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7. Abstract

The total production of plutonium and tritium in the Hanford production reactors was determined from the most reliable sources available. These sources are semi-annual summaries of official accountability reports. Independent modeling using reactor production history and validated production conversion factors gave independent verification of the accountability reports. Full documentation of all sources and operational data are provided in this report.

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PLUTONIUM AND TRITIUM PRODUCED IN THE HANFORD SITE PRODUCTION REACTORS

EXECUTIVE SUMMARY

In a news release on December 7, 1993, the Secretary of Energy announced declassification action that included totals for plutonium and tritium production in the Hanford Site production reactors. This information was reported as being preliminary because it was not fully supported by documentation. Subsequently, production data were made available from the U.S. Department of Energy-Headquarters (DOE-HQ) records that indicated an increase of about one and one-half metric tons in total plutonium production. The Westinghouse Hanford Company was tasked by the U.S. Department of Energy-Richland Operations Office to substantiate production figures and DOE-HQ data and to provide a defensible report of weapons- (6 wt% ^{240}Pu) and nonweapons- (fuels-) grade (nominally 9 wt% or higher ^{240}Pu) plutonium and tritium production in the Hanford Site production reactors.

The task was divided into three parts. The first part was to determine plutonium and tritium production based on available reported accountability records. The second part was to determine plutonium production independently by calculational checks based on reactor thermal power generation and plutonium conversion factors representing the various reactor fuels. The third part was to resolve differences, if they occurred, in the reported and calculational results.

Reported production of plutonium and tritium is recognized as a process estimate that was refined with operating experience as chemical process data and fuel design models became more complete and sophisticated. The basis for reporting values also changed with time and was reported variously as chemically processed quantities, discharged fuel awaiting processing, and estimated production based on reactor power. The calculated plutonium production determined from reactor power levels and discharged fuel provided a consistent basis on which to compare the reported accountability values. The reported and calculated estimates of plutonium production in annual summaries and total quantities are in very good agreement. The small differences on a yearly comparison are explainable by considering the options used in reporting.

The production of tritium was fully supported by documentation and was included in this study for completeness. A calculational check of the reported tritium accountability was not attempted, nor would it have been feasible due to the lack of definitive operating data.

The quantity of nonweapons- (fuels-) grade plutonium produced was also addressed in this report. The nonweapons-grade plutonium was produced by the Hanford Site reactors from fical year (FY) 1963 through FY 1981. The calculational estimates based on fuel discharge fully confirmed the quantities reported by records from DOE-HQ sources.

All references pertaining to plutonium and tritium production have been identified. These references cover the entire plutonium production period from the Hanford Site production reactors with the exception of initial reactor operation through calendar year 1946. There are no accountability records available for October 1944 through December 1946. However, DOE-HQ has provided an undocumented source that places the plutonium production at 493 kg for this period. This quantity was in very good agreement with calculational estimates. The DOE-HQ quantity of plutonium produced was confirmed with a high degree of confidence.

The independent check of the reported plutonium production required a database of reactor production history. The documentation of reactor production history is referenced from 1951 through the end of operation. The period of operation prior to 1951 is consistent with that used in the dose reconstruction study where considerable effort was expended to provide the best estimate of production. Documentation of all available reactor operating data or best-estimate of reactor operating history has been provided in this report.

In summary, the DOE-HQ-reported accountability records of plutonium and tritium production were determined to be the most defensible record of Hanford Site reactor production. The DOE-HQ records were consistently supported by the independent calculational checks and the records of operational data. Total production quantities are 67.4 MT total plutonium, which includes 12.9 MT of nonweapons-grade plutonium. The total tritium production was 10.6 kg.

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LIST OF TERMS

DOE-HQ	U.S. Department of Energy - Headquarters
FY	fiscal year
GWd	gigawatt days
I&E	internal- and external- (coolant)

1.0 INTRODUCTION

The total production quantities of plutonium and tritium from the Hanford Site production reactors were made public by the Secretary of Energy on December 7, 1993. These production numbers included weapons- and nonweapons- (fuels-) grade plutonium, losses to the waste storage tanks, and unprocessed fuel in the storage basins. These production quantities were announced as preliminary at that time based on nonclassified sources.

A difference of about one and one-half metric tons of total plutonium was identified between the U.S. Department of Energy-Headquarters (DOE-HQ) records and the public announcement of December 7, 1993. The purpose of this report is to substantiate the production history of plutonium and tritium by independent calculations and from available and documented references.

Historically, the production of plutonium and other isotopes in the Hanford Site production reactors was estimated from a process flow. At any given time, some plutonium inventory would exist in the reactor core, other plutonium would exist in discharged fuel awaiting chemical processing, and the balance would be in material produced through or undergoing chemical processing (including losses).

The production of plutonium and other isotopes was estimated from fuel exposure, from reactor power production, and from conversion factors adjusted with chemical processing data. These estimates were improved as more processing data and better fuel design models became available. It was recognized from the start of this study that the reporting of plutonium accountability can be, and was, historically determined by three methods. The first method was to estimate production by reactor power operation and plutonium conversion factors. The second method was to determine production from discharged fuel whose power exposure was determined from individual process tube power measurements. The third method was to determine plutonium production from the processed output of the chemical separations plants. Each method will produce identical total quantities of plutonium. However, time delays in reporting will be caused by processing holdup, where applicable. The independent modeling of plutonium production provided very helpful insight in determining the most likely reporting method used at various times.

Two analysis approaches are discussed in this report. One approach computes plutonium production from reactor power data and the other from discharged fuel information. The consistency of the analyses provided supporting data for plutonium production estimates for the first three years of production where production records are not available. The results of these analyses also provided an independent check on the reported plutonium accountability.

The analyses use a database of the reactor production history and a conversion factor model for the individual fuel types. The production history database provides monthly reactor power generation, discharge of fuel by type, quantity of fuel, and fuel exposure history. These operations data were substantiated by full documentation from 1951 to the end of production reactor operation. The database is consistent with estimates of reactor operation determined by the Hanford environmental dose reconstruction studies for production prior to 1951. The documented plutonium conversion factors for fuels used near the end of reactor operations were used to determine plutonium production from reactor power and discharged fuel during the maximum production operating periods. Conversion factors for the fuels not included in available documentation were determined by state-of-the-art physics computer codes or engineering estimates.

The results of this study show a very good correlation of accountability reporting with operating records. The study also provides documented justification of the results and conclusions made in this report.

2.0 DISCUSSION

The total production quantity of plutonium was determined by independent approaches that involved checking accountability records and making a calculational check. The reported accountability records consisted of semiannual summaries in classified, unclassified, or declassified documents. In those reports that are still classified, the data needed for this report have been declassified. The calculational check involved development of a database characterizing the historical operation of the reactors and the conversion factors for plutonium production. The different approaches are discussed below.

2.1 REPORTED PLUTONIUM AND TRITIUM PRODUCTION VALUES

The reported production values were determined from official accountability reports that summarized the production of plutonium and tritium on a semiannual basis. These reports were written at the time the production occurred when the most knowledgeable resources and detailed data were available to determine the best measurement or estimate of production. However, these reported production values were based on various accounting methods. For example, one reference (Nolan 1982) states that production was based on separated plutonium ready to be shipped offsite from the years 1945 to 1948. During part of 1948 and 1949, plutonium production was based on the quantity through final chemical processing. After that time, plutonium production was based on discharged fuel. It is apparent from personal knowledge and from comparison with calculated results that eventually plutonium production was also determined by estimates of monthly reactor power production.

The reported plutonium production was always forward looking. That is, a report of production was not changed once it was issued. If an adjustment was required from a previous report, this adjustment was made to the current report. The result was that the cumulative production was reasonably close to the accepted total and the final quantity was fully corrected. Comparisons of the cumulative production between reported accountability and calculated estimates generally were free of small fluctuations in annual summaries and thus provided the most consistent comparisons.

Semiannual plutonium and tritium production is listed in Tables 1 and 2, respectively. This production is documented in semiannual reports except for the transition period from July 1976 through March 1977, when the beginning of the fiscal year was changed from July to September. The document number is provided for each reported accountability value. These documents cover the time from January 1948 through the end of production. An estimate of the plutonium production prior to 1948 was given as 493 kg. This estimate was taken from the data provided informally by DOE-HQ. The estimate is in reasonable agreement with a calculational check for that time period. The calculational check will be discussed in Section 2.2.3.

