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ACRONYMS AND ABBREVIATIONS

Bq	becquerel
d	day
DCF	dose conversion factor
DOE	U.S. Department of Energy
dpm	disintegrations per minute
HRTM	human respiratory tract model
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
IREP	Interactive RadioEpidemiological Program
IRF	intake retention fraction
LANL	Los Alamos National Laboratory
NIOSH	National Institute for Occupational Safety and Health
ORAU	Oak Ridge Associated Universities
RTG	radioisotopic thermoelectric generator
SNAP	Systems for Nuclear Auxiliary Power
SRDB Ref ID	Site Research Database Reference Identification (number)
Sv	sievert
TIB	technical information bulletin
U.S.C.	United States Code
§	section or sections

1.0 INTRODUCTION

Technical information bulletins (TIBs) are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance concerning the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). TIBs may be used to assist NIOSH staff in the completion of individual dose reconstructions.

In this document, the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy (DOE) facility" as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [42 U.S.C. § 7384l(5) and (12)].

1.1 PURPOSE

This TIB reviews two specific examples of non-standard urinary excretion patterns following intakes of ^{238}Pu and provides parameters for their use in IMBA. These parameters are not intended to be applied to all ^{238}Pu dose assessments. Site profiles provide guidance as to when a specific model is appropriate and under what circumstances it should be considered,

1.2 OVERVIEW

Workers who are exposed to ^{238}Pu can exhibit a wide variety of urinary excretion patterns that are indicative of very different dissolution rates of the plutonium in the lung. For example, Guilmette, Griffith, and Hickman (1994) described the urinary excretion resulting from exposures to ^{238}Pu at three different facilities, and the urinary excretion patterns were very different. Perhaps the most interesting excretion patterns were those observed after the acute exposures of seven individuals at the Los Alamos National Laboratory (LANL) Wing-9 facility (Facility 1 in Guilmette et al.) in 1971 to a ^{238}Pu cermet. These individuals exhibited nonmonotonic urinary excretion patterns like the one shown in Figure 1-1, which suggests that the ^{238}Pu (type J in the plot) was very insoluble at the time it was inhaled and became more soluble over a period of time.

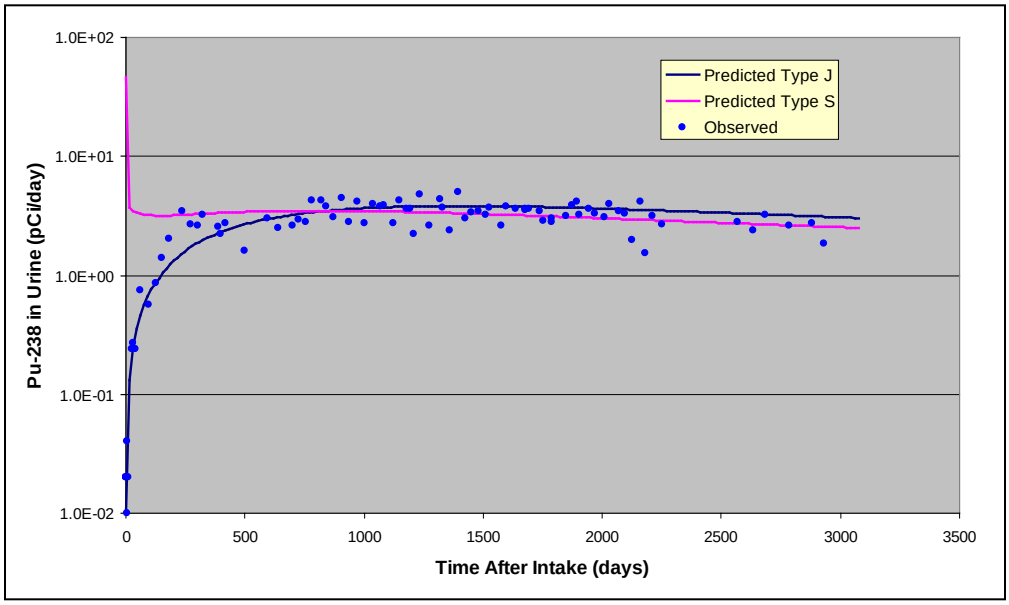

Figure 1-1. LANL urinary excretion curve modeled with type S and type J dissolution types.

This behavior has not been observed with ^{239}Pu and is linked to the fact that ^{238}Pu has a specific activity about 270 times higher than that of ^{239}Pu (Mewhinney and Diel 1983). The high specific activity of the ^{238}Pu causes aggregate recoil of ^{238}Pu particles and radiation damage to the structure of the material. This results in relatively insoluble compounds like ^{238}Pu oxide being more soluble than ^{239}Pu oxide in aqueous environments like those in the human body.

The increasing solubility over time depicted in Figure 1-1 was modeled using the type J dissolution type, which refers to the dissolution model proposed by James et al. (2003) (see the discussion in Sections 3.0 and 4.0). A dissolution model that better describes ^{238}Pu urinary excretion patterns that have been observed at Mound was derived from five Mound intake cases that were reported by Woods and Sheehan (1971) (see Section 3.2). An example is shown in Figure 1-2. The Mound-specific dissolution type is called type L to distinguish it from type J. The type L dissolution type has a greater initial solubility than type J and also has a higher rate of dissolution. The type L and type J dissolution models use custom dissolution functions within the framework of the standard ICRP Publication 66 respiratory tract model (ICRP 1994). The use of such custom dissolution functions is the approach recommended by the International Commission on Radiological Protection (ICRP) in ICRP (2000, Section 5.5.2) and allows the models to be implemented in Integrated Modules for Bioassay Analysis (IMBA).

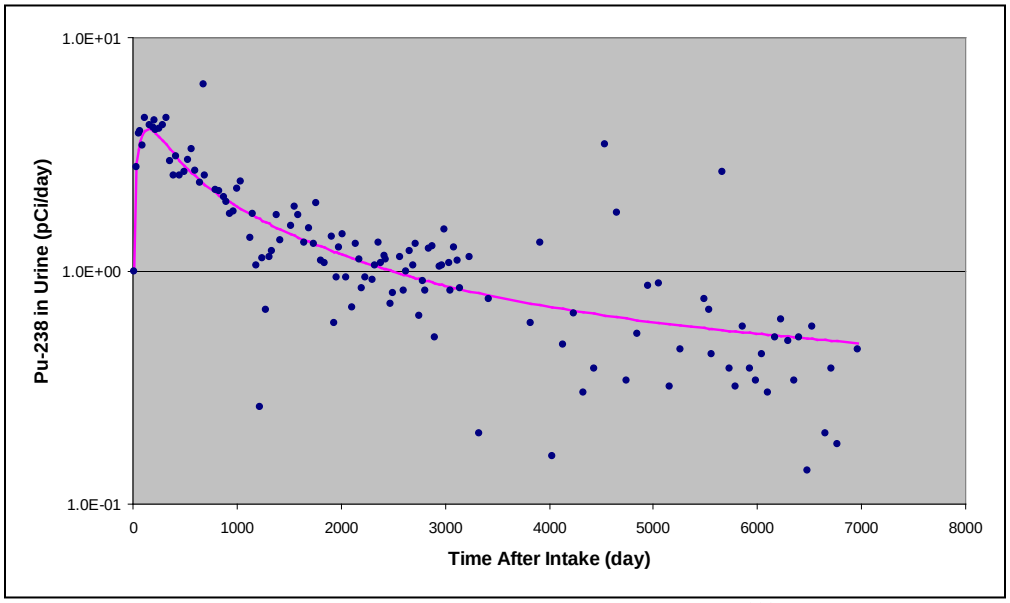

Figure 1-2. Mound urinary excretion curve fit with type L ^{238}Pu.

The nonmonotonic urinary excretion curves that result from inhalation intakes of materials like type L ^{238}Pu are of interest for dose reconstruction for two reasons. First, the urinary excretion rate can be relatively low immediately after the inhalation intake – right when it might be expected to be highest with type M or S plutonium. This can result in an intake not being confirmed if urine bioassay alone is used to confirm the intake and no additional urine samples are collected.

Second, for a positive urine result not associated with a known intake the current practice is to apply the ICRP recommendation in Publication 78 of assigning the intake date to the midpoint between the positive result and the last "less-than" result (ICRP 1998). With type M and type S plutonium the magnitude of an intake calculated from a single urine sample increases as the elapsed time between the assumed intake and the sample increases. There is a period for type J and type L materials where this relationship is reversed – the intake calculated from a single urine sample increases as the elapsed time between the intake and the sample decreases. These relationships are illustrated in Figure 1-3.

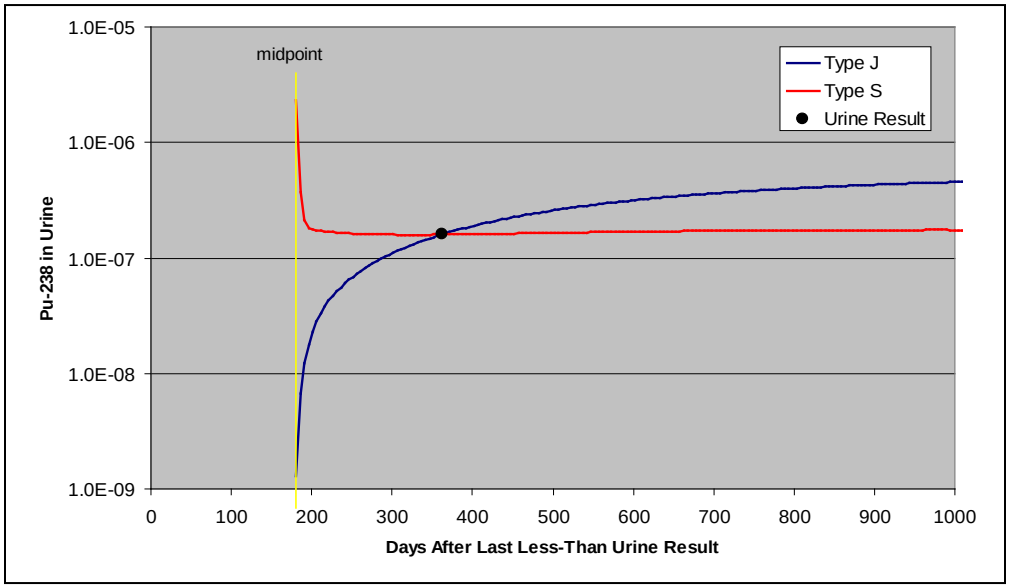

Figure 1-3. Evaluation of a single positive urine result on day 365 assuming an acute intake occurred at the midpoint (day 183) between the positive result and a less-than result 1 year earlier (day 0).

2.0 LIMITING DISSOLUTION TYPES

There are certain intake scenarios in which the assumption of standard type M or S plutonium results in higher organ dose estimates than the assumption of type L plutonium, and there are scenarios in which the assumption of type L plutonium results in higher dose estimates. In Section 4, evidence is presented that supports the assertion that type J plutonium is a material that would be rarely encountered in the workplace. For this reason type J plutonium is not considered in this section and will be addressed on a case-by-case basis. The dissolution types that result in the highest organ doses for typical dose reconstruction scenarios are identified in Tables 2-1 and 2-2. The calculations that were used to construct these tables are given in Section 3. The overall conclusion is that standard plutonium dissolution types (M and S) should be assumed for cases when urine samples were collected more than 2 weeks after an acute intake and for chronic intakes in excess of 3 months in duration. Under these conditions types M and S will result in the highest organ doses for all organs (i.e., type M or S plutonium is limiting). The type L dissolution type should be used for cases that do not meet these criteria. Therefore, type L will in practice be added to the evaluation regimen and applied in the same fashion as types M and S, selecting whichever results in the largest dose for the particular case

Table 2-1. Summary of limiting dissolution type versus the duration of a chronic inhalation intake of ^{238}Pu. The urine sample is assumed to be collected at the end of the chronic intake.

Organ or tissue	Chronic intake period (d)					
	10,000	1,000	400	100	40	10
Adrenals	S	S	S	S	L	L
Urinary bladder	S	S	S	S	L	L
Brain	S	S	S	S	L	L
Breast	S	S	S	S	L	L
Gall bladder	S	S	S	S	L	L
Heart wall	S	S	S	S	L	L
Kidneys	S	S	S	S	L	L
Liver	S	S	S	S	L	L

Organ or tissue	Chronic intake period (d)					
	10,000	1,000	400	100	40	10
Muscle	S	S	S	S	L	L
Ovaries	S	S	S	S	L	L
Pancreas	S	S	S	S	L	L
Testes	S	S	S	S	L	L
Thyroid	S	S	S	S	L	L
R.B.M.	S	S	S	S	L	L
Bone surface	S	S	S	S	L	L
Stomach	S	S	S	S	L	L
S.I.	S	S	S	S	L	L
U.L.I.	S	S	S	S	L	L
L.L.I.	S	S	S	S	L	L
Skin	S	S	S	S	L	L
Spleen	S	S	S	S	L	L
Thymus	S	S	S	S	L	L
Uterus	S	S	S	S	L	L
ET	S	S	S	S	S	S
Lung	S	S	S	S	S	S
Colon	S	S	S	S	L	L
ET1	S	S	S	S	S	L
ET2	S	S	S	S	S	S
LN(ET)	S	S	S	S	S	S
BBsec	S	S	S	S	S	L
BBbas	S	S	S	S	S	L
bb	S	S	S	S	S	S
AI	S	S	S	S	S	S
LN(TH)	S	S	S	S	S	S
Esophagus	S	S	S	S	L	L

Table 2-2. Summary of limiting dissolution type versus the time after an acute intake a single urine sample is collected.

Organ or tissue	Day sample collected after acute intake (d)							
	10,000	1,000	400	100	40	15	10	2
Adrenals	M	S	S	S	S	S	L	L
Urinary bladder	M	S	S	S	S	S	L	L
Brain	M	S	S	S	S	S	L	L
Breast	M	S	S	S	S	S	L	L
Gall bladder	M	S	S	S	S	S	L	L
Heart wall	M	S	S	S	S	S	L	L
Kidneys	M	S	S	S	S	S	L	L
Liver	M	S	S	S	S	S	L	L
Muscle	M	S	S	S	S	S	L	L
Ovaries	M	S	S	S	S	S	L	L
Pancreas	M	S	S	S	S	S	L	L
Testes	M	S	S	S	S	S	L	L
Thyroid	M	S	S	S	S	S	L	L
R.B.M.	M	S	S	S	S	S	L	L
Bone surface	M	S	S	S	S	S	L	L
Stomach	M	S	S	S	S	S	L	L
S.I.	M	S	S	S	S	S	L	L
U.L.I.	M	S	S	S	S	S	L	L
L.L.I.	M	S	S	S	S	S	L	L
Skin	M	S	S	S	S	S	L	L
Spleen	M	S	S	S	S	S	L	L

Thymus	M	S	S	S	S	S	L	L
Uterus	M	S	S	S	S	S	L	L
ET	S	S	S	S	S	S	S	L
Lung	S	S	S	S	S	S	S	L
Colon	M	S	S	S	S	S	L	L
ET1	S	S	S	S	S	S	S	L
ET2	S	S	S	S	S	S	S	L
LN(ET)	S	S	S	S	S	S	S	S
BBsec	S	S	S	S	S	S	S	L
BBbas	S	S	S	S	S	S	S	L
bb	S	S	S	S	S	S	S	L
AI	S	S	S	S	S	S	S	S
LN(TH)	S	S	S	S	S	S	S	S
Esophagus	M	S	S	S	S	S	L	L

3.0 CALCULATIONS FOR LIMITING DISSOLUTION TYPES

The general approach was to examine the dose to organs from various exposure scenarios to determine if and when type L ^{238}Pu would deliver a dose that is higher than that from type M or S ^{238}Pu. If type L delivers the highest dose, it is "limiting" and the case should be evaluated using the type L dissolution model. Each of Tables 3-2 through 3-16 consists of three parts (see example in Table 3-1):

- A: The first is a matrix of intake-to-organ dose conversion factors (DCFs) for ^{238}Pu. The DCF for acute intakes give the 50-year committed organ dose in sievert per unit intake whereas for chronic intakes the DCFs give the 50-year committed organ dose in sievert per total intake. For example, in the case of a 10-day chronic intake of 1 Bq/d the total intake is (10 d)(1 Bq/d) = 10 Bq. The DCFs are given for 5-µm activity median aerodynamic diameter type L, M, and S ^{238}Pu.

- B: The second matrix contains the urine intake retention fractions (IRFs) for the given time after an acute intake or the start of a chronic intake. For an acute intake, *IRF*(*t*) is the fraction of a unit intake in the 24-hour urine sample collected on day *t* after intake. For a chronic intake, *IRF*(*t*) is the becquerels of ^{238}Pu in the 24-hour urine sample collected on the last day after the end of the chronic intake. For example, in the case of a 10-day chronic intake, the urine sample is collected from *t* = 9 days to *t* = 10 days.

- C: The third matrix gives the organ dose *H* in sievert implied by 1 Bq/d of ^{238}Pu excreted on day *t*, as shown in Equation 3-1:

$$H = \left(\frac{1\,Bq}{IRF(t)} \right) (DCF) \qquad (3\text{-}1)$$

For a given intake scenario the organ doses are calculated for all organs and solubility types of plutonium. The solubility type with the highest dose is referred to as the "limiting" solubility type. The results are summarized in Tables 3-1 and 3-2. In general, the standard type M and type S ^{238}Pu are limiting if:

- The urine sample was collected more than approximately 2 weeks after an acute inhalation intake, or

- The chronic intake period is longer than approximately 3 months and the urine sample was collected at the end of the chronic intake period.

Table 3-1. Example of limiting dose calculation for ^{238}Pu (100-day chronic intake). A is the matrix of DCFs for an intake rate of 1 Bq/d (total intake of 100 Bq), B are the Bq in the urine on the last day of the chronic intake period, and C are the doses implied by observing 1 Bq in the urine sample.

A **C**

Organ or tissue	DCF (Sv/intake)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Urinary bladder	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Brain	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Breast	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Gall bladder	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Heart wall	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Kidneys	3.930E-04	3.590E-05	1.950E-04	2.793E-01	1.629E+00	9.515E-01	S
Liver	1.910E-02	1.690E-03	9.490E-03	1.357E+01	7.667E+01	4.631E+01	S
Muscle	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Ovaries	1.190E-03	1.050E-04	5.900E-04	8.456E-01	4.763E+00	2.879E+00	S
Pancreas	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Testes	1.210E-03	1.070E-04	6.010E-04	8.598E-01	4.854E+00	2.933E+00	S
Thyroid	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
R.B.M.	4.480E-03	4.070E-04	2.230E-03	3.183E+00	1.846E+01	1.088E+01	S
Bone surface	9.060E-02	7.950E-03	4.490E-02	6.438E+01	3.607E+02	2.191E+02	S
Stomach	1.580E-04	1.370E-05	7.810E-05	1.123E-01	6.215E-01	3.811E-01	S
S.I.	1.580E-04	1.380E-05	7.820E-05	1.123E-01	6.260E-01	3.816E-01	S
U.L.I.	1.590E-04	1.450E-05	7.890E-05	1.130E-01	6.578E-01	3.850E-01	S
L.L.I.	1.600E-04	1.630E-05	8.060E-05	1.137E-01	7.395E-01	3.933E-01	S
Skin	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Spleen	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Thymus	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Uterus	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
ET	1.520E-03	8.110E-03	2.460E-03	1.080E+00	3.679E+02	1.200E+01	S
Lung	2.350E-03	5.130E-03	2.970E-03	1.670E+00	2.327E+02	1.449E+01	S
Colon	1.590E-04	1.530E-05	7.970E-05	1.130E-01	6.941E-01	3.889E-01	S
ET1	3.160E-03	3.020E-03	3.080E-03	2.245E+00	1.370E+02	1.503E+01	S
ET2	1.520E-03	8.110E-03	2.460E-03	1.080E+00	3.679E+02	1.200E+01	S
LN(ET)	2.190E-04	1.320E-02	2.430E-04	1.556E-01	5.988E+02	1.186E+00	S
BBsec	6.360E-03	8.120E-03	7.760E-03	4.519E+00	3.684E+02	3.787E+01	S
BBbas	7.820E-04	9.500E-04	9.000E-04	5.557E-01	4.310E+01	4.392E+00	S
bb	2.460E-03	3.570E-03	2.970E-03	1.748E+00	1.620E+02	1.449E+01	S
AI	1.040E-03	7.160E-03	1.600E-03	7.390E-01	3.248E+02	7.808E+00	S
LN(TH)	4.430E-04	4.450E-02	7.280E-04	3.148E-01	2.019E+03	3.552E+00	S
Esophagus	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S

B

	Type M	Type S	Type L
IRF	1.407E-03	2.204E-05	2.049E-04

Table 3-2. 10-day chronic exposure of 1 Bq/d.

