

SECTION 9.0

PLUTONIUM AND AMERICIUM

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This section provides information on the sources, characteristics, and biokinetics of plutonium and americium and summarizes the technical basis for their internal dosimetry at Hanford.

Historically, the general approach to plutonium internal dosimetry at Hanford has been to evaluate the systemic deposition based on urine data, and compare the result to a referenced MPBB. The most common reference for MPBBs has been ICRP 2 (1959). Prior to that publication, other reports containing MPBBs (for plutonium) consistent with those of ICRP 2 were referenced.

Prior to November 1986, evaluations of plutonium systemic deposition at Hanford were based on Langham's model for excretion of soluble plutonium (Langham et al. 1950), Healy's model for excretion of initially insoluble plutonium (Healy 1957), or a combination of both. The procedures used for plutonium evaluation have been maintained in the Hanford Radiation Protection Historical Files of the Radiation Records Library. The most recent of these is the Hanford Dosimetry Evaluation Manual (PNL-MA-575).^(a)

Hanford plutonium evaluations have generally assessed systemic deposition and have not emphasized dose equivalent to specific organs. The assessed systemic deposition has been a "committed" systemic deposition, i.e., an estimate of the total amount of activity that would eventually reach systemic compartments. The calculated depositions have not addressed the time post intake at which the maximum systemic deposition might be expected, nor the amount of activity that might be retained in the body at various times post intake. Once the committed systemic deposition has been calculated, its value has been assumed to remain constant for the worker's life. The percentage of the MPBB has been used to indicate the degree of compliance (or noncompliance) with Atomic Energy Commission, Energy Research and Development Agency, and DOE standards for radiation protection.

(a) Pacific Northwest Laboratory. 1982. Hanford Dosimetry Evaluation Manual. PNL-MA-575, Richland, Washington.

Historically, lung dose equivalents have been assessed in cases where in vivo measurements have observed activity in the lung. The approach used for assessment was documented on a case-by-case basis in the specific case evaluation. Generally, the approach was to use the best available information regarding isotope ratios, estimates of lung clearance rates based on ^{241}Am in vivo measurements, and fecal data (when available). Lacking such data, default assumptions have been used and documented in evaluations. The techniques for calculating dose were similar to those used in ICRP 2 (1959) and ICRP 10 (1969) and applied a quality factor of 10 for alpha particle emissions. The results of these lung dose estimates were compared with the long-standing 15-rem/yr limit of ICRP 2.

Changes in the technical approach to plutonium dosimetry at Hanford are being documented by this technical basis. These changes are required by DOE 5480.11 (DOE 1988), which addresses occupational radiation protection. The change entails a shift from the ICRP 2 critical organ dose limitation approach to the ICRP 26/30 (1977/1979) concepts of weighted summing of organ doses to give an effective dose equivalent. In addition, advances in measurement technology and modeling have improved the capabilities for plutonium dosimetry.

With this technical basis, a new term, "presystemic deposition," is introduced for the purpose of simulating biokinetic behavior in estimating internal doses. The presystemic deposition is defined as the component(s) of an initial deposition that will ultimately translocate to the blood, regardless of the time required to translocate. A transfer rate from the initial deposition into the systemic compartment is linked with each component of the presystemic deposition. Once material from the presystemic deposition has reached the systemic compartment, it is assumed to behave in accordance with the applicable biokinetic model. The presystemic deposition specifically excludes material that is permanently retained at the entry site or in lymphatic tissues.

9.1 SOURCES AND CHARACTERISTICS

This section provides general information on the isotopes, mixtures, and forms of plutonium that are commonly found at Hanford. The physical and

biological data were taken directly from, or calculated based on, information in ICRP 30, ICRP 38 (1983), and ICRP 48 (1986).

9.1.1 Isotope Decay Data

The plutonium and plutonium decay product isotopes of concern at Hanford and selected decay data are listed in Table 9.1. The radiological constants given in Table 9.1 are taken or calculated from data in ICRP 30 and 38 (1979, 1983).

9.1.2 Reference Plutonium Mixtures

At Hanford production and utilization facilities, pure isotopes of plutonium are seldom encountered. Instead, plutonium is usually encountered as a mixture of isotopes. For specific exposure situations where the isotopic composition of a mixture is known, that composition should be used for dosimetry purposes. In situations where mixtures are unknown, or for bio-assay planning purposes, assumptions regarding the mixture should be made.

The isotopic composition of a plutonium mixture is related to several variables:

- the length of time fuel was irradiated (fuel exposure or burn-up time)
- the time since irradiation (cooling time)
- the time since processing of fuel or purification of plutonium.

TABLE 9.1. Plutonium and Americium Decay Data

<u>Isotope</u>	<u>Half-Life,</u>	<u>Decay Constant,</u>		<u>Decay Mode</u>	<u>Specific Activity, Ci/g</u>
	<u>yr</u>	<u>yr⁻¹</u>	<u>day⁻¹</u>		
²³⁸ Pu	87.7	7.90E-3	2.16E-5	alpha	1.71E+1
²³⁹ Pu	24,065	2.88E-5	7.89E-8	alpha	6.21E-2
²⁴⁰ Pu	6,537	1.06E-4	2.90E-7	alpha	2.27E-1
²⁴¹ Pu	14.4	4.81E-2	1.32E-4	beta	1.03E+2
²⁴² Pu	376,300	1.84E-6	5.05E-9	alpha	3.92E-3
²⁴¹ Am	432.2	1.60E-3	4.39E-6	alpha	3.43E+0

Typically, plutonium at Hanford falls into one of two generic mixtures. These mixtures are defined by the weight percent (wt%) of ^{240}Pu . Thus, 6% plutonium has a nominal ^{240}Pu content of 6 wt% and 12% plutonium has a nominal ^{240}Pu content of 12 wt%. Other isotopic compositions may be encountered and should be addressed as needed.

Reference plutonium mixtures, prior to any ^{241}Am ingrowth, are provided in Table 9.2. These reference mixtures are approximations based on the isotopic composition of a number of batches of freshly processed plutonium and are not intended to represent any specific batch. Actual exposures may or may not reflect these compositions. When the actual compositions of exposures can be obtained, such data should be used.

In the typical plutonium mixture, the plutonium-alpha activity is relatively constant over time due to the long decay half-life of the alpha emitters. The plutonium-beta activity (^{241}Pu) decays with a 14-year half-life into ^{241}Am . Thus, over a period of years, plutonium-beta activity in a mixture will decrease while at the same time the ^{241}Am activity and the total alpha activity of the mixture will increase. Serial decay relationships can be used to estimate the activity of each isotope for any decay time.

For each reference mixture, a family of curves can be developed to describe the changing activity relationships between isotopes. These curves can then be used to identify, for dosimetry purposes, the plutonium mixture

TABLE 9.2. Reference Plutonium Isotope Mixtures Immediately Post Separation, wt%

<u>Isotope</u>	<u>6% Plutonium Mixture</u>	<u>12% Plutonium Mixture</u>
^{238}Pu	0.05	0.10
^{239}Pu	93.0	84.4
^{240}Pu	6.1	12.4
^{241}Pu	0.8	3.0
^{242}Pu	0.05	0.1
^{241}Am	0.0	0.0

and approximate age after processing or purification. These curves have been developed for three activity ratios (see Figures 9.1 through 9.3) using a technique developed by Rittman (1984).

When information about isotopic composition or activity ratios is lacking, assumptions must be made for dose assessment. Four reference plutonium mixtures are discussed in this technical basis. These four are referred to as fresh (or aged) 6% plutonium and fresh (or aged) 12% plutonium. As previously discussed, the percentage refers to the weight percent of ^{240}Pu in the mixture. Fresh mixtures are defined as having 2 weeks of ^{241}Am ingrowth following chemical separation. Aged mixtures are defined as having 5 years of ^{241}Am ingrowth following chemical separation. These mixtures effectively cover most of the potential plutonium exposures at Hanford. The primary use for these reference mixtures is in the planning of bioassay monitoring frequencies and methods, and for stating the capability of the internal dosimetry program.

Table 9.3 provides the specific activities of each isotope in the reference mixtures and isotope ratios relative to $^{239+240}\text{Pu}$ and ^{241}Am . Table 9.3 clearly shows that ^{242}Pu is an insignificant contributor to the specific activity of both reference mixtures.

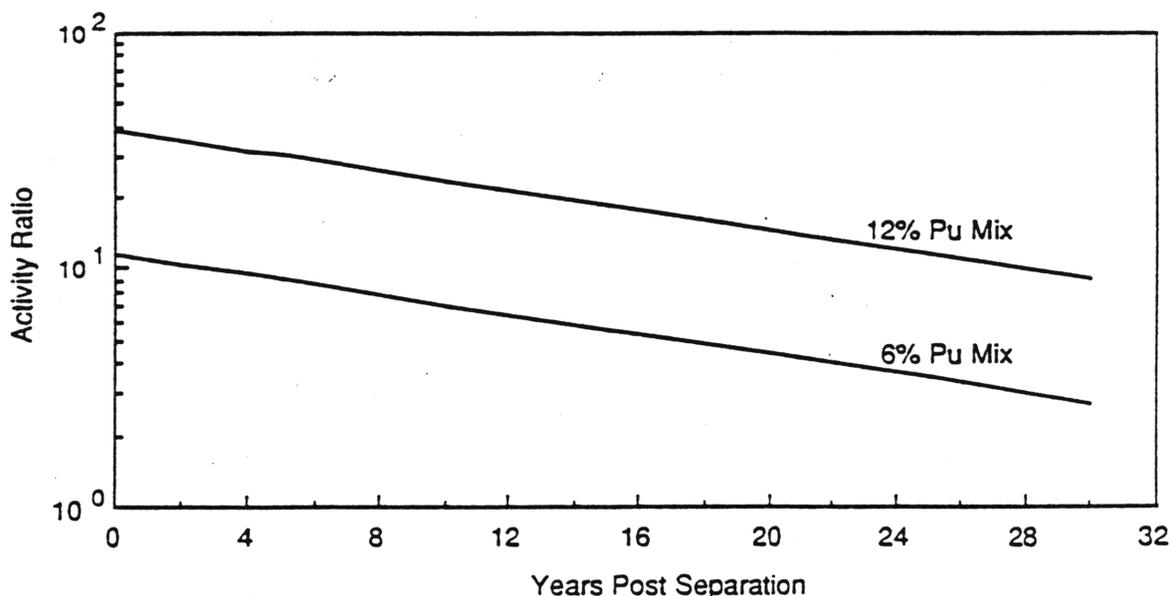


FIGURE 9.1. $^{241}\text{Pu}/^{239+240}\text{Pu}$ Ratio as a Function of Time Post Separation

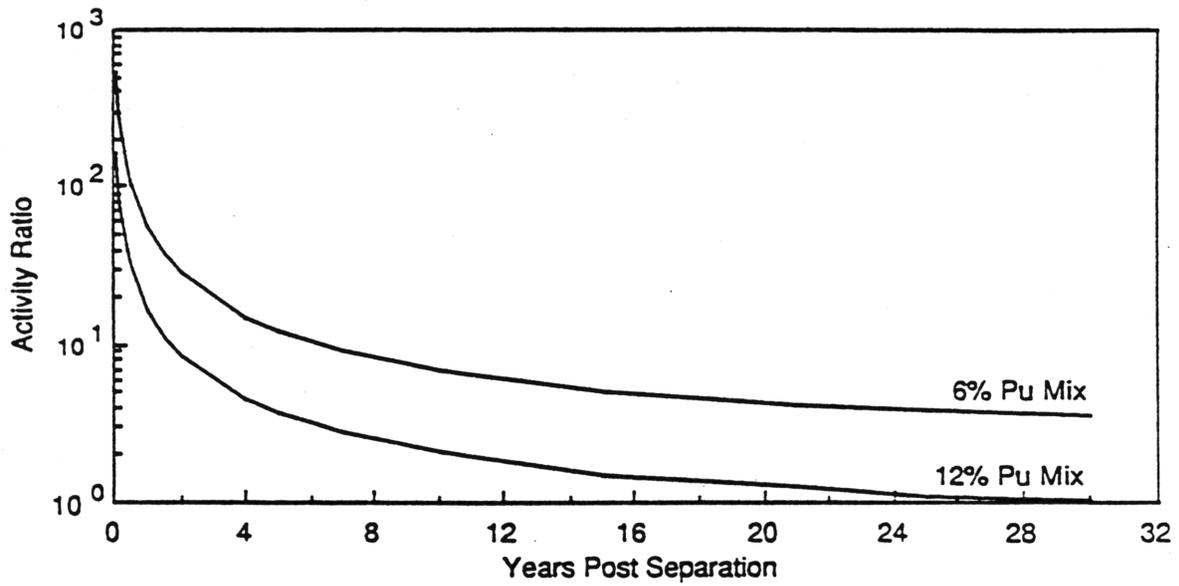


FIGURE 9.2. $^{239+240}\text{Pu}/^{241}\text{Am}$ Ratio as a Function of Time Post Separation

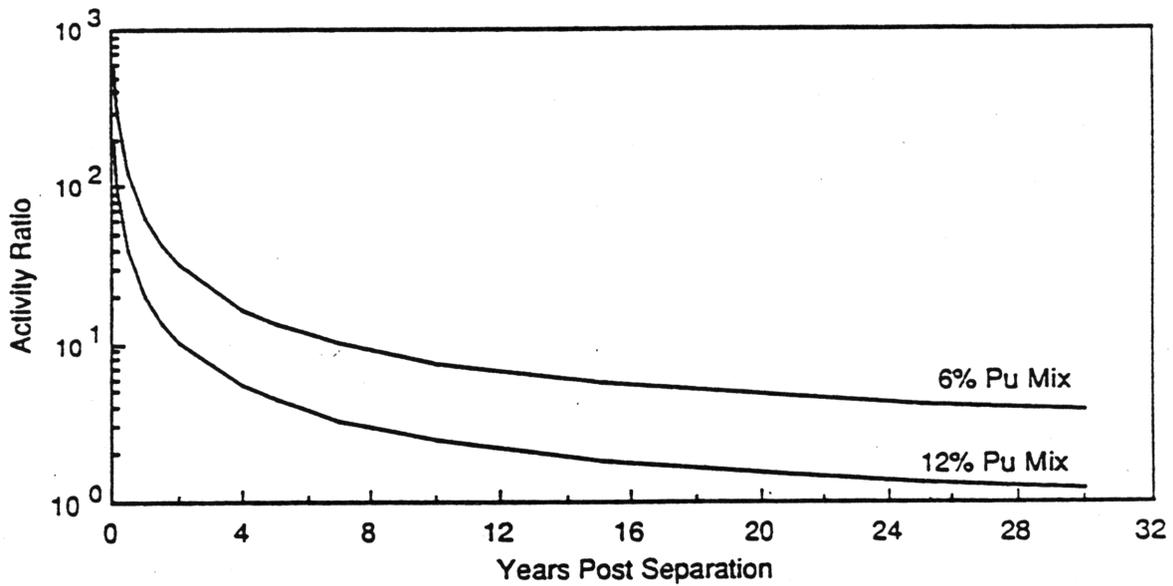


FIGURE 9.3. Plutonium-Alpha/ ^{241}Am Ratio as a Function of Time Post Separation

TABLE 9.3. Activity Composition for Reference Plutonium Mixtures

Isotopic Component	Reference Plutonium Mixture ^(a)			
	6% Pu Mix		12% Pu Mix	
	Fresh	Aged	Fresh	Aged
<u>Specific Activity in Mixture, Ci/g</u>				
²³⁸ Pu	8.6E-3	8.2E-3	1.7E-2	1.6E-2
²³⁹⁺²⁴⁰ Pu	7.2E-2	7.2E-2	8.0E-2	8.0E-2
²⁴¹ Pu	8.2E-1	6.5E-1	3.1E+0	2.4E+0
²⁴² Pu	2.0E-6	2.0E-6	3.9E-6	3.9E-6
²⁴¹ Am	5.3E-5	5.8E-3	2.0E-4	2.2E-2
Pu-alpha	8.1E-2	8.0E-2	9.7E-2	9.6E-2
Total alpha	8.1E-2	8.6E-2	9.7E-2	1.2E-1
<u>Activity Ratios</u>				
²³⁹⁺²⁴⁰ Pu: ²⁴¹ Am	1.3E+3	1.2E+1	4.1E+2	3.7E+0
Pu-alpha: ²⁴¹ Am	1.5E+3	1.4E+1	4.9E+2	4.4E+0
²⁴¹ Pu: ²³⁹⁺²⁴⁰ Pu	1.2E+1	9.1E+0	3.8E+1	3.0E+1

(a) % refers to nominal ²⁴⁰Pu weight percent in mixtures.
 Fresh = 2 weeks of ²⁴¹Am ingrowth following separation.
 Aged = 5 years of ²⁴¹Am ingrowth following separation.