2.2 PLUTONIUM CALCULATIONAL ESTIMATES

The production of plutonium was determined by calculations from reactor powers and historical data for discharged fuel. These calculations were performed as a check of the reported plutonium production based on accountability records. These calculations also provided a consistent basis for comparing and understanding accounting methods. The first calculational method was based on reactor power, the second calculational method was based on exposure and mass of discharged fuel.

The first task of the calculational approach was to develop a database of reactor-power history and fuel-discharge history. The second task of the calculational approach was to determine conversion factors relating power to plutonium. These databases and conversion factors are discussed below.

2.2.1 Reactor History Databases

A historic data library of reactor power production and fuel discharge is essential for the calculational model of plutonium production. Historic reactor power-production data is documented in monthly reports beginning in 1948. A listing of these documents is provided in Appendix A. Prior to 1948, the production was estimated from available data pertaining to reactor operation. Considerable work on dose reconstruction (Heeb and Bates 1994) has provided a best-estimate of reactor operation during the period beginning operation in 1944 through 1971. Fuel-discharge data were available from the TRAC study (Jungfleish 1984 and 1992) for production from 1944 through 1971. The format of the TRAC database was extended to include the balance of N Reactor operation. Reactor power production and fuel discharge beyond 1972 pertained only to N Reactor. The power production was determined from monthly reports referenced in Appendix A. The fuel discharge beyond 1971 was determined from operational records of individual process tube discharges.

A self-consistent check of the reactor power and fuel discharge data was made. Cumulative reactor production and fuel discharge, in gigawatt-days (GWd), is shown in Figure 1 and in Table 3. The agreement between these data are very good. Differences in the reactor production are due to measurement uncertainties in bulk reactor power and in individual tube powers.

Table 1. Hanford Plutonium Production 1944 - 1988. (1 of 3)

FISCAL YEAR		DuPont RIS-HAA (kg)	General Electric RIS-HGE (kg)	General Electric RIS-HZA (kg)	Douglas United Nuclear RIS-HXA (kg)	United Nuclear Corp RIS-HXA (kg)	Total Production Fiscal Year (kg)	Document Number
1944								
1945								
1946								
1947							493 *	
	Jan-Jun	68						FTS-667
1948	Jul-Dec	115					183	FTS-667
	Jan-Jun	124						FTS-668
1949	Jul-Dec	146					270	FTS-668
	Jan-Jun	185						FTS-669
1950	Jul-Dec	206					392	FTS-670
1951	Jan-Jun		288				288	FTS-845
	Jul-Dec		312					FTS-00864
1952	Jan-Jun		350				662	FTS-00953
	Jul-Dec		397					FTS-01012
1953	Jan-Jun		441				838	FTS-01085
	Jul-Dec		543					FTS-01203
1954	Jan-Jun		570				1,113	FTS-01311
	Jul-Dec		625					FTS-01375
1955	Jan-Jun		788				1,413	FTS-01481
	Jul-Dec		927					FTS-01549
1956	Jan-Jun		1,147				2,074	FTS-01644
	Jul-Dec		1,269					FTS-01880
1957	Jan-Jun		1,392				2,662	FTS-01980
	Jul-Dec		1,608					FTS-CLVI-294
1958	Jan-Jun		1,695				3,303	FTS-CLVI-463
	Jul-Dec		1,719					HAN-75996
1959	Jan-Jun		1,861				3,581	HAN-72720
	Jul-Dec		2,103					HAN-74367
1960	Jan-Jun		2,163				4,266	HAN-75996
	Jul-Dec		2,206					HAN-77472
1961	Jan-Jun		2,243				4,449	HAN-79125,79134

Table 1. Hanford Plutonium Production 1944 - 1988. (2 of 3)

	Jul-Dec	2,064					HAN-80684,80718
1962	Jan-Jun	2,105				4,169	HAN-82406
	Jul-Dec	2,027					HAN-83974
1963	Jan-Jun	2,159				4,187	HAN-85615
	Jul-Dec	2,110					HAN-87271
1964	Jan-Jun	2,393				4,503	HAN-88957
	Jul-Dec		2,555				HAN-90402,90424
1965	Jan-Jun		2,215			4,770	HAN-92119
	Jul-Dec		1,371	539			HAN-93628,DUN-509
1966	Jan-Jun		272	1,748		3,930	HAN-95393,DUN-1303
	Jul-Dec		217	1,318			HAN-96400,94417
1967	Jan-Jun		272	1,848		3,655	HAN-98194,98198
	Jul-Dec			1,543			HAN-98550,98434
1968	Jan-Jun			1,480		3,023	DUN-4436
	Jul-Dec			1,350			DUN-5250
1969	Jan-Jun			1,189		2,539	DUN-5942
	Jul-Dec			1,011			DUN-6557
1970	Jan-Jun			673		1,684	DUN-7049
	Jul-Dec			592			DUN-7457
1971	Jan-Jun			145		737	DUN-7682
	Jul-Dec			311			DUN-7828
1972	Jan-Jun			103		414	DUN-7991
	Jul-Dec			353			DUN-8093
1973	Jan-Jun			320		673	DUN-8137
	Jul-Dec			306			DUN-8137
1974	Jan-Jun				301	607	UNI-117
	Jul-Dec				268		UNI-117
1975	Jan-Jun				288	557	UNI-117
	Jul-Dec				215		UNI-117
1976	Jan-Jun				214	429	UNI-509
	Jul-Mar				334		UNI-509
1977	Apr-Sept				226	560	UNI-848
	Oct-Mar				358		UNI-1032
1978	Apr-Sept				200	559	UNI-1154
	Oct-Mar				367		UNI-1286
1979	Apr-Sept				177	544	UNI-1356-2
	Oct-Mar				307		UNI-1356-8
1980	Apr-Sept				105	413	UNI-1356-14

Table 1. Hanford Plutonium Production 1944 - 1988. (3 of 3)

	Oct-Mar	16		UNI-1356-20
1981	Apr-Sept	181	196	UNI-1356-26
	Oct-Mar	262		UNI-1860-6
1982	Apr-Sept	187	449	UNI-1860-12
	Oct-Mar	374		UNI-1860-18
1983	Apr-Sept	249	624	UNI-1860-24
	Oct-Mar	194		UNI-1860-30
1984	Apr-Sept	100	294	UNI-1860-36
	Oct-Mar	297		UNI-1860-42
1985	Apr-Sep	336	633	UNI-1860-48
	Oct-Mar	176		UNI-1860-54
1986	Apr-Sept	758	934	UNI-3964-06
	Oct-Mar	312		UNI-4171-06
1987	Apr-Sept	0	312	WHC-SFGD-00043 3
	Oct-Mar	(19)		WHC-SFGD-00031 6
1988	Apr-Sept	(2)	(21)	WHC-SFGD-00031 12
	Oct-Mar	0		WHC-SFGD-00031 18
1989	Apr-Sept	2	2	WHC-SFGD-00031 24
	Total		67,362	

*Based on number from HQ, no information on 1944,1945,1946, and 1947 at Hanford

Table 2. Hanford Tritium Production 1944 - 1973. (1 of 2)

FISCAL YEAR			Product cc	By-Product cc*	Over 90%	Under 90%	Total liters	Semi-Annual Production In grams	Total Production Fiscal Year In Grams	Document Number
1944										
1945										
1946										
1947										
1948										
1949	Nov-Dec		16543	38970			56		15	FTS-668
1950	Jan-Dec									
		From extraction			138870					
		From outgas				7594				
		Not extracted		21684	399		169		45	FTS-670
1951	Jan-Dec									
		From extraction			440433	9287				
		From outgas				233				
		Not extracted			1073					
		Reprocessed				375	451		121	FTS-864
1952	Jan-Dec									
		From extraction			1376071	100360				
		From outgas				200				
		Not extracted			1630					
		Reprocessed				760	1479		398	FTS-953
1953	Jan-Dec									
							953		257	FTS-1203
1954	Jan-Jun						2863		770	FTS-1311
	Jul-Dec							428		FTS-1375
1955	Jan-Jun							110	538	FTS-1481
	Jul-Dec							40		FTS-1549
1956	Jan-Jun							39	79	FTS-1644
	Jul-Dec							41		FTS-1880
1957	Jan-Jun							30	71	FTS-1980
	Jul-Dec							45		FTS-CLVI-294
1958	Jan-Jun							64	109	FTS-CLVI-463
	Jul-Dec							71		HAN-72996
1959	Jan-Jun							78	149	HAN-72720
	Jul-Dec							121		HAN-74376