Organ or tissue	DCF (Sv/intake)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
Urinary bladder	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
Brain	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
Breast	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
Gall bladder	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
Heart wall	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
Kidneys	3.930E-05	3.590E-06	1.950E-05	6.216E-02	5.208E-01	3.357E+00	L
Liver	1.910E-03	1.690E-04	9.490E-04	3.021E+00	2.452E+01	1.634E+02	L
Muscle	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
Ovaries	1.190E-04	1.050E-05	5.900E-05	1.882E-01	1.523E+00	1.016E+01	L
Pancreas	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
Testes	1.210E-04	1.070E-05	6.010E-05	1.914E-01	1.552E+00	1.035E+01	L
Thyroid	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
R.B.M.	4.480E-04	4.070E-05	2.230E-04	7.085E-01	5.904E+00	3.839E+01	L
Bone surface	9.060E-03	7.950E-04	4.490E-03	1.433E+01	1.153E+02	7.729E+02	L
Stomach	1.580E-05	1.370E-06	7.810E-06	2.499E-02	1.987E-01	1.344E+00	L
S.I.	1.580E-05	1.380E-06	7.820E-06	2.499E-02	2.002E-01	1.346E+00	L
U.L.I.	1.590E-05	1.450E-06	7.890E-06	2.515E-02	2.103E-01	1.358E+00	L
L.L.I.	1.600E-05	1.630E-06	8.060E-06	2.530E-02	2.365E-01	1.387E+00	L
Skin	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
Spleen	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
Thymus	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
Uterus	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L
ET	1.520E-04	8.110E-04	2.460E-04	2.404E-01	1.176E+02	4.234E+01	S
Lung	2.350E-04	5.130E-04	2.970E-04	3.717E-01	7.442E+01	5.112E+01	S
Colon	1.590E-05	1.530E-06	7.970E-06	2.515E-02	2.220E-01	1.372E+00	L
ET1	3.160E-04	3.020E-04	3.080E-04	4.998E-01	4.381E+01	5.302E+01	L
ET2	1.520E-04	8.110E-04	2.460E-04	2.404E-01	1.176E+02	4.234E+01	S
LN(ET)	2.190E-05	1.320E-03	2.430E-05	3.464E-02	1.915E+02	4.183E+00	S
BBsec	6.360E-04	8.120E-04	7.760E-04	1.006E+00	1.178E+02	1.336E+02	L
BBbas	7.820E-05	9.500E-05	9.000E-05	1.237E-01	1.378E+01	1.549E+01	L
bb	2.460E-04	3.570E-04	2.970E-04	3.891E-01	5.179E+01	5.112E+01	S
AI	1.040E-04	7.160E-04	1.600E-04	1.645E-01	1.039E+02	2.754E+01	S
LN(TH)	4.430E-05	4.450E-03	7.280E-05	7.006E-02	6.455E+02	1.253E+01	S
Esophagus	1.580E-05	1.360E-06	7.810E-06	2.499E-02	1.973E-01	1.344E+00	L

IRF	6.323E-04	6.893E-06	5.810E-06

Table 3-3. 100-day chronic exposure of 1 Bq/d.

Organ or tissue	DCF (Sv/intake)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Urinary bladder	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Brain	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Breast	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Gall bladder	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Heart wall	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Kidneys	3.930E-04	3.590E-05	1.950E-04	2.793E-01	1.629E+00	9.515E-01	S
Liver	1.910E-02	1.690E-03	9.490E-03	1.357E+01	7.667E+01	4.631E+01	S
Muscle	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Ovaries	1.190E-03	1.050E-04	5.900E-04	8.456E-01	4.763E+00	2.879E+00	S
Pancreas	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Testes	1.210E-03	1.070E-04	6.010E-04	8.598E-01	4.854E+00	2.933E+00	S
Thyroid	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
R.B.M.	4.480E-03	4.070E-04	2.230E-03	3.183E+00	1.846E+01	1.088E+01	S
Bone surface	9.060E-02	7.950E-03	4.490E-02	6.438E+01	3.607E+02	2.191E+02	S
Stomach	1.580E-04	1.370E-05	7.810E-05	1.123E-01	6.215E-01	3.811E-01	S
S.I.	1.580E-04	1.380E-05	7.820E-05	1.123E-01	6.260E-01	3.816E-01	S
U.L.I.	1.590E-04	1.450E-05	7.890E-05	1.130E-01	6.578E-01	3.850E-01	S
L.L.I.	1.600E-04	1.630E-05	8.060E-05	1.137E-01	7.395E-01	3.933E-01	S
Skin	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Spleen	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Thymus	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
Uterus	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S
ET	1.520E-03	8.110E-03	2.460E-03	1.080E+00	3.679E+02	1.200E+01	S
Lung	2.350E-03	5.130E-03	2.970E-03	1.670E+00	2.327E+02	1.449E+01	S
Colon	1.590E-04	1.530E-05	7.970E-05	1.130E-01	6.941E-01	3.889E-01	S
ET1	3.160E-03	3.020E-03	3.080E-03	2.245E+00	1.370E+02	1.503E+01	S
ET2	1.520E-03	8.110E-03	2.460E-03	1.080E+00	3.679E+02	1.200E+01	S
LN(ET)	2.190E-04	1.320E-02	2.430E-04	1.556E-01	5.988E+02	1.186E+00	S
BBsec	6.360E-03	8.120E-03	7.760E-03	4.519E+00	3.684E+02	3.787E+01	S
BBbas	7.820E-04	9.500E-04	9.000E-04	5.557E-01	4.310E+01	4.392E+00	S
bb	2.460E-03	3.570E-03	2.970E-03	1.748E+00	1.620E+02	1.449E+01	S
AI	1.040E-03	7.160E-03	1.600E-03	7.390E-01	3.248E+02	7.808E+00	S
LN(TH)	4.430E-04	4.450E-02	7.280E-04	3.148E-01	2.019E+03	3.552E+00	S
Esophagus	1.580E-04	1.360E-05	7.810E-05	1.123E-01	6.170E-01	3.811E-01	S

IRF	1.407E-03	2.204E-05	2.049E-04

Table 3-4. 400-day chronic exposure of 1 Bq/d.

Organ or tissue	DCF (Sv/intake)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
Urinary bladder	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
Brain	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
Breast	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
Gall bladder	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
Heart wall	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
Kidneys	1.570E-03	1.440E-04	7.810E-04	5.514E-01	2.035E+00	7.789E-01	S
Liver	7.660E-02	6.770E-03	3.790E-02	2.690E+01	9.569E+01	3.780E+01	S
Muscle	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
Ovaries	4.760E-03	4.200E-04	2.360E-03	1.672E+00	5.936E+00	2.354E+00	S
Pancreas	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
Testes	4.860E-03	4.280E-04	2.410E-03	1.707E+00	6.050E+00	2.404E+00	S
Thyroid	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
R.B.M.	1.790E-02	1.630E-03	8.900E-03	6.286E+00	2.304E+01	8.876E+00	S
Bone surface	3.620E-01	3.180E-02	1.790E-01	1.271E+02	4.495E+02	1.785E+02	S
Stomach	6.320E-04	5.480E-05	3.120E-04	2.220E-01	7.746E-01	3.112E-01	S
S.I.	6.320E-04	5.510E-05	3.130E-04	2.220E-01	7.788E-01	3.122E-01	S
U.L.I.	6.350E-04	5.820E-05	3.160E-04	2.230E-01	8.226E-01	3.151E-01	S
L.L.I.	6.420E-04	6.530E-05	3.230E-04	2.255E-01	9.230E-01	3.221E-01	S
Skin	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
Spleen	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
Thymus	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
Uterus	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S
ET	6.070E-03	3.240E-02	9.850E-03	2.132E+00	4.580E+02	9.823E+00	S
Lung	9.420E-03	2.050E-02	1.190E-02	3.308E+00	2.898E+02	1.187E+01	S
Colon	6.380E-04	6.120E-05	3.190E-04	2.241E-01	8.650E-01	3.181E-01	S
ET1	1.260E-02	1.210E-02	1.230E-02	4.425E+00	1.710E+02	1.227E+01	S
ET2	6.070E-03	3.240E-02	9.850E-03	2.132E+00	4.580E+02	9.823E+00	S
LN(ET)	8.760E-04	5.290E-02	9.710E-04	3.076E-01	7.477E+02	9.684E-01	S
BBsec	2.540E-02	3.250E-02	3.100E-02	8.920E+00	4.594E+02	3.092E+01	S
BBbas	3.130E-03	3.800E-03	3.600E-03	1.099E+00	5.371E+01	3.590E+00	S
bb	9.840E-03	1.430E-02	1.190E-02	3.456E+00	2.021E+02	1.187E+01	S
AI	4.150E-03	2.860E-02	6.410E-03	1.457E+00	4.042E+02	6.393E+00	S
LN(TH)	1.770E-03	1.780E-01	2.910E-03	6.216E-01	2.516E+03	2.902E+00	S
Esophagus	6.320E-04	5.450E-05	3.120E-04	2.220E-01	7.703E-01	3.112E-01	S

IRF	2.847E-03	7.075E-05	1.003E-03

Table 3-5. 1,000-day chronic exposure of 1 Bq/d.

Organ or tissue	DCF (Sv/intake)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
Urinary bladder	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
Brain	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
Breast	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
Gall bladder	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
Heart wall	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
Kidneys	3.930E-03	3.590E-04	1.950E-03	8.573E-01	2.057E+00	9.613E-01	S
Liver	1.910E-01	1.690E-02	9.490E-02	4.166E+01	9.682E+01	4.679E+01	S
Muscle	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
Ovaries	1.190E-02	1.050E-03	5.900E-03	2.596E+00	6.015E+00	2.909E+00	S
Pancreas	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
Testes	1.210E-02	1.070E-03	6.010E-03	2.639E+00	6.130E+00	2.963E+00	S
Thyroid	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
R.B.M.	4.480E-02	4.070E-03	2.230E-02	9.772E+00	2.332E+01	1.099E+01	S
Bone surface	9.060E-01	7.950E-02	4.490E-01	1.976E+02	4.555E+02	2.214E+02	S
Stomach	1.580E-03	1.370E-04	7.810E-04	3.446E-01	7.849E-01	3.850E-01	S
S.I.	1.580E-03	1.380E-04	7.820E-04	3.446E-01	7.906E-01	3.855E-01	S
U.L.I.	1.590E-03	1.450E-04	7.890E-04	3.468E-01	8.307E-01	3.890E-01	S
L.L.I.	1.600E-03	1.630E-04	8.060E-04	3.490E-01	9.338E-01	3.974E-01	S
Skin	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
Spleen	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
Thymus	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
Uterus	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S
ET	1.520E-02	8.110E-02	2.460E-02	3.316E+00	4.646E+02	1.213E+01	S
Lung	2.350E-02	5.130E-02	2.970E-02	5.126E+00	2.939E+02	1.464E+01	S
Colon	1.590E-03	1.530E-04	7.970E-04	3.468E-01	8.765E-01	3.929E-01	S
ET1	3.160E-02	3.020E-02	3.080E-02	6.893E+00	1.730E+02	1.518E+01	S
ET2	1.520E-02	8.110E-02	2.460E-02	3.316E+00	4.646E+02	1.213E+01	S
LN(ET)	2.190E-03	1.320E-01	2.430E-03	4.777E-01	7.562E+02	1.198E+00	S
BBsec	6.360E-02	8.120E-02	7.760E-02	1.387E+01	4.652E+02	3.826E+01	S
BBbas	7.820E-03	9.500E-03	9.000E-03	1.706E+00	5.443E+01	4.437E+00	S
bb	2.460E-02	3.570E-02	2.970E-02	5.366E+00	2.045E+02	1.464E+01	S
AI	1.040E-02	7.160E-02	1.600E-02	2.269E+00	4.102E+02	7.888E+00	S
LN(TH)	4.430E-03	4.450E-01	7.280E-03	9.663E-01	2.549E+03	3.589E+00	S
Esophagus	1.580E-03	1.360E-04	7.810E-04	3.446E-01	7.791E-01	3.850E-01	S

IRF	4.584E-03	1.746E-04	2.028E-03

Table 3-6. 10,000-day chronic exposure of 1 Bq/d.

Organ or tissue	DCF (Sv/intake)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
Urinary bladder	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
Brain	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
Breast	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
Gall bladder	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
Heart wall	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
Kidneys	3.930E-02	3.590E-03	1.950E-02	2.981E+00	3.275E+00	2.992E+00	S
Liver	1.910E+00	1.690E-01	9.490E-01	1.449E+02	1.542E+02	1.456E+02	S
Muscle	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
Ovaries	1.190E-01	1.050E-02	5.900E-02	9.026E+00	9.578E+00	9.051E+00	S
Pancreas	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
Testes	1.210E-01	1.070E-02	6.010E-02	9.178E+00	9.760E+00	9.220E+00	S
Thyroid	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
R.B.M.	4.480E-01	4.070E-02	2.230E-01	3.398E+01	3.712E+01	3.421E+01	S
Bone surface	9.060E+00	7.950E-01	4.490E+00	6.872E+02	7.252E+02	6.888E+02	S
Stomach	1.580E-02	1.370E-03	7.810E-03	1.198E+00	1.250E+00	1.198E+00	S
S.I.	1.580E-02	1.380E-03	7.820E-03	1.198E+00	1.259E+00	1.200E+00	S
U.L.I.	1.590E-02	1.450E-03	7.890E-03	1.206E+00	1.323E+00	1.210E+00	S
L.L.I.	1.600E-02	1.630E-03	8.060E-03	1.214E+00	1.487E+00	1.236E+00	S
Skin	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
Spleen	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
Thymus	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
Uterus	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S
ET	1.520E-01	8.110E-01	2.460E-01	1.153E+01	7.398E+02	3.774E+01	S
Lung	2.350E-01	5.130E-01	2.970E-01	1.782E+01	4.679E+02	4.556E+01	S
Colon	1.590E-02	1.530E-03	7.970E-03	1.206E+00	1.396E+00	1.223E+00	S
ET1	3.160E-01	3.020E-01	3.080E-01	2.397E+01	2.755E+02	4.725E+01	S
ET2	1.520E-01	8.110E-01	2.460E-01	1.153E+01	7.398E+02	3.774E+01	S
LN(ET)	2.190E-02	1.320E+00	2.430E-02	1.661E+00	1.204E+03	3.728E+00	S
BBsec	6.360E-01	8.120E-01	7.760E-01	4.824E+01	7.407E+02	1.190E+02	S
BBbas	7.820E-02	9.500E-02	9.000E-02	5.931E+00	8.666E+01	1.381E+01	S
bb	2.460E-01	3.570E-01	2.970E-01	1.866E+01	3.256E+02	4.556E+01	S
AI	1.040E-01	7.160E-01	1.600E-01	7.888E+00	6.531E+02	2.455E+01	S
LN(TH)	4.430E-02	4.450E+00	7.280E-02	3.360E+00	4.059E+03	1.117E+01	S
Esophagus	1.580E-02	1.360E-03	7.810E-03	1.198E+00	1.241E+00	1.198E+00	S

IRF	1.318E-02	1.096E-03	6.518E-03

Table 3-7. Acute exposure of 1 Bq with urine sample 2 days later.

Organ or tissue	DCF (Sv/Bq)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
Urinary bladder	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
Brain	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
Breast	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
Gall bladder	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
Heart wall	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
Kidneys	3.930E-06	3.590E-07	1.950E-06	3.007E-02	2.646E-01	5.671E+00	L
Liver	1.910E-04	1.690E-05	9.490E-05	1.462E+00	1.246E+01	2.760E+02	L
Muscle	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
Ovaries	1.190E-05	1.050E-06	5.900E-06	9.106E-02	7.740E-01	1.716E+01	L
Pancreas	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
Testes	1.210E-05	1.070E-06	6.010E-06	9.259E-02	7.887E-01	1.748E+01	L
Thyroid	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
R.B.M.	4.480E-05	4.070E-06	2.230E-05	3.428E-01	3.000E+00	6.486E+01	L
Bone surface	9.060E-04	7.950E-05	4.490E-04	6.933E+00	5.860E+01	1.306E+03	L
Stomach	1.580E-06	1.370E-07	7.810E-07	1.209E-02	1.010E-01	2.271E+00	L
S.I.	1.580E-06	1.380E-07	7.820E-07	1.209E-02	1.017E-01	2.274E+00	L
U.L.I.	1.590E-06	1.450E-07	7.890E-07	1.217E-02	1.069E-01	2.295E+00	L
L.L.I.	1.600E-06	1.630E-07	8.060E-07	1.224E-02	1.202E-01	2.344E+00	L
Skin	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
Spleen	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
Thymus	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
Uterus	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L
ET	1.520E-05	8.110E-05	2.460E-05	1.163E-01	5.978E+01	7.154E+01	L
Lung	2.350E-05	5.130E-05	2.970E-05	1.798E-01	3.782E+01	8.638E+01	L
Colon	1.590E-06	1.530E-07	7.970E-07	1.217E-02	1.128E-01	2.318E+00	L
ET1	3.160E-05	3.020E-05	3.080E-05	2.418E-01	2.226E+01	8.958E+01	L
ET2	1.520E-05	8.110E-05	2.460E-05	1.163E-01	5.978E+01	7.154E+01	L
LN(ET)	2.190E-06	1.320E-04	2.430E-06	1.676E-02	9.730E+01	7.067E+00	S
BBsec	6.360E-05	8.120E-05	7.760E-05	4.867E-01	5.986E+01	2.257E+02	L
BBbas	7.820E-06	9.500E-06	9.000E-06	5.984E-02	7.003E+00	2.617E+01	L
bb	2.460E-05	3.570E-05	2.970E-05	1.882E-01	2.632E+01	8.638E+01	L
AI	1.040E-05	7.160E-05	1.600E-05	7.958E-02	5.278E+01	4.653E+01	S
LN(TH)	4.430E-06	4.450E-04	7.280E-06	3.390E-02	3.280E+02	2.117E+01	S
Esophagus	1.580E-06	1.360E-07	7.810E-07	1.209E-02	1.003E-01	2.271E+00	L

IRF	1.307E-04	1.357E-06	3.438E-07

Table 3-8. Acute exposure of 1 Bq with urine sample 5 days later.