9.2 BIOKINETIC BEHAVIOR

This section discusses the internal distribution and retention, transportability class, and urinary excretion of plutonium.

9.2.1 Transportability Class

The transportability classes for plutonium are similar to those used in the ICRP 30 respiratory tract model and are sometimes referred to as solubility or inhalation classes. The class designation represents the relative speed at which material is solubilized and translocated into the transfer compartment.

The term "transportable injection" is used in this technical basis to refer to the material that is essentially immediately taken up by the transfer

compartment upon intake. Classes W and Y, as used in this technical basis, are identical to the ICRP 30 classes of the same name.

Recent work by Stradling and Stather (1989) indicates that residual plutonium that has been subject to air oxidation for several years at normal room temperature and humidity may best be characterized as class Y material. Stradling and Stather studied the behavior of two dusts in rat lungs. One dust was a plutonium dioxide corrosion product of plutonium metal oxidized in air under ambient conditions (20° to 25°C and relative humidity of 60 to 70%) over a period of about 15 years. The second dust was a dry powder, process line residue consisting of an atmospherically degraded mixture of plutonium and uranium nitrates (originally 1.2M HNO₃) intimately mixed and highly diluted with inactive debris, resulting from the corrosion of an experimental rig over 15 years (i.e., rust). The plutonium oxide powder was found to exhibit very definite class Y behavior characteristics. The translocation rate for plutonium in the nitrate-bearing residues was about three times faster than for a class Y compound, but about 10 times slower than for a class W compound; i.e., the nitrate-bearing residue came closer to being class Y than class W in behavior. These findings imply that dry, residual plutonium contamination within facilities and gloveboxes should be treated as class Y material regardless of its original chemical form. Designation of plutonium as a class W material should be limited to current processes generating nitrates or residuals from recent runs of such processes. Plutonium worker bioassay programs should consider the potential exposure to aged plutonium oxides if there is any source of old residual contamination.

In addition to the above classes, a fourth class of material has been defined for use in this technical basis. Super class Y (super Y) has been established by the Hanford Internal Dosimetry Program to define highly non-transportable forms of plutonium based on some actual observed cases at Hanford (Bihl et al. 1988). For inhalation exposures, super Y material has been defined as being similar to class Y material with respect to compartment deposition fractions in the respiratory tract model. However, retention half-lives for the transport from the lung to the blood (ICRP 30 lung compartments a, c, e, and i [see Appendix D]) have been adjusted to 10,000 days. The

precise nature of super class Y material is not known, although it appears to have been associated with certain Hanford processes involving fired plutonium oxides.

When combinations of transportability classes may exist in a matrix, the transportability of the mixture is assumed to be that of the predominant material. For example, in a plutonium oxide matrix containing americium oxide as an ingrown impurity, the transportability of the americium oxide is assumed to be the same as that of the major mass constituent of the matrix (Eidson 1980). Thus, the americium is assumed to exhibit the class Y behavior of the host matrix (plutonium oxide), rather than the class W behavior normally expected of americium oxide. The above-described behavior would not be the case if the mixture were merely a blend of the two oxide powders. In this latter case, each element would be expected to exhibit its own characteristic behavior. These assumptions are also consistent with the observations by Stradling and Stather (1989).

The fractional lung retention factors (lung + lymph nodes) for Class W, y, and super Y forms of plutonium are given in Table 9.4 for selected days post acute intake. These values were obtained using the GENMOD code.

9.2.2 Systemic Distribution and Retention

The ICRP 48 (1986) model is used for calculating the distribution and retention of plutonium in the body. For dissolved plutonium reaching the transfer compartment (i.e., the blood stream), the ICRP recommends the distribution and organ clearance (or retention) half-times shown in Table 9.5.

The activity deposited in bone is assumed to be deposited uniformly over bone surfaces of both cortical and trabecular bone, where it remains until it decays or is excreted. The "all other" deposition fraction is assumed to represent direct excretion and any short-term holdup in the tissues of the circulatory or urinary systems. For purposes of dosimetry, this fraction is considered to be an insignificant contributor to effective dose equivalent (relative to bone, red marrow, liver, and gonad dose contributors), and is ignored.

TABLE 9.4. Selected Lung Retention Factors Expressed as a Fraction of Acute Inhalation of ^{239}Pu (a,b)

<u>Days Post Intake</u>	<u>Class W Lung</u>	<u>Class Y Lung</u>	<u>Super Y Lung</u>
0	3.3E-1	3.3E-1	3.3E-1
1	2.2E-1	2.1E-1	2.2E-1
2	1.8E-1	1.8E-1	1.8E-1
5	1.5E-1	1.5E-1	1.5E-1
7	1.4E-1	1.5E-1	1.5E-1
14	1.3E-1	1.5E-1	1.5E-1
30	1.0E-1	1.5E-1	1.5E-1
60	7.0E-2	1.4E-1	1.4E-1
90	4.8E-2	1.4E-1	1.4E-1
180	1.5E-2	1.3E-1	1.3E-1
365	1.4E-3	1.0E-1	1.1E-1
730	1.1E-5	7.3E-2	8.6E-2
1825	0.0E+0	2.9E-2	5.5E-2
3650	0.0E+0	9.6E-3	4.2E-2
7300	0.0E+0	4.2E-3	3.3E-2
18,250	0.0E+0	3.7E-3	1.7E-2

(a) Assumes 1- μm -AMAD particle size.

(b) Factors also apply to comparably long half-life plutonium isotopes.

TABLE 9.5. ICRP 48 Biokinetic Constants for Plutonium (a)

<u>Organ</u>	<u>Translocated Fraction</u>	<u>Biological Half-Time</u>	<u>Biological Rate</u>
Bone	0.50	50 yr	3.8E-5/day
Liver	0.30	20 yr	9.5E-5/day
Gonads			
Testes	3.4E-4	(permanent)	0
Ovaries	1.0E-4	(permanent)	0
All Other (b)	0.20		

(a) From ICRP 1986.

(b) Includes tissue and early excretion.

Although the translocated fractions for testes and ovaries shown in Table 9.5 differ, the gonadal dose equivalent for males and females is identical. This is attributed to the substantially differing masses of the two organs, with the result that the alpha activity concentration within the tissues, and therefore the tissue doses, are the same.

9.2.3 Urinary Excretion

In its Report 84 (NCRP 1985), the NCRP states that, "interpretation of excretion data for purposes of body burden estimation should be based on models derived with that application primarily in mind. The models of ICRP 30 and ICRP 48 (1986) were derived for the estimation of organ dose and were not necessarily intended to account for excretion." In recognition of this, the Hanford Internal Dosimetry Program has selected the Jones function (Jones 1985) to relate the urine excretion of plutonium to systemic uptake.

The Jones function is based on human injection studies originally reported by Langham et al. (1950) and Langham (1956) and follow-up work by Rundo et al. (1976) and Moss and Gautier (1985). The studies involved direct intravenous injection of plutonium citrate. The application of the function to observed excretion data results in an estimate of the uptake of plutonium by systemic circulation.

The Jones function models urinary excretion of plutonium following systemic uptake as a four-component exponential function. Jones emphasized that his function was an empirical fit to human data and should not be interpreted as modeling retention in specifically identifiable compartments. Thus, its application at Hanford is limited to estimating uptake and predicting excretion based on uptake. It is specifically not being used for organ dose calculations.

The Jones function is mathematically defined as:

$$e_u^a(t) = 0.00475 \exp(-0.558t) + 0.000239 \exp(-0.0442t) \quad (9.1) \\ + 0.0000855 \exp(-0.00380t) \\ + 0.0000142 \exp(-0.0000284t)$$

where $e_{u^a}(t)$ is the fraction of uptake to blood excreted in urine on day t post uptake, and t is the days post uptake (note: $t = 0$ is time of intake; $t = 1$ represents the first 24 hours following intake; $t = 2$ represents the second day post uptake; etc.).

The Jones excretion function described above has replaced the Langham and Healy (Healy 1957) functions for evaluating plutonium depositions at Hanford. Further discussion of this change can be found in the Hanford Radiation Protection Historical Files of the Radiation Records Library.^(a) The effective date for this change was November 1986.

The Jones excretion function has been applied to material that is not readily transportable to the systemic compartment through the use of one or more isolated presystemic compartments, initially containing all of the material that will ultimately become systemic uptake. Each presystemic compartment clears to the systemic compartment by an associated fractional transfer rate using simple first-order kinetics.

The PUCALC computer program has been developed by Internal Dosimetry to calculate presystemic depositions and urinary excretion based on a single presystemic-to-systemic uptake transfer rate. The program allows for fits of various combinations of transfer rate and presystemic deposition estimates to urine data and is particularly useful in cases involving substantial excretion data, where multiple presystemic components may be identifiable. The evaluation process is described in Section 9.5.

The GENMOD computer code can also be used to estimate the excretion. The Jones empirical excretion function is implemented as a pseudo uptake retention function (Skrable 1987) by GENMOD to describe excretion following an uptake. GENMOD is particularly useful for evaluating plutonium excretion following inhalation of class W, Y, or super Y material. A description of the plutonium model parameters for GENMOD is included in Appendix A.

(a) Carbaugh, E. H., and M. J. Sula. 1986. "Proposed Change to Plutonium Excretion Function Used for Hanford Internal Dosimetry." Letter report to the Hanford Radiation Protection Historical Files, December 11, 1986, Pacific Northwest Laboratory, Richland, Washington.

9.3 INTERNAL DOSIMETRY FACTORS

This section contains factors that are useful in making internal dosimetry calculations. The factors included in this section are derived from the GENMOD computer code and incorporate standard assumptions. Their application is intended for those circumstances where such assumptions are appropriate or more specific information is lacking. Variation from these factors is appropriate if sufficient data are available.

9.3.1 Intake Excretion Factors

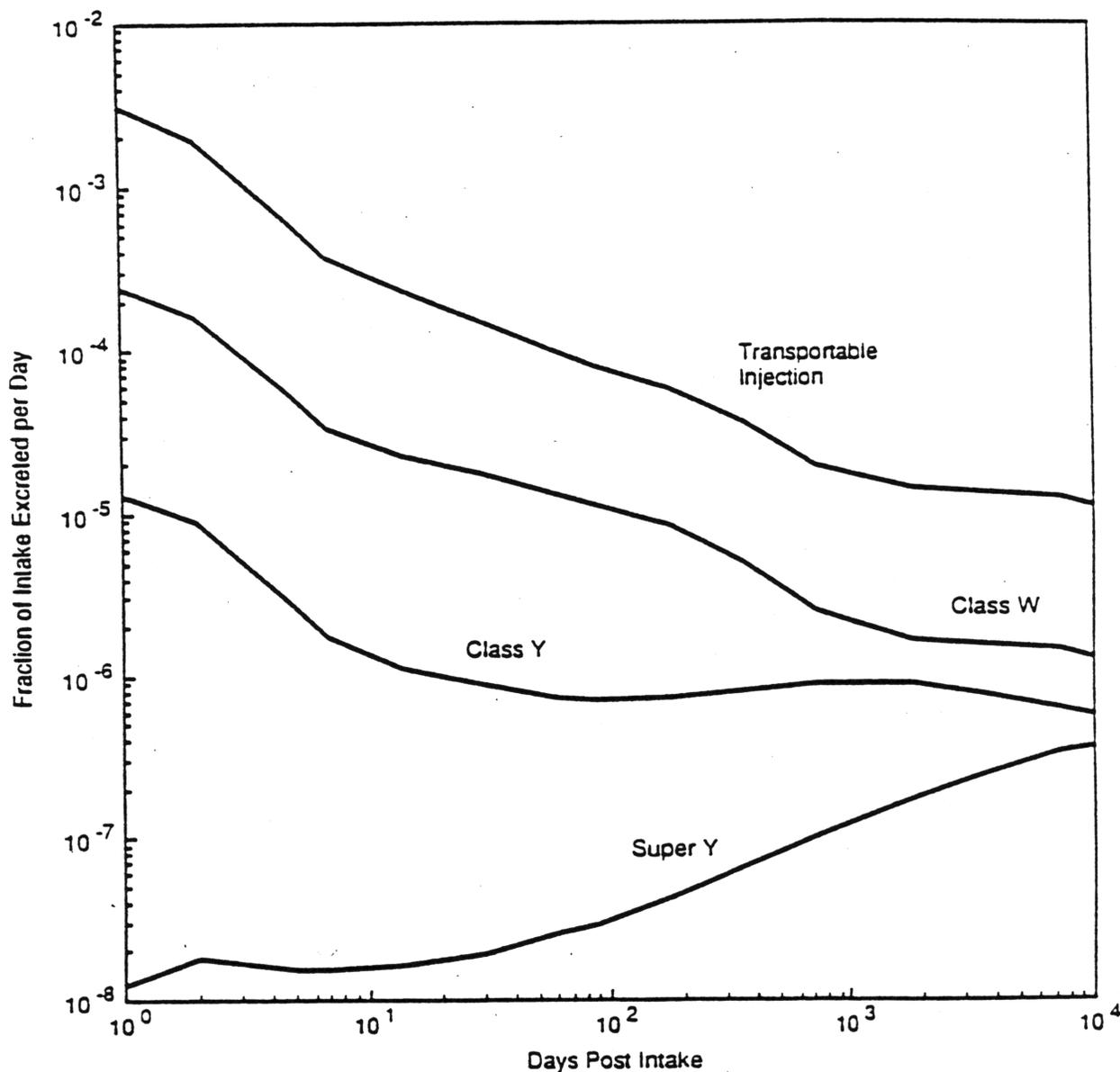
The intake excretion factor expresses the fraction of intake excreted by a particular pathway (urine or feces) at a given time post intake. For plutonium and americium excretion in urine, this factor is based on the Jones excretion function (discussed in Section 9.2). The intake urinary excretion functions for an acute transportable injection and for inhalation classes of ^{239}Pu are shown in Figure 9.4, and selected values are given in Table 9.6. Tabulated values for fecal excretion factors are shown in Table 9.7. Values for days other than those tabulated here can be obtained by linear interpolation between the tabulated data, or by obtaining the values directly from GENMOD.

9.3.2 Dose Conversion Factors

Activity deposited in a source organ is assumed to irradiate the target organ according to the ICRP 30 models. Dose conversion factors for potentially significant source and target organ combinations are tabulated by nuclide in Tables 9.8 through 9.11. These factors are derived by units conversion from the GENMOD computer code. They have been compared with results hand-calculated from ICRP 30 data tables, and they were found to agree within calculational rounding errors of about 5%. These factors can provide a convenient reference for dose equivalent to a target organ from decay occurring in a source organ. Dose conversion factors for other source and target organs can be obtained from GENMOD if desired.

