8.0 Plutonium

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

Prior to 1989, the general approach to plutonium internal dosimetry at Hanford was to evaluate the systemic deposition based on urine data, and compare the result with a referenced maximum permissible body burden (MPBB) such as those contained in ICRP publication 2 (1959). The assessed systemic deposition was a "committed" systemic deposition, i.e., an estimate of the total amount of activity that would eventually reach systemic compartments. The calculated depositions did not address 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 was calculated, its value was assumed to remain constant for the worker's life. The percentage of the MPBB was used to indicate the degree of compliance (or noncompliance) with Atomic Energy Commission, Energy Research and Development Agency, and DOE standards for radiation protection. Initially, systemic depositions below 5% MPBB were not reported as confirmed depositions. This cutoff for recording and reporting was lowered to 1% MPBB in the 1970s.

Lung dose equivalents were assessed prior to 1989 in cases where in vivo measurements had 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 and estimates of lung clearance rates based on ^{241}Am in vivo measurements, urine data, and fecal data when they were available. Lacking such data, default assumptions were used and documented in evaluations. The techniques for calculating dose were similar to those used in ICRP 2 and ICRP 10 (1969) and applied a quality factor of 10 for alpha particle emissions. The results of those lung dose estimates were compared with the long-standing 15-rem/yr limit of ICRP 2.

In late 1988, the technical approach to plutonium dosimetry at Hanford changed to the dosimetry approach of ICRP 26/30 (1977/1979), incorporating the concepts of organ and tissue weighting factors to give an effective dose equivalent from specific organ doses. The alpha particle quality factor was also changed from 10 to 20, and the concepts of stochastic and deterministic (nonstochastic) dose limits were adopted. In addition, advances in

measurement technology and modeling improved the capabilities for plutonium dosimetry. The concept of "presystemic deposition" was introduced by Sula, Carbaugh, and Bihl (1989) for the purpose of simulating biokinetic behavior in estimating internal doses. The presystemic deposition was defined as the component(s) of an initial deposition that would ultimately translocate to the blood, regardless of the time required to translocate. A transfer rate from the initial deposition into the systemic compartment was linked with each component of the presystemic deposition. Once material from the presystemic deposition reached the systemic compartment, it was assumed to behave in accordance with the applicable biokinetic model. The presystemic deposition specifically excluded material permanently retained at the entry site or in lymphatic tissues.

A further shift in internal dosimetry for plutonium occurred in 1992 with requirements to report intake magnitude in addition to dose equivalents (10 CFR 835, DOE 1992). This resulted in a shift away from presystemic deposition assessments (which ignored intake fractions not retained, such as the material exhaled immediately following inhalation) to the total intake assessment. The adoption of the CINDY computer code (Strenge et al. 1992) as the principal calculational tool for Hanford internal dosimetry facilitated this shift to intake assessment.

8.1 Sources and Characteristics

This section provides general information on the isotopes, mixtures, and forms of plutonium that are commonly found at Hanford. The physical data were taken directly from, or calculated based on, information in ICRP 30 and ICRP 38 (1983).

8.1.1 Sources of Plutonium

Production of plutonium was the original mission for Hanford. It was produced by irradiation of uranium fuel elements in reactors in the 100 Areas, then separated and purified in the 200 Area chemical processing facilities. After purification, it underwent conversion to final metallic form at the Plutonium Finishing Plant (PFP [234-5Z Building]) in the 200-West Area, where it was stored until it was shipped to other DOE sites for component fabrication. Plutonium-contaminated waste is buried or stored in a variety of waste management facilities. Trace plutonium and americium levels can be found in some of the high-level waste storage facilities (e.g., 100-K Spent Fuel Storage Basins, 200 Area tank farms and associated facilities).

Plutonium can also be found at Hanford as a result of research projects that involved spent fuel associated with nuclear power plants, breeder reactor applications, and radioisotope applications. Many of these research projects were in 300 Area facilities. Analytical chemistry laboratories may contain plutonium standard solutions.

Plutonium has also been distributed in the worldwide environment at very low levels as a result of atmospheric testing of nuclear devices. Wrenn, Singh, and Xue (1994) indicated that persons living in the northern hemisphere have accumulated about 3 pCi of $^{239+240}$Pu from fallout from the weapons tests of the 1950s, and reported a background mean urine excretion of 3 to 8 H 10^{-5} dpm/day resulting from that body burden. Similar levels of body burden have been reported by McInroy et al. (1979); McInroy, Boyd, and Eutsler (1981); and Nelson, Thomas, and Kathren (1993). Ibrahim et al. (1999) reported a mean ^{239}Pu urine excretion rate of 1.1 μBq/d (9.2H10^{-5} dpm/d) in a group of long-term residents near the Rocky Flats Site. These body burdens and the urine results suggest that normal background urinary excretion levels of plutonium are far below the nominal 0.02 dpm minimum detectable activity routinely available for Hanford urine bioassay measurements.

8.1.2 Isotope Decay Data

The plutonium and plutonium decay product isotopes of concern at Hanford and selected decay data are listed in Table 8.1. The radiological constants given in Table 8.1 are taken or calculated from data in ICRP 30 and 38.

Table 8.1. Plutonium and Americium Decay Data

		Half-Life		Decay Constant		Specific Activity
Isotope	**Decay Mode**	**Years**	**Days**	**Year^{-1}**	**Day^{-1}**	**Ci/g**
^{238}Pu	Alpha	87.7	3.20E+04	7.90E-03	2.16E-05	1.71E+01
^{239}Pu	Alpha	24,065	8.78E+06	2.88E-05	7.89E-08	6.21E-02
^{240}Pu	Alpha	6,537	2.39E+06	1.06E-04	2.90E-07	2.27E-01
^{241}Pu	Beta	14.4	5.26E+03	4.81E-02	1.32E-04	1.03E+02
^{242}Pu	Alpha	376,300	1.37E+08	1.84E-06	5.05E-09	3.92E-03
^{241}Am	Alpha	432.2	1.58E+05	1.60E-03	4.39E-06	3.43E+00

8.1.3 Reference Isotope Mixtures

Pure isotopes of plutonium are seldom encountered at Hanford facilities. 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 bioassay planning purposes, assumptions regarding the mixture should be made.

The isotopic composition of a plutonium mixture is related to several variables, including the following:

- 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.

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%. The 6% plutonium mixture is commonly referred to as "weapons grade" because that was the nominal target mixture for nuclear weapons components. Weapons-grade plutonium had a relatively short reactor exposure time. The 12% plutonium mixture is commonly referred to at Hanford as "fuel grade," and resulted from lengthier reactor exposure for research or power production purposes.

Plutonium mixtures are also associated with the much longer fuel cycle of large-scale power production reactors. The spent fuel from the power reactor fuel cycle demonstrates a significant buildup of ^{240}Pu, e.g., 25 wt% would not be an unusual number. This form of plutonium can be associated with Hanford research projects involving commercial fuel, such as the Nuclear Waste Vitrification Project (NWVP), circa 1970s.

Other isotopic compositions may be encountered and should be addressed as needed. In a discussion of the manufacture of plutonium, the *DOE Standard Guide of Good Practices for Occupational Radiological Protection in Plutonium Facilities* (DOE 1998) identified isotopic mixtures for heat source, weapons-grade and reactor-grade plutonium mixtures. The weapons-grade mixture is similar to the Hanford weapons-grade mixture, and the reactor-grade mixture is similar to the NWVP mixture described

above. In the internal dosimetry section of that standard, the Hanford weapons grade and fuel-grade mixtures are specifically listed as example mixtures. The heat-source mixture refers to material used for radioisotope thermal generators, which are primarily ^{238}Pu. Heat-source plutonium is not a typical Hanford mixture.

Reference Hanford plutonium mixtures, prior to any ^{241}Am ingrowth, are provided in Table 8.2. 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 composition of a mixture to which a worker has been exposed can be obtained, such data should be used.

Table 8.2. Reference Hanford Plutonium Mixtures Prior to Aging (wt%)

Isotope	Weapons Grade	Fuels Grade	Commercial Power Grade
^{238}Pu	0.05	0.10	1
^{239}Pu	93.1	84.8	55
^{240}Pu	6.0	12.0	26
^{241}Pu	0.8	3.0	13
^{242}Pu	0.05	0.1	5
^{241}Am	0.0	0.0	0.0

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. A hand-calculator program developed at Hanford by Rittman (1984) and written into a computer utility for personal computers (PCs)[(a)] is used to solve these decay relationships, which can also be solved using computer spreadsheet application software. Tables 8.3, 8.4, and 8.5 provide the specific activities of each isotope in the reference mixtures and isotope ratios relative to $^{239+240}$Pu and ^{241}Am. These tables clearly show that ^{242}Pu is an insignificant contributor to the specific activity of the reference mixtures, and may be ignored for purposes of dosimetry.

(a) Personal correspondence between P. D. Rittman and E. H. Carbaugh, 1993, Pacific Northwest National Laboratory.

Table 8.3. Activity Composition of Hanford Reference Weapons-Grade Plutonium Mixture

Mixture Designation:	**Fresh**	**5-Year**	**10-Year**	**15-Year**	**20-Year**	**25-Year**	**30-Year**	**40-Year**	**50-Year**
Years of Aging:	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**40**	**50**
Specific Activity									
in Mixture (Ci/g)									
^{238}Pu	8.56E-03	8.23E-03	7.91E-03	7.60E-03	7.31E-03	7.03E-03	6.75E-03	6.24E-03	5.77E-03
^{239}Pu	5.77E-02	5.77E-02	5.77E-02	5.77E-02	5.77E-02	5.77E-02	5.77E-02	5.76E-02	5.76E-02
^{240}Pu	1.36E-02	1.36E-02	1.36E-02	1.36E-02	1.36E-02	1.36E-02	1.36E-02	1.35E-02	1.35E-02
^{241}Pu	8.24E-01	6.48E-01	5.09E-01	4.00E-01	3.15E-01	2.48E-01	1.95E-01	1.20E-01	7.44E-02
^{242}Pu	1.97E-06	1.97E-06	1.97E-06	1.97E-06	1.97E-06	1.97E-06	1.97E-06	1.97E-06	1.97E-06
^{241}Am	0	5.83E-03	1.04E-02	1.39E-02	1.66E-02	1.87E-02	2.03E-02	2.25E-02	2.36E-02
$^{239+240}$Pu	7.13E-02	7.13E-02	7.13E-02	7.13E-02	7.12E-02	7.12E-02	7.12E-02	7.12E-02	7.11E-02
Pu-alpha	7.99E-02	7.95E-02	7.92E-02	7.89E-02	7.85E-02	7.83E-02	7.80E-02	7.74E-02	7.69E-02
Total alpha	7.99E-02	8.53E-02	8.96E-02	9.28E-02	9.52E-02	9.70E-02	9.83E-02	9.99E-02	1.01E-01
Activity Ratios									
$^{239+240}$Pu:^{241}Am	NA	1.22E+01	6.87E+00	5.13E+00	4.28E+00	3.80E+00	3.50E+00	3.17E+00	3.01E+00
^{241}Am:^{238}Pu	NA	7.09E-01	1.31E+00	1.83E+00	2.27E+00	2.66E+00	3.01E+00	3.60E+00	4.09E+00
^{241}Pu:$^{239+240}$Pu	1.16E+01	9.09E+00	7.15E+00	5.62E+00	4.42E+00	3.48E+00	2.73E+00	1.69E+00	1.05E+00
Total alpha:$^{239+240}$Pu	1.12E+00	1.20E+00	1.26E+00	1.30E+00	1.34E+00	1.36E+00	1.38E+00	1.40E+00	1.41E+00
Total alpha:^{241}Am	NA	1.46E+01	8.63E+00	6.67E+00	5.72E+00	5.18E+00	4.84E+00	4.45E+00	4.26E+00
NA = not applicable									

Table 8.4. Activity Composition of Hanford Reference Fuel-Grade Plutonium Mixture

Mixture Designation:	**Fresh**	**5-Year**	**10-Year**	**15-Year**	**20-Year**	**25-Year**	**30-Year**	**40-Year**	**50-Year**
Years of Aging:	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**40**	**50**
Specific Activity									
in Mixture (Ci/g)									
^{238}Pu	1.71E-02	1.64E-02	1.58E-02	1.52E-02	1.46E-02	1.40E-02	1.35E-02	1.25E-02	1.15E-02
^{239}Pu	5.26E-02	5.26E-02	5.26E-02	5.26E-02	5.26E-02	5.26E-02	5.25E-02	5.25E-02	5.25E-02
^{240}Pu	2.72E-02	2.72E-02	2.72E-02	2.72E-02	2.72E-02	2.71E-02	2.71E-02	2.71E-02	2.71E-02
^{241}Pu	3.09E+00	2.43E+00	1.91E+00	1.50E+00	1.18E+00	9.29E-01	7.30E-01	4.51E-01	2.79E-01
^{242}Pu	3.93E-06	3.93E-06	3.93E-06	3.93E-06	3.93E-06	3.93E-06	3.93E-06	3.93E-06	3.93E-06
^{241}Am	0	2.19E-02	3.89E-02	5.22E-02	6.24E-02	7.03E-02	7.63E-02	8.43E-02	8.86E-02
$^{239+240}$Pu	7.98E-02	7.98E-02	7.98E-02	7.97E-02	7.97E-02	7.97E-02	7.97E-02	7.96E-02	7.96E-02
Pu-alpha	9.69E-02	9.62E-02	9.56E-02	9.49E-02	9.43E-02	9.37E-02	9.32E-02	9.21E-02	9.11E-02
Total alpha	9.69E-02	1.18E-01	1.35E-01	1.47E-01	1.57E-01	1.64E-01	1.69E-01	1.76E-01	1.80E-01
Activity Ratios									
$^{239+240}$Pu:^{241}Am	NA	3.64E+00	2.05E+00	1.53E+00	1.28E+00	1.13E+00	1.04E+00	9.45E-01	8.98E-01
^{241}Am:^{238}Pu	NA	1.33E+00	2.46E+00	3.43E+00	4.27E+00	5.01E+00	5.65E+00	6.76E+00	7.69E+00
^{241}Pu:$^{239+240}$Pu	3.87E+01	3.05E+01	2.40E+01	1.88E+01	1.48E+01	1.17E+01	9.17E+00	5.67E+00	3.51E+00
Total alpha:$^{239+240}$Pu	1.21E+00	1.48E+00	1.69E+00	1.84E+00	1.97E+00	2.06E+00	2.13E+00	2.21E+00	2.26E+00
Total alpha:^{241}Am	NA	5.40E+00	3.45E+00	2.82E+00	2.51E+00	2.33E+00	2.22E+00	2.09E+00	2.03E+00
NA = not applicable									

Table 8.5. Activity Composition of Hanford Reference Commercial Power-Grade Plutonium Mixture

Mixture Designation:	**Fresh**	**5-Year**	**10-Year**	**15-Year**	**20-Year**	**25-Year**	**30-Year**	**40-Year**	**50-Year**
Years of Aging:	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**40**	**50**
Specific Activity									
in Mixture (Ci/g)									
^{238}Pu	1.71E-01	1.65E-01	1.58E-01	1.52E-01	1.46E-01	1.41E-01	1.35E-01	1.25E-01	1.15E-01
^{239}Pu	3.41E-02	3.41E-02	3.41E-02	3.41E-02	3.41E-02	3.41E-02	3.41E-02	3.41E-02	3.41E-02
^{240}Pu	5.90E-02	5.89E-02	5.89E-02	5.89E-02	5.89E-02	5.88E-02	5.88E-02	5.87E-02	5.87E-02
^{241}Pu	1.34E+01	1.05E+01	8.28E+00	6.51E+00	5.12E+00	4.03E+00	3.17E+00	1.96E+00	1.21E+00
^{242}Pu	1.97E-04	1.97E-04	1.97E-04	1.97E-04	1.97E-04	1.97E-04	1.97E-04	1.97E-04	1.97E-04
^{241}Am	0	9.49E-02	1.69E-01	2.26E-01	2.70E-01	3.04E-01	3.31E-01	3.65E-01	3.84E-01
$^{239+240}$Pu	9.31E-02	9.31E-02	9.30E-02	9.30E-02	9.29E-02	9.29E-02	9.29E-02	9.28E-02	9.27E-02
Pu-alpha	2.65E-01	2.58E-01	2.52E-01	2.45E-01	2.39E-01	2.34E-01	2.28E-01	2.18E-01	2.08E-01
Total alpha	2.65E-01	3.53E-01	4.20E-01	4.71E-01	5.10E-01	5.38E-01	5.59E-01	5.83E-01	5.92E-01
Activity Ratios									
$^{239+240}$Pu:^{241}Am	NA	9.81E-01	5.51E-01	4.11E-01	3.44E-01	3.05E-01	2.81E-01	2.54E-01	2.41E-01
^{241}Am:^{238}Pu	NA	5.76E-01	1.07E+00	1.49E+00	1.85E+00	2.17E+00	2.45E+00	2.92E+00	3.33E+00
^{241}Pu:$^{239+240}$Pu	1.44E+02	1.13E+02	8.91E+01	7.00E+01	5.51E+01	4.33E+01	3.41E+01	2.11E+01	1.30E+01
Total alpha:$^{239+240}$Pu	2.84E+00	3.79E+00	4.52E+00	5.07E+00	5.48E+00	5.79E+00	6.02E+00	6.28E+00	6.39E+00
Total alpha:^{241}Am	NA	3.72E+00	2.49E+00	2.09E+00	1.89E+00	1.77E+00	1.69E+00	1.60E+00	1.54E+00
NA = not applicable									

For each reference mixture, a family of curves can be developed to describe the changing activity relationships between isotopes (see Figures 8.1 through 8.4). These curves can then be used to identify, for dosimetry purposes, the plutonium mixture and its approximate age after processing or purification. When information about isotopic composition or activity ratios is lacking, assumptions must be made for dose assessment. Hanford internal dosimetry applications of these curves were developed by Sula, Carbaugh, and Bihl (1989; 1991) for freshly separated and 5-year aged conditions of 6% Pu and 12% Pu. Since that time, production of plutonium at Hanford has ceased and mixtures have continued to age. Thus, presentations of such relationships for freshly irradiated or separated plutonium mixtures are no longer needed, while the need for data about additional mixture ages has presented itself. Consequently, this manual now uses, as the basis for bioassay program design and interpretation, reference mixtures of 10-, 20-, and 40-year-old weapons- and fuel-grade plutonium. The primary use for these reference mixtures is in the planning of bioassay monitoring frequencies and methods, and for defining the capability of the internal dosimetry program.

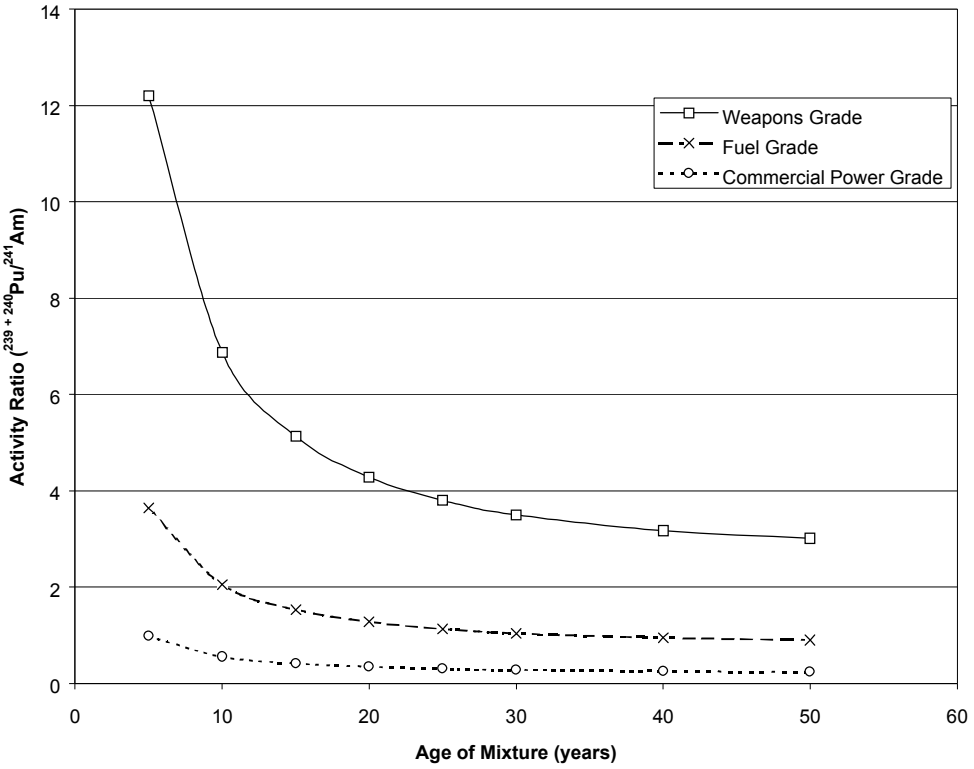

Figure 8.1. $^{239+240}$Pu/^{241}Am Activity Ratio for Hanford Reference Plutonium Mixtures

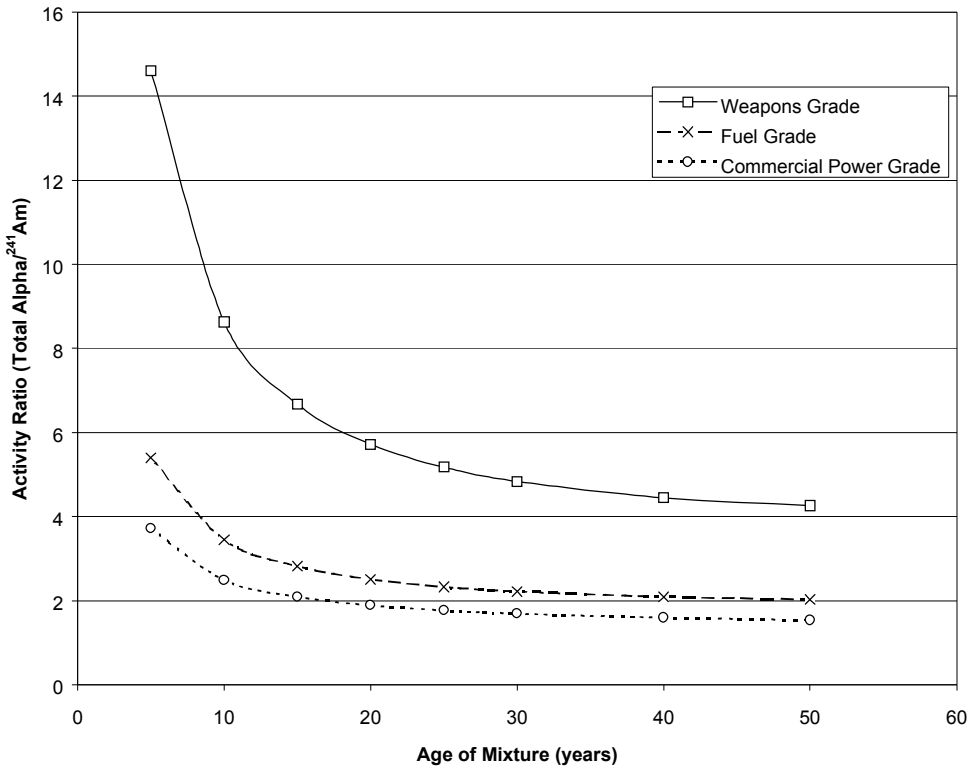

Figure 8.2. Total Alpha/^{241}Am Activity Ratio for Hanford Reference Plutonium Mixtures

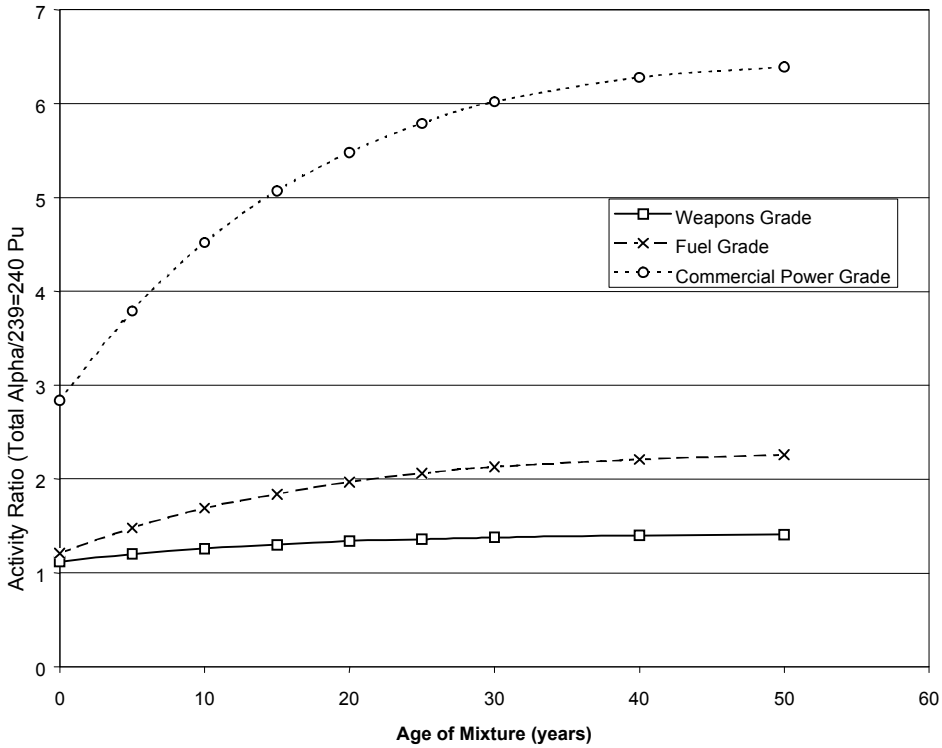

Figure 8.3. Total Alpha/$^{239+240}$Pu Activity Ratio for Hanford Reference Plutonium Mixtures

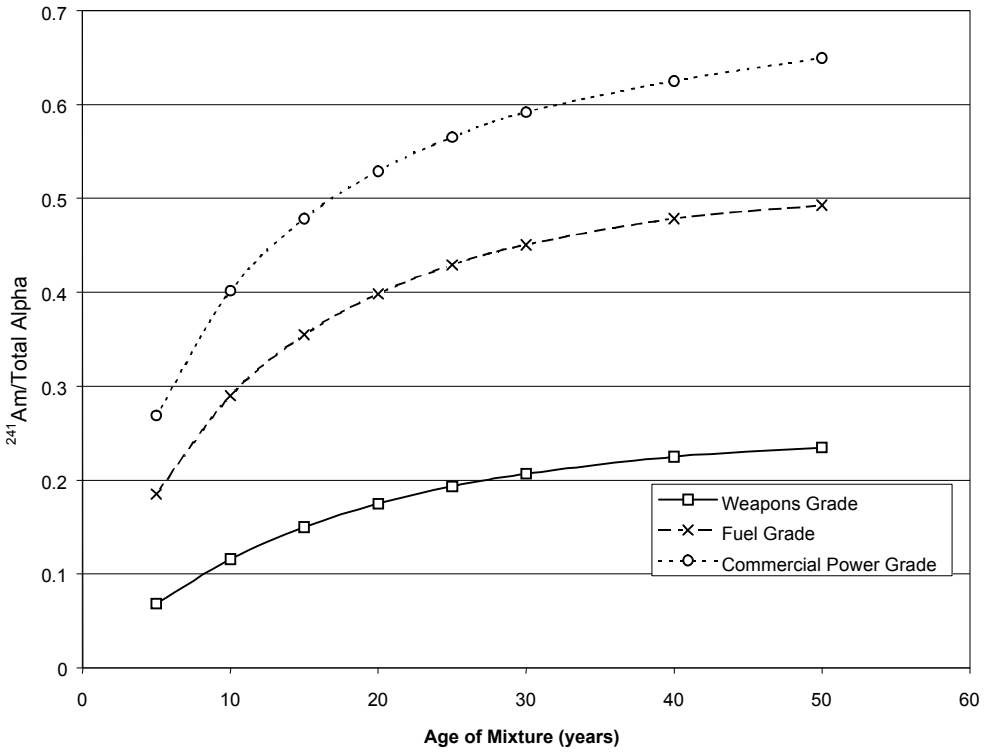

Figure 8.4. ^{241}Am/Total Alpha Activity Ratio for Hanford Reference Plutonium Mixtures

8.2 Biokinetic Behavior

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

8.2.1 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 from the deep pulmonary (or alveolar) region of the lung. Classes D, W, and Y as used in this technical basis are identical to the ICRP 30 classes of the same name. The term “instantaneous uptake” is used in this technical basis to refer to the material that is essentially immediately taken up by the transfer compartment upon intake, and is typically applied to wound scenarios.

The new respiratory tract model presented in ICRP publication 66 (1994a), replaced the ICRP 30 concepts of inhalation class D, W, and Y, with absorption types F, M, and S. Whereas the ICRP 30 inhalation classes described overall clearance (i.e., absorption and mechanical clearance), the ICRP 66 type refers only to the absorption characteristics (i.e., dissolution and absorption into blood). With regard to the dissolution and absorption rates, the ICRP 30 classes D, W, and Y correspond to the characteristics of ICRP 66 types F, M, and S, respectively. Although Hanford has not adopted the ICRP 66 respiratory tract model, the use of the absorption types as a supplemental concept to the ICRP 30 inhalation classes may be useful, particularly with the application of newly published solubility studies or animal study data. Unless specifically indicated, the chemical forms assigned to the ICRP 30 classes can be assumed to be assigned to the corresponding ICRP 66 absorption types (and vice versa).

The transportability of plutonium varies greatly depending on the chemical form. In ICRP publication 19 (1972), plutonium oxides were identified as belonging to class Y, and other forms of plutonium (e.g., nitrates, carbonates, carbides, fluorides) were identified as most appropriately belonging to class W. It was specifically noted that no plutonium compounds were assigned to class D. This approach was essentially endorsed by ICRP publication 68 (1994b), which assigned insoluble plutonium oxides to absorption type S and unspecified compounds to type M. Caution should be used in applying these categorizations, because significant variations have been observed, as discussed below.

Plutonium nitrate, as might be found in chemistry lab solutions and the early phases of plutonium finishing, was identified by ICRP 30 as class W. However, work by Moody, Stradling, and Britcher (1994) concluded that plutonium nitrate behavior was something between class W and Y, with aged nitrate residues being very similar to class Y.

Stradling and Stather (1989) indicated 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 HNO_3) 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 3 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 for exposure to aged plutonium oxides if there is any source of old residual contamination.

La Bone et al. (1992) identified a circumstance in which a ^{238}Pu-oxide inhalation case appeared to exhibit biokinetic behavior more characteristic of a class D material. This characteristic for ^{238}Pu has been informally discussed among internal dosimetrists and radiation protection staff for years. One explanation for it is that the alpha particle recoil from decay of the very high specific activity ^{238}Pu may serve to break down the matrix to forms readily absorbed by blood.

