The high ^{243}Cm content of batch CMP-10B increased the gamma dose rate for this batch significantly, thus preventing us from loading more than about 200 mg of curium per bottle (vs 500 mg of batch CMP-11). About 3 mg of 70% ^{245}Cm was recovered from 1.1 g of batch CMP-10B by the isotope separation group. The 2.6 g of batch CMP-11 yielded about 11 mg of 95% ^{246}Cm plus small amounts of material enhanced in ^{247}Cm , ^{248}Cm , and ^{250}Cm .

Table 4.1. Isotopic Compositions of Two Special Batches of Curium

Isotope	Atom %	
	CMP-10B	CMP-11
^{242}Cm	0.001	--
^{243}Cm	1.48	--
^{244}Cm	93.474	88.993
^{245}Cm	3.94	0.759
^{246}Cm	1.07	9.59
^{247}Cm	0.019	0.264
^{248}Cm	0.016	0.394

5. REFERENCES

1. W. D. Burch, J. E. Bigelow, and L. J. King, Transuranium Processing Plant Semiannual Report of Production, Status, and Plans for Period Ending July 30, 1968, ORNL-4376.
2. L. J. King and E. D. Collins, Summary of the Campaign to Process Fourteen Irradiated HFIR Targets in the Transuranium Processing Plant, ORNL-TM-2434 (to be published).
3. J. Halperin, C. E. Bemis, Jr., and R. Eby, Chem. Div. Ann. Progr. Rept. May 20, 1967, ORNL-4306, p. 31.
4. C. M. Lederer, J. M. Hallander, and I. Perlman, Table of Isotopes, 6th ed., Wiley, New York, 1967.
5. A. H. Wapstra, "Actinide Fingerprints," Actinides Review 1, 39-53 (1967).

6. 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. These tabulations will be reproduced completely in each semiannual report, and changes made since the preceding report will be indicated. We wish to state clearly that these 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 Lederer⁴ and Wapstra,⁵ 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.

6.1 Decay Data

Table A-1 is a list of all nuclides of interest to the Transplutonium Element Production Program, (i.e., all that can be produced by neutron bombardment of ^{238}U). The list includes values for half-lives and branching ratios or partial decay half-lives, along with literature references, if they are available. In many cases, the half-life of an isotope was determined by relating it to the half-life of some other, reference isotope. In a few cases, a newer value has been accepted for the half-life of the reference isotope, and the values of the half-lives that were dependent upon it have been recalculated. Such cases are footnoted because the half-life value in our table no longer agrees with the value given in the reference. However, we did use the relationship given in the referenced work.

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

Underlines indicate new values since the previous report.

