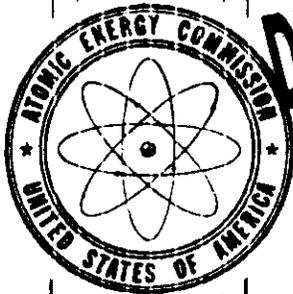


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SUMMARY

MFC-8 - Studies of Palladium and Rhodium, and Support of Technetium Recovery. The final flow sheet developed under this MFC is now being tested. Batch contacts of ion exchange resin with supernatant from Purex high-level wastes showed that the optimum rhodium elution was obtained with 50-100 mesh resin having a 2% crosslinkage. (p. 6)

MFC-13 - Applications for Hanford-Produced Cobalt-60. Plans have been made to visit Atlantic Research, NUMEC, and BNL to discuss possible Co-60 applications such as combating bacterial problems in industrial cutting fluids, jet fuel, and other hydrocarbons and the use of high-energy gamma radiation in oxidizing and precipitating contaminants in mine drainage water. (p. 6)

Conceptual Processes for High Enrichment Fuels and Neptunium Target Element Processing-Fluoride Volatility. Because of unexpected delays in constructing and testing the necessary facilities, the initial "cold" hydrochlorination experiments will be delayed until October 1967. (p. 7)

CAGE Program Status (as of August 31, 1967). CAGE programming progress will be reported in a more general fashion than in previous reports. (p. 8)

CAGE Problem Status (as of August 31, 1967). The status of CAGE problems is tabulated in Table I. (p. 10)

Pu-238 Production Program at Hanford - Near Term. In order to implement a near-term Pu-238 production program at Hanford and to do so promptly at low capital cost, laboratory facilities operated by Battelle-Northwest will be used for chemically processing irradiated neptunium, and facilities in the Z-plant will be used both for denitrating neptunium and plutonium and for fabricating neptunium targets. (p. 14)

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Long-Range Hanford Capability for Pu-238 Production. Information on Hanford capability for Pu-238 production has been assembled in support of AECOP Task Assignment No. 5, "Conversion of Np-237 to Pu-238," and has been forwarded to AECOP in four letters: DUN-2900 (July 27), DUN-AOP-49 (August 3), DUN-AOP-50 (August 17), and DUN-AOP-51 (August 25). If the Redox plant were used for chemically processing irradiated neptunium, the total required capital costs would be \$2,400,000 and \$3,200,000 for neptunium annual throughputs of 600 and 1200 kg, respectively. (p. 14)

An Optimization Code for Fuel-Cycle Analysis. Modification of the Battelle-Northwest OPTIM Code for use in fuel-cycle analysis is nearly complete and ready for debugging. The initial optimization case will be used for recalibrating the resource shielding coefficients used in the cross-section calculation for various isotopes. (p. 16)

DECAY Computer Code for Use with the ISOTOPIC DATA TAPE. Briefly described are the ISOTOPIC DATA TAPE and the DECAY Code, which were recently developed for use in AOP work. (p. 17)

A Dosimetry Code for Use with the ISOTOPIC DATA TAPE. A dosimetry code that is being modified for use with the Battelle-Northwest ISOTOPIC DATA TAPE will, after the first stage of its development, indicate both the curies produced by each isotope in a mixture and the total curies being radiated at any specified time. (p. 17)

Calculated Decay of One-Gram Amounts of Selected Uranium, Plutonium, Protactinium, and Neptunium Isotopes. A total of 13 tables show the amount of decay products originating from one-gram amounts of the following 13 isotopes: U-232, U-233, U-234, Pu-236, Pu-237, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Pa-232, Np-238, Np-239. The data in these tables were produced by the DECAY program linked to the Battelle-Northwest ISOTOPIC DATA TAPE. (p. 17)

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The Impact of Advanced Technology on the Adjusted Total Includable Cost and on the Plutonium Marginal Unit Cost. Summarized and commented upon are representative results from the DUN document entitled, "The Impact of Advanced Technology--Marginal Cost Analysis," D. H. Bangerter, to be issued (Secret)

(p. 32 )

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MFC AND OTHER PROPOSAL PROGRESS

MFC-8-Studies of Palladium, Rhodium, and Support of Technetium Recovery

The progress in developing the final flowsheet is summarized in Reference 1 and detailed in Reference 2 below. This flowsheet is now being tested.

Batch contacts of ion exchange resin with supernatant from Purex high-level wastes showed that the optimum rhodium elution was obtained with 50-100 mesh resin having a 2 percent crosslinkage. Column studies with up to 100 ml resin are near completion. Rhodium was eluted from resin with 8 M HNO<sub>3</sub>. This solution was concentrated 100-fold to remove H<sub>2</sub>O and most of the HNO<sub>3</sub>. HClO<sub>4</sub> was added, and distillation removed Tc and Ru. A cationic complex of Rh (supposedly Rh(H<sub>2</sub>O)<sub>6</sub><sup>+++</sup>) in the resulting solution was loaded on Dowex 50 resin. HCl was used to elute the rhodium. The final solution contained the following impurities, as calculated on the basis of one gram of Rh: Co-60 - 8 μCi; Cs-137 - 6 μCi; Sb-125 - 8 μCi; Ru - 0; Tc - 0. Continued study of the flowsheet is planned.

MFC-13-Applications for Hanford Produced Co-60

Two developments currently under investigation have come to our attention as possible large-scale uses of cobalt-60. One development is the use of radiation to combat bacterial problems in industrial cutting fluids, jet fuel, and other hydrocarbons; the other is purification of mine drainage water by using high energy gamma radiation is used to oxidize and precipitate contaminants. Arrangements have been made to visit Atlantic Research, NUMEC, and Brookhaven National Laboratory, where this research is going on, and to discuss and review latest developments in each of these, and possibly other, areas.

- 
- (1) "Monthly Report May - June, 1967," p. 5. DUN-AOP-20 (Secret).  
(2) J. V. Panesco. "Quarterly Report - Development Program for Recovery of Palladium, Rhodium, and Technetium (MFC- 8) - April - June, 1967," ISO-913. (Unclassified)

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ADVANCED CONCEPTS

Conceptual Processes for High Enrichment Fuels and Neptunium Target  
Element Processing - Fluoride Volatility

Initial "cold" hydrochlorination experiments will be delayed at Battelle-Northwest until October. The construction and testing of the fluorine storage building (adjacent to 325 Building) and the installation of the coaxial fluorine transfer line into Room 400 has required more time than anticipated. This facility will supply a constant flow of fluorine at up to 40 psig for laboratory use. A complete operational test of fluorine metering equipment in Room 400 must be completed before experiments are conducted.

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SYSTEMS ANALYSIS

CAGE Program Status (as of August 31, 1967)

Previous reporting of CAGE progress and status was in terms of various tasks. Such a reporting procedure has become inadequate and sometimes confusing in that CAGE studies are now performed on a problem basis; it is therefore more meaningful to report them in terms of problems. The progress of CAGE programming, which also needs periodical reporting, will be reported in a more general fashion.

The initial Richland CAGE program was completed in April of 1966. It has since been identified as Mark I. The Mark I program was limited in many ways, the principal one being that only one shutdown sequence was permitted. Since that time the Mark II program has been completed, with the principal additional feature being the ability to study any shutdown sequence. A more recent version of the Mark II program (Mark IIa) is now operational. The principal additional capability that is now provided is generalized shutdown-startup, with capability to shut down to and start from a minimum level of one reactor operating. The Mark IIa program also includes revisions from Mark II as follows: more up-to-date capital estimates (summarized in the March-April AOP report, DUN-AOP-19),<sup>(1)</sup> allocation of overheads to various intermediate printout line items, and modifications of the separations part of the program to insure that proper modes are brought in automatically. There have also been some minor refinements in cost calculations.

An item still planned for the Mark IIa program is that of updating the N-Reactor variables fuels costs calculation so as to reflect recent experience on uranium utilization and zirconium prices. Startup manpower is still not included in Mark IIa. The N-Reactor revised neptunium conversion constants, which were described in the May-June AOP report, DUN-AOP-20, still remain to be included, as do more up-to-date information on NFS fuels, more up-to-date assessment of U-236 inventories in fuel in the system, and more up-to-date cycle times.

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(1) "Monthly Report March-April, 1967," DUN-AOP-19. (Secret)

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Limited progress was made, during the reporting period, on adding isotopes to CAGE.

