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Internal Dosimetry Model for Applications to Bioassay at Uranium Mills

U.S. Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

R. E. Alexander, R. B. Neel, J. S. Puskin, A. Brodsky

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ABSTRACT

The internal dosimetry model developed in this study is intended for use in estimating the urinary natural uranium concentration at various times after inhalation of yellowcake or ore dust. New experimental data that illustrate the dependence of lung solubility on the thermal history of the inhaled yellowcake are incorporated into the model. The dosimetric model adopted is primarily that published by the International Commission for Radiological Protection (ICRP) in Publication 30.

This study employs the model of the ICRP Task Group on Lung Dynamics to represent the deposition of uranium in the respiratory tract and its clearance into the blood. According to the model developed in this report, 67 percent of the uranium entering the blood is excreted in urine the first day without appreciable uptake by body tissues. The uptake by kidney tissues is 11 percent, which is subsequently excreted. The systemic uptake by all other organs is 22 percent; this uranium is subsequently released to the blood from which 67 percent is excreted each day, 11 percent is absorbed by the kidney and excreted, and 22 percent is reabsorbed by the system. The availability and use of a computer program of this model is described in Appendix B.

Based on this internal dosimetry model, the time interval for the collection of bioassay specimens following inhalation exposure to airborne yellowcake (dried at high or low temperature) or to ore dust should not exceed 40 days. In vivo thorax scanning techniques are shown to be sufficiently sensitive to confirm excessive exposures to natural uranium inhaled in yellowcake dried at high temperature, but, for yellowcake dried at low temperature and ore dust, the usefulness of in vivo measurement is limited.

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PREFACE

In developing the Nuclear Regulatory Commission's Regulatory Guide 8.22, "Bioassay at Uranium Mills," it became apparent that the technical basis for the recommendations should be available to Commission licensees. It also became evident that inclusion of such information would make the guide excessively complex and difficult to follow. Therefore, a decision was made to issue a guide that would omit technical justifications and to issue that information in a separate report.

The purpose of the regulatory guide is to establish the NRC staff position regarding bioassay for uranium at uranium mills, thus defining a comprehensive uranium bioassay program. The purpose of this report is to provide additional explanatory information as technical background for the guide. This report is programmatic in nature and does not deal with laboratory techniques and procedures. The topics that are treated include (1) graphs of organ burdens and urinary uranium concentrations at various times after initiation of a single (or continuous) inhalation exposure to yellowcake or ore dust and (2) recommended limiting values for the concentration of selected compounds of natural uranium in air during occupational exposure. Also included is guidance on the difficult problem of estimating, after an exposure, the quantity of uranium present in the body organs. This document considers mixtures of U-234, U-235, and U-238 as found in yellowcake and also mixtures of the radioisotopes of uranium with those of Th-230, Ra-226, and Po-210 as found in ore dust. The work is based on the most up-to-date scientific information available to the authors.

Uranium may enter the body through inhalation, through ingestion, by absorption through normal skin, and through lesions in the skin. However, inhalation is by far the most prevalent mode of entry for occupational exposure. The internal dosimetry model described in this document is applicable to the inhalation of yellowcake (dried at high and at low temperatures) and of ore dust.

Official guidance on the subject of bioassay for uranium is given in Regulatory Guide 8.22.

SUMMARY

This report describes a model that permits analytical estimates regarding the behavior of uranium following inhalation by uranium mill workers. From the estimates performed, conclusions are drawn for the development of a standardized, routine bioassay program at the mills. The report also contains limiting values for the intake, intake rate, and concentration of uranium in air derived from recommendations presented in the International Commission on Radiological Protection (ICRP) Publication 26 (Ref. S-1) and ICRP Publication 30 (Ref. S-2) using the model developed in this report. A computer program for this model is described in Appendix B.

The Model

The metabolic model is diagrammed in Figure 1-1. As shown in this diagram, uranium is assumed to reach the blood in accordance with the model developed by the ICRP Task Group on Lung Dynamics. It is further assumed that 11 percent of the uranium reaching the blood is deposited in kidney tissues and is subsequently excreted with a 15-day half-life. It is also assumed that 67 percent of the uranium reaching the blood is excreted within 24 hours without being deposited in any organ. It is assumed that the remaining 22 percent is deposited in organs other than the kidney and that this uranium is released back to the blood in accordance with a power function (which may be represented for analytical convenience by the sum of two exponential functions as recommended in ICRP-30). This uranium then follows the model as described above. Subsequent excretion of the uranium redeposited in organs other than the kidney is about 4 percent of that initially reaching the blood and is ignored.