9.3.3 Intake Dose Equivalent Factors

Intake dose equivalent factors, in units of dose equivalent per unit activity of intake (rem per nanocurie of acute intake or rem per nanocurie per



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FIGURE 9.4. ^{239}Pu Acute Intake Urinary Excretion Functions

day of chronic intake), are a convenient shortcut to estimating doses based on standard assumptions when the magnitude of an intake is known or assumed. Acute intake dose equivalent factors have been tabulated for the first-year and 50-yr committed dose equivalents resulting from readily transportable injection and class W, Y, and super Y inhalation (based on $1\text{-}\mu\text{m-AMAD}$ particle size). Factors for single isotopes are shown in Tables 9.12 through 9.15. In the case of ^{241}Pu , the ^{241}Am ingrown from the time of intake is included in

TABLE 9.6. Selected ^{239}Pu Urinary Excretion Fractions Expressed as a Fraction of Acute Intake

Days Post Intake	Transportable Injection	Inhalation ^(a)		
		Class W	Class Y	Super Y
1	3.3E-3	2.4E-4	1.3E-5	1.2E-8
2	2.2E-3	1.6E-4	8.7E-6	1.8E-8
5	6.6E-4	5.1E-5	2.7E-6	1.5E-8
7	4.0E-4	3.3E-5	1.7E-6	1.5E-8
14	2.3E-4	2.2E-5	1.1E-6	1.6E-8
30	1.6E-4	1.7E-5	8.6E-7	1.9E-8
60	1.0E-4	1.3E-5	7.1E-7	2.5E-8
90	8.0E-5	1.2E-5	6.9E-7	2.9E-8
180	5.7E-5	8.3E-6	7.2E-7	4.2E-8
365	3.5E-5	4.8E-6	8.0E-7	6.6E-8
730	1.9E-5	2.5E-6	8.8E-7	1.0E-7
1,825	1.4E-5	1.6E-6	8.8E-7	1.7E-7
3,650	1.3E-5	1.5E-6	7.4E-7	2.4E-7
7,300	1.2E-5	1.4E-6	6.1E-7	3.2E-7
18,250	8.5E-6	1.0E-6	4.4E-7	4.1E-7

(a) Assumes 1- μm -AMAD particle size.

TABLE 9.7. Selected Fecal Excretion Factors Expressed as a Fraction of Acute Inhalation of ^{239}Pu (a,b,c)

Days Post Intake	Class W Lung	Class Y Lung	Super Y Lung
0	0.0E+0	0.0E+0	0.0E+0
1	1.1E-1	1.3E-1	1.3E-1
2	1.3E-1	1.6E-1	1.8E-1
5	2.4E-2	2.5E-2	2.5E-2
7	6.4E-3	5.5E-3	5.5E-3
14	1.2E-3	1.7E-4	1.7E-4
30	9.6E-4	1.3E-4	1.3E-4
60	6.3E-4	1.3E-4	1.3E-4
90	4.2E-4	1.2E-4	1.2E-4
180	1.3E-4	1.3E-4	1.1E-4
365	1.4E-5	8.5E-5	8.4E-5
730	2.5E-6	5.1E-5	5.1E-5
1,825	1.6E-6	1.2E-5	1.1E-5
3,650	1.5E-6	1.4E-6	1.1E-6
7,300	1.4E-6	6.2E-7	3.2E-7
18,250	1.0E-6	4.4E-7	4.1E-7

(a) Assumes 1- μm -AMAD particle size.

(b) Factors also apply to comparably long half-life isotopes of plutonium.

(c) Assumes 50% of excretion from systemic organs is via feces.

TABLE 9.8. ^{238}Pu Dose Conversion Factors

Target Organ	Source Organ	Dose Conversion Factors, rem/nCi-day	
		Tissue	Weighted
Lung	Lung	5.62E-3	6.73E-4
Bone surface	Bone surface	1.17E-2	3.52E-4
Red marrow	Bone surface	9.44E-4	1.13E-4
Liver	Liver	3.17E-3	1.90E-4
Gonads	Gonads	1.64E-1	4.09E-2
Gut	Gut	1.13E-4	6.77E-6
SI ^(a)	SI	7.07E-5	4.26E-6
ULI ^(b)	ULI	1.28E-4	7.66E-6
LLI ^(c)	LLI	2.08E-4	1.25E-5

- (a) SI = small intestine.
 (b) ULI = upper large intestine.
 (c) LLI = lower large intestine.

TABLE 9.9. ^{239}Pu and/or ^{240}Pu Dose Conversion Factors^(a)

Target Organ	Source Organ	Dose Conversion Factors, rem/nCi-day	
		Tissue	Weighted
Lung	Lung	5.37E-3	6.44E-4
Bone surface	Bone surface	1.03E-2	3.10E-4
Red marrow	Bone surface	8.81E-4	1.06E-4
Liver	Liver	2.98E-3	1.79E-4
Gonads	Gonads	1.53E-1	3.85E-2
Gut	Gut	1.06E-4	6.36E-6
SI ^(b)	SI	6.62E-5	3.96E-6
ULI ^(c)	ULI	1.18E-4	7.10E-6
LLI ^(d)	LLI	1.96E-4	1.18E-5

- (a) ^{239}Pu and ^{240}Pu are dosimetrically equivalent, thus these factors can be used for the pure isotopes or the combined isotopes.
 (b) SI = small intestine.
 (c) ULI = upper large intestine.
 (d) LLI = lower large intestine.

TABLE 9.10. ^{241}Pu Dose Conversion Factors

<u>Target Organ</u>	<u>Source Organ</u>	<u>Dose Conversion Factors,</u> <u>rem/nCi-day</u>	
		<u>Tissue</u>	<u>Weighted</u>
Lung	Lung	3.92E-7	4.70E-8
Bone surface	Bone surface	8.14E-7	2.44E-8
Red marrow	Bone surface	6.51E-8	7.81E-9
Liver	Liver	2.18E-7	1.31E-8
Gonads	Gonads	1.12E-5	2.81E-6
Gut	Gut	5.40E-7	3.24E-8
SI ^(a)	SI	3.37E-7	2.02E-8
ULI ^(b)	ULI	6.11E-7	3.66E-8
LLI ^(c)	LLI	9.99E-7	5.99E-8

- (a) SI = small intestine.
 (b) ULI = upper large intestine.
 (c) LLI = lower large intestine.

TABLE 9.11. ^{241}Am Dose Conversion Factors

<u>Target Organ</u>	<u>Source Organ</u>	<u>Dose Conversion Factors,</u> <u>rem/nCi-day</u>	
		<u>Tissue</u>	<u>Weighted</u>
Lung	Lung	5.70E-3	6.85E-4
Bone surface	Bone surface	1.17E-2	3.51E-4
Red marrow	Bone surface	9.36E-4	1.12E-4
Liver	Liver	3.17E-3	1.90E-4
Gonads	Gonads	1.63E-1	4.07E-2
Gut	Gut	1.17E-4	6.99E-6
SI ^(a)	SI	7.29E-5	4.37E-6
ULI ^(b)	ULI	1.30E-4	7.81E-6
LLI ^(c)	LLI	2.16E-4	1.30E-5

- (a) SI = small intestine.
 (b) ULI = upper large intestine.
 (c) LLI = lower large intestine.

the ^{241}Pu dose equivalent factor, whereas ^{241}Am that existed at the time of intake is treated separately as pure ^{241}Am , but having the transportability characteristics of the host matrix.

The factors in Tables 9.12 through 9.15 were used in conjunction with the reference isotope mixtures defined in Section 9.1 to derive intake dose equivalent factors for the reference mixtures, which are tabulated in

TABLE 9.12. ^{238}Pu Acute Intake Dose Equivalent Factors^(a)
for First-Year and 50-Year Committed Doses

Tissue	Transportable Injection ^(b)	Inhalation ^(c)		
		Class W	Class Y	Super Y
Effective				
First-year	1.1E-1	2.0E-2	3.2E-2	3.2E-2
50-year	3.2E+0	4.0E-1	2.9E-1	4.6E-1
Lung				
First-year	NA ^(d)	6.7E-2	2.6E-1	2.7E-1
50-year	NA ^(d)	6.8E-2	1.2E+0	3.2E+0
Bone surface				
First-year	2.1E+0	2.3E-1	1.5E-2	5.8E-4
50-year	6.5E+1	7.8E+0	3.0E+0	1.4E+0
Red marrow				
First-year	1.7E-1	1.8E-2	1.2E-3	4.7E-5
50-year	5.2E+0	6.3E-1	2.4E-1	1.1E-1
Liver				
First-year	3.4E-1	3.7E-2	2.4E-3	9.4E-5
50-year	7.2E+0	8.6E-1	3.4E-1	1.7E-1
Gonads				
First-year	2.0E-2	2.2E-3	1.5E-4	5.7E-6
50-year	8.4E-1	1.0E-1	3.8E-2	1.7E-2

(a) Units are rem/nCi of acute intake.

(b) Assumes all plutonium is readily transportable.

(c) Assumes 1- μm -AMAD particle size.

(d) Not applicable.

TABLE 9.13. ^{239}Pu and/or ^{240}Pu Acute Intake Dose Equivalent Factors^(a)
for First-Year and 50-Year Committed Doses

Tissue	Transportable Injection ^(b)	Inhalation ^(c)		
		Class W	Class Y	Super Y
Effective				
First-year	1.0E-1	1.9E-2	3.0E-2	3.1E-2
50-year	3.2E+0	4.4E-1	3.1E-1	5.0E-1
Lung				
First-year	NA ^(d)	6.4E-2	2.5E-1	2.5E-1
50-year	NA ^(d)	6.4E-2	1.2E+0	3.4E+0
Bone surface				
First-year	2.0E+0	2.1E-1	1.4E-2	5.5E-4
50-year	7.2E+1	8.6E+0	3.4E+0	1.6E+0
Red marrow				
First-year	1.6E-1	1.7E-2	1.1E-3	4.4E-5
50-year	5.8E+0	6.9E-1	2.7E-1	1.3E-1
Liver				
First-year	3.2E-1	3.5E-2	2.3E-3	8.9E-5
50-year	7.7E+0	9.3E-1	3.7E-1	2.0E-1
Gonads				
First-year	1.9E-2	2.1E-3	1.4E-4	5.4E-6
50-year	9.5E-1	1.2E-1	4.4E-2	2.0E-2

(a) Units are rem/nCi of acute intake.

(b) Assumes all plutonium is readily transportable.

(c) Assumes 1- μm -AMAD particle size.

(d) Not applicable.

TABLE 9.14. ^{241}Pu Acute Intake Dose Equivalent Factors^(a)
for First-Year and 50-Year Committed Doses

Tissue	Transportable Injection ^(b)	Inhalation ^(c)		
		Class W	Class Y	Super Y
Effective				
First-year	9.3E-5	1.4E-5	2.6E-5	2.6E-5
50-year	7.0E-2	8.5E-3	5.1E-3	9.1E-3
Lung				
First-year	NA ^(d)	2.6E-5	2.1E-4	2.2E-4
50-year	NA ^(d)	2.7E-5	1.2E-2	5.8E-2
Bone surface				
First-year	1.8E-3	2.1E-4	1.5E-5	6.6E-7
50-year	1.4E+0	1.7E-1	7.3E-2	4.1E-2
Red marrow				
First-year	1.4E-4	1.7E-5	1.2E-6	5.3E-8
50-year	1.1E-1	1.4E-2	5.9E-3	3.3E-3
Liver				
First-year	2.9E-4	3.3E-5	2.4E-6	1.1E-7
50-year	1.3E-1	1.6E-2	7.4E-3	4.8E-3
Gonads				
First-year	1.7E-5	2.0E-6	1.4E-7	6.4E-9
50-year	2.0E-2	2.5E-3	1.0E-3	5.1E-4

(a) Units are rem/nCi of ^{241}Pu for acute intake; includes contribution from ^{241}Am ingrowth.

(b) Assumes all plutonium is readily transportable.

(c) Assumes 1- μm -AMAD particle size.

(d) Not applicable.

TABLE 9.15. ^{241}Am Acute Intake Dose Equivalent Factors^(a)
for First-Year and 50-Year Committed Doses

Tissue	Transportable Injection ^(b)	Inhalation ^(c)		
		Class W	Class Y	Super Y
Effective				
First-year	1.1E-1	2.0E-2	3.2E-2	3.3E-2
50-year	3.7E+0	4.5E-1	3.2E-1	5.1E-2
Lung				
First-year	NA ^(d)	6.7E-2	2.6E-1	2.7E-1
50-year	NA ^(d)	6.8E-2	1.3E+0	3.6E+0
Bone surface				
First-year	2.1E+0	2.3E-1	1.5E-2	5.8E-4
50-year	7.4E+1	8.9E+0	3.5E+0	1.7E+0
Red marrow				
First-year	1.7E-1	1.8E-2	1.2E-3	4.7E-5
50-year	6.0E+0	7.1E-1	2.8E-1	1.3E-1
Liver				
First-year	3.4E-1	3.7E-2	2.4E-3	9.5E-5
50-year	8.0E+0	9.6E-1	3.8E-1	2.0E-1
Gonads				
First-year	2.0E-2	2.2E-3	1.5E-4	5.7E-6
50-year	9.7E-1	1.2E-1	4.5E-2	2.1E-2

- (a) Units are rem/nCi of ^{241}Am of acute intake.
 (b) Assumes all plutonium is readily transportable.
 (c) Assumes 1- μm -AMAD particle size.
 (d) Not applicable.

Tables 9.16 through 9.19. The reference mixture first-year dose equivalent factors are subsequently used in Section 9.4 to describe the bioassay monitoring capability for inhalation intakes.

Intake dose equivalent factors have not been provided for ingestion intakes, because historically ingestion has not been considered a significant mode of occupational exposure, due to extremely low GI tract uptake of plutonium. If an ingestion intake occurs, the dose to organs of the GI tract can be calculated using the GENMOD code.

9.3.4 Cumulative Dose Equivalents

The cumulative dose equivalent from an intake through various times post intake is frequently of interest with regard to tenaciously retained radionuclides. The most commonly referenced cumulative dose is the committed dose equivalent through a 50-year period following an intake. The cumulative effective dose equivalents (expressed as a percentage of the 50-year committed effective dose equivalent) through various times post intake are shown in Table 9.20 for ^{239}Pu class W, Y, and super Y inhalation intakes. Cumulative dose equivalents for other forms of plutonium or other time intervals can be readily obtained from the GENMOD computer code.

The ICRP 30 ALIs are 5.4 nCi (class W) and 14 nCi (class Y) for ^{238}Pu , ^{239}Pu , ^{240}Pu , and ^{241}Am . For ^{241}Pu , the ALIs are 270 nCi (class W) and 540 nCi (class Y). These ALIs are based on a 50-year committed dose equivalent to the bone surfaces of 50 rem.

9.4 BIOASSAY MONITORING

This section discusses the general techniques and applicability of bioassay monitoring and describes the capabilities of excreta sample bioassay and in vivo measurements. Recommendations are also provided for routine bioassay monitoring for plutonium.

9.4.1 General Techniques and Applicability

Bioassay monitoring for plutonium can be provided by both radiochemistry analysis of excreta and direct in vivo measurements. The application of these

TABLE 9.16. Acute Intake Dose Equivalent Factors, ^(a) Fresh 6% Plutonium Mixture ^(b) First-Year and 50-Year Committed Doses

Tissue	Transportable Injection ^(b)	Inhalation ^(c)		
		Class W	Class Y	Super Y
Effective				
First-year	1.1E-1	1.9E-2	3.1E-2	3.1E-2
50-year	4.2E+0	5.2E-1	3.6E-1	5.9E-1
Lung				
First-year	NA ^(e)	6.4E-2	2.5E-1	2.5E-1
50-year	NA ^(e)	6.5E-2	1.3E+0	4.0E+0
Bone surface				
First-year	2.0E+0	2.2E-1	1.4E-2	5.6E-4
50-year	8.6E+1	1.0E+1	4.1E+0	2.0E+0
Red marrow				
First-year	1.6E-1	1.8E-2	1.2E-3	4.5E-5
50-year	6.9E+0	8.2E-1	3.3E-1	1.6E-1
Liver				
First-year	3.3E-1	3.5E-2	2.3E-3	9.1E-5
50-year	9.1E+0	1.1E+0	4.4E-1	2.4E-1
Gonads				
First-year	1.9E-2	2.2E-3	1.4E-4	5.5E-6
50-year	1.2E+0	1.4E-1	5.4E-2	2.5E-2

- (a) Units are rem/nCi of total-alpha of acute intake.
 (b) 6% ²⁴⁰Pu, aged 2 weeks after ²⁴¹Am separation.
 (c) Assumes 1- μ m-AMAD particle size.
 (d) Assumes all plutonium is readily transportable.
 (e) Not applicable.