Nuclide	Total Half-Life	Reference ^b	Partial Half-Life for Spontaneous Fission	Reference ^b
²³⁷ Np	$(2.14 \pm 0.01) \times 10^6$ y	60Br12	$>10^{18}$ y	61Dr4
²³⁸ Np	2.10 ± 0.01 d	50F53		
²³⁹ Np	2.359 ± 0.010 d	59C93		
²⁴⁰ Np	63 ± 2 m	60Le3		
^{240m} Np	7.3 ± 0.3 m	48H61		
²⁴¹ Np	16 m	60Le3		
^{241m} Np	3.4 h	60Le3		
²³⁸ Pu	<u>87.404 ± 0.041 y</u>	68Jo15	$(5 \pm 0.6) \times 10^{10}$ y	61Dr4
²³⁹ Pu	$24,413 \pm 30$ y	59M126	5.5×10^{15} y	52S67
²⁴⁰ Pu	$6,580 \pm 40$ y	51I3	$(1.340 \pm 0.015) \times 10^{11}$ y	62Wa13
²⁴¹ Pu	<u>14.98 ± 0.33 y</u>	68Ca19		
²⁴² Pu	$(3.869 \pm 0.016) \times 10^5$ y	68Ha41	$(7.45 \pm 0.17) \times 10^{10}$ y	63Ma50
²⁴³ Pu	<u>4.955 ± 0.003 h</u>	68D109		
²⁴⁴ Pu	$(8.28 \pm 0.10) \times 10^7$ y	68Ha41	$(6.55 \pm 0.32) \times 10^{10}$ y	66F107
²⁴⁵ Pu	10.6 ± 0.4 h	56B92		
²⁴⁶ Pu	10.85 ± 0.02 d	56H23		
²⁴¹ Am	<u>432.7 ± 0.7 y</u>	67Oe01	$(2.3 \pm 0.8) \times 10^{14}$ y	61Dr4
²⁴² Am	16.01 ± 0.02 h	53K38		
^{242m} Am	<u>144 ± 7 y</u>	59B221 ^c		
²⁴³ Am	7340 ± 50 y			
²⁴⁴ Am	10.1 ± 0.1 h	62Va8		
^{244m} Am	26 m	54G24		
²⁴⁵ Am	2.07 ± 0.02 h	56B92		
²⁴⁶ Am	25.0 ± 0.2 m	55E16		
^{246m} Am	40 ± 7 m	67Or02		
²⁴⁷ Am	24 ± 3 m	67Or02		
²⁴² Cm	162.7 ± 0.1 d	57P52	7.2×10^6 y	51H87
²⁴³ Cm	32 y	57A70		
²⁴⁴ Cm	<u>$18,099 \pm 0.015$ y</u>	68Be26	$(1.346 \pm 0.006) \times 10^7$ y	65Me02
²⁴⁵ Cm	9600 ± 290 y	61Ca1 ^d		
²⁴⁶ Cm	5640 ± 140 y	61Ca1 ^d	$(1.66 \pm 0.10) \times 10^7$ y	65Me02
²⁴⁷ Cm	$(1.64 \pm 0.20) \times 10^7$ y	63F108		
²⁴⁸ Cm	$(4.2 \pm 0.3) \times 10^5$ y	56B91 ^e	$(4.6 \pm 0.5) \times 10^6$ y	56B91
²⁴⁹ Cm	64 ± 3 m	58E06		
²⁵⁰ Cm	$(1.74 \pm 0.24) \times 10^4$ y	66RG01	$(1.74 \pm 0.24) \times 10^4$ y	66RG01
²⁴⁹ Bk	314 d	57E01	$>1.4 \times 10^9$ y	57E01
²⁵⁰ Bk	3.222 ± 0.005 h	59V02		
²⁵¹ Bk	57 ± 1.7 m	66RG04		

Table A-1 (continued)

Nuclide	Total Half-Life	Reference ^b	Partial Half-Life for Spontaneous Fission	Reference ^b
²⁴⁹ Cf	323 y		$>4.5 \times 10^8$ y	57E01
²⁵⁰ Cf	13.2 ± 0.5 y	65Me02	$(1.73 \pm 0.06) \times 10^4$ y	63Ph01
²⁵¹ Cf	892 y			
²⁵² Cf	2.646 ± 0.004 y	65Me02	85.5 ± 0.5 y	65Me02
²⁵³ Cf	<u>18.1 ± 0.3 d</u>	65Me02 ^f		
²⁵⁴ Cf	60.5 ± 0.2 d	63Ph01	60.5 ± 0.2 d	63Ph01
²⁵³ Es	<u>20.5 d</u>	68Be49	$(6.3 \pm 0.2) \times 10^5$ y	65Me02
²⁵⁴ Es	276 d	67Un01	$>2.5 \times 10^7$ y	
^{254m} Es	39.3 ± 0.2 h	62Un1		
²⁵⁵ Es	39.8 ± 1.2 d	66RG01	2440 ± 140 y	
²⁵⁶ Es	<u>25 ± 3 m</u>	68Lo11		
²⁵⁴ Fm	3.24 ± 0.01 h	56J09	228 ± 1 d	
²⁵⁵ Fm	20.07 ± 0.07 h	64As01	$(1.0 \pm 0.6) \times 10^4$ y	
²⁵⁶ Fm	<u>2.62 ± 0.03 h</u>	68Ho13	<u>2.62 ± 0.03 h</u>	68Ho13
²⁵⁷ Fm	94 ± 10 d	66RG01		
²⁵⁸ Fm				

^aThe half-life values used in this table were being used at TRU on January 1, 1969.

^bReferences are decoded in Table A-2.

^cPublished value was adjusted for ²⁴¹Am half-life of 432.7 y.