Organ or tissue	DCF (Sv/Bq)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
Urinary bladder	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
Brain	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
Breast	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
Gall bladder	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
Heart wall	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
Kidneys	3.930E-06	3.590E-07	1.950E-06	1.006E-01	7.894E-01	3.117E+00	L
Liver	1.910E-04	1.690E-05	9.490E-05	4.887E+00	3.716E+01	1.517E+02	L
Muscle	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
Ovaries	1.190E-05	1.050E-06	5.900E-06	3.045E-01	2.309E+00	9.430E+00	L
Pancreas	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
Testes	1.210E-05	1.070E-06	6.010E-06	3.096E-01	2.353E+00	9.606E+00	L
Thyroid	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
R.B.M.	4.480E-05	4.070E-06	2.230E-05	1.146E+00	8.950E+00	3.564E+01	L
Bone surface	9.060E-04	7.950E-05	4.490E-04	2.318E+01	1.748E+02	7.177E+02	L
Stomach	1.580E-06	1.370E-07	7.810E-07	4.043E-02	3.013E-01	1.248E+00	L
S.I.	1.580E-06	1.380E-07	7.820E-07	4.043E-02	3.035E-01	1.250E+00	L
U.L.I.	1.590E-06	1.450E-07	7.890E-07	4.068E-02	3.188E-01	1.261E+00	L
L.L.I.	1.600E-06	1.630E-07	8.060E-07	4.094E-02	3.584E-01	1.288E+00	L
Skin	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
Spleen	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
Thymus	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
Uterus	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L
ET	1.520E-05	8.110E-05	2.460E-05	3.889E-01	1.783E+02	3.932E+01	S
Lung	2.350E-05	5.130E-05	2.970E-05	6.013E-01	1.128E+02	4.747E+01	S
Colon	1.590E-06	1.530E-07	7.970E-07	4.068E-02	3.364E-01	1.274E+00	L
ET1	3.160E-05	3.020E-05	3.080E-05	8.086E-01	6.641E+01	4.923E+01	S
ET2	1.520E-05	8.110E-05	2.460E-05	3.889E-01	1.783E+02	3.932E+01	S
LN(ET)	2.190E-06	1.320E-04	2.430E-06	5.604E-02	2.903E+02	3.884E+00	S
BBsec	6.360E-05	8.120E-05	7.760E-05	1.627E+00	1.786E+02	1.240E+02	S
BBbas	7.820E-06	9.500E-06	9.000E-06	2.001E-01	2.089E+01	1.439E+01	S
bb	2.460E-05	3.570E-05	2.970E-05	6.295E-01	7.850E+01	4.747E+01	S
AI	1.040E-05	7.160E-05	1.600E-05	2.661E-01	1.574E+02	2.557E+01	S
LN(TH)	4.430E-06	4.450E-04	7.280E-06	1.134E-01	9.785E+02	1.164E+01	S
Esophagus	1.580E-06	1.360E-07	7.810E-07	4.043E-02	2.991E-01	1.248E+00	L

IRF	3.908E-05	4.548E-07	6.257E-07

Table 3-9. Acute exposure of 1 Bq with urine sample 10 days later.

Organ or tissue	DCF (Sv/Bq)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
Urinary bladder	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
Brain	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
Breast	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
Gall bladder	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
Heart wall	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
Kidneys	3.930E-06	3.590E-07	1.950E-06	2.556E-01	1.596E+00	2.038E+00	L
Liver	1.910E-04	1.690E-05	9.490E-05	1.242E+01	7.512E+01	9.920E+01	L
Muscle	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
Ovaries	1.190E-05	1.050E-06	5.900E-06	7.739E-01	4.667E+00	6.167E+00	L
Pancreas	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
Testes	1.210E-05	1.070E-06	6.010E-06	7.869E-01	4.756E+00	6.282E+00	L
Thyroid	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
R.B.M.	4.480E-05	4.070E-06	2.230E-05	2.914E+00	1.809E+01	2.331E+01	L
Bone surface	9.060E-04	7.950E-05	4.490E-04	5.892E+01	3.534E+02	4.693E+02	L
Stomach	1.580E-06	1.370E-07	7.810E-07	1.028E-01	6.090E-01	8.163E-01	L
S.I.	1.580E-06	1.380E-07	7.820E-07	1.028E-01	6.134E-01	8.174E-01	L
U.L.I.	1.590E-06	1.450E-07	7.890E-07	1.034E-01	6.445E-01	8.247E-01	L
L.L.I.	1.600E-06	1.630E-07	8.060E-07	1.041E-01	7.245E-01	8.425E-01	L
Skin	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
Spleen	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
Thymus	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
Uterus	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L
ET	1.520E-05	8.110E-05	2.460E-05	9.886E-01	3.605E+02	2.571E+01	S
Lung	2.350E-05	5.130E-05	2.970E-05	1.528E+00	2.280E+02	3.104E+01	S
Colon	1.590E-06	1.530E-07	7.970E-07	1.034E-01	6.801E-01	8.331E-01	L
ET1	3.160E-05	3.020E-05	3.080E-05	2.055E+00	1.342E+02	3.219E+01	S
ET2	1.520E-05	8.110E-05	2.460E-05	9.886E-01	3.605E+02	2.571E+01	S
LN(ET)	2.190E-06	1.320E-04	2.430E-06	1.424E-01	5.867E+02	2.540E+00	S
BBsec	6.360E-05	8.120E-05	7.760E-05	4.136E+00	3.609E+02	8.111E+01	S
BBbas	7.820E-06	9.500E-06	9.000E-06	5.086E-01	4.223E+01	9.407E+00	S
bb	2.460E-05	3.570E-05	2.970E-05	1.600E+00	1.587E+02	3.104E+01	S
AI	1.040E-05	7.160E-05	1.600E-05	6.764E-01	3.183E+02	1.672E+01	S
LN(TH)	4.430E-06	4.450E-04	7.280E-06	2.881E-01	1.978E+03	7.609E+00	S
Esophagus	1.580E-06	1.360E-07	7.810E-07	1.028E-01	6.045E-01	8.163E-01	L

IRF	1.538E-05	2.250E-07	9.567E-07

Table 3-10. Acute exposure of 1 Bq with urine sample 15 days later.

Organ or tissue	DCF (Sv/Bq)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
Urinary bladder	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
Brain	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
Breast	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
Gall bladder	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
Heart wall	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
Kidneys	3.930E-06	3.590E-07	1.950E-06	3.503E-01	1.934E+00	1.598E+00	S
Liver	1.910E-04	1.690E-05	9.490E-05	1.702E+01	9.105E+01	7.779E+01	S
Muscle	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
Ovaries	1.190E-05	1.050E-06	5.900E-06	1.061E+00	5.657E+00	4.836E+00	S
Pancreas	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
Testes	1.210E-05	1.070E-06	6.010E-06	1.078E+00	5.765E+00	4.926E+00	S
Thyroid	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
R.B.M.	4.480E-05	4.070E-06	2.230E-05	3.993E+00	2.193E+01	1.828E+01	S
Bone surface	9.060E-04	7.950E-05	4.490E-04	8.075E+01	4.283E+02	3.680E+02	S
Stomach	1.580E-06	1.370E-07	7.810E-07	1.408E-01	7.381E-01	6.402E-01	S
S.I.	1.580E-06	1.380E-07	7.820E-07	1.408E-01	7.435E-01	6.410E-01	S
U.L.I.	1.590E-06	1.450E-07	7.890E-07	1.417E-01	7.812E-01	6.467E-01	S
L.L.I.	1.600E-06	1.630E-07	8.060E-07	1.426E-01	8.782E-01	6.607E-01	S
Skin	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
Spleen	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
Thymus	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
Uterus	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S
ET	1.520E-05	8.110E-05	2.460E-05	1.355E+00	4.369E+02	2.016E+01	S
Lung	2.350E-05	5.130E-05	2.970E-05	2.094E+00	2.764E+02	2.434E+01	S
Colon	1.590E-06	1.530E-07	7.970E-07	1.417E-01	8.243E-01	6.533E-01	S
ET1	3.160E-05	3.020E-05	3.080E-05	2.816E+00	1.627E+02	2.525E+01	S
ET2	1.520E-05	8.110E-05	2.460E-05	1.355E+00	4.369E+02	2.016E+01	S
LN(ET)	2.190E-06	1.320E-04	2.430E-06	1.952E-01	7.112E+02	1.992E+00	S
BBsec	6.360E-05	8.120E-05	7.760E-05	5.668E+00	4.375E+02	6.361E+01	S
BBbas	7.820E-06	9.500E-06	9.000E-06	6.970E-01	5.118E+01	7.377E+00	S
bb	2.460E-05	3.570E-05	2.970E-05	2.193E+00	1.923E+02	2.434E+01	S
AI	1.040E-05	7.160E-05	1.600E-05	9.269E-01	3.858E+02	1.311E+01	S
LN(TH)	4.430E-06	4.450E-04	7.280E-06	3.948E-01	2.398E+03	5.967E+00	S
Esophagus	1.580E-06	1.360E-07	7.810E-07	1.408E-01	7.327E-01	6.402E-01	S

IRF	1.122E-05	1.856E-07	1.220E-06

Table 3-11. Acute exposure of 1 Bq with urine sample 40 days later.

Organ or tissue	DCF (Sv/Bq)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
Urinary bladder	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
Brain	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
Breast	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
Gall bladder	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
Heart wall	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
Kidneys	3.930E-06	3.590E-07	1.950E-06	4.381E-01	2.126E+00	9.424E-01	S
Liver	1.910E-04	1.690E-05	9.490E-05	2.129E+01	1.001E+02	4.587E+01	S
Muscle	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
Ovaries	1.190E-05	1.050E-06	5.900E-06	1.327E+00	6.217E+00	2.851E+00	S
Pancreas	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
Testes	1.210E-05	1.070E-06	6.010E-06	1.349E+00	6.336E+00	2.905E+00	S
Thyroid	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
R.B.M.	4.480E-05	4.070E-06	2.230E-05	4.994E+00	2.410E+01	1.078E+01	S
Bone surface	9.060E-04	7.950E-05	4.490E-04	1.010E+02	4.707E+02	2.170E+02	S
Stomach	1.580E-06	1.370E-07	7.810E-07	1.761E-01	8.112E-01	3.775E-01	S
S.I.	1.580E-06	1.380E-07	7.820E-07	1.761E-01	8.171E-01	3.779E-01	S
U.L.I.	1.590E-06	1.450E-07	7.890E-07	1.772E-01	8.586E-01	3.813E-01	S
L.L.I.	1.600E-06	1.630E-07	8.060E-07	1.784E-01	9.652E-01	3.895E-01	S
Skin	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
Spleen	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
Thymus	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
Uterus	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S
ET	1.520E-05	8.110E-05	2.460E-05	1.694E+00	4.802E+02	1.189E+01	S
Lung	2.350E-05	5.130E-05	2.970E-05	2.620E+00	3.038E+02	1.435E+01	S
Colon	1.590E-06	1.530E-07	7.970E-07	1.772E-01	9.060E-01	3.852E-01	S
ET1	3.160E-05	3.020E-05	3.080E-05	3.523E+00	1.788E+02	1.489E+01	S
ET2	1.520E-05	8.110E-05	2.460E-05	1.694E+00	4.802E+02	1.189E+01	S
LN(ET)	2.190E-06	1.320E-04	2.430E-06	2.441E-01	7.816E+02	1.174E+00	S
BBsec	6.360E-05	8.120E-05	7.760E-05	7.090E+00	4.808E+02	3.750E+01	S
BBbas	7.820E-06	9.500E-06	9.000E-06	8.717E-01	5.625E+01	4.350E+00	S
bb	2.460E-05	3.570E-05	2.970E-05	2.742E+00	2.114E+02	1.435E+01	S
AI	1.040E-05	7.160E-05	1.600E-05	1.159E+00	4.240E+02	7.733E+00	S
LN(TH)	4.430E-06	4.450E-04	7.280E-06	4.938E-01	2.635E+03	3.518E+00	S
Esophagus	1.580E-06	1.360E-07	7.810E-07	1.761E-01	8.053E-01	3.775E-01	S

IRF	8.971E-06	1.689E-07	2.069E-06

Table 3-12. Acute exposure of 1 Bq with urine sample 100 days later.

Organ or tissue	DCF (Sv/Bq)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
Urinary bladder	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
Brain	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
Breast	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
Gall bladder	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
Heart wall	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
Kidneys	3.930E-06	3.590E-07	1.950E-06	5.743E-01	2.245E+00	6.972E-01	S
Liver	1.910E-04	1.690E-05	9.490E-05	2.791E+01	1.057E+02	3.393E+01	S
Muscle	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
Ovaries	1.190E-05	1.050E-06	5.900E-06	1.739E+00	6.565E+00	2.110E+00	S
Pancreas	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
Testes	1.210E-05	1.070E-06	6.010E-06	1.768E+00	6.690E+00	2.149E+00	S
Thyroid	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
R.B.M.	4.480E-05	4.070E-06	2.230E-05	6.547E+00	2.545E+01	7.973E+00	S
Bone surface	9.060E-04	7.950E-05	4.490E-04	1.324E+02	4.971E+02	1.605E+02	S
Stomach	1.580E-06	1.370E-07	7.810E-07	2.309E-01	8.566E-01	2.792E-01	S
S.I.	1.580E-06	1.380E-07	7.820E-07	2.309E-01	8.628E-01	2.796E-01	S
U.L.I.	1.590E-06	1.450E-07	7.890E-07	2.324E-01	9.066E-01	2.821E-01	S
L.L.I.	1.600E-06	1.630E-07	8.060E-07	2.338E-01	1.019E+00	2.882E-01	S
Skin	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
Spleen	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
Thymus	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
Uterus	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S
ET	1.520E-05	8.110E-05	2.460E-05	2.221E+00	5.071E+02	8.796E+00	S
Lung	2.350E-05	5.130E-05	2.970E-05	3.434E+00	3.207E+02	1.062E+01	S
Colon	1.590E-06	1.530E-07	7.970E-07	2.324E-01	9.566E-01	2.850E-01	S
ET1	3.160E-05	3.020E-05	3.080E-05	4.618E+00	1.888E+02	1.101E+01	S
ET2	1.520E-05	8.110E-05	2.460E-05	2.221E+00	5.071E+02	8.796E+00	S
LN(ET)	2.190E-06	1.320E-04	2.430E-06	3.201E-01	8.253E+02	8.689E-01	S
BBsec	6.360E-05	8.120E-05	7.760E-05	9.295E+00	5.077E+02	2.775E+01	S
BBbas	7.820E-06	9.500E-06	9.000E-06	1.143E+00	5.940E+01	3.218E+00	S
bb	2.460E-05	3.570E-05	2.970E-05	3.595E+00	2.232E+02	1.062E+01	S
AI	1.040E-05	7.160E-05	1.600E-05	1.520E+00	4.477E+02	5.721E+00	S
LN(TH)	4.430E-06	4.450E-04	7.280E-06	6.474E-01	2.782E+03	2.603E+00	S
Esophagus	1.580E-06	1.360E-07	7.810E-07	2.309E-01	8.503E-01	2.792E-01	S

IRF	6.843E-06	1.599E-07	2.797E-06

Table 3-13. Acute exposure of 1 Bq with urine sample 400 days later.

Organ or tissue	DCF (Sv/Bq)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
Urinary bladder	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
Brain	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
Breast	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
Gall bladder	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
Heart wall	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
Kidneys	3.930E-06	3.590E-07	1.950E-06	1.070E+00	2.137E+00	8.648E-01	S
Liver	1.910E-04	1.690E-05	9.490E-05	5.200E+01	1.006E+02	4.209E+01	S
Muscle	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
Ovaries	1.190E-05	1.050E-06	5.900E-06	3.240E+00	6.250E+00	2.617E+00	S
Pancreas	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
Testes	1.210E-05	1.070E-06	6.010E-06	3.294E+00	6.369E+00	2.665E+00	S
Thyroid	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
R.B.M.	4.480E-05	4.070E-06	2.230E-05	1.220E+01	2.423E+01	9.890E+00	S
Bone surface	9.060E-04	7.950E-05	4.490E-04	2.467E+02	4.732E+02	1.991E+02	S
Stomach	1.580E-06	1.370E-07	7.810E-07	4.302E-01	8.155E-01	3.464E-01	S
S.I.	1.580E-06	1.380E-07	7.820E-07	4.302E-01	8.215E-01	3.468E-01	S
U.L.I.	1.590E-06	1.450E-07	7.890E-07	4.329E-01	8.631E-01	3.499E-01	S
L.L.I.	1.600E-06	1.630E-07	8.060E-07	4.356E-01	9.703E-01	3.575E-01	S
Skin	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
Spleen	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
Thymus	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
Uterus	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S
ET	1.520E-05	8.110E-05	2.460E-05	4.139E+00	4.828E+02	1.091E+01	S
Lung	2.350E-05	5.130E-05	2.970E-05	6.398E+00	3.054E+02	1.317E+01	S
Colon	1.590E-06	1.530E-07	7.970E-07	4.329E-01	9.108E-01	3.535E-01	S
ET1	3.160E-05	3.020E-05	3.080E-05	8.604E+00	1.798E+02	1.366E+01	S
ET2	1.520E-05	8.110E-05	2.460E-05	4.139E+00	4.828E+02	1.091E+01	S
LN(ET)	2.190E-06	1.320E-04	2.430E-06	5.963E-01	7.858E+02	1.078E+00	S
BBsec	6.360E-05	8.120E-05	7.760E-05	1.732E+01	4.834E+02	3.442E+01	S
BBbas	7.820E-06	9.500E-06	9.000E-06	2.129E+00	5.655E+01	3.991E+00	S
bb	2.460E-05	3.570E-05	2.970E-05	6.698E+00	2.125E+02	1.317E+01	S
AI	1.040E-05	7.160E-05	1.600E-05	2.832E+00	4.262E+02	7.096E+00	S
LN(TH)	4.430E-06	4.450E-04	7.280E-06	1.206E+00	2.649E+03	3.229E+00	S
Esophagus	1.580E-06	1.360E-07	7.810E-07	4.302E-01	8.096E-01	3.464E-01	S

IRF	3.673E-06	1.680E-07	2.255E-06

Table 3-14. Acute exposure of 1 Bq with urine sample 1,000 days later.

Organ or tissue	DCF (Sv/Bq)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
Urinary bladder	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
Brain	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
Breast	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
Gall bladder	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
Heart wall	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
Kidneys	3.930E-06	3.590E-07	1.950E-06	1.648E+00	2.071E+00	1.447E+00	S
Liver	1.910E-04	1.690E-05	9.490E-05	8.008E+01	9.751E+01	7.044E+01	S
Muscle	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
Ovaries	1.190E-05	1.050E-06	5.900E-06	4.989E+00	6.058E+00	4.379E+00	S
Pancreas	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
Testes	1.210E-05	1.070E-06	6.010E-06	5.073E+00	6.174E+00	4.461E+00	S
Thyroid	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
R.B.M.	4.480E-05	4.070E-06	2.230E-05	1.878E+01	2.348E+01	1.655E+01	S
Bone surface	9.060E-04	7.950E-05	4.490E-04	3.799E+02	4.587E+02	3.333E+02	S
Stomach	1.580E-06	1.370E-07	7.810E-07	6.624E-01	7.904E-01	5.797E-01	S
S.I.	1.580E-06	1.380E-07	7.820E-07	6.624E-01	7.962E-01	5.805E-01	S
U.L.I.	1.590E-06	1.450E-07	7.890E-07	6.666E-01	8.366E-01	5.857E-01	S
L.L.I.	1.600E-06	1.630E-07	8.060E-07	6.708E-01	9.405E-01	5.983E-01	S
Skin	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
Spleen	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
Thymus	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
Uterus	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
ET	1.520E-05	8.110E-05	2.460E-05	6.373E+00	4.679E+02	1.826E+01	S
Lung	2.350E-05	5.130E-05	2.970E-05	9.853E+00	2.960E+02	2.205E+01	S
Colon	1.590E-06	1.530E-07	7.970E-07	6.666E-01	8.828E-01	5.916E-01	S
ET1	3.160E-05	3.020E-05	3.080E-05	1.325E+01	1.742E+02	2.286E+01	S
ET2	1.520E-05	8.110E-05	2.460E-05	6.373E+00	4.679E+02	1.826E+01	S
LN(ET)	2.190E-06	1.320E-04	2.430E-06	9.182E-01	7.616E+02	1.804E+00	S
BBsec	6.360E-05	8.120E-05	7.760E-05	2.667E+01	4.685E+02	5.760E+01	S
BBbas	7.820E-06	9.500E-06	9.000E-06	3.279E+00	5.481E+01	6.681E+00	S
bb	2.460E-05	3.570E-05	2.970E-05	1.031E+01	2.060E+02	2.205E+01	S
AI	1.040E-05	7.160E-05	1.600E-05	4.360E+00	4.131E+02	1.188E+01	S
LN(TH)	4.430E-06	4.450E-04	7.280E-06	1.857E+00	2.568E+03	5.404E+00	S
Esophagus	1.580E-06	1.360E-07	7.810E-07	6.624E-01	7.847E-01	5.797E-01	S
IRF	2.385E-06	1.733E-07	1.347E-06				

Table 3-15. Acute exposure of 1 Bq with urine sample 4,000 days later.