In addition to classes D, W, and Y, the possibility of a super class Y (super Y) form has been identified. Super Y was defined by the HIDP in 1988 to describe highly nontransportable forms of plutonium based on some actual observed cases at Hanford (Bihl et al. 1988; Carbaugh, Bihl, and Sula 1991). For general discussion of inhalation exposures, super Y material has been defined as being similar to class Y material with respect to compartment deposition fractions in the ICRP 30 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) have been adjusted from 500 days to 10,000 days, representing the highly insoluble (i.e., very slow dissolution rate) of the super class Y material. The 500-day clearance half-time of ICRP 30 lung compartment g was left unchanged, representing particle clearance from the pulmonary region by mechanical processes not affected by the highly insoluble nature of super class Y material. The precise nature of super class Y material is not known, although it appears to have been associated with processes involving high-fired plutonium oxides. The phenomenon has been informally verified by dosimetry personnel at Rocky Flats, Savannah River, and Los Alamos sites, and is supported in the literature by Foster (1991).

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 wide range of transportability for plutonium compounds, and its variability from the standard ICRP recommendations, emphasizes the importance of addressing the uniqueness of individual workers and exposure circumstances when dealing with known intakes. When limited information is available, the Hanford practice is to use class W for exposure to plutonium nitrate solutions (e.g., wet solutions, trace contaminants in high-level waste tanks) and class Y for oxides involving either high-firing or room temperature oxidation processes. Super class Y is not routinely used as a default program design form. Based on personal communication with a Hanford soil chemist,[(a)] plutonium in soil is assumed to be class Y unless the plutonium came from a recent release of plutonium nitrate (class W). Plutonium nitrate converts to the hydroxide form in the soil and oxides of plutonium are stable unless the soil is acidified (pH<5).

8.2.2 Gastrointestinal Uptake to Blood (f_1 Factor)

The uptake of plutonium from the gastrointestinal (GI) tract is quite small and is dependent on its chemical form. The fraction of material taken up by the blood from the total in the GI tract is called the f_1 factor. In ICRP 30 Part 4 (1988), the ICRP recommended that 10^{-5} be used for oxides of plutonium, 10^{-4} for nitrates, and 10^{-3} for other compounds. In ICRP 56 (1989), the 10^{-3} value was used for adult members of the public. Based on additional published studies, ICRP 67 (1993) recommended a value of 5×10^{-4} for unknown forms. This recommendation was adopted in ICRP 68 (1994b) for occupational exposures to all other compounds of plutonium except nitrate (10^{-4}) and oxide (10^{-5}). However, the tabulated plutonium dose coefficients in ICRP 68 showed the use of 5×10^{-4} for type M, rather than the nitrate value. For application to worker monitoring programs, ICRP 78 (1997) retained the ICRP 68 values for ingestion, and used 10^{-5} for inhalation of type S compounds (insoluble oxides) and used 5×10^{-4} for inhalation of Type M compounds (unspecified compounds). No specific f_1 factor was identified for nitrates.

(a) Conversation between D. A. Cataldo and D. E. Bihl, 1995.

For Hanford plutonium internal dose applications, the f_1 factors of ICRP 78 are preferred, unless otherwise specified. The type M factor (5×10^{-4}) is applied to inhalation class W material, and the type S factor (1×10^{-5}) is applied to class Y forms. Ingestion intakes will use the f_1 factors specified in ICRP 78, namely, 1×10^{-4} for nitrates, 1×10^{-5} for oxides, and 5×10^{-4} for other compounds.

8.2.3 Distribution and Retention in Systemic Organs and Tissues

The ICRP 30 Part 4 model is used for calculating the distribution and retention of plutonium in the body. For dissolved (ionic form) plutonium reaching the transfer compartment (i.e., the blood stream), this ICRP model distributes 45% to the bone surfaces from which it clears with a biological half-time of 50 years, and 45% to the liver from which it clears with a biological half-time of 20 years. 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. A small fraction is permanently retained in the gonads (0.035% for testes and 0.011% for ovaries). Although the translocated fractions for testes and ovaries 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.

The remaining 10% is assumed to go directly to 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.

The shift to the ICRP 30 Part 4 model from the ICRP 48 (1986) model used since 1988 is based on the better agreement with human autopsy data, as initially reported by Sula et al. (1987) and addressed in greater depth by Kathren (1993). Consideration was given to newer models such as the USTUR model presented by Kathren, and the recycling models used in ICRP publications 56 (1989) and 67 (1993). The USTUR plutonium model is thought by HIDP staff to be a more technically correct model, however it could not be fully implemented using the standard resources currently available to the HIDP (notably, the CINDY computer code). Comparison of dose estimates based on the ICRP 30 Part 4 model and the USTUR model were performed by the HIDP as part of this technical basis development, and showed that the USTUR model resulted in committed doses ranging up to 20% lower than those provided using

the ICRP 30 Part 4 model. The recycling models could not be implemented at all using the current standard tools of the HIDP and thus were not considered to be viable options.

8.2.4 Urinary Excretion

The NCRP, in its Report 84 (NCRP 1985), 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 HIDP 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 a four-component exponential sum, mathematically defined as

$$e_u(t) = 4.75\times10^{-3}e^{-0.558t} + 2.39\times10^{-4}e^{-0.0442t} + 8.55\times10^{-5}e^{-0.00380t} + 1.42\times10^{-5}e^{-0.0000284t} \tag{8.1}$$

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

The Jones excretion function described above 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 also 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 was developed by the HIDP to calculate presystemic depositions and urinary excretion based on a single pre-systemic-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 8.5.

8.2.5 Fecal Excretion

The excretion of bile to the GI tract provides a pathway for systemic excretion of plutonium to feces from the liver. Few data are available to quantify this pathway relative to urine, however the assumption of an equal amount excreted from the systemic compartment by way of feces and urine is not uncommon. For inhalation intakes, the fecal excretion is typically dominated by clearance from the respiratory tract, even at long-times post intake for class Y forms.

8.3 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 CINDY computer code and incorporate the models and assumptions described in the preceding section. 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.

(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.

8.3.1 Intake Retention and Excretion Fractions

The intake retention (or excretion) fraction expresses the fraction of intake retained in a particular compartment or excreted by a particular pathway (urine or feces) at a given time post intake. Although excretion implies elimination rather than retention, conventional models include excretion compartments under the general term retention and use the term "intake retention fraction" (IRF) to describe both. IRFs for various times post intake are tabulated as described below for ^{239}Pu. These values are also suitable for other isotopes of plutonium, with appropriate correction for different radiological half-lives.

Lung retention fractions for the class W, class Y, and super class Y inhalations of 1-µm and 5-µm AMAD particles of ^{239}Pu are tabulated in Table 8.6 and plotted in Figure 8.5. Urine excretion fractions for an instantaneous uptake, acute inhalations, and acute ingestions of ^{239}Pu are shown in Table 8.7 and Figure 8.6. Tabulated values for fecal excretion factors are shown in Table 8.8 and Figure 8.7. Values for days other than those tabulated here can be obtained by interpolation between the tabulated data, or by obtaining the values directly from the CINDY computer code. The ratio of fecal to urinary excretion is shown for these same intakes in Table 8.9 and Figure 8.8. This latter table may be useful for identifying the appropriate type of intake for unknown circumstances, if sufficient data are obtained.

8.3.2 Dose Coefficients

Dose coefficients, expressed as committed dose equivalent per unit activity of intake (rem per nanocurie of acute intake or rem per nanocurie per 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 coefficients have been tabulated in this section for instantaneous uptake, class W, Y, and super class Y inhalations (for both 1-µm and 5-µm-AMAD particle sizes) and for ingestion. These dose coefficients were all derived using the CINDY computer code.

Dose coefficients for single isotopes are shown in Tables 8.10 through 8.13. In the case of ^{241}Pu, the ^{241}Am ingrown from the time of intake is included in Table 8.12. The ^{241}Am values tabulated in Table 8.13 assume that behavior is characteristic of plutonium; i.e., the plutonium biokinetic model is used for americium because the americium is considered trapped in a plutonium matrix, which limits its behavior to that of the predominant matrix. Dose coefficients have been derived for intakes of some mixtures representing the

Table 8.6. Lung Retention for 1-µm and 5-µm-AMAD Particles Plutonium Inhalation Intake (fraction of intake)

Days Post Intake	Class W		Class Y		Super Class Y	
	1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
0	0.33	0.17	0.33	0.17	0.33	0.17
1	0.21	0.075	0.21	0.077	0.21	0.078
2	0.18	0.063	0.18	0.064	0.18	0.065
5	0.15	0.051	0.15	0.054	0.15	0.055
7	0.14	0.049	0.15	0.053	0.15	0.054
14	0.13	0.044	0.15	0.052	0.15	0.053
30	0.10	0.036	0.15	0.051	0.15	0.052
60	0.070	0.025	0.14	0.050	0.14	0.051
90	0.048	0.017	0.14	0.048	0.14	0.049
180	0.015	0.0053	0.12	0.044	0.13	0.046
365	0.0014	4.80E-04	0.10	0.036	0.11	0.039
730	1.10E-05	3.90E-06	0.073	0.026	0.086	0.031
1,825	insig.	insig.	0.029	0.010	0.057	0.020
3,600	insig.	insig.	0.0096	0.0034	0.048	0.017
7,300	insig.	insig.	0.0042	0.0015	0.042	0.015
18,250	insig.	insig.	0.0037	0.0013	0.029	0.010

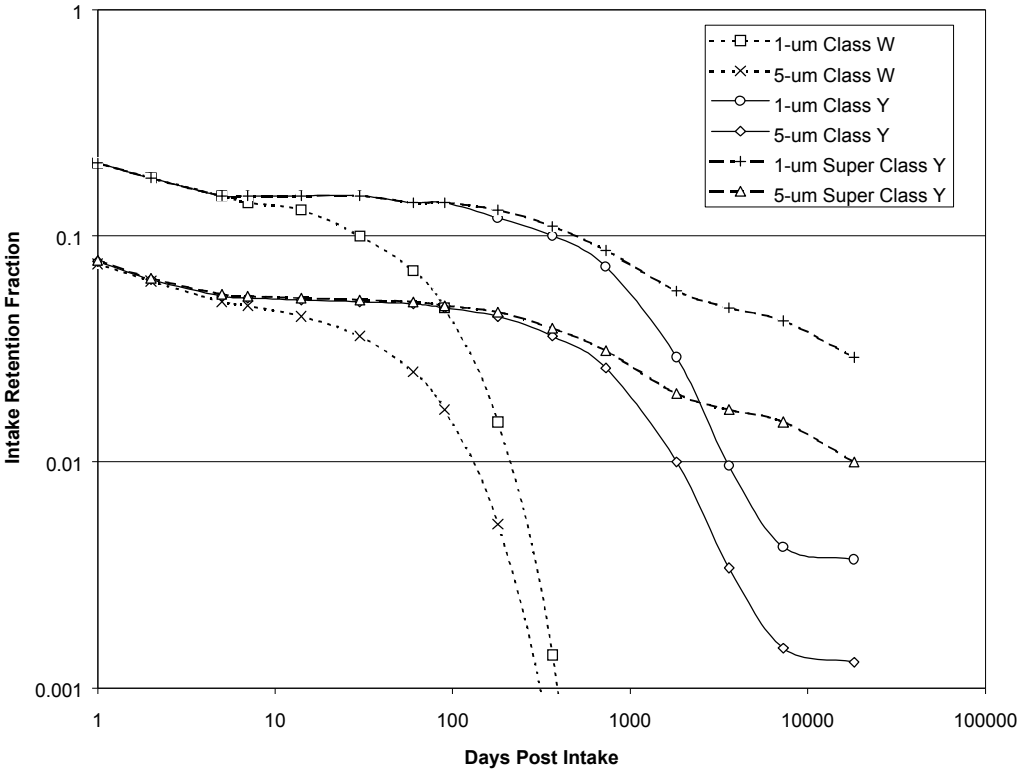

Figure 8.5. ^{239}Pu Lung Retention

Table 8.7. ^{239}Pu Urine Excretion Fractions for Instantaneous Uptake, Inhalation, and Ingestion Intakes

Days Post Intake	Instantaneous Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation		Ingestion	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm	f_1=5E-04	f_1=1E-05
1	3.0E-03	2.2E-04	3.5E-04	1.2E-05	2.5E-05	1.7E-08	2.8E-08	1.7E-06	3.4E-08
2	1.9E-03	1.4E-04	2.2E-04	7.3E-06	1.6E-05	1.9E-08	2.7E-08	1.0E-06	2.1E-08
5	5.8E-04	4.6E-05	6.9E-05	2.4E-06	4.9E-06	1.5E-08	1.5E-08	3.1E-07	6.2E-09
7	3.7E-04	3.1E-05	4.4E-05	1.6E-06	3.1E-06	1.4E-08	1.3E-08	1.9E-07	3.8E-09
14	2.3E-04	2.2E-05	2.8E-05	1.1E-06	1.9E-06	1.5E-08	1.3E-08	1.1E-07	2.3E-09
30	1.5E-04	1.7E-05	2.0E-05	8.5E-07	1.4E-06	1.8E-08	1.5E-08	7.7E-08	1.5E-09
60	9.9E-05	1.3E-05	1.4E-05	7.1E-07	9.3E-07	2.2E-08	1.7E-08	5.0E-08	9.9E-10
90	7.9E-05	1.1E-05	1.1E-05	6.9E-07	7.9E-07	2.5E-08	2.0E-08	4.0E-08	8.0E-10
180	5.7E-05	8.3E-06	8.1E-06	7.2E-07	6.5E-07	3.2E-08	2.5E-08	2.9E-08	5.8E-10
365	3.5E-05	4.8E-06	4.9E-06	8.0E-07	5.2E-07	4.2E-08	3.2E-08	1.8E-08	3.5E-10
730	1.9E-05	2.5E-06	2.6E-06	8.9E-07	4.4E-07	5.3E-08	4.0E-08	9.6E-09	2.0E-10
1,825	1.4E-05	1.6E-06	1.8E-06	8.8E-07	4.0E-07	7.6E-08	5.3E-08	6.8E-09	1.3E-10
3,600	1.3E-05	1.5E-06	1.7E-06	7.4E-07	3.5E-07	1.1E-07	7.3E-08	6.4E-09	1.3E-10
7,300	1.2E-05	1.4E-06	1.5E-06	6.1E-07	2.9E-07	1.7E-07	1.1E-07	5.8E-09	1.2E-10
18,250	8.4E-06	1.0E-06	1.1E-06	4.4E-07	2.1E-07	3.1E-07	1.6E-07	4.2E-09	8.4E-11

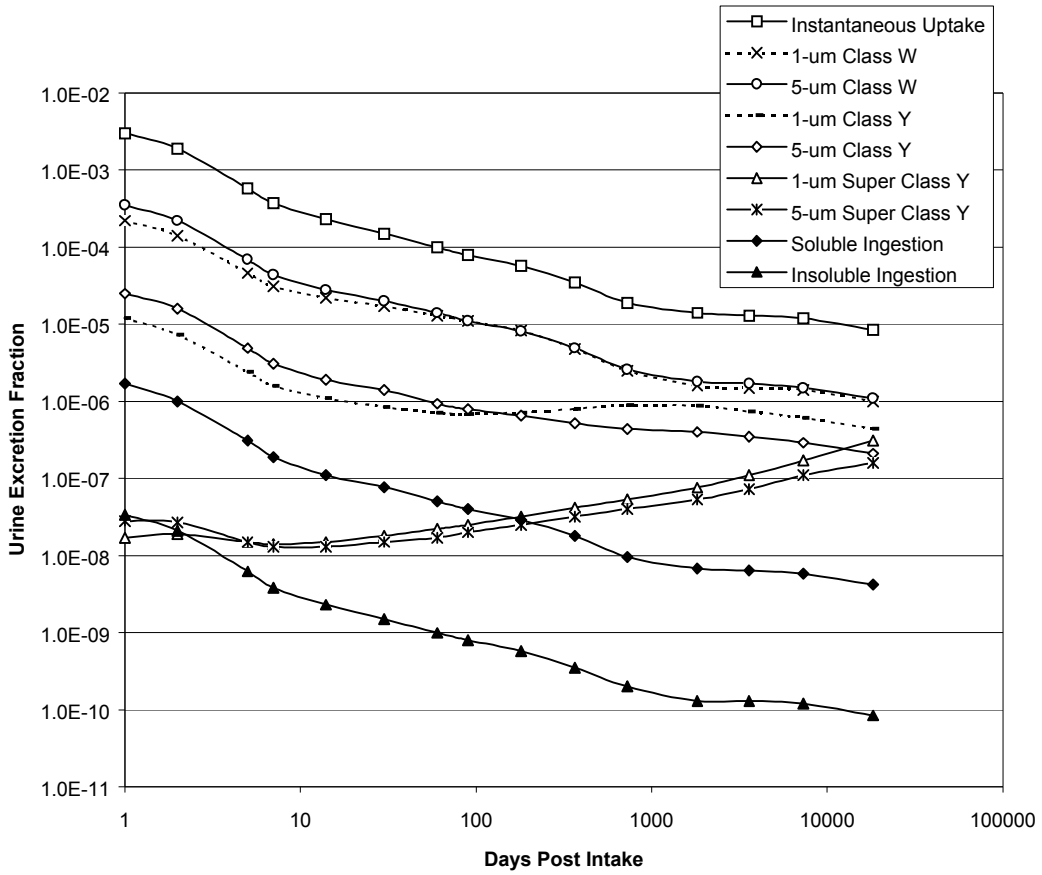

Figure 8.6. ^{239}Pu Urinary Excretion

Table 8.8. ^{239}Pu Fecal Excretion Fractions for Instantaneous Uptake, Inhalation, and Ingestion Intakes

Days Post Intake	Instantaneous Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation		Ingestion	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm	f_1=5E-04	f_1=1E-05
1	3.0E-03	1.1E-01	2.2E-01	1.3E-01	2.5E-01	1.3E-01	2.5E-01	4.7E-01	4.7E-01
2	1.9E-03	1.3E-01	2.6E-01	1.6E-01	2.9E-01	1.6E-01	2.9E-01	2.8E-01	2.8E-01
5	5.8E-04	2.3E-02	3.1E-02	2.4E-02	3.4E-02	2.4E-02	3.4E-02	1.8E-02	1.8E-02
7	3.7E-04	6.3E-03	5.6E-03	5.4E-03	5.7E-03	5.4E-03	5.7E-03	2.5E-03	2.5E-03
14	2.3E-04	1.2E-03	4.6E-04	1.7E-04	6.5E-05	1.7E-04	6.3E-05	2.4E-06	2.3E-06
30	1.5E-04	9.6E-04	3.5E-04	1.3E-04	4.8E-05	1.3E-04	4.7E-05	7.7E-08	1.5E-09
60	9.9E-05	6.3E-04	2.3E-04	1.3E-04	4.6E-05	1.3E-04	4.5E-05	5.0E-08	9.9E-10
90	7.9E-05	4.2E-04	1.6E-04	1.2E-04	4.4E-05	1.2E-04	4.3E-05	4.0E-08	8.0E-10
180	5.7E-05	1.3E-04	4.9E-05	1.1E-04	3.9E-05	1.1E-04	3.8E-05	2.9E-08	5.8E-10
365	3.5E-05	1.4E-05	8.1E-06	8.5E-05	3.0E-05	8.4E-05	3.0E-05	1.8E-08	3.5E-10
730	1.9E-05	2.5E-06	2.6E-06	5.1E-05	1.8E-05	5.1E-05	1.8E-05	9.6E-09	2.0E-10
1,825	1.4E-05	1.6E-06	1.8E-06	1.2E-05	4.3E-06	1.1E-05	4.0E-06	6.8E-09	1.3E-10
3,600	1.3E-05	1.5E-06	1.7E-06	1.6E-06	6.6E-07	9.9E-07	3.8E-07	6.4E-09	1.3E-10
7,300	1.2E-05	1.5E-06	1.5E-06	6.2E-07	3.0E-07	1.8E-07	1.1E-07	5.8E-09	1.2E-10
18,250	8.4E-06	1.0E-06	1.1E-06	4.4E-07	2.1E-07	3.1E-07	1.6E-07	4.2E-09	8.4E-11

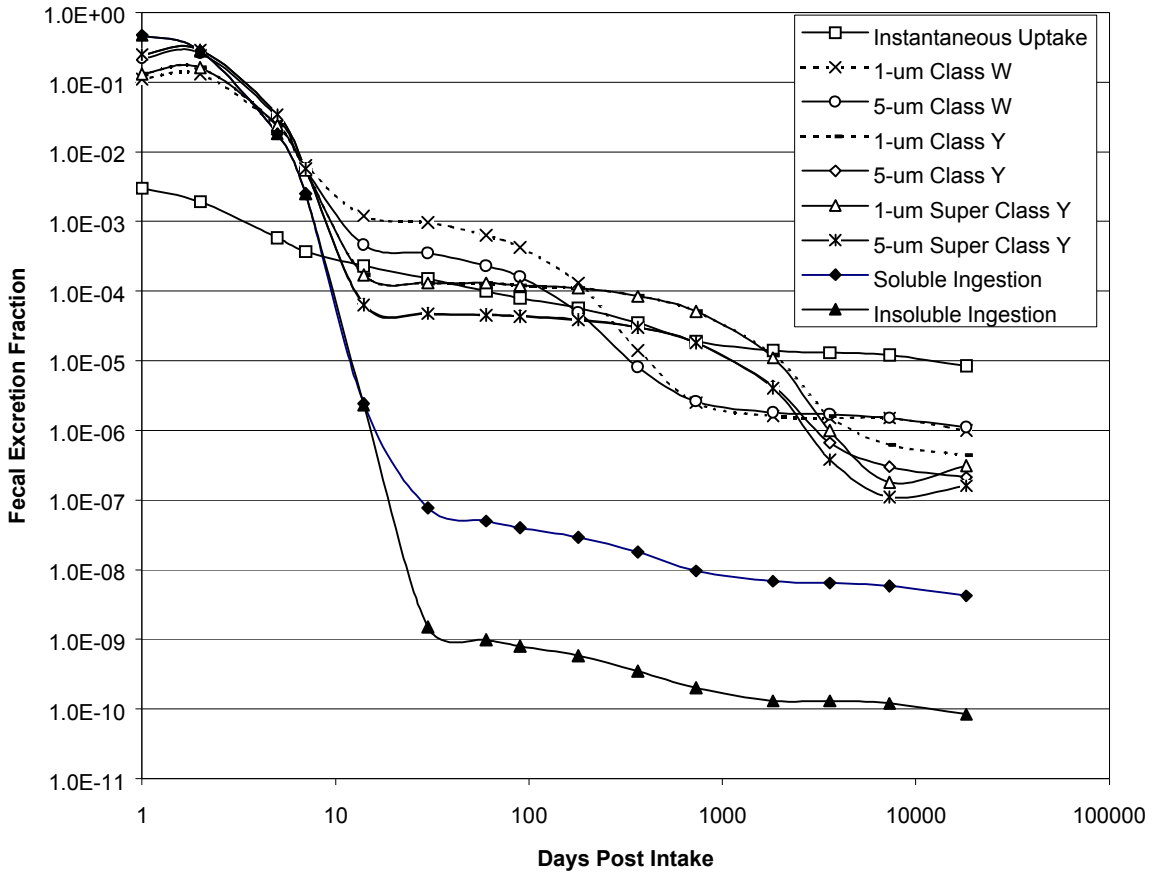

Figure 8.7. ^{239}Pu Fecal Excretion

Table 8.9. Fecal-to-Urine Ratios for ^{239}Pu Intakes

Days Post Intake	Instantaneous Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation		Ingestion	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm	f_1=5E-4	f_1=1E-5
1	1.0E+00	5.0E+02	6.3E+02	1.1E+04	1.0E+04	7.6E+06	8.9E+06	2.8E+05	1.4E+07
2	1.0E+00	9.3E+02	1.2E+03	2.2E+04	1.8E+04	8.4E+06	1.1E+07	2.8E+05	1.3E+07
5	1.0E+00	5.0E+02	4.5E+02	1.0E+04	6.9E+03	1.6E+06	2.3E+06	5.8E+04	2.9E+06
7	1.0E+00	2.0E+02	1.3E+02	3.4E+03	1.8E+03	3.9E+05	4.4E+05	1.3E+04	6.6E+05
14	1.0E+00	5.5E+01	1.6E+01	1.5E+02	3.4E+01	1.1E+04	4.8E+03	2.2E+01	1.0E+03
30	1.0E+00	5.6E+01	1.8E+01	1.5E+02	3.4E+01	7.2E+03	3.1E+03	1.0E+00	1.0E+00
60	1.0E+00	4.8E+01	1.6E+01	1.8E+02	4.9E+01	5.9E+03	2.6E+03	1.0E+00	1.0E+00
90	1.0E+00	3.8E+01	1.5E+01	1.7E+02	5.6E+01	4.8E+03	2.2E+03	1.0E+00	1.0E+00
180	1.0E+00	1.6E+01	6.0E+00	1.5E+02	6.0E+01	3.4E+03	1.5E+03	1.0E+00	1.0E+00
365	1.0E+00	2.9E+00	1.7E+00	1.1E+02	5.8E+01	2.0E+03	9.4E+02	1.0E+00	1.0E+00
730	1.0E+00	1.0E+00	1.0E+00	5.7E+01	4.1E+01	9.6E+02	4.5E+02	1.0E+00	1.0E+00
1,825	1.0E+00	1.0E+00	1.0E+00	1.4E+01	1.1E+01	1.4E+02	7.5E+01	1.0E+00	1.0E+00
3,600	1.0E+00	1.0E+00	1.0E+00	2.1E+00	1.9E+00	9.0E+00	5.2E+00	1.0E+00	1.0E+00
7,300	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.1E+00	1.0E+00	1.0E+00	1.0E+00
18,250	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00

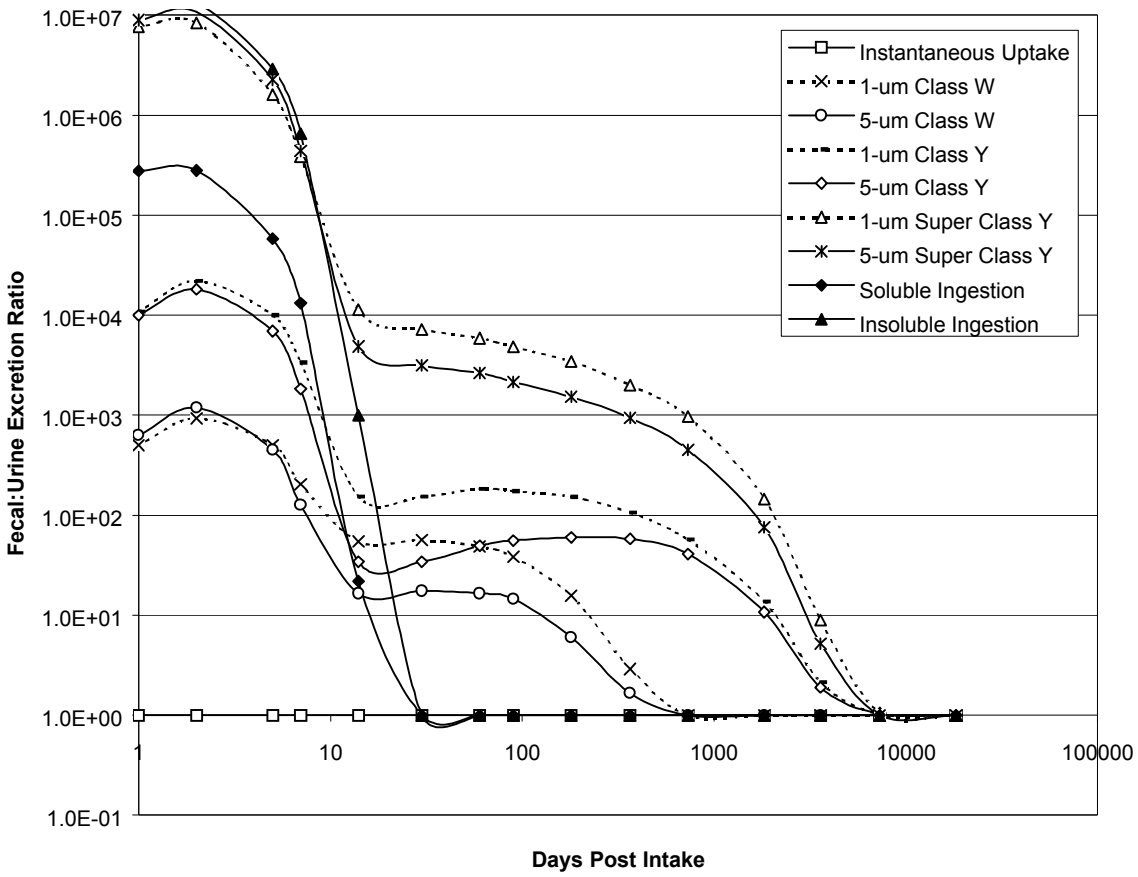

Figure 8.8. Feces-to-Urine Excretion Ratios for ^{239}Pu Intakes

Table 8.10. Committed Dose Coefficients for Acute Intakes of ^{238}Pu (rem/nCi)

Organ or Tissue	Instantaneous Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation		Ingestion	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm	f_1=5E-04	f_1=1E-05
Effective	3.2E+00	4.0E-01	4.3E-01	2.9E-01	1.2E-01	5.1E-01	1.9E-01	1.6E-03	5.0E-05
Bone Surface	5.9E+01	7.1E+00	7.8E+00	2.7E+00	1.4E+00	7.3E-01	4.4E-01	2.9E-02	5.9E-04
Red Marrow	4.7E+00	5.7E-01	6.3E-01	2.2E-01	1.1E-01	5.9E-02	3.5E-02	2.4E-03	4.7E-05
Liver	1.1E+01	1.3E+00	1.4E+00	5.1E-01	2.5E-01	1.5E-01	8.8E-02	5.4E-03	1.1E-04
Lung	3.2E-05	6.7E-02	2.4E-02	1.2E+00	4.1E-01	3.9E+00	1.4E+00	1.6E-08	3.2E-10
Gonads	8.6E-01	1.0E-01	1.1E-01	3.9E-02	2.0E-02	9.7E-03	5.8E-03	4.3E-04	8.6E-06
Lower Large Intestine	insig.	insig.	insig.	insig.	insig.	insig.	insig.	2.1E-04	2.1E-04

Table 8.11. Committed Dose Coefficients for Acute Intakes of ^{239}Pu and/or ^{240}Pu (rem/nCi)[(a)]

Organ or Tissue	Instantaneous Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation		Ingestion	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm	f_1=5E-04	f_1=1E-05
Effective	3.6E+00	4.4E-01	4.8E-01	3.1E-01	1.3E-01	5.5E-01	2.1E-01	1.8E-03	5.2E-05
Bone Surface	6.7E+01	8.0E+00	8.8E+00	3.1E+00	1.6E+00	9.0E-01	5.3E-01	3.3E-02	6.7E-04
Red Marrow	5.2E+00	6.2E-01	6.8E-01	2.4E-01	1.2E-01	6.9E-02	4.1E-02	2.6E-03	5.2E-05
Liver	1.2E+01	1.4E+00	1.5E+00	5.6E-01	2.8E-01	1.8E-01	1.0E-01	5.8E-03	1.2E-04
Lung	2.9E-05	6.1E-02	2.2E-02	1.1E+00	4.0E-01	4.1E+00	1.5E+00	1.4E-08	2.9E-10
Gonads	9.8E-01	1.2E-01	1.3E-01	4.5E-02	2.5E-02	1.2E-02	7.1E-03	4.9E-04	9.8E-06
Lower Large Intestine	insig.	insig.	insig.	insig.	insig.	insig.	insig.	1.9E-04	1.9E-04

(a) ^{239}Pu and ^{240}Pu are dosimetrically equivalent.