^dPublished value was adjusted for ²⁴⁴Cm half-life of 18.099 y.

^ePublished value was adjusted for ²⁵²Cf half-life of 2.646 y.

^fPublished value was adjusted for ²⁵³Es half-life of 20.5 d.

^g²⁵⁸Fm has been removed from the table pending proof that it exists.

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.

6.2 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:

$$\sigma_{\text{eff}}^{\text{c}} = \sigma_{2000}^{\text{c}} + \frac{\phi_{\text{res}}}{\phi_{2200}} \frac{\text{RI}}{\sqrt{1 + \text{CN}}}$$

where σ_{2000}^{c} is the thermal-neutron capture cross section, N is the number of grams of the particular nuclide in one target rod, ϕ_{res} is the average flux per unit lethargy width in the resonance region, and ϕ_{2200} is the equivalent flux of 2200-m/sec neutrons that would give the same reaction rate with a 1/v absorber as would the actual reactor flux. The effective cross section for fission is computed by a similar relationship among the last three parameters.

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

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

Table A-2. References for Table A-1

Code	Reference	Code	Reference
48H61	E. K. Hyde, M. H. Studier, and W. M. Manning, ANL-4143 (April 15, 1948) and ANL-4182 (August 4, 1948).	61Ca1	W. T. Carnall, S. Fried, and A. L. Harkness, <i>J. Inorg. Nucl. Chem.</i> , 17 , 12-14 (1961).
50F53	M. S. Freedman, A. H. Jaffey, and F. Wagner, <i>Phys. Rev.</i> , 79 , 410-411 (1950).	61Dr4	V. A. Druin, V. P. Perelegin, and G. I. Khlebnikov, <i>Sov. Phys. JETP</i> , 13 , 913-914 (1961).
51H87	G. C. Hanna, B. G. Harvey, N. Moss, and P. R. Tunncliffe, <i>Phys. Rev.</i> , 81 , 466-467 (1951).	62Un1	J. Unik, P. Day, and S. Vandenbosch, <i>Nucl. Phys.</i> , 36 , 284-304 (1962).
51I13	M. G. Inghram, D. C. Hess, P. R. Fields, and G. L. Pyle, <i>Phys. Rev.</i> , 83 , 1250 (1951).	62Va8	S. E. Vandenbosch and P. Day, <i>Nucl. Phys.</i> , 30 , 177-190 (1962).
52S67	E. Segrè, <i>Phys. Rev.</i> , 86 , 21-28 (1952).	62Wa13	D. E. Watt, F. J. Bannister, J. B. Laidler, and F. Brown, <i>Phys. Rev.</i> , 126 , 264-265 (1962).
53K38	T. K. Keenan, R. A. Penneman, and B. B. McInteer, <i>J. Chem. Phys.</i> , 21 , 1802-1803 (1953).	63F108	P. R. Fields, A. M. Friedman, J. Lerner, D. Metta, and R. Sjolblom, <i>Phys. Rev.</i> , 131 , 1249-1250 (1963).
54G24	A. Chiorso, S. G. Thompson, G. R. Choppin, and B. G. Harvey, <i>Phys. Rev.</i> , 94 , 1081 (1954).	63Ma50	L. Z. Malkin, et al., <i>At. Energ. (USSR)</i> , 15 , 158 (1963).
55E16	D. Engelkemeir, P. R. Fields, T. Fried, G. L. Pyle, C. M. Stevens, L. B. Aspree, C. I. Browne, H. Louise Smith, and R. W. Spence, <i>J. Inorg. Nucl. Chem.</i> , 1 , 345-351 (1955).	63Ph01	L. Phillips, R. Gatti, R. Brandt, and S. G. Thompson, <i>J. Inorg. Nucl. Chem.</i> , 25 , 1085-1087 (1963).
56B91	J. P. Butler, T. A. Eastwood, H. G. Jackson, and R. P. Schuman, <i>Phys. Rev.</i> , 103 , 965 (1956).	64As01	F. Asaro, S. Bjrnholm, and I. Perlman, <i>Phys. Rev.</i> , 133 , B291-B300 (1964).
56B92	J. P. Butler, T. A. Eastwood, T. L. Collins, M. E. Jones, F. M. Rourke, and R. P. Schuman, <i>Phys. Rev.</i> , 103 , 634 (1956).	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> , 27 , 33 (1965).
56H23	D. C. Hoffman and C. I. Browne, <i>J. Inorg. Nucl. Chem.</i> , 2 , 209 (1956).	66F107	P. R. Fields, A. M. Friedman, J. Milsted, J. Lerner, C. M. Stevens, D. Metta, and W. K. Sabine, <i>Nature</i> , 212 , 131 (1966).
56J09	M. Jones, R. P. Schuman, J. P. Butler, G. Cowper, T. A. Eastwood, and H. G. Jackson, <i>Phys. Rev.</i> , 102 , 203-207 (1956).	66RG01	Combined Radiochemistry Group, LRL, LASL, and ANL, <i>Phys. Rev.</i> , 148 , No. 3, 1192-1198 (1966).
57A70	F. Asaro, S. G. Thompson, F. S. Stephens, Jr., and I. Perlman, <i>Bull. Am. Phys. Soc.</i> , 8 , 393 (1957).	66RG04	Argonne Heavy Element Group (unpublished data).
57E01	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> , 107 , 1635-1638 (1957).	670e01	F. L. Oetting and S. R. Gunn, <i>J. Inorg. Nucl. Chem.</i> , 29 , 2659-64 (1967).
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Table A-3. Properties^a of Transuranium Nuclides
 Underlines indicate new values since the previous report.