This model is subsequently used in the report for calculations with uranium as contained in ore dust, yellowcake dried at high temperature, and yellowcake dried at low temperature. Dissolution half-lives for each type of material were taken from recent experiment results that were obtained using simulated lung fluids.

Analytical Procedure

The analytical procedure followed in the preparation of this report includes four elements. The first element (Chapter 2) is the calculation of kidney, lung, and system (other than kidney) burdens per unit intake. These calculations are performed for all three types of material and for both single and continuous exposure conditions. The second element (Chapter 3) is the determination of intake criteria for each type of material and exposure condition. Criteria are given for chemical toxicity and radiological toxicity (the latter using recommendations from ICRP-26 and ICRP-30). The third element (Chapter 4) is the use of the burden data with the limiting intake criteria to calculate burdens of interest with respect to a urinalysis program, which in turn permits the calculation of the urinary uranium concentration as a function of time following or during exposure to each type of material. The fourth element (Chapter 5) is the calculation of the lung burden as a function of time to facilitate decisions regarding in vivo counting. Calculational details are given as necessary to permit reproduction of results by the interested reader.

Limiting Uranium Intakes and Intake Rates

The limiting uranium intakes and intake rates, as derived and used in this study, are shown in Table S-1.

TABLE S-1

Limiting Intakes and Intake Rates

Type of Airborne Material	Single Exposure Intake (μg U)	Continuous Exposure Intake Rate (μg U/d)
Ore dust (10-μm AMAD)	0.8×10^5	320
Yellowcake, dried at low temperature	2.6×10^5	1094
Yellowcake, dried at high temperature	1.6×10^5	626

Bioassay Program Recommendations

In Section 4.4, the analytical results obtained in this analysis are used to formulate recommendations for a urinalysis program, including the maximum specimen collection frequency and action points. Recommendations regarding in vivo measurements are provided in Section 5.4. These recommendations and several points of interest that may prove helpful to the reader may be summarized as follows:

1. The primary method for determining worker inhalation of airborne uranium is air sampling. Urinalysis is considered a secondary method needed to ensure that the air sampling program is effective. In vivo counting is considered a tertiary method to be used when urinalysis results are unusually high and it is necessary to ensure that the model has not greatly underestimated the radiological risk for the affected worker.

2. Each set of bioassay results should be reviewed by a qualified person and should be displayed in a manner permitting the reviewer to readily examine previous results for each worker.

3. For exposures to airborne uranium in any form at a uranium mill, urinalysis is an effective monitoring method that can be used as the basis for corrective action.

4. The action points selected for urinalysis are approximately the equilibrium urinary uranium concentration values under continuous exposure conditions. The same values are also assigned to single exposure conditions for simplicity and conservatism and because exposure conditions are not always known. The action points for 40-day sampling intervals, as derived in this report, are 10 μg/l for ore dust; 20 μg/l for high-temperature-dried yellowcake; and 60 μg/l for low-temperature-dried yellowcake. Chapter 6 describes how these action levels were adjusted for a monthly sampling interval, as used in Regulatory Guide 8.22, "Bioassay at Uranium Mills."

5. For workers exposed to both ore dust and high-temperature-dried yellowcake, an action point between 10 and 20 μg/l should be derived as shown in

Section 4.4.2. For workers exposed to both ore dust and low-temperature-dried yellowcake, an action point between 10 and 60 μg/l should be derived as shown in Section 4.4.2.

6. The total time period between specimen collections should not exceed 40 days. This limit was derived from curves of urinary uranium concentration versus time after a single exposure, assuming an intake equal to the limiting intake criterion. For each type of material, the action point was used as the ordinate value, and the number of days following exposure was then determined by the curve. In each case, the number of days was very near 40. The same maximum time interval, of course, is applicable for continuous exposure conditions.

7. The 40-day maximum time interval between specimen collections is considered to be an outer bound that should not be exceeded; specimens should be obtained more frequently if it is practical to do so. For ease of program management, Regulatory Guide 8.22 action levels are based on a monthly sampling interval. In a report of animal studies prepared for the NRC at the University of Rochester (Ref. S-3), the investigators conclude that 3 μg U/g of kidney tissue (the nephrotoxic limit) may be too high, and that the biological half-life for uranium in the kidney may considerably exceed 15 days. Both of these values are used in this model. Lowering the nephrotoxic limit and increasing the half-life for the kidney would cause the maximum time interval to be reduced.