A major improvement in printout capability realized during the reporting period was that of making available detailed edit printouts. The detail edit program was used to generate data for a special non-defense plutonium pricing study. And since it was recently felt that an improved basis for the neutron factors used for allocating costs to plutonium was needed, new neutron factors are being developed and, when available, will be programmed into the CAGE Mark IIa detail edit program.

A preliminary computer definition for routines to be used in the green sheet estimate has been prepared. Programming is being held up at the present time so as to not compromise other higher priority AOP activities.

Considerable progress has been made in the reprogramming of CAGE for the major step up to Mod 2. For example, coding for neptunium irradiations is complete and fully debugged. Pu-238 enhancement coding (recycle) is completed if it is carried over from Mod 1. Some additional coding will be required, however, if multiple schedules of available civilian power reactor tails are to be included. The remainder of the items needed for the descriptor cards 001 and 002 are in the conceptual planning stage. The only item which appears to require appreciable programming effort will be the automatic determination of reactor loading modes. Comment cards will be a simple carry over from Mod 1. Burnout costs and uranium losses will also be carried over from Mod 1 unless major revisions result from current studies of interest charges on inventories. The fuel flow from the feed sites, cards 050-075, requires extension, or requires expansion from 10 types to 26 types of fuel. This is not felt to be a major problem.

Mod 1 is currently using the first 23 entries of the 40-element product array to report the products generated. Even though 76 cards are available for product reporting in Mod 2 (cards 100-175), it is believed

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that the 40-element array should be adequate, assuming that no single case will involve more than 40 different products in a campaign. All of the uranium buying cards (cards 200-299), with the exception of onsite recycle, are now operational in Mod 1 and require no change to Mod 2. The uranium selling cards (300-399) are currently available from Mod 1. Although, it is a part of the program complex file, the report generator used for calculating the annual buying and selling of spent fuel is currently on an inactive status. It can be reactivated to supply these calculated buying and selling items as part of Mod 2 output.

On the annual inventory cards (400-499), no progress has been made, pending precise clarification of the quantities desired. Simple algorithms applicable to steady-state operation can yield erroneous results at the point of the change in the reactor operational mode. Refined algorithms to provide credible match to "real world" will require extensive programming effort and approximately 1000 additional library entries.

#### CAGE Problem Status

The status of CAGE problems as of the end of August is tabulated in Table I. Some of these problems are discussed in detail in the text below.

1. Problem 1 - Use of the Mark II CAGE System to Analyze the Impact of Advanced Technology on Hanford Unit Cost.

This has been a continuing study and has been reported in earlier AOP reports, where total includable costs, plutonium residual costs, and Pu/Oy were examined. A marginal cost analysis has now been completed<sup>(1)</sup> and is summarized in the Appendix of this report.

2. Problem 2 - Headquarters Reactor Comparison Study

A total of 85 cases has been run as of the end of August to permit a Headquarter's study related to renegotiation of

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(1) D. H. Bangerter. "The Impact of Advanced Technology - Marginal Cost Analysis." DUN-AOP-56, to be issued. (Secret)

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TABLE I. Cage-Mark II Index and Status of Study Problems

Problem Number	Objective	Number of Cases	Submitted to OR	NFS Tails Used	Burnout Cost Method	Technical Program Output Tape	August 25 Status	Reference Document
1	Study the impact of advanced technology on RL Pu unit cost	124	Yes	Yes	Regular	HT-520 (39-71)	Complete	DUN-AOP-19
1 Sup.	Assist in the analysis of Problem 1	136	No	Yes	Regular	HT-520 (39-71)	Complete	
2	HQ reactor comparison study	21	Yes	Yes	Regular	HT-609 (39-99)		DUN-2419
2A	HQ reactor comparison study	6	Yes	Yes	5% Disc.	HT-609 (39-99)		DUN-2419
2A-1	HQ reactor comparison study	2	No	No	5% Disc.	HT-609 (39-99)		DUN-2419
2A-2	HQ reactor comparison study	2	No	No	5% Disc.	HT-609 (39-99)		DUN-2419
2B	HQ reactor comparison study	3	Yes	Yes	5% Disc.	HT-609 (39-99)		DUN-2460
2C	HQ reactor comparison study	10	Yes	5 Yes 5 No	5% Disc.	HT-609 (39-99)		DUN-2496
2C-1	HQ reactor comparison study	1	Yes	No	5% Disc.	HT-609 (39-99)		
2D	HQ reactor comparison study	5	Yes	No	5% Disc.	HT-609 (39-99)	Complete	DUN-2532
2E	HQ reactor comparison study	5	No	No	5% Disc. <sup>(a)</sup>	HT-609 (39-99)		DUN-2886
2F	HQ reactor comparison study	24	No	No	5% Disc.	HT-609 (39-99)		DUN-2967
2G	HQ reactor comparison study	6	No	No	5% Disc. <sup>(a)</sup>	HT-609 (39-99)		DUN-3005
3	Long-range plan	26	No	Yes	Regular	HT-689 (41-67)	Complete	
4	HQ Pu-Oy study	14	Yes	Yes	5% Disc.	HT-527 (39-83)		
4A	HQ Pu-Oy study	5	Yes	Yes	5% Disc.	HT-527 (39-83)	Complete	

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TABLE I. (contd)

Problem Number	Objective	Number of Cases	Submitted to OR	NFS Tails Used	Burnout Cost Method	Technical Program Output Tape	August 25 Status	Reference Document
5	Pu assay study	38	Yes	Yes	5% Disc.	HT-527 (39-83)	Complete	
6	FY 69 budget study	6	No	Yes <sup>(b)</sup>	Regular	HT-241 (39-88)	Complete	DUN-2728
7	Pu-Oy aspects of Problem 1	91	No	Yes	5% Disc.	HT-157 (39-70)	Complete	DUN-AOP-20 DUN-AOP-46
8	Peaceful Pu pricing	60	To be determined		Federal Register and UO <sub>3</sub> credit schedule	HT-456 (41-63)	In preparation	To be issued as DUN-AOP-61
9	Case B	10	No	No	5% Disc. <sup>(a)</sup>		Problem definition in progress, cases to be run	
10	Neptunium study	10	No	No <sup>(c)</sup>	Regular		Complete	DUN-AOP-20
11	HQ planning estimate <sup>(d)</sup>						PEA-PEB complete. PEC in progress	DUN-AOP-47 (To be issued)
12	HQ K level study	2	No	No	5% Disc.	HT-527 (39-83)	Complete	DUN-2825
13	AECOP inventory study	6	Yes	No	5% Disc. <sup>(a)</sup>	HT-036 (39-93)	Complete	DUN-AOP-48 RD

(a) With varying cascade tail assays.  
 (b) Modified to eliminate tails rich in U-236 and scheduled for use in feed for FY 68 charging.  
 (c) One Case examined the effect of a 50-ton batch of Yankee tails scheduled through NPS in FY 68.  
 (d) A number of cases were prepared manually and submitted informally to HQ and AECOP. Additional cases are in preparation. It is expected that some of these cases will be run on CAGE.

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the steam credit schedule for N Reactor. Since these studies have been carried on without site participation, no reporting will be made.

3. Problem 8 - Peaceful Plutonium Pricing Study

A total of 58 CAGE cases have now been designed and run through CAGE to produce costs for peaceful plutonium at two rates of production and with two burnout costing methods. The percent Pu-240 covered in these studies ranged from 3% to 30%. Data processing for these cases has been completed and tabulation analysis results are proceeding. The new CAGE detail printout program was used to allocate costs in these cases. Completion of the study is being delayed until revised cost allocation factors are developed.

4. Problem 9 - Case B

Agreement was reached with duPont representatives on the design of 13 cases. Detail reactor operating plans have been prepared for seven of these cases for which Hanford has the first priority on product assignments; CAGE input is being prepared. Work on the six cases in which Savannah River has first priority can begin when Savannah River's production deficit is available to us.

5. Problem 11 - Planning Estimates

Ultimately, planning estimates will be computed with CAGE. However, the planning estimates which have been worked on to date were hand-generated and for the most part involved only reactor assignments from a production standpoint. The planning estimates describe the plant operation for producing specific requirements of peaceful plutonium, tritium, and selected isotopes. Complete details on this effort will be given in the next AOP report.