Organ or tissue	DCF (Sv/Bq)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
Urinary bladder	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
Brain	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
Breast	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
Gall bladder	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
Heart wall	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
Kidneys	3.930E-06	3.590E-07	1.950E-06	4.052E+00	3.275E+00	3.901E+00	M
Liver	1.910E-04	1.690E-05	9.490E-05	1.969E+02	1.542E+02	1.899E+02	M
Muscle	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
Ovaries	1.190E-05	1.050E-06	5.900E-06	1.227E+01	9.579E+00	1.180E+01	M
Pancreas	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
Testes	1.210E-05	1.070E-06	6.010E-06	1.248E+01	9.762E+00	1.202E+01	M
Thyroid	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
R.B.M.	4.480E-05	4.070E-06	2.230E-05	4.620E+01	3.713E+01	4.461E+01	M
Bone surface	9.060E-04	7.950E-05	4.490E-04	9.342E+02	7.253E+02	8.983E+02	M
Stomach	1.580E-06	1.370E-07	7.810E-07	1.629E+00	1.250E+00	1.562E+00	M
S.I.	1.580E-06	1.380E-07	7.820E-07	1.629E+00	1.259E+00	1.564E+00	M
U.L.I.	1.590E-06	1.450E-07	7.890E-07	1.640E+00	1.323E+00	1.578E+00	M
L.L.I.	1.600E-06	1.630E-07	8.060E-07	1.650E+00	1.487E+00	1.612E+00	M
Skin	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
Spleen	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
Thymus	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
Uterus	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M
ET	1.520E-05	8.110E-05	2.460E-05	1.567E+01	7.399E+02	4.921E+01	S
Lung	2.350E-05	5.130E-05	2.970E-05	2.423E+01	4.680E+02	5.942E+01	S
Colon	1.590E-06	1.530E-07	7.970E-07	1.640E+00	1.396E+00	1.594E+00	M
ET1	3.160E-05	3.020E-05	3.080E-05	3.258E+01	2.755E+02	6.162E+01	S
ET2	1.520E-05	8.110E-05	2.460E-05	1.567E+01	7.399E+02	4.921E+01	S
LN(ET)	2.190E-06	1.320E-04	2.430E-06	2.258E+00	1.204E+03	4.861E+00	S
BBsec	6.360E-05	8.120E-05	7.760E-05	6.558E+01	7.408E+02	1.552E+02	S
BBbas	7.820E-06	9.500E-06	9.000E-06	8.064E+00	8.667E+01	1.801E+01	S
bb	2.460E-05	3.570E-05	2.970E-05	2.537E+01	3.257E+02	5.942E+01	S
AI	1.040E-05	7.160E-05	1.600E-05	1.072E+01	6.532E+02	3.201E+01	S
LN(TH)	4.430E-06	4.450E-04	7.280E-06	4.568E+00	4.060E+03	1.456E+01	S
Esophagus	1.580E-06	1.360E-07	7.810E-07	1.629E+00	1.241E+00	1.562E+00	M

IRF	9.698E-07	1.096E-07	4.999E-07

Table 3-16. Acute exposure of 1 Bq with urine sample 10,000 days later.

Organ or tissue	DCF (Sv/Bq)			Implied dose (Sv)			Limiting solubility type
	Type M	Type S	Type L	Type M	Type S	Type L	
Adrenals	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
Urinary bladder	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
Brain	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
Breast	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
Gall bladder	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
Heart wall	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
Kidneys	3.930E-06	3.590E-07	1.950E-06	7.144E+00	5.402E+00	7.021E+00	M
Liver	1.910E-04	1.690E-05	9.490E-05	3.472E+02	2.543E+02	3.417E+02	M
Muscle	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
Ovaries	1.190E-05	1.050E-06	5.900E-06	2.163E+01	1.580E+01	2.124E+01	M
Pancreas	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
Testes	1.210E-05	1.070E-06	6.010E-06	2.199E+01	1.610E+01	2.164E+01	M
Thyroid	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
R.B.M.	4.480E-05	4.070E-06	2.230E-05	8.144E+01	6.125E+01	8.029E+01	M
Bone surface	9.060E-04	7.950E-05	4.490E-04	1.647E+03	1.196E+03	1.617E+03	M
Stomach	1.580E-06	1.370E-07	7.810E-07	2.872E+00	2.062E+00	2.812E+00	M
S.I.	1.580E-06	1.380E-07	7.820E-07	2.872E+00	2.077E+00	2.815E+00	M
U.L.I.	1.590E-06	1.450E-07	7.890E-07	2.890E+00	2.182E+00	2.841E+00	M
L.L.I.	1.600E-06	1.630E-07	8.060E-07	2.908E+00	2.453E+00	2.902E+00	M
Skin	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
Spleen	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
Thymus	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
Uterus	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
ET	1.520E-05	8.110E-05	2.460E-05	2.763E+01	1.220E+03	8.857E+01	S
Lung	2.350E-05	5.130E-05	2.970E-05	4.272E+01	7.720E+02	1.069E+02	S
Colon	1.590E-06	1.530E-07	7.970E-07	2.890E+00	2.302E+00	2.869E+00	M
ET1	3.160E-05	3.020E-05	3.080E-05	5.744E+01	4.545E+02	1.109E+02	S
ET2	1.520E-05	8.110E-05	2.460E-05	2.763E+01	1.220E+03	8.857E+01	S
LN(ET)	2.190E-06	1.320E-04	2.430E-06	3.981E+00	1.986E+03	8.749E+00	S
BBsec	6.360E-05	8.120E-05	7.760E-05	1.156E+02	1.222E+03	2.794E+02	S
BBbas	7.820E-06	9.500E-06	9.000E-06	1.421E+01	1.430E+02	3.240E+01	S
bb	2.460E-05	3.570E-05	2.970E-05	4.472E+01	5.372E+02	1.069E+02	S
AI	1.040E-05	7.160E-05	1.600E-05	1.890E+01	1.077E+03	5.761E+01	S
LN(TH)	4.430E-06	4.450E-04	7.280E-06	8.053E+00	6.697E+03	2.621E+01	S
Esophagus	1.580E-06	1.360E-07	7.810E-07	2.872E+00	2.047E+00	2.812E+00	M
IRF	5.501E-07	6.645E-08	2.778E-07				

4.0 A DISCUSSION OF DISSOLUTION MODELS

The standard (left) and alternate (right) representations of the dissolution model in the ICRP Publication 66 human respiratory tract model (HRTM) are shown below in Figure 4-1 (ICRP 1994).

These two models are mathematically equivalent; that is, values for the parameters in the models can be selected so that identical rates of dissolution and absorption into the blood stream will result. The alternate form of the dissolution model can be used to represent the fraction $F(t)$ of the initial contents of the rapid and slow compartments that has not yet dissolved as:

$$F(t) = f_r e^{-k_r t} + (1 - f_r) e^{-k_s t} \quad (4\text{-}1)$$

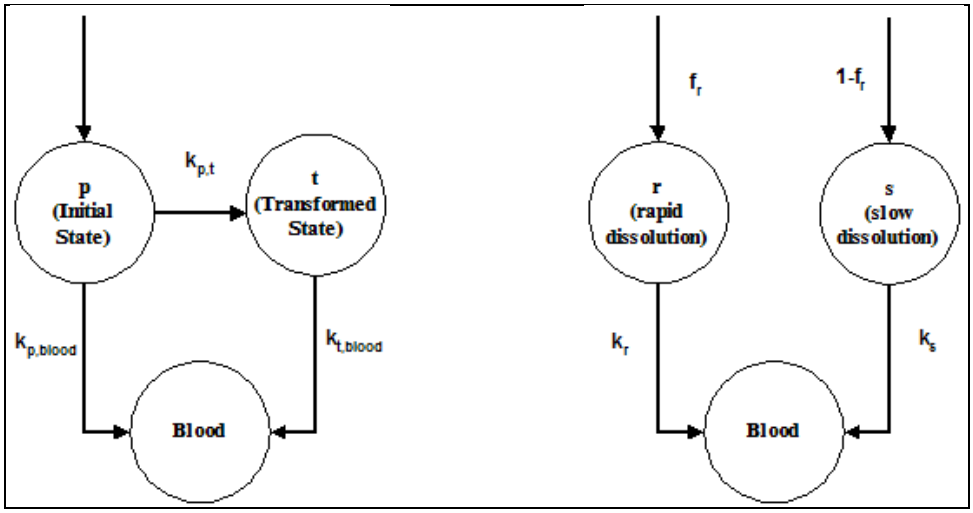

Figure 4-1. Standard (left) and alternate (right) forms of the ICRP Publication 66 dissolution model (ICRP 1994).

As discussed below, this formulation is useful for incorporating experimental dissolution data into the HRTM.

An in vitro lung solubility test is a method for estimating the rate at which inhaled material will dissolve in the lungs. The static method (Ansoborlo et al. 1999) consists of placing a sample of the material of interest between two permeable membranes. The test assembly is immersed in simulated lung fluid and allowed to sit for a period of time, during which some of the material between the membranes dissolves and goes into solution. After a prescribed length of time the test assembly is placed in fresh simulated lung fluid and the old fluid is analyzed to measure how much material has dissolved. This procedure is repeated over time and the undissolved fraction $F(t)$ at each time is plotted versus time. For example, the dissolution data for ^{238}Pu from an actual incident (Cheng et al. 2004) at LANL is shown in Figure 4-2 along with theoretical curves for type M and type S ^{238}Pu.

The experimental data were fit with a sum of two exponentials, the coefficients and rate constants of which correspond to the coefficients and rate constants of the dissolution model $F(t)$ (e.g., $f_r = 0.023$).

In a dissolution test on material that dissolved exactly like standard type M material, the dissolution curve in Figure 4-3 would be produced (note the linear-log scales). The parameters of the type M dissolution model, along with the parameters of other models, are presented in Table 4-1.

Two important characteristics of this curve are:

- Approximately 10% of the material dissolves rapidly (in less than a day), which is why the curve starts out at 0.9 on the *y*-axis rather than 1.0.

- Essentially all of the material dissolves in about 1,000 days.

The instantaneous rate at which the material is dissolving as a function of time is shown in Figure 4-4. (The curve in Figure 4-4 is the negative of the derivative of the curve in Figure 4-3 in relation to time.)

When material dissolves it goes to the bloodstream and part of it goes to the urine. Therefore, the urinary excretion rate of the material, ^{238}Pu in this case, would be expected to be highest shortly after the intake and then decrease monotonically. This is indeed what happens. The large rapidly dissolving fraction and overall high dissolution rate are what makes it relatively easy to detect intakes

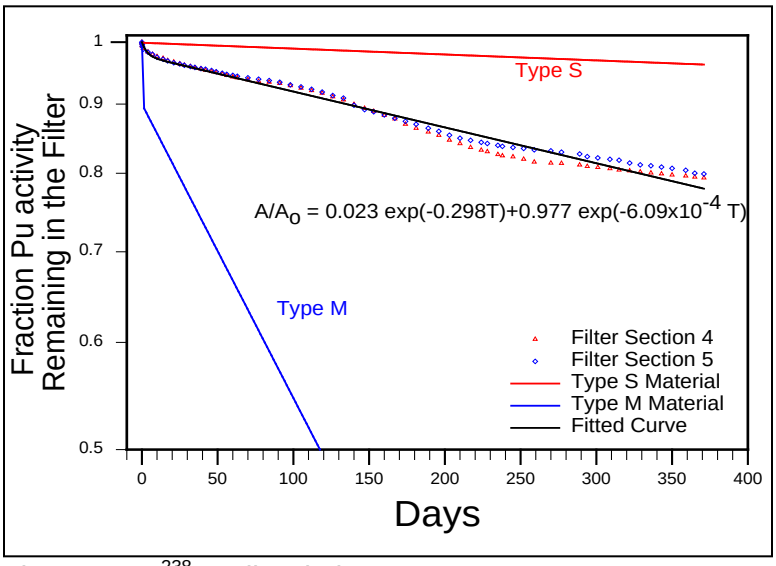

Figure 4-2. ^{238}Pu dissolution curve.

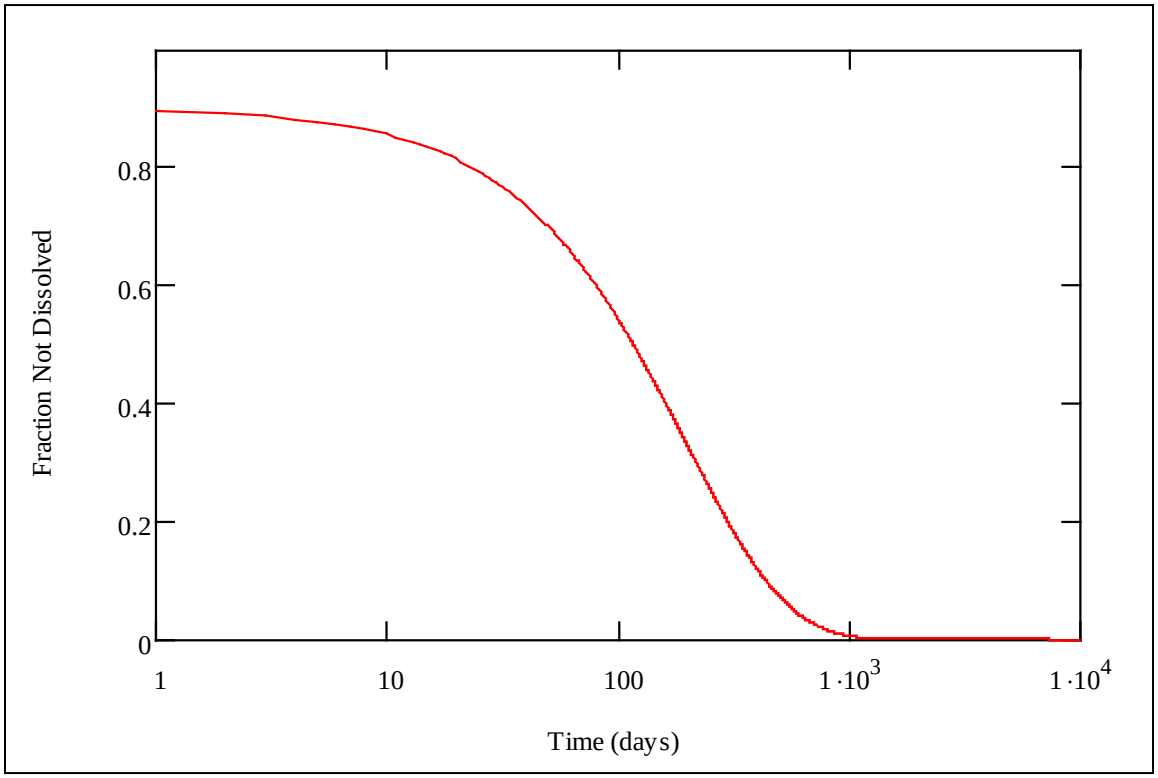

Figure 4-3. Dissolution curve for type M material.

Table 4-1. Summary of dissolution rate constants in both the standard and alternate forms (with IMBA notation).

IMBA	OTIB-83	M	S	J	L
Spt	k_{pt}	90	100	0.00189	0.02
St	$k_{t,blood}$	0.005	0.0001	0.000257	0.003341
Sp	$k_{p,blood}$	10	0.1	1.00E-06	1.00E-06
Sr	k_r	100	100.1	0.001891	0.02
Ss	k_s	0.005	0.0001	0.000257	0.003341
Fr	f_r	0.09995	0.001	-0.156671	-0.20048

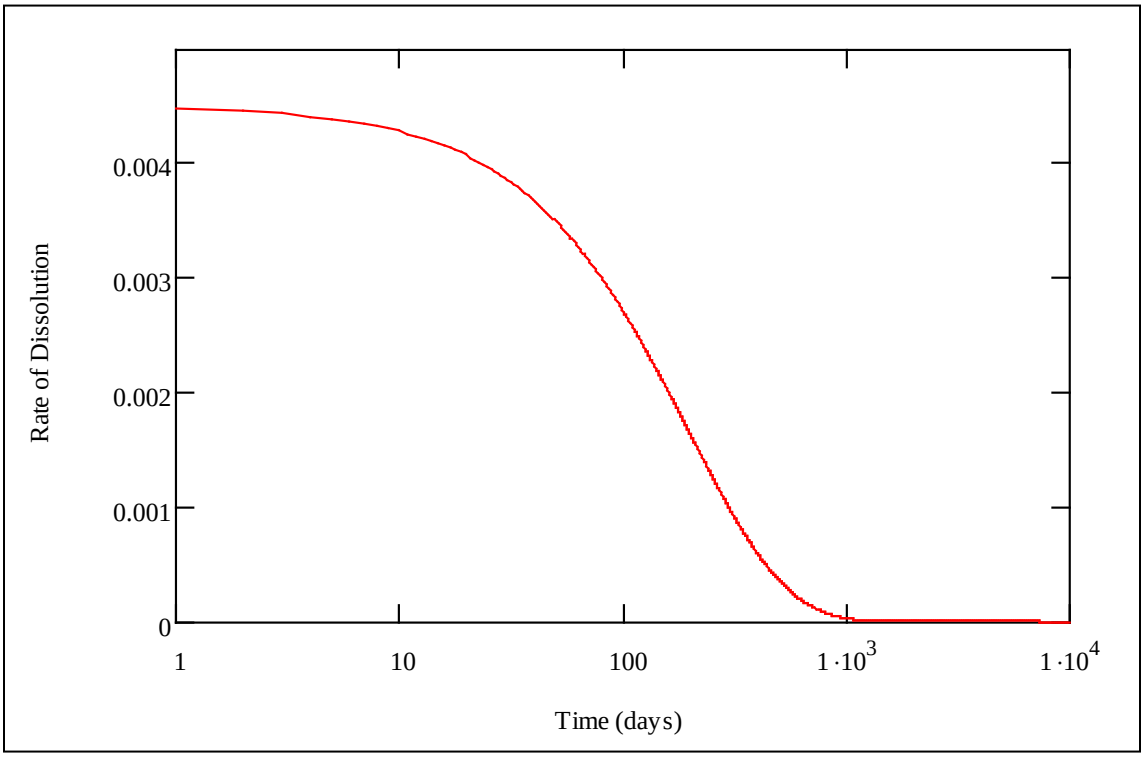

Figure 4-4. Rate of dissolution for type M material.

of type M ^{238}Pu by urine bioassay. The corresponding curves for type S material are given in Figures 4-5 to 4-7, with Figure 4-6 being Figure 4-5 with an expanded scale on the *y*-axis.