Table 2. Hanford Tritium Production 1944 - 1973. (2 of 2)

FISCAL YEAR		Product cc	By-Product cc*	Over 90%	Under 90%	Total liters	Semi-Annual Production In grams	Total Production Fiscal Year In Grams	Document Number
1960	Jan-Jun						137	258	HAN-75996
	Jul-Dec						145		HAN-77472,77488
1961	Jan-Jun						302	447	HAN-79134,79125
	Jul-Dec						644		HAN-80684
1962	Jan-Jun						261	905	HAN-82406
	Jul-Dec						257		HAN-83974
1963	Jan-Jun						740	998	HAN-85615
	Jul-Dec						842		HAN-87271
1964	Jan-Jun						933	1,776	HAN-88974
	Jul-Dec						648		HAN-90402
1965	Jan-Jun						209	857	HAN-92119
	Jul-Dec						49		HAN-93628
1966	Jan-Jun						2	51	HAN-95170
	Jul-Dec						133		HAN-96413,98194
1967	Jan-Jun						964	1,096	HAN-98198
	Jul-Dec						685		HAN-98434
1968	Jan-Jun						560	1,245	DUN-4436
	Jul-Dec						46		DUN-5250
1969	Jan-Jun						89	135	DUN-5942
	Jul-Dec						0		DUN-6557
1970	Jan-Jun						11	11	DUN-7049
	Jul-Dec						69		DUN-7457
1971	Jan-Jun						11	79	DUN-7682
	Jul-Dec						0		DUN-7828
1972	Jan-Jun						0	0	DUN-7991
	Jul-Dec						149		DUN-8093
1973	Jan-Jun							149	
	Jul-Dec								
	Totals							10,559	

*Cubic Centimeter

Figure 1. Total Production of Hanford Site Production Reactors by Bulk Power and Fuel Discharge.

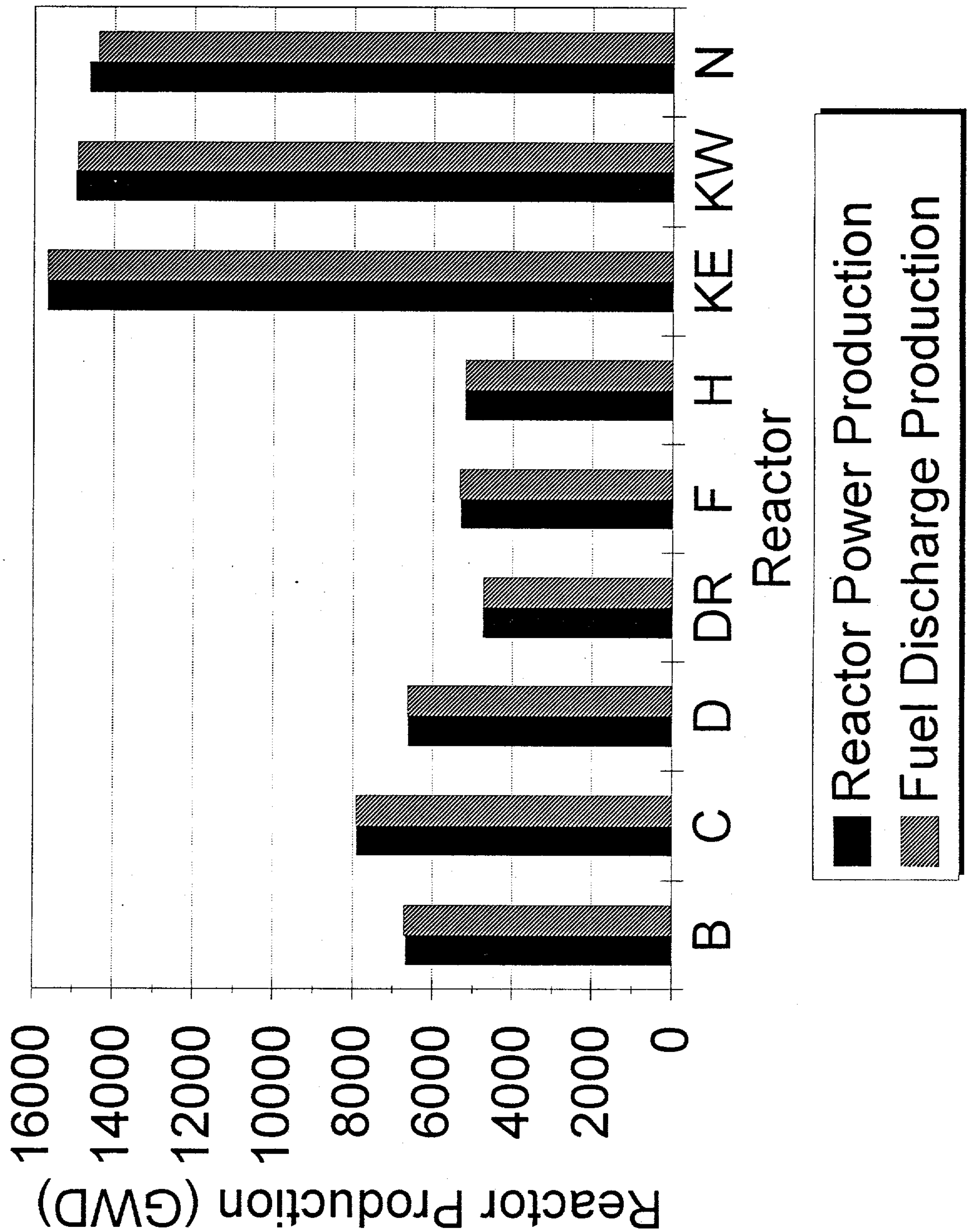

Table 3. Total Production of Hanford Site Production Reactors by Bulk Power and Fuel Discharge.

	Reactor Power Production (GWD)	Fuel Discharge Production (GWD)
B	6,668	6,702
C	7,898	7,905
D	6,609	6,628
DR	4,750	4,733
F	5,307	5,332
H	5,199	5,196
KE	15,649	15,648
KW	14,960	14,920
N	14,610	14,394
Total	81,651	81,457

Note: Reactor power production is a summation of bulk reactor power. Fuel discharge production is a summation of product of fuel discharge mass and exposure.

2.2.2 Plutonium Conversion Factors

The quantity of plutonium produced typically was estimated from reactor power and discharged fuel by using a plutonium conversion factor with units of grams per megawatt-day (g/MWd). The reactor power was reported in megawatt days (MWd), the fuel exposure was reported in megawatt days per ton (MWd/t), and the fuel discharge quantity was reported in short tons (t = 2,000 lb).

The plutonium conversion factor and ^{240}Pu content are dependent on the fuel design, uranium enrichment, and exposure. The plutonium conversion factors and ^{240}Pu content are expressed as exposure-dependent polynomials and are described in Appendix B.

The plutonium conversion factors for fuels from the single-pass reactors (B, C, D, DR, F, H, KE, and KW), and for N Reactor MKI fuels were documented in declassified production tables (Perl 1967) for internal- and external-coolant (I&E) fuels that have a central water-cooled annulus. These tables represented a final estimate of plutonium production as determined by the predictive models and as validated with data from chemical-separations measurements. An earlier fuel type used in the single-pass reactors was a solid-slug fuel that had the same outer dimensions as the I&E fuels. The heavier solid-slug fuels had a higher plutonium conversion factor than the I&E fuels. Documentation of plutonium conversion factors and operating conditions is no longer available on which to reconstruct these data. Therefore, plutonium conversion factors were estimated. A corrected plutonium conversion factor for the solid fuel was determined by increasing the coefficients by two percent. This correction is reasonable given expected production of a heavier fuel design and provides very good agreement with the reported accountability results.

Plutonium production from N Reactor fuel was also represented by the same polynomials discussed in Appendix B. The polynomial coefficients for MKIV and MKIA fuels were determined from data in the final revised production tables (Eaves and Toffer 1982). The plutonium coefficients for MKII N Reactor fuel were determined by special calculations with the DCODE N Reactor fuel design analysis code (Thierer 1968). The MKII fuel was a unique N Reactor fuel type that produced tritium.