TABLE 9.17. Acute Intake Dose Equivalent Factors, ^(a) Aged 6% Plutonium Mixture ^(b) First-Year and 50-Year Committed Doses

Tissue	Transportable Injection ^(b)	Inhalation ^(c)		
		Class W	Class Y	Super Y
Effective				
First-year	1.1E-1	1.9E-2	3.1E-2	3.4E-2
50-year	4.1E+0	4.9E-1	3.5E-1	5.7E-1
Lung				
First-year	NA ^(e)	6.4E-2	2.5E-1	2.7E-1
50-year	NA ^(e)	6.5E-2	1.3E+0	4.1E+0
Bone surface				
First-year	2.0E+0	2.2E-1	1.4E-2	6.0E-4
50-year	8.3E+1	9.9E+0	3.9E+0	2.0E+0
Red marrow				
First-year	1.6E-1	1.8E-2	1.2E-3	4.8E-5
50-year	6.6E+0	7.9E-1	3.1E-1	1.6E-1
Liver				
First-year	3.3E-1	3.5E-2	2.3E-3	9.7E-5
50-year	8.7E+0	1.0E+0	4.2E-1	2.5E-1
Gonads				
First-year	1.9E-2	2.2E-3	1.4E-4	5.9E-6
50-year	1.1E+0	1.3E-1	5.1E-2	5.4E-2

- (a) Units are rem/nCi of total-alpha for acute intake.
 (b) 6% ²⁴⁰Pu, aged 5 years after ²⁴¹Am separation.
 (c) Assumes 1- μ m-AMAD particle size.
 (d) Assumes all plutonium is readily transportable.
 (e) Not applicable.

TABLE 9.18. Acute Intake Dose Equivalent Factors, ^(a) Fresh 12% Plutonium Mixture ^(b) First-Year and 50-Year Committed Doses

Tissue	Transportable Injection ^(b)	Inhalation ^(c)		
		Class W	Class Y	Super Y
Effective				
First-year	1.1E-1	1.9E-2	3.1E-2	3.2E-2
50-year	5.7E+0	6.9E-1	4.6E-1	7.8E-1
Lung				
First-year	NA ^(e)	6.5E-2	2.6E-1	2.6E-1
50-year	NA ^(e)	6.6E-2	1.6E+0	5.2E+0
Bone surface				
First-year	2.1E+0	2.2E-1	1.5E-2	5.8E-4
50-year	1.2E+2	1.4E+1	5.6E+0	2.9E+0
Red marrow				
First-year	1.7E-1	1.8E-2	1.2E-3	4.6E-5
50-year	9.3E+0	1.1E+0	4.5E-1	2.3E-1
Liver				
First-year	3.3E-1	3.6E-2	2.4E-3	9.4E-5
50-year	1.2E+1	1.4E+0	6.0E-1	3.5E-1
Gonads				
First-year	2.0E-2	2.2E-3	1.5E-4	5.7E-6
50-year	1.6E-0	1.9E-1	7.5E-2	3.6E-2

- (a) Units are rem/nCi of total-alpha for acute intake.
 (b) 12% ²⁴⁰Pu, aged 2 weeks after ²⁴¹Am separation.
 (c) Assumes 1- μ m-AMAD particle size.
 (d) Assumes all plutonium is readily transportable.
 (e) Not applicable.

TABLE 9.19. Acute Intake Dose Equivalent Factors,^(a) Aged 12% Plutonium Mixture^(b) First-Year and 50-Year Committed Doses

Tissue	Transportable Injection ^(b)	Inhalation ^(c)		
		Class W	Class Y	Super Y
Effective				
First-year	1.1E-1	1.9E-2	3.1E-2	3.9E-2
50-year	5.0E+0	6.0E-1	4.1E-1	7.3E-1
Lung				
First-year	NA ^(e)	6.5E-2	2.6E-1	3.2E-1
50-year	NA ^(e)	6.6E-2	1.4E+0	5.6E+0
Bone surface				
First-year	2.1E+0	2.2E-1	1.5E-2	7.0E-4
50-year	1.0E+2	1.2E+1	4.8E+0	3.0E+0
Red marrow				
First-year	1.7E-1	1.8E-2	1.2E-3	5.7E-5
50-year	8.1E+0	9.7E-1	3.9E-1	2.4E-1
Liver				
First-year	3.3E-1	3.6E-2	2.4E-3	1.1E-4
50-year	1.1E+1	1.3E+0	5.2E-1	3.6E-1
Gonads				
First-year	2.0E-2	2.2E-3	1.5E-4	6.9E-6
50-year	1.4E+0	1.7E-1	6.4E-2	3.3E-2

- (a) Units are rem/nCi of total-alpha for acute intake.
 (b) 12% ²⁴⁰Pu, aged 5 years after ²⁴¹Am separation.
 (c) Assumes 1-μm-AMAD particle size.
 (d) Assumes all plutonium is readily transportable.
 (e) Not applicable.

TABLE 9.20. Cumulative Effective Dose Equivalent for ^{239}Pu Intakes (expressed as percentage of 50-year committed dose)

Cumulative Time Post Intake		Inhalation Intake		
<u>days</u>	<u>years</u>	<u>Class W</u>	<u>Class Y</u>	<u>Super Y</u>
90	0.25	1.7%	2.8%	1.7%
180	0.5	2.7%	5.2%	3.3%
365	1	4.3%	10%	6.1%
730	2	7.1%	17%	11%
1825	5	15%	30%	20%
3650	10	28%	43%	32%
7300	20	50%	60%	53%
18,250	50	100%	100%	100%

techniques, and the interpretation of the resulting data, are highly dependent upon the type of plutonium to which a worker may be exposed.

Although the ICRP considers plutonium to be an inhalation class W or Y compound, substantially more and less transportable forms have apparently been observed in past Hanford cases. For this reason, bioassay guidance has been developed for readily transportable, class W, Y, and super Y compounds. The readily transportable form is assumed to behave as a direct injection of plutonium into the transfer compartment. The class W and Y forms are assumed to behave according to the ICRP 30 respiratory tract model. The super Y form is defined as being identical to class Y with respect to compartment deposition fractions, however the transport rate from lung to blood (lung compartments a, c, e, and i) have been adjusted for a retention half-time of 10,000 days.

9.4.2 Urine Sample Bioassay

Urine sample analysis is the standard technique for confirming and evaluating the magnitude of uptakes. Uptake is required in order for material to be excreted by the urine pathway. It can also be used for estimating

inhalation intakes and initial lung burdens of slowly transportable compounds; however, fecal samples and in vivo measurements are usually the preferred techniques.

To reach the urine, plutonium must first reach the transfer compartment (blood) in a soluble (dissolved) form, from which it can then be removed by the kidneys through normal metabolic processes. Insoluble material in the transfer compartment is assumed not to be excreted by the urine pathway until it has been dissolved.

In reviewing urine sample results, anomalous results could be indicative of urine contamination from external sources (hands, sample container, clothing). Caution needs to be exercised when samples are obtained from externally contaminated workers.

The typical urine sampling practice is to collect a urine sample over a specified time interval and perform a chemical separation for plutonium. This technique is followed by electroplating and quantitative alpha spectrometry. The final results are reported as ^{238}Pu and ^{239}Pu . The reported ^{239}Pu result is actually the sum of the measured $^{239+240}\text{Pu}$, because the alpha spectrometry system does not have the capability to differentiate between the alpha energies for ^{239}Pu and ^{240}Pu decay emissions. This does not pose a significant problem because the dosimetry for the two isotopes is essentially the same. When considering the total plutonium-alpha activity of a sample, it is important to combine the ^{238}Pu with the ^{239}Pu results.

Prior to October 1983, an autoradiography procedure was used instead of the electroplating/alpha spectrometry procedure. This autoradiography procedure actually measured the total plutonium-alpha activity, which was reported as ^{239}Pu . This point should be remembered when comparing sample results and may help account for potential shifts in long-term data trends.

The reported detection levels for historical urine sample analysis procedures at various times are shown in Table 9.21. The method used to define the detection level has changed over time, so the values in Table 9.21 are not strictly comparable with each other.

TABLE 9.21. Detection Limits for Routine Hanford Analyses of Plutonium in Urine

<u>Time Period</u>	<u>Detection Limit, dpm/routine sample</u>
Prior to June 1949	0.66
June 1949 to Dec. 1952	0.33
Dec. 1952 to 01/28/53	0.18
01/28/53 to 03/27/53	0.15
03/27/53 to 11/07/53	0.05
11/07/53 to 12/04/53	0.07
12/53 to 05/55	0.057
05/55 to 09/55	0.027
09/55 to 10/55	0.04
10/55 to 10/01/83	0.05 ^(a)
10/01/83 to 12/31/83	0.035
12/31/83 to present	0.02

(a) During part of this period, results that were less than the detection limit were reported as 0.025.

Special rapid analytical procedures are available for special circumstances. These procedures can be executed and results obtained in substantially shorter times than the routine procedure, but they are less sensitive. Their use is primarily for diagnostic bioassay of suspected internal contamination related to unplanned exposures (incidents). The decision to use such procedures involves considering the probability and potential magnitude of the exposure. The detection limits for plutonium in urine (based on the FY 1989 contractual requirements) are listed in Table 9.22.

9.4.3 Fecal Sample Bioassay

Fecal samples are useful for confirming and evaluating suspected inhalation and ingestion exposures. The sample results can be used in conjunction with the ICRP 30 respiratory tract model to estimate the magnitudes of intakes and initial lung depositions as a basis for lung dose assessment. They can

TABLE 9.22. Contractual Detection Levels for Plutonium in Urine During FY 1989, dpm/sample

<u>Isotope</u>	<u>Category of Analysis^(a)</u>			
	<u>Routine</u>	<u>Priority</u>	<u>Expedite</u>	<u>Emergency</u>
^{238}Pu	0.02	0.02	0.08	0.5
$^{239+240}\text{Pu}$	0.02	0.02	0.08	0.5
^{241}Pu	NA ^(b)	2	4	20
^{241}Am	0.02	0.02	0.08	1

(a) Categories refer to different options for sensitivity and turnaround time.

(b) Not applicable.

also be used as checks on urine-based estimates of presystemic deposition. In addition, fecal samples can provide radionuclide identification data and isotope ratios. Fecal samples are of primary value immediately following a suspected intake, when material is rapidly clearing the respiratory and GI tracts. They may also be of value at long times post intake as an aid to estimating residual lung burdens and isotope ratios, however substantial uncertainties exist for such applications.

Most fecal excretion following an intake occurs shortly after the intake. According to the ICRP 30 respiratory tract model, approximately one-half (48%) of an intake of class Y plutonium (1- μm -AMAD particle size) would be excreted in the first 5 days following intake. Additional long-term clearance from the lung by the fecal pathway would total approximately 10% of the intake, excreted at the fractional biological clearance rate of 0.0014/day.

Additional fecal excretion comes via the biliary pathway. This pathway represents fecal excretion from systemic deposition. While the magnitude of this pathway relative to the urine pathway has been investigated, it is not recommended that fecal excretion be used for evaluating systemic deposition. The primary reason for this is the interference that can be caused by very slight acute or chronic inhalation or ingestion exposures and the uncertainty of the magnitude of the biliary excretion relative to urinary excretion.

There is no way to differentiate the source of fecal excretion (lung clearance, ingestion, or bile) when interpreting fecal sample results. For the purpose of modelling systemic excretion, it is assumed that systemic excretion is evenly distributed between the urine and biliary excretion pathways.

The complications of interpreting long-term fecal excretions do not rule out their potential value, particularly if certain conditions can be met regarding their collection; notably, lack of potential additional exposure immediately prior to collection of the sample and collection of more than one sample.

Multiple fecal samples are recommended if the data are critical for an evaluation. Normal daily fecal excretion rates vary greatly from those of ICRP 23 (1974) Reference Man and can be offset to some extent by collecting consecutive samples and averaging the results. Additional information on fecal sample interpretation is provided in Appendix E.

The laboratory plutonium analysis procedure for fecal samples involves wet ashing, dry ashing, chemical separation of plutonium, followed by electroplating and alpha spectrometry using a ^{242}Pu tracer to determine yield. The presence of ^{241}Pu is determined by liquid scintillation counting of the separated plutonium. The detection levels for the plutonium in feces analyses (based on the FY 1989 contractual capabilities) are shown in Table 9.23.

TABLE 9.23. Contractual Detection Levels for Plutonium in Feces During FY 1989, dpm/sample

<u>Isotope</u>	<u>Category of Analysis^(a)</u>		
	<u>Priority</u>	<u>Expedite</u>	<u>Emergency</u>
^{238}Pu	0.2	3	9
$^{239+240}\text{Pu}$	0.2	3	9
^{241}Pu	7	70	200
^{241}Am	0.8	6	20

(a) Categories refer to different options for sensitivity and turnaround time.

9.4.4 In Vivo Measurement

A variety of in vivo measurement techniques is available at the Hanford IVRRF (see Table 9.24). Most of these procedures involve measurement of the 60-keV photons from the ^{241}Am present as an ingrown impurity in a plutonium mixture. Direct measurement of the 17-keV plutonium L x-rays is possible, but the sensitivity of the measurement is not adequate to detect most internal organ depositions. Direct measurement of plutonium in wounds is also feasible and commonly used.

TABLE 9.24. Sensitivities of Typical In Vivo Measurements for Plutonium and Americium^(a)

Measurement	Minimum Detectable Activity, nCi			
	Direct ^{241}Am	Inferred Pu-alpha ^(b)	Direct ^{239}Pu ^(c)	Direct ^{238}Pu ^(c)
Chest counts				
1000 s	0.26	3.8	110	40
2000 s	0.18	2.7	75	30
Skeleton burden				
Head count				
3000 s	0.36	5.4	75	30
Liver count (2000 s)	0.15	2.3	150	60
Wound count (600 s)				
EDF ^(d) system	0.01	0.15	0.4	0.17
WBC ^(e) system	0.0015	0.023	0.09	0.04
Upper extremity lymph nodes	(being developed)			
Scanning lung count	(being developed)			

(a) Based on Table 7.1 of the Whole Body Counting Manual (Palmer et al. 1990).

(b) Based on 15:1 plutonium-alpha to ^{241}Am activity ratio.

(c) Based on 17.0-keV and 20.4-keV x rays and a 3-cm chest wall thickness.

(d) EDF = Emergency Decontamination Facility.

(e) WBC = Whole Body Counter.

Because of the relative insensitivity of direct in vivo plutonium measurement techniques at low levels (other than for wounds), the presence of plutonium is inferred by detection of ^{241}Am . Estimation of the amount of plutonium must be made using known or assumed isotope ratios. Such ratios may be obtained from workplace data (smear samples, air samples, etc.), inferred from excreta data (recognizing that fecal or urine samples may be biased by different clearance rates from the body), or from assumptions regarding material composition based on the facility and process involved.

The following subsections briefly describe the types of in vivo measurements available at the Hanford IVRRF. Nominal sensitivities for these measurements are summarized in Table 9.20. Further discussion of these measurement techniques can be found in the Whole Body Counting Manual (Palmer et al. 1990).

Chest Counts

Chest counting is a standard measurement technique used for monitoring plutonium workers. A count is performed by placing planar germanium detectors over the subject's chest.

Because of the potential impact of chest wall thickness on measurement sensitivity, measurement corrections are made on all workers based on a height-to-weight ratio. In addition, measurements on workers with known depositions will usually be corrected based on direct measurement of chest wall thickness using ultrasound techniques. Chest measurement results may not represent actual lung burdens unless they have been corrected for interference from activity deposited in other organs (notably the skeleton). When such a correction has been made the result is more correctly referred to as a lung burden estimate rather than a chest count result. Lacking such corrections, chest measurement results may conservatively be assumed to represent lung burdens.