The plot in Figure 4-6 shows that the rapidly dissolving fraction for type S material is approximately 100 times smaller (0.1 ÷ 0.001 = 100) than the rapidly dissolving fraction for type M. This, combined with the much lower dissolution rate (compare the scale of the *y*-axis in Figure 4-7 to that of Figure 4-4) means that the urinary excretion rate after an intake of type S ^{238}Pu will be much lower than that after an intake of type M ^{238}Pu.

The dissolution model developed by James et al. (2003) for the ^{238}Pu cermet inhaled by the LANL workers in 1971 is referred to here as type J (see Section 4 for more details). The parameters for type J material are given in Table 4-1, and the dissolution curves expected from an *in vitro* lung solubility test of this material are given in Figures 4-8 to 4-10. Two important aspects of these curves are:

- Very little of the type J material dissolves in the first few months after the intake. In other words, type J material has essentially no rapidly dissolving fraction. Comparison of Figure 4-6 (type S) to Figure 4-9 (type J) makes this clear.

- The rate of dissolution is very low initially, increases over time, and peaks about 1,000 days after intake (Figure 4-8).

The practical implication of this behavior is that the urinary excretion rates after an intake of type J ^{238}Pu will be very low initially, increase over time, and peak at about 1,000 days after intake (the time of the peak in Figure 4-8). The nonmonotonic dissolution results in a nonmonotonic urinary excretion curve. This is illustrated in Figure 4-11, which shows the ^{238}Pu urinary excretion data for one of the 1971 LANL workers modeled with the type J model.

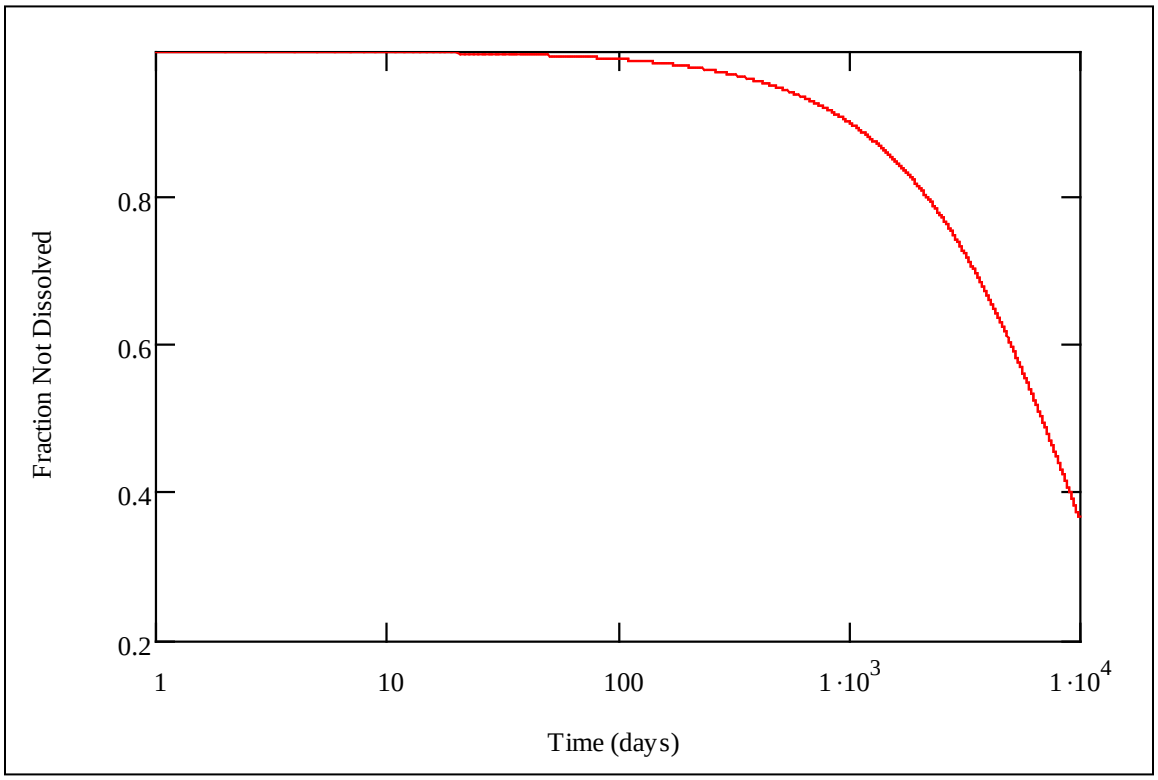

Figure 4-5. Dissolution curve for type S material.

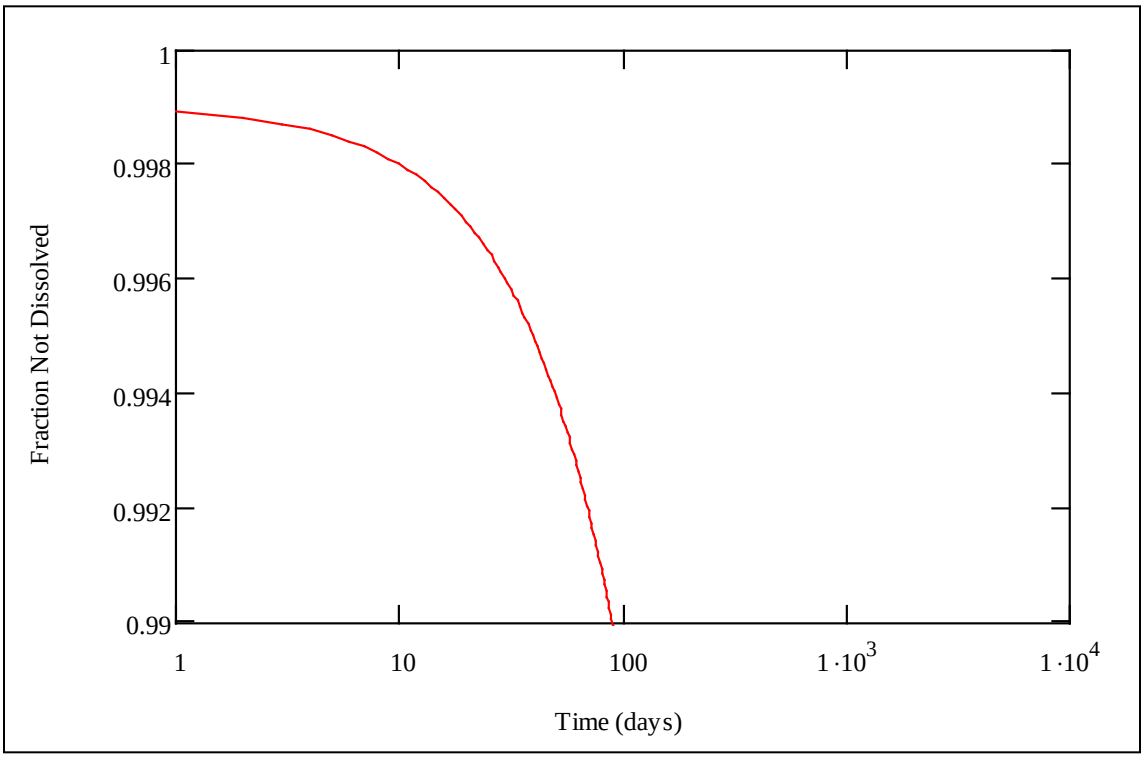

Figure 4-6. Dissolution curve for type S material (expanded *y*-axis).

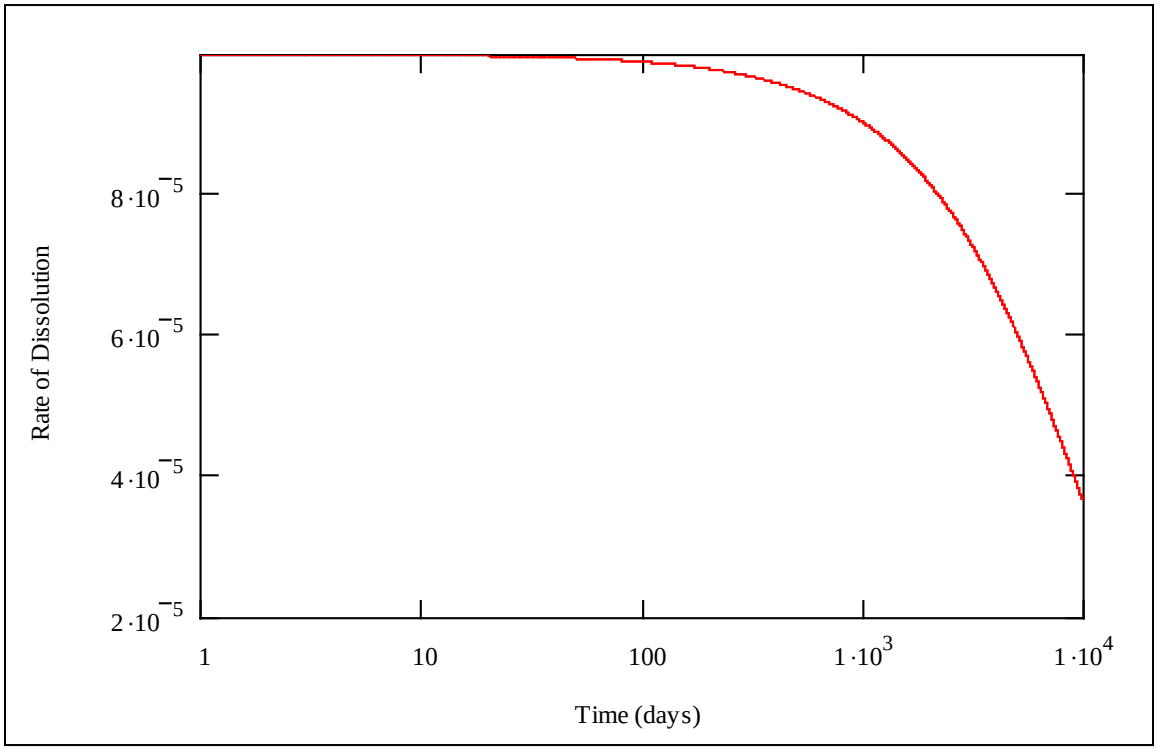

Figure 4-7. Rate of dissolution for type S material.

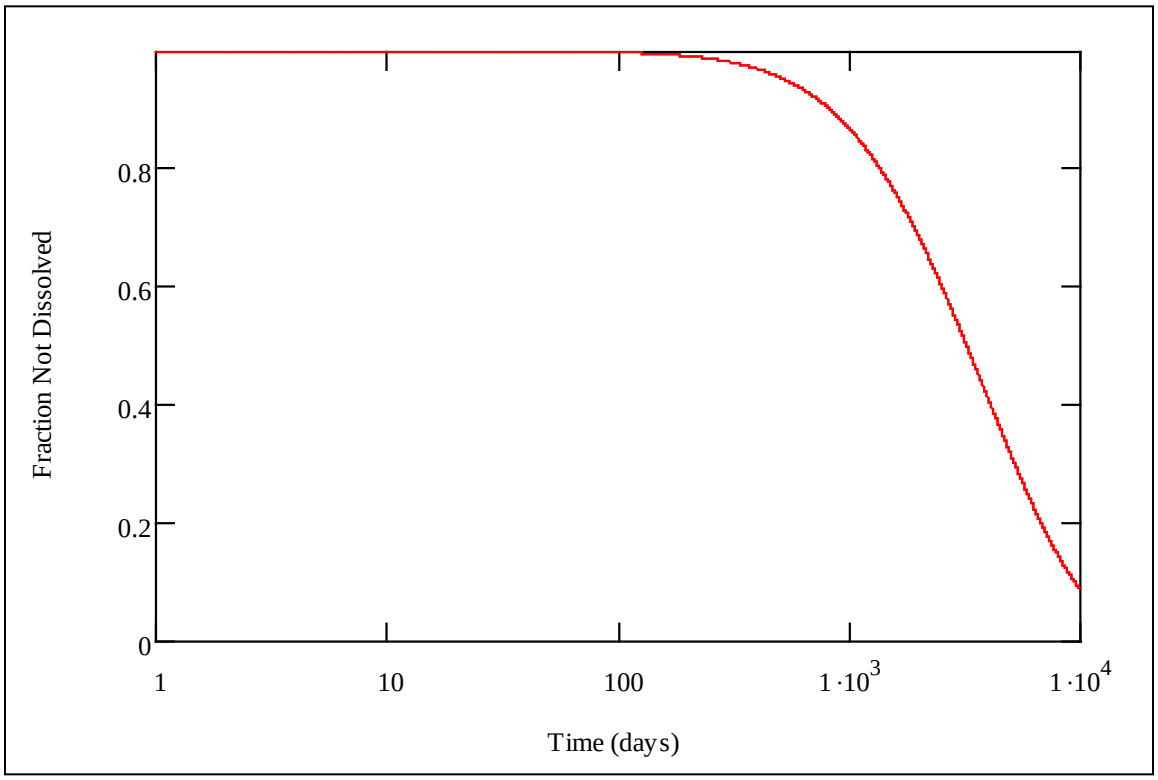

Figure 4-8. Dissolution for type J material.

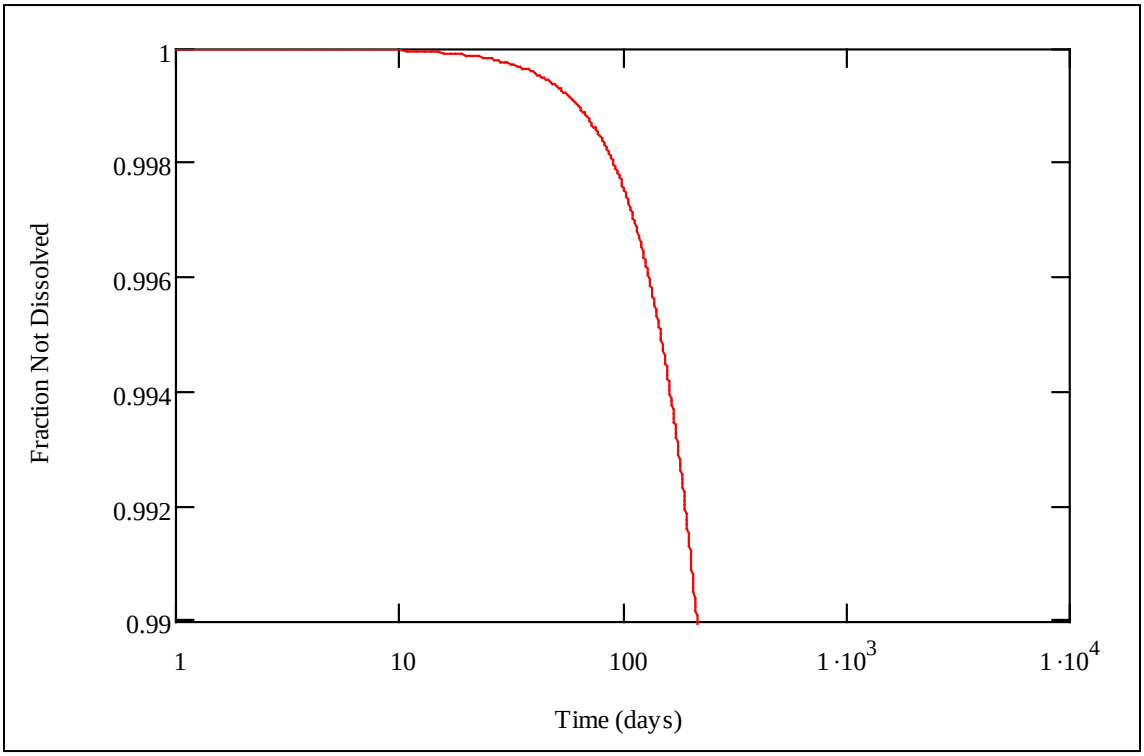

Figure 4-9. Dissolution curve for type J material (expanded *y*-axis).

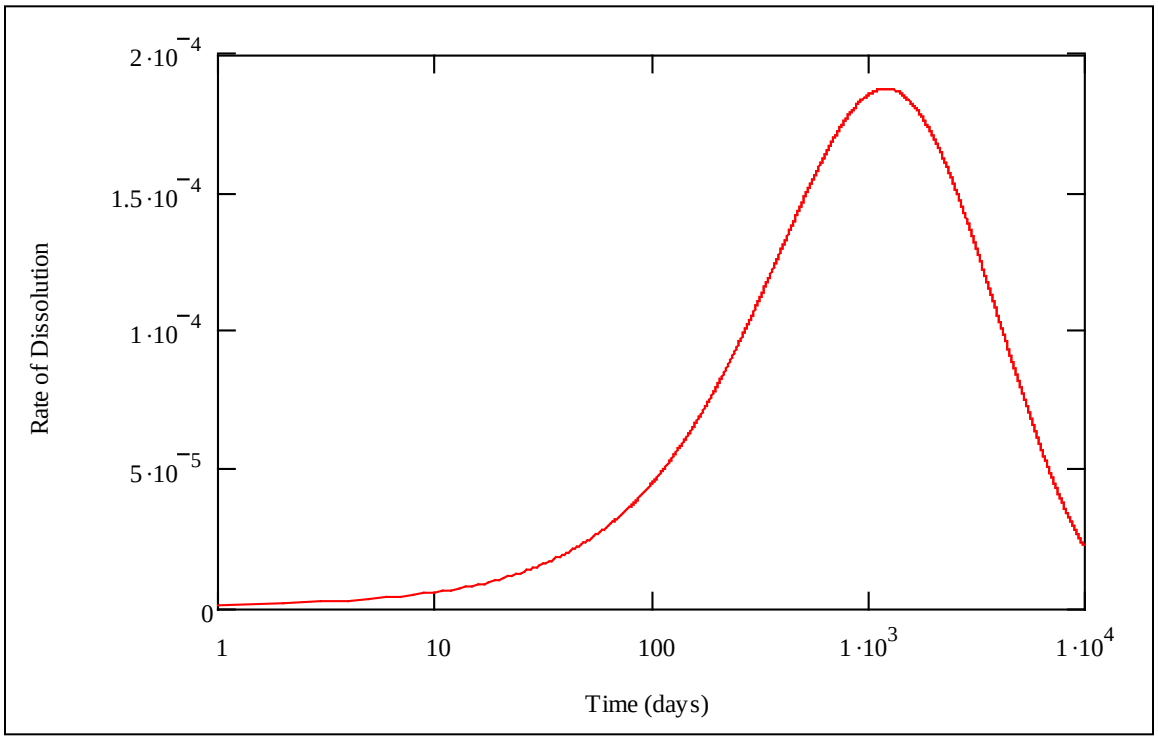

Figure 4-10. Dissolution rate for type J material.