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SPECIAL STUDIES

Pu-238 Production Program at Hanford - Near Term

Current forecasts of neptunium production are substantially less than the forecasts made last winter, causing some concern over the ability of the production complex to meet commitments for plutonium-238 through FY 1971. Hanford has proposed (Document DUN-AOP-44) that neptunium recovered from the Purex plant be irradiated in the Hanford-produced reactors, that Pu-238 production be increased by making 90 percent pure Pu-238 rather than the present 80 percent pure Pu-238, and that Pu-238 production be increased by accelerating the handling of neptunium so that there would be an out-of-reactor time of only 60 days between irradiations. Under these conditions Pu-238 production from Hanford neptunium will be increased about 20 percent over the next three years, compared to the present process, and less neptunium will be destroyed per unit of Pu-238 formed.

In order to implement the Pu-238 production program at Hanford and to do so promptly at low capital cost, laboratory facilities operated by Battelle-Northwest will be used for chemically processing irradiated neptunium, and facilities in the Z-Plant will be used both for denitrating neptunium and plutonium and for fabricating neptunium target cores. No general plant capital will be required during the first two or three years of the program; capital equipment costs might run as high as \$180,000. As an example, a Pu-238 unit cost in FY 1969, excluding depreciation and neptunium feed cost, is estimated to be \$115 per gram during the production of 7 kg of 90 percent pure Pu-238 in that year. Hanford Pu-238 production is assumed as starting in FY 1968. More detailed information is given in Table II, which is reproduced from DUN-AOP-44.

Long-Range Hanford Capability for Pu-238 Production

Information on Hanford's large-scale capability for Pu-238 production has been assembled in support of AECOP Task Assignment No. 5,

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TABLE II  
COSTS OF EARLY PU-238 PRODUCTION AT HANFORD

- I. General Plant Capital Cost None
- II. Capital Equipment Cost \$180,000
- III. Incremental Operating Cost to Production Division

	<u>FY 1968</u>	<u>FY 1969</u>
IV. Unit Cost Approximations		
Normal Operating Cost* Pu-238 Separated, gms		
Normal Operating Cost, \$/gm		
Neutron Allocation Cost, \$/gm		
Np Feed Material Cost, \$/gm, with Np at \$100/gm		
Approximate Unit Cost, \$/gm Pu-238 (without depreciation)		245

\*Defined as neutron-allocated, total includable cost (CAGE type).

\*\*Includes start-up cost of \$175,000.

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"Conversion of Np-237 to Pu-238, " and has been forwarded to AECOP in four letters: DUN-2900 (July 27), DUN-AOP -49 (August 3), DUN-AOP-50 (August 17), and DUN-AOP-51 (August 25).

The studies were based upon assumed neptunium processing rates of 600 and 1200 kg per year, with irradiation times varied to yield 85 and 95 percent pure Pu-238 and Pu-238 production rates of from 75 to 220 kg per year. If the Redox plant were used for chemically processing irradiated neptunium, the total required capital costs would be \$2, 400, 000 and \$3, 200, 000 for neptunium throughputs of 600 and 1200 kg, respectively. Conversion costs forecasts (excluding capital charges, inventory charges, and neptunium feed costs) are as follows:

Np-237 processing rate, kg/year	600	600	1200	1200
Pu-238 isotopic purity, %	85	90	85	90

The above Pu-238 costs have not been optimized. Under some circumstances, the use of target elements containing smaller amounts of neptunium than those used for the above calculations and so causing the Pu-238 conversion costs to be higher, may be warranted in order to reduce the neptunium inventory costs.

An Optimization Code for Fuel-Cycle Analysis

Modification of the Battelle-Northwest OPTIM code for use in fuel-cycle analysis is nearly complete and ready for debugging. OPTIM, which is being jointly funded by MFC-12 and the Reactor Development and Technology Division, is a high-speed, non-linear, optimization computer program. When debugged, OPTIM will communicate with such Battelle-Northwest chain codes as ALTHAEA (which performs burnup calculations), JASON (which performs cell physics calculations), PLOTTER (which prints out pertinent data on mass balances, cross sections, etc.), and QUICK (which can calculate dollars per unit of product as well as mills/kWh). Compared with linear programming models, OPTIM has the advantage, besides that of being non-linear, of not requiring all the cases to be run before the solution is found: OPTIM generates all the cases it needs in solving a problem. The problems it solves can have up to 10 variables.

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The first task of OPTIM will be to recalibrate the resonance shielding coefficients used in the cross-section calculation for various isotopes.

DECAY Computer Code for Use With the ISOTOPIC DATA TAPE

Recently developed for use in AOP work are the ISOTOPIC DATA TAPE and the DECAY computer code. The ISOTOPIC DATA TAPE is a library of information on the nuclear properties of isotopes, and its function is to serve specially designed computer codes. The computer code DECAY, for example, will, when provided with the starting amount of a parent isotope, use the information in the ISOTOPIC DATA TAPE to calculate how much of the original material and how much of the radioactive daughters are present at the end of a specified decay period.

A Dosimetry Code For Use With the ISOTOPIC DATA TAPE

A dosimetry code that is being modified for use with the Battelle-Northwest ISOTOPIC DATA TAPE will, after the first stage of its development, indicate both the curies produced by each isotope in a mixture and the total curies being radiated at any specified time. In the next stage of its development the dosimetry code will indicate dose rates for each isotope in a mixture, and these will be classified according to the type and energy of radiations.

Calculated Decay of One-Gram Amounts of Selected Uranium, Plutonium, Protactinium, and Neptunium Isotopes

The data in the 13 tables below were produced by the DECAY program linked to the Battelle-Northwest ISOTOPIC DATA TAPE. This combination of tape and program is capable of calculating the one-gram decay of almost any radioactive isotope of interest. The tables below also show the amount of decay products originating from one-gram amounts over different time intervals. The trace level

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indicated in the tables is equal to less than  $10^{-8}$  gram. Although all amounts shown in the tables are based on the Bateman solution for radioactive decay, <sup>(1)</sup> work is under way to improve the Bateman solution so that trace amounts smaller than  $10^{-8}$  gram can be indicated.

The tables can be useful in characterizing the time-dependent radiation from combinations of isotopes. For example, linear combinations (properly scaled) of U-232 and U-233 data could represent various degrees of clean U-233. A similar calculation can be done for clean Pu-238 containing a small amount of Pu-236.

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(1) H. Bateman. "Solution of a System of Differential Equations Occurring in the Theory of Radioactive Transformations." Proc. Cambridge Phil. Soc., vol 1r, pp. 423-427. 1910.

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TABLE III

DECAY OF ONE GRAM OF U<sup>232</sup>

Half-Life of Isotope and Decay Products, in Days <u>9.066x10<sup>-7</sup></u>	Grams After 0.5 Years	Grams After 1 Year	Grams After 5 Years	Grams After 10 Years	Grams After 20 Years
U <sup>232</sup> 2.70x10 <sup>4</sup>	9.953x10 <sup>-1</sup>	9.907x10 <sup>-1</sup>	9.542x10 <sup>-1</sup>	9.106x10 <sup>-1</sup>	8.292x10 <sup>-1</sup>
Th <sup>228</sup> 6.98x10 <sup>2</sup>	4.200x10 <sup>-3</sup>	7.683x10 <sup>-3</sup>	2.061x10 <sup>-2</sup>	2.302x10 <sup>-2</sup>	2.157x10 <sup>-2</sup>
Ra <sup>224</sup> 3.6	2.096x10 <sup>-5</sup>	3.891x10 <sup>-5</sup>	1.055x10 <sup>-4</sup>	1.180x10 <sup>-4</sup>	1.106x10 <sup>-4</sup>
Rn <sup>220</sup> 6.48x10 <sup>-4</sup>	Trace	Trace	1.845x10 <sup>-8</sup>	2.063x10 <sup>-5</sup>	1.934x10 <sup>-8</sup>
Po <sup>216</sup> 1.85x10 <sup>-6</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>212</sup> 4.43x10 <sup>-1</sup>	2.406x10 <sup>-6</sup>	4.475x10 <sup>-6</sup>	1.215x10 <sup>-5</sup>	1.359x10 <sup>-5</sup>	1.274x10 <sup>-5</sup>
Bi <sup>212</sup> 4.2x10 <sup>-2</sup>	2.281x10 <sup>-7</sup>	4.242x10 <sup>-7</sup>	1.152x10 <sup>-6</sup>	1.289x10 <sup>-6</sup>	1.208x10 <sup>-6</sup>
Po <sup>212</sup> 3.5x10 <sup>-12</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>208</sup> 2.15x10 <sup>-3</sup>	Trace	Trace	2.109x10 <sup>-8</sup>	2.358x10 <sup>-8</sup>	2.210x10 <sup>-8</sup>
Pb <sup>208</sup> Stable	3.363x10 <sup>-4</sup>	1.310x10 <sup>-3</sup>	2.211x10 <sup>-2</sup>	5.904x10 <sup>-2</sup>	1.334x10 <sup>-1</sup>