Table 8.12. Committed Dose Coefficients for Acute Intakes of ^{241}Pu (rem/nCi)

Organ or Tissue	Instantaneous Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation		Ingestion	
		1-μm	5-μm	1-μm	5-μm	1-μm	5-μm	f_1=5E-04	f_1=1E-05
Effective	6.9E-02	8.3E-03	9.1E-03	5.0E-03	2.2E-03	1.1E-02	4.2E-03	3.5E-05	7.7E-07
Bone Surface	1.3E+00	1.6E-01	1.7E-01	6.6E-02	3.2E-02	2.3E-02	1.3E-02	6.5E-04	1.3E-05
Red Marrow	1.0E-01	1.2E-02	1.3E-02	5.2E-03	2.5E-03	1.8E-03	1.0E-03	5.1E-05	1.0E-06
Liver	2.0E-01	2.4E-02	2.7E-02	1.1E-02	5.3E-03	4.5E-03	2.6E-03	1.0E-04	2.0E-06
Lung	1.7E-06	2.7E-05	9.7E-06	1.2E-02	4.1E-03	7.9E-02	2.8E-02	8.3E-10	1.7E-11
Gonads	2.1E-02	2.5E-03	2.8E-03	1.0E-03	5.0E-04	3.1E-04	1.8E-04	1.1E-05	2.1E-07
Lower Large Intestine	insig.	insig.	insig.	insig.	insig.	insig.	insig.	9.7E-07	9.8E-07

Table 8.13. Committed Dose Coefficients for Acute Intakes of ^{241}Am in a Plutonium Matrix (rem/nCi)

Organ or Tissue	Instantaneous Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation		Ingestion	
		1-μm	5-μm	1-μm	5-μm	1-μm	5-μm	f_1=5E-04	f_1=1E-05
Effective	3.7E+00	4.5E-01	4.9E-01	3.2E-01	1.4E-01	5.8E-01	2.2E-01	1.9E-03	5.5E-05
Bone Surface	6.7E+01	8.1E+00	8.9E+00	3.1E+00	1.6E+00	8.9E-01	5.3E-01	3.4E-02	6.7E-04
Red Marrow	5.3E+00	6.3E-01	7.0E-01	2.5E-01	1.2E-01	7.0E-02	4.1E-02	2.6E-03	5.3E-05
Liver	1.2E+01	1.4E+00	1.6E+00	5.8E-01	2.9E-01	1.8E-01	1.1E-01	6.0E-03	1.2E-04
Lung	1.2E-04	6.7E-02	2.4E-02	1.2E+00	4.4E-01	4.4E+00	1.6E+00	6.3E-08	2.8E-10
Gonads	1.0E+00	1.2E-01	1.3E-01	4.6E-02	2.3E-02	1.2E-02	7.2E-03	5.0E-04	1.0E-05
Lower Large Intestine	insig.	insig.	insig.	insig.	insig.	insig.	insig.	2.2E-04	2.2E-04

types of plutonium most typically encountered at Hanford. The dose coefficients are tabulated in Table 8.14 for weapons-grade plutonium and in Table 8.15 for fuel-grade plutonium. The mixtures are weapons-grade and fuel-grade plutonium aged 10 years, 20 years, and 40 years. For each of these mixtures, dose coefficients have been tabulated for instantaneous uptake, and class W, Y, and super class Y inhalations of 1-µm- and 5-µm-AMAD particles. Previous HIDP documentation (Sula, Carbaugh, and Bihl 1989; 1991) provided dose coefficients for fresh and 5-year aged weapons and fuel-grade mixtures for instantaneous uptake and inhalation of 1-µm-AMAD particles. As discussed in Section 8.2, the retention model used for the super class Y form is highly speculative and subject to great uncertainty. The super class Y dose coefficients are intended for comparison with other more widely accepted models, rather than confident dosimetry. Reference mixture dose coefficients have not been provided for ingestion intakes, because ingestion has not historically 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 significant organs can be calculated using the CINDY computer code, or using the individual nuclide dose coefficients for ingestion listed in Tables 8.10 through 8.13.

8.3.3 Cumulative Dose Equivalents

The cumulative dose equivalent from an intake through various times post intake is sometimes of interest with regard to tenaciously retained radionuclides. The most commonly referenced cumulative dose for occupational exposure 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 8.16 for ^{239}Pu class W, Y, and super Y inhalation intakes of 1-µm-AMAD particles. Cumulative dose equivalents for other forms of plutonium or other time intervals can be readily obtained from the CINDY computer code. Cumulative doses are of principal interest with regard to potential biological effects, because they represent the dose received through a time interval, as opposed to a projected dose expected to be received in the future from an intake.

Table 8.14. Committed Dose Coefficients for Acute Intakes of Weapons-Grade Plutonium (rem/nCi)[(a)]

Organ or Tissue	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
10-Year Aged Weapons-Grade Mixture							
Effective	4.0E+00	4.8E-01	5.0E-01	3.4E-01	1.4E-01	6.1E-01	2.3E-01
Bone Surface	7.4E+01	8.8E+00	9.7E+00	3.4E+00	1.8E+00	1.0E+00	6.0E-01
Red Marrow	5.7E+00	6.8E-01	6.8E-01	2.7E-01	1.3E-01	7.8E-02	4.6E-02
Liver	1.3E+01	1.5E+00	1.7E+00	6.2E-01	3.1E-01	2.0E-01	1.1E-01
Lung	insig.	6.2E-02	2.2E-02	1.2E+00	4.3E-01	4.6E+00	1.7E+00
Gonads	1.1E+00	1.3E-01	1.4E-01	5.0E-02	3.0E-02	1.4E-02	8.6E-03
20-Year Aged Weapons-Grade Mixture							
Effective	3.8E+00	4.7E-01	4.8E-01	3.3E-01	1.4E-01	5.9E-01	2.2E-01
Bone Surface	7.1E+01	8.5E+00	9.3E+00	3.3E+00	1.7E+00	9.6E-01	5.7E-01
Red Marrow	5.5E+00	6.6E-01	6.1E-01	2.6E-01	1.3E-01	7.4E-02	4.4E-02
Liver	1.3E+01	1.5E+00	1.6E+00	6.0E-01	3.0E-01	1.9E-01	1.1E-01
Lung	insig.	6.3E-02	2.3E-02	1.2E+00	4.2E-01	4.4E+00	1.6E+00
Gonads	1.0E+00	1.3E-01	1.4E-01	4.8E-02	2.9E-02	1.3E-02	8.5E-03
40-Year Aged Weapons-Grade Mixture							
Effective	3.7E+00	4.5E-01	4.6E-01	3.2E-01	1.3E-01	5.7E-01	2.2E-01
Bone Surface	6.8E+01	8.2E+00	9.0E+00	3.2E+00	1.6E+00	9.1E-01	5.4E-01
Red Marrow	5.3E+00	6.3E-01	5.6E-01	2.5E-01	1.2E-01	7.1E-02	4.2E-02
Liver	1.2E+01	1.4E+00	1.5E+00	5.7E-01	2.9E-01	1.8E-01	1.0E-01
Lung	insig.	6.3E-02	2.3E-02	1.1E+00	4.1E-01	4.3E+00	1.5E+00
Gonads	1.0E+00	1.2E-01	1.3E-01	4.6E-02	2.8E-02	1.2E-02	8.3E-03
(a) nCi of total alpha activity in mixture.							

8.3.4 Comparison of Published Dosimetry Factors

A comparison of dosimetry factors, including dose coefficients, annual limits on intake (ALIs), and derived air concentrations (DACs) published in several sources is shown in Table 8.17. For Hanford applications, the DAC values of 10 CFR 835 Appendix A are typically used to control facility operations.

8.3.5 Derived Reference Levels

Unlike other radionuclides, such as ^{137}Cs or ^{90}Sr, derived bioassay reference levels are of little value for plutonium. The ^{239}Pu intake that would correspond to a 10-mrem screening level is only 0.02 nCi for a class W inhalation, and a 0.2 nCi intake would correspond to an

Table 8.15. Committed Dose Coefficients for Acute Intakes of Hanford Fuel-Grade Plutonium Mixtures (rem/nCi)[(a)]

Organ or Tissue	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
10-Year Aged Fuel-Grade Mixture							
Effective	4.6E+00	5.6E-01	6.1E-01	3.8E-01	1.6E-01	7.1E-01	2.7E-01
Bone Surface	8.5E+01	1.0E+01	1.1E+01	4.0E+00	2.0E+00	1.2E+00	7.0E-01
Red Marrow	6.6E+00	7.9E-01	8.6E-01	3.1E-01	1.5E-01	9.4E-02	5.5E-02
Liver	1.5E+01	1.8E+00	1.9E+00	7.2E-01	3.5E-01	2.4E-01	1.4E-01
Lung	insig.	6.4E-02	2.3E-02	1.3E+00	4.7E-01	5.3E+00	1.9E+00
Gonads	1.3E+00	1.5E-01	1.7E-01	5.9E-02	2.9E-02	1.6E-02	9.5E-03
20-Year Aged Fuel-Grade Mixture							
Effective	4.1E+00	5.0E-01	5.5E-01	3.5E-01	1.5E-01	6.4E-01	2.4E-01
Bone Surface	7.6E+01	9.2E+00	1.0E+01	3.6E+00	1.8E+00	1.1E+00	6.2E-01
Red Marrow	5.9E+00	7.1E-01	7.8E-01	2.8E-01	1.4E-01	8.2E-02	4.8E-02
Liver	1.3E+01	1.6E+00	1.7E+00	6.5E-01	3.2E-01	2.1E-01	1.2E-01
Lung	insig.	6.4E-02	2.3E-02	1.2E+00	4.5E-01	4.8E+00	1.7E+00
Gonads	1.1E+00	1.4E-01	1.5E-01	5.2E-02	2.6E-02	1.4E-02	8.4E-03
40-Year Aged Fuel-Grade Mixture							
Effective	3.8E+00	4.6E-01	5.0E-01	3.3E-01	1.4E-01	5.9E-01	2.2E-01
Bone Surface	7.0E+01	8.4E+00	9.2E+00	3.2E+00	1.7E+00	9.4E-01	5.6E-01
Red Marrow	5.5E+00	6.5E-01	7.2E-01	2.6E-01	1.3E-01	7.3E-02	4.3E-02
Liver	1.2E+01	1.5E+00	1.6E+00	5.9E-01	3.0E-01	1.9E-01	1.1E-01
Lung	insig.	6.4E-02	2.3E-02	1.2E+00	4.3E-01	4.4E+00	1.6E+00
Gonads	1.0E+00	1.2E-01	1.4E-01	4.8E-02	2.4E-02	1.3E-02	7.5E-03

(a) nCi of total alpha activity in mixture.

Table 8.16. Cumulative Effective Dose Equivalent for ^{239}Pu Intakes

Cumulative Time Post Intake		Inhalation Intake (expressed as percentage of 50-year committed dose)		
Days	Years	Class W	Class Y	Super Y
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%

Table 8.17. Comparison of Selected Published Dosimetry Factors for ^{239}Pu

Reference	Soluble Inhalation	Insoluble Inhalation
Dose Coefficients Effective Dose		
CINDY ($h_{e,50}$)	0.44 rem/nCi (1-µm class W) 0.48 rem/nCi (5-µm class W)	0.31 rem/nCi (1-µm class Y) 0.13 rem/nCi (5-µm class Y)
ICRP 30 Part 4 and ICRP 54 (1988) ($h_{e,50}$)	1.1E-04 Sv/Bq (1-µm class W) (0.41 rem/nCi)	8.1E-05 Sv/Bq (1-µm class Y) (.30 rem/nCi)
EPA Federal Guidance Report No. 11 ($h_{e,50)}$	1.16E-04 Sv/Bq (1-µm class W) (0.43 rem/nCi)	8.33E-05 Sv/Bq (1-µm class Y) (0.31 rem/nCi)
ICRP 68 (1994) [e(50)]	4.7E-05 Sv/Bq (1-µm type M) (0.17 rem/nCi)	1.5E-05 Sv/Bq (1-µm type S) (0.055 rem/nCi)
	3.2E-05 Sv/Bq (5-µm type M) (0.12 rem/nCi)	8.3E-06 Sv/Bq (5-µm type S) (0.030 rem/nCi)
Bone Surfaces Dose		
CINDY ($h_{t,50}$)	8.0 rem/nCi (1-µm class W) 8.8 rem/nCi (5-µm class W)	3.1 rem/nCi (1-µm class Y) 1.6 rem/nCi (5-µm class Y)
ICRP 30 Part 4 and ICRP 54 (1988) ($h_{e,50}$)	2.1E-03 Sv/Bq (1-µm class W) (7.8 rem/nCi)	8.2E-04 Sv/Bq (1-µm class Y) (3.0 rem/nCi)
EPA Federal Guidance Report No. 11 ($h_{t,50}$)	2.11E-03 Sv/Bq (1-µm class W) (7.8 rem/nCi)	8.21E-04 Sv/Bq (1-µm class Y) (3.0 rem/nCi)
Derived Air Concentration (based on bone surface dose)		
10 CFR 835 Appendix A	2E-12 µCi/ml (class W) 8E-02 Bq/m^3 (class W)	6E-12 µCi/ml (class Y) 2E-01 Bq/m^3 (class Y)
EPA Federal Guidance Report No. 11	3E-12 µCi/ml (class W) 1E-07 MBq/m^3 (class W)	7E-12 µCi/ml (class Y) 3E-07 MBq/m^3 (class Y)
ICRP 30 Part 4	1E-01 Bq/m^3 (class W)	3E-01 Bq/m^3 (class Y)
Annual Limit on Intake (based on bone surface dose)		
ICRP 30 Part 4	2E+02 Bq (class W)	6E+02 Bq (class Y)
EPA Federal Guidance Report No. 11	2E-4 MBq (class W) 0.006 µCi (class Y)	6E-4 Bq (class Y) 0.02 µCi (class Y)

investigation level of 100 mrem. The associated urine excretion from these intakes is sufficiently low that a derived screening or investigation level has no practical value for routine monitoring. Likewise, a derived bioassay level for medical referral is not of practical value for routine bioassay monitoring, because such monitoring is typically done on an annual basis. Medical referral criteria have been established based on workplace indicators of potential intake, and are contained in the *Hanford Internal Dosimetry Project Manual*, PNL-MA-552, Chapter 7.[(a)] Those criteria were established based on historical Hanford experience as a good practice and not on a rigid set of technical conditions or models.

The Hanford practice is to investigate all routine (periodic) urine or in vivo measurements that show indications of potential plutonium intake and to calculate doses for any confirmed intake. Thus the derived screening and investigation level concepts of calculated bioassay results against which actual measurements are compared are not applicable.

8.4 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. General recommendations are also provided for routine bioassay monitoring for plutonium.

8.4.1 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 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 been observed in past Hanford cases. For this reason, bioassay guidance has been developed for instantaneous uptake, class W, Y, and super class Y compounds. The instantaneous uptake 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

(a) Pacific Northwest National Laboratory (PNNL). *Hanford Internal Dosimetry Project Manual*. PNNL-MA-552, Richland, Washington. (Internal manual.) Available URL: http://www.pnl.gov/eshs/pub/pnnl552.html

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.

8.4.2 Urine Sampling and Analysis

Urine sample analysis is the standard technique for confirming and evaluating the magnitude of systemic 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, and clothing). Caution needs to be exercised when samples are obtained from workers who have recently had external contamination. The extreme sensitivity of urine sample analysis lends itself to the possibility of the sample being contaminated by trace particles well below the level that can be observed by standard personal survey and workplace control practices. This was one of the reasons why at-home sampling was originally selected for the Hanford Site in lieu of obtaining a sample at work.

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 $^{239+240}$Pu, because alpha spectrometry systems do 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, the Hanford radiochemistry bioassay laboratory used an autoradiography procedure 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 analyzed by autoradiography with sample results obtained from alpha spectrometry, 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 8.18. The method used to define the detection level has changed over time, so the values in Table 8.18 are not strictly comparable with each other.

Table 8.18. Detection Limits for Routine Hanford Analyses of Plutonium in Urine

Time Period	Detection Limit, dpm/routine sample
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 05/90	0.02
06/90 to 11/91	0.03
11/91 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 contractual detection limit for plutonium in urine can be found in the radiochemistry bioassay laboratory statement of work available from the HIDP) and in the *Hanford Internal Dosimetry Project Manual* (PNL-MA-552).[(a)]

(a) Pacific Northwest National Laboratory (PNNL). *Hanford Internal Dosimetry Project Manual*. PNNL-MA-552, Richland, Washington. (Internal manual.) Available URL: http://www.pnl.gov/eshs/pub/pnnl552.html

8.4.3 Fecal Sampling and Analysis

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 also be used as checks on urine- or in vivo-based estimates of intake. 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. Long-term sampling following intake can be useful for differentiating ingestion from inhalation, and class W from class Y inhalation. It 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. For a 5-µm particle size, the early fecal excretion is a higher fraction of intake.

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 modeling 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 the 135 g/d of ICRP 23 (1974) Reference Man and can be offset to some extent by collecting consecutive samples and averaging the results.

The laboratory plutonium analysis procedure for fecal samples involves wet ashing and dry ashing to destroy organic elements, redissolution to a standard volume using nitric acid, extraction of an aliquot representing 25% of the sample, additional dissolution using hydrofluoric acid, chemical separation of plutonium, followed by electroplating and alpha spectrometry. A ^{242}Pu tracer is used for determining chemical yields.

Contractual detection levels are established in the radiochemical bioassay laboratory statement of work, as approximations for the minimum detectable activity (MDA) desired for the analysis.

8.4.4 In Vivo Measurements

In vivo measurement techniques suitable for plutonium applications and routinely performed at the Hanford In Vivo Radioassay and Research Facility (IVRRF) include chest counting, skeleton measurement by head counting, liver counting, and wound counting. Less common measurements include upper extremity lymph node counting (e.g., axillary lymph nodes), and a scanning lung count to identify the likelihood of a nonuniform distribution of activity in the lung (e.g., a hot particle). 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 can also be performed. Minimum detectable activities for these measurements are described in the *In Vivo Monitoring Project Manual* (PNL-MA-574)[(a)] and the *Hanford Internal Dosimetry Program Manual* (PNL-MA-552).[(b)]

Because of the relative insensitivity of direct in vivo plutonium measurement techniques at low levels (other than for wounds), the presence of plutonium is often inferred by detection of ^{241}Am.

(a) Pacific Northwest National Laboratory (PNNL). *In Vivo Monitoring Project Manual*. PNNL-MA-574, Richland, Washington. (Internal manual.)

(b) Pacific Northwest National Laboratory (PNNL). *Hanford Internal Dosimetry Project Manual*. PNNL-MA-552, Richland, Washington. (Internal manual.) Available URL: http://www.pnl.gov/eshs/pub/pnnl552.html

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 paragraphs briefly describe the types of in vivo measurements available at the Hanford IVRRF. Further discussion of these measurement techniques can be found in the *In Vivo Monitoring Program Manual* (PNL-MA-574).

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 and, to a lesser extent, the liver). 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, especially at short times after intake.

Head counts (also called skull counts) will usually be performed when chest counts confirm detectable activity to determine if modification for skeleton activity is needed. 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 can also be used as an approximate check on urine-based systemic deposition estimates, recognizing that ionic americium in the blood may not behave the same as plutonium.

Liver counts provide a direct estimate of activity in the liver based on the Livermore calibration phantom (Griffith et al. 1978). These counts are used to correct chest counts for interference from activity deposited in the liver and are primarily used for long-term follow-up and as an approximate check on urine-based systemic deposition estimates. They can also provide a check on the assumptions used in the computer codes for calculating committed dose equivalents.

Wound counts using a single planar germanium detector can directly measure plutonium and americium. 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 IVRRF due to the use of shielded counting rooms. The ^{239}Pu results (based on the 17 keV L x-rays) can be significantly underestimated if the activity is deeply embedded in tissue.

Upper extremity lymph node counts are used to identify potential deposition sites for non-transportable or slowly transportable material deposited in extremity wounds. These nodes include the supratracular 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 not available.

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 retention 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.

8.4.5 Bioassay Monitoring Capability

The bioassay monitoring capability for plutonium can be discussed as the minimum detectable intake (MDI) or minimum detectable dose (MDD) associated with a bioassay measurement at the minimum detectable activity (MDA) at some time post intake. Analyses of the MDIs and MDDs (committed effective dose equivalents and committed bone surface dose equivalent for cases where the bone surface dose was more limiting than the effective dose) have been performed for three bioassay methods (^{239}Pu in urine, ^{239}Pu in feces, and in vivo ^{241}Am lung counting). These analyses included instant uptake, and class W, Y, and super class Y inhalations (1-µm and 5-µm-AMAD particles) for both weapons-grade and fuel-grade reference plutonium mixtures, aged 10, 20, and 40 years. The analyses assumed MDAs for the bioassay measurements to be slightly higher than those that have been observed for

most Hanford bioassay measurements. Thus, the stated MDIs and MDDs in the following tables are slightly higher than those expected to be achieved by routine worker monitoring.

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 8.19. Based on the activity ratios described in Section 8.1, the total-alpha intake was estimated for the mixtures, and the committed dose equivalents were calculated using the dose coefficients of Tables 8.14 and 8.15. The results are summarized in Tables 8.20 through 8.31 and graphically presented in Figures 8.9 through 8.20.

The minimum detectable committed doses associated with ^{241}Am detection by chest counting are shown in Tables 8.32 through 8.43 and Figures 8.21 through 8.32.

The capability for plutonium fecal bioassay is addressed in a similar manner, with the ^{239}Pu intakes compiled in Table 8.44. The corresponding minimum detectable committed effective dose equivalents are shown in Tables 8.45 through 8.56 and in Figures 8.33 through 8.44.

Table 8.19. Minimum Detectable Intakes (nCi) of ^{239}Pu Based on Detection of 0.02 dpm/d in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	3.0E-03	4.1E-02	2.6E-02	7.5E-01	3.6E-01	5.3E+02	3.2E+02
2	4.7E-03	6.4E-02	4.1E-02	1.2E+00	5.6E-01	4.7E+02	3.3E+02
5	1.6E-02	2.0E-01	1.3E-01	3.8E+00	1.8E+00	6.0E+02	6.0E+02
7	2.4E-02	2.9E-01	2.0E-01	5.6E+00	2.9E+00	6.4E+02	6.9E+02
14	3.9E-02	4.1E-01	3.2E-01	8.2E+00	4.7E+00	6.0E+02	6.9E+02
30	6.0E-02	5.3E-01	4.5E-01	1.1E+01	6.4E+00	5.0E+02	6.0E+02
60	9.1E-02	6.9E-01	6.4E-01	1.3E+01	9.7E+00	4.1E+02	5.3E+02
90	1.1E-01	8.2E-01	8.2E-01	1.3E+01	1.1E+01	3.6E+02	4.5E+02
180	1.6E-01	1.1E+00	1.1E+00	1.3E+01	1.4E+01	2.8E+02	3.6E+02
365	2.6E-01	1.9E+00	1.8E+00	1.1E+01	1.7E+01	2.1E+02	2.8E+02
730	4.7E-01	3.6E+00	3.5E+00	1.0E+01	2.0E+01	1.7E+02	2.3E+02
1,825	6.4E-01	5.6E+00	5.0E+00	1.0E+01	2.3E+01	1.2E+02	1.7E+02
3,600	6.9E-01	6.0E+00	5.3E+00	1.2E+01	2.6E+01	8.2E+01	1.2E+02
7,300	7.5E-01	6.4E+00	6.0E+00	1.5E+01	3.1E+01	5.3E+01	8.2E+01
18,250	1.1E+00	9.0E+00	8.2E+00	2.0E+01	4.3E+01	2.9E+01	5.6E+01

Table 8.20. Minimum Detectable Committed Effective Dose Equivalent (rem) for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	1.5E-02	2.5E-02	1.6E-02	3.2E-01	6.3E-02	4.1E+02	9.3E+01
2	2.4E-02	3.9E-02	2.6E-02	5.3E-01	9.9E-02	3.6E+02	9.6E+01
5	7.8E-02	1.2E-01	8.2E-02	1.6E+00	3.2E-01	4.6E+02	1.7E+02
7	1.2E-01	1.8E-01	1.3E-01	2.4E+00	5.1E-01	4.9E+02	2.0E+02
14	2.0E-01	2.5E-01	2.0E-01	3.5E+00	8.3E-01	4.6E+02	2.0E+02
30	3.0E-01	3.2E-01	2.8E-01	4.5E+00	1.1E+00	3.8E+02	1.7E+02
60	4.6E-01	4.2E-01	4.0E-01	5.4E+00	1.7E+00	3.1E+02	1.5E+02
90	5.7E-01	4.9E-01	5.1E-01	5.6E+00	2.0E+00	2.8E+02	1.3E+02
180	7.9E-01	6.5E-01	7.0E-01	5.3E+00	2.4E+00	2.2E+02	1.0E+02
365	1.3E+00	1.1E+00	1.2E+00	4.8E+00	3.0E+00	1.6E+02	8.1E+01
730	2.4E+00	2.2E+00	2.2E+00	4.3E+00	3.6E+00	1.3E+02	6.5E+01
1,825	3.2E+00	3.4E+00	3.1E+00	4.4E+00	4.0E+00	9.1E+01	4.9E+01
3,600	3.5E+00	3.6E+00	3.3E+00	5.2E+00	4.5E+00	6.3E+01	3.6E+01
7,300	3.8E+00	3.9E+00	3.8E+00	6.3E+00	5.5E+00	4.1E+01	2.4E+01
18,250	5.4E+00	5.4E+00	5.1E+00	8.7E+00	7.5E+00	2.2E+01	1.6E+01

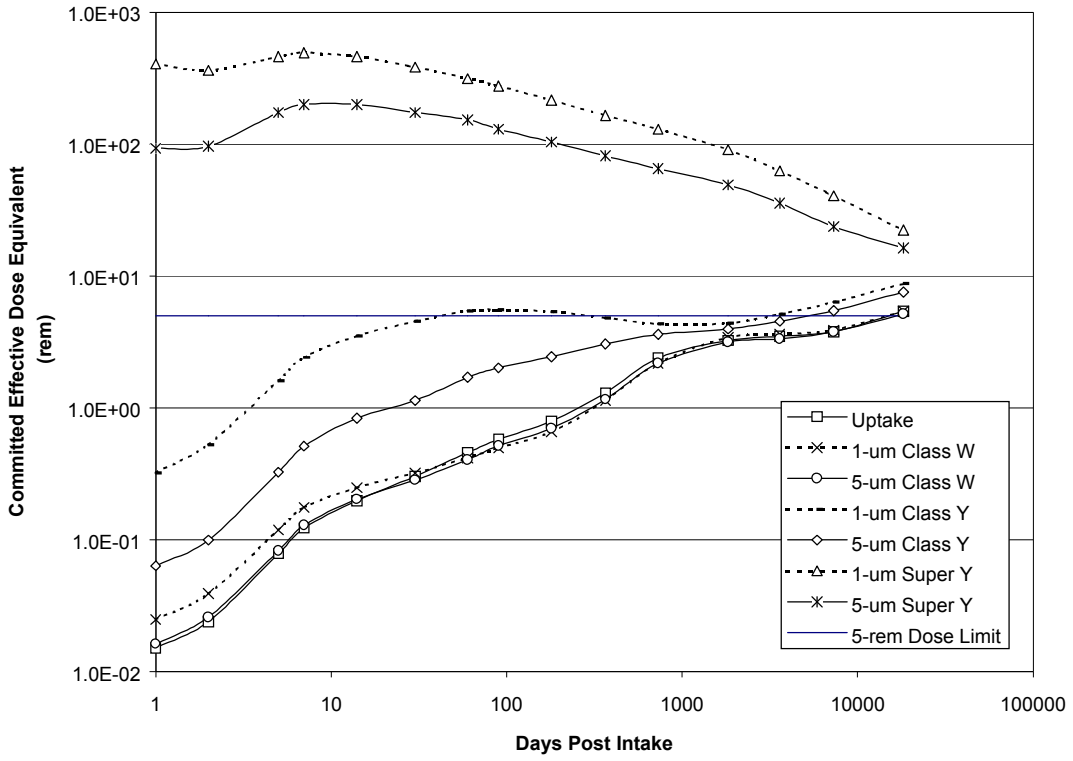

Figure 8.9. Minimum Detectable Committed Effective Doses for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.21. Minimum Detectable Committed Effective Dose Equivalent (rem) for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	1.5E-02	2.6E-02	1.7E-02	3.3E-01	6.8E-02	4.2E+02	9.5E+01
2	2.4E-02	4.1E-02	2.6E-02	5.5E-01	1.1E-01	3.7E+02	9.8E+01
5	7.9E-02	1.2E-01	8.4E-02	1.7E+00	3.4E-01	4.7E+02	1.8E+02
7	1.2E-01	1.8E-01	1.3E-01	2.5E+00	5.5E-01	5.1E+02	2.0E+02
14	2.0E-01	2.6E-01	2.1E-01	3.6E+00	8.9E-01	4.7E+02	2.0E+02
30	3.1E-01	3.3E-01	2.9E-01	4.7E+00	1.2E+00	4.0E+02	1.8E+02
60	4.6E-01	4.4E-01	4.1E-01	5.6E+00	1.8E+00	3.2E+02	1.6E+02
90	5.8E-01	5.2E-01	5.3E-01	5.8E+00	2.1E+00	2.8E+02	1.3E+02
180	8.0E-01	6.8E-01	7.2E-01	5.5E+00	2.6E+00	2.2E+02	1.1E+02
365	1.3E+00	1.2E+00	1.2E+00	5.0E+00	3.3E+00	1.7E+02	8.3E+01
730	2.4E+00	2.3E+00	2.2E+00	4.5E+00	3.8E+00	1.3E+02	6.6E+01
1,825	3.3E+00	3.5E+00	3.2E+00	4.5E+00	4.2E+00	9.4E+01	5.0E+01
3,600	3.5E+00	3.8E+00	3.4E+00	5.3E+00	4.8E+00	6.5E+01	3.6E+01
7,300	3.8E+00	4.1E+00	3.9E+00	6.5E+00	5.8E+00	4.2E+01	2.4E+01
18,250	5.5E+00	5.7E+00	5.3E+00	9.1E+00	8.0E+00	2.3E+01	1.7E+01