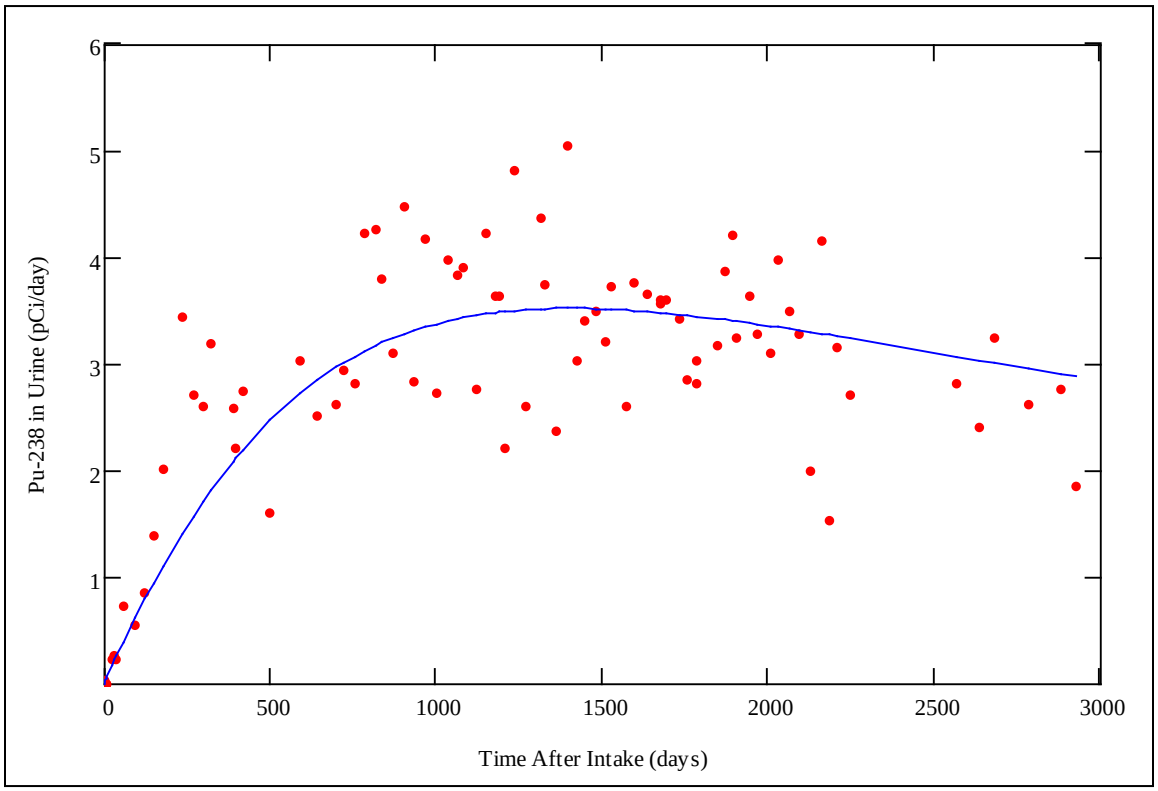

Figure 4-11. Urine data from 1971 LANL case modeled with type J ^{238}Pu.

The dissolution model for the ^{238}Pu oxide that was inhaled by the Mound workers in 1968 (as described by Woods and Sheehan 1971) is referred to here as type L. The parameters for type L material were estimated by starting with the type J parameters and modifying them iteratively until an acceptable fit to the urinary excretion data was obtained. The parameters for type L material are

given in Table 4-1, and the fits to the urine bioassay data are shown in Figures 4-12 to 4-16. (The value of k_r for Case 1 is 2 times the value given in Table 4-1 for Type L material; that is, the initial dissolution rate for Case 1 was twice that of the other four cases.)

The expected dissolution curves from an *in vitro* lung solubility test of type L material are given in Figures 4-17 through 4-19. The dissolution rate curve for type L material (Figure 4-19) resembles the dissolution rate curve for type J material (Figure 4-10) in that it is nonmonotonic. Perhaps for this reason the two types of material are frequently discussed together as if they were the same.

However, if the dissolution rate curves for type L and type J material are presented on the same plot (Figure 4-20) the differences in the materials becomes apparent:

- Type L material has a much higher rapidly dissolving fraction than type J material.
- The dissolution rate for type L is much higher than for type J.
- The dissolution rate (and therefore the urinary excretion rate) for type L peaks in about 100 days versus 1,000 days for type J.

High specific activity ^{238}Pu materials experience self-irradiation damage and fragmentation to some extent even if the materials do not happen to be in the lung (Icenhour 2005). This results in the eventual formation of more soluble ^{238}Pu compounds as the initially insoluble material ages (ORAUT 2008), which in turn tends to support a higher short-term urinary excretion rate. The practical

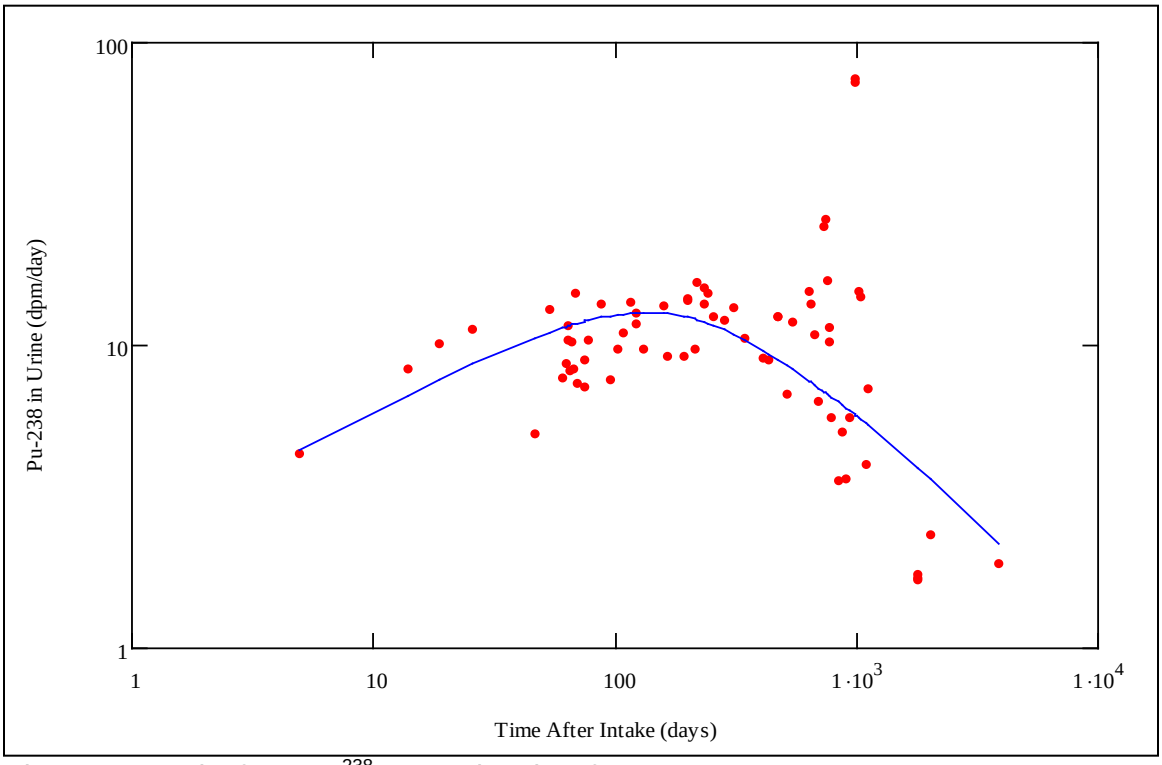

Figure 4-12. Fit of type L ^{238}Pu to urine data from Case 1.

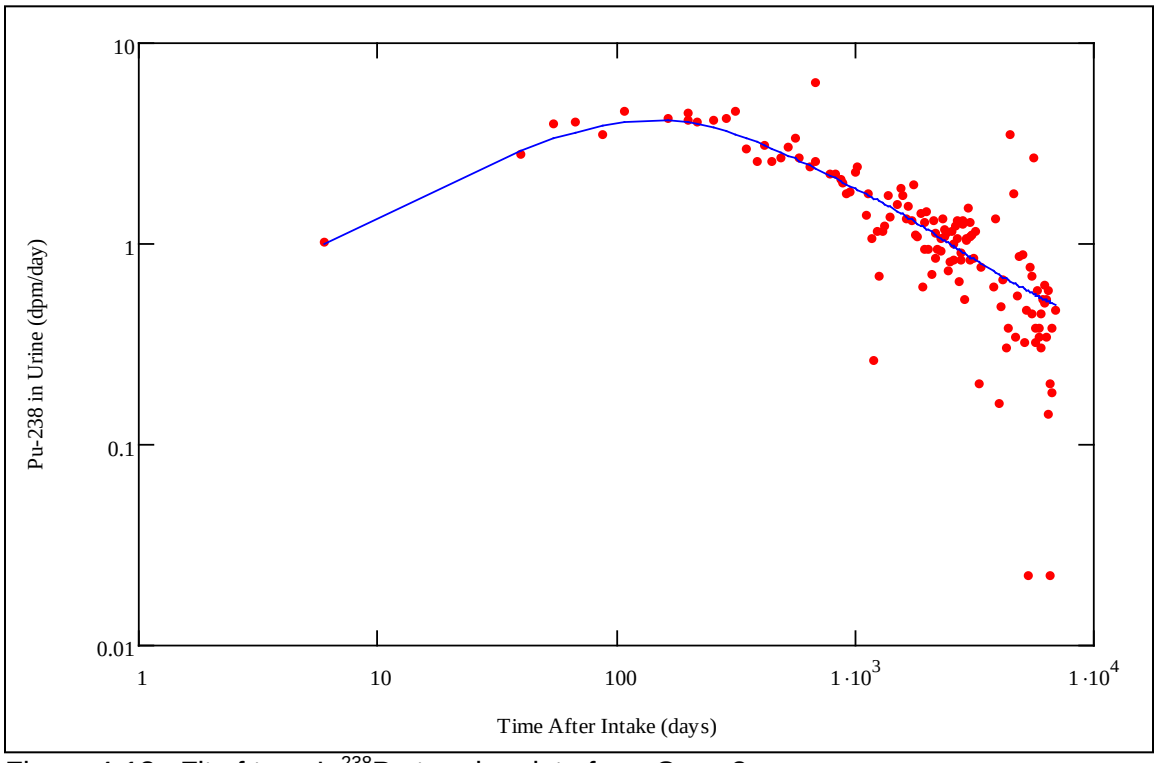

Figure 4-13. Fit of type L ^{238}Pu to urine data from Case 2.

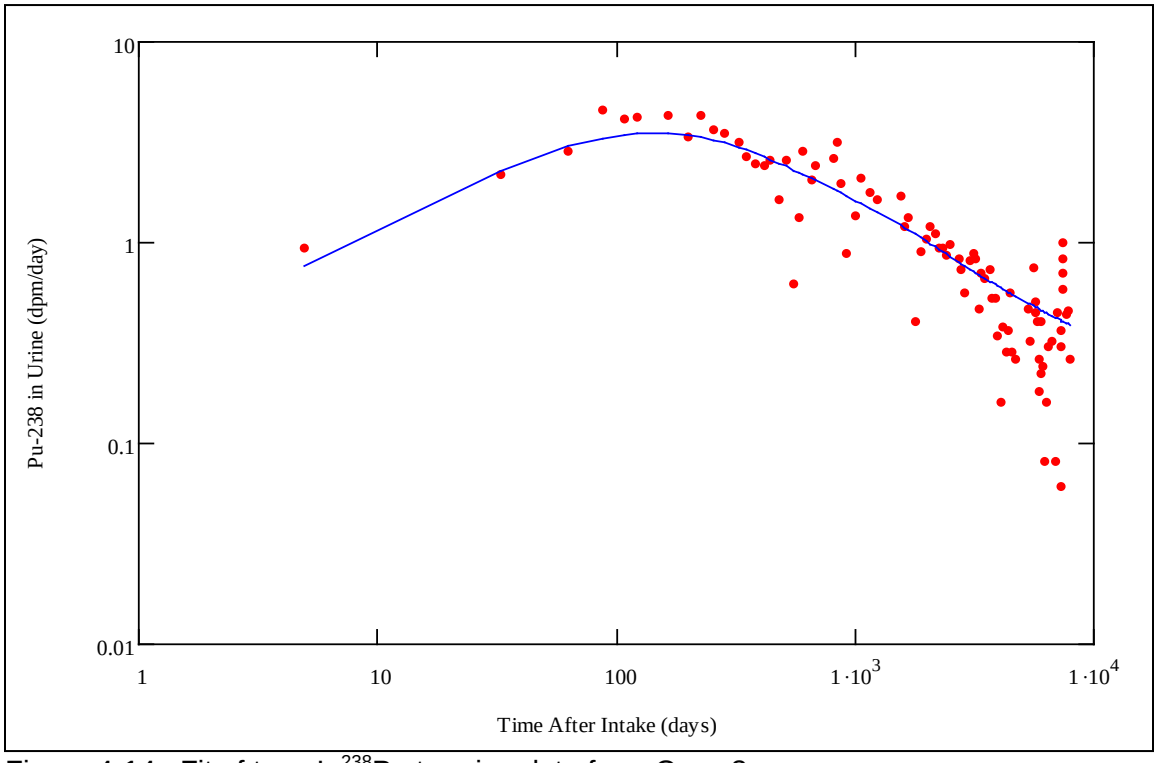

Figure 4-14. Fit of type L ^{238}Pu to urine data from Case 3.

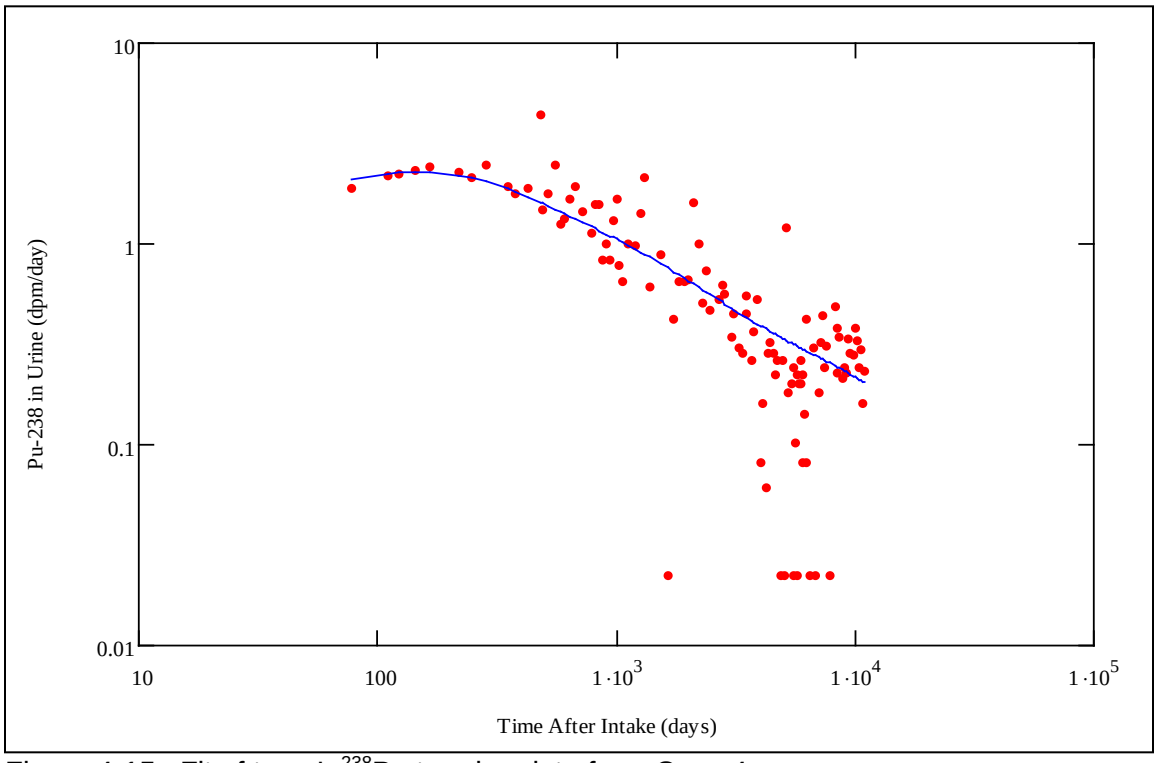

Figure 4-15. Fit of type L ^{238}Pu to urine data from Case 4.

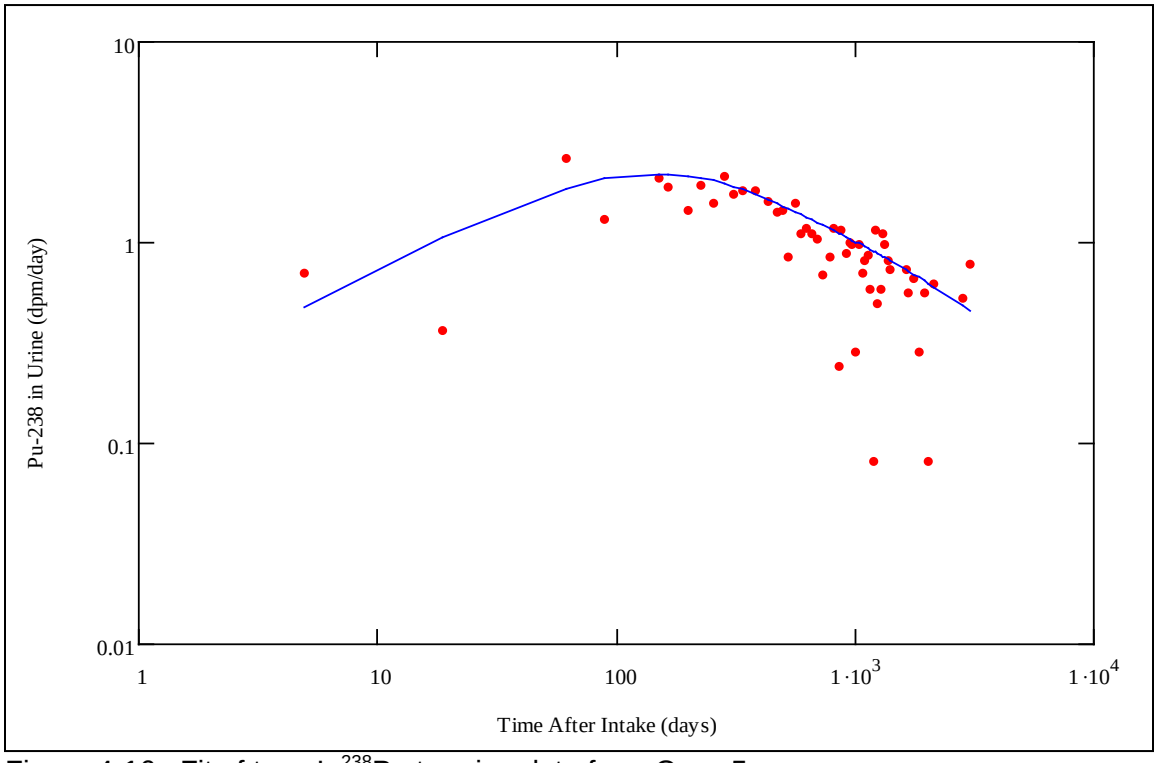

Figure 4-16. Fit of type L ^{238}Pu to urine data from Case 5.