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TABLE IV

DECAY OF ONE GRAM OF U<sup>233</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 0.5 Years	Grams After 1 Year	Grams After 5 Years	Grams After 10 Years	Grams After 20 Years
U <sup>233</sup> 5.92x10 <sup>7</sup>	1.000	1.000	1.000	1.000	9.999x10 <sup>-1</sup>
Th <sup>229</sup> 2.67x10 <sup>6</sup>	2.103x10 <sup>-6</sup>	4.206x10 <sup>-6</sup>	2.67x10 <sup>6</sup>	4.202x10 <sup>-5</sup>	8.404x10 <sup>-5</sup>
Ra <sup>225</sup> 1.48x10	Trace	Trace	Trace	Trace	Trace
Ac <sup>225</sup> 1.00x10	Trace	Trace	Trace	Trace	Trace
Fr <sup>221</sup> 3.33x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
At <sup>217</sup> 3.70x10 <sup>-7</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>213</sup> 3.26x10 <sup>-2</sup>	Trace	Trace	Trace	Trace	Trace
Po <sup>213</sup> 4.63x10 <sup>-10</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>209</sup> 1.53x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>209</sup> 1.37x10 <sup>-1</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>209</sup> Stable	Trace	Trace	Trace	1.731x10 <sup>-8</sup>	6.947x10 <sup>-8</sup>

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TABLE V  
DECAY OF ONE GRAM OF U<sup>234</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 0.5 Years	Grams After 1 Year	Grams After 5 Years	Grams After 10 Years	Grams After 20 Years
U <sup>234</sup> 9.05x10 <sup>7</sup>	1.000	1.000	1.000	1.000	9.999x10 <sup>-1</sup>
Th <sup>230</sup> 2.78x10 <sup>7</sup>	1.373x10 <sup>-6</sup>	2.749x10 <sup>-6</sup>	1.374x10 <sup>-5</sup>	2.749x10 <sup>-5</sup>	5.498x10 <sup>-5</sup>
Ra <sup>226</sup> 5.92x10 <sup>5</sup>	Trace	Trace	Trace	Trace	Trace
Rn <sup>222</sup> 3.82	Trace	Trace	Trace	Trace	Trace
Po <sup>218</sup> 2.12x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
At <sup>218</sup> 1.5x10 <sup>-5</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>214</sup> 1.86x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>214</sup> 1.37x10 <sup>-2</sup>	Trace	Trace	Trace	Trace	Trace
Po <sup>214</sup> 1.90x10 <sup>-9</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>210</sup> 9.03x10 <sup>-4</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>210</sup> 7.09x10 <sup>3</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>210</sup> 5.00	Trace	Trace	Trace	Trace	Trace
Po <sup>210</sup> 1.38x10 <sup>2</sup>	Trace	Trace	Trace	Trace	Trace
Hg <sup>206</sup> 5.62x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>206</sup> 2.99x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>206</sup> Stable	Trace	Trace	Trace	Trace	1.705x10 <sup>-8</sup>

TABLE VI  
DECAY OF ONE GRAM OF Pu<sup>236</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 0.5 Years	Grams After 1 Year	Grams After 5 Years	Grams After 10 Years	Grams After 20 Years
Pu <sup>236</sup> 1.04x10 <sup>3</sup>	3.855x10 <sup>-1</sup>	7.841x10 <sup>-1</sup>	2.964x10 <sup>-1</sup>	8.785x10 <sup>-2</sup>	7.718x10 <sup>-3</sup>
U <sup>232</sup> 2.70x10 <sup>4</sup>	1.123x10 <sup>-1</sup>	2.112x10 <sup>-1</sup>	6.725x10 <sup>-1</sup>	8.410x10 <sup>-1</sup>	8.397x10 <sup>-1</sup>
Th <sup>228</sup> 6.98x10 <sup>2</sup>	2.484x10 <sup>-4</sup>	8.987x10 <sup>-4</sup>	1.057x10 <sup>-2</sup>	1.871x10 <sup>-2</sup>	2.150x10 <sup>-2</sup>
Ra <sup>224</sup> 3.64	1.206x10 <sup>-6</sup>	4.489x10 <sup>-6</sup>	5.401x10 <sup>-5</sup>	9.585x10 <sup>-5</sup>	1.102x10 <sup>-4</sup>
Rn <sup>220</sup> 6.48x10 <sup>-4</sup>	Trace	Trace	Trace	1.676x10 <sup>-8</sup>	1.927x10 <sup>-8</sup>
Po <sup>216</sup> 1.85x10 <sup>-6</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>212</sup> 4.43x10 <sup>-1</sup>	1.379x10 <sup>-7</sup>	5.153x10 <sup>-7</sup>	6.218x10 <sup>-6</sup>	1.104x10 <sup>-5</sup>	1.269x10 <sup>-5</sup>
Bi <sup>212</sup> 4.884x10 <sup>-8</sup>	1.307x10 <sup>-8</sup>	4.884x10 <sup>-8</sup>	5.895x10 <sup>-7</sup>	1.047x10 <sup>-6</sup>	1.204x10 <sup>-6</sup>
Po <sup>212</sup> 3.50x10 <sup>-12</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>208</sup> 2.15x10	Trace	Trace	1.079x10 <sup>-8</sup>	1.915x10 <sup>-8</sup>	2.203x10 <sup>-8</sup>
Pb <sup>208</sup> Stable	1.280x10 <sup>-5</sup>	9.963x10 <sup>-5</sup>	7.399x10 <sup>-3</sup>	3.258x10 <sup>-2</sup>	1.018x10 <sup>-1</sup>

TABLE VII  
DECAY OF ONE GRAM OF Pu<sup>237</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 0.5 Years	Grams After 1 Year	Grams After 5 Years	Grams After 10 Years	Grams After 20 Years
Pu <sup>237</sup> 4.56x10 <sup>1</sup>	6.229x10 <sup>-2</sup>	3.880x10 <sup>-3</sup>	Trace	Trace	0.000
Np <sup>237</sup> 7.81x10 <sup>8</sup>	9.375x10 <sup>-1</sup>	9.959x10 <sup>-1</sup>	9.998x10 <sup>-1</sup>	9.998x10 <sup>-1</sup>	9.998x10 <sup>-1</sup>
Pa <sup>233</sup> 2.74x10 <sup>1</sup>	2.961x10 <sup>-8</sup>	3.415x10 <sup>-8</sup>	3.448x10 <sup>-8</sup>	3.448x10 <sup>-8</sup>	3.448x10 <sup>-8</sup>
U <sup>233</sup> 5.92x10 <sup>7</sup>	1.851x10 <sup>-5</sup>	1.981x10 <sup>-5</sup>	2.116x10 <sup>-5</sup>	2.275x10 <sup>-5</sup>	2.594x10 <sup>-5</sup>
Th <sup>229</sup> 2.67x10 <sup>6</sup>	Trace	Trace	Trace	Trace	Trace
Ra <sup>225</sup> 1.48x10 <sup>1</sup>	Trace	Trace	Trace	Trace	Trace
Ac <sup>225</sup> 1.00x10 <sup>1</sup>	Trace	Trace	Trace	Trace	Trace
Fr <sup>221</sup> 3.33x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
At <sup>217</sup> 3.70x10 <sup>-7</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>213</sup> 3.26x10 <sup>-2</sup>	Trace	Trace	Trace	Trace	Trace
Po <sup>213</sup> 4.63x10 <sup>-10</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>209</sup> 1.53x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>209</sup> Trace	Trace	Trace	Trace	Trace	1.37x10 <sup>-1</sup>
Bi <sup>209</sup> Stable	Trace	Trace	Trace	Trace	Trace