8. The limiting consideration for ore dust is the nonstochastic radiological risk (50-year dose commitment of 50 rems to the bone). The limiting consideration for high-temperature-dried yellowcake is the stochastic radiological risk (summed risk to all affected organs is equivalent to risk from 5 rems external dose in 1 year). The limiting consideration for low-temperature-dried yellowcake is chemical toxicity to the kidney.

9. The limiting intake criterion used for urinalysis for both single and continuous exposure conditions (ore dust and high-temperature-dried yellowcake) is one Annual Limit on Intake (ALI). For continuous exposure

conditions, the criterion for urinalysis in the case of low-temperature-dried yellowcake is 3 μg U/g kidney maintained continuously; for single exposure conditions, the criterion is 3 μg U/g kidney at 56 days following exposure.

10. The criterion selected for making a decision as to whether a urinalysis result following a single exposure is high enough to justify an in vivo measurement is an intake of 1 ALI, i.e., a urinary uranium concentration associated with a 1-ALI exposure occurring 40 days prior to specimen collection. If a 1-ALI intake cannot be detected 40 days following exposure using in vivo techniques, the decision criterion is the intake associated with the 3-nCi in vivo detection limit (Ref. S-4).

11. The model's results suggest that an in vivo measurement should be made if the following urinary uranium concentration values are exceeded following a single exposure:

Ore Dust	22 μg/l 40 days following exposure (based on 3-nCi detection limit)
High-Temperature-Dried Yellowcake	20 μg/l 40 days following exposure (based on 1-ALI intake, radiological)
Low-Temperature-Dried Yellowcake	621 μg/l 40 days following exposure (based on 1-ALI intake, radiological)

For workers exposed to both ore dust and high-temperature-dried yellowcake or to both ore dust and low-temperature-dried yellowcake, investigate to determine where the intake occurred and use the appropriate concentration value.

12. The criterion selected for making a decision as to whether a urinalysis result during continuous exposure conditions is high enough to justify an in vivo measurement is 1 ALI inhaled during a period of 1 year, i.e., a urinary uranium concentration associated with continuous exposure conditions under which an intake of 1 ALI occurs during 1 year. If such an intake cannot be detected using in vivo techniques, the decision

criterion is the intake associated with the 3-nCi in vivo detection limit. The 1-ALI values are equivalent to the action points presented in item 4 above.

13. An in vivo measurement should be made if the following urinary uranium values are exceeded under continuous exposure conditions (i.e., where a large single exposure has not occurred):

Ore Dust	33 µg/l (based on 3-nCi detection limit)
High-Temperature-Dried Yellowcake	20 µg/l (based on 1-ALI intake in 1 year)
Low-Temperature-Dried Yellowcake	See item 14 below.

14. Under continuous exposure conditions, in vivo counting is assumed never to be necessary for a worker exposed only to low-temperature-dried yellowcake, i.e., that it would never be necessary to ensure that such a worker's radiological risk is not considerably greater than indicated by the model. The reason for this position is that it does not seem likely that chronic conditions could ever exist under which a worker's urinary concentration would be allowed to gradually climb to a value of 600 µg/l, the radiological action point.

15. For workers exposed to both ore dust and high-temperature-dried yellowcake under continuous exposure conditions, in vivo counting is indicated if the urinary uranium concentration rises above 33 µg/l. If the concentration is between 20 and 33 µg/l, an in vivo criterion should be derived as shown in Section 5.4.4.2.

16. For workers exposed to both ore dust and low-temperature-dried yellowcake under continuous exposure conditions, in vivo counting is indicated if, according to air sampling records, the ore dust intake for the 40-day bioassay period in question exceeded 7.8×10^4 µg U. The reason for

resorting to the air sampling intake estimate is that for a given urinary uranium concentration above 33 μg/l there is no other known way of estimating the concentration fraction contributed by ore dust. According to the model, 7.8×10^4 μg is the quantity of uranium in ore dust that would be inhaled in a 40-day period under equilibrium conditions if the urinary uranium concentration is 33 μg/l. It is, of course, extremely unlikely that the concentration could get this high with an action point of 10 μg/l. However, 33 μg/l is the concentration, and 7.8×10^4 μg U is the intake, associated with the 3-nCi detection limit.