Plutonium conversion factors were also determined on a reactor-average basis. These plutonium conversion factors were used to estimate plutonium production from reactor power. This approach provides an estimate of the plutonium production that is based on representative fuel types and operating conditions typical of the various reactor operations campaigns. The reactor-average plutonium conversion factor for each reactor was weighted by the power fractions of the base-load fuel and the enriched fuels and their respective plutonium conversion factors. A summary of the reactor-average plutonium conversion factors is listed in Table 4.

2.2.3 Calculated Plutonium Production Estimates

The calculated estimates of plutonium production were made on the basis of reactor power and discharged fuel. These calculational methods were consistent with the methods used historically to estimate plutonium from reactor power and from discharged fuel.

Table 4. Plutonium Conversion Factors Used in Bulk Reactor Power Calculations.

Plutonium Conversion Factors

Reactor	Base Fuel	Base Fuel conv fact (g/MWd)	Base Fuel exposure (MWd/t)	Base pwr. fract	Driver Fuel	Driver Fuel conv fact (g/MWd)	Driver Fuel exposure (MWd/t)	Driver pwr. fract	reactor ave conv fact (g/MWd)
B	O3N	0.846	600	0.86	O3E	0.687	850	0.14	0.824
C	C5N	0.854	650	0.86	C3E	0.694	860	0.14	0.831
D	O3N	0.846	600	0.86	O3E	0.687	850	0.14	0.824
DR	O3N	0.846	600	0.86	O3E	0.687	850	0.14	0.824
F	O3N	0.846	600	0.86	O3E	0.687	850	0.14	0.824
H	O3N	0.846	600	0.86	O3E	0.687	850	0.14	0.824
KE	K5N	0.914	640	0.86	K5E	0.742	890	0.14	0.890
KW	K5N	0.914	640	0.86	K5E	0.742	890	0.14	0.890
N	Mark IV	0.872	1030	0.78	Mark IA	0.763	1280	0.22	0.848
N (non w.g)	Mark IV	0.732	2700	0.78	Mark IA	0.640	3230	0.22	0.712

The plutonium production totals estimated from reactor power were determined from a database assembled in Section 2.2.1 and the plutonium conversion factors discussed in Section 2.2.2. Plutonium production based on reactor power for a given month consisted of plutonium discharged in fuel that month and plutonium that was resident in the partially exposed fuel in the reactor core. The plutonium estimates were based on the reactor-averaged conversion factors of the fuels used in the reactors. In the single-pass reactors (B, C, D, DR, F, H, KE, and KW), the production of reactor power consumed to produce tritium was subtracted from the total reactor power. This correction involved a plutonium equivalent, which is the mass of tritium production multiplied by the atomic weight ratio of plutonium and tritium. The plutonium equivalent of tritium production was deleted from the reactor-average plutonium production.

The distinction of weapons- and nonweapons- (fuels-) grade plutonium was not attempted with the calculation from reactor power. The problem was complicated by periods when the reactors were operated in a partial nonweapons-grade mode. The calculational refinement would thus have required extensive analyses. The production of weapons- and nonweapons-grade plutonium was calculated only from fuel discharge information.

The calculation of plutonium production from fuel discharges determined the unique plutonium conversion factor and ^{240}Pu content from the average discharge exposure of each monthly discharge by fuel type. Such a calculation is an accurate and direct method to determine the quantity by nonweapons-grade plutonium. It also provides the needed information to arrive at the split between the weapons and nonweapons grades of plutonium production.

The identity of discharged fuels is generally clear in the discharged-fuel part of the database. Some clarifications are listed to explain some of the data. The first clarification is for thoria. Thoria, being a low-power target, was tracked by the power in adjacent process tubes. Therefore, the power in these tubes, which was generally from enriched fuel, was not included in the power production because it was already included in the discharge of enriched fuel. The second clarification is for N Reactor. The transition from MKI and MKIV base-fuel loadings occurred during the MKII fuel campaign. The database identifies the MKI and MKIV fuels as a single fuel type. The adoption of MKIV fuel was assumed to be after June 1966, which occurred in the middle of the MKII campaign.

Weapons- and nonweapons-grade plutonium consists of a blend of plutonium having a ^{240}Pu content within an accepted minimum and maximum range of a nominal value. Therefore, the distinction between weapons- and nonweapons-grade plutonium is established by a cutoff value for ^{240}Pu content. The weapons- and nonweapons-grade plutonium categories were established for plutonium produced after June 1964 with a cutoff value of 7.4 wt% ^{240}Pu. The cutoff date was consistent with reported values of reactor-grade plutonium that were provided by DOE-HQ. A single cutoff value of ^{240}Pu was used in these calculations. This cutoff value most likely varied from year to year by those reporting plutonium productions. The variations in the ^{240}Pu cutoff would depend on the judgement of borderline cases on whether or not plutonium in certain keys could be blended in the weapons-grade plutonium streams. However, the single ^{240}Pu cutoff value was chosen by some experimentation and gave satisfactory results, which are discussed below.

2.3 COMPARISONS OF REPORTED AND CALCULATED PLUTONIUM PRODUCTION

Annual summaries of the calculated plutonium production estimate and the DOE-HQ-reported plutonium production are listed in Table 5. These summaries show the grades of plutonium as weapons- and nonweapons- (fuels-) grade. Generally, these annual summaries are in good agreement. The differences in each annual reactor total production reflect the delay in reporting resulting from holdup until fuel discharge or from further delays in chemical processing.

The agreement between total annual plutonium production from the estimates based on reactor power and discharged fuel and from reported accountability values are shown in Figure 2. The annual reported accountability in fiscal year (FY) 1947 was a summary of plutonium that included plutonium produced prior to that date. From 1947 through the end of operation, the calculated estimates are in close agreement with reported accountability values. However, some variances are noted caused by annual accountability adjustments that appear to reflect corrections to previous reports. These corrections and differences are minimized when the cumulative totals are compared. The cumulative total plutonium production is shown in Figure 3 for the reported accountability values and for calculated estimates from reactor power and discharged fuel. This figure shows the excellent agreement between these independent methods.

The nonweapons- (fuels-) grade plutonium annual production and cumulative production are shown in Figures 4 and 5, respectively. The production of plutonium calculated from discharged fuel precedes the reported accountability values by about half a year from the time period of FY 1967 through FY 1971. This condition suggests that the reported nonweapons-grade plutonium was based on chemically separated plutonium during this time period. The production of nonweapons-grade plutonium from FY 1972 through FY 1979 shows very close agreement between reported and calculated estimates based on discharged fuel. The agreement between reported and calculated nonweapons-grade plutonium from FY 1980 through the end of production in FY 1983 is also good. The comparison between reported and calculated values in this time period shows that corrections were incorporated into the reported values to compensate for corrections needed in earlier reports. These results indicate that the reported levels of nonweapons-grade plutonium were probably based on chemically separated values before FY 1972, and on the estimates from discharged fuel after and including FY 1972.

3.0 RESULTS

Plutonium and tritium production in the Hanford Site reactors is summarized in Tables 1 and 2. The calculated production of total and fuels-grade plutonium is summarized in Table 6. In this summary, the total plutonium and the fuels-grade plutonium productions are listed for each reactor as determined from the fuel-discharge calculated estimates. The weapons- and nonweapons-grade plutonium totals from reported sources are also listed as a comparison with the calculated estimates. The results in Table 5 demonstrate the good agreement between calculational estimates and reported plutonium production.

Table 5. Annual Production of Total and Fuels-Grade Plutonium by Reported Accountability and Calculations.