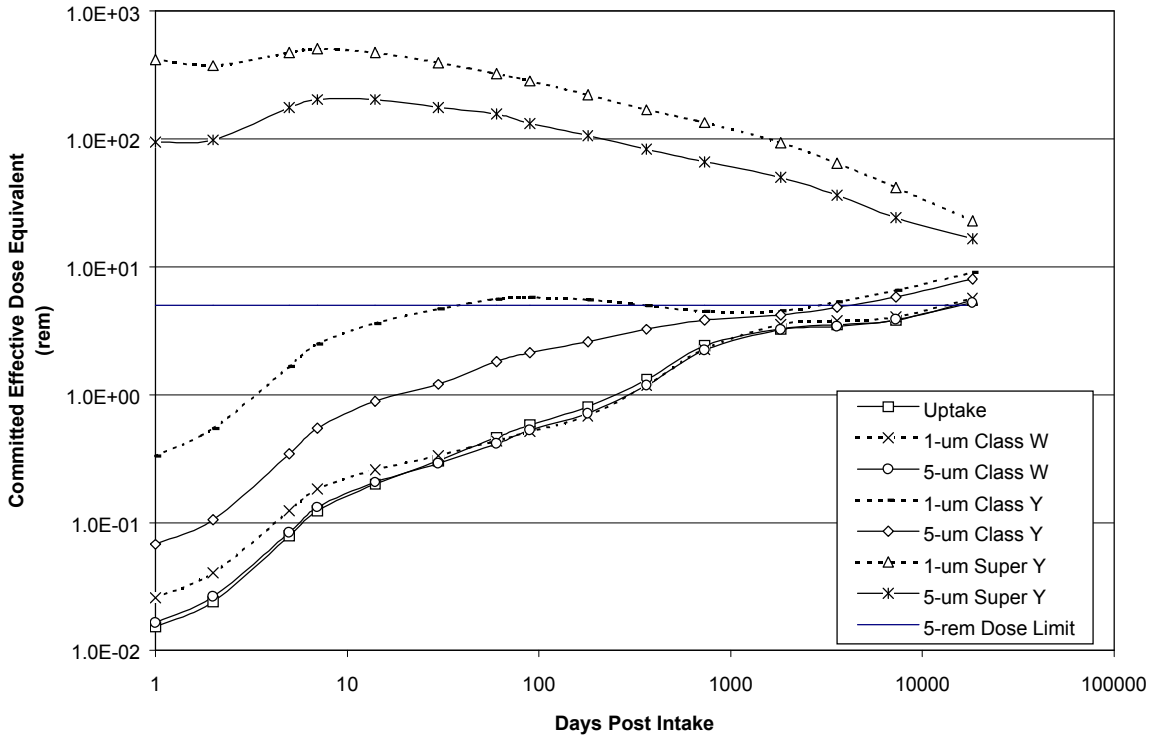

Figure 8.10. Minimum Detectable Committed Effective Doses for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.22. Minimum Detectable Committed Effective Dose Equivalent (rem) for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	1.6E-02	2.6E-02	1.7E-02	3.4E-01	6.6E-02	4.2E+02	9.9E+01
2	2.5E-02	4.1E-02	2.6E-02	5.5E-01	1.0E-01	3.8E+02	1.0E+02
5	8.0E-02	1.2E-01	8.4E-02	1.7E+00	3.3E-01	4.8E+02	1.8E+02
7	1.3E-01	1.8E-01	1.3E-01	2.5E+00	5.3E-01	5.1E+02	2.1E+02
14	2.0E-01	2.6E-01	2.1E-01	3.7E+00	8.6E-01	4.8E+02	2.1E+02
30	3.1E-01	3.3E-01	2.9E-01	4.7E+00	1.2E+00	4.0E+02	1.8E+02
60	4.7E-01	4.4E-01	4.1E-01	5.7E+00	1.8E+00	3.3E+02	1.6E+02
90	5.9E-01	5.2E-01	5.3E-01	5.8E+00	2.1E+00	2.9E+02	1.4E+02
180	8.2E-01	6.8E-01	7.2E-01	5.6E+00	2.5E+00	2.2E+02	1.1E+02
365	1.3E+00	1.2E+00	1.2E+00	5.0E+00	3.2E+00	1.7E+02	8.7E+01
730	2.5E+00	2.3E+00	2.2E+00	4.5E+00	3.7E+00	1.4E+02	6.9E+01
1,825	3.3E+00	3.5E+00	3.2E+00	4.6E+00	4.1E+00	9.5E+01	5.2E+01
3,600	3.6E+00	3.8E+00	3.4E+00	5.4E+00	4.7E+00	6.5E+01	3.8E+01
7,300	3.9E+00	4.1E+00	3.9E+00	6.6E+00	5.7E+00	4.2E+01	2.5E+01
18,250	5.6E+00	5.7E+00	5.3E+00	9.2E+00	7.8E+00	2.3E+01	1.7E+01

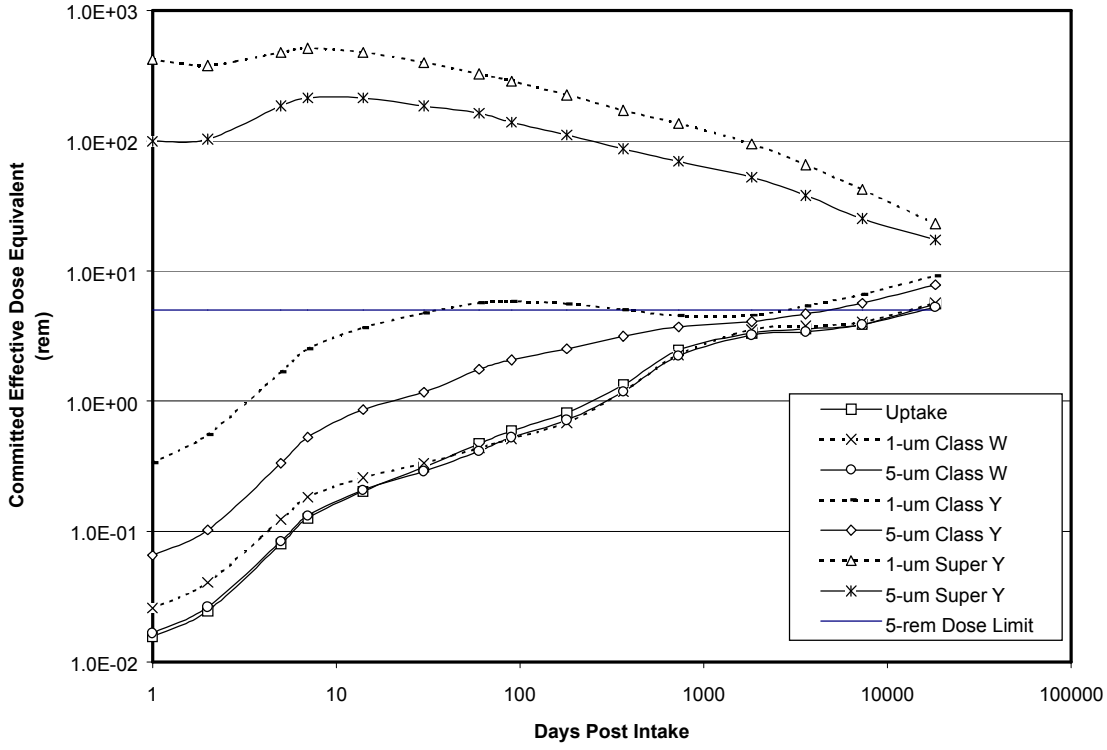

Figure 8.11. Minimum Detectable Committed Effective Doses for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.23. Minimum Detectable Committed Effective Dose Equivalent (rem) for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	2.3E-02	3.9E-02	2.7E-02	4.8E-01	9.7E-02	6.4E+02	1.5E+02
2	3.7E-02	6.1E-02	4.2E-02	7.9E-01	1.5E-01	5.7E+02	1.5E+02
5	1.2E-01	1.9E-01	1.3E-01	2.4E+00	5.0E-01	7.2E+02	2.7E+02
7	1.9E-01	2.8E-01	2.1E-01	3.6E+00	7.9E-01	7.7E+02	3.2E+02
14	3.0E-01	3.9E-01	3.3E-01	5.3E+00	1.3E+00	7.2E+02	3.2E+02
30	4.7E-01	5.0E-01	4.6E-01	6.8E+00	1.7E+00	6.0E+02	2.7E+02
60	7.1E-01	6.6E-01	6.6E-01	8.1E+00	2.6E+00	4.9E+02	2.4E+02
90	8.9E-01	7.8E-01	8.4E-01	8.4E+00	3.1E+00	4.3E+02	2.1E+02
180	1.2E+00	1.0E+00	1.1E+00	8.0E+00	3.7E+00	3.4E+02	1.6E+02
365	2.0E+00	1.8E+00	1.9E+00	7.2E+00	4.7E+00	2.6E+02	1.3E+02
730	3.7E+00	3.4E+00	3.6E+00	6.5E+00	5.5E+00	2.0E+02	1.0E+02
1,825	5.0E+00	5.3E+00	5.2E+00	6.6E+00	6.1E+00	1.4E+02	7.8E+01
3,600	5.4E+00	5.7E+00	5.5E+00	7.7E+00	7.0E+00	9.8E+01	5.6E+01
7,300	5.8E+00	6.1E+00	6.2E+00	9.5E+00	8.4E+00	6.4E+01	3.7E+01
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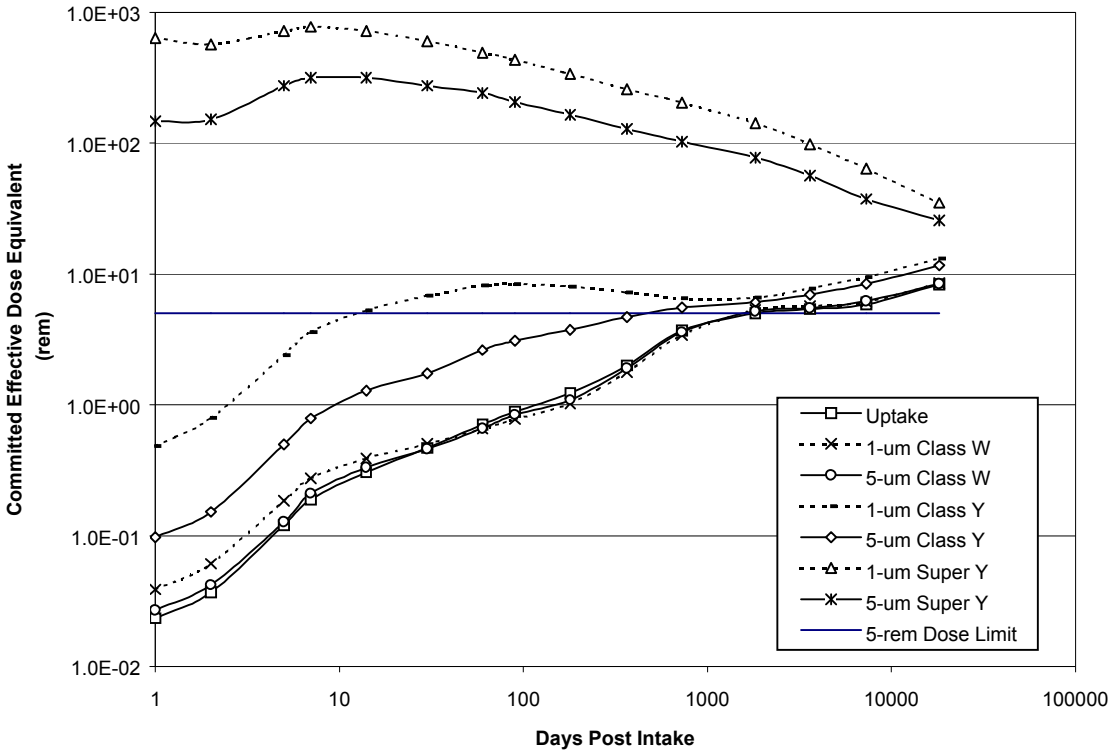

Figure 8.12. Minimum Detectable Committed Effective Doses for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.24. Minimum Detectable Committed Effective Dose Equivalent (rem) for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	2.4E-02	4.0E-02	2.8E-02	5.2E-01	1.1E-01	6.7E+02	1.5E+02
2	3.8E-02	6.3E-02	4.4E-02	8.5E-01	1.7E-01	6.0E+02	1.6E+02
5	1.3E-01	1.9E-01	1.4E-01	2.6E+00	5.4E-01	7.6E+02	2.8E+02
7	2.0E-01	2.9E-01	2.2E-01	3.9E+00	8.6E-01	8.1E+02	3.3E+02
14	3.2E-01	4.0E-01	3.5E-01	5.6E+00	1.4E+00	7.6E+02	3.3E+02
30	4.9E-01	5.2E-01	4.9E-01	7.3E+00	1.9E+00	6.3E+02	2.8E+02
60	7.4E-01	6.8E-01	7.0E-01	8.7E+00	2.9E+00	5.2E+02	2.5E+02
90	9.2E-01	8.1E-01	8.9E-01	9.0E+00	3.4E+00	4.5E+02	2.1E+02
180	1.3E+00	1.1E+00	1.2E+00	8.6E+00	4.1E+00	3.5E+02	1.7E+02
365	2.1E+00	1.8E+00	2.0E+00	7.8E+00	5.1E+00	2.7E+02	1.3E+02
730	3.8E+00	3.5E+00	3.8E+00	7.0E+00	6.1E+00	2.1E+02	1.1E+02
1,825	5.2E+00	5.5E+00	5.4E+00	7.1E+00	6.7E+00	1.5E+02	8.0E+01
3,600	5.6E+00	5.9E+00	5.7E+00	8.3E+00	7.6E+00	1.0E+02	5.8E+01
7,300	6.1E+00	6.3E+00	6.5E+00	1.0E+01	9.2E+00	6.7E+01	3.9E+01
18,250	8.7E+00	8.9E+00	8.9E+00	1.4E+01	1.3E+01	3.7E+01	2.7E+01

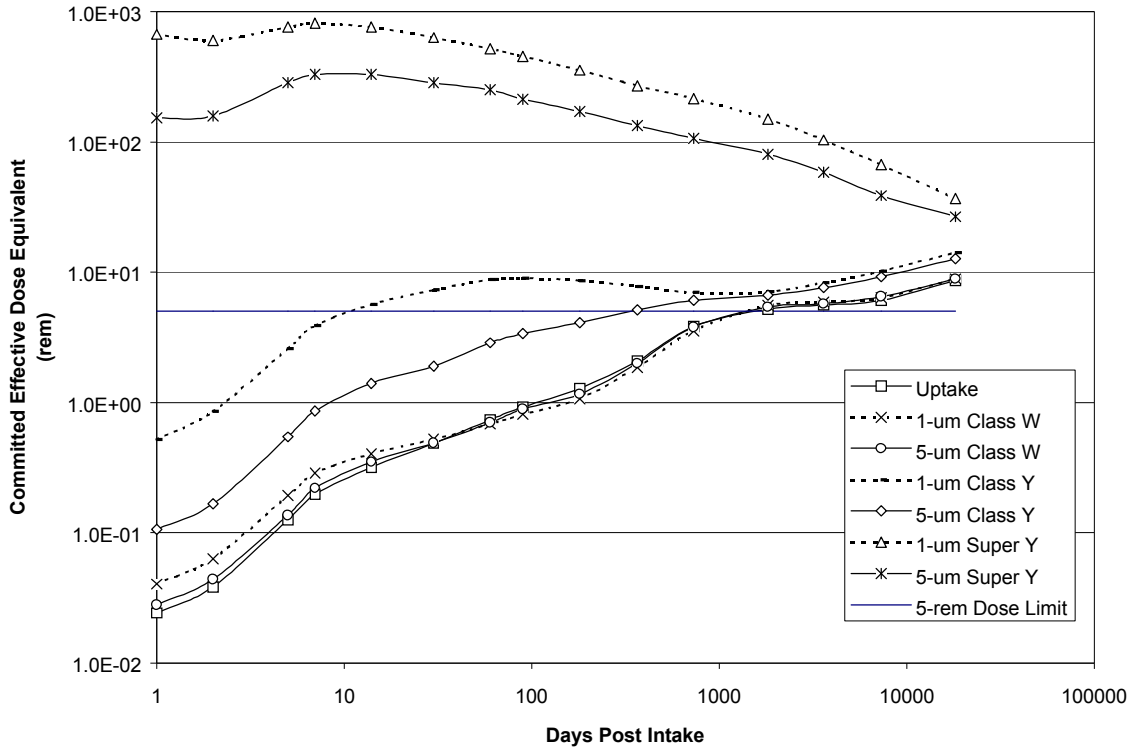

Figure 8.13. Minimum Detectable Committed Effective Doses for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.25. Minimum Detectable Committed Effective Dose Equivalent (rem) for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	2.5E-02	4.2E-02	2.8E-02	5.5E-01	1.1E-01	6.9E+02	1.6E+02
2	4.0E-02	6.5E-02	4.5E-02	9.0E-01	1.7E-01	6.2E+02	1.6E+02
5	1.3E-01	2.0E-01	1.4E-01	2.7E+00	5.7E-01	7.8E+02	2.9E+02
7	2.0E-01	3.0E-01	2.3E-01	4.1E+00	9.0E-01	8.4E+02	3.4E+02
14	3.3E-01	4.2E-01	3.6E-01	6.0E+00	1.5E+00	7.8E+02	3.4E+02
30	5.0E-01	5.4E-01	5.0E-01	7.7E+00	2.0E+00	6.5E+02	2.9E+02
60	7.6E-01	7.0E-01	7.1E-01	9.3E+00	3.0E+00	5.3E+02	2.6E+02
90	9.6E-01	8.3E-01	9.0E-01	9.5E+00	3.5E+00	4.7E+02	2.2E+02
180	1.3E+00	1.1E+00	1.2E+00	9.1E+00	4.3E+00	3.7E+02	1.8E+02
365	2.2E+00	1.9E+00	2.0E+00	8.2E+00	5.4E+00	2.8E+02	1.4E+02
730	4.0E+00	3.7E+00	3.8E+00	7.4E+00	6.3E+00	2.2E+02	1.1E+02
1,825	5.4E+00	5.7E+00	5.5E+00	7.5E+00	7.0E+00	1.5E+02	8.3E+01
3,600	5.8E+00	6.1E+00	5.9E+00	8.8E+00	8.0E+00	1.1E+02	6.0E+01
7,300	6.3E+00	6.5E+00	6.6E+00	1.1E+01	9.6E+00	6.9E+01	4.0E+01
18,250	9.0E+00	9.2E+00	9.0E+00	1.5E+01	1.3E+01	3.8E+01	2.7E+01

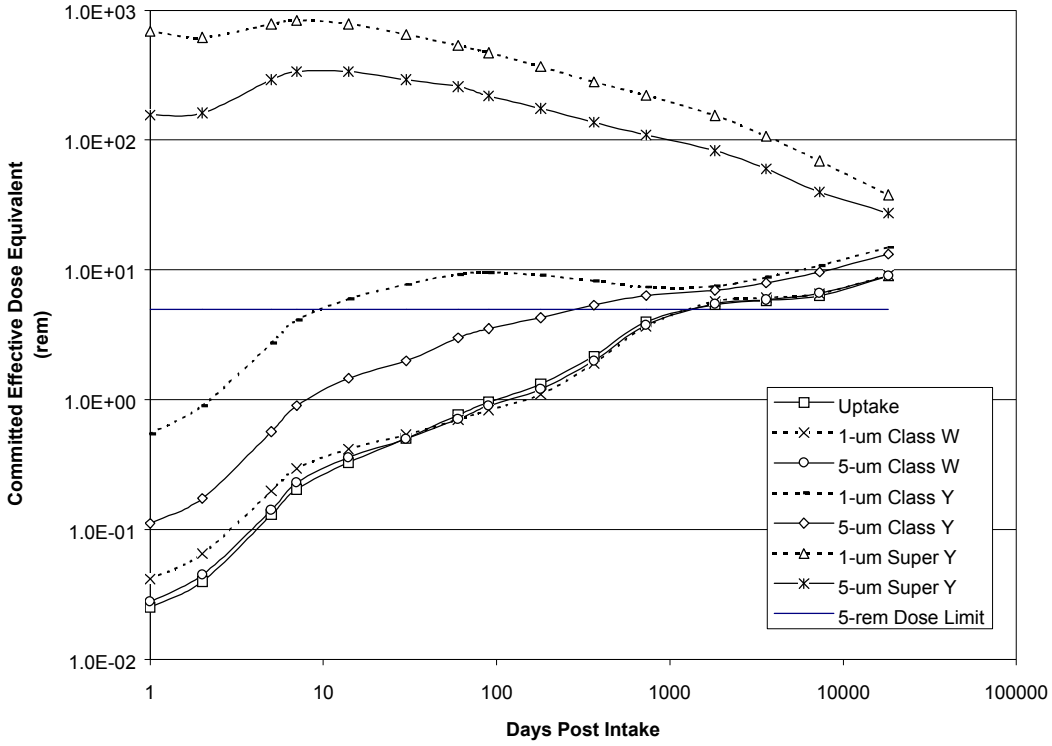

Figure 8.14. Minimum Detectable Committed Effective Doses for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.26. Minimum Detectable Committed Bone Surfaces Dose Equivalent (rem) for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	2.8E-01	4.5E-01	3.1E-01	3.2E+00	8.2E-01
2	4.4E-01	7.1E-01	5.0E-01	5.3E+00	1.3E+00
5	1.4E+00	2.2E+00	1.6E+00	1.6E+01	4.2E+00
7	2.3E+00	3.2E+00	2.5E+00	2.4E+01	6.6E+00
14	3.6E+00	4.5E+00	3.9E+00	3.5E+01	1.1E+01
30	5.6E+00	5.9E+00	5.5E+00	4.5E+01	1.5E+01
60	8.5E+00	7.7E+00	7.8E+00	5.4E+01	2.2E+01
90	1.1E+01	9.1E+00	1.0E+01	5.6E+01	2.6E+01
180	1.5E+01	1.2E+01	1.4E+01	5.3E+01	3.1E+01
365	2.4E+01	2.1E+01	2.2E+01	4.8E+01	3.9E+01
730	4.4E+01	4.0E+01	4.2E+01	4.3E+01	4.6E+01
1,825	6.0E+01	6.2E+01	6.1E+01	4.4E+01	5.1E+01
3,600	6.4E+01	6.6E+01	6.5E+01	5.2E+01	5.8E+01
7,300	7.0E+01	7.1E+01	7.3E+01	6.3E+01	7.0E+01
18,250	1.0E+02	1.0E+02	1.0E+02	8.7E+01	9.7E+01

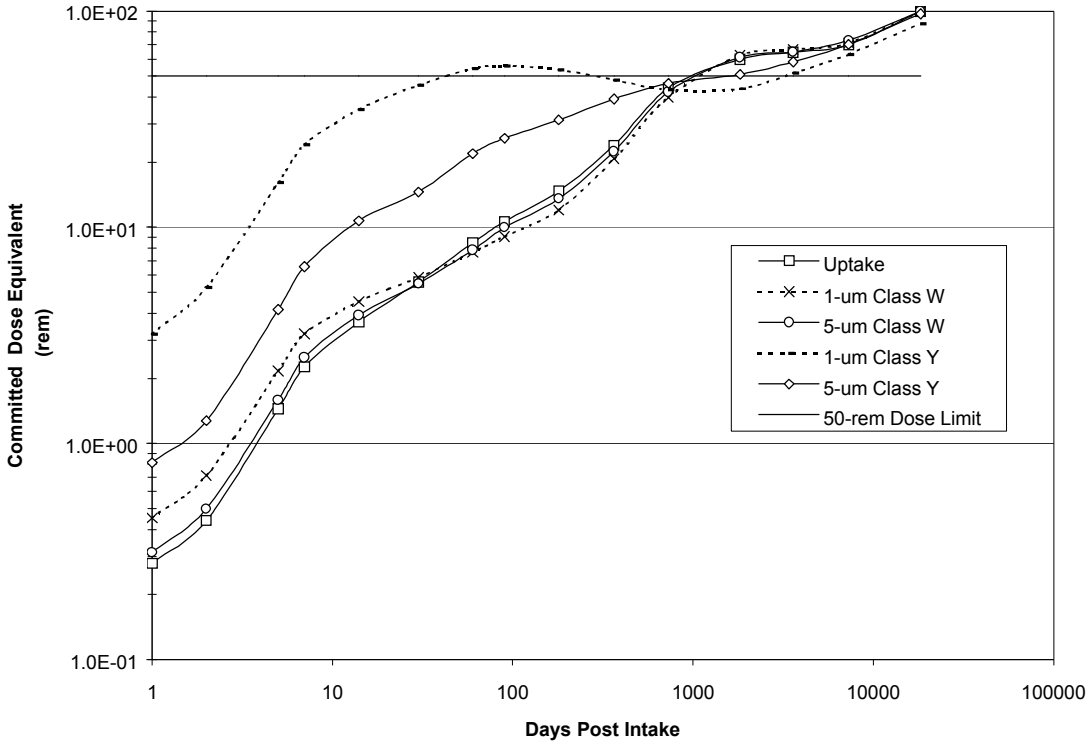

Figure 8.15. Minimum Detectable Bone Surface Dose for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.27. Minimum Detectable Committed Bone Surfaces Dose Equivalent (rem) for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	2.9E-01	4.7E-01	3.2E-01	3.3E+00	8.2E-01
2	4.5E-01	7.3E-01	5.1E-01	5.5E+00	1.3E+00
5	1.5E+00	2.2E+00	1.6E+00	1.7E+01	4.2E+00
7	2.3E+00	3.3E+00	2.6E+00	2.5E+01	6.6E+00
14	3.7E+00	4.7E+00	4.0E+00	3.6E+01	1.1E+01
30	5.7E+00	6.0E+00	5.6E+00	4.7E+01	1.5E+01
60	8.7E+00	7.9E+00	8.0E+00	5.6E+01	2.2E+01
90	1.1E+01	9.3E+00	1.0E+01	5.8E+01	2.6E+01
180	1.5E+01	1.2E+01	1.4E+01	5.5E+01	3.2E+01
365	2.4E+01	2.1E+01	2.3E+01	5.0E+01	3.9E+01
730	4.5E+01	4.1E+01	4.3E+01	4.5E+01	4.7E+01
1,825	6.1E+01	6.4E+01	6.2E+01	4.5E+01	5.1E+01
3,600	6.6E+01	6.8E+01	6.6E+01	5.3E+01	5.9E+01
7,300	7.1E+01	7.3E+01	7.5E+01	6.5E+01	7.1E+01
18,250	1.0E+02	1.0E+02	1.0E+02	9.1E+01	9.8E+01

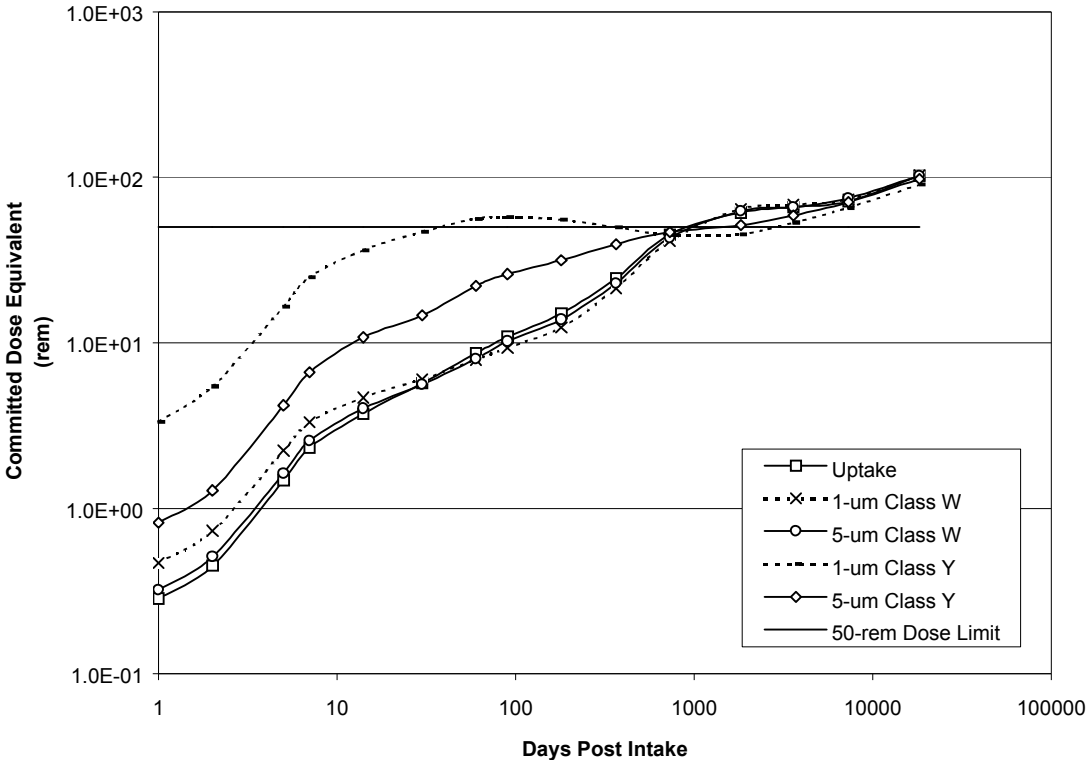

Figure 8.16. Minimum Detectable Bone Surface Dose for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.28. Minimum Detectable Committed Bone Surfaces Dose Equivalent (rem) for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	2.9E-01	4.7E-01	3.2E-01	3.4E+00	8.1E-01
2	4.5E-01	7.4E-01	5.2E-01	5.5E+00	1.3E+00
5	1.5E+00	2.2E+00	1.6E+00	1.7E+01	4.1E+00
7	2.3E+00	3.3E+00	2.6E+00	2.5E+01	6.5E+00
14	3.7E+00	4.7E+00	4.1E+00	3.7E+01	1.1E+01
30	5.7E+00	6.1E+00	5.7E+00	4.7E+01	1.4E+01
60	8.7E+00	8.0E+00	8.1E+00	5.7E+01	2.2E+01
90	1.1E+01	9.4E+00	1.0E+01	5.8E+01	2.6E+01
180	1.5E+01	1.2E+01	1.4E+01	5.6E+01	3.1E+01
365	2.5E+01	2.2E+01	2.3E+01	5.0E+01	3.9E+01
730	4.5E+01	4.1E+01	4.4E+01	4.5E+01	4.6E+01
1,825	6.1E+01	6.5E+01	6.3E+01	4.6E+01	5.0E+01
3,600	6.6E+01	6.9E+01	6.7E+01	5.4E+01	5.8E+01
7,300	7.1E+01	7.4E+01	7.6E+01	6.6E+01	7.0E+01
18,250	1.0E+02	1.0E+02	1.0E+02	9.2E+01	9.6E+01