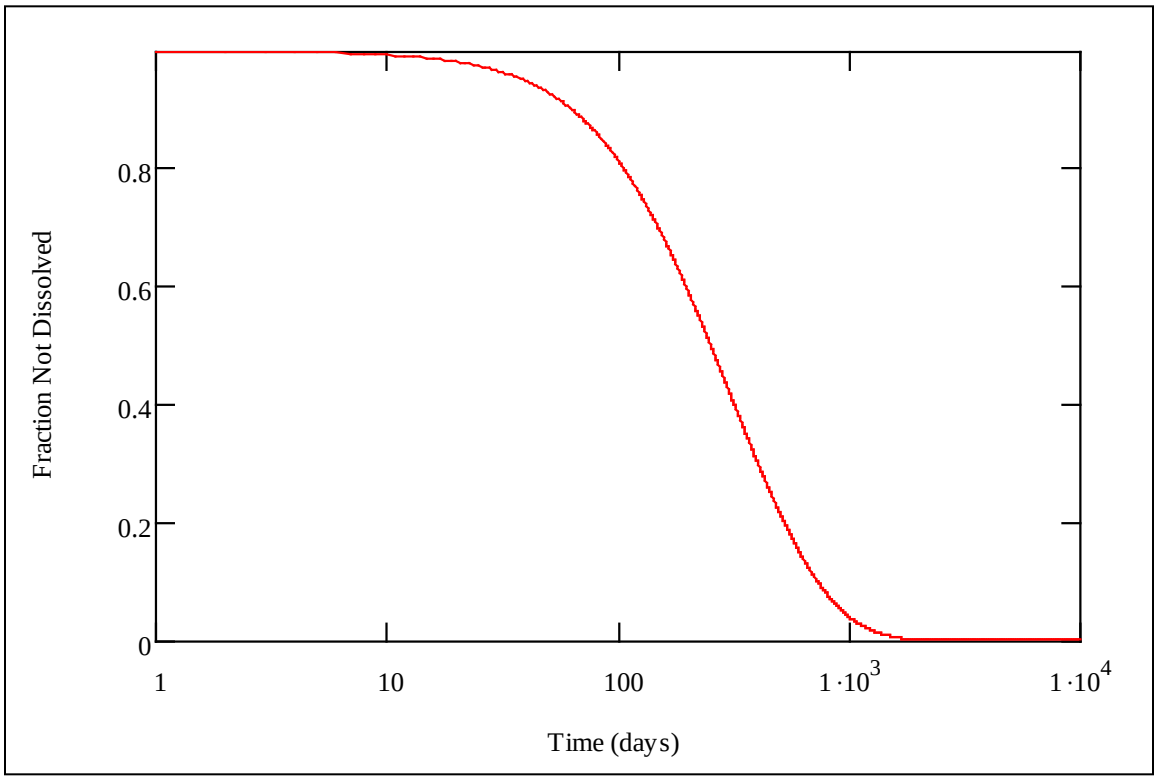

Figure 4-17. Dissolution curve for type L material.

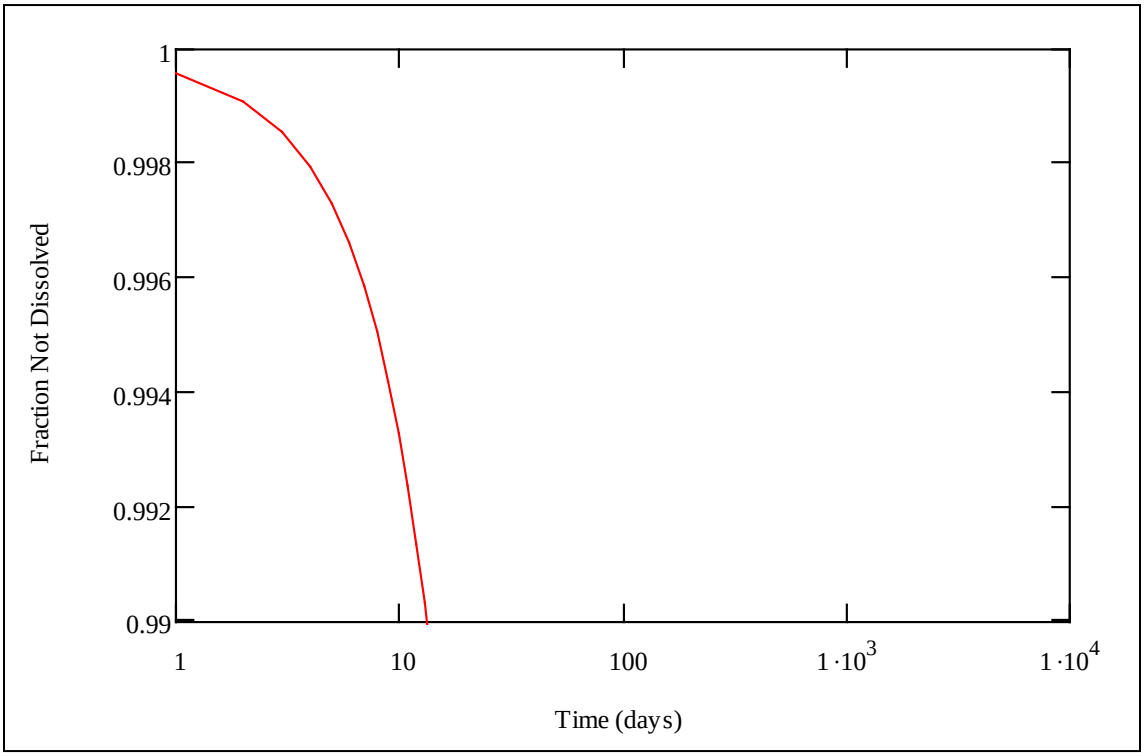

Figure 4-18. Dissolution curve for type L material (expanded *y*-axis).

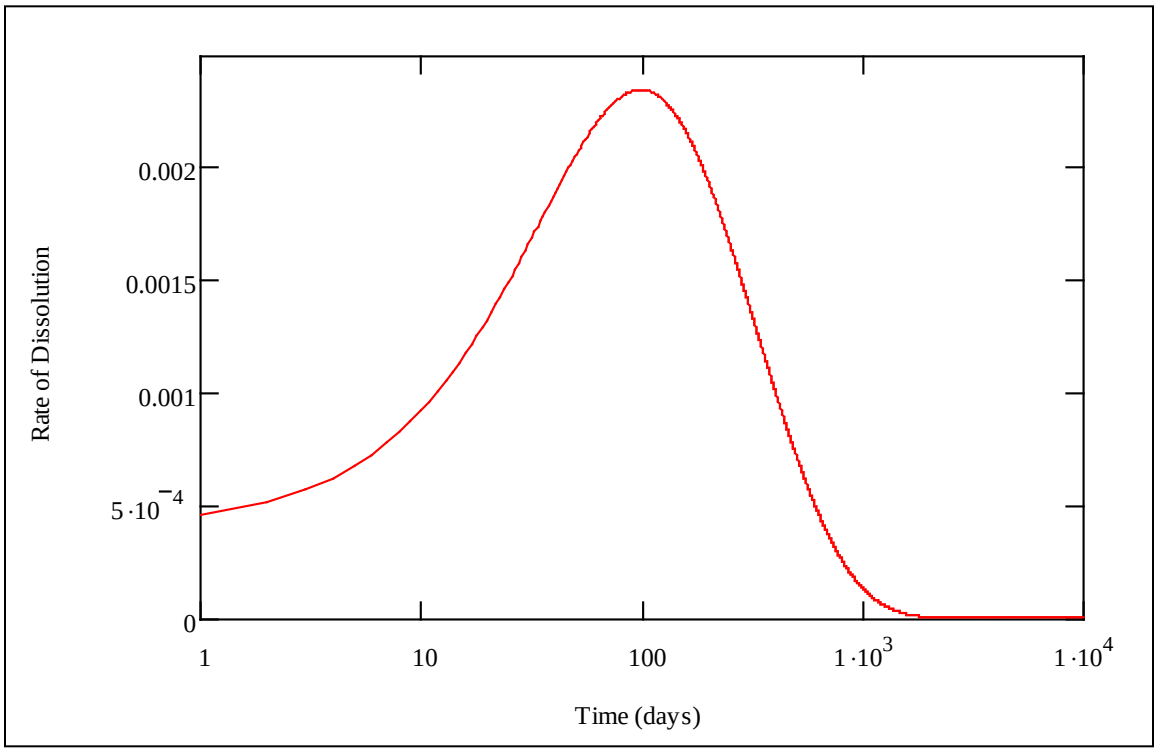

Figure 4-19. Rate of dissolution for type L material.

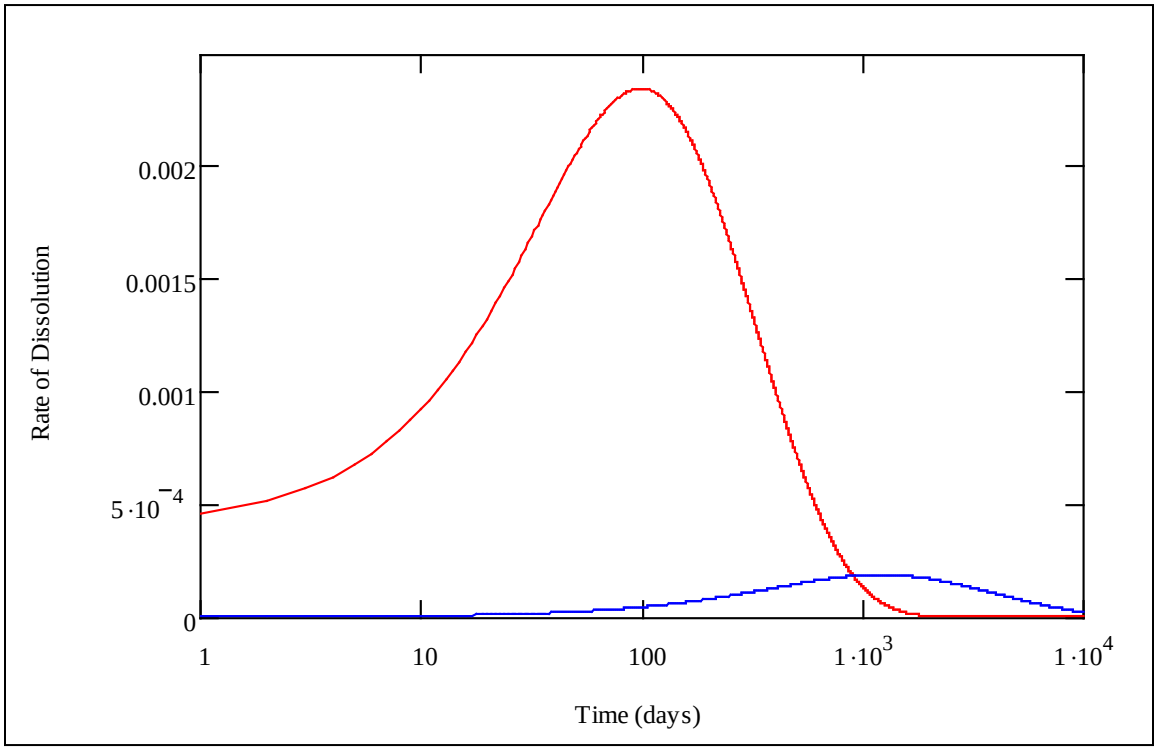

Figure 4-20. Comparison of rate of dissolution curves for types J (in red) and L (in blue) material.

consequence of this is that, even if it is present, type L or J ^{238}Pu eventually partially degrade into more soluble forms that more closely resemble standard dissolution types.

In summary, parameters for a dissolution model (type L material) based on exposures of Mound personnel is presented here.

5.0 A DISCUSSION OF THE WING-9 PLUTONIUM-238 CERMET

One of the primary industrial applications of ^{238}Pu uses its high specific activity in a radioisotopic thermoelectric generator (RTG) to generate heat, which is in turn converted to electricity. These RTGs are used when a reliable, compact source of electricity is needed (e.g., deep space missions). One type of RTG was fabricated out of an extremely stable ceramic ^{238}Pu (DOE 1993, Section 2.2.1.2) that was designed to survive reentry into the earth's atmosphere from space. In 1971, seven individuals in Wing-9 at LANL were working with such an RTG in a glovebox when they were inadvertently exposed to airborne material that was released through a hole in the glove. The material was described as a ceramic ^{238}Pu with a molybdenum binder. There are few other details on the specifics of this event; the available information comes from brief descriptions in the open literature like those by Miller, Inkret, and Martz (1999), Guilmette, Griffith, and Hickman (1994), and Hickman et al. (1995).

Discussions with individuals who were involved in the event that were published in 1995 indicate that they were disassembling Systems for Nuclear Auxiliary Power (SNAP)-19 RTGs, which were used on the Pioneer deep space probes and the Transit navigation satellites (LANL 1995, pp. 137, 145). SNAP-19s were constructed from ^{238}Pu cermet (DOE 1993, Table II.3). A "cermet" is a composite material composed of a metal and a ceramic, which are molybdenum and high-fired plutonium oxide, respectively, in this case. A cermet is produced by coating high-fired plutonium oxide with molybdenum and then heating the mixture under extreme pressure. The cermet is technically the chunk of material, not the ingredients that go into it. This means that to be exposed to a plutonium-bearing cermet, there must be a mechanism that generates a respirable airborne aerosol from the chunk of material.

The principal investigator present during the Wing 9 event wrote a report in 1975 in which he discussed the results of studies on the degradation of the capsule that was used to keep the plutonium from dispersing as a result of a launch accident (Mulford 1975). The RTG that was the source of the contamination that night was designated[1] TF-1, and it had been subjected to a fairly violent vibration test meant to reproduce launch conditions and then destructively analyzed (cut open) (Mulford 1975). Some contamination was always produced in a test like this, but if the cermet disks did not fit snugly in the outer capsule a relatively large amount of respirable cermet aerosol could be produced (Johnson 2008). It appears that TF-1 was subjected to a vibration test that created powdered cermet of respirable size in the RTG. The RTG was cut open, and it released the cermet powder into the hot cell. Because of over pressurization in the containment (the operation had to be performed in an inert atmosphere) and a leak in a manipulator boot, the respirable aerosol was released into the cold area where the seven workers were exposed.

Three different models are known to have been used to evaluate the urinary excretion data from the workers involved in the Wing 9 incident. For the first, LANL developed an in-house model that was described briefly by Miller, Inkret, and Martz (1999), but it has not been published in a peer-reviewed journal. The model is based on ICRP Publication 30 models (1979) but uses rate functions rather than rate constants; that is, the rate constants in the model change over time. For the second, Hickman used a modified Mewhinney "beagle" model to evaluate the urinary excretion data from the LANL workers. This is a custom compartmental model based on neither the Publication 30 nor the Publications 66 and 68 (ICRP 1994, 1995) models. In the third, James et al. (2003) modeled the urinary excretion and autopsy data from one of the individuals involved in the LANL incident. They

[1] Indicating that it was for a Transit satellite rather than a Pioneer probe.

found that the case could be adequately modeled using the standard Publications 66 and 68 biokinetic model with the modified dissolution function shown in Figure 5-1 (as entered into IMBA).

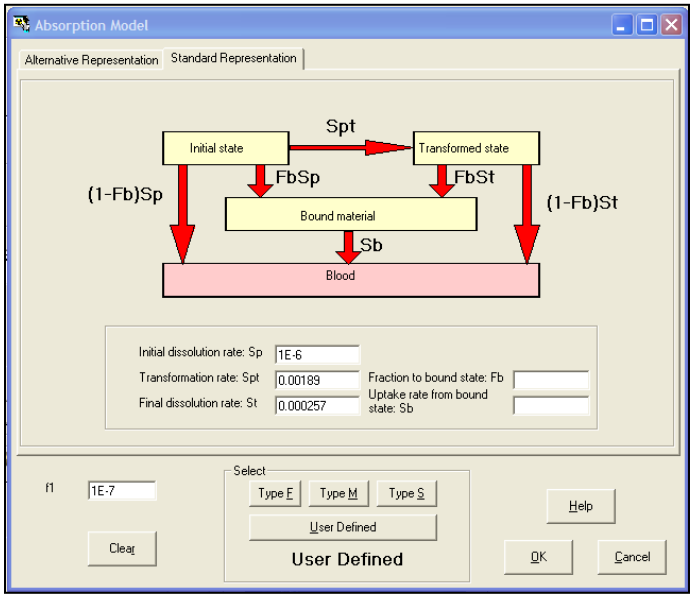

Figure 5-1. Type J dissolution parameters in IMBA.

The James et al. (2003) model is considered to be the most appropriate of the three because:

- The model uses a custom dissolution function within the framework of the standard ICRP Publications 66 and 68 models (ICRP 1994, 1995). The use of custom dissolution functions is the approach recommended in ICRP (2000, Section 5.5.2) and it allows the model to be implemented in IMBA.
- The custom dissolution function is based on human urinary excretion and autopsy data.
- The model was published in a peer-reviewed journal; it is not an in-house model.
- As shown below, the model provides an acceptable fit to the urinary excretion data of six of the seven the workers exposed the ceramic ^{238}Pu at LANL in 1971 (the urine data for the seventh worker are not available).

Fits to six of the LANL ceramic ^{238}Pu cases are shown in Figures 5-2 through 5-7.

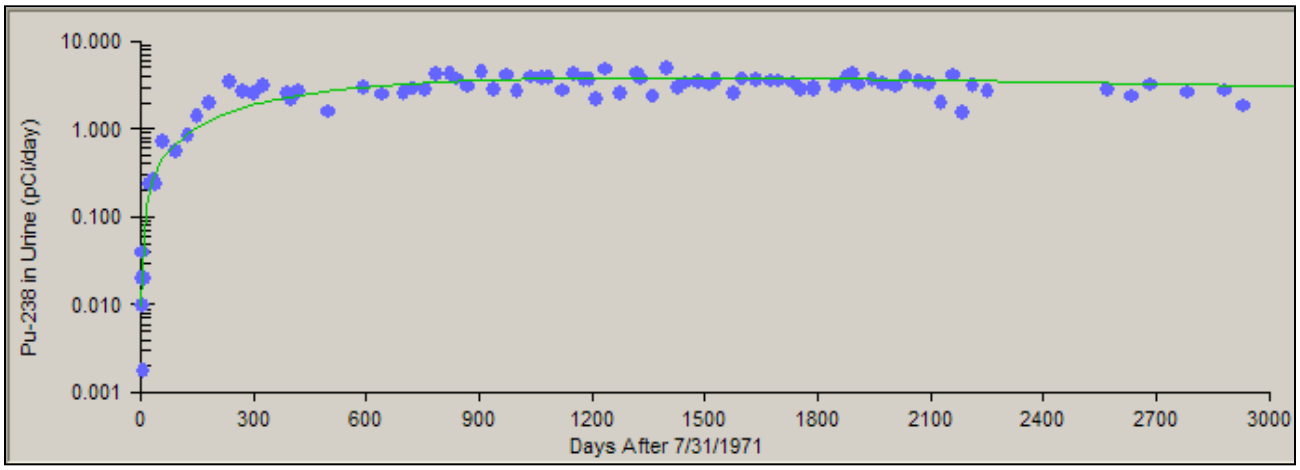

Figure 5-2. Fit to urinary excretion from LANL Case 1 with type J plutonium.

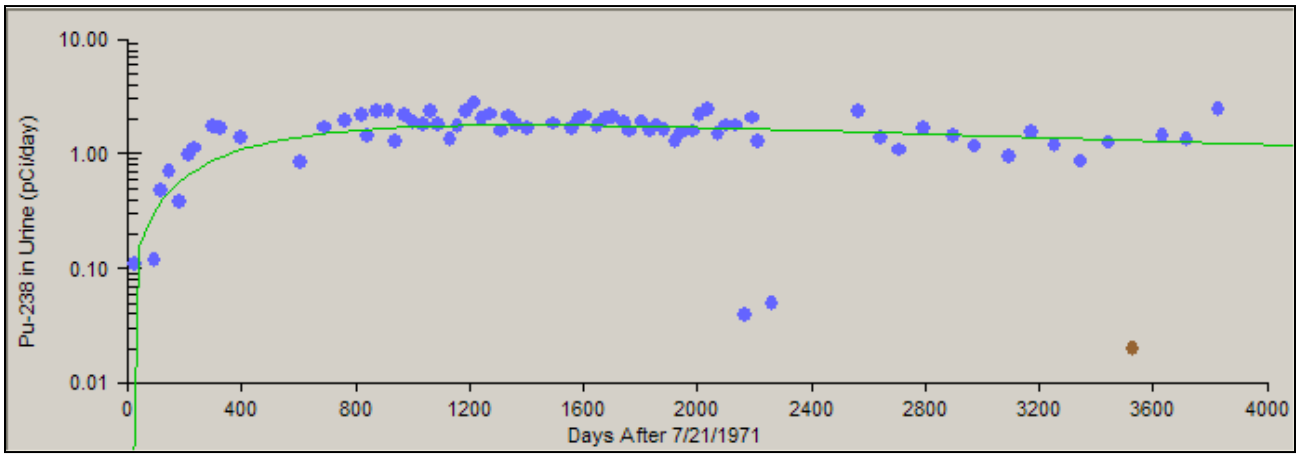

Figure 5-3. Fit to urinary excretion from LANL Case 2 with type J plutonium.