Fiscal Year	Calculated Plutonium Production: Reactor Power Total kg	Calculated: Fuel Discharge Weapon Grade Total kg	Calculated: Fuel Discharge Fuel Grade Single Pass Reactor kg	Calculated: Fuel Discharge Fuel Grade N Reactor kg	Calculated: Fuel Discharge Total kg	Reported Plutonium Production: Weapon Grade Total kg	Reported: Fuel Grade Single Pass Reactor kg	Reported: Fuel Grade N Reactor kg	Reported: Total kg
45	100	29			29				
46	174	213			213				
47	121	139			139	493			493
48	117	138			138	183			183
49	212	173			173	270			270
50	295	257			257	392			392
51	450	376			376	288			288
52	599	639			639	662			662
53	783	821			821	838			838
54	1,032	1,138			1,138	1,113			1,113
55	1,311	1,249			1,249	1,413			1,413
56	2,060	1,843			1,843	2,074			2,074
57	2,628	2,897			2,897	2,662			2,662
58	3,212	3,173			3,173	3,303			3,303
59	3,497	3,483			3,483	3,581			3,581
60	4,227	4,262			4,262	4,266			4,266
61	4,482	4,517			4,517	4,449			4,449
62	4,233	4,283			4,283	4,169			4,169
63	4,207	3,766	282		4,047	4,187			4,187
64	4,496	3,727	931		4,658	4,247	*249	7	4,503
65	4,839	4,527	58	40	4,625	4,208	249	313	4,770
66	4,148	3,037	375	491	3,903	3,130	249	551	3,930
67	3,809	2,403	584	732	3,719	2,586	815	254	3,655
68	3,242	1,400	1,607	301	3,308	1,494	1,348	182	3,024
69	2,855	974	1,023	447	2,444	430	1,488	621	2,539
70	1,783	1,267	7	665	1,939	977	198	509	1,684
71	696	701		216	917	270	232	235	737
72	378			344	344	0		414	414
73	614			592	592	0		673	673
74	588			627	627	0		607	607
75	549			488	488	0		557	557
76	418			483	483	0		429	429
77	564			574	574	0		560	560
78	547			506	506	0		559	559
79	535			527	527	0		544	544
80	410			581	581	0		413	413
81	183			51	51	0		196	196
82	414	153		507	660	0		449	449
83	617	689			689	624			624
84	578	493			493	294			294
85	648	807			807	633			633
86	427	415			415	934			934
87	127	235			235	312			312
						(19)			(19)
Total	67,202	54,222	4,867	8,173	67,262	54,463	4,828	8,073	67,364

* Fuels grade plutonium of single pass reactors were based on average production for FY 1964, 1965, and 1966.

Figure 2. Total Annual Plutonium by Reported Accountability and Calculated Methods.

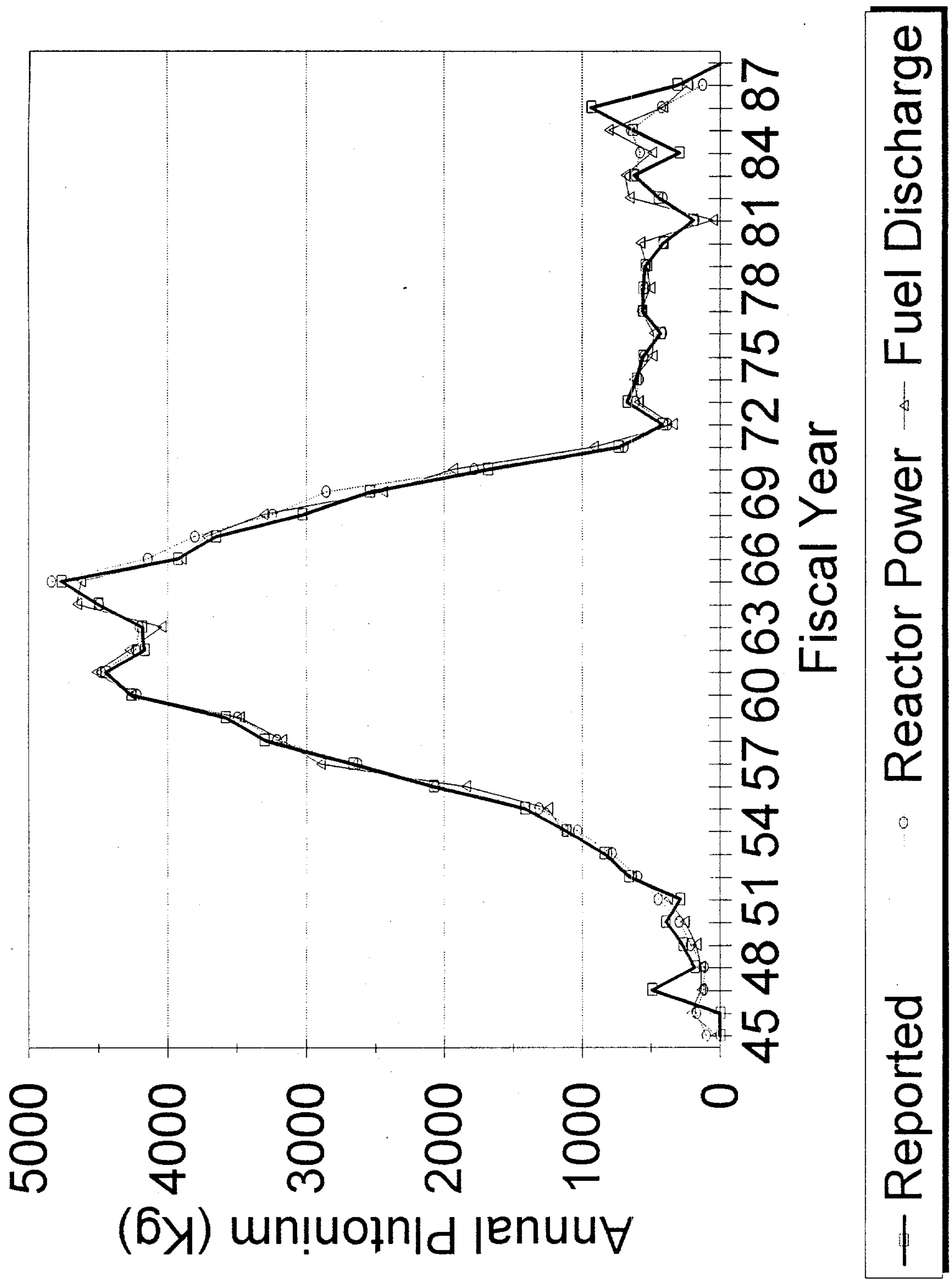

Figure 3. Total Cumulative Plutonium Production by Reported Accountability and Calculated Methods.