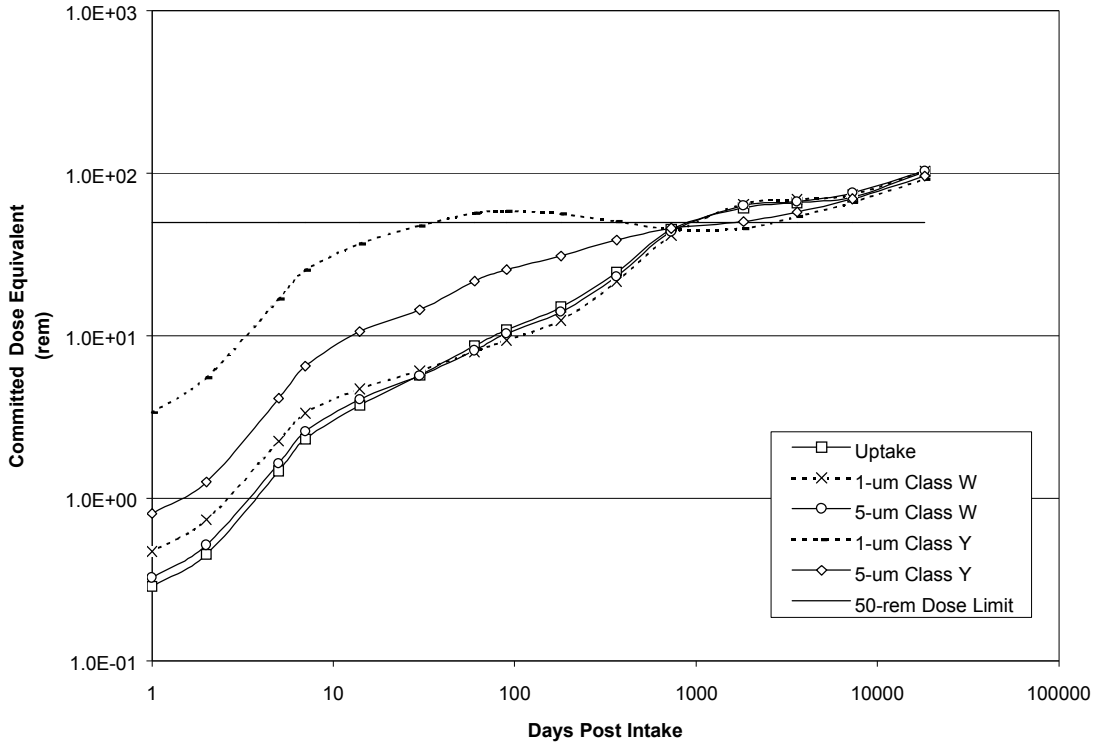

Figure 8.17. Minimum Detectable Bone Surface Dose for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.29. Minimum Detectable Committed Bone Surfaces Dose Equivalent (rem) for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	4.3E-01	6.9E-01	4.8E-01	5.1E+00	1.2E+00
2	6.8E-01	1.1E+00	7.6E-01	8.3E+00	1.9E+00
5	2.2E+00	3.3E+00	2.4E+00	2.5E+01	6.2E+00
7	3.5E+00	4.9E+00	3.8E+00	3.8E+01	9.8E+00
14	5.6E+00	6.9E+00	6.0E+00	5.5E+01	1.6E+01
30	8.6E+00	9.0E+00	8.4E+00	7.2E+01	2.2E+01
60	1.3E+01	1.2E+01	1.2E+01	8.6E+01	3.3E+01
90	1.6E+01	1.4E+01	1.5E+01	8.8E+01	3.9E+01
180	2.3E+01	1.8E+01	2.1E+01	8.5E+01	4.7E+01
365	3.7E+01	3.2E+01	3.4E+01	7.6E+01	5.9E+01
730	6.8E+01	6.1E+01	6.4E+01	6.8E+01	6.9E+01
1,825	9.2E+01	9.5E+01	9.3E+01	6.9E+01	7.6E+01
3,600	1.0E+02	1.0E+02	9.9E+01	8.2E+01	8.7E+01
7,300	1.1E+02	1.1E+02	1.1E+02	1.0E+02	1.1E+02
18,250	1.5E+02	1.5E+02	1.5E+02	1.4E+02	1.5E+02

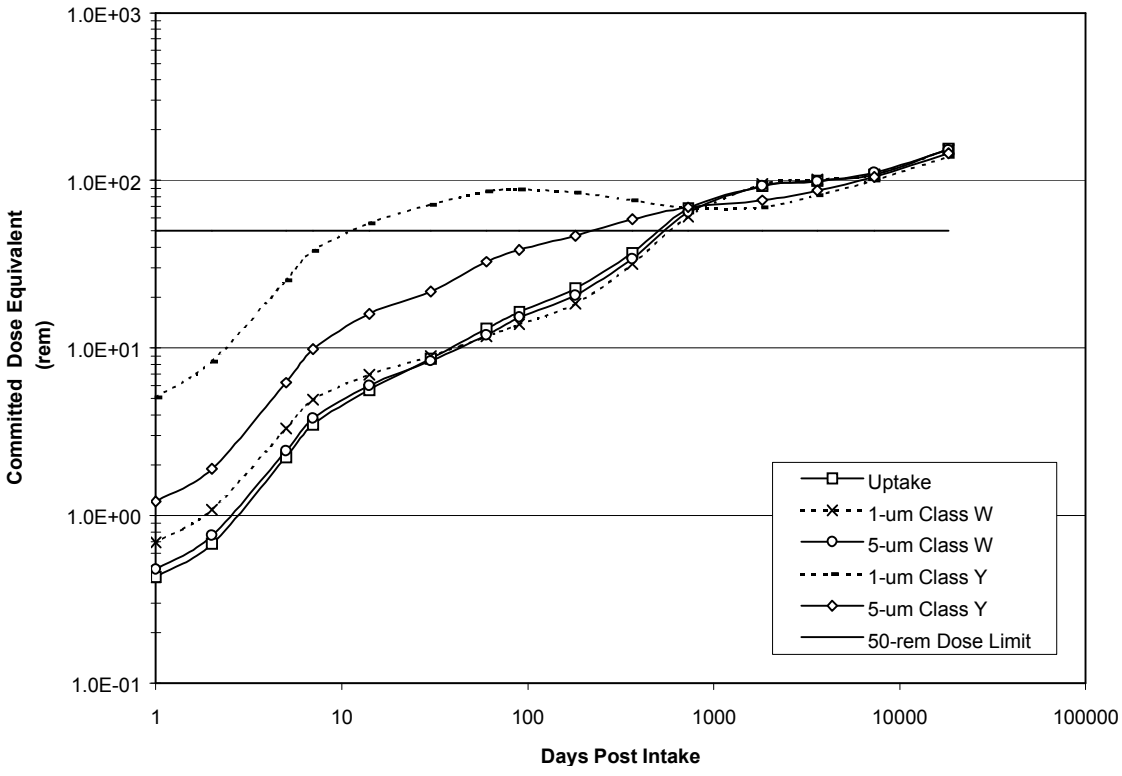

Figure 8.18. Minimum Detectable Bone Surface Dose for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.30. Minimum Detectable Committed Bone Surfaces Dose Equivalent (rem) for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	4.5E-01	7.4E-01	5.1E-01	5.3E+00	1.3E+00
2	7.1E-01	1.2E+00	8.1E-01	8.8E+00	2.0E+00
5	2.3E+00	3.5E+00	2.6E+00	2.7E+01	6.5E+00
7	3.6E+00	5.3E+00	4.0E+00	4.0E+01	1.0E+01
14	5.9E+00	7.4E+00	6.3E+00	5.8E+01	1.7E+01
30	9.0E+00	9.6E+00	8.9E+00	7.5E+01	2.3E+01
60	1.4E+01	1.3E+01	1.3E+01	9.0E+01	3.4E+01
90	1.7E+01	1.5E+01	1.6E+01	9.3E+01	4.0E+01
180	2.4E+01	2.0E+01	2.2E+01	8.9E+01	4.9E+01
365	3.9E+01	3.4E+01	3.6E+01	8.0E+01	6.1E+01
730	7.1E+01	6.5E+01	6.8E+01	7.2E+01	7.3E+01
1,825	9.6E+01	1.0E+02	9.9E+01	7.3E+01	8.0E+01
3,600	1.0E+02	1.1E+02	1.0E+02	8.6E+01	9.1E+01
7,300	1.1E+02	1.2E+02	1.2E+02	1.0E+02	1.1E+02
18,250	1.6E+02	1.6E+02	1.6E+02	1.5E+02	1.5E+02

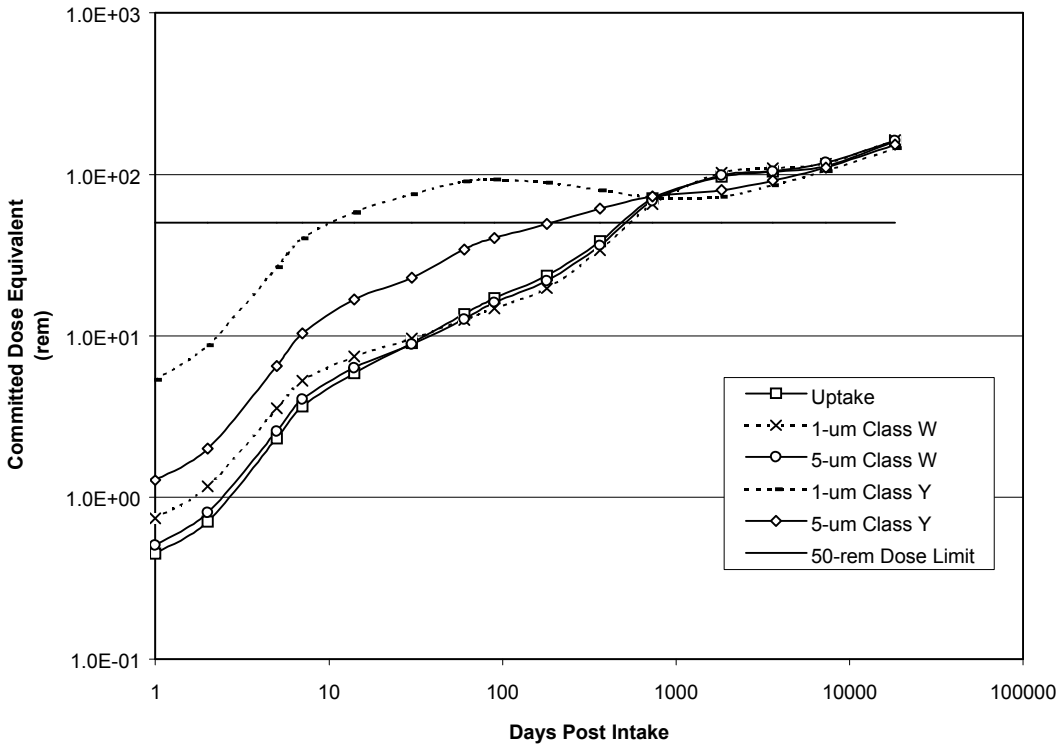

Figure 8.19. Minimum Detectable Bone Surface Dose for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.31. Minimum Detectable Committed Bone Surfaces Dose Equivalent (rem) for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	4.6E-01	7.6E-01	5.2E-01	5.3E+00	1.4E+00
2	7.3E-01	1.2E+00	8.3E-01	8.7E+00	2.1E+00
5	2.4E+00	3.6E+00	2.7E+00	2.7E+01	6.9E+00
7	3.8E+00	5.4E+00	4.2E+00	4.0E+01	1.1E+01
14	6.1E+00	7.6E+00	6.5E+00	5.8E+01	1.8E+01
30	9.3E+00	9.8E+00	9.2E+00	7.5E+01	2.4E+01
60	1.4E+01	1.3E+01	1.3E+01	9.0E+01	3.6E+01
90	1.8E+01	1.5E+01	1.7E+01	9.2E+01	4.3E+01
180	2.4E+01	2.0E+01	2.3E+01	8.8E+01	5.2E+01
365	4.0E+01	3.5E+01	3.7E+01	8.0E+01	6.5E+01
730	7.3E+01	6.7E+01	7.0E+01	7.2E+01	7.7E+01
1,825	1.0E+02	1.0E+02	1.0E+02	7.2E+01	8.5E+01
3,600	1.1E+02	1.1E+02	1.1E+02	8.5E+01	9.7E+01
7,300	1.2E+02	1.2E+02	1.2E+02	1.0E+02	1.2E+02
18,250	1.7E+02	1.7E+02	1.7E+02	1.4E+02	1.6E+02

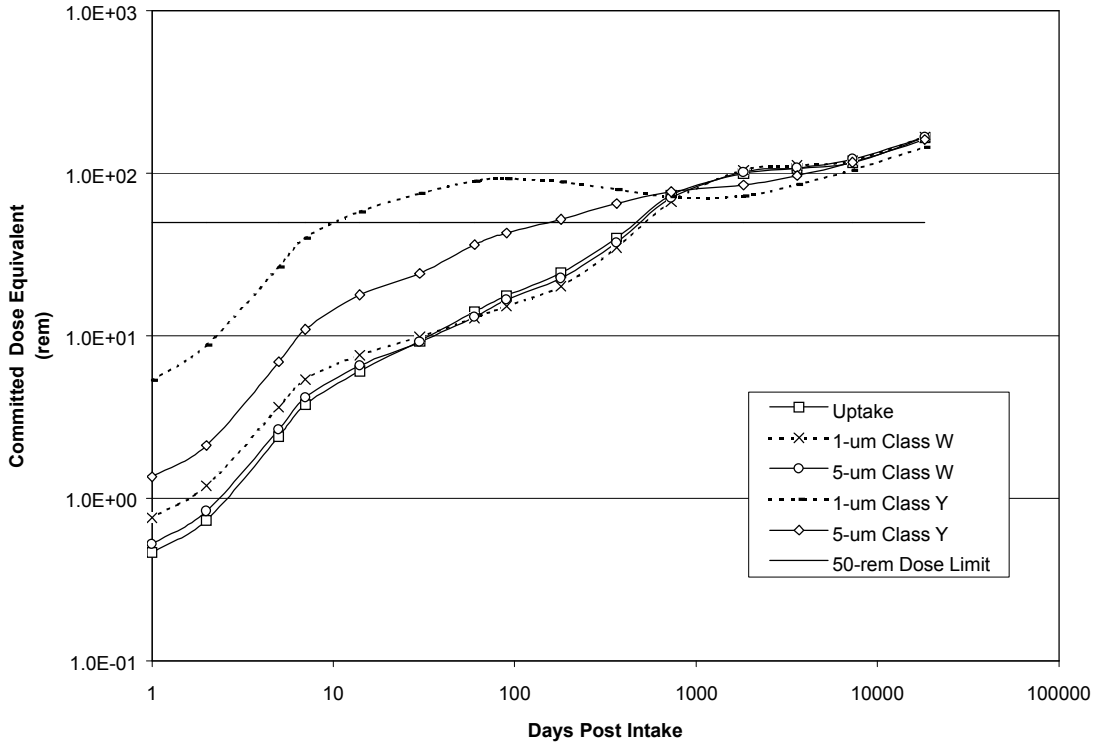

Figure 8.20. Minimum Detectable Bone Surface Dose for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.02 dpm/d ^{239}Pu in Urine

Table 8.32. Minimum Detectable Committed Effective Dose Equivalent (rem) for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
Intake	1-um	5-um	1-um	5-um	1-um	5-um
0	2.0E+00	4.2E+00	1.4E+00	1.2E+00	2.6E+00	1.9E+00
1	3.1E+00	9.2E+00	2.2E+00	2.5E+00	3.9E+00	4.1E+00
2	3.7E+00	1.1E+01	2.6E+00	3.0E+00	4.6E+00	4.9E+00
5	4.5E+00	1.4E+01	3.0E+00	3.6E+00	5.4E+00	5.8E+00
7	4.8E+00	1.4E+01	3.2E+00	3.7E+00	5.4E+00	5.9E+00
14	5.1E+00	1.5E+01	3.2E+00	3.7E+00	5.7E+00	5.9E+00
30	6.4E+00	1.9E+01	3.2E+00	3.7E+00	5.7E+00	6.0E+00
60	9.4E+00	2.8E+01	3.2E+00	3.9E+00	5.7E+00	6.1E+00
90	1.4E+01	4.0E+01	3.4E+00	3.9E+00	6.1E+00	6.3E+00
180	4.3E+01	1.3E+02	3.6E+00	4.2E+00	6.5E+00	6.7E+00
365	4.5E+02	1.3E+03	4.2E+00	5.0E+00	7.0E+00	7.5E+00
730	5.1E+04	1.5E+05	5.6E+00	6.6E+00	8.9E+00	9.0E+00
1,825	8.3E+09	2.1E+10	1.2E+01	1.4E+01	1.1E+01	1.2E+01
3,600	1.9E+10	1.2E+12	3.0E+01	3.5E+01	1.1E+01	1.2E+01
7,300	2.6E+11	2.5E+11	5.7E+01	6.8E+01	1.0E+01	1.1E+01
18,250	5.1E+12	1.0E+12	5.4E+01	6.2E+01	1.2E+01	1.3E+01

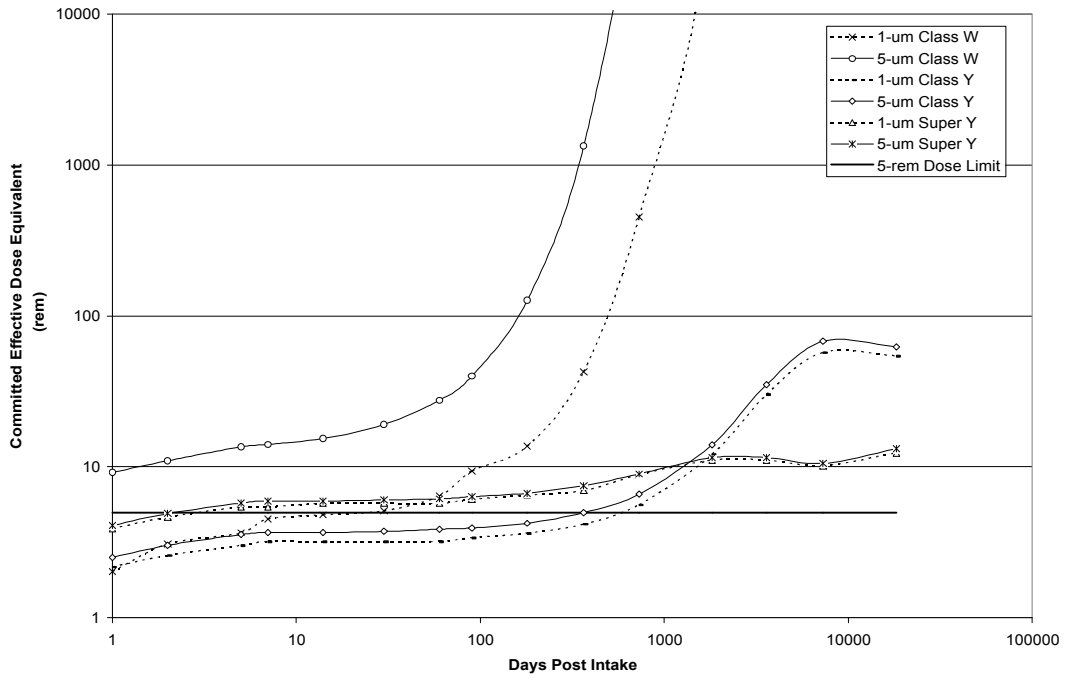

Figure 8.21. Minimum Detectable Committed Effective Doses for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.33. Minimum Detectable Committed Effective Dose Equivalent (rem) for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
Intake	1-um	5-um	1-um	5-um	1-um	5-um
0	1.3E+00	2.6E+00	9.1E-01	7.7E-01	1.6E+00	1.2E+00
1	2.0E+00	5.9E+00	1.4E+00	1.7E+00	2.5E+00	2.5E+00
2	2.4E+00	7.0E+00	1.7E+00	2.0E+00	3.0E+00	3.2E+00
5	3.0E+00	8.6E+00	2.0E+00	2.4E+00	3.5E+00	3.7E+00
7	3.1E+00	9.0E+00	2.0E+00	2.4E+00	3.6E+00	3.7E+00
14	3.4E+00	9.8E+00	2.0E+00	2.5E+00	3.6E+00	3.8E+00
30	4.2E+00	1.2E+01	2.0E+00	2.5E+00	3.6E+00	3.8E+00
60	6.3E+00	1.8E+01	2.1E+00	2.6E+00	3.8E+00	4.0E+00
90	9.0E+00	2.6E+01	2.2E+00	2.6E+00	3.9E+00	4.0E+00
180	2.8E+01	8.2E+01	2.4E+00	2.9E+00	4.1E+00	4.3E+00
365	3.1E+02	8.9E+02	2.8E+00	3.4E+00	4.7E+00	5.0E+00
730	3.6E+04	1.1E+05	4.1E+00	4.8E+00	5.9E+00	6.2E+00
1,825	1.7E+10	2.8E+08	9.3E+00	1.1E+01	8.6E+00	8.8E+00
3,600	4.4E+11	4.5E+09	2.5E+01	3.0E+01	9.4E+00	9.5E+00
7,300	6.3E+12	2.6E+11	5.3E+01	6.4E+01	9.4E+00	9.8E+00
18,250	1.0E+13	2.1E+13	5.5E+01	6.6E+01	1.3E+01	1.3E+01

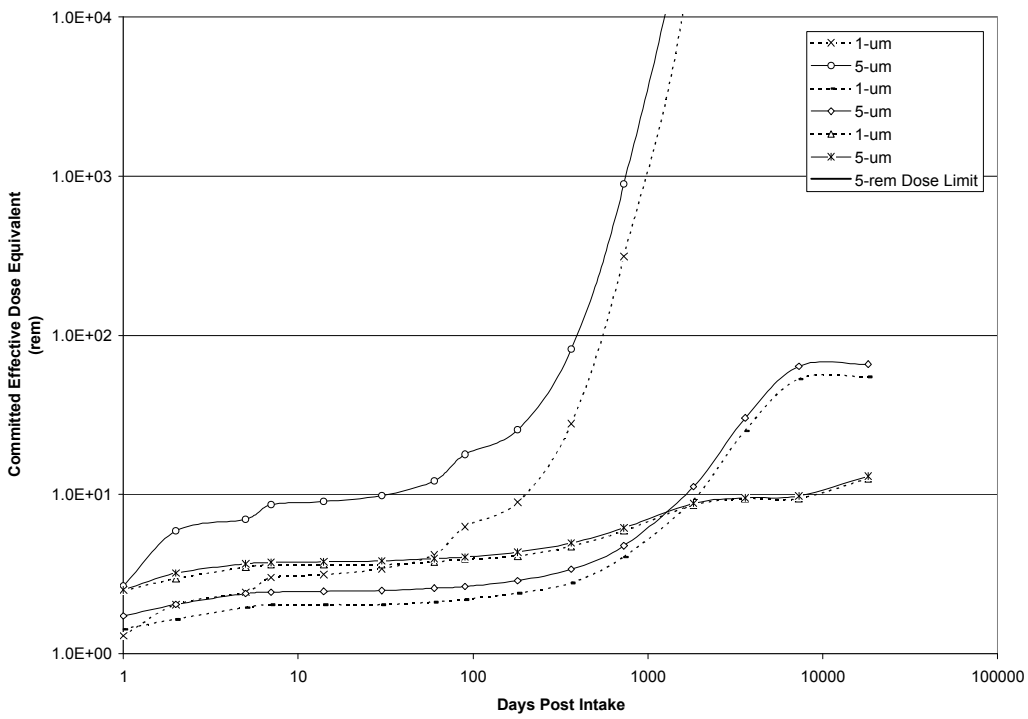

Figure 8.22. Minimum Detectable Committed Effective Doses for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.34. Minimum Detectable Committed Effective Dose Equivalent (rem) for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
Intake	1-um	5-um	1-um	5-um	1-um	5-um
0	9.7E-01	1.9E+00	6.9E-01	5.5E-01	1.2E+00	9.3E-01
1	1.5E+00	4.3E+00	1.1E+00	1.2E+00	1.9E+00	2.1E+00
2	1.8E+00	5.3E+00	1.2E+00	1.5E+00	2.2E+00	2.3E+00
5	2.2E+00	6.7E+00	1.5E+00	1.7E+00	2.6E+00	2.9E+00
7	2.3E+00	6.7E+00	1.5E+00	1.7E+00	2.7E+00	2.9E+00
14	2.6E+00	7.4E+00	1.6E+00	1.7E+00	2.7E+00	2.9E+00
30	3.1E+00	9.1E+00	1.6E+00	1.7E+00	2.8E+00	2.9E+00
60	4.5E+00	1.3E+01	1.6E+00	1.9E+00	2.9E+00	3.2E+00
90	6.5E+00	1.9E+01	1.7E+00	1.9E+00	2.9E+00	3.2E+00
180	2.1E+01	6.1E+01	1.8E+00	2.1E+00	3.1E+00	3.5E+00
365	2.3E+02	6.7E+02	2.2E+00	2.5E+00	3.6E+00	4.0E+00
730	2.9E+04	8.2E+04	3.0E+00	3.5E+00	4.6E+00	5.0E+00
1,825	2.3E+09	1.9E+09	7.6E+00	8.7E+00	7.0E+00	7.3E+00
3,600	1.1E+10	3.2E+11	2.2E+01	2.5E+01	8.3E+00	8.6E+00
7,300	1.0E+12	3.7E+12	5.1E+01	5.8E+01	9.1E+00	9.5E+00
18,250	2.2E+12	6.7E+14	5.6E+01	6.5E+01	1.3E+01	1.4E+01

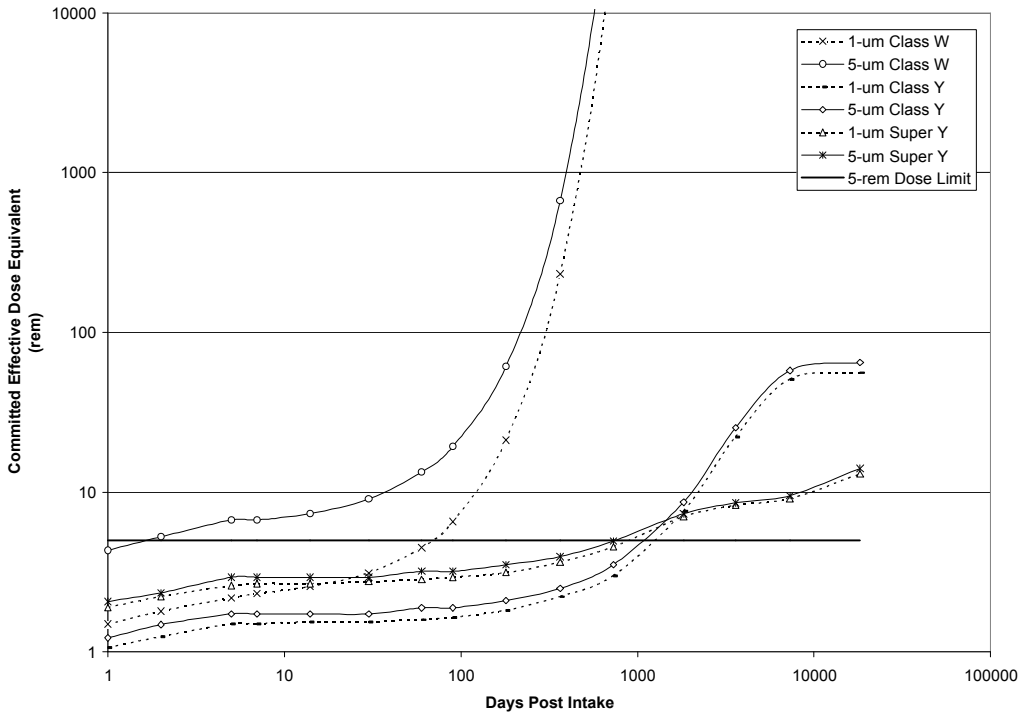

Figure 8.23. Minimum Detectable Committed Effective Doses for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.35. Minimum Detectable Committed Effective Dose Equivalent (rem) for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
Intake	1-um	5-um	1-um	5-um	1-um	5-um
0	9.3E-01	2.0E+00	6.3E-01	5.2E-01	1.2E+00	8.8E-01
1	1.5E+00	4.4E+00	9.8E-01	1.2E+00	1.8E+00	1.9E+00
2	1.7E+00	5.4E+00	1.1E+00	1.3E+00	2.1E+00	2.3E+00
5	2.1E+00	6.5E+00	1.4E+00	1.6E+00	2.5E+00	2.7E+00
7	2.2E+00	7.0E+00	1.4E+00	1.7E+00	2.6E+00	2.7E+00
14	2.4E+00	7.5E+00	1.4E+00	1.7E+00	2.6E+00	2.9E+00
30	3.0E+00	8.9E+00	1.4E+00	1.7E+00	2.6E+00	2.9E+00
60	4.3E+00	1.4E+01	1.5E+00	1.7E+00	2.7E+00	2.9E+00
90	6.4E+00	2.0E+01	1.5E+00	1.8E+00	2.8E+00	2.9E+00
180	2.0E+01	6.1E+01	1.6E+00	2.0E+00	2.9E+00	3.1E+00
365	2.1E+02	6.5E+02	1.9E+00	2.3E+00	3.2E+00	3.6E+00
730	2.4E+04	7.5E+04	2.5E+00	3.0E+00	3.9E+00	4.3E+00
1,825	6.9E+09	8.1E+09	5.5E+00	6.4E+00	5.2E+00	5.5E+00
3,600	1.2E+12	2.2E+10	1.4E+01	1.6E+01	5.2E+00	5.5E+00
7,300	9.0E+12	7.0E+10	2.5E+01	3.1E+01	4.7E+00	5.0E+00
18,250	1.4E+14	1.6E+13	2.4E+01	2.9E+01	5.7E+00	6.2E+00

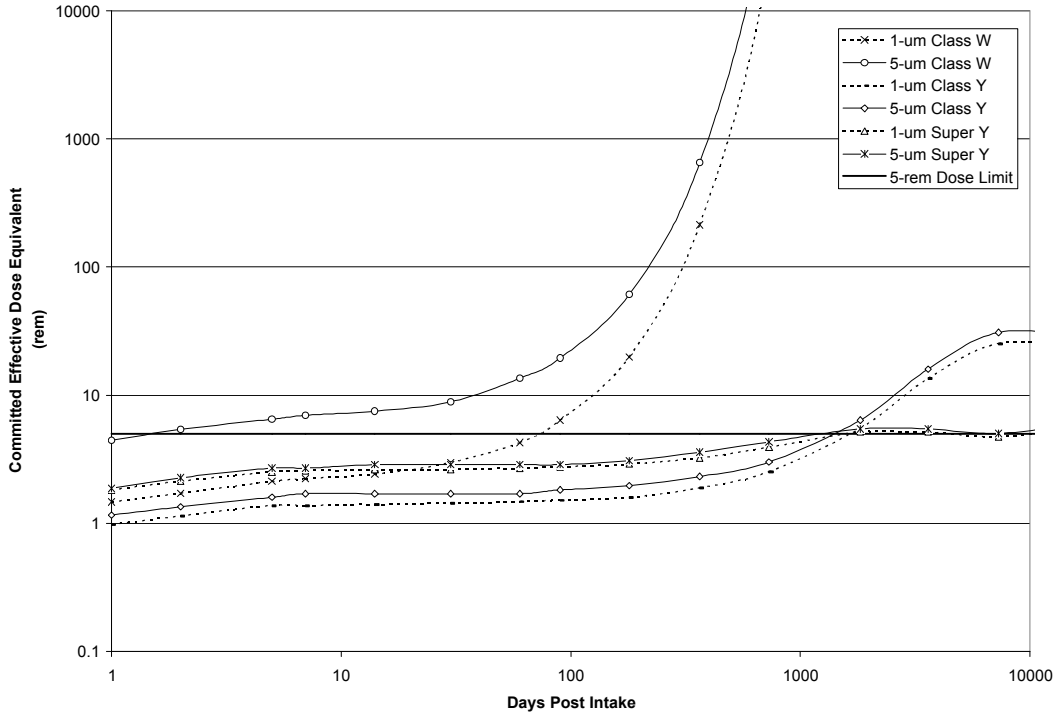

Figure 8.24. Minimum Detectable Committed Effective Doses for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.36. Minimum Detectable Committed Effective Dose Equivalent (rem) for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
Intake	1-um	5-um	1-um	5-um	1-um	5-um
0	6.2E-01	1.3E+00	4.3E-01	3.6E-01	7.9E-01	5.7E-01
1	9.5E-01	2.9E+00	6.6E-01	7.7E-01	1.2E+00	1.2E+00
2	1.1E+00	3.5E+00	7.8E-01	9.6E-01	1.4E+00	1.5E+00
5	1.4E+00	4.4E+00	9.2E-01	1.1E+00	1.7E+00	1.7E+00
7	1.5E+00	4.6E+00	9.3E-01	1.1E+00	1.7E+00	1.8E+00
14	1.6E+00	4.9E+00	9.5E-01	1.1E+00	1.7E+00	1.8E+00
30	2.0E+00	6.3E+00	9.7E-01	1.2E+00	1.7E+00	1.8E+00
60	2.9E+00	8.9E+00	1.0E+00	1.2E+00	1.8E+00	1.9E+00
90	4.2E+00	1.3E+01	1.0E+00	1.3E+00	1.8E+00	1.9E+00
180	1.3E+01	4.2E+01	1.1E+00	1.3E+00	2.0E+00	2.1E+00
365	1.5E+02	4.4E+02	1.3E+00	1.6E+00	2.3E+00	2.4E+00
730	1.7E+04	5.5E+04	1.8E+00	2.2E+00	2.8E+00	3.0E+00
1,825	2.1E+09	4.9E+09	4.3E+00	5.2E+00	3.9E+00	4.2E+00
3,600	7.3E+09	2.6E+10	1.2E+01	1.4E+01	4.5E+00	4.6E+00
7,300	8.0E+10	3.1E+11	2.5E+01	3.0E+01	4.5E+00	4.7E+00
18,250	3.1E+12	1.4E+12	2.5E+01	3.1E+01	6.0E+00	6.3E+00