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TABLE VIII  
DECAY OF ONE GRAM OF Pu<sup>238</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 0.5 Years	Grams After 1 Year	Grams After 5 Years	Grams After 10 Years	Grams After 20 Years
Pu <sup>238</sup> 3.29x10 <sup>4</sup>	9.962x10 <sup>-1</sup>	9.923x10 <sup>-1</sup>	9.622x10 <sup>-1</sup>	9.259x10 <sup>-1</sup>	8.572x10 <sup>-1</sup>
U <sup>234</sup> 9.05x10 <sup>7</sup>	3.780x10 <sup>-3</sup>	7.545x10 <sup>-3</sup>	3.715x10 <sup>-2</sup>	7.289x10 <sup>-2</sup>	1.404x10 <sup>-1</sup>
Th <sup>230</sup> 2.78x10 <sup>7</sup>	Trace	1.03x10 <sup>-8</sup>	2.546x10 <sup>-7</sup>	1.013x10 <sup>-6</sup>	3.957x10 <sup>-6</sup>
Ra <sup>226</sup> 5.92x10 <sup>5</sup>	Trace	Trace	Trace	Trace	Trace
Rn <sup>222</sup> 3.82	Trace	Trace	Trace	Trace	Trace
Po <sup>218</sup> 2.12x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
At <sup>218</sup> 1.50x10 <sup>-5</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>214</sup> 1.86x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Po <sup>214</sup> 1.90x10 <sup>-9</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>210</sup> 9.03x10 <sup>-4</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>210</sup> 7.09x10 <sup>3</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>210</sup> 5.00	Trace	Trace	Trace	Trace	Trace
Po <sup>210</sup> 1.38x10 <sup>2</sup>	Trace	Trace	Trace	Trace	Trace
Hg <sup>206</sup> 5.62x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>206</sup> 2.99x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>206</sup> Stable	Trace	Trace	Trace	Trace	Trace

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TABLE IX  
DECAY OF ONE GRAM OF Pu<sup>239</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 0.5 Years	Grams After 1 Year	Grams After 5 Years	Grams After 10 Years	Grams After 20 Years
Pu <sup>239</sup> 8.90x10 <sup>6</sup>	1.000	1.000	9.999x10 <sup>-1</sup>	9.997x10 <sup>-1</sup>	9.994x10 <sup>-1</sup>
U <sup>235</sup> 2.60x10 <sup>11</sup>	1.399x10 <sup>-5</sup>	2.798x10 <sup>-5</sup>	1.399x10 <sup>-4</sup>	2.797x10 <sup>-4</sup>	5.594x10 <sup>-4</sup>
Th <sup>231</sup> 1.07	Trace	Trace	Trace	Trace	Trace
Pa <sup>231</sup> 1.19x10 <sup>7</sup>	Trace	Trace	Trace	Trace	Trace
Ac <sup>227</sup> 7.74x10 <sup>3</sup>	Trace	Trace	Trace	Trace	Trace
Th <sup>227</sup> 1.82x10 <sup>1</sup>	Trace	Trace	Trace	Trace	Trace
Fr <sup>223</sup> 1.53x10 <sup>-2</sup>	Trace	Trace	Trace	Trace	Trace
Ra <sup>223</sup> 1.17x10 <sup>1</sup>	Trace	Trace	Trace	Trace	Trace
At <sup>219</sup> 6.25x10 <sup>-4</sup>	Trace	Trace	Trace	Trace	Trace
Rn <sup>219</sup> 1.50x10 <sup>-5</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>215</sup> 5.56x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Po <sup>215</sup> 2.08x10 <sup>-7</sup>	Trace	Trace	Trace	Trace	Trace
At <sup>215</sup> 1.16x10 <sup>-9</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>211</sup> 2.51x10 <sup>-2</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>211</sup> 1.49x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Po <sup>211</sup> 6.02x10 <sup>-6</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>207</sup> 3.32x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>207</sup> Stable	Trace	Trace	Trace	Trace	Trace

TABLE X  
DECAY OF ONE GRAM OF Pu<sup>240</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 0.5 Years	Grams After 1 Year	Grams After 5 Years	Grams After 10 Years	Grams After 20 Years
Pu <sup>240</sup> 2.47x10 <sup>6</sup>	9.999x10 <sup>-1</sup>	9.999x10 <sup>-1</sup>	9.995x10 <sup>-1</sup>	9.990x10 <sup>-1</sup>	9.980x10 <sup>-1</sup>
U <sup>236</sup> 8.73x10 <sup>9</sup>	5.042x10 <sup>-5</sup>	1.008x10 <sup>-4</sup>	5.040x10 <sup>-4</sup>	1.008x10 <sup>-3</sup>	2.014x10 <sup>-3</sup>
Th <sup>232</sup> 5.15x10 <sup>12</sup>	Trace	Trace	Trace	Trace	Trace
Ra <sup>228</sup> 2.08x10 <sup>3</sup>	Trace	Trace	Trace	Trace	Trace
Ac <sup>228</sup> 2.55x10 <sup>-1</sup>	Trace	Trace	Trace	Trace	Trace
Th <sup>228</sup> 6.98x10 <sup>2</sup>	Trace	Trace	Trace	Trace	Trace
Ra <sup>224</sup> 3.64	Trace	Trace	Trace	Trace	Trace
Rn <sup>220</sup> 6.48x10 <sup>-4</sup>	Trace	Trace	Trace	Trace	Trace
Po <sup>216</sup> 1.85x10 <sup>-6</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>212</sup> 4.43x10 <sup>-1</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>212</sup> 4.20x10 <sup>-2</sup>	Trace	Trace	Trace	Trace	Trace
Po <sup>212</sup> 3.50x10 <sup>-12</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>208</sup> 2.15x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>208</sup> Stable	Trace	Trace	Trace	Trace	Trace

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TABLE XI

DECAY OF ONE GRAM OF Pu<sup>241</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 0.5 Years	Grams After 1 Year	Grams After 5 Years	Grams After 10 Years	Grams After 20 Years
Pu <sup>241</sup> 4.82x10 <sup>3</sup>	9.741x10 <sup>-1</sup>	9.488x10 <sup>-1</sup>	7.691x10 <sup>-1</sup>	5.915x10 <sup>-1</sup>	3.499x10 <sup>-1</sup>
Am <sup>241</sup> 1.67x10 <sup>5</sup>	2.590x10 <sup>-2</sup>	5.112x10 <sup>-2</sup>	2.300x10 <sup>-1</sup>	4.052x10 <sup>-1</sup>	6.387x10 <sup>-1</sup>
U <sup>237</sup> 6.75	3.120x10 <sup>-8</sup>	3.039x10 <sup>-8</sup>	2.463x10 <sup>-8</sup>	1.895x10 <sup>-8</sup>	1.121x10 <sup>-8</sup>
Np <sup>237</sup> 7.81x10 <sup>8</sup>	1.024x10 <sup>-5</sup>	3.952x10 <sup>-5</sup>	8.997x10 <sup>-4</sup>	3.297x10 <sup>-3</sup>	1.123x10 <sup>-2</sup>
Pa <sup>233</sup> 2.74x10 <sup>1</sup>	Trace	Trace	Trace	Trace	Trace
U <sup>233</sup> 5.92x10 <sup>7</sup>	Trace	Trace	Trace	Trace	Trace
Th <sup>229</sup> 2.67x10 <sup>6</sup>	Trace	Trace	Trace	Trace	2.476x10 <sup>-8</sup>
Ra <sup>225</sup> 1.48x10 <sup>1</sup>	Trace	Trace	Trace	Trace	Trace
Ac <sup>225</sup> 1.0x10 <sup>1</sup>	Trace	Trace	Trace	Trace	Trace
Fr <sup>221</sup> 3.33x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
At <sup>217</sup> 3.70x10 <sup>-7</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>213</sup> 3.26x10 <sup>-2</sup>	Trace	Trace	Trace	Trace	Trace
Po <sup>213</sup> 4.63x10 <sup>-10</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>209</sup> 1.53x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>209</sup> 1.37x10 <sup>-1</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>209</sup>	Trace	Trace	Trace	Trace	Trace
Stable	Trace	Trace	Trace	Trace	Trace