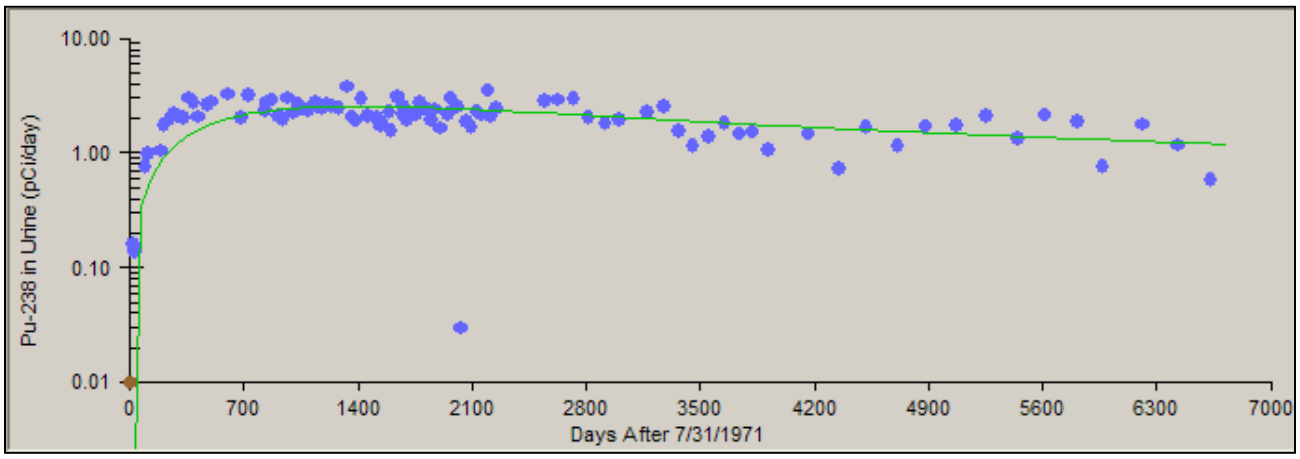

Figure 5-4. Fit to urinary excretion from LANL Case 3 with type J plutonium.

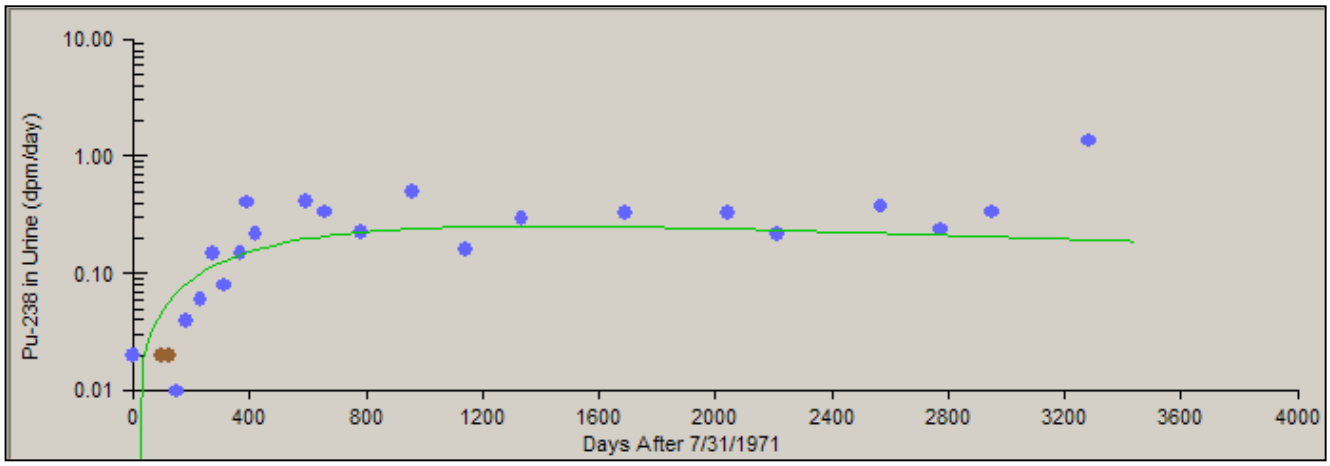

Figure 5-5. Fit to urinary excretion from LANL Case 4 with type J plutonium.

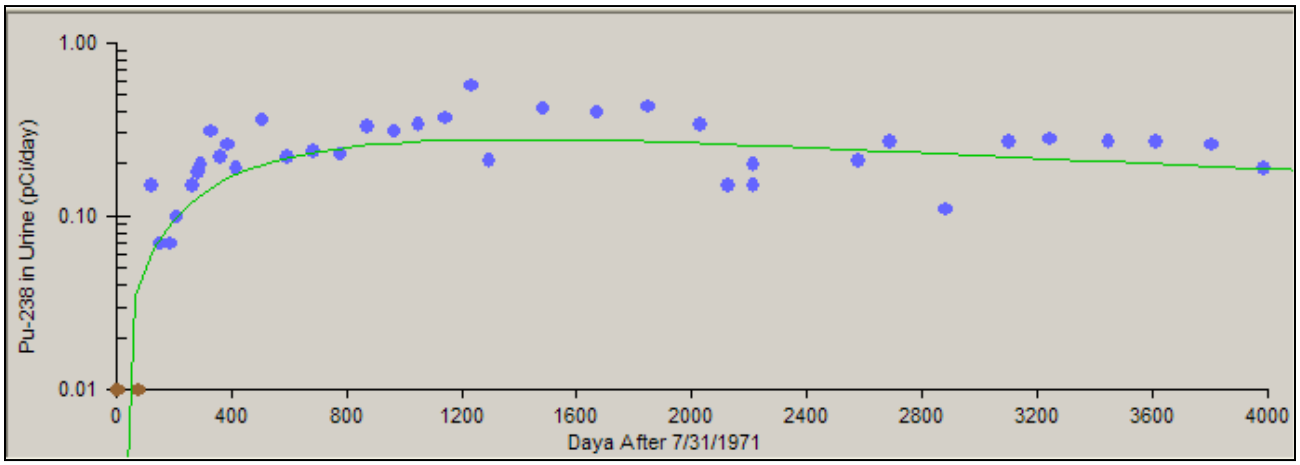

Figure 5-6. Fit to urinary excretion from LANL Case 5 with type J plutonium.

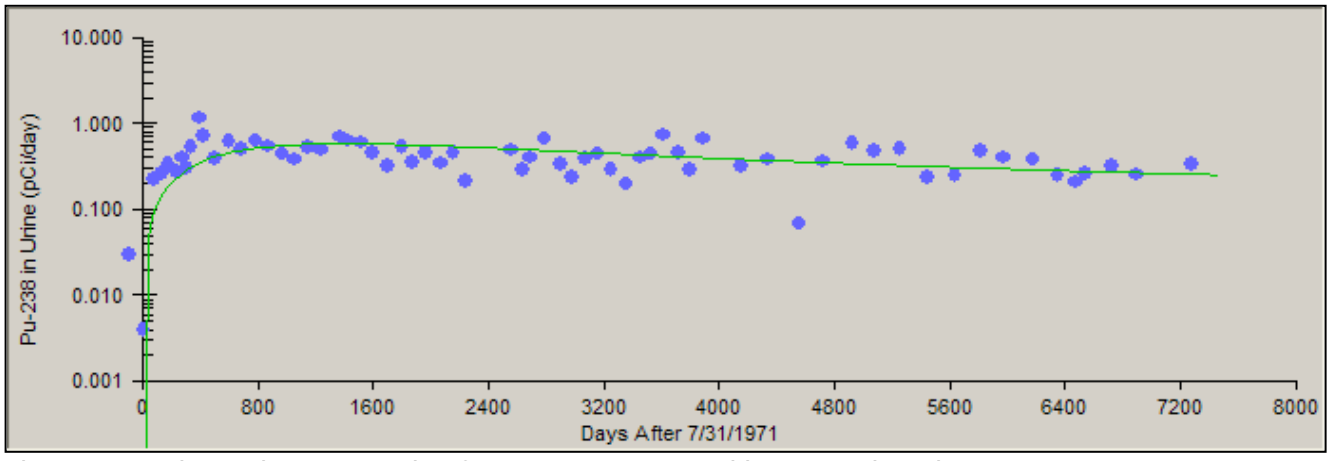

Figure 5-7. Fit to urinary excretion from LANL Case 6 with type J plutonium.

No other known occupational exposure cases with urinary excretion patterns that exhibited the extreme initial insolubility in the LANL Wing 9 cases have been observed at LANL or elsewhere in the DOE complex[2]. For example, a LANL case with an excretion pattern similar to what might be

[2] This is in agreement with comments made by [Name Redacted], the former [Title Redacted] at LANL, and the personal experiences of [Name Redacted], the former [Title Redacted] at SRS.

expected from type J material was described by Miller et al. (2002) and is shown in Figures 5-8 and 5-9.[3]

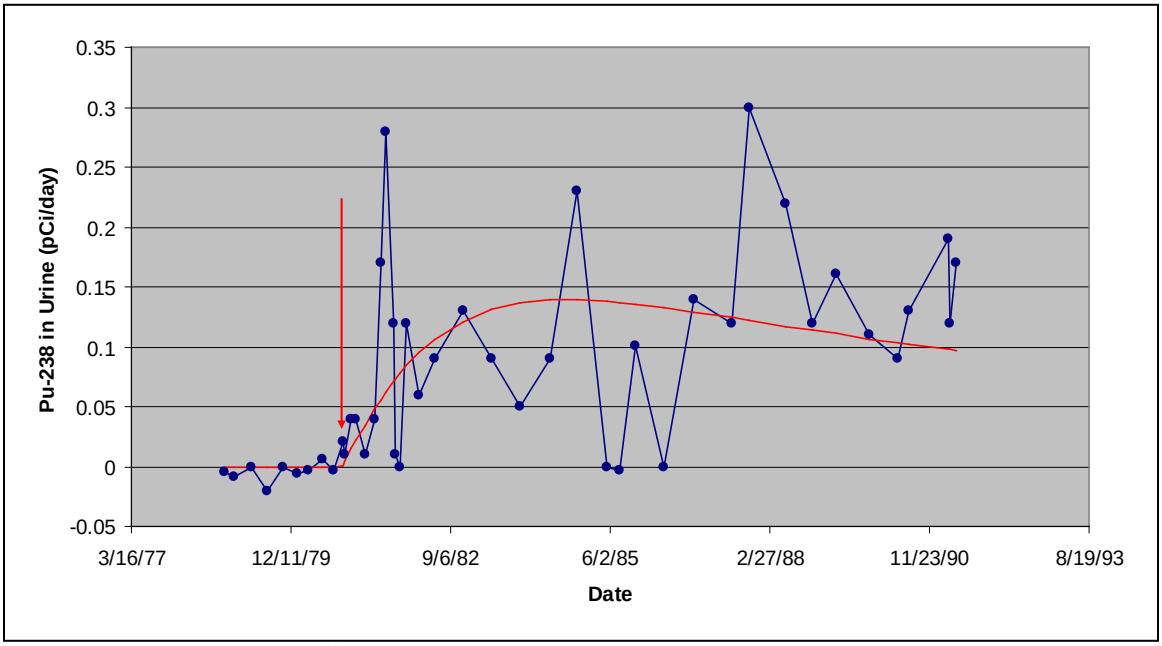

Figure 5-8. Fit of type J ^{238}Pu to urinary excretion data. The intake was a known incident that occurred on October 31, 1980 (red arrow on the plot).

The observed urinary excretion shortly after the intake (0.02 pCi/day on 11/3/1980), which is key in detecting intakes by urine bioassay, is over 20 times higher than what the type J model predicts on the same day (9.43E-4 pCi/day). The main point here is that ^{238}Pu compounds can exhibit a range of solubility characteristics and that the behavior of the LANL ^{238}Pu cermet in the Wing 9 incident, especially the initial solubility, should be considered to be extreme rather than typical.

[3] There is a considerable amount of variability in the daily excretion rates, which suggests that these were not true 24-hour urine samples.

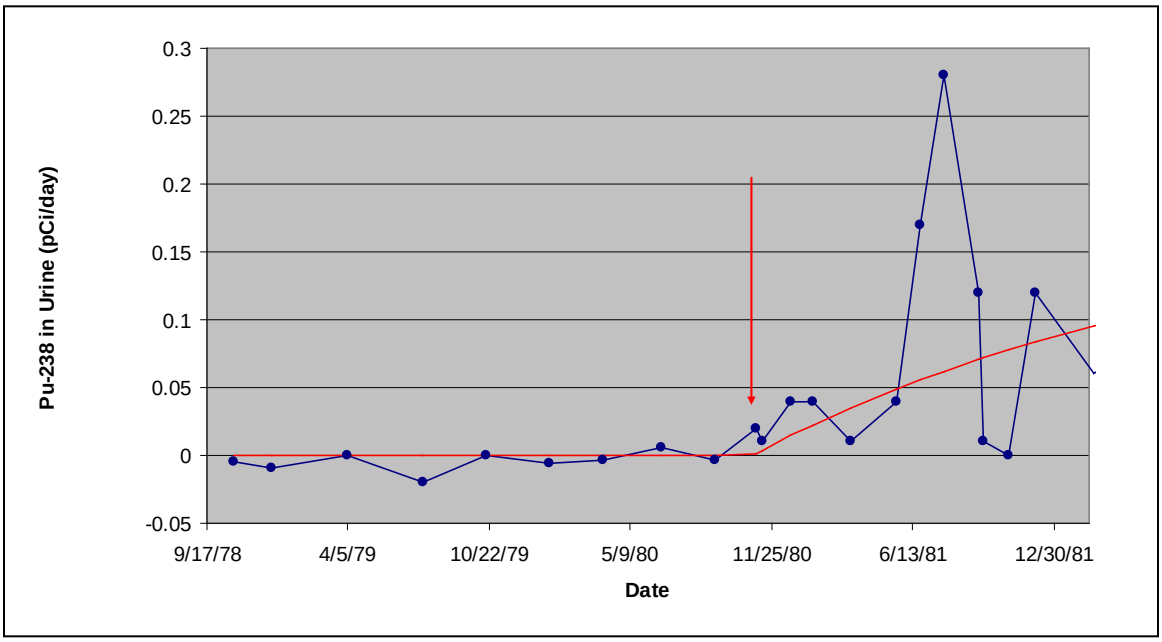

Figure 5-9. Figure 5-8 with expanded time scale to show details at time of intake.

6.0 ATTRIBUTIONS AND ANNOTATIONS

All information requiring identification was addressed via references integrated into the reference section of this document.

REFERENCES

Ansoborlo, E., M. H. Hengé-Napoli, V. Chazel, R. Gibert, and R. A. Guilmette, 1999, "Review and Critical Analysis of Available In Vitro Dissolution Tests," *Heath Physics*, volume 77, number 6, pp. 638–645.

Cheng, Y. S., R. A. Guilmette, Y. Zhou, J. Gao, T. Labone, J. J. Whicker, and M. D. Hoover, 2004, "Characterization of Plutonium Aerosol Collected During an Accident," *Health Physics*, volume 87, number 6, pp. 596–605. [SRDB Ref ID: 25247]

DOE (U.S. Department of Energy), 1993, *Operable Unit 9, Site Scoping Report: Volume 7 - Waste Management*, Final (Rev. 0), EG&G MOUND-29-01-01-07-07-9502080001, Albuquerque Field Office, Albuquerque, New Mexico, February. [SRDB Ref ID: 11877].

Guilmette, R. A., W. C. Griffith, and A. W. Hickman, 1994, "Intake Assessment for Workers Who Have Inhaled Pu-238 Aerosols," *Radiation Protection Dosimetry*, volume 53, numbers 1–4, pp. 127–131. [SRDB Ref ID: 120904]

Hickman, A. W., W. C. Griffith, G. S. Roessler, and R. A. Guilmette, 1995, "Application of a Canine ^{238}Pu Biokinetics/Dosimetry Model to Human Bioassay Data," *Health Physics*, volume 68, number 3, pp. 359–370.

Icenhour, A. S., 2005, *Transport of Radioactive Material by Alpha Recoil*, ORNL/TM-2005/22, UT-Battelle, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May.

ICRP (International Commission for Radiological Protection), 1979, *Limits for Intakes of Radionuclides by Workers*, Publication 30, Part 1, Pergamon Press, Oxford, England. [SRDB Ref ID: 22733]

ICRP (International Commission for Radiological Protection), 1994, *Human Respiratory Tract Model for Radiological Protection*, Publication 66, Pergamon Press, Oxford, England. [SRDB Ref ID: 22732]

ICRP (International Commission for Radiological Protection), 1995, *Dose Coefficients for Intakes of Radionuclides by Workers*, Publication 68, Pergamon Press, Oxford, England. [SRDB Ref ID: 22731]

ICRP (International Commission for Radiological Protection), 1998, *Individual Monitoring for Internal Exposure of Workers*, Publication 78, Pergamon Press, Oxford, England. [SRDB Ref ID: 36902]

ICRP (International Commission on Radiological Protection), 2000, "Supporting Guidance 3: Guide for the Application of the ICRP Human Respiratory Tract Model," *Annals of the ICRP*, volume 32, numbers 1–2.

James, A. C., R. E. Filipy, J. J. Russell, and J. F. McInroy, 2003, "USTUR Case 0259 Whole Body Donation: A Comprehensive Test of the Current ICRP Models for the Behavior of Inhaled $^{238}PuO_2$ Ceramic Particles," *Health Physics*, volume 84, number 1, pp. 2-33. [SRDB Ref ID: 77731]

LANL (Los Alamos National Laboratory), 1995, "On the Front Lines, Plutonium Workers Past and Present Share Their Experiences," *Los Alamos Science*, number 23, University of California, Los Alamos, New Mexico.

Mewhinney, J. A., and J. H. Diel, 1983, "Retention of Inhaled $^{238}PuO_2$ in Beagles: A Mechanistic Approach to Description," *Health Physics*, volume 45, number 1, pp. 39–60.

Miller, G., H. F. Martz, T. T. Little, and R. Guilmette, 2002, "Bayesian Internal Dosimetry Calculations Using Markov Chain Monte Carlo," *Radiation Protection Dosimetry*, volume 98, number 2, pp. 191–198.

Miller, G., W. C. Inkret, and H. F. Martz, 1999, "Internal Dosimetry Estimation Using Bayesian Methods," *Radiation Protection Dosimetry*, volume 82, number 1, pp. 5–17.

Mulford, R. N. R., 1975, *Degradation of Pioneer-Type Tantalum Alloy-PuO_2 Heat Sources*, LA-5932, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, July. [SRDB Ref ID: 12332]

ORAUT (Oak Ridge Associated Universities Team) 2008. Personal Communication Regarding the Behavior of Pu-238 Ceramic, Oak Ridge, Tennessee, May 19. [SRDB Ref ID: 123961]

Woods, W. R. Jr., and W. E. Sheehan, 1971, "Evaluation of the PUQFUA Method of Calculating Systemic Burdens," *American Industrial Hygiene Association Journal*, volume 32, number 1, pp. 58–63. [SRDB Ref ID: 46799]