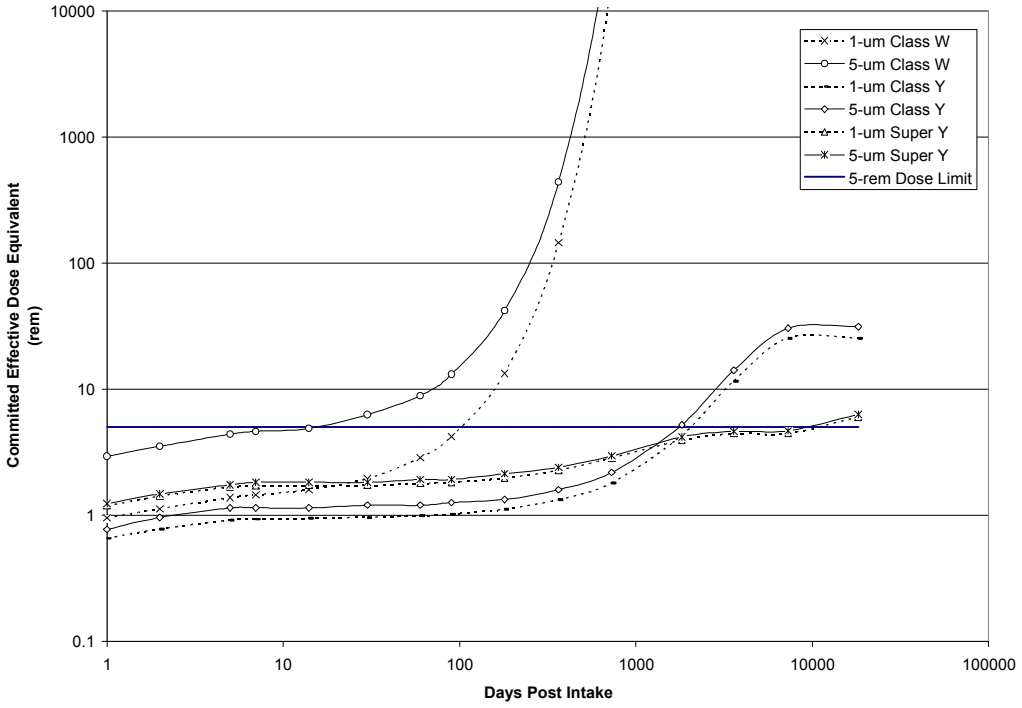

Figure 8.25. Minimum Detectable Committed Effective Doses for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.37. Minimum Detectable Committed Effective Dose Equivalent (rem) for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
Intake	1-um	5-um	1-um	5-um	1-um	5-um
0	4.6E-01	1.0E+00	3.3E-01	2.8E-01	5.9E-01	4.4E-01
1	7.4E-01	2.2E+00	5.3E-01	6.1E-01	9.4E-01	9.5E-01
2	8.7E-01	2.7E+00	6.1E-01	7.5E-01	1.1E+00	1.1E+00
5	1.1E+00	3.3E+00	7.2E-01	8.6E-01	1.3E+00	1.4E+00
7	1.1E+00	3.5E+00	7.3E-01	9.0E-01	1.3E+00	1.4E+00
14	1.2E+00	3.8E+00	7.4E-01	9.0E-01	1.3E+00	1.4E+00
30	1.5E+00	4.7E+00	7.5E-01	9.3E-01	1.3E+00	1.4E+00
60	2.3E+00	6.7E+00	7.9E-01	9.3E-01	1.4E+00	1.5E+00
90	3.2E+00	1.0E+01	8.1E-01	9.7E-01	1.4E+00	1.5E+00
180	1.0E+01	3.2E+01	8.8E-01	1.1E+00	1.5E+00	1.6E+00
365	1.1E+02	3.5E+02	1.1E+00	1.2E+00	1.8E+00	1.9E+00
730	1.4E+04	4.2E+04	1.5E+00	1.9E+00	2.2E+00	2.3E+00
1,825	6.1E+09	1.8E+10	3.8E+00	4.5E+00	3.4E+00	3.5E+00
3,600	9.7E+09	3.6E+11	1.1E+01	1.3E+01	3.9E+00	4.1E+00
7,300	3.9E+10	1.7E+13	2.4E+01	2.9E+01	4.3E+00	4.5E+00
18,250	4.6E+11	5.0E+14	2.8E+01	3.3E+01	6.3E+00	6.6E+00

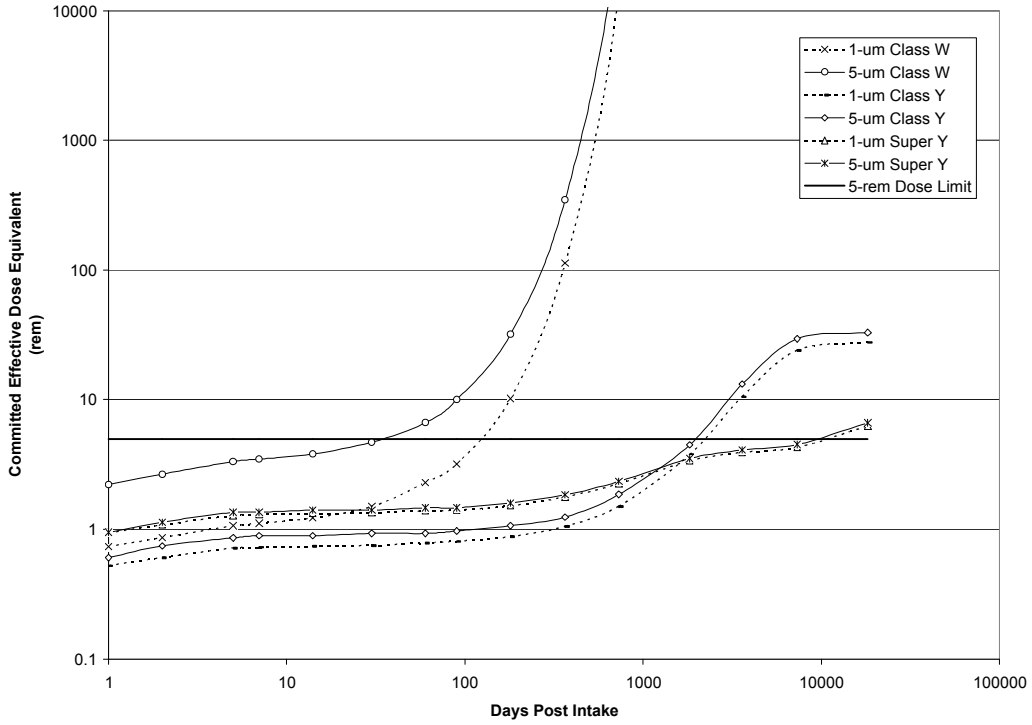

Figure 8.26. Minimum Detectable Committed Effective Doses for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.38. Minimum Detectable Committed Bone Surface Doses for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post Intake	Class W Inhalation		Class Y Inhalation	
	1-mm	5-mm	1-mm	5-mm
0	3.7E+01	8.2E+01	1.4E+01	1.5E+01
1	5.6E+01	1.8E+02	2.2E+01	3.2E+01
2	6.7E+01	2.1E+02	2.6E+01	3.9E+01
5	8.3E+01	2.6E+02	3.0E+01	4.6E+01
7	8.8E+01	2.7E+02	3.2E+01	4.7E+01
14	9.4E+01	3.0E+02	3.2E+01	4.7E+01
30	1.2E+02	3.7E+02	3.2E+01	4.8E+01
60	1.7E+02	5.4E+02	3.2E+01	5.0E+01
90	2.5E+02	7.8E+02	3.4E+01	5.1E+01
180	7.8E+02	2.5E+03	3.6E+01	5.4E+01
365	8.3E+03	2.6E+04	4.2E+01	6.4E+01
730	9.4E+05	3.0E+06	5.6E+01	8.5E+01
1,825	1.5E+11	4.1E+11	1.2E+02	1.8E+02
3,600	3.4E+11	2.2E+13	3.0E+02	4.5E+02
7,300	3.6E+12	4.9E+12	5.7E+02	8.7E+02
18,250	9.4E+13	2.0E+13	5.4E+02	8.0E+02
NA = not applicable				

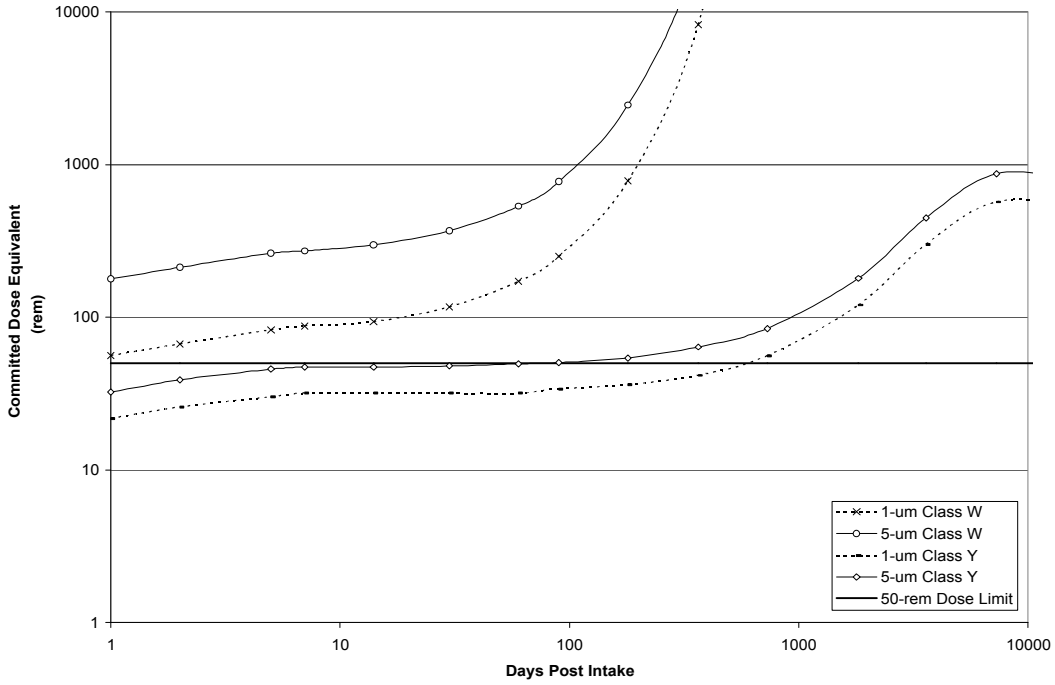

Figure 8.27. Minimum Detectable Bone Surface Doses for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.39. Minimum Detectable Committed Bone Surface Doses for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post Intake	Class W Inhalation		Class Y Inhalation	
	1-mm	5-mm	1-mm	5-mm
0	2.3E+01	5.1E+01	9.1E+00	9.4E+00
1	3.7E+01	1.1E+02	1.4E+01	2.1E+01
2	4.4E+01	1.4E+02	1.7E+01	2.5E+01
5	5.4E+01	1.7E+02	2.0E+01	2.9E+01
7	5.7E+01	1.8E+02	2.0E+01	3.0E+01
14	6.2E+01	1.9E+02	2.0E+01	3.0E+01
30	7.6E+01	2.4E+02	2.0E+01	3.0E+01
60	1.1E+02	3.5E+02	2.1E+01	3.1E+01
90	1.6E+02	5.0E+02	2.2E+01	3.2E+01
180	5.0E+02	1.6E+03	2.4E+01	3.5E+01
365	5.7E+02	1.7E+04	2.8E+01	4.1E+01
730	6.5E+05	2.1E+06	4.1E+01	5.8E+01
1,825	3.2E+11	5.5E+09	9.3E+01	1.4E+02
3,600	8.0E+12	8.8E+10	2.5E+02	3.7E+02
7,300	1.1E+14	5.1E+12	5.3E+02	7.8E+02
18,250	1.9E+14	4.1E+14	5.5E+02	7.8E+02
NA = not applicable				

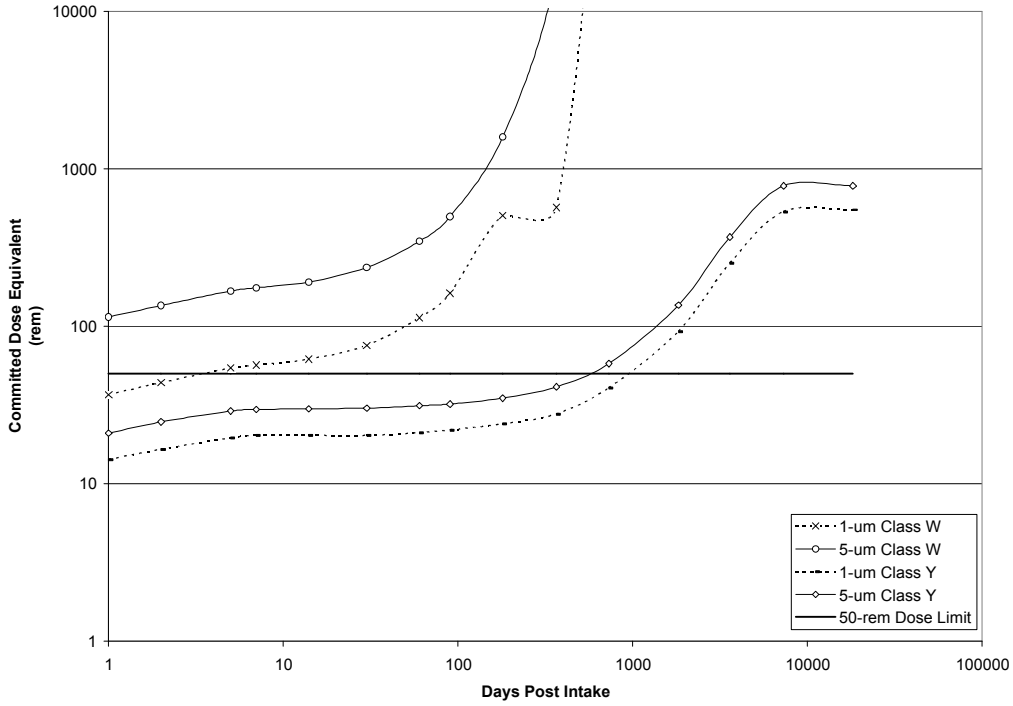

Figure 8.28. Minimum Detectable Bone Surface Doses for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.40. Minimum Detectable Committed Bone Surface Doses for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post Intake	Class W Inhalation		Class Y Inhalation	
	1-mm	5-mm	1-mm	5-mm
0	1.8E+01	3.8E+01	6.9E+00	6.7E+00
1	2.7E+01	8.5E+01	1.1E+01	1.5E+01
2	3.3E+01	1.0E+02	1.2E+01	1.8E+01
5	4.0E+01	1.3E+02	1.5E+01	2.1E+01
7	4.2E+01	1.3E+02	1.5E+01	2.1E+01
14	4.7E+01	1.4E+02	1.6E+01	2.1E+01
30	5.7E+01	1.8E+02	1.6E+01	2.1E+01
60	8.2E+01	2.6E+02	1.6E+01	2.3E+01
90	1.2E+02	3.8E+02	1.7E+01	2.3E+01
180	3.9E+02	1.2E+03	1.8E+01	2.6E+01
365	4.2E+03	1.3E+04	2.2E+01	3.1E+01
730	5.2E+05	1.6E+06	3.0E+01	4.3E+01
1,825	4.2E+10	3.7E+10	7.6E+01	1.1E+02
3,600	2.0E+11	6.3E+12	2.2E+02	3.1E+02
7,300	1.8E+13	7.2E+13	5.1E+02	7.1E+02
18,250	4.0E+13	1.3E+16	5.6E+02	8.0E+02
NA = not applicable				

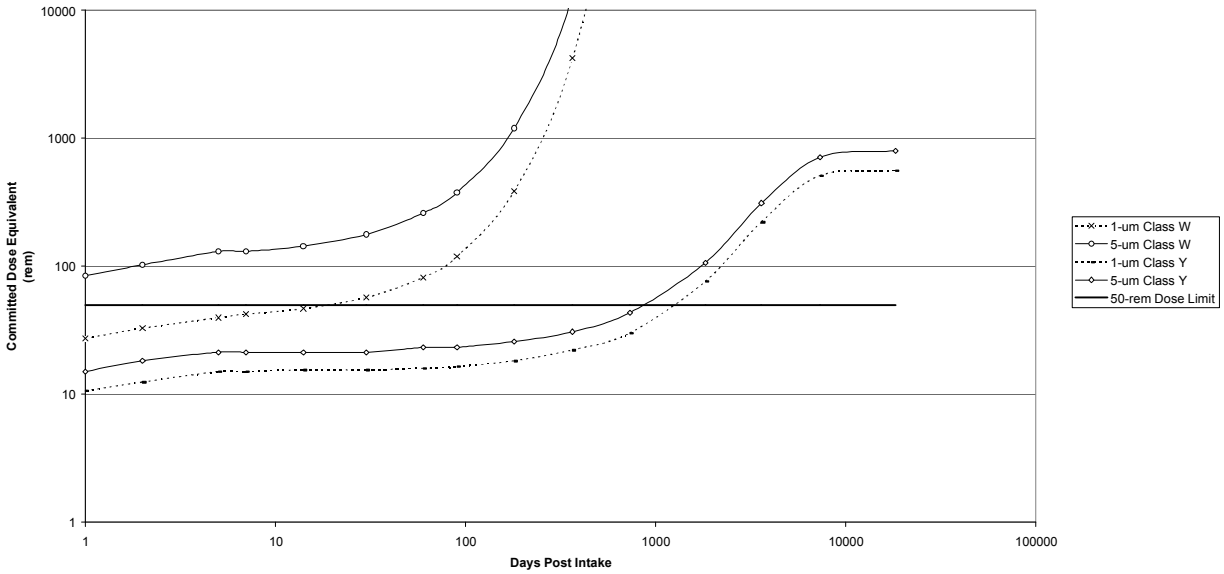

Figure 8.29. Minimum Detectable Bone Surface Doses for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.41. Minimum Detectable Committed Bone Surface Dose Equivalent (rem) for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post Intake	Class W Inhalation		Class Y Inhalation	
	1-mm	5-mm	1-mm	5-mm
0	1.7E+01	3.6E+01	6.7E+00	6.5E+00
1	2.6E+01	8.0E+01	1.0E+01	1.5E+01
2	3.1E+01	9.8E+01	1.2E+01	1.7E+01
5	3.8E+01	1.2E+02	1.5E+01	2.0E+01
7	4.0E+01	1.3E+02	1.5E+01	2.1E+01
14	4.3E+01	1.4E+02	1.5E+01	2.1E+01
30	5.3E+01	1.6E+02	1.5E+01	2.1E+01
60	7.6E+01	2.4E+02	1.6E+01	2.1E+01
90	1.1E+02	3.5E+02	1.6E+01	2.3E+01
180	3.6E+02	1.1E+03	1.7E+01	2.5E+01
365	3.8E+03	1.2E+04	2.0E+01	2.9E+01
730	4.3E+05	1.4E+06	2.7E+01	3.8E+01
1,825	1.2E+11	1.5E+11	5.8E+01	8.0E+01
3,600	2.2E+13	4.0E+11	1.4E+02	2.0E+02
7,300	1.6E+14	1.3E+12	2.7E+02	3.9E+02
18,250	2.6E+15	2.9E+14	2.6E+02	3.6E+02
NA = not applicable				

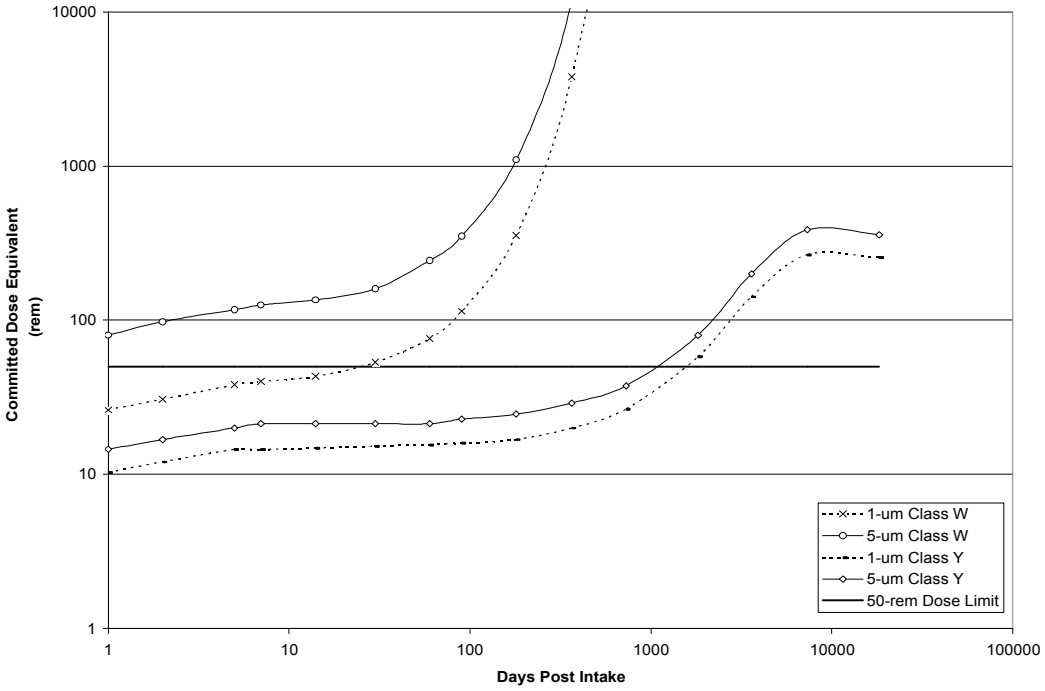

Figure 8.30. Minimum Detectable Bone Surface Doses for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.42. Minimum Detectable Committed Bone Surface Dose Equivalent (rem) for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post Intake	Class W Inhalation		Class Y Inhalation	
	1-mm	5-mm	1-mm	5-mm
0	1.1E+01	2.4E+01	4.4E+00	4.3E+00
1	1.8E+01	5.3E+01	6.8E+00	9.3E+00
2	2.1E+01	6.4E+01	8.0E+00	1.2E+01
5	2.5E+01	8.0E+01	9.4E+00	1.4E+01
7	2.7E+01	8.4E+01	9.6E+00	1.4E+01
14	2.9E+01	8.9E+01	9.8E+00	1.4E+01
30	3.6E+01	1.1E+02	9.9E+00	1.4E+01
60	5.3E+01	1.6E+02	1.0E+01	1.4E+01
90	7.7E+01	2.4E+02	1.0E+01	1.5E+01
180	2.5E+02	7.6E+02	1.2E+01	1.6E+01
365	2.7E+03	8.0E+03	1.4E+01	1.9E+01
730	3.1E+05	1.0E+06	1.9E+01	2.6E+01
1,825	3.9E+10	8.9E+10	4.4E+01	6.3E+01
3,600	1.3E+11	4.7E+11	1.2E+02	1.7E+02
7,300	1.5E+12	5.7E+12	2.6E+02	3.6E+02
18,250	5.7E+13	2.6E+13	2.6E+02	3.7E+02
NA = not applicable				

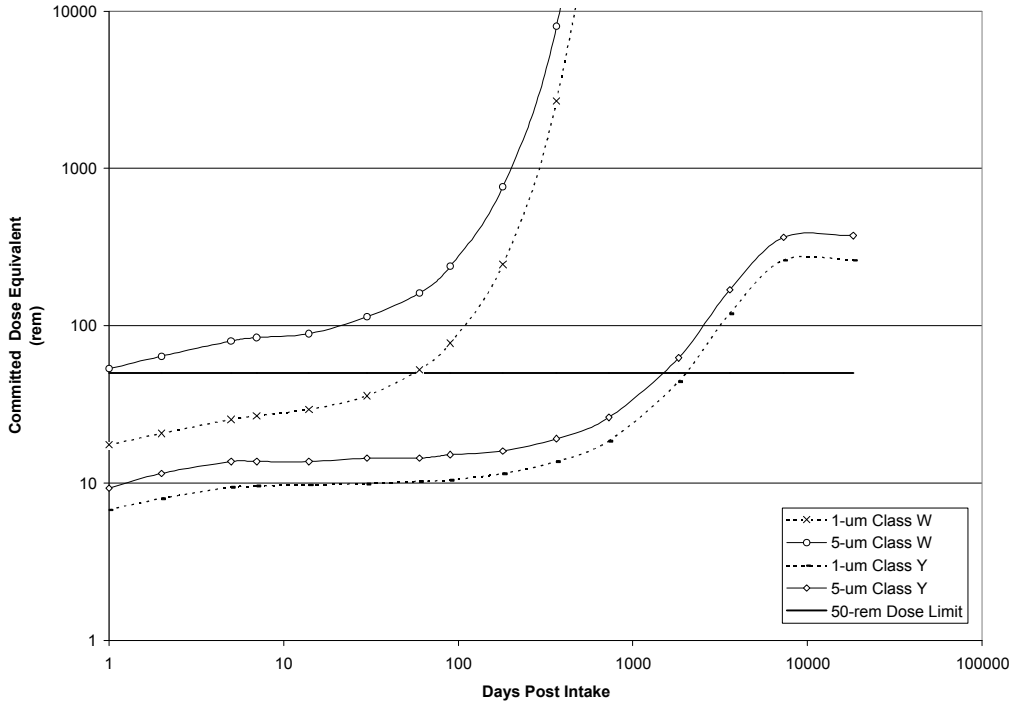

Figure 8.31. Minimum Detectable Bone Surface Doses for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.43. Minimum Detectable Committed Bone Surface Dose Equivalent (rem) for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Days Post Intake	Class W Inhalation		Class Y Inhalation	
	1-mm	5-mm	1-mm	5-mm
0	8.4E+00	1.8E+01	3.2E+00	3.4E+00
1	1.3E+01	4.1E+01	5.1E+00	7.4E+00
2	1.6E+01	4.9E+01	5.9E+00	9.1E+00
5	1.9E+01	6.1E+01	7.0E+00	1.0E+01
7	2.0E+01	6.4E+01	7.1E+00	1.1E+01
14	2.2E+01	7.0E+01	7.2E+00	1.1E+01
30	2.7E+01	8.7E+01	7.3E+00	1.1E+01
60	4.1E+01	1.2E+02	7.6E+00	1.1E+01
90	5.8E+01	1.8E+02	7.9E+00	1.2E+01
180	1.9E+02	5.9E+02	8.5E+00	1.3E+01
365	2.1E+03	6.4E+03	1.0E+01	1.5E+01
730	2.5E+05	7.7E+05	1.5E+01	2.3E+01
1,825	1.1E+11	3.3E+11	3.7E+01	5.4E+01
3,600	1.8E+11	6.7E+12	1.0E+02	1.6E+02
7,300	7.1E+11	3.1E+14	2.3E+02	3.6E+02
18,250	8.4E+12	9.2E+15	2.7E+02	4.0E+02
NA = not applicable				

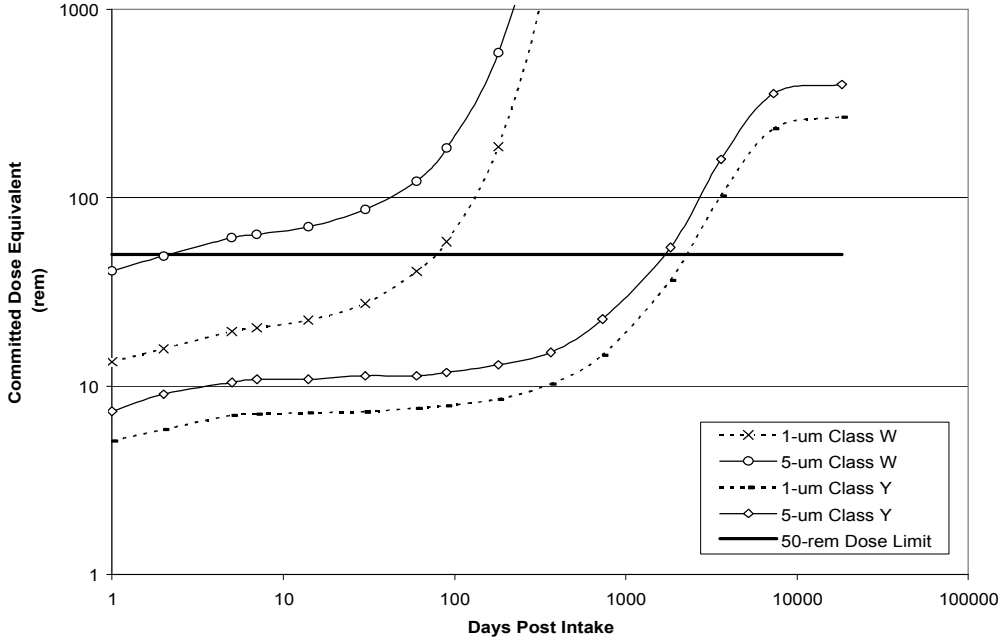

Figure 8.32. Minimum Detectable Bone Surface Doses for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.16 nCi ^{241}Am in the Lungs