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TABLE XII  
DECAY OF ONE GRAM OF Pu<sup>242</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 0.5 Years	Grams After 1 Year	Grams After 5 Years	Grams After 10 Years	Grams After 20 Years
Pu <sup>242</sup> 1.38x10 <sup>8</sup>	1.000	1.000	1.000	1.000	1.000
U <sup>238</sup> 1.65x10 <sup>12</sup>	9.066x10 <sup>-7</sup>	1.801x10 <sup>-6</sup>	8.997x10 <sup>-6</sup>	1.799x10 <sup>-5</sup>	3.597x10 <sup>-5</sup>
Th <sup>234</sup> 2.41x10 <sup>1</sup>	Trace	Trace	Trace	Trace	Trace
Pa <sup>234</sup> 2.77x10 <sup>-1</sup>	Trace	Trace	Trace	Trace	Trace
U <sup>234</sup> 9.05x10 <sup>7</sup>	Trace	Trace	Trace	Trace	Trace
Th <sup>230</sup> 2.78x10 <sup>7</sup>	Trace	Trace	Trace	Trace	Trace
Ra <sup>226</sup> 5.92x10 <sup>5</sup>	Trace	Trace	Trace	Trace	Trace
Rn <sup>222</sup> 3.82	Trace	Trace	Trace	Trace	Trace
Po <sup>218</sup> 2.12x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
At <sup>218</sup> 1.50x10 <sup>-5</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>214</sup> 1.86x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>214</sup> 1.37x10 <sup>-2</sup>	Trace	Trace	Trace	Trace	Trace
Po <sup>214</sup> 1.90x10 <sup>-9</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>210</sup> 9.03x10 <sup>-4</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>210</sup> 7.09x10 <sup>3</sup>	Trace	Trace	Trace	Trace	Trace
Bi <sup>210</sup> 5.00	Trace	Trace	Trace	Trace	Trace
Po <sup>210</sup> 1.38x10 <sup>2</sup>	Trace	Trace	Trace	Trace	Trace
Hg <sup>206</sup> 5.62x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Tl <sup>206</sup> 2.99x10 <sup>-3</sup>	Trace	Trace	Trace	Trace	Trace
Pb <sup>206</sup> Stable	Trace	Trace	Trace	Trace	Trace

TABLE XIII

DECAY OF ONE GRAM OF Pa<sup>232</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 1 Day	Grams After 5 Days	Grams After 10 Days	Grams After 15 Days
Pa <sup>232</sup> 1.32	$5.19 \times 10^{-1}$	$7.240 \times 10^{-2}$	$5.242 \times 10^{-3}$	$3.795 \times 10^{-4}$
U <sup>232</sup> $2.70 \times 10^4$	$4.085 \times 10^{-1}$	$9.275 \times 10^{-1}$	$9.946 \times 10^{-1}$	$9.993 \times 10^{-1}$
Th <sup>228</sup> $6.98 \times 10^2$	$5.595 \times 10^{-6}$	$8.134 \times 10^{-5}$	$2.034 \times 10^{-4}$	$3.279 \times 10^{-4}$
Ra <sup>224</sup> 3.64	Trace	$1.220 \times 10^{-7}$	$5.237 \times 10^{-7}$	$1.069 \times 10^{-6}$
Rn <sup>220</sup> $6.48 \times 10^{-4}$	Trace	Trace	Trace	Trace
Po <sup>216</sup> $1.85 \times 10^{-6}$	Trace	Trace	Trace	Trace
Pb <sup>212</sup> $4.43 \times 10^{-1}$	Trace	$1.051 \times 10^{-8}$	$5.330 \times 10^{-8}$	$1.146 \times 10^{-7}$
Bi <sup>212</sup> $4.20 \times 10^{-2}$	Trace	Trace	Trace	$1.079 \times 10^{-8}$
Po <sup>212</sup> $3.50 \times 10^{-12}$	Trace	Trace	Trace	Trace
Tl <sup>208</sup> $2.15 \times 10^{-3}$	Trace	Trace	Trace	Trace
Pb <sup>208</sup> Stable	Trace	$1.574 \times 10^{-8}$	$2.542 \times 10^{-7}$	$8.800 \times 10^{-7}$

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TABLE XIV

DECAY OF ONE GRAM OF Np<sup>238</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 1 Day	Grams After 5 Days	Grams After 10 Days	Grams After 15 Days
Np <sup>238</sup> 2.10	7.189x10 <sup>-1</sup>	1.920x10 <sup>-1</sup>	3.686x10 <sup>-2</sup>	7.076x10 <sup>-3</sup>
Pu <sup>238</sup> 3.29x10 <sup>4</sup>	2.811x10 <sup>-1</sup>	8.080x10 <sup>-1</sup>	9.630x10 <sup>-1</sup>	9.927x10 <sup>-1</sup>
U <sup>234</sup> 9.05x10 <sup>7</sup>	3.074x10 <sup>-6</sup>	5.291x10 <sup>-5</sup>	1.468x10 <sup>-4</sup>	2.486x10 <sup>-4</sup>
Th <sup>230</sup> 2.78x10 <sup>7</sup>	Trace	Trace	Trace	Trace
Ra <sup>226</sup> 5.92x10 <sup>5</sup>	Trace	Trace	Trace	Trace
Rn <sup>222</sup> 3.82	Trace	Trace	Trace	Trace
Po <sup>218</sup> 2.12x10 <sup>-3</sup>	Trace	Trace	Trace	Trace
At <sup>218</sup> 1.50x10 <sup>-5</sup>	Trace	Trace	Trace	Trace
Pb <sup>214</sup> 1.86x10 <sup>-3</sup>	Trace	Trace	Trace	Trace
Bi <sup>214</sup> 1.37x10 <sup>-2</sup>	Trace	Trace	Trace	Trace
Po <sup>214</sup> 1.90x10 <sup>-9</sup>	Trace	Trace	Trace	Trace
Tl <sup>210</sup> 9.03x10 <sup>-4</sup>	Trace	Trace	Trace	Trace
Pb <sup>210</sup> 7.09x10 <sup>3</sup>	Trace	Trace	Trace	Trace
Bi <sup>210</sup> 5.00	Trace	Trace	Trace	Trace
Po <sup>210</sup> 1.38x10 <sup>2</sup>	Trace	Trace	Trace	Trace
Hg <sup>206</sup> 5.62x10 <sup>-3</sup>	Trace	Trace	Trace	Trace
Tl <sup>206</sup> 2.99x10 <sup>-3</sup>	Trace	Trace	Trace	Trace
Pb <sup>206</sup> Stable	Trace	Trace	Trace	Trace

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TABLE XV

DECAY OF ONE GRAM OF Np<sup>239</sup>

Half-Life of Isotope and Decay Products, in Days	Grams After 1 Day	Grams After 5 Days	Grams After 10 Days	Grams After 15 Days
Np <sup>239</sup> 2.35	7.446x10 <sup>-1</sup>	2.288x10 <sup>-1</sup>	5.236x10 <sup>-2</sup>	1.198x10 <sup>-2</sup>
Pu <sup>239</sup> 8.9x10 <sup>6</sup>	2.555x10 <sup>-1</sup>	7.713x10 <sup>-1</sup>	9.478x10 <sup>-1</sup>	9.882x10 <sup>-1</sup>
U <sup>235</sup> 2.60x10 <sup>11</sup>	Trace	1.806x10 <sup>-7</sup>	5.159x10 <sup>-7</sup>	8.958x10 <sup>-7</sup>
Th <sup>231</sup> 1.07	Trace	Trace	Trace	Trace
Pa <sup>231</sup> 1.19x10 <sup>7</sup>	Trace	Trace	Trace	Trace
Ac <sup>227</sup> 7.74x10 <sup>3</sup>	Trace	Trace	Trace	Trace
Th <sup>227</sup> 1.82x10 <sup>1</sup>	Trace	Trace	Trace	Trace
Fr <sup>223</sup> 1.53x10 <sup>-2</sup>	Trace	Trace	Trace	Trace
Ra <sup>223</sup> 1.17x10 <sup>1</sup>	Trace	Trace	Trace	Trace
At <sup>219</sup> 6.25x10 <sup>-4</sup>	Trace	Trace	Trace	Trace
Rn <sup>219</sup> 1.50x10 <sup>-5</sup>	Trace	Trace	Trace	Trace
Bi <sup>215</sup> 5.56x10 <sup>-3</sup>	Trace	Trace	Trace	Trace
Po <sup>215</sup> 2.08x10 <sup>-9</sup>	Trace	Trace	Trace	Trace
At <sup>215</sup> 1.16x10 <sup>-9</sup>	Trace	Trace	Trace	Trace
Pb <sup>211</sup> 2.51x10 <sup>-2</sup>	Trace	Trace	Trace	Trace
Bi <sup>211</sup> 1.49x10 <sup>-3</sup>	Trace	Trace	Trace	Trace
Po <sup>211</sup> 6.02x10 <sup>-6</sup>	Trace	Trace	Trace	Trace
Tl <sup>207</sup> 3.32x10 <sup>-3</sup>	Trace	Trace	Trace	Trace
Pb <sup>207</sup> Stable	Trace	Trace	Trace	Trace