Nuclide	Half-Life	Energies of Prin. Emissions (MeV)		Specific Activity				Hazard ^b			
		α	β	(Ci/g)	(w/g)	(α cpm/mg ^c)	(β dpm/mg)	(Neutrons min ⁻¹ mg ⁻¹)	MPC _{a(40)} (μ Ci/cm ³)	Body Burden (μ Ci)	(μ g)
²³⁷ Np	2.14 x 10 ⁶ y	4.78		7.07 x 10 ⁻⁴	2.07 x 10 ⁻⁵	8.01 x 10 ⁵			4 x 10 ⁻¹²	0.06	84.9
²³⁸ Np	2.10 d		0.25 1.24	2.61 x 10 ⁵	1.27 x 10 ³		5.80 x 10 ¹⁴				
²³⁹ Np	2.359 d		0.332 0.427	2.32 x 10 ⁵	5.86 x 10 ²		5.14 x 10 ¹⁴		8 x 10 ⁻⁷	30	1.29 x 10 ⁻⁴
²⁴⁰ Np	63 m		0.89	1.24 x 10 ⁷	1.03 x 10 ⁵		2.76 x 10 ¹⁶				
^{240m} Np	7.3 m		2.18 1.6	1.07 x 10 ⁸	5.33 x 10 ⁵		2.38 x 10 ¹⁷				
²⁴¹ Np	16 m			4.86 x 10 ⁷			1.08 x 10 ¹⁷				
^{241m} Np	3.4 h			3.82 x 10 ⁶			8.49 x 10 ¹⁵				
²³⁸ Pu	<u>87.404 y</u>	5.49		17.2	0.570	1.94 x 10 ¹⁰	148	2 x 10 ⁻¹²	0.04	2.32 x 10 ⁻³	
²³⁹ Pu	24,413 y	5.15		6.13 x 10 ⁻²	1.913 x 10 ⁻³	6.94 x 10 ⁷		2 x 10 ⁻¹²	0.04	0.654	
²⁴⁰ Pu	6,580 y	5.16		0.227	7.097 x 10 ⁻³	2.57 x 10 ⁸	66	2 x 10 ⁻¹²	0.04	0.176	
²⁴¹ Pu	<u>14.98 y</u>	4.9	0.02	99.1	4.06 x 10 ⁻³	2.94 x 10 ⁶	2.20 x 10 ¹¹	9 x 10 ⁻¹¹	0.9	9.08 x 10 ⁻³	
²⁴² Pu	3.869 x 10 ⁵ y	4.90		3.82 x 10 ⁻³	1.13 x 10 ⁻⁴	4.32 x 10 ⁶	124	2 x 10 ⁻¹²	0.05	13.0	
²⁴³ Pu	<u>4,955 h</u>		0.49 0.58	2.60 x 10 ⁶	3.34 x 10 ³		5.78 x 10 ¹⁵	2 x 10 ⁻⁶	7.2	2.78 x 10 ⁻⁶	
²⁴⁴ Pu	8.28 x 10 ⁷ y	4.587		1.77 x 10 ⁻⁵	4.93 x 10 ⁻⁷	2.00 x 10 ⁴	374	2 x 10 ⁻¹²	0.04	2.23 x 10 ³	
²⁴⁵ Pu	10.6 h			1.21 x 10 ⁶			2.68 x 10 ¹⁵	2 x 10 ⁻⁷	3.0	4.03 x 10 ⁵	
²⁴⁶ Pu	10.85 d		0.15	4.91 x 10 ⁴	66.9		1.09 x 10 ¹⁴				
²⁴¹ Am	<u>432.7 y</u>	5.48		3.43	0.1145	3.88 x 10 ⁹	0.04	6 x 10 ⁻¹²	0.1	0.0292	
²⁴² Am	16.01 h		0.63 0.67	8.11 x 10 ⁵	2.08 x 10 ³		1.80 x 10 ^{15d}	4 x 10 ⁻⁸	0.06	7.39 x 10 ⁻⁸	