Table 8.44. Minimum Detectable Intakes (nCi) of ^{239}Pu Based on Detection of 0.2 dpm/d in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	3.0E-02	8.2E-04	4.1E-04	6.9E-04	3.6E-04	6.9E-04	3.6E-04
2	4.7E-02	6.9E-04	3.5E-04	5.6E-04	3.1E-04	5.6E-04	3.1E-04
5	1.6E-01	3.9E-03	2.9E-03	3.8E-03	2.6E-03	3.8E-03	2.6E-03
7	2.4E-01	1.4E-02	1.6E-02	1.7E-02	1.6E-02	1.7E-02	1.6E-02
14	3.9E-01	7.5E-02	2.0E-01	5.3E-01	1.4E+00	5.3E-01	1.4E+00
30	6.0E-01	9.4E-02	2.6E-01	6.9E-01	1.9E+00	6.9E-01	1.9E+00
60	9.1E-01	1.4E-01	3.9E-01	6.9E-01	2.0E+00	6.9E-01	2.0E+00
90	1.1E+00	2.1E-01	5.6E-01	7.5E-01	2.0E+00	7.5E-01	2.1E+00
180	1.6E+00	6.9E-01	1.8E+00	8.2E-01	2.3E+00	8.2E-01	2.4E+00
365	2.6E+00	1.9E+01	1.1E+01	1.1E+00	3.0E+00	1.1E+00	3.0E+00
730	4.7E+00	3.6E+01	3.5E+01	1.8E+00	5.0E+00	1.8E+00	5.0E+00
1,825	6.4E+00	5.6E+01	5.0E+01	7.5E+00	2.1E+01	8.2E+00	2.3E+01
3,600	6.9E+00	6.0E+01	5.3E+01	5.6E+01	1.4E+02	9.1E+01	2.4E+02
7,300	7.5E+00	6.0E+01	6.0E+01	1.5E+02	3.0E+02	5.0E+02	8.2E+02
18,250	1.1E+01	9.0E+01	8.2E+01	2.0E+02	4.3E+02	2.9E+02	5.6E+02

Table 8.45. Minimum Detectable Committed Effective Dose Equivalent (rem) for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	1.5E-01	4.9E-04	2.6E-04	3.0E-04	6.3E-05	5.3E-04	1.0E-04
2	2.4E-01	4.2E-04	2.2E-04	2.4E-04	5.5E-05	4.3E-04	9.0E-05
5	7.8E-01	2.4E-03	1.8E-03	1.6E-03	4.7E-04	2.9E-03	7.7E-04
7	1.2E+00	8.6E-03	1.0E-02	7.1E-03	2.8E-03	1.3E-02	4.6E-03
14	2.0E+00	4.5E-02	1.2E-01	2.3E-01	2.4E-01	4.1E-01	4.1E-01
30	3.0E+00	5.7E-02	1.6E-01	3.0E-01	3.3E-01	5.3E-01	5.5E-01
60	4.6E+00	8.6E-02	2.5E-01	3.0E-01	3.4E-01	5.3E-01	5.8E-01
90	5.7E+00	1.3E-01	3.5E-01	3.2E-01	3.6E-01	5.8E-01	6.1E-01
180	7.9E+00	4.2E-01	1.2E+00	3.5E-01	4.1E-01	6.3E-01	6.9E-01
365	1.3E+01	1.1E+01	7.0E+00	4.5E-01	5.3E-01	8.2E-01	8.7E-01
730	2.4E+01	2.2E+01	2.2E+01	7.5E-01	8.8E-01	1.4E+00	1.4E+00
1,825	3.2E+01	3.4E+01	3.1E+01	3.2E+00	3.7E+00	6.3E+00	6.5E+00
3,600	3.5E+01	3.6E+01	3.3E+01	2.4E+01	2.4E+01	7.0E+01	6.9E+01
7,300	3.8E+01	3.6E+01	3.8E+01	6.2E+01	5.3E+01	3.8E+02	2.4E+02
18,250	5.4E+01	5.4E+01	5.1E+01	8.7E+01	7.5E+01	2.2E+02	1.6E+02

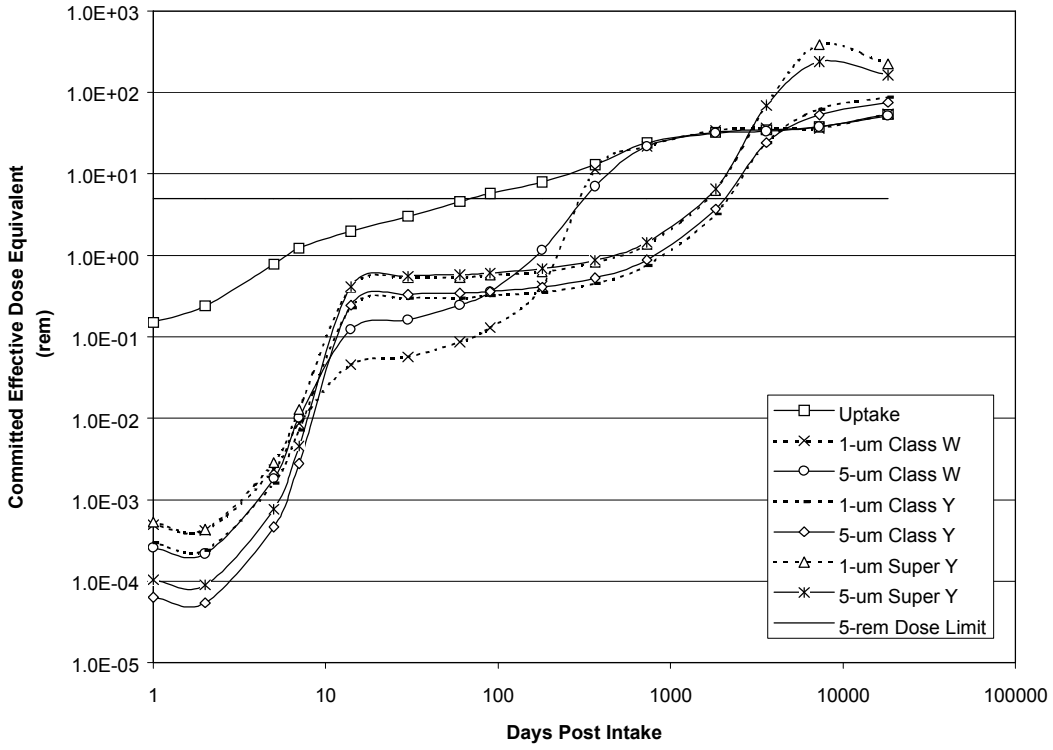

Figure 8.33. Minimum Detectable Committed Effective Doses for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Table 8.46. Minimum Detectable Committed Effective Dose Equivalent (rem) for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	1.5E-01	5.2E-04	2.6E-04	3.1E-04	6.8E-05	5.5E-04	1.1E-04
2	2.4E-01	4.4E-04	2.2E-04	2.5E-04	5.8E-05	4.5E-04	9.2E-05
5	7.9E-01	2.5E-03	1.9E-03	1.7E-03	5.0E-04	3.0E-03	7.8E-04
7	1.2E+00	9.0E-03	1.0E-02	7.4E-03	3.0E-03	1.3E-02	4.7E-03
14	2.0E+00	4.7E-02	1.3E-01	2.3E-01	2.6E-01	4.2E-01	4.2E-01
30	3.1E+00	5.9E-02	1.7E-01	3.1E-01	3.5E-01	5.5E-01	5.7E-01
60	4.6E+00	9.0E-02	2.5E-01	3.1E-01	3.7E-01	5.5E-01	5.9E-01
90	5.8E+00	1.4E-01	3.6E-01	3.3E-01	3.8E-01	5.9E-01	6.2E-01
180	8.0E+00	4.4E-01	1.2E+00	3.6E-01	4.3E-01	6.5E-01	7.0E-01
365	1.3E+01	1.2E+01	7.2E+00	4.7E-01	5.6E-01	8.5E-01	8.9E-01
730	2.4E+01	2.3E+01	2.2E+01	7.8E-01	9.4E-01	1.4E+00	1.5E+00
1,825	3.3E+01	3.5E+01	3.2E+01	3.3E+00	3.9E+00	6.5E+00	6.6E+00
3,600	3.5E+01	3.8E+01	3.4E+01	2.5E+01	2.6E+01	7.2E+01	7.0E+01
7,300	3.8E+01	3.8E+01	3.9E+01	6.4E+01	5.6E+01	4.0E+02	2.4E+02
18,250	5.5E+01	5.7E+01	5.3E+01	9.1E+01	8.0E+01	2.3E+02	1.7E+02

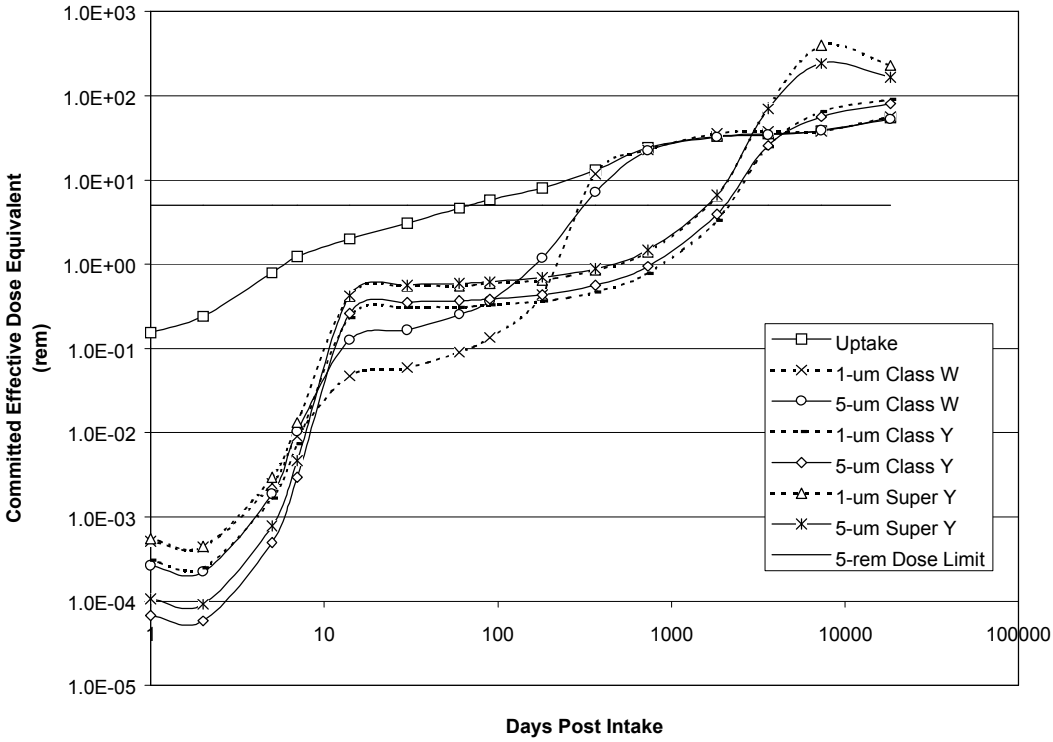

Figure 8.34. Minimum Detectable Committed Effective Doses for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Table 8.47. Minimum Detectable Committed Effective Dose Equivalent (rem) for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	1.6E-01	5.2E-04	2.6E-04	3.1E-04	6.6E-05	5.5E-04	1.1E-04
2	2.5E-01	4.4E-04	2.2E-04	2.5E-04	5.7E-05	4.5E-04	9.6E-05
5	8.0E-01	2.5E-03	1.9E-03	1.7E-03	4.8E-04	3.0E-03	8.2E-04
7	1.3E+00	9.0E-03	1.0E-02	7.5E-03	2.9E-03	1.3E-02	4.9E-03
14	2.0E+00	4.7E-02	1.3E-01	2.4E-01	2.5E-01	4.2E-01	4.4E-01
30	3.1E+00	5.9E-02	1.7E-01	3.1E-01	3.4E-01	5.5E-01	5.9E-01
60	4.7E+00	9.0E-02	2.5E-01	3.1E-01	3.6E-01	5.5E-01	6.2E-01
90	5.9E+00	1.4E-01	3.6E-01	3.4E-01	3.7E-01	6.0E-01	6.5E-01
180	8.2E+00	4.4E-01	1.2E+00	3.7E-01	4.2E-01	6.5E-01	7.3E-01
365	1.3E+01	1.2E+01	7.2E+00	4.7E-01	5.5E-01	8.6E-01	9.2E-01
730	2.5E+01	2.3E+01	2.2E+01	7.9E-01	9.1E-01	1.4E+00	1.5E+00
1,825	3.3E+01	3.5E+01	3.2E+01	3.4E+00	3.8E+00	6.5E+00	6.9E+00
3,600	3.6E+01	3.8E+01	3.4E+01	2.5E+01	2.5E+01	7.3E+01	7.3E+01
7,300	3.9E+01	3.8E+01	3.9E+01	6.5E+01	5.5E+01	4.0E+02	2.5E+02
18,250	5.6E+01	5.7E+01	5.3E+01	9.2E+01	7.8E+01	2.3E+02	1.7E+02

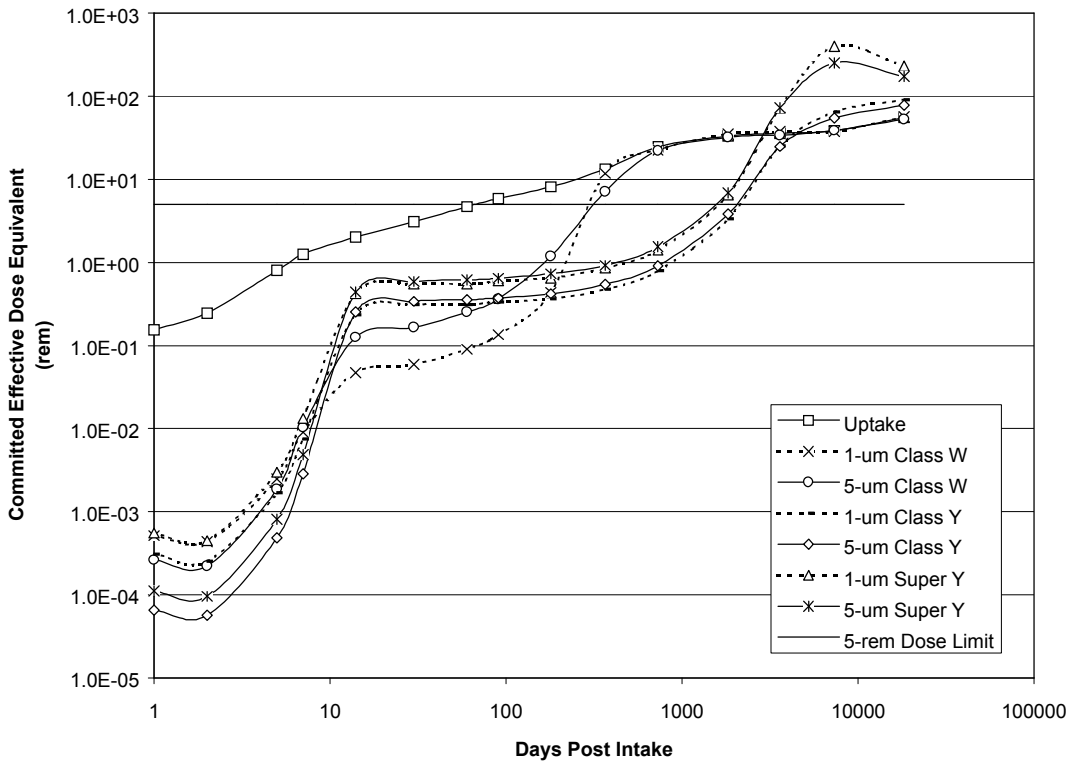

Figure 8.35. Minimum Detectable Committed Effective Doses for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Table 8.48. Minimum Detectable Committed Effective Dose Equivalent (rem) for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	2.3E-01	7.8E-04	4.2E-04	4.5E-04	9.7E-05	8.3E-04	1.6E-04
2	3.7E-01	6.6E-04	3.6E-04	3.6E-04	8.4E-05	6.8E-04	1.4E-04
5	1.2E+00	3.7E-03	3.0E-03	2.4E-03	7.2E-04	4.5E-03	1.2E-03
7	1.9E+00	1.4E-02	1.7E-02	1.1E-02	4.3E-03	2.0E-02	7.2E-03
14	3.0E+00	7.1E-02	2.0E-01	3.4E-01	3.7E-01	6.4E-01	6.5E-01
30	4.7E+00	8.9E-02	2.7E-01	4.5E-01	5.1E-01	8.3E-01	8.7E-01
60	7.1E+00	1.4E-01	4.0E-01	4.5E-01	5.3E-01	8.3E-01	9.1E-01
90	8.9E+00	2.0E-01	5.8E-01	4.8E-01	5.5E-01	9.0E-01	9.6E-01
180	1.2E+01	6.6E-01	1.9E+00	5.3E-01	6.2E-01	9.8E-01	1.1E+00
365	2.0E+01	1.8E+01	1.1E+01	6.8E-01	8.1E-01	1.3E+00	1.4E+00
730	3.7E+01	3.4E+01	3.6E+01	1.1E+00	1.4E+00	2.1E+00	2.3E+00
1,825	5.0E+01	5.3E+01	5.2E+01	4.8E+00	5.7E+00	9.8E+00	1.0E+01
3,600	5.4E+01	5.7E+01	5.5E+01	3.6E+01	3.7E+01	1.1E+02	1.1E+02
7,300	5.8E+01	5.7E+01	6.2E+01	9.3E+01	8.1E+01	6.0E+02	3.7E+02
18,250	8.3E+01	8.5E+01	8.4E+01	1.3E+02	1.2E+02	3.5E+02	2.6E+02

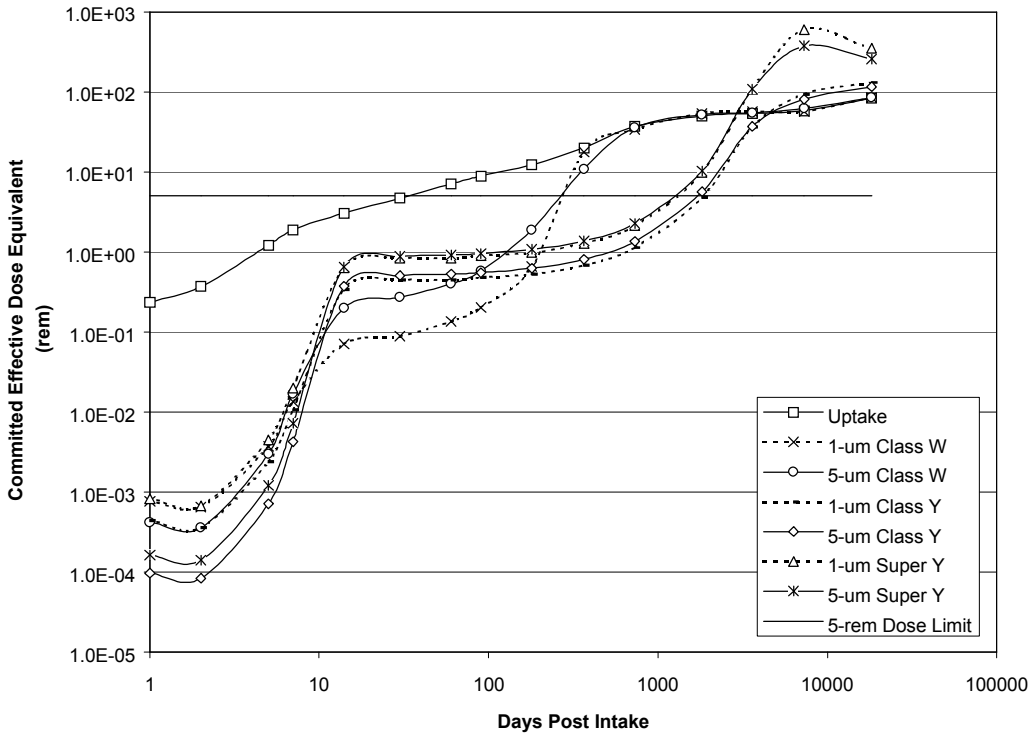

Figure 8.36. Minimum Detectable Committed Effective Doses for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Table 8.49. Minimum Detectable Committed Effective Dose Equivalent (rem) for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	2.4E-01	8.1E-04	4.4E-04	4.8E-04	1.1E-04	8.7E-04	1.7E-04
2	3.8E-01	6.8E-04	3.8E-04	3.9E-04	9.2E-05	7.1E-04	1.5E-04
5	1.3E+00	3.9E-03	3.1E-03	2.6E-03	7.8E-04	4.7E-03	1.3E-03
7	2.0E+00	1.4E-02	1.7E-02	1.2E-02	4.7E-03	2.1E-02	7.5E-03
14	3.2E+00	7.4E-02	2.1E-01	3.7E-01	4.1E-01	6.7E-01	6.8E-01
30	4.9E+00	9.2E-02	2.8E-01	4.8E-01	5.5E-01	8.7E-01	9.1E-01
60	7.4E+00	1.4E-01	4.2E-01	4.8E-01	5.8E-01	8.7E-01	9.5E-01
90	9.2E+00	2.1E-01	6.1E-01	5.2E-01	6.1E-01	9.5E-01	9.9E-01
180	1.3E+01	6.8E-01	2.0E+00	5.6E-01	6.8E-01	1.0E+00	1.1E+00
365	2.1E+01	1.8E+01	1.2E+01	7.3E-01	8.9E-01	1.4E+00	1.4E+00
730	3.8E+01	3.5E+01	3.8E+01	1.2E+00	1.5E+00	2.2E+00	2.4E+00
1,825	5.2E+01	5.5E+01	5.4E+01	5.2E+00	6.2E+00	1.0E+01	1.1E+01
3,600	5.6E+01	5.9E+01	5.7E+01	3.9E+01	4.0E+01	1.1E+02	1.1E+02
7,300	6.1E+01	5.9E+01	6.5E+01	1.0E+02	8.9E+01	6.3E+02	3.9E+02
18,250	8.7E+01	8.9E+01	8.9E+01	1.4E+02	1.3E+02	3.7E+02	2.7E+02

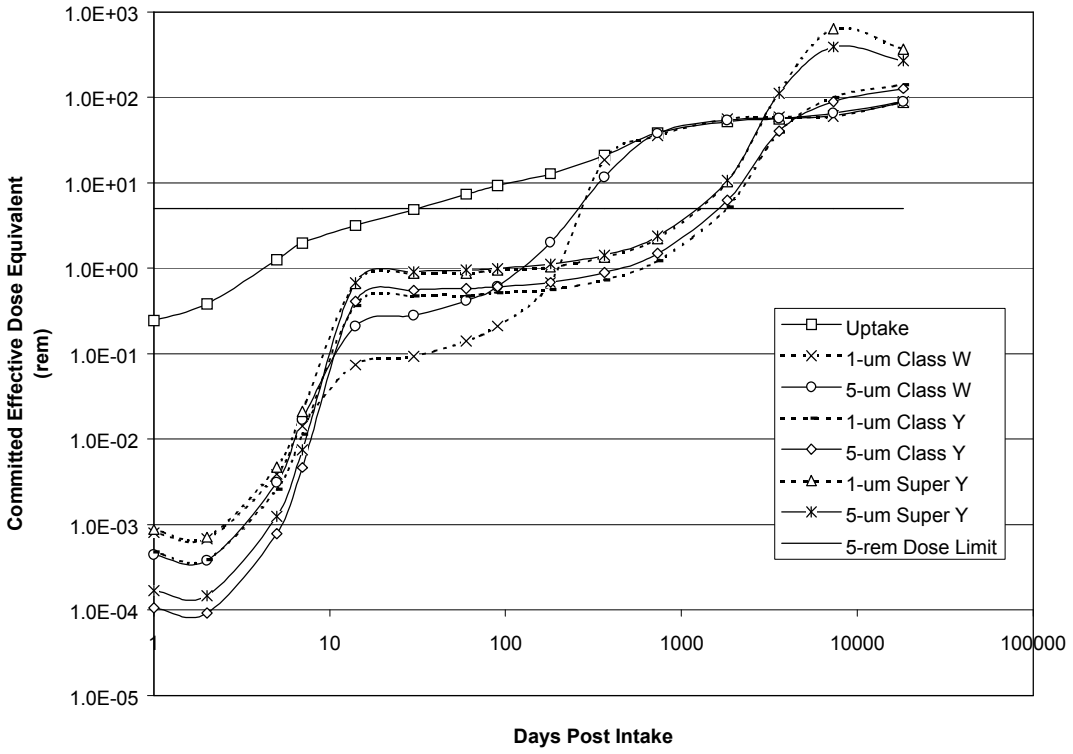

Figure 8.37. Minimum Detectable Committed Effective Doses for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Table 8.50. Minimum Detectable Committed Effective Dose Equivalent (rem) for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation		Super Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm	1-mm	5-mm
1	2.5E-01	8.3E-04	4.5E-04	5.1E-04	1.1E-04	9.0E-04	1.8E-04
2	4.0E-01	7.0E-04	3.8E-04	4.1E-04	9.6E-05	7.3E-04	1.5E-04
5	1.3E+00	4.0E-03	3.2E-03	2.7E-03	8.2E-04	4.9E-03	1.3E-03
7	2.0E+00	1.5E-02	1.8E-02	1.2E-02	4.9E-03	2.2E-02	7.7E-03
14	3.3E+00	7.6E-02	2.2E-01	3.9E-01	4.3E-01	6.9E-01	7.0E-01
30	5.0E+00	9.5E-02	2.8E-01	5.1E-01	5.8E-01	9.0E-01	9.3E-01
60	7.6E+00	1.5E-01	4.3E-01	5.1E-01	6.1E-01	9.0E-01	9.7E-01
90	9.6E+00	2.2E-01	6.2E-01	5.5E-01	6.3E-01	9.8E-01	1.0E+00
180	1.3E+01	7.0E-01	2.0E+00	6.0E-01	7.1E-01	1.1E+00	1.2E+00
365	2.2E+01	1.9E+01	1.2E+01	7.7E-01	9.3E-01	1.4E+00	1.5E+00
730	4.0E+01	3.7E+01	3.8E+01	1.3E+00	1.5E+00	2.3E+00	2.4E+00
1,825	5.4E+01	5.7E+01	5.5E+01	5.5E+00	6.5E+00	1.1E+01	1.1E+01
3,600	5.8E+01	6.1E+01	5.9E+01	4.1E+01	4.2E+01	1.2E+02	1.2E+02
7,300	6.3E+01	6.1E+01	6.6E+01	1.1E+02	9.3E+01	6.5E+02	4.0E+02
18,250	9.0E+01	9.2E+01	9.0E+01	1.5E+02	1.3E+02	3.8E+02	2.7E+02

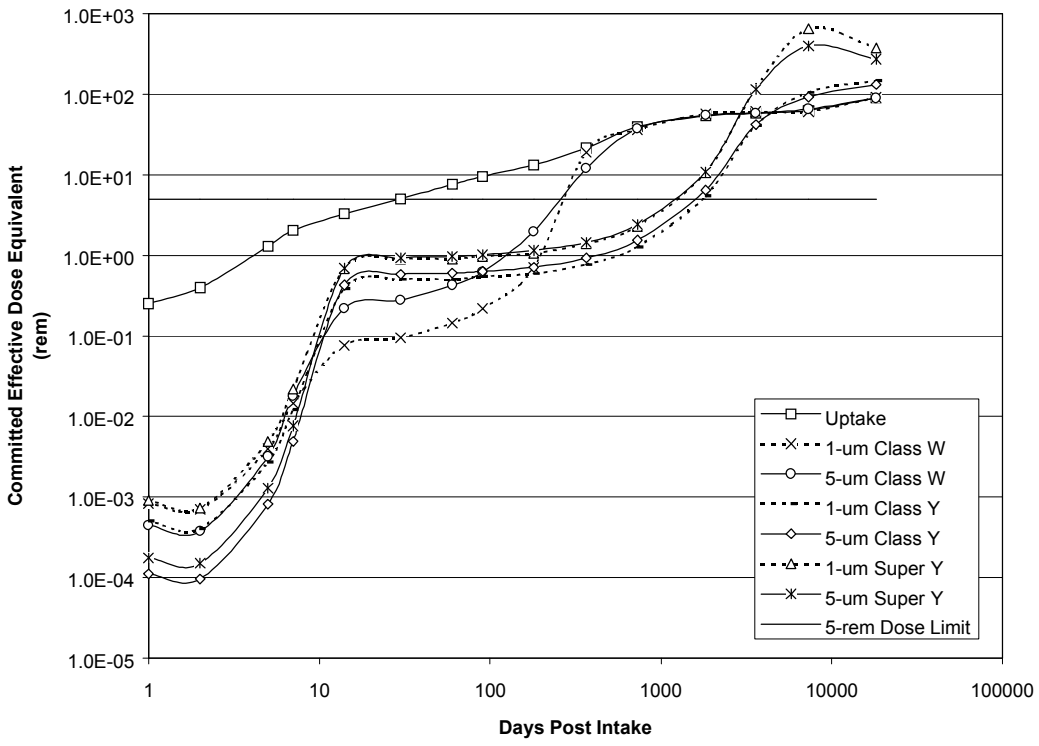

Figure 8.38. Minimum Detectable Committed Effective Doses for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Table 8.51. Minimum Detectable Committed Bone Surface Dose Equivalent (rem) for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	2.8E+00	9.1E-03	5.0E-03	3.0E-03	8.2E-04
2	4.4E+00	7.7E-03	4.2E-03	2.4E-03	7.0E-04
5	1.4E+01	4.3E-02	3.5E-02	1.6E-02	6.0E-03
7	2.3E+01	1.6E-01	2.0E-01	7.1E-02	3.6E-02
14	3.6E+01	8.3E-01	2.4E+00	2.3E+00	3.1E+00
30	5.6E+01	1.0E+00	3.1E+00	3.0E+00	4.2E+00
60	8.5E+01	1.6E+00	4.8E+00	3.0E+00	4.4E+00
90	1.1E+02	2.4E+00	6.9E+00	3.2E+00	4.6E+00
180	1.5E+02	7.7E+00	2.2E+01	3.5E+00	5.2E+00
365	2.4E+02	2.1E+02	1.4E+02	4.5E+00	6.8E+00
730	4.4E+02	4.0E+02	4.2E+02	7.5E+00	1.1E+01
1,825	6.0E+02	6.2E+02	6.1E+02	3.2E+01	4.7E+01
3,600	6.4E+02	6.6E+02	6.5E+02	2.4E+02	3.1E+02
7,300	7.0E+02	6.6E+02	7.3E+02	6.2E+02	6.8E+02
18,250	1.0E+03	1.0E+03	1.0E+03	8.7E+02	9.7E+02