The typical minimum detectable lung burden, assuming a 3-cm chest wall thickness, is 0.26 nCi of ^{241}Am for a 1000-second count, and 0.18 nCi for a 2000-second count.

Head Counts (Skeleton Burdens)

Head counts are performed using two planar germanium detectors and a 3000-second counting time. The results of the head count are extrapolated to an estimate of the total quantity retained in the skeleton using a human skeleton calibration phantom. Head counts will usually be performed when chest counts show detectable activity to determine if modification for skeleton activity is needed. Head counts can also be used as a check on urine-based systemic deposition estimates.

The typical MDA in the skeleton, as determined by head counting, is 0.36 nCi of ^{241}Am .

Liver Counts

Liver counts provide a direct estimate of activity in the liver based on the Livermore calibration phantom (Griffith et al. 1978). These counts are primarily used for long-term follow-up and as a check on urine-based systemic deposition estimates. They also provide a check on the assumptions used in the computer codes for calculating annual and committed dose equivalents. The counting time is 2000 seconds.

The MDA for a typical liver count is 0.15 nCi of ^{241}Am .

Wound Counts

Wound counts can directly measure plutonium and americium using a single planar germanium detector. Wound counts can be performed either at the Emergency Decontamination Facility (EDF) or at the IVRRF. The detection equipment is similar at both facilities, however MDAs are substantially better at the WBC due to the use of shielded counting rooms. Counts at either facility are typically 600-seconds long.

Directly measured MDAs are typically 0.01 nCi of ^{241}Am and 0.4 nCi of ^{239}Pu at the EDF, and 0.0015 nCi of ^{241}Am and 0.09 nCi of ^{239}Pu at the WBC. The ^{239}Pu results can be significantly underestimated if the activity is deeply embedded in tissue.

Upper Extremity Lymph Node Counts

The upper extremity lymph nodes are potential deposition sites for non-transportable or slowly transportable material deposited in extremity wounds. These nodes include the supratrachal lymph nodes located near the elbow and the axillary lymph nodes located near the armpit. The nodes are counted by placing planar germanium detectors in the lymph node region. Activity deposited in the axillary lymph nodes has the potential for interfering with chest count results. Precise calibrations for these counts are still under development.

Scanning Lung Counts

Scanning lung counts are used to determine the distribution of activity deposited in the lung. By a series of counts, the extent to which activity is deposited in the tracheal-bronchial region (including the lymph nodes) and the left and right pulmonary regions can be reasonably determined. The results of these counts are not likely to affect lung dose estimates, except to the extent that they shed light on the nature of the deposition and potential lung dynamics. The calibration for these counts is still under development. Results may be expressed as the percentage of total lung activity in a given counting region.

9.4.5 Bioassay Monitoring Capability

The bioassay monitoring capability for plutonium can be discussed as the intake or dose associated with an MDA bioassay measurement at some time post intake. Analyses of the first-year and 50-year effective dose equivalents have been performed for fresh 6% and aged 12% reference plutonium mixtures using two bioassay methods, ^{239}Pu in urine and in vivo ^{241}Am lung counting.

To determine the capability of bioassay of plutonium by urine analysis, the intakes of ^{239}Pu associated with minimum detectable urine analysis results were calculated for transportable injection, and class W, Y, and super Y inhalations. These intakes are given in Table 9.25. Based on the activity ratios described in Section 9.1, the plutonium-alpha intake was estimated for fresh 6% and aged 12% reference plutonium mixtures, and the first-year and 50-year committed effective dose equivalents were calculated using the factors

TABLE 9.25. Acute ^{239}Pu Intake Associated with the Minimum Detectable Activity Urine Bioassay Measurement (MDA = 0.02 dpm/day)

Days Post Intake	^{239}Pu Intake, nCi			
	Transportable Injection	Inhalation		
		Class W	Class Y	Super Y
1	3.0E-3	3.8E-2	6.9E-1	7.5E+2
2	4.7E-3	5.6E-2	1.0E+0	5.0E+2
5	1.6E-2	1.8E-1	3.3E+0	6.0E+2
7	2.4E-2	2.7E-1	5.3E+0	6.0E+2
14	3.9E-2	4.1E-1	8.2E+0	5.6E+2
30	6.0E-2	5.3E-1	1.0E+1	4.7E+2
60	9.1E-2	6.9E-1	1.3E+1	3.6E+2
90	1.1E-1	8.2E-1	1.3E+1	3.1E+2
180	1.6E-1	1.1E+0	1.3E+1	2.1E+2
365	2.6E-1	1.9E+0	1.1E+1	1.4E+2
730	4.7E-1	3.8E+0	1.0E+1	9.0E+1
1825	6.4E-1	5.6E+0	1.0E+1	5.3E+1
3650	6.9E-1	6.0E+0	1.2E+1	3.8E+1

of Tables 9.16 and 9.19. The results are summarized in Tables 9.26 through 9.29 and graphically presented in Figures 9.5 through 9.9.

The capability of bioassay by in vivo chest counting was calculated assuming the presence of the MDA of ^{241}Am in the lung (0.18 nCi) at a given time post intake. Based on activity relationships for fresh 6% and aged 12% reference plutonium mixtures, the corresponding intake of each mixture was calculated and the first-year and 50-year committed effective dose equivalents were calculated using the factors of Tables 9.16 and 9.19. The results are summarized in Tables 9.30 through 9.33 and graphically presented in Figures 9.9 through 9.12.

9.4.6 Recommended Bioassay Monitoring Program

The recommended bioassay monitoring program for plutonium is to perform annual in vivo lung measurements and annual plutonium-in-urine assessments. These recommendations do not provide the high degree of sensitivity for

TABLE 9.26. Potentially Undetected First-Year Effective Dose Equivalent (rem) for a Single Acute Intake of Fresh 6% Reference Plutonium Mixture Based on an MDA of 0.02 dpm/day of ^{239}Pu Detected in Urine

Days Post Intake	Mode of Intake			
	Transportable Injection	Inhalation		
		Class W	Class Y	Super Y
1	3.7E-4	8.1E-4	2.4E-2	2.6E+1
2	5.8E-4	1.2E-3	3.5E-2	1.7E+1
5	2.0E-3	3.8E-3	1.2E-1	2.1E+1
7	3.0E-3	5.8E-3	1.8E-1	2.1E+1
14	4.8E-3	8.8E-3	2.9E-1	2.0E+1
30	7.4E-3	1.1E-2	3.5E-1	1.6E+1
60	1.1E-2	1.5E-2	4.5E-1	1.3E+1
90	1.4E-2	1.8E-2	4.5E-1	1.1E+1
180	2.0E-2	2.4E-2	4.5E-1	7.3E+0
365	3.2E-2	4.1E-2	3.8E-1	4.9E+0
730	5.8E-2	8.1E-2	3.5E-1	3.1E+0
1825	7.9E-2	1.2E-1	3.5E-1	1.8E+0

TABLE 9.27. Potentially Undetected 50-Year Committed Effective Dose Equivalent (rem) for a Single Acute Intake of Fresh 6% Reference Plutonium Mixture Based on an MDA of 0.02 dpm/day of ^{239}Pu Detected in Urine

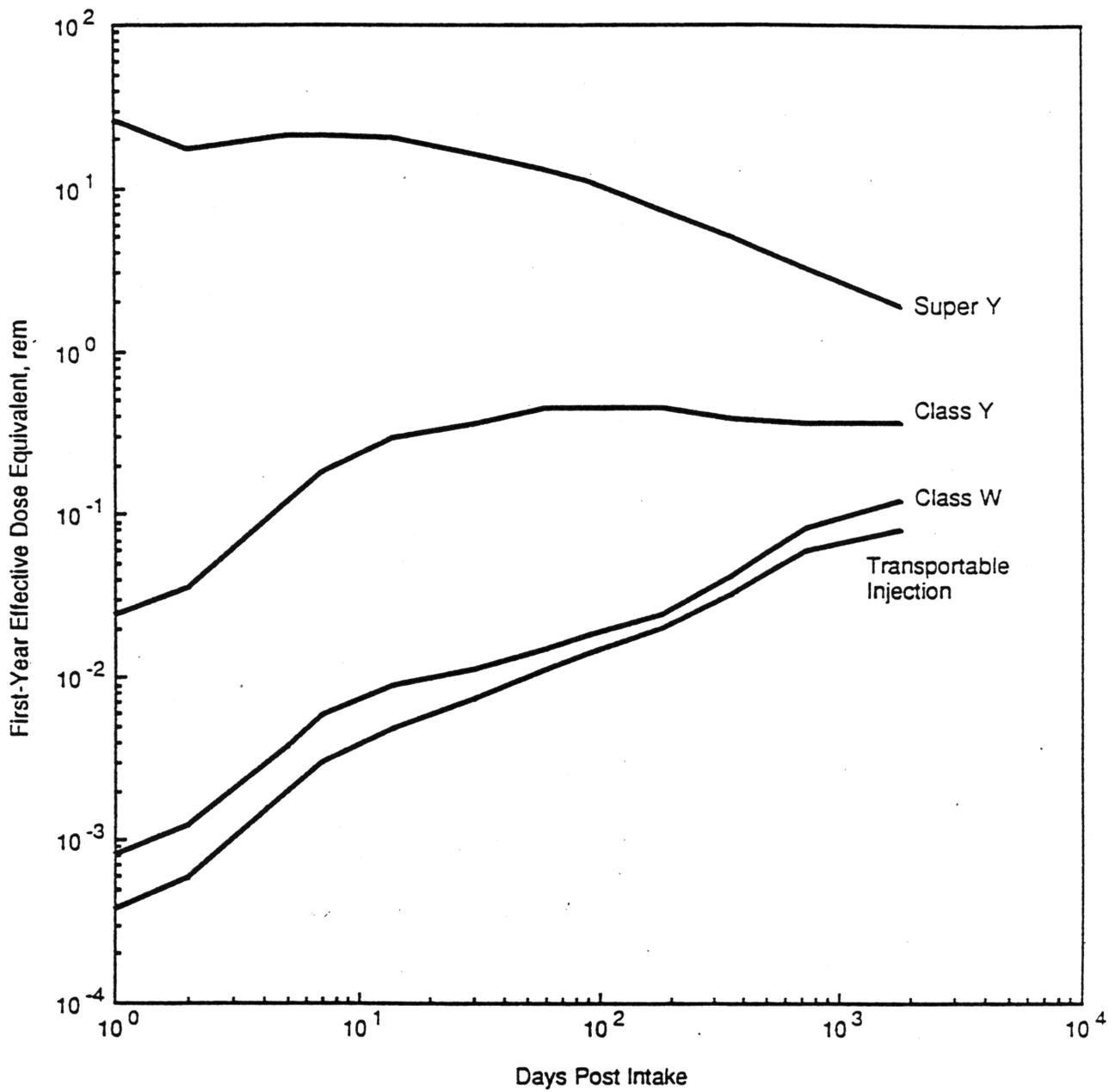
Days Post Intake	Mode of Intake			
	Transportable Injection	Inhalation		
		Class W	Class Y	Super Y
1	1.4E-2	2.2E-2	2.8E-1	4.9E+2
2	2.2E-2	3.3E-2	4.1E-1	3.2E+2
5	7.6E-2	1.0E-1	1.4E+0	4.0E+2
7	1.1E-1	1.6E-1	2.1E+0	4.0E+2
14	1.8E-1	2.4E-1	3.4E+0	3.8E+2
30	2.8E-1	3.0E-1	4.1E+0	3.0E+2
60	4.2E-1	4.1E-1	5.2E+0	2.5E+2
90	5.3E-1	4.9E-1	5.2E+0	2.1E+2
180	7.6E-1	6.6E-1	5.2E+0	1.4E+2
365	1.2E+0	1.1E+0	4.4E+0	9.3E+1
730	2.2E+0	2.2E+0	4.1E+0	5.9E+1
1825	3.0E+0	3.3E+0	4.1E+0	3.4E+1

TABLE 9.28. Potentially Undetected First-Year Effective Dose Equivalent (rem) for a Single Acute Intake of Aged 12% Reference Plutonium Mixture Based on an MDA of 0.02 dpm/day of ^{239}Pu Detected in Urine

Days Post Intake	Mode of Intake			
	Transportable Injection	Inhalation		
		Class W	Class Y	Super Y
1	4.0E-4	8.7E-4	2.6E-2	3.5E+1
2	6.2E-4	1.3E-3	3.7E-2	2.3E+1
5	2.1E-3	4.1E-3	1.2E-1	2.8E+1
7	3.2E-3	6.2E-3	2.0E-1	2.8E+1
14	5.1E-3	9.3E-3	3.1E-1	2.6E+1
30	7.9E-3	1.2E-2	3.7E-1	2.2E+1
60	1.2E-2	1.6E-2	4.8E-1	1.7E+1
90	1.5E-2	1.9E-2	4.8E-1	1.5E+1
180	2.1E-2	2.5E-2	4.8E-1	9.8E+0
365	3.4E-2	4.3E-2	4.1E-1	6.6E+0
730	6.2E-2	8.7E-2	3.7E-1	4.2E+0
1825	8.4E-2	1.3E-1	3.7E-1	2.5E+0

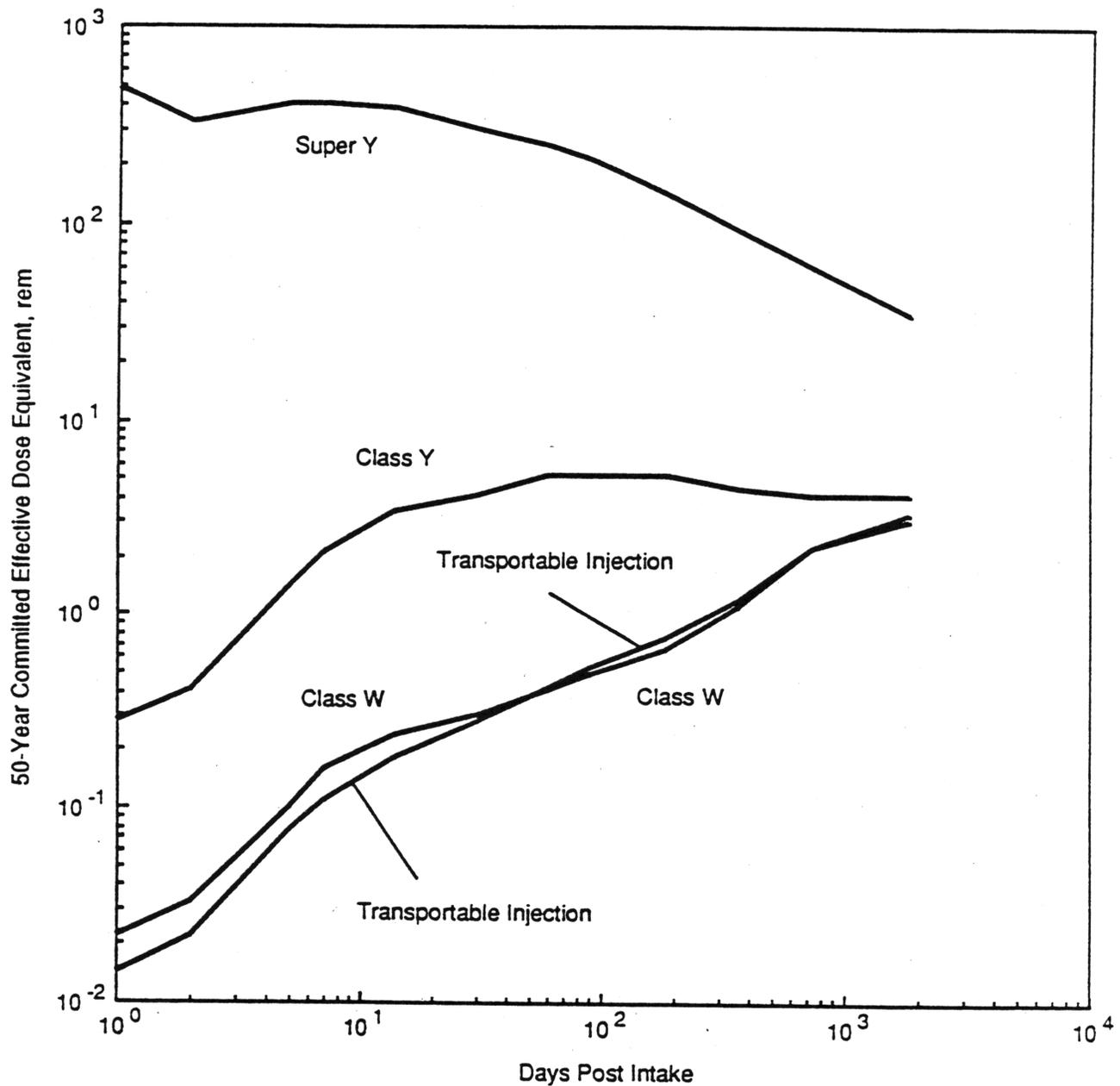
TABLE 9.29. Potentially Undetected 50-Year Committed Effective Dose Equivalent (rem) for a Single Acute Intake of Aged 12% Reference Plutonium Mixture Based on an MDA of 0.02 dpm/day of ^{239}Pu Detected in Urine