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APPENDIX

THE IMPACT OF ADVANCED TECHNOLOGY  
ON THE ADJUSTED TOTAL INCLUDABLE COST  
AND ON THE PLUTONIUM MARGINAL UNIT COST

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## INTRODUCTION

Several reports have been issued describing calculations of the impact that advanced technology exerts on Hanford unit cost. (1, 2, 3) The marginal cost analysis presented herein is a continuation of the overall study to characterize the cost-production features of the Hanford reactors. The results are based on CAGE Mark II Problem 1 cases. Additional detailed results will be reported later. (4)

## TECHNOLOGIES AND REACTOR DECREMENTS STUDIED

The present study is primarily directed toward evaluating advanced technology cases, but current technology cases are included for reference purposes. The technologies studied are defined below and listed in Table A-I. The five modes are identified by Roman numerals and this identification will be used here throughout.

### Current Technology Modes

- Weapons plutonium production with LiAl blankets at the small and K reactors. The K-Reactor power levels are limited to the administrative level of 4400 MW; N Reactor is limited to its design level of 4000 MW and produces weapons-grade plutonium.
- Coproduction of weapons plutonium and tritium using the 95\* coproduct (E-N) mode at the small and K Reactors and the 210\* coproduct loading at N Reactor. Power levels are limited as above. LiAl targets are used in the 95 coproduct loadings and LiAlO<sub>2</sub> targets in the N-Reactor coproduct loading.

- 
- (1) "Monthly Report - March - April, 1967, " DUN-AOP-19. (Secret)
  - (2) "Monthly Report - May - June, 1967, " DUN-AOP-20. (Secret)
  - (3) D. H. Bangerter. "Hanford Pu/Oy Ratios, " DUN-AOP-46. August 11, 1967. (Secret).
  - (4) D. H. Bangerter. "The Impact of Advanced Technology-Marginal Cost Analysis, DUN-AOP-56. To be issued. (Secret)

\* 95 and 210 designations indicate uranium drivers of 0.95 percent U-235 and 2.10 percent U-235 enrichment, respectively.

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Advanced Technology Modes

- Weapons plutonium production in all reactors. The small and K reactors have their central zone tubes overbored (1500 tubes overbored 1.0 inch in B and C reactors, and 2400 tubes overbored 0.925 inches in KE and KW reactors).
- Coproduction of plutonium and tritium in all reactors, with each of them using  $\text{LiAlO}_2$  targets and 210 drivers. Fuel and targets are housed in separate tubes, as contrasted to "stripe" charges in the 95 coproduct loadings.
- Coproduction of plutonium and tritium in all reactors, with small and K reactors overbored as described above. All reactors use 210 drivers.

In the advanced technology cases N Reactor is assumed to operate at 4800 MW (as soon as possible) and the K Reactors are no longer limited to the administrative power level of 4400 MW, so that each of them has an annual average level of 4700-4800 MW.

TABLE A-I. Technology Listing

	Current Technology Modes		Advanced Technology Modes		
	I	II	III	IV	V
	Pu	Coproduct	Pu	Coproduct	Coproduct
<u>Small and K Reactors</u>					
Power Level - K Reactors(a)	4380 MW	4380 MW	4775 MW	4710 MW	4775 MW
Fuel Geometry	Current	Current	Overbore	Current	Overbore
Uranium Enrichment	71 <sup>(b)</sup> 95 <sup>(c)</sup>	95	71, 95	210 <sup>(d)</sup>	210
<u>N Reactor</u>					
Power Level	4000 MW	4000 MW	4800 MW	4800 MW	4800 MW
Uranium Enrichment	100 <sup>(e)</sup>	210	100	210	210

(a) Annual Average  
 (b) 0.711% U-235  
 (c) 0.947% U-235  
 (d) 2.10% U-235  
 (e) 0.947% U-235 + 1.25% U-235 spike, resulting in an approximate average enrichment of 1% U-235.

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Decremental unit costs have customarily been employed in marginal cost analysis of the reactor sites. In calculating decremental unit costs for this study, three reactor shutdown sequences were studied:

- 1) B, C, N, and K
- 2) B, C, K, and N
- 3) B, C, K, and K

These shutdown sequences yielded the following reactor decrements for marginal cost analysis:

- $B_1$  = B Reactor in shutdown position one.
- $C_2$  = C Reactor in shutdown position two.
- $K_3$  = K Reactor in shutdown position three.
- $N_3$  = N Reactor transferred in position three.
- $K_4$  = K Reactor in shutdown position four when the other K Reactor is shut down in position three.
- $K'_4$  = K Reactor in shutdown position four when N Reactor is transferred in position three.

$N_4$  = N Reactor transferred in position four.

The decrements defined above will be identified throughout this document by the codes indicated.

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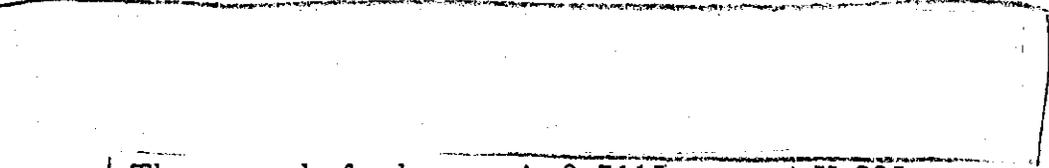
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GENERAL ASSUMPTIONS

- In all cases, D Reactor is shut down on July 1, 1967. It is also assumed, in those cases of fewer than five reactors operating, that the other reactors are shut down and N Reactor is transferred to WPPSS on July 1, 1968.
- All unit cost calculations are based on grams of product delivered.
- Offsite fuel fabrication and tritium separation costs exclude incremental research and development costs and capital expenditures.
- Offsite fabrication costs are based on the assumption that, beginning in FY 1969, all Savannah River reactors are operating on 1.5 percent coproducer fuel. SR Case 431 is used.



The cascade feed assay is 0.7115 percent U-235, and the tails assay is 0.2 percent U-235 (valued at zero dollars).

- Savannah River tritium separation costs are based on data received from Savannah River. <sup>(1)</sup>



- FY 1978 is chosen to represent an equilibrium year. The steam credit for N Reactor in that year is \$6.7 million.

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(1) F. E. Kruessi. "Tritium Separations Costs," DPST-66-95-00053 (HAN-95870). October 17, 1966. (Secret)

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- During the preparation of this study, a reevaluation of neptunium yield data for N Reactor showed that the neptunium production in CAGE is overstated for that reactor. <sup>(1)</sup> An adjustment in the neptunium production has not yet been made in the CAGE model or in the data presented in this document.
- Recent information indicates that the NFS schedule used in CAGE as a source of fuel recycle blend stock is obsolete. No attempt has been made to change that schedule for this study.
- In the advanced technology cases, the new modes are assumed initiated as follows:
  1. Overbore sequence is BCKK, with the first reactor being shut down for modernization on July, 1970. Each small reactor requires three months for overboring and each K requires six months.
  2. The 210 coproduct mode for all conventional reactors is begun on July 1, 1970. N Reactor goes on sustained 210 coproduct operation July 1, 1968.
  3. Complete conversion of the fuel manufacturing plant to the hot-die-sized fuel process on July 1, 1970 has been assumed in CAGE programming and, hence, is included in these study cases. However, due to uncertainties in the future product mix, a recent decision was made to proceed only with partial conversion of the facilities to hot-die-sizing. Under the reduced scope, only sufficient hot-die-sizing equipment will be installed to produce fuel for two overbored reactors operating on either weapons grade plutonium or 210 coproduct modes. This study does not reflect this latest change.