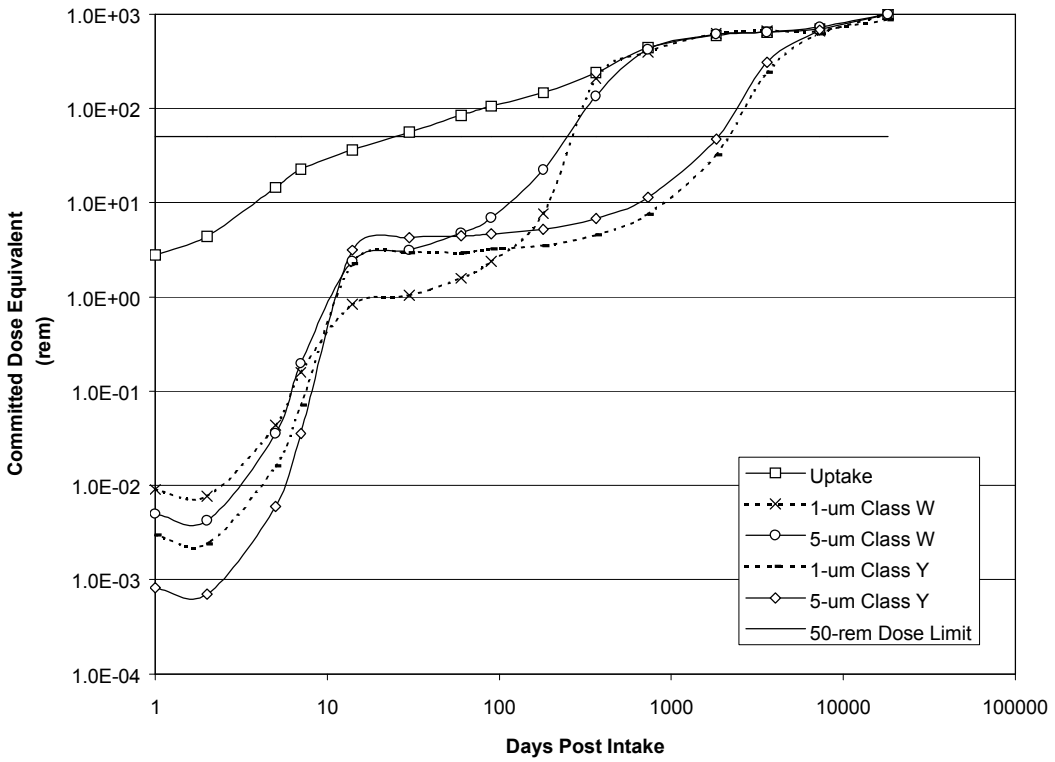

Figure 8.39. Minimum Detectable Bone Surface Doses for 10-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Table 8.52. Minimum Detectable Committed Bone Surface Dose Equivalent (rem) for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	2.9E+00	9.3E-03	5.1E-03	3.1E-03	8.2E-04
2	4.5E+00	7.9E-03	4.3E-03	2.5E-03	7.1E-04
5	1.5E+01	4.5E-02	3.6E-02	1.7E-02	6.0E-03
7	2.3E+01	1.6E-01	2.0E-01	7.4E-02	3.6E-02
14	3.7E+01	8.6E-01	2.4E+00	2.3E+00	3.2E+00
30	5.7E+01	1.1E+00	3.2E+00	3.1E+00	4.3E+00
60	8.7E+01	1.6E+00	4.9E+00	3.1E+00	4.5E+00
90	1.1E+02	2.4E+00	7.0E+00	3.3E+00	4.7E+00
180	1.5E+02	7.9E+00	2.3E+01	3.6E+00	5.3E+00
365	2.4E+02	2.1E+02	1.4E+02	4.7E+00	6.8E+00
730	4.5E+02	4.1E+02	4.3E+02	7.8E+00	1.1E+01
1,825	6.1E+02	6.4E+02	6.2E+02	3.3E+01	4.8E+01
3,600	6.6E+02	6.8E+02	6.6E+02	2.5E+02	3.1E+02
7,300	7.1E+02	6.8E+02	7.5E+02	6.4E+02	6.8E+02
18,250	1.0E+03	1.0E+03	1.0E+03	9.1E+02	9.8E+02

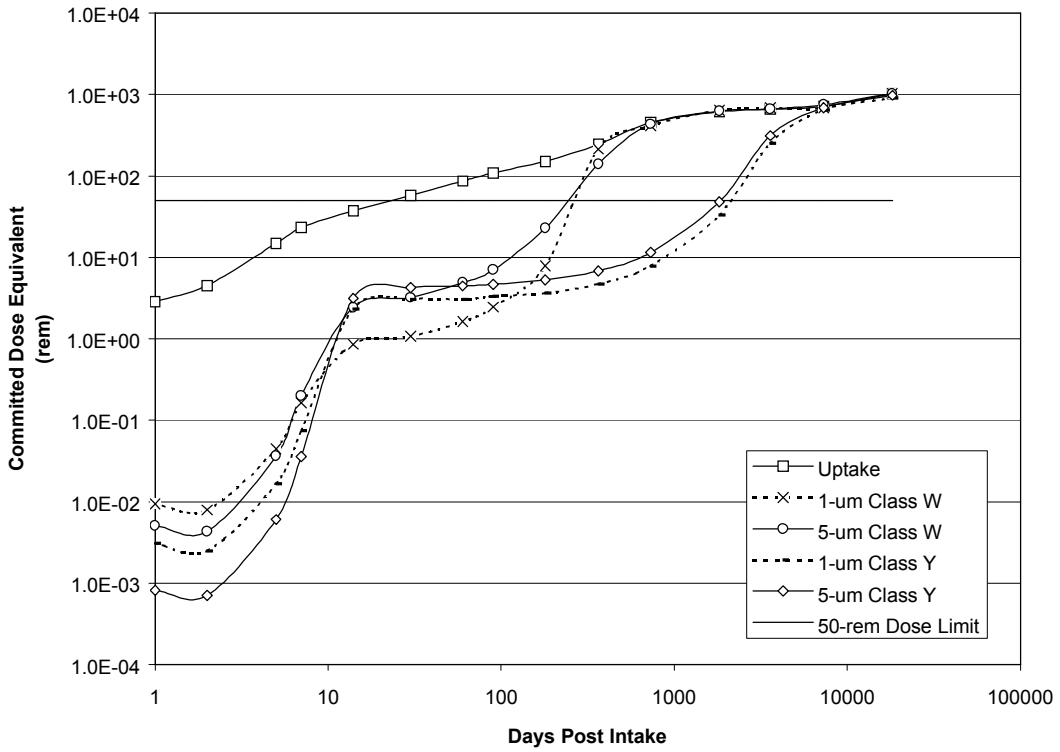

Figure 8.40. Minimum Detectable Bone Surface Doses for 20-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Table 8.53. Minimum Detectable Committed Bone Surface Dose Equivalent (rem) for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	2.9E+00	9.4E-03	5.2E-03	3.1E-03	8.1E-04
2	4.5E+00	8.0E-03	4.4E-03	2.5E-03	7.0E-04
5	1.5E+01	4.5E-02	3.7E-02	1.7E-02	5.9E-03
7	2.3E+01	1.6E-01	2.0E-01	7.5E-02	3.5E-02
14	3.7E+01	8.6E-01	2.5E+00	2.4E+00	3.1E+00
30	5.7E+01	1.1E+00	3.2E+00	3.1E+00	4.2E+00
60	8.7E+01	1.6E+00	4.9E+00	3.1E+00	4.4E+00
90	1.1E+02	2.5E+00	7.1E+00	3.4E+00	4.6E+00
180	1.5E+02	8.0E+00	2.3E+01	3.7E+00	5.2E+00
365	2.5E+02	2.2E+02	1.4E+02	4.7E+00	6.7E+00
730	4.5E+02	4.1E+02	4.4E+02	7.9E+00	1.1E+01
1,825	6.1E+02	6.5E+02	6.3E+02	3.4E+01	4.7E+01
3,600	6.6E+02	6.9E+02	6.7E+02	2.5E+02	3.1E+02
7,300	7.1E+02	6.9E+02	7.6E+02	6.5E+02	6.7E+02
18,250	1.0E+03	1.0E+03	1.0E+03	9.2E+02	9.6E+02

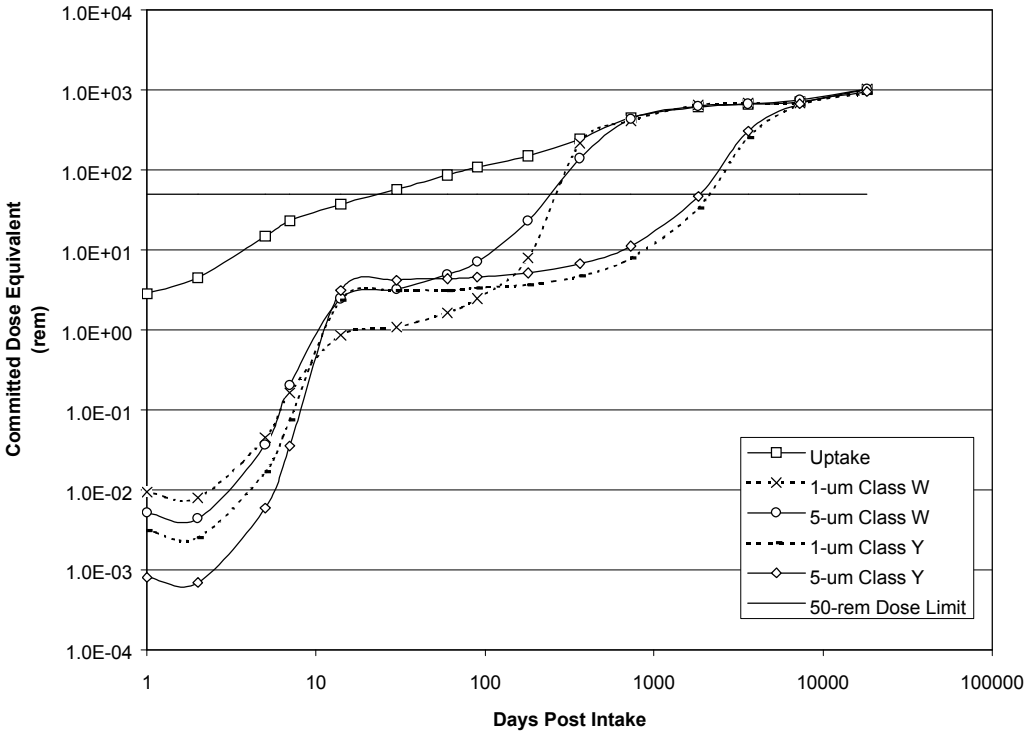

Figure 8.41. Minimum Detectable Bone Surface Doses for 40-Year Aged Weapons-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Table 8.54. Minimum Detectable Committed Bone Surface Dose Equivalent (rem) for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	4.3E+00	1.4E-02	7.6E-03	4.7E-03	1.2E-03
2	6.8E+00	1.2E-02	6.4E-03	3.8E-03	1.1E-03
5	2.2E+01	6.6E-02	5.4E-02	2.5E-02	9.0E-03
7	3.5E+01	2.4E-01	3.0E-01	1.1E-01	5.3E-02
14	5.6E+01	1.3E+00	3.6E+00	3.6E+00	4.7E+00
30	8.6E+01	1.6E+00	4.8E+00	4.7E+00	6.3E+00
60	1.3E+02	2.4E+00	7.3E+00	4.7E+00	6.6E+00
90	1.6E+02	3.6E+00	1.0E+01	5.1E+00	6.9E+00
180	2.3E+02	1.2E+01	3.4E+01	5.5E+00	7.8E+00
365	3.7E+02	3.2E+02	2.1E+02	7.2E+00	1.0E+01
730	6.8E+02	6.1E+02	6.4E+02	1.2E+01	1.7E+01
1,825	9.2E+02	9.5E+02	9.3E+02	5.1E+01	7.1E+01
3,600	1.0E+03	1.0E+03	9.9E+02	3.8E+02	4.6E+02
7,300	1.1E+03	1.0E+03	1.1E+03	9.8E+02	1.0E+03
18,250	1.5E+03	1.5E+03	1.5E+03	1.4E+03	1.5E+03

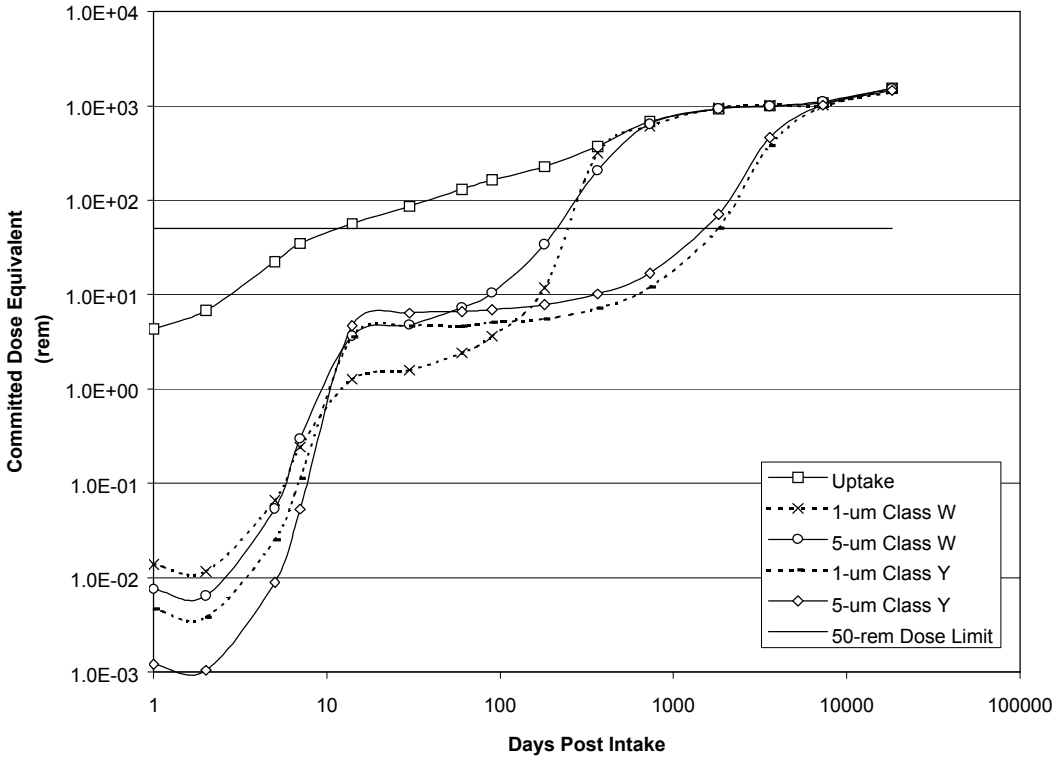

Figure 8.42. Minimum Detectable Bone Surface Doses for 10-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Table 8.55. Minimum Detectable Committed Bone Surface Dose Equivalent (rem) for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	4.5E+00	1.5E-02	8.1E-03	4.9E-03	1.3E-03
2	7.1E+00	1.3E-02	6.8E-03	4.0E-03	1.1E-03
5	2.3E+01	7.1E-02	5.7E-02	2.7E-02	9.4E-03
7	3.6E+01	2.6E-01	3.2E-01	1.2E-01	5.6E-02
14	5.9E+01	1.4E+00	3.9E+00	3.8E+00	4.9E+00
30	9.0E+01	1.7E+00	5.1E+00	4.9E+00	6.7E+00
60	1.4E+02	2.6E+00	7.7E+00	4.9E+00	6.9E+00
90	1.7E+02	3.9E+00	1.1E+01	5.3E+00	7.3E+00
180	2.4E+02	1.3E+01	3.6E+01	5.8E+00	8.2E+00
365	3.9E+02	3.4E+02	2.2E+02	7.5E+00	1.1E+01
730	7.1E+02	6.5E+02	6.8E+02	1.3E+01	1.8E+01
1,825	9.6E+02	1.0E+03	9.9E+02	5.3E+01	7.4E+01
3,600	1.0E+03	1.1E+03	1.0E+03	4.0E+02	4.8E+02
7,300	1.1E+03	1.1E+03	1.2E+03	1.0E+03	1.1E+03
18,250	1.6E+03	1.6E+03	1.6E+03	1.5E+03	1.5E+03

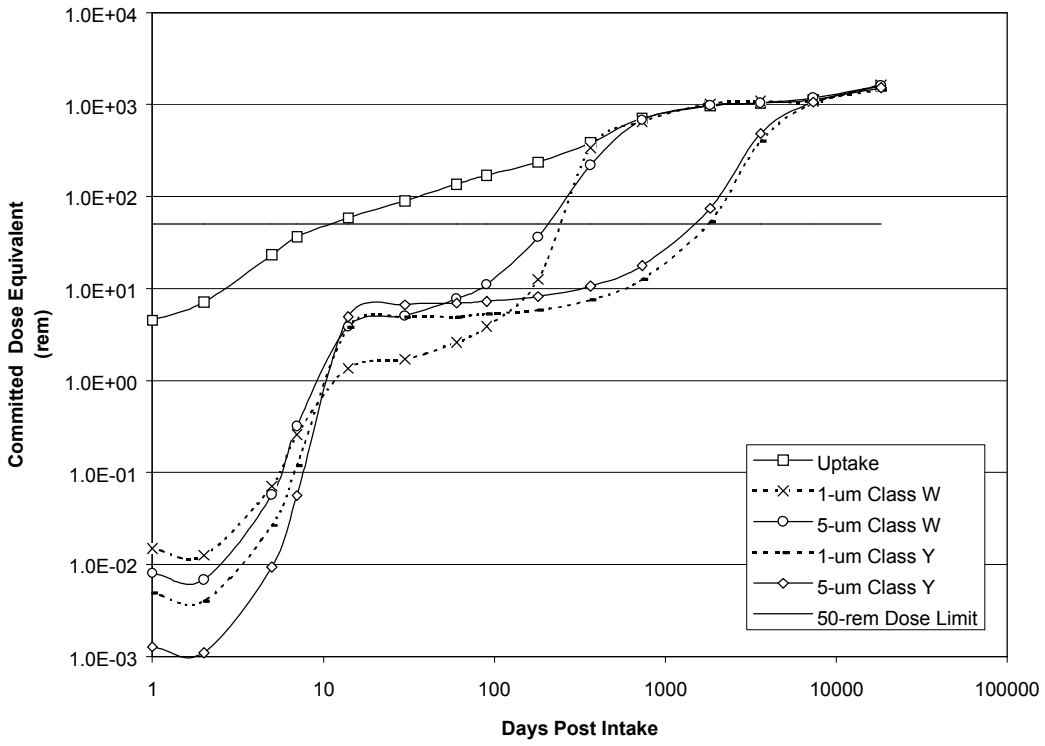

Figure 8.43. Minimum Detectable Bone Surface Doses for 20-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Table 8.56. Minimum Detectable Committed Bone Surface Dose Equivalent (rem) for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

Days Post Intake	Instant Uptake	Class W Inhalation		Class Y Inhalation	
		1-mm	5-mm	1-mm	5-mm
1	4.6E+00	1.5E-02	8.3E-03	4.9E-03	1.4E-03
2	7.3E+00	1.3E-02	7.0E-03	4.0E-03	1.2E-03
5	2.4E+01	7.3E-02	5.9E-02	2.7E-02	1.0E-02
7	3.8E+01	2.7E-01	3.3E-01	1.2E-01	5.9E-02
14	6.1E+01	1.4E+00	4.0E+00	3.7E+00	5.2E+00
30	9.3E+01	1.7E+00	5.2E+00	4.9E+00	7.1E+00
60	1.4E+02	2.7E+00	8.0E+00	4.9E+00	7.4E+00
90	1.8E+02	4.0E+00	1.1E+01	5.3E+00	7.7E+00
180	2.4E+02	1.3E+01	3.7E+01	5.8E+00	8.7E+00
365	4.0E+02	3.5E+02	2.3E+02	7.5E+00	1.1E+01
730	7.3E+02	6.7E+02	7.0E+02	1.2E+01	1.9E+01
1,825	1.0E+03	1.0E+03	1.0E+03	5.3E+01	7.9E+01
3,600	1.1E+03	1.1E+03	1.1E+03	4.0E+02	5.1E+02
7,300	1.2E+03	1.1E+03	1.2E+03	1.0E+03	1.1E+03
18,250	1.7E+03	1.7E+03	1.7E+03	1.4E+03	1.6E+03

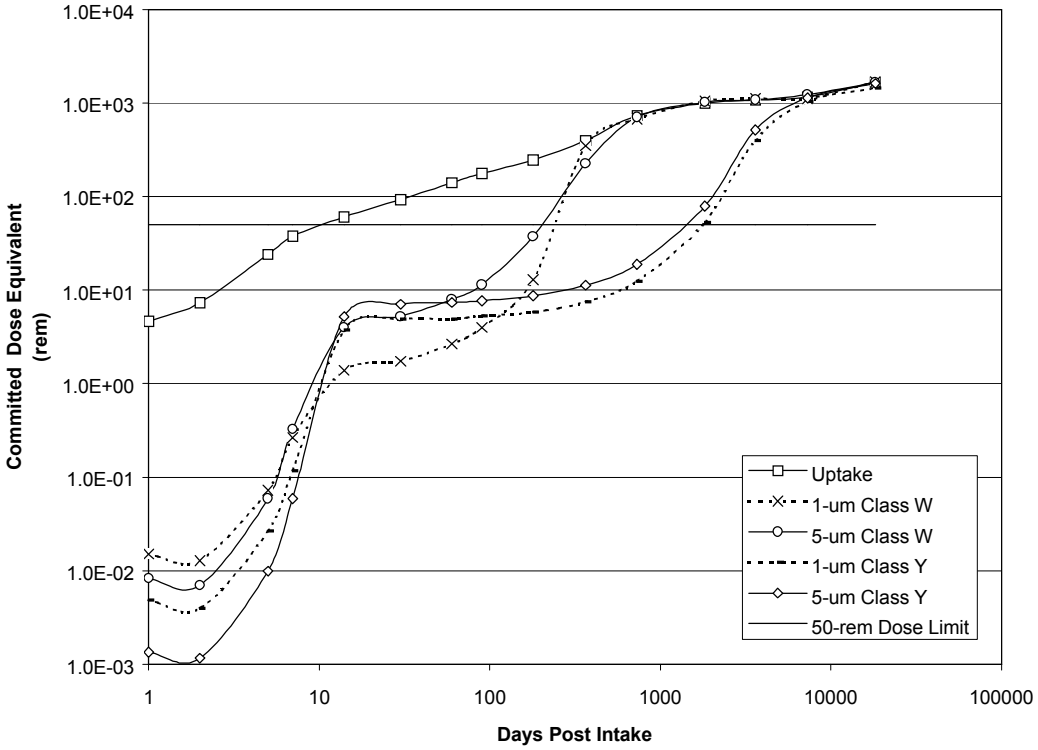

Figure 8.44. Minimum Detectable Bone Surface Doses for 40-Year Aged Fuel-Grade Plutonium Based on Detection of 0.2 dpm/d ^{239}Pu in Feces

8.4.6 Recommended Bioassay Monitoring Program

The recommended periodic bioassay-monitoring program for plutonium is to perform annual in vivo lung measurements and annual plutonium-in-urine assessments. Annual chest counts provide a reasonable capability of demonstrating compliance with the 50-rem deterministic dose limit for the bone surfaces as the most limiting intake condition for class Y inhalations, and also are likely to be capable of demonstrating compliance for inhalation of super class Y based on the effective dose equivalent as the most restrictive dose limit. More frequent chest counting is not particularly effective in lowering the MDD unless it is performed immediately after an intake. Annual urine sampling provides capability for demonstrating compliance with both deterministic and stochastic dose limits for instantaneous uptake and inhalations of class W material. Substantially more frequent urine sampling can lower the MDD for instantaneous uptakes or class W inhalations; however, the improvement in sensitivity is not necessarily commensurate with the added cost (e.g., going from annual to quarterly urine samples quadruples the cost but only improves the MDD by a little over a factor of 2). Routine fecal sampling could provide some improvements for class Y inhalation monitoring, however the attendant difficulties with collection (worker inconvenience), analysis (a very difficult matrix to analyze), and interpretation (potential interference from minor ingestion) suggest that fecal sampling is best applied to special investigations.

These recommendations do not provide the high degree of sensitivity for 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.

Because of the lack of sensitivity of periodic 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.

8.4.7 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.

How many special bioassay measurements to obtain is a matter of professional judgment, factoring in the potential significance of the exposure, the appropriate types of measurements, worker inconvenience, cost, and the degree of confidence required in the assessment. Generally, if an initial chest count shows detectable lung activity, a next-day follow-up chest count should be performed to monitor early lung clearance. Additional counts are warranted if detection continues. Total fecal sample collections for the first week allow for complete observation of the early fecal clearance pattern and permit a higher degree of confidence in the intake estimate than does a single sample. Because the general early fecal clearance pattern is not significantly different for inhalation class W or Y, the fecal-based intake estimate needs to be coupled with at least one early urine sample representing a period concurrent with at least one fecal sample to allow for a determination of inhalation class based on the ratio of fecal to urine excretion. The extent of this collection protocol can pose substantial inconvenience to the worker and can be costly. Such inconvenience and cost may be justified when doses are considered relatively high (e.g., greater than 500- to 1000-mrem committed effective dose equivalent). At lower doses, reliance on more limited measurements (e.g., one or two fecal samples and a urine sample) and standard assumptions of the source material and ICRP Reference Man biokinetic behavior may be appropriate.

8.4.8 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 a previous intake, 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 baseline “noise” level. Guidance concerning the minimum detectable dose from potential additional 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.

8.5 Assessment of Internal Dose

The following subsections discuss two general approaches to internal dosimetry and highlight some applications and caveats associated with different types of bioassay data. The most typical method used for plutonium internal dosimetry is intake assessment using fecal, urine, and in vivo data, as available. This method has been used for most Hanford assessments since the early 1990s. Prior to that the predominant method was a deposition assessment based primarily on urine data. It is a good practice to compare estimates based on different bioassay data sets for the same intake.

8.5.1 Intake Assessment

An intake of plutonium can be estimated by fitting the bioassay data to the appropriate retention or 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 retention function for the appropriate day after intake represented by the sample in a manner similar to Equation 2.5. Values for the retention function can be obtained from those tabulated in this chapter, or directly from running the CINDY computer code. For multiple data points, the CINDY code provides a choice of fitting routines, or a manually determined fit of the data to the expected function can be performed. Once the intake is calculated, appropriate internal doses may be calculated by applying the dose coefficients of this chapter to Equation 2.10 or 2.11. The CINDY computer code may also be used to directly calculate internal doses, and is particularly appropriate for complex cases.

In addition to their use for dose calculations, intakes calculated by the above techniques may also be compared with intake estimates based on air sample results. When bioassay data are not available or not sufficiently sensitive, air sample results may be the basis for estimating intake.

8.5.2 Deposition Assessment

Deposition assessment involves determining the amount of material deposited in a body or tissue compartment of interest. Whereas the term intake includes all material taken into the body regardless of its subsequent fate, deposition is a more limited quantity that excludes material not retained (e.g., that immediately exhaled) and material not systemically absorbed (e.g., material cleared to the GI tract and excreted in feces without absorption). The HIDP coined the term presystemic deposition in the mid-1980s to precisely define what was being evaluated and avoid terms that had developed generic, nebulous, or varied meanings (e.g., deposition, uptake, burden). In addition, the term deposition was gaining preference in the field of internal dosimetry as a process term associated with the respiratory tract, rather than a retained quantity. The HIDP defined presystemic deposition 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 was the quantity compared with the maximum permissible body burden (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 was 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 available from the HIDP and the Hanford Radiation Records Historical File.

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 or captured by lymph nodes and is 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.

8.5.3 Applications of Fecal Data

Fecal data can be used in two ways for plutonium assessments. First, it can provide isotopic composition information for use with other bioassay and monitoring data. Secondly, it can be used in conjunction with a biokinetic 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 inhalation intake 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. Early fecal sampling is typically the most sensitive bioassay indicator of plutonium intake. Experience with Hanford cases suggests that the first fecal sample following an intake is likely to bias inhalation intake estimates high due to possible concurrent ingestion of large, nonrespirable particles. Undue emphasis should not be placed on the first fecal sample when other data appear to contradict it. For this reason, collection of multiple fecal samples is a good practice.

8.5.4 Applications of Urine Data

Urine sampling is the simplest and most accepted excreta sampling method by workers, however it is not particularly sensitive to low-level intakes. It is most appropriate for instantaneous uptake (wound) and class W inhalations, and as a tool to compare with fecal samples to determine the inhalation class of an intake.

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) 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:

$$P_0 = U_\infty(e+h) \times \frac{F_e + F_g + F_h}{F_e + F_h} \tag{8.2}$$

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.

8.5.5 Applications of In Vivo Data

Chest counting data for plutonium is subject to some significant interpretation pitfalls, especially when it shows ^{241}Am detection over very long periods. Evaluations of chest count data must consider the potential for interference from activity deposited in other organs (particularly the skeleton and liver), as well as the specific chest-wall thickness of the individual. In addition, ^{241}Am ingrowth over time can complicate the determination of actual retention. The HIDP has developed the AMERIN computer code to assist with case evaluations as a tool to identify an ^{241}Am biological clearance rate consistent with observed ingrowth in a single compartment. This tool is particularly applicable to long-term lung retention of ^{241}Pu and ^{241}Am.

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).

Lung measurement results are also useful as an appropriate upper bound estimate for use with other intake estimates.

8.5.6 Assessing Organ and Effective 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 academic interest as the result of a wound intake of slowly transportable materials, even though doses to such tissues are not considered doses of record for compliance purposes. 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 assumed to be distributed to the liver, bone surfaces, and the gonads according to the ICRP 30 Part 4 biokinetic model. Once deposited in these tissues, the ICRP 30 Part 4 clearance rates are assumed to apply. Thus, for calculating organ doses, the ICRP 30 Part 4 organ-retention functions and dosimetry factors are normally 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 HIDP uses the CINDY computer code to aid in dose calculations. More detailed explanations and a copy of the code are maintained in the Hanford Radiation Protection Historical Files.

8.6 Management of Internal Contamination Cases

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

8.6.1 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.

The primary method of identifying potential intakes is 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 intake, 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 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.

8.6.2 Therapeutic Actions

Therapeutic actions for potential internal contamination includes 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 intake of radioactivity. The decision to undertake one or more of these therapeutic actions is the responsibility of the participating HEHF Occupational Medicine care provider 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. Guidance for the methods of therapy can be found in NCRP Report 65 (1980) and in the "Guidebook for the Treatment of Accidental Internal Radionuclide Contamination of Workers" (Bhattacharyya et al. 1992). Guidance for circumstances under which therapy may be warranted is contained in PNL-MA-552,[(a)] but was established as a good practice based on experience rather than a detailed technical analysis.

Decorporation therapy, also referred to as chelation therapy, involves the chemical removal of radioactivity from the bloodstream through drug administration. The drug DTPA has U.S. Food and Drug Administration approval as an investigational new drug for use in removing plutonium and other heavy metals from the body. Under the investigational new drug category, the patient must provide

(a) Pacific Northwest National Laboratory (PNNL). *Hanford Internal Dosimetry Project Manual*. PNNL-MA-552, Richland, Washington. (Internal manual.) Available URL: http://www.pnl.gov/eshs/pub/pnnl552.html

informed consent to HEHF before the drug can be administered. Other drugs are also available to HEHF Occupational Medicine, but none has demonstrated the efficacy of DTPA for plutonium chelation. The decision to administer DTPA is usually made based on workplace indicators suggesting the likelihood of a significant uptake. Urinalysis is required to determine the actual efficacy of treatment. When DTPA is indicated, special emergency processing of a single void urine sample should be performed to determine if additional (i.e., extended) therapy might be warranted. Professional judgment is required on the part of the medical and exposure evaluator staff to determine if continued therapy is warranted. DTPA chelation therapy can enhance urine excretion of plutonium by up to a factor of 100 or more for highly soluble forms of plutonium. For insoluble forms, it is relatively ineffective. Because of this wide range of effectiveness, dosimetric interpretation of the urine data of a person undergoing chelation therapy is problematic. Bihl (1994) has suggested a dose-averted method for interpreting urine data. The historical practice at Hanford was to base final dosimetry on urine samples obtained long after the excretion enhancement effect of DTPA had passed (typically 30 to 100 days following therapy).

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 blood stream 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 uptake, particularly when coupled with decorporation therapy. Minor excisions are usually performed at the Emergency Decontamination Facility (EDF) by HEHF Occupational Medicine staff, assisted by PNNL exposure evaluation and radiation protection personnel.

8.6.3 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 8.4.8.

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

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