Days Post Intake	Mode of Intake			
	Transportable Injection	Inhalation		
		Class W	Class Y	Super Y
1	1.8E-2	2.7E-2	3.4E-1	6.6E+2
2	2.8E-2	4.1E-2	4.9E-1	4.3E+2
5	9.5E-2	1.3E-1	1.6E+0	5.2E+2
7	1.5E-1	2.0E-1	2.6E+0	5.2E+2
14	2.3E-1	2.9E-1	4.1E+0	4.9E+2
30	3.6E-1	3.8E-1	4.9E+0	4.1E+2
60	5.5E-1	5.1E-1	6.3E+0	3.2E+2
90	6.8E-1	6.0E-1	6.3E+0	2.8E+2
180	9.5E-1	7.9E-1	6.3E+0	1.8E+2
365	1.5E+0	1.4E+0	5.4E+0	1.2E+2
730	2.8E+0	2.7E+0	4.9E+0	7.9E+1
1825	3.8E+0	4.1E+0	4.9E+0	4.7E+1



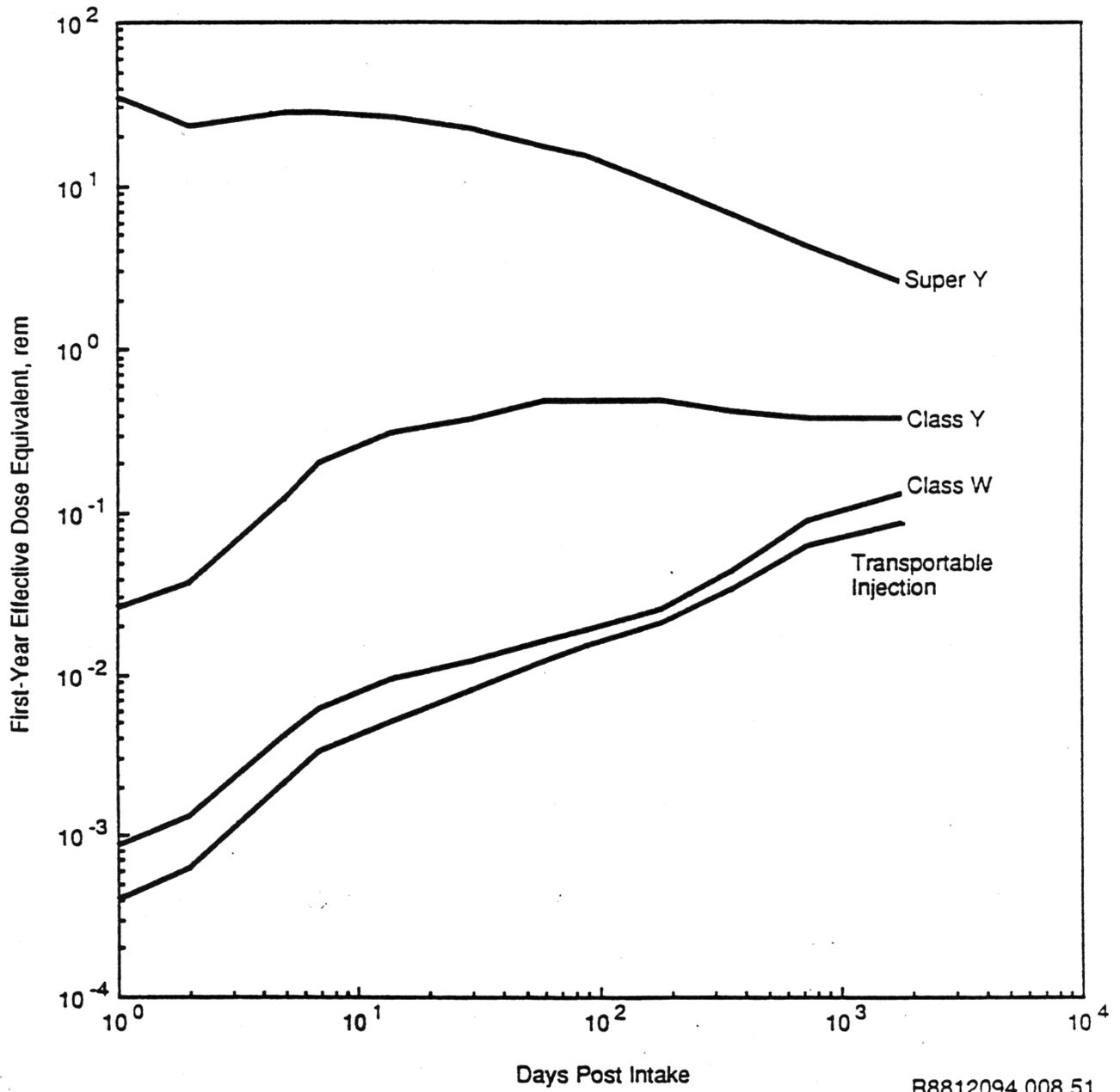
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FIGURE 9.5. Potentially Undetected First-Year Effective Dose Equivalent (rem) for a Single Acute Intake of Fresh 6% Reference Plutonium Mixture Based on an MDA of 0.02 dpm/day of ²³⁹Pu Detected in Urine



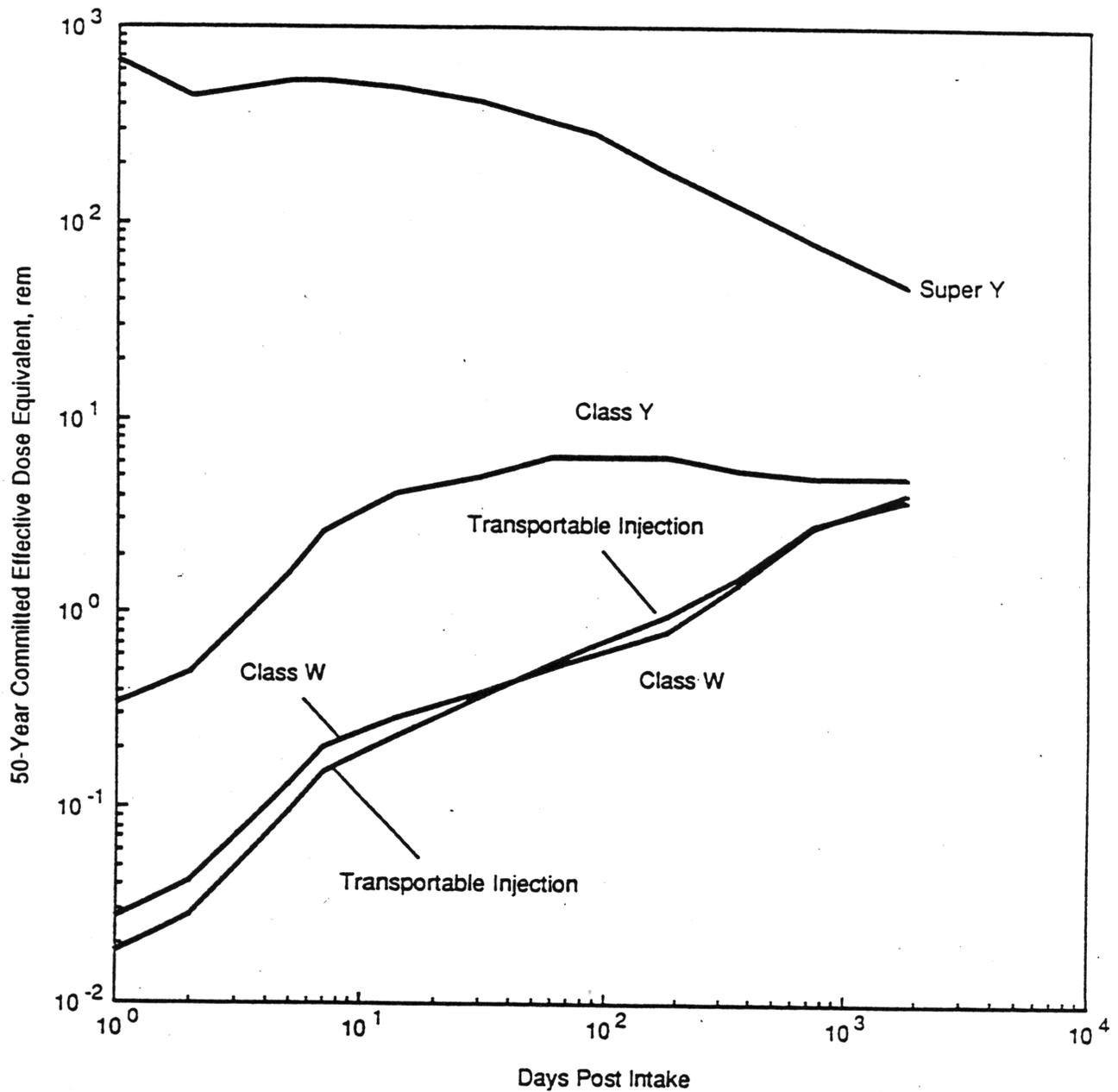
R8812094 014 51

FIGURE 9.6. Potentially Undetected 50-Year Committed Effective Dose Equivalent (rem) for a Single Acute Intake of Fresh 6% Reference Plutonium Mixture Based on an MDA of 0.02 dpm/day of ^{239}Pu Detected in Urine



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FIGURE 9.7. Potentially Undetected First-Year Effective Dose Equivalent (rem) for a Single Acute Intake of Aged 12% Reference Plutonium Mixture Based on an MDA of 0.02 dpm/day of ²³⁹Pu Detected in Urine



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FIGURE 9.8. Potentially Undetected 50-Year Committed Effective Dose Equivalent (rem) for a Single Acute Intake of Aged 12% Reference Plutonium Mixture Based on an MDA of 0.02 dpm/day of ^{239}Pu Detected in Urine

TABLE 9.30. Potentially Undetected First-Year Effective Dose Equivalent (rem) for a Single Acute Intake of Fresh 6% Reference Plutonium Mixture Based on an MDA of 0.18 nCi of ^{241}Am Detected by Lung Counting

<u>Days Post Intake</u>	<u>First-Year Effective Dose Equivalent (rem) from Inhalation Intake (1-μm-AMAD particles)</u>		
	<u>Class W</u>	<u>Class Y</u>	<u>Super Y</u>
0	1.6E+1	2.6E+1	2.6E+1
1	2.3E+1	3.7E+1	3.7E+1
2	2.6E+1	4.1E+1	4.1E+1
5	2.7E+1	4.1E+1	4.1E+1
7	2.5E+1	3.8E+1	3.8E+1
14	2.1E+1	2.9E+1	2.9E+1
30	1.6E+1	1.9E+1	1.9E+1
60	1.4E+1	1.2E+1	1.1E+1
90	1.5E+1	8.7E+0	8.5E+0
180	2.6E+1	5.1E+0	5.0E+0
365	1.5E+2	3.2E+0	3.0E+0
730	9.8E+3	2.4E+0	2.0E+0
1825	--	2.6E+0	1.4E+0

TABLE 9.31. Potentially Undetected 50-Year Committed Effective Dose Equivalent (rem) for a Single Acute Intake of Fresh 6% Reference Plutonium Mixture Based on an MDA of 0.18 nCi of ^{241}Am Detected by Lung Counting

<u>Days Post Intake</u>	<u>Fifty-Year Committed Effective Dose Equivalent (rem) from Inhalation Intake (1-μm-AMAD particles)</u>		
	<u>Class W</u>	<u>Class Y</u>	<u>Super Y</u>
0	4.3E+2	3.0E+2	4.9E+2
1	6.2E+2	4.3E+2	7.0E+2
2	7.0E+2	4.8E+2	7.8E+2
5	7.3E+2	4.8E+2	7.8E+2
7	6.9E+2	4.4E+2	7.2E+2
14	5.7E+2	3.4E+2	5.5E+2
30	4.5E+2	2.2E+2	3.6E+2
60	4.0E+2	1.4E+2	2.2E+2
90	4.2E+2	1.0E+2	1.6E+2
180	7.2E+2	6.0E+1	9.5E+1
365	4.1E+3	3.7E+1	5.7E+1
730	2.7E+5	2.8E+1	3.9E+1
1825	--	3.0E+1	2.6E+1

TABLE 9.32. Potentially Undetected First-Year Effective Dose Equivalent (rem) for a Single Acute Intake of Aged 12% Reference Plutonium Mixture Based on an MDA of 0.18 nCi of ^{241}Am Detected by Lung Counting

<u>Days Post Intake</u>	<u>First-Year Effective Dose Equivalent (rem) from Inhalation Intake (1-μm-AMAD particles)</u>		
	<u>Class W</u>	<u>Class Y</u>	<u>Super Y</u>
0	4.6E-2	7.5E-2	9.4E-2
1	7.0E-2	1.2E-1	1.4E-1
2	8.5E-2	1.4E-1	1.7E-1
5	1.0E-1	1.6E-1	2.0E-1
7	1.1E-1	1.6E-1	2.1E-1
14	1.2E-1	1.7E-1	2.1E-1
30	1.5E-1	1.7E-1	2.1E-1
60	2.1E-1	1.7E-1	2.1E-1
90	3.0E-1	1.7E-1	2.1E-1
180	9.3E-1	1.8E-1	2.2E-1
365	9.5E+0	2.0E-1	2.4E-1
730	1.0E+3	2.5E-1	2.7E-1
1825	--	4.8E-1	3.2E-1

TABLE 9.33. Potentially Undetected 50-Year Committed Effective Dose Equivalent (rem) for a Single Acute Intake of Aged 12% Reference Plutonium Mixture Based on an MDA of 0.18 nCi of ^{241}Am Detected by Lung Counting

<u>Days Post Intake</u>	<u>Fifty-Year Committed Effective Dose Equivalent (rem) from Inhalation Intake (1-μm-AMAD particles)</u>		
	<u>Class W</u>	<u>Class Y</u>	<u>Super Y</u>
0	1.4E+0	9.9E-1	1.8E+0
1	2.2E+0	1.5E+0	2.7E+0
2	2.7E+0	1.8E+0	3.2E+0
5	3.3E+0	2.1E+0	3.8E+0
7	3.4E+0	2.2E+0	3.8E+0
14	3.8E+0	2.2E+0	3.9E+0
30	4.6E+0	2.2E+0	3.9E+0
60	6.6E+0	2.2E+0	3.9E+0
90	9.6E+0	2.3E+0	4.0E+0
180	2.9E+1	2.4E+0	4.2E+0
365	3.0E+2	2.7E+0	4.5E+0
730	3.3E+4	3.3E+0	5.1E+0
1825	--	6.3E+0	6.0E+0