^{242m} Am	<u>144 y</u>	5.207	I. T.	10.3	3.08 x 10 ⁻²	5.53 x 10 ⁷	2.28 x 10 ^{10e}	6 x 10 ⁻¹²	0.07	6.80 x 10 ⁻³	
²⁴³ Am	7340 y	5.27		0.200	6.45 x 10 ⁻³	2.27 x 10 ⁸		6 x 10 ⁻¹²	0.05	0.25	
²⁴⁴ Am	10.1 h		0.387	1.27 x 10 ⁶	8.74 x 10 ³		2.82 x 10 ¹⁵	2 x 10 ⁻⁷	0.18	1.42 x 10 ⁻⁷	
^{244m} Am	26 m		1.5	2.96 x 10 ⁷	8.98 x 10 ⁴		6.58 x 10 ^{16f}	4 x 10 ⁻⁶	0.18	6.08 x 10 ⁻⁹	
²⁴⁵ Am	2.07 h		0.91	6.17 x 10 ⁶	1.20 x 10 ⁴		1.37 x 10 ¹⁶	3 x 10 ⁻⁶	12	1.94 x 10 ⁻⁶	
²⁴⁶ Am	25 m		1.31	3.06 x 10 ⁷	2.48 x 10 ⁵		6.79 x 10 ¹⁶				
^{246m} Am	40 m			1.91 x 10 ⁷			4.24 x 10 ¹⁶				
²⁴⁷ Am	24 m			3.17 x 10 ⁷			7.04 x 10 ¹⁶				
²⁴² Cm	162.7 d	6.11		3.32 x 10 ³	122	3.76 x 10 ¹²	1.20 x 10 ⁶	1 x 10 ⁻¹⁰	0.05	6.27 x 10 ⁻⁷	
²⁴³ Cm	32 y	5.79		45.9	1.677	5.20 x 10 ¹⁰	3.27 x 10 ⁸	6 x 10 ⁻¹²	0.09	1.96 x 10 ⁻³	
²⁴⁴ Cm	<u>18.099 y</u>	5.80		80.94	2.832	9.16 x 10 ¹⁰	6.68 x 10 ⁵	9 x 10 ⁻¹²	0.1	1.24 x 10 ⁻³	
²⁴⁵ Cm	9600 y	5.36		0.152	5.07 x 10 ⁻³	1.72 x 10 ⁸		5 x 10 ⁻¹²	0.04	0.263	
²⁴⁶ Cm	5640 y	5.4		0.258	8.45 x 10 ⁻³	2.92 x 10 ⁸	5.03 x 10 ⁵	5 x 10 ⁻¹²	0.05	0.194	
²⁴⁷ Cm	1.64 x 10 ⁷ y			8.83 x 10 ⁻⁵	~2.8 x 10 ⁻⁶	1.00 x 10 ⁵		5 x 10 ⁻¹²	0.04	453	
²⁴⁸ Cm	4.2 x 10 ⁵ y	5.05		3.43 x 10 ⁻³	4.78 x 10 ⁻³	3.53 x 10 ⁶		2.32 x 10 ⁶	6 x 10 ⁻¹³	0.01	2.91
²⁴⁹ Cm	64 m		0.9	1.18 x 10 ⁷	2.064 x 10 ⁴		2.62 x 10 ¹⁶	8 x 10 ⁻⁶	0.8	6.78 x 10 ⁻⁸	
²⁵⁰ Cm	1.74 x 10 ⁴ y			8.20 x 10 ⁻²	~0.1		6.50 x 10 ⁸				
²⁴⁹ Bk	314 d	5.4	0.125	1.67 x 10 ³	0.358	4.16 x 10 ⁷	3.71 x 10 ¹²	7.92 x 10 ³	9 x 10 ⁻¹⁰	0.7	419
²⁵⁰ Bk	3.222 h		0.23	3.89 x 10 ⁶	2.75 x 10 ⁴		8.62 x 10 ¹⁵	1 x 10 ⁻⁷	0.04	1.03 x 10 ⁻⁷	
²⁵¹ Bk	57 m			1.32 x 10 ⁷			2.92 x 10 ¹⁶				