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(1) "Monthly Report - May - June, 1967," DUN-AOP-20. (Secret)

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Plutonium Marginal Unit Cost \$/g

Tritium Value \$/g

FIGURE A-6. Marginal Unit Cost  
IV - Advanced Technology - Coproduct  
FY 1978

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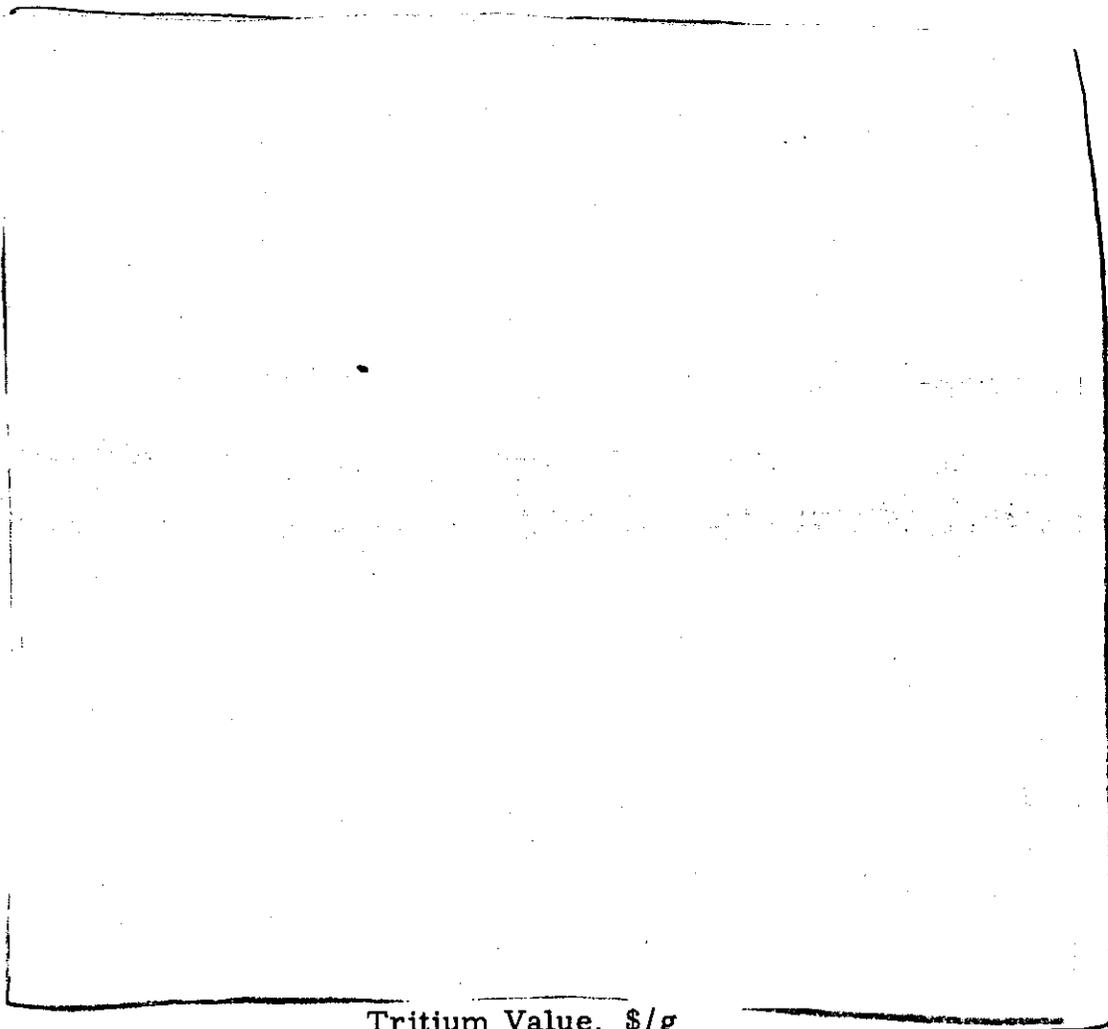
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Plutonium Marginal Unit Cost, \$/g



Tritium Value, \$/g

FIGURE A-5. Marginal Unit Cost  
III - Advanced Technology - Plutonium  
FY 1978

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Plutonium Marginal Unit Cost, \$/g

Tritium Value, \$/g

FIGURE A-4. Adjusted Total Includable Cost  
I - Current Technology - Plutonium  
FY 1978

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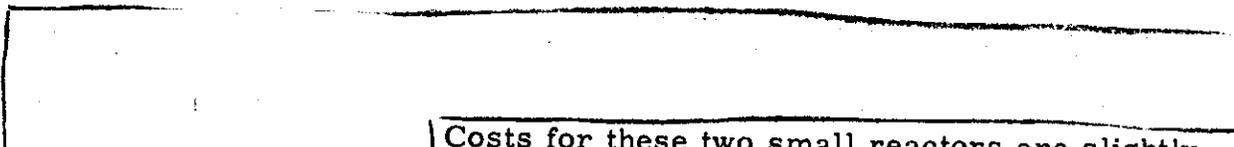
Plutonium Marginal Unit Cost

The marginal unit cost of plutonium is shown on Figures A-4, A-5, and A-6, as a function of the value placed on tritium.



Each line in the figure represents marginal unit costs for a specific reactor decrement. Table A-II lists the marginal unit costs for each of the decrements studied in Reference 1.

The coproduct mode (Figure A-6) indicates the very obvious sensitivity of plutonium marginal unit costs to the value placed on tritium.



Costs for these two small reactors are slightly lower when overbore is combined with the 2.1 coproduct mode, as shown on Table A-II.

TABLE A-II. Plutonium Marginal Unit Cost  
FY 1978

<u>Reactor Decrement</u>	<u>Mode I, Pu Unit Cost</u>	<u>Mode II, Pu Unit Cost</u>	<u>Mode III, Pu Unit Cost</u>	<u>Mode IV, Pu Unit Cost</u>	<u>Mode V, Pu Unit Cost</u>
B <sub>1</sub>					
C <sub>2</sub>					
K <sub>3</sub>					
N <sub>3</sub>					
K <sub>4</sub>					
K <sub>4</sub> <sup>1</sup>					
N <sub>4</sub>					

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Adjusted Total Includable Cost, \$ in Millions

Plutonium Delivered, Kg

FIGURE A-3. Adjusted Total Includable Cost  
IV - Advanced Technology - Coproduct  
FY 1978

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Adjusted Total Includable Cost (\$ in millions)

Plutonium Delivered, Kg

**FIGURE A-2.** Adjusted Total Includable Cost  
III - Advanced Technology Overbore - Plutonium  
FY 1978

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Adjusted Total Includable Cost, \$ in millions

Plutonium Delivered, Kg

FIGURE A-1. Adjusted Total Includable Cost  
I-Current Technology-Plutonium  
FY 1978

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RESULTS

A detailed treatment of all modes in the adjusted total includable cost and in the plutonium marginal unit cost cases can be found in Reference 1 below. Only representative results from that document are included in this report.

Adjusted Total Includable Cost

Adjusted total includable cost, as used in Figures A-1, A-2, and A-3, may be defined as the Hanford total includable costs, plus an allocated portion of the offsite fabrication and tritium separations costs, less dollar credits for the production of tritium, neptunium, and steam.

Figures A-1, A-2, and A-3 show the relationship of adjusted total includable cost to the quantity of plutonium delivered at various levels of operation. The lines connecting the points indicate the changing relationship between costs and production as each of the three different shutdown sequences are followed.

The plutonium modes (Figures A-1 and A-2) show a much higher adjusted total includable cost and plutonium production than the coproduct mode (Figure A-3) for the following reasons:

- The plutonium mode produces more plutonium than the coproduct mode, in which up to half the plutonium has been traded off for tritium.
- The coproduct mode adjusted total includable costs are much lower because of the high tritium credits applied against them.

In Figures A-1, A-2, and A-3, the difference between the higher residual cost line (B, C, N, and K shutdown sequence) and the lower residual cost line (B, C, K, and K shutdown sequence) may be explained by the \$6.7 million N-Reactor steam credit and by a large N-Reactor neptunium credit (with neptunium credited at \$150 per gram).

(1) D. H. Bangerter. "The Impact of Advanced Technology-Marginal Cost Analysis," DUN-AOP-56, to be issued. (Secret)

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