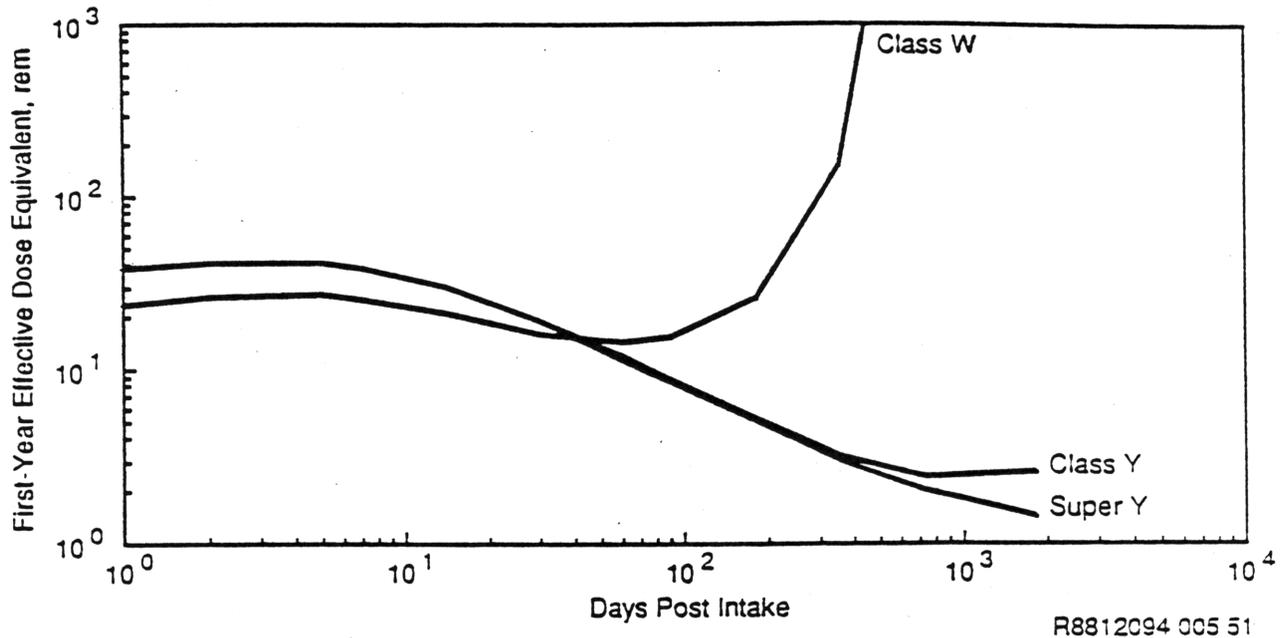


FIGURE 9.9. Potentially Undetected First-Year Effective Dose Equivalent (rem) for a Single Acute Intake of Fresh 6% Reference Plutonium Mixture Based on an MDA of 0.18 nCi of ^{241}Am Detected by Lung Counting

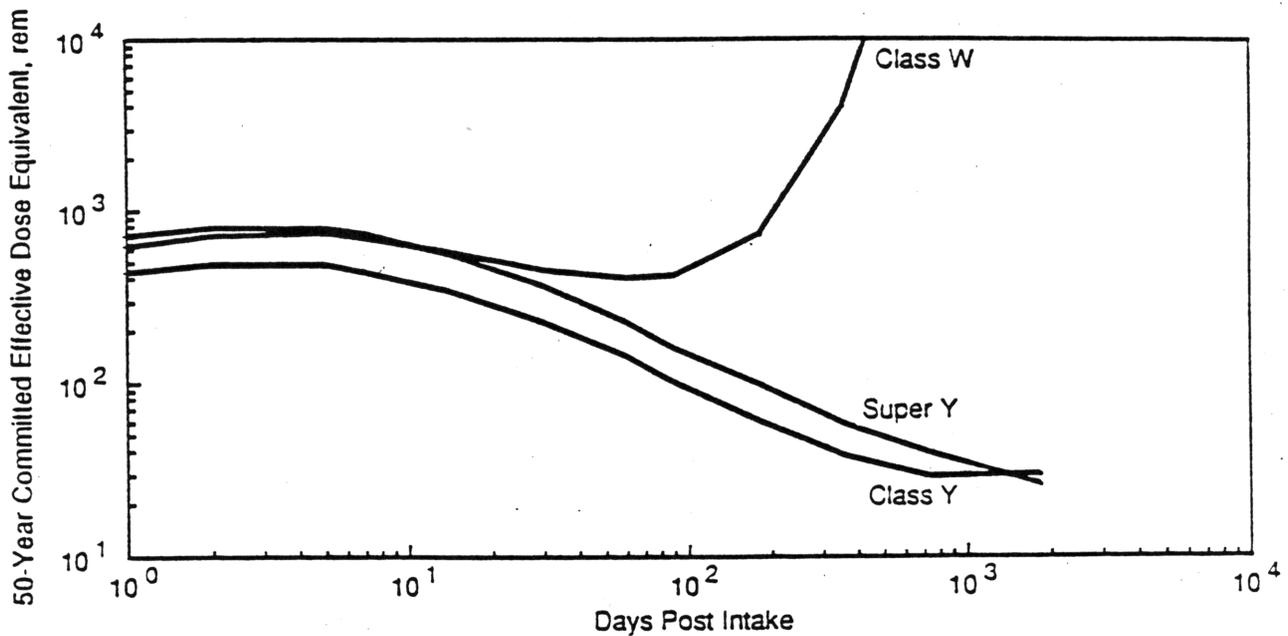
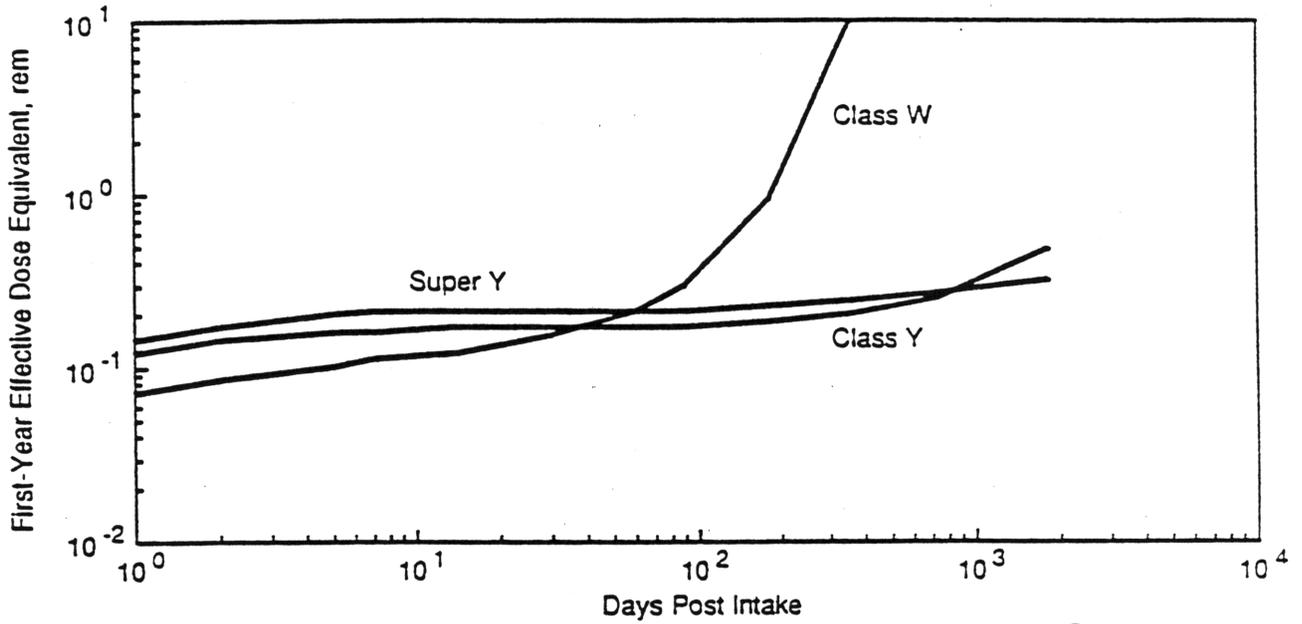
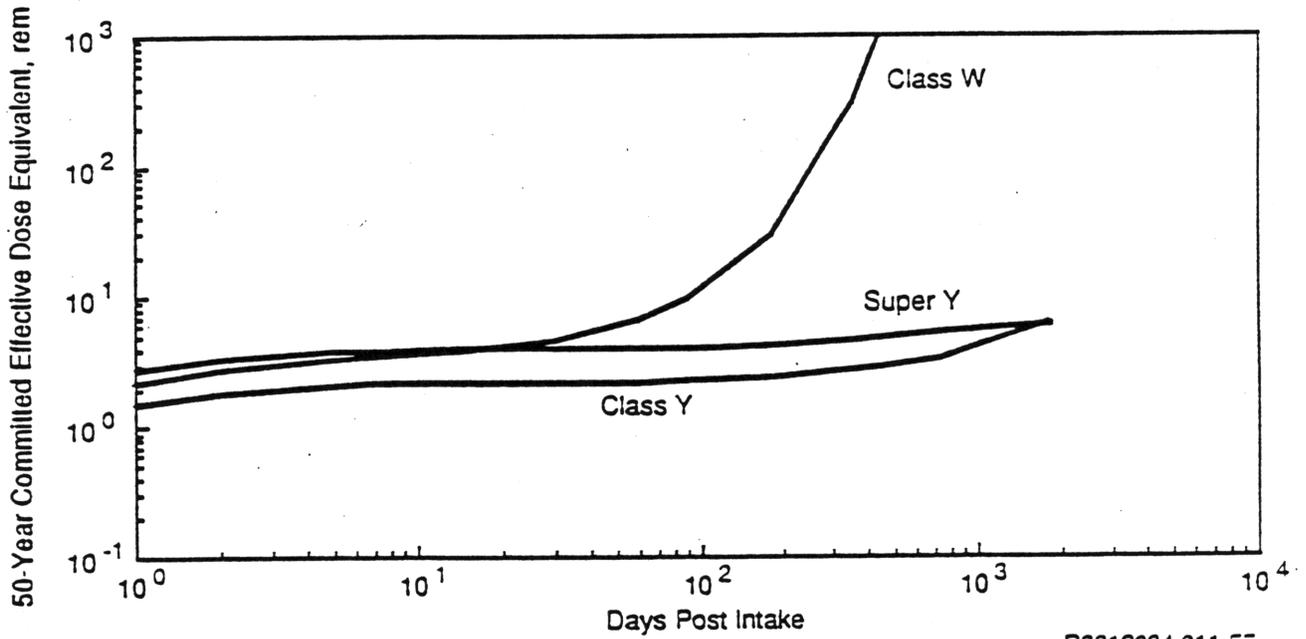


FIGURE 9.10. Potentially Undetected 50-Year Committed Effective Dose Equivalent (rem) for a Single Acute Intake of Fresh 6% Reference Plutonium Mixture Based on an MDA of 0.18 nCi ^{241}Am Detected by Lung Counting



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FIGURE 9.11. Potentially Undetected First-Year Effective Dose Equivalent (rem) for a Single Acute Intake of Aged 12% Reference Plutonium Mixture Based on an MDA of 0.18 nCi of ^{241}Am Detected by Lung Counting



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FIGURE 9.12. Potentially Undetected 50-Year Committed Effective Dose Equivalent (rem) for a Single Acute Intake of Aged 12% Reference Plutonium Mixture Based on an MDA of 0.18 nCi of ^{241}Am Detected by Lung Counting

internal dose estimation available for fission products. The lack of sensitivity is due to the much higher dose per unit intake associated with tenaciously retained alpha-emitting radionuclides as compared with beta- and gamma-emitting fission products. As can be seen by the discussion in the previous subsection, more frequent routine bioassay measurements are unlikely to significantly improve this sensitivity. Some effort has been undertaken at Hanford to assess and develop improved methods of monitoring for super Y forms of plutonium (Bihl et al. 1988). However, this work is in the development phase, and its conclusions are too preliminary for inclusion in this technical basis.

Because of the lack of sensitivity of routine bioassay, special bioassay monitoring as a supplement to the routine program should be promptly initiated by workplace indications of potential internal exposure to plutonium. When adequate measurements are made promptly after a suspected intake, good sensitivity to potential dose can be obtained.

9.4.7 Special Bioassay Monitoring

If a potential intake of plutonium is suspected, special bioassay monitoring should be quickly initiated. Typically this monitoring should include same-day in vivo measurements, overnight or first-day urine collection, and early fecal sample collection. The early fecal samples are particularly important for relatively insoluble forms of plutonium (class Y and super Y) because in vivo and urine sample measurements are relatively insensitive to these intakes. An early single voiding urine sample may also be warranted for determining the need for potential dose-reduction therapy. If DTPA chelation therapy was administered, then a total urine sample collection is recommended to reduce any uncertainties associated with sample normalization. Total urine sample collection should be continued until the excretion pattern is established.

9.4.8 Bioassay Monitoring Capability for Workers with Known Plutonium

Depositions

The capability of a bioassay program is directly dependent upon the magnitude of an identifiable increase in a bioassay measurement. When a

worker has a positive baseline bioassay level due to previous exposure, the ability to detect a subsequent increase in the bioassay level from an additional intake is more dependent on the variability of current bioassay levels and less dependent on analytical capability. In other words, to be detected, subsequent intakes must result in increases in bioassay measurements that exceed the background "noise" level. Guidance concerning the potential dose from potentially undetected intakes must be developed on a case-by-case basis. Appropriate adjustments to measurement frequencies can then be determined based on the potential undetected dose. As an approximate rule-of-thumb, a single bioassay measurement will probably have to be at least twice the baseline level to be readily recognized, due to the substantial variability in single bioassay measurements on individual people. For many situations, this may imply that a normally detectable intake may not be detectable on top of a pre-existing internal plutonium deposition. Like most rules-of-thumb, this is only a rough suggestion; cases of significance must be addressed individually.

9.5 ASSESSMENT OF INTERNAL DOSE

The following subsections discuss the general approach for assessing internal dose, estimating presystemic and lung depositions, assessing organ dose equivalents, estimating intake, and making simplified dose assessments.

9.5.1 General Approach

The dosimetry for plutonium involves a four-step process for in-depth assessments that roughly proceeds as follows:

- Estimate the clearance component rates.
- Estimate the presystemic deposition for each clearance component.
- Estimate the initial lung deposition for each clearance component.
- Assess the internal dose equivalents (organ and effective, annual and committed) based on deposition estimates and assumptions of Section 9.2.1.

Alternatively, a simplified dose assessment process can be used when only limited data are available. This process involves the following:

- Estimate the intake.

- Assess the internal dose equivalents.

The techniques used for calculating these estimates are discussed in the following subsections. Assumptions about systemic organ biokinetics, organ mass, tissue or organ weighting factors, and transportability classes are those used in ICRP 26, 30, and 48 (1977; 1979; and 1986).

9.5.2 Estimating Presystemic Deposition

The presystemic deposition is defined as the total radioactivity that will ultimately translocate into the transfer compartment from a metabolically isolated pool; in other words, the activity ultimately reaching the blood. Historically at Hanford, this has been the quantity that has been compared with the MPBB of 0.04 μCi (^{239}Pu) listed in National Bureau of Standards Handbook 69 (NBS 1959), NCRP 22 (1959), and ICRP 2 (1959). It is related to, but significantly different from intake, lung deposition, long-term lung burden, and instantaneous body burden (or retained quantity).

Activity is deposited in presystemic compartments at the time of intake. From there, systemic uptake may be essentially instantaneous (as with a readily transportable wound intake), or it may occur gradually over an extended period of time (as in the case of an inhalation of class Y material). Transfer from the presystemic compartment into systemic circulation is assumed to be governed by linear first-order kinetics, and can be described in terms of a transfer rate constant.

The computer program PUCALC has been written to evaluate alternate values of the transfer rate and presystemic deposition, based on the urinary excretion data. The program describes the urinary excretion of plutonium for user-selected values for the transfer rate and presystemic deposition. Additional information on PUCALC is provided in Appendix F.