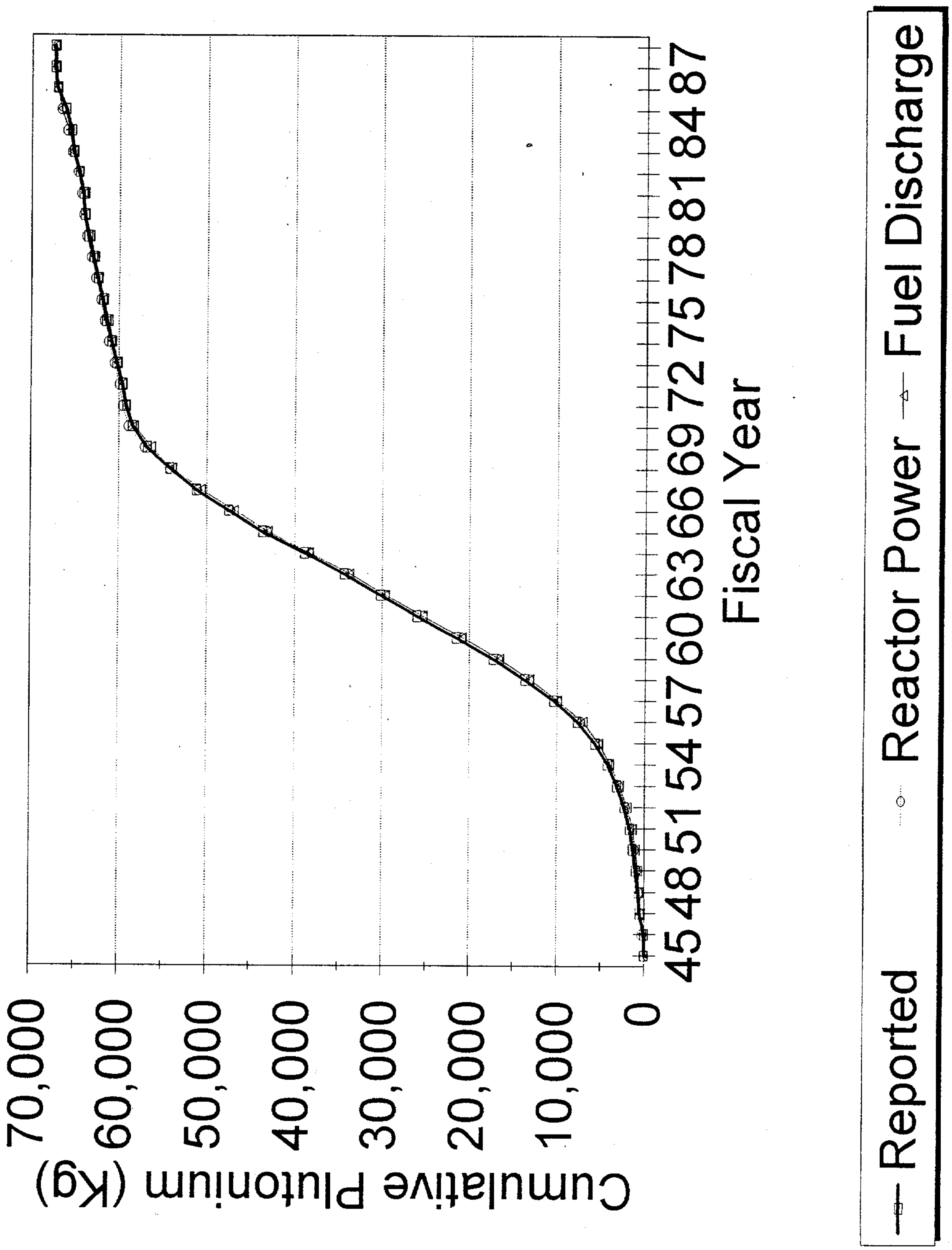

Figure 4. Cumulative Production of Fuels-Grade Plutonium by Reported Accountability and Calculated Methods.

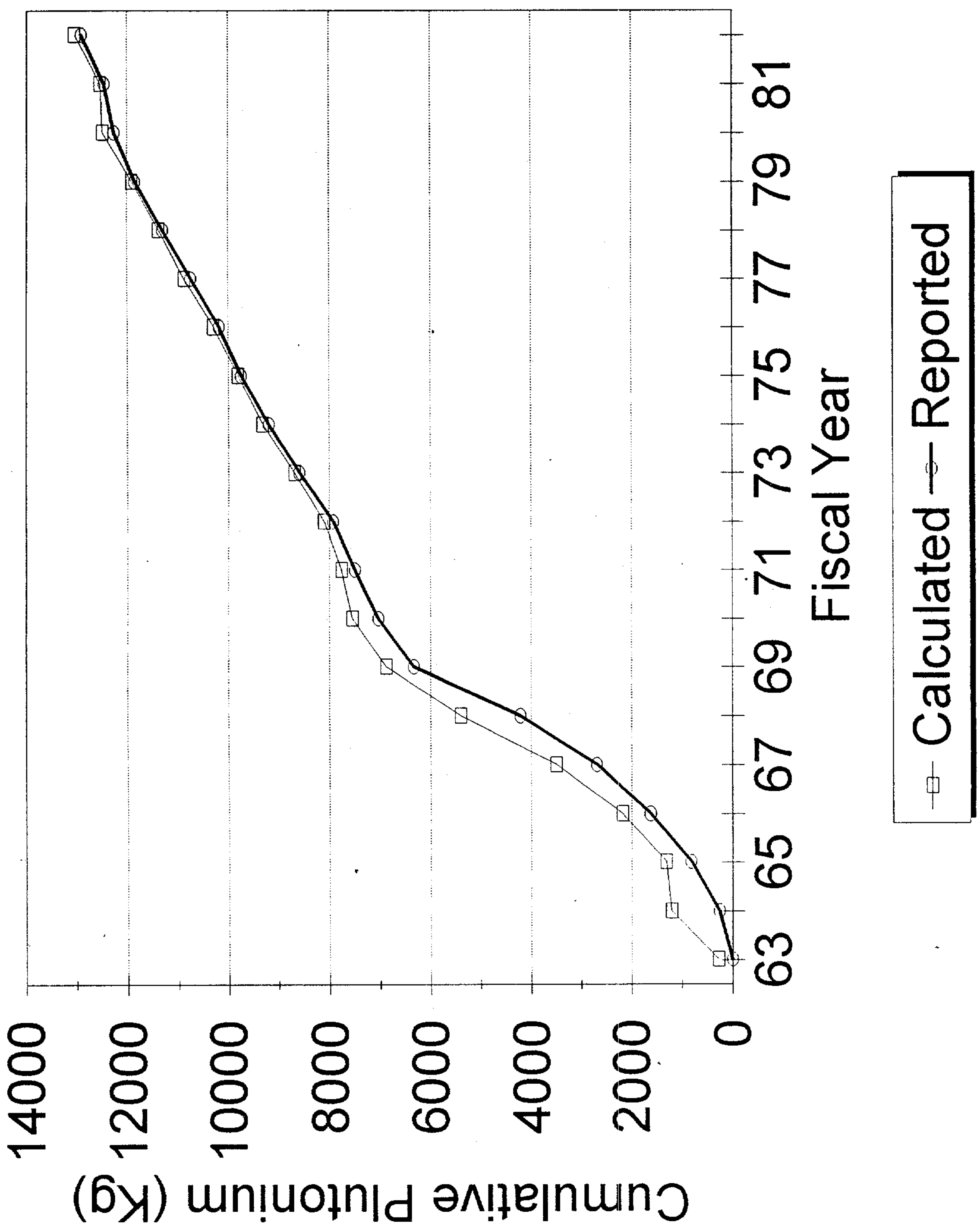

Figure 5. Annual Production of Fuels-Grade Plutonium by Reported Accountability and Calculated Methods.