Table A-3 (continued)

Nuclide	Half-Life	Energies of Prin. Emissions (MeV)		Specific Activity				Hazard ^b			
		α	β	(Ci/R)	(w/R)	(α cpm/mg ^c)	(β dpm/mg)	(Neutrons min ⁻¹ mg ⁻¹)	MPC ^a (40) (μ Ci/cm ³)	Body Burden (μ Ci)	(μ g)
²⁴⁹ Cf	323 y	5.81		4.45	0.166	5.03×10^9		$\sim 2 \times 10^3$	2×10^{-12}	0.04	8.98×10^{-3}
²⁵⁰ Cf	13.2 y	6.03		108	4.02	1.22×10^{11}		2.12×10^8	5×10^{-12}	0.04	3.70×10^{-4}
²⁵¹ Cf	892 y			1.60	5.84×10^{-2}	1.80×10^9			2×10^{-12}	0.04	2.50×10^{-2}
²⁵² Cf	2,646 y	6.11		536	39.0	5.88×10^{11}		1.40×10^{11}	2×10^{-11}	0.04	7.46×10^{-5}
²⁵³ Cf	<u>18.1 d</u>		0.27	2.85×10^4	13.67		6.32×10^{13}		8×10^{-10}	0.04	1.40×10^{-6}
²⁵⁴ Cf	60.5 d	5.84		8.51×10^3	1.06×10^4			7.37×10^{13}	5×10^{-12}	0.01	1.18×10^{-6}
²⁵³ Es	<u>20.5 d</u>	6.63		2.52×10^4	1.01×10^3	2.86×10^{13}		1.95×10^7	7×10^{-10}	0.04	1.59×10^{-6}
²⁵⁴ Es	276 d	6.42		1.86×10^3	71.9	2.11×10^{12}		8.39×10^7	2×10^{-11}	0.02	1.08×10^{-5}
^{254m} Es	39.3 h		0.48	3.14×10^5	1.18×10^3		6.97×10^{14}		5×10^{-9}	0.02	6.37×10^{-8}
²⁵⁵ Es	39.8 d			1.29×10^4			2.86×10^{13}		6×10^{-10}	0.04	3.10×10^{-6}
²⁵⁶ Es	<u>25 m</u>			2.94×10^7			6.52×10^{16}				
²⁵⁴ Fm	3.24 h	7.20		3.81×10^6	1.68×10^5	4.31×10^{15}		2.09×10^{11}	6×10^{-8}	0.02	5.25×10^{-9}
²⁵⁵ Fm	20.07 h	7.03		6.13×10^5	2.79×10^4	6.94×10^{14}		1.29×10^9	2×10^{-8}	0.04	6.53×10^{-8}
²⁵⁶ Fm	<u>2.62 h</u>			4.67×10^6	5.85×10^6			4.31×10^{16}	2×10^{-9}	0.01	2.14×10^{-9}
²⁵⁷ Fm	94 d			5.41×10^3	~ 200	6.12×10^{12}					

^aThe values for properties included in this table are those in use at TRU on January 1, 1969.