It must be remembered that the presystemic deposition may be only part of the initial deposition in the body. In the case of the lung, the ICRP 30 lung model predicts that the presystemic deposition represents about one-third of the total deposition in the slowly clearing compartments of the lung. The total long-term lung deposition must be considered when assessing lung doses. Experience with wounds has shown that a significant fraction of slowly

transportable activity can become bound up in tissue at the wound site and essentially walled-off or permanently isolated from the transfer compartment. Whether this might represent a true isolation, or merely an extremely slow transfer rate, is a matter of some speculation. The need to determine localized tissue deposits for potentially small wound areas from slowly transportable plutonium must be decided on a case-by-case basis.

9.5.3 Estimating Initial Lung Deposition

Initial lung depositions can be estimated based on direct in vivo measurements, fecal data, urine data, or a combination of such data. When there is direct knowledge, or a reasonable assumption, of the isotopic composition of a plutonium mixture, direct in vivo measurement of ^{241}Am in the lung can be used to evaluate lung depositions. A series of detectable ^{241}Am measurements can be used to establish the effective lung clearance rate, and the plutonium depositions can be estimated by activity ratios relative to ^{241}Am . In analyzing long-term lung measurement data, consideration must be given to the potential impact of the ingrowth of ^{241}Am from ^{241}Pu . This requires that the clearance rate of the ^{241}Am relative to that of ^{241}Pu be known. Laboratory animal research data have indicated that early clearance of plutonium mixtures from the lung may be enriched in ^{241}Am relative to the intake composition. This has been attributed to a more rapidly clearing component of the ^{241}Am that is initially deposited in the lung along with the plutonium. Once this initially soluble ^{241}Am has been cleared, the observed clearance rate for the remaining ^{241}Am will be similar to that of the host matrix material, i.e., plutonium (Eidson 1980).

Fecal data can be used for estimating lung depositions in two ways. First, it can provide isotopic composition information for use with in vivo measurements. Secondly, it can be used in conjunction with the ICRP 30 respiratory tract model to estimate intake or initial depositions in various compartments of the respiratory tract. Caution must be exercised in interpreting fecal data because a slight ingestion intake can significantly bias lung deposition estimates. There is no way to differentiate inhalation from ingestion intakes by early fecal data. Follow-up fecal samples somewhat removed in time from the intake (2 to 4 weeks or more) may be helpful in

determining if observed fecal activity is from lung clearance or ingestion clearance. Fecal excretion is also highly dependent on particle size, with larger sizes being more readily excreted in feces. Appendix E provides additional information on assessment of fecal sample data.

Urine sample data are generally not considered a good basis for estimating initial lung depositions; however, they can be helpful and occasionally may be the only data available. For known inhalation exposures, the presystemic deposition estimated using the technique described in the preceding section can provide an indication of initial lung deposition. By using the presystemic deposition estimate as the ultimate quantity to be translocated into the transfer compartment, the compartment fractions of the ICRP 30 respiratory tract model can be used to estimate initial deposition in the various compartments. For example, the initial deposition in the long-term pulmonary region compartments (ICRP 30 lung model compartments e, g, and h) (see Appendix D) can be estimated by attributing the slowly transportable presystemic deposition to pulmonary compartments e and h, and then multiplying that value by the ratio of the total long-term compartment fractions to the fraction in the presystemic compartments as follows:

$$P_0 = U_{\infty}(e+h) * (F_e + F_g + F_h)/(F_e + F_h) \quad (9.2)$$

where P_0 is the initial long-term pulmonary deposition, $U_{\infty}(e+h)$ is the slowly transportable presystemic deposition, and F_e , F_g , F_h are ICRP 30 lung model compartment deposition fractions.

The long-term pulmonary deposition estimate, based on fecal, urine, or air sample data, should be compared with the estimates from in vivo measurements and activity relationships for consistency. In this example, the in vivo ^{241}Am MDA multiplied by the plutonium-ameridium ratio may be used as an upper bound for dose assessment with the "best" estimate within this bound based on the evaluation of urine sample data.

9.5.4 Assessing Organ Dose Equivalents

The organs of primary interest for plutonium dose evaluations are the bone surface, red marrow, liver, and gonads. The lung is also an organ of interest for inhalations.

Other organs or tissues may be of interest depending on the nature of an intake. For example, the dose to a specific lymph node or small volume of tissue may be of interest as the result of a wound intake of slowly transportable materials. Such cases can be dealt with as they arise and are beyond the general scope of this technical basis.

Plutonium reaching the transfer compartment is distributed to the liver, bone surfaces, and the gonads according to the ICRP 48 (1986) biokinetic model. Once deposited in these tissues, the ICRP 48 clearance rates are assumed to apply. Thus, for calculating organ doses, the ICRP 48 organ-retention functions and dosimetry factors are used.

Because plutonium cannot be effectively measured in the systemic organs, and because plutonium and americium may not behave similarly after reaching the systemic organs, caution must be exercised in using measurements of americium in systemic organs for plutonium dose calculations based on the isotope ratios existing at the time of intake. Isotope ratios can change with time due to the different solubility rates and retention characteristics of plutonium and americium. However, americium measurements can be used for americium dose calculations.

Once the magnitude of an intake, presystemic deposition, or initial lung deposition has been determined, organ dose equivalents and the effective dose equivalent can be assessed using hand-calculation techniques or computer codes. The Hanford Internal Dosimetry Program uses two computer codes to aid in dose calculations, GENMOD, and PLUDO. Each of these codes is briefly discussed in the following paragraphs. More detailed explanations and copies of the codes are maintained in the Hanford Radiation Protection Historical Files.

The GENMOD code (Johnson and Carver 1981), calculates organ retention and organ and effective dose equivalents for any time after intake based on

default ICRP 30 parameters or user-modified parameters. For applications with the Hanford Internal Dosimetry Program, the biokinetic parameters of GENMOD have been modified to reflect the ICRP 48 (1986) model for distribution and retention of radionuclides within the body and the Jones urinary excretion function. Further discussion of GENMOD is provided in Appendix A.

The PLUDO computer code is a Hanford adaptation of the GENMOD code to calculate committed and calendar year organ and effective dose equivalents based on estimates of lung deposition and committed systemic uptake. These estimates of deposition and their associated transport rate constants are derived directly from analysis of urine excretion data, using PUCALC and evaluation of direct (in vivo) bioassay measurement results.

PLUDO implements GENMOD for ^{238}Pu , $^{239/240}\text{Pu}$, ^{241}Pu , and ^{241}Am . Rather than specifying intake quantities, the user provides quantities deposited in the lung and presystemic compartments. The user also specifies the transport rate constants for retention of the plutonium in the lung and for uptake of plutonium from the presystemic compartment. The "presystemic compartment" is used to represent any site of radionuclide deposition from which uptake by systemic circulation occurs. For example, presystemic compartments may be associated with activity in the lung or a wound site. The presystemically deposited activity is the activity deposited that will eventually become systemically absorbed. PLUDO allows for specification of up to three lung and three presystemic compartments, each with a unique transport rate constant, for each radionuclide. PLUDO then invokes GENMOD to compute cumulated activities in source organs for each calendar year beginning with the year of intake, calculates resulting organ and effective dose equivalents for each calendar year, and sums these over all deposition compartments and radionuclides.

9.5.5 Estimating Intake

An intake of plutonium can be estimated by fitting the urinary excretion data to the appropriate intake excretion function, using manual or computerized techniques. For a single data point, the intake can be estimated by dividing the measured excretion by the value of the intake excretion function on the day after intake represented by the sample in a manner similar to

Equation (9.3). Values for the fractional intake excretion function can be obtained from Figure 9.4, Table 9.6, or directly from running the GENMOD computer code. For multiple data points, a least-squares fit of the data to the expected excretion function should be used, as described in Appendix C.

In addition to their use for dose calculations, intakes calculated by the above techniques may also be compared with the ICRP ALIs or intake estimates based on air sample results. When bioassay data are not available, air sample results may be the basis for estimating intake. An intake may also be estimated from the fecal data explained in Appendix E.

9.5.6 Simplified Dose Assessments

Simplified dose assessments use the techniques and biokinetic models described previously and assume ICRP 23 (1974) Reference Man parameters, without correction for individual-specific characteristics. These assessments provide a basis for prospective bioassay program design, initial estimates when bioassay data are few, and retrospective evaluation of intakes that are too small to yield sufficient bioassay data to empirically describe the biokinetic processes. In addition, the bioassay projections associated with simplified assessments can be used as a trigger point for more in-depth measurements or dose assessments.

The procedure for performing a simplified dose assessment is as follows:

1. Normalize the result to the daily excretion rate, if necessary (see Appendix C).
2. Select the intake date (known or assumed).
3. Estimate the intake by fitting the data to the excretion model (see Appendix C).
4. Calculate the dose equivalents by multiplying the estimated intake by the appropriate intake dose equivalent factor from GENMOD.

The intakes of fresh 6% and aged 12% reference plutonium mixtures resulting in a first-year effective dose equivalent of 100 mrem have been calculated using the simplified dose assessment procedure. The results of these calculations are shown in Table 9.34.

TABLE 9.34. Intakes for Reference Plutonium Mixtures Resulting in a First-Year Effective Dose Equivalent of 100 mrem

Mode of Intake Mixture ^(a)	Mass of Intake, ng	Isotopic Composition of Intake			
		²³⁸ Pu, nCi	²³⁹ + ²⁴⁰ Pu, nCi	²⁴¹ Pu, nCi	²⁴¹ Am, nCi
Readily transportable injection					
6% Pu - fresh	12	1.0E-1	8.5E-1	9.7E+0	6.0E-4
6% Pu - aged	11	9.1E-2	8.0E-1	7.2E+0	6.5E-2
12% Pu - fresh	9.6	1.6E-1	7.7E-1	2.9E+1	1.8E-3
12% Pu - aged	7.9	1.3E-1	6.3E-1	1.9E+1	1.7E-1
Class W inhalation					
6% Pu - fresh	66	5.6E-1	4.7E+0	5.4E+1	3.3E-3
6% Pu - aged	61	5.0E-1	4.4E+0	4.0E+1	3.6E-1
12% Pu - fresh	53	9.0E-1	4.2E+0	1.6E+2	1.0E-2
12% Pu - aged	43	7.1E-1	3.5E+0	1.1E+2	9.5E-1
Class Y inhalation					
6% Pu - fresh	41	3.5E-1	2.9E+0	3.3E+1	2.1E-3
6% Pu - aged	38	3.1E-1	2.7E+0	2.5E+1	2.2E-1
12% Pu - fresh	33	5.6E-1	2.6E+0	1.0E+2	6.2E-3
12% Pu - aged	27	4.4E-1	2.2E+0	6.5E+1	5.9E-1
Super Y inhalation					
6% Pu - fresh	39	3.4E-1	2.8E+0	3.3E+1	2.1E-3
6% Pu - aged	37	3.0E-1	2.6E+0	2.4E+1	2.1E-1
12% Pu - fresh	32	5.5E-1	2.6E+0	1.0E+2	6.5E-3
12% Pu - aged	27	4.3E-1	2.1E+0	6.4E+1	5.9E-1

(a) % = nominal ²⁴⁰Pu weight percent in mixture.
 Fresh = 2 weeks of ²⁴¹Am ingrowth following separation.
 Aged = 5 years of ²⁴¹Am ingrowth following separation.
 Inhalation intakes assume 1- μ m-AMAD particle size.

The simplified dose assessment procedure was also used for determining the bioassay program capabilities described in Section 9.4.

9.6 MANAGEMENT OF INTERNAL CONTAMINATION CASES

This section discusses the diagnostic procedures, therapeutic actions, and long-term monitoring of internal depositions.

9.6.1 Diagnostic Procedures

The diagnosis of an intake involves a combination of workplace monitoring to identify on-the-job potential intakes and bioassay measurements to confirm and quantify internal contamination.

Potential intakes are intended to be identified by workplace monitoring, such as personal contamination surveys, nasal smear analyses, air sample results, or workers' identifications of unusual conditions. These techniques provide qualitative screening to alert radiation protection staff to potential internal exposure, rather than absolute confirmation that exposure has or has not occurred. For example, activity detected on nasal smears is usually an indication of an inhalation intake; however, the absence of activity does not necessarily mean that an intake did not occur. The absence of nasal smear activity following an inhalation intake can be explained by a sufficient delay between the time of intake and the collection of nasal smears to allow for complete clearance of activity from the nares. The ICRP 30 respiratory tract model indicates that a delay of as little as 30 to 60 minutes may be adequate for this in some cases. Alternatively, some individuals are mouth-breathers, whose noses are partially or completely bypassed in the respiratory process, hence no activity may be deposited in the nares, despite the occurrence of an inhalation intake. Particle size can also significantly affect nasal deposition and clearance.

Once a worker has been identified as having incurred a potential internal exposure, the initial diagnostic measurements are arranged. These may include a chest count, wound count, single voiding (spot) urine sample analysis, first-day fecal sampling, and overnight urine sampling.

The purpose of these initial procedures is to provide an order-of-magnitude estimate of the potential internal exposure and dose. Initial diagnostic measurements are usually sufficient for final evaluations only when all results collectively rule out the possibility of an intake. In reality, initial measurements are not generally expected to do this, and follow-up measurements are necessary.

Follow-up diagnostic measurements may include additional urine and fecal samples, chest counts, liver counts, head counts, and lymph node counts. These analyses aid in determining the magnitude, location, and retention characteristics of the deposited material. In some cases, blood samples or tissue specimens may also be appropriate.

In addition, workplace or clothing contamination analyses, air sample analyses, particle size analyses, and/or solubility analyses may also be performed to more clearly define the physical and radiological characteristics of the material to which the worker was exposed.

It is the responsibility of the exposure evaluator, working closely with contractor radiation protection staff, to determine the appropriate diagnostic protocols. Scheduling of follow-up measurements will normally be done by the appropriate contractor radiation protection staff.

9.6.2 Therapeutic Actions

Therapeutic actions for potential internal contamination include the use of decorporation agents, catharsis, and surgical excision. For the purposes of this discussion, the normal skin decontamination procedures of Hanford contractors are not considered therapeutic actions, although it is acknowledged that these procedures can be quite effective in preventing the internal deposition of radioactivity.

The decision to undertake one or more of these measures is the responsibility of the participating HEHF Occupational Medicine physician with the concurrence of the patient. The exposure evaluator will provide advice and consultation to the physician and patient regarding the potential dose implications and efficacy of alternative actions.

Decorporation therapy is also referred to as chelation therapy, and involves the chemical removal of radioactivity from the bloodstream through drug administration. The drug DTPA has U.S. Food and Drug Administration approval for use in removing plutonium and other heavy metals from the body. Other drugs are also available to HEHF Occupational Medicine.

Catharsis involves accelerating the passage of material through the GI tract by means of laxative drugs or physical means such as an enema. Catharsis has potential value in reducing the adsorption of material into the bloodstream from the GI tract and in reducing the dose to the GI tract organs from material passing through the GI tract. These measures are not generally considered for occupational exposures to plutonium, because the GI tract adsorption of plutonium is so slight, and the dose to the GI tract organs is usually an insignificant fraction of the total effective dose.

Surgical excision following wounds can be extremely effective in reducing the potential internal deposition, particularly when coupled with decorporation therapy. Minor excisions are usually performed at the EDF by HEHF Occupational Medicine staff, assisted by a PNL exposure evaluator and radiation protection personnel.

9.6.3 Long-Term Monitoring of Internal Depositions

Once an internal dosimetry evaluation has been completed, it may be recommended that the worker be placed on a specialized long-term bioassay monitoring schedule. The reasons for this are twofold: first, long-term follow-up monitoring results that are consistent with the projected results verify the conclusions of the evaluation. Second, if long-term results are projected to be detectable, and the worker returns to plutonium work, then the capability of a routine bioassay monitoring program to detect an additional intake may be affected. This latter point is addressed in greater detail in Section 9.4.8.

Specialized bioassay monitoring programs may be required for workers with known internal depositions of plutonium. These programs may include head counts, liver counts, periodic chest counts, and urine samples. In some cases fecal sampling may also be desired. It is the responsibility of the exposure

evaluator to recommend appropriate long-term bioassay monitoring to the contractor dosimetry or radiation protection organization that has the responsibility for acting on these recommendations.