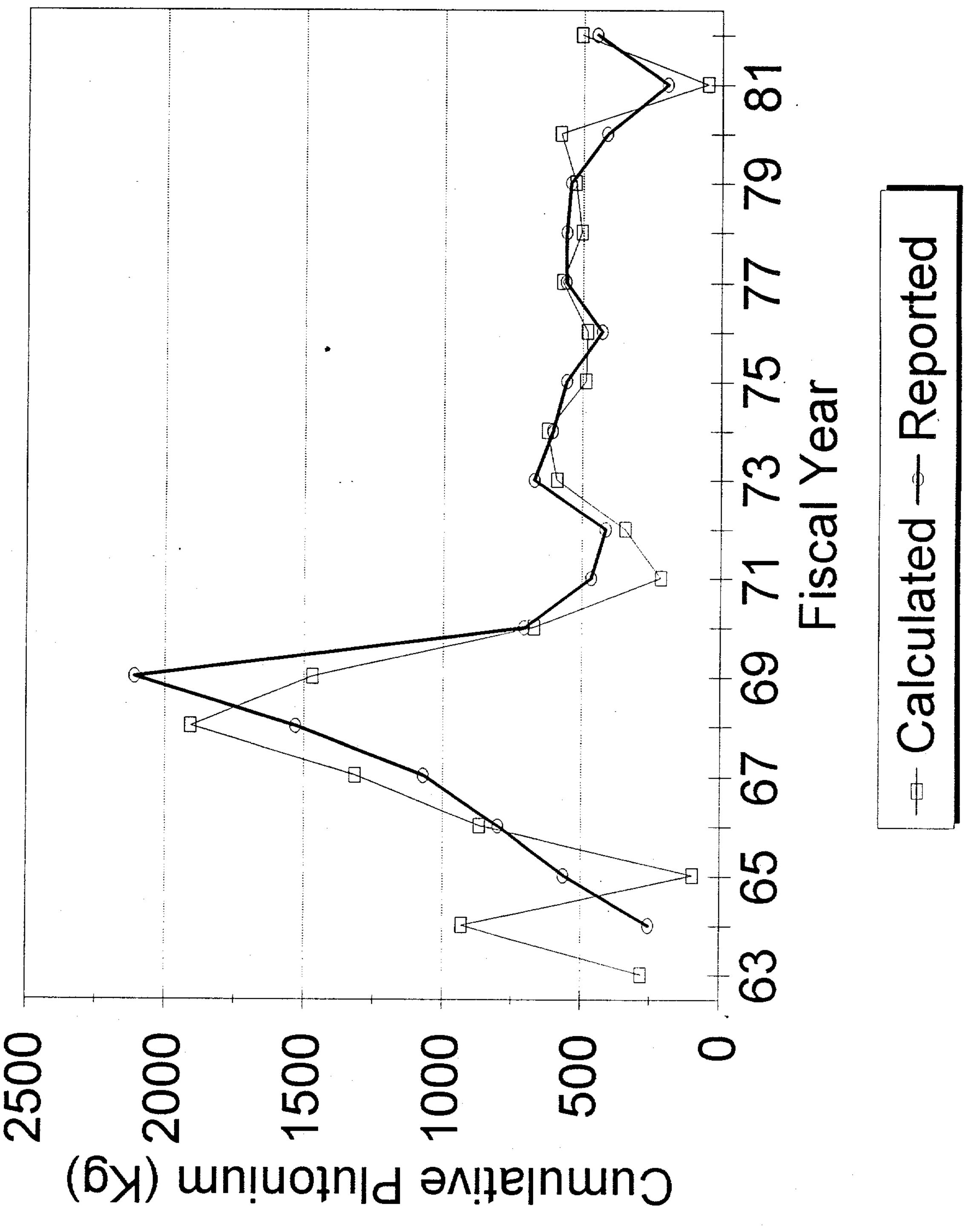

Table 6. Total and Fuels-Grade Plutonium Calculated for Hanford Site Production Reactors.

Reactor	Total Plutonium kg	Fuels Grade Plutonium kg
B	5,532	606
C	6,471	571
D	5,489	654
DR	3,836	51
F	4,499	55
H	4,136	99
KE	13,498	1,042
KW	12,836	1,789
N	10,965	8,173
Total	**67,262**	**13,040**

The reported plutonium production is in complete agreement with the production totals provided informally by DOE-HQ for both the total and fuels-grade plutonium production. The supporting results of the calculational estimate provide details of individual reactor production and an independent verification of the reported results.

4.0 CONCLUSIONS

The primary objective of this study was to substantiate the quantity of weapons- and nonweapons-grade plutonium produced in the Hanford Site production reactors based on Hanford Site records and modeling. A secondary objective of this study was to document the total production of tritium from official accountability records.

The production of plutonium in the Hanford Site production reactors was determined by an extensive check of reported accountability documentation and by two independent calculational checks. The reported accountability documents were issued on a semiannual basis from calendar year 1948 through the end of reactor operation in 1987. The production of plutonium from October 1944 through calendar year 1947 involved production in the B, D, and H Reactors. Production from this time period was from low-power reactor operation and was very small compared to the later power levels of these reactors and of the other Hanford Site production reactors. The estimate of 493 kg from DOE-HQ records is very reasonable for this time period and agrees well with independent calculational estimates. Additionally, the reported plutonium accountability from references from FY 1948 through FY 1989 were found to be in full agreement with DOE-HQ records on a year by year basis. Therefore, the accountability of plutonium production from documented references has been well established.

A check of the reported plutonium accountability was made by two independent calculational estimates. One estimate was based on a database of reactor power production and representative plutonium conversion factors, which were power-weighted conversion factors of various reactor loadings. The other estimate was based on a database of reactor fuel discharge and exposure-dependent conversion factors. The results of the calculational checks were in good agreement with each other and with the reported plutonium accountability. The calculated estimates also provided a consistent basis that supplied insight into understanding the reporting basis of plutonium. The comparison of calculational estimates and reported plutonium accountability was explainable with reasonable understanding of the various reporting practices.

The production of nonweapons- (fuels-) grade plutonium was also compared between the reported quantity informally provided by DOE-HQ and calculational estimates based on discharged fuel. This comparison was in very good agreement. The comparison between reported and calculated estimates indicates that the reported nonweapons-grade plutonium values were based on chemically separated plutonium from FY 1963 through FY 1971. The reported values of nonweapons-grade plutonium for the period of FY 1972 through the end of nonweapons-grade production in FY 1982 were based on discharged fuel.

The reported accountability of tritium was summarized in this document. The documentation for tritium production is fully complete and is the most accurate and reliable source of data available. The annual accountability of tritium fully supports the data received informally from DOE-HQ.

In conclusion, the objectives of this study to provide an accurate and defensible accounting of the weapons-grade and nonweapons-grade plutonium and of tritium production in the Hanford Site reactors has been met.

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APPENDIX A

REFERENCES OF REACTOR POWER OPERATION FROM 1945 THROUGH FISCAL YEAR 1986

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REFERENCES OF REACTOR POWER OPERATION FROM 1945 THROUGH FISCAL YEAR 1986

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APPENDIX B

FORMULAS AND COEFFICIENTS OF PLUTONIUM AND PLUTONIUM-240 CONTENT IN HANFORD SITE PRODUCTION REACTOR FUELS

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FORMULAS AND COEFFICIENTS OF PLUTONIUM AND PLUTONIUM-240 CONTENT IN HANFORD SITE PRODUCTION REACTOR FUELS

The plutonium producing fuels in the single-pass (once-through cooling) Hanford Site reactors were typically natural or low-enriched metallic uranium clad in aluminum. The earlier fuels were solid rods arranged end to end in a fuel charge. The solid, high-enriched uranium-aluminum fuel rods were also used for early tritium loads. Later, as the power of the reactors increased, the metallic fuel was tube-shaped, with an inner cooling annulus. The typical N Reactor fuels were concentric, low-enriched, metallic uranium tubes with zirconium alloy cladding. The only exceptional fuel design was a MKII fuel with an enriched uranium outer tube and a solid, nonuranium, inner target-material rod.

The fuel designs varied for each reactor type and were also modified with design improvements. These different fuel designs each had unique plutonium production characteristics.

The plutonium buildup in Hanford Site reactor fuels was related to the fission power or heat production measured in a fuel charge. The powers were typically specified in kilowatts (kW) or megawatts (MW). The time-integrated power of exposure of a discharged fuel mass was expressed in megawatt days (MWd/t), where the ton is a short ton (2000 lb).

The production of total plutonium for a particular fuel design is dependent on fuel exposure. Also, the quantity of the ^{240}Pu isotope in the plutonium is dependent on fuel exposure. This dependence is expressed quantitatively as polynomials with exposure as the independent variable. The plutonium conversion factor, with units of gram of plutonium per megawatt-day, is given by the following.

$$\text{Conv fact} = C_o + C_i E + C_2 E^2 + C_3 E^3 + C_4 E^4 \text{ (g/MWd)} \quad (1)$$

where:

$C_1, C_2, \ldots, C_4$ are constants, and
E = fuel exposure (MWd/t).

The ^{240}Pu isotope content of the plutonium is expressed in percent.

$$^{240}\text{Pu} = C_1 E + C_2 E^2 + C_3 E^3 + C_4 E^4 + C_5 E^5 \text{ (percent)} \quad (2)$$

where:

$C_1, C_2, \ldots, C_4$ are constants independent of those in Equation 1.

The application of these formulas and the coefficients are summarized in Tables B-1, B-2, and B-3. Table B-1 lists the fuel names as they appeared in the expanded TRAC database. A fuel-type number was assigned to each fuel type. The equation numbers are the same, as much as possible, as those in the original references. The equation number 00 was assigned where the fuel was not used. Table B-3 lists the constants used with Equations 1 and 2.

Table B-1. Fuel Types and Identifiers used for Fuel Discharge Calculations of Plutonium Production.

Fuel Type Identifier and Name of Fuel	
Fuel Type	Fuel Name
0	Natural U - Solid Slug Low neutron flux (mgs)
1	Natural U - Solid Slug High neutron flux (mgs)
2	Natural U - Cored Slug Lo mgs
3	Natural U - Cored Slug Hi mgs
4	Natural U - I&E Slug
5	Natural U - N Reactor
6	Enriched U - Solid E slug
7	Enriched U - Solid C slug
8	Enriched U - Solid J slug
9	Enriched U - Cored slug
10	Enriched U - I&E
11	Enriched U - N Reactor .94 (Mark IV Fuel) [Except before Jan 1968 Treat as Mark I]
12	Enriched U - N Reactor 1.25
13	Enriched U - N Reactor 2.10 al clad
14	Enriched U - N Reactor 2.10 zr clad
15	Enriched U - N Reactor hybrid .94 & 1.25
16	Enriched U - N Reactor 1.25 & 2.10
17	Enriched U - N Reactor 1.15 - 1.25 (Mark I-A Fuel)
18	Enriched U - N Reactor 100 - 200
19	Depleted U
20	Special Depleted
21	Natural & Depleted
22	N Reactor Nat & Dep (Natural)
23	Thoria
24	Chalk River

Table B-2. Equation Numbers Used by Reactor and Fuel Type.