^bFrom IRCP Publication 2, "Report of Committee II on Permissible Dose for Internal Radiation (1959)" and the 1962 Supplement.

^cCounting geometry, 51%.

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

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

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

Table A-4. Neutron Cross Sections Used to Compute Transmutations in HFIR Target Irradiations (January 1, 1969)

Underlines indicate new values since the previous report.

Nuclide	Half-Life	Capture			Fission		
		2200-m/s Cross Section (barns)	Resonance Self-Shielding Constant	Resonance Integral (barns)	2200-m/s Cross Section (barns)	Resonance Self-Shielding Constant	Resonance Integral (barns)
²³⁸ Pu	<u>87.404 y</u>	<u>560</u>	0	150	<u>16.5</u>	0	25
²³⁹ Pu	24,413 y	265.7	0	195	<u>742.4</u>	0	324
²⁴⁰ Pu	6580 y	<u>290</u>	0	8453	<u>0.05</u>	0	0
²⁴¹ Pu	<u>14.98 y</u>	<u>360</u>	0	166	<u>1011</u>	0	541
²⁴² Pu	386,900	18.5	7.409	1280	0	0	0
²⁴³ Pu	<u>4.955 h</u>	80	0	0	210	0	0
²⁴⁴ Pu	8.28 x 10 ⁷ y	1.6	0	0	0	0	0
²⁴⁵ Pu	10.6 h	277	0	0	0	0	0
²⁴⁶ Pu	10.85 d	0	0	0	0	0	0
²⁴³ Am	7340 y	75	2.126	1500	0	0	0
²⁴⁴ Cm ^a	27.3 m	0	0	0	130	0	0
²⁴⁵ Am	2.07 h	0	0	0	0	0	0
²⁴⁶ Am	25 m	0	0	0	0	0	0
²⁴⁴ Cm	<u>18.099 y</u>	10	6.9	650	2.7	<u>6.9</u>	72
²⁴⁵ Cm	9600 y	<u>445.3</u>	<u>1.4</u>	<u>90</u>	<u>1544</u>	<u>1.4</u>	<u>600</u>
²⁴⁶ Cm	5640 y	5	0.866	<u>170</u>	0	0	0
²⁴⁷ Cm	1.64 x 10 ⁷ y	<u>77.63</u>	0	<u>200</u>	<u>281.33</u>	0	<u>1000</u>
²⁴⁸ Cm	420,000 y	5.2	1.447	250	0	0	0
²⁴⁹ Cm	64 m	<u>2.8</u>	0	0	50	0	0
²⁵⁰ Cm	17,400 y	2	0	0	0	0	0
²⁴⁹ Bk	314 d	<u>1706</u>	0	<u>1850</u>	<u>553.5</u>	0	0
²⁵⁰ Bk	3.222 h	350	0	0	<u>960</u>	0	0
²⁴⁹ Cf	323 y	<u>300</u>	0	0	<u>1735</u>	0	0
²⁵⁰ Cf	13.2 y	<u>2000</u>	0	0	0	0	0
²⁵¹ Cf	892 y	<u>1948</u>	0	0	<u>5126</u>	0	0
²⁵² Cf	2.646 y	<u>19.8</u>	0	<u>44</u>	0	0	0
²⁵³ Cf	<u>18.1 d</u>	<u>12.6</u>	0	0	<u>1300</u>	0	0
²⁵⁴ Cf	60.5 d	<u>75</u>	0	<u>1650</u>	0	0	0
²⁵³ Es	<u>20.5 d</u>	345	0	0	0	0	0
²⁵⁴ Es	276 d	20	0	0	3060	0	0
^{254m} Es	39.3 h	1.26	0	0	1840	0	0
²⁵⁵ Es	39.8 d	<u>60</u>	0	0	0	0	0
²⁵⁶ Es	25 m	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>
²⁵⁴ Fm	3.24 h	<u>76</u>	0	0	0	0	0
²⁵⁵ Fm	20.07 h	<u>26</u>	0	0	100	0	0
²⁵⁶ Fm	<u>2.62 h</u>	20	0	0	0	0	0
²⁵⁷ Fm	94 d	<u>10</u>	0	0	100	0	0

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

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