Table of Equation Number by Reactor by Fuel Type

Reactor	Fuel Type Identifier																								
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
B	97	97	11	11	11	00	35	00	00	35	35	00	00	00	00	00	00	00	00	33	33	11	00	00	00
C	98	98	19	19	19	00	42	00	00	42	42	00	00	00	00	00	00	00	00	33	33	19	00	00	00
D	97	97	11	11	11	00	35	00	00	35	35	00	00	00	00	00	00	00	00	33	33	11	00	00	00
DR	97	97	11	11	11	00	35	00	00	35	35	00	00	00	00	00	00	00	00	33	33	11	00	00	00
F	97	97	11	11	11	00	35	00	00	35	35	00	00	00	00	00	00	00	00	33	33	11	00	00	00
H	97	97	11	11	11	00	35	00	00	35	35	00	00	00	00	00	00	00	00	33	33	11	00	00	00
KE	99	99	30	30	30	00	49	00	00	49	49	00	00	00	00	00	00	00	00	33	33	30	00	00	30
KW	99	99	30	30	30	00	49	00	00	49	49	00	00	00	00	00	00	00	00	33	33	30	00	00	00
N	00	00	00	00	00	93	00	00	00	00	00	93	94	00	95	00	94	94	94	00	00	00	93	00	00

Table B-3. Polynomial Coefficients of Equations Used to Determine Conversion Factors and ^{240}Pu Content in Hanford Site Production Reactors. (1 of 2)

EQ #	Equation Type	C_1 (Pu Total) / C_1 (^{240}Pu)	C_2 (Pu Total) / C_2 (^{240}Pu)	C_3 (Pu Total) / C_3 (^{240}Pu)	C_4 (Pu Total) / C_4 (^{240}Pu)	C_5 (Pu Total) / C_5 (^{240}Pu)	Comments
0	Total Pu	0	0	0	0	0	No Plutonium Generation
	% ^{240}Pu	0	0	0	0	0	
1	Total Pu	0.97123	$-1.374000 \times 10^{-04}$	1.637000×10^{-08}	$-8.690800 \times 10^{-13}$	0	MarkI
	% ^{240}Pu	7.052000×10^{-03}	$-8.551000 \times 10^{-07}$	5.448000×10^{-11}	$-6.974000 \times 10^{-16}$	0	
11	Total Pu	9.616089×10^{-01}	$-2.290010 \times 10^{-04}$	7.217750×10^{-08}	$-1.745093 \times 10^{-11}$	1.929012×10^{-15}	
	% ^{240}Pu	1.164293×10^{-02}	$-3.054738 \times 10^{-06}$	8.149073×10^{-10}	$-1.749711 \times 10^{-13}$	1.908196×10^{-17}	
19	Total Pu	9.717102×10^{-01}	$-2.177954 \times 10^{-04}$	6.565824×10^{-08}	$-1.534772 \times 10^{-11}$	1.706968×10^{-15}	
	% ^{240}Pu	1.085901×10^{-02}	$-2.782792 \times 10^{-06}$	7.130438×10^{-10}	$-1.518785 \times 10^{-13}$	1.658829×10^{-17}	
30	Total Pu	1.042664×10^{-00}	$-2.428293 \times 10^{-04}$	7.660128×10^{-08}	$-1.864464 \times 10^{-11}$	2.081668×10^{-15}	
	% ^{240}Pu	1.127100×10^{-02}	$-3.341585 \times 10^{-06}$	9.440555×10^{-10}	$-2.069456 \times 10^{-13}$	2.265982×10^{-17}	
33	Total Pu	3.338	$-2.879000 \times 10^{-03}$	1.571000×10^{-06}	$-4.188000 \times 10^{-10}$	4.246000×10^{-14}	
	% ^{240}Pu	3.095000×10^{-02}	$-2.444000 \times 10^{-05}$	1.269000×10^{-08}	$-3.303000 \times 10^{-12}$	3.259000×10^{-16}	
35	Total Pu	7.704163×10^{-01}	$-1.140833 \times 10^{-04}$	2.281740×10^{-08}	$-3.467449 \times 10^{-12}$	2.844946×10^{-16}	
	% ^{240}Pu	8.050203×10^{-03}	$-1.287088 \times 10^{-06}$	1.828084×10^{-10}	$-1.909584 \times 10^{-14}$	1.029992×10^{-18}	
42	Total Pu	7.772827×10^{-01}	$-1.136065 \times 10^{-04}$	2.223533×10^{-08}	$-3.581135 \times 10^{-12}$	2.567391×10^{-16}	
	% ^{240}Pu	7.944822×10^{-03}	$-1.278706 \times 10^{-06}$	1.964509×10^{-10}	$-2.486900 \times 10^{-14}$	1.951564×10^{-18}	
49	Total Pu	8.347778×10^{-01}	$-1.224279 \times 10^{-04}$	2.357410×10^{-08}	$-3.751666 \times 10^{-12}$	2.810252×10^{-16}	
	% ^{240}Pu	7.884264×10^{-03}	$-1.496635 \times 10^{-06}$	2.460183×10^{-10}	$-3.197442 \times 10^{-14}$	2.087089×10^{-18}	
93	Total Pu	1.033209723	-0.00017543	3.747020×10^{-08}	$-5.378200 \times 10^{-12}$	3.266300×10^{-16}	MarkIV
	% ^{240}Pu	0.00613129	1.379660×10^{-06}	$-1.710100 \times 10^{-09}$	5.480300×10^{-13}	$-5.960800 \times 10^{-17}$	

Table B-3. Polynomial Coefficients of Equations Used to Determine Conversion Factors and ^{240}Pu Content in Hanford Site Production Reactors. (2 of 2)

94	Total Pu	0.85221873	$-9.305900 \times 10^{-05}$	7.566410×10^{-09}	1.178900×10^{-12}	$-2.793000 \times 10^{-16}$	MarkIA
	% ^{240}Pu	0.00416645	2.190570×10^{-06}	$-1.869100 \times 10^{-09}$	5.584500×10^{-13}	$-5.901500 \times 10^{-17}$	
95	Total Pu	0.530245797	$-7.724900 \times 10^{-06}$	$-5.971400 \times 10^{-09}$	1.145730×10^{-12}	$-6.725400 \times 10^{-17}$	Mark II
	% ^{240}Pu	0.00281416	$-3.287000 \times 10^{-07}$	6.872440×10^{-11}	$-9.026040 \times 10^{-15}$	4.599870×10^{-19}	
97	Total Pu	9.808411×10^{-01}	$-2.335810 \times 10^{-04}$	7.362105×10^{-08}	$-1.779995 \times 10^{-11}$	1.967592×10^{-15}	B D DR F H Solid Slug (1.02 x eq # 11)
	% ^{240}Pu	1.164293×10^{-02}	$-3.054738 \times 10^{-06}$	8.149073×10^{-10}	$-1.749711 \times 10^{-13}$	1.908196×10^{-17}	
98	Total Pu	9.911444×10^{-01}	$-2.221513 \times 10^{-04}$	6.697140×10^{-08}	$-1.565467 \times 10^{-11}$	1.741107×10^{-15}	C Reactor Solid Slug (1.02 x eq # 19)
	% ^{240}Pu	1.085901×10^{-02}	$-2.782792 \times 10^{-06}$	7.130438×10^{-10}	$-1.518785 \times 10^{-13}$	1.658829×10^{-17}	
99	Total Pu	1.063517×10^{-00}	$-2.476859 \times 10^{-04}$	7.813331×10^{-08}	$-1.901753 \times 10^{-11}$	2.123301×10^{-15}	K Reactor Solid Slug (1.02 x eq # 30)
	% ^{240}Pu	1.127100×10^{-02}	$-3.341585 \times 10^{-06}$	9.440555×10^{-10}	$-2.069456 \times 10^{-13}$	2.265982×10^{-17}	