17. With regard to particle size for the ore dust, measurements performed for the NRC by the Environmental Measurements Laboratory (Ref. S-5) indicate that 10-μm AMAD (Activity Median Aerodynamic Diameter) is an acceptable choice for the model. 1-μm AMAD is used for yellowcake. In the report, ore dust results are shown for both 1- and 10-μm AMAD for purposes of comparison.

18. In the instances of combined exposure to both ore dust and yellowcake, the harmonic mean equation is recommended in the text to derive the needed criteria and action points.

19. Bioassay data for the period 1977-1980 that were received by the NRC from 11 uranium mills (Ref. S-4) are shown in Figures S-1 and S-2. Figure S-1 is based on 17,039 specimens, and Figure S-2 is based on 1,677 measurements. Information received with the data does not permit segregation of the results according to the type of material to which the workers were exposed.

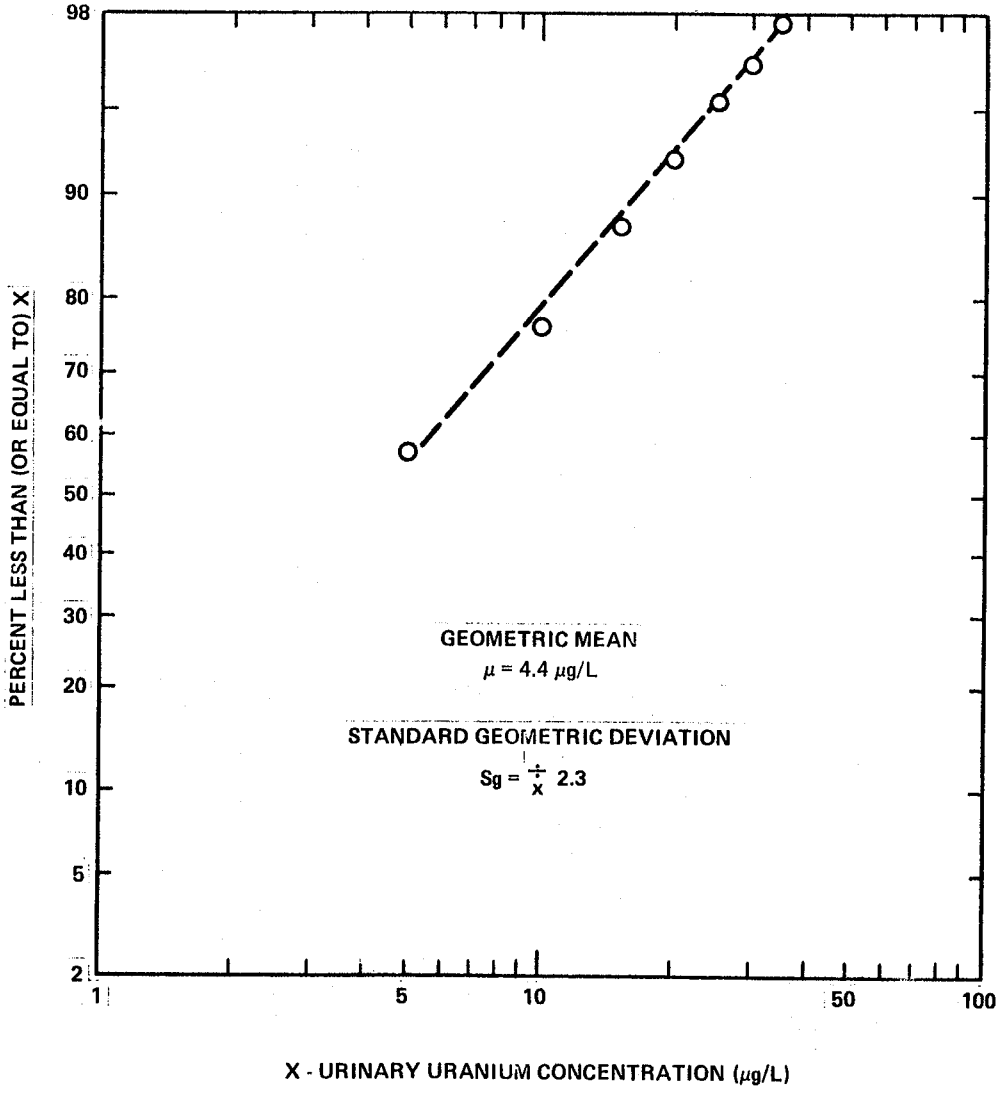

FIGURE S-1: Composite Frequency Distribution of Single Urine Sample Concentrations from Uranium Mill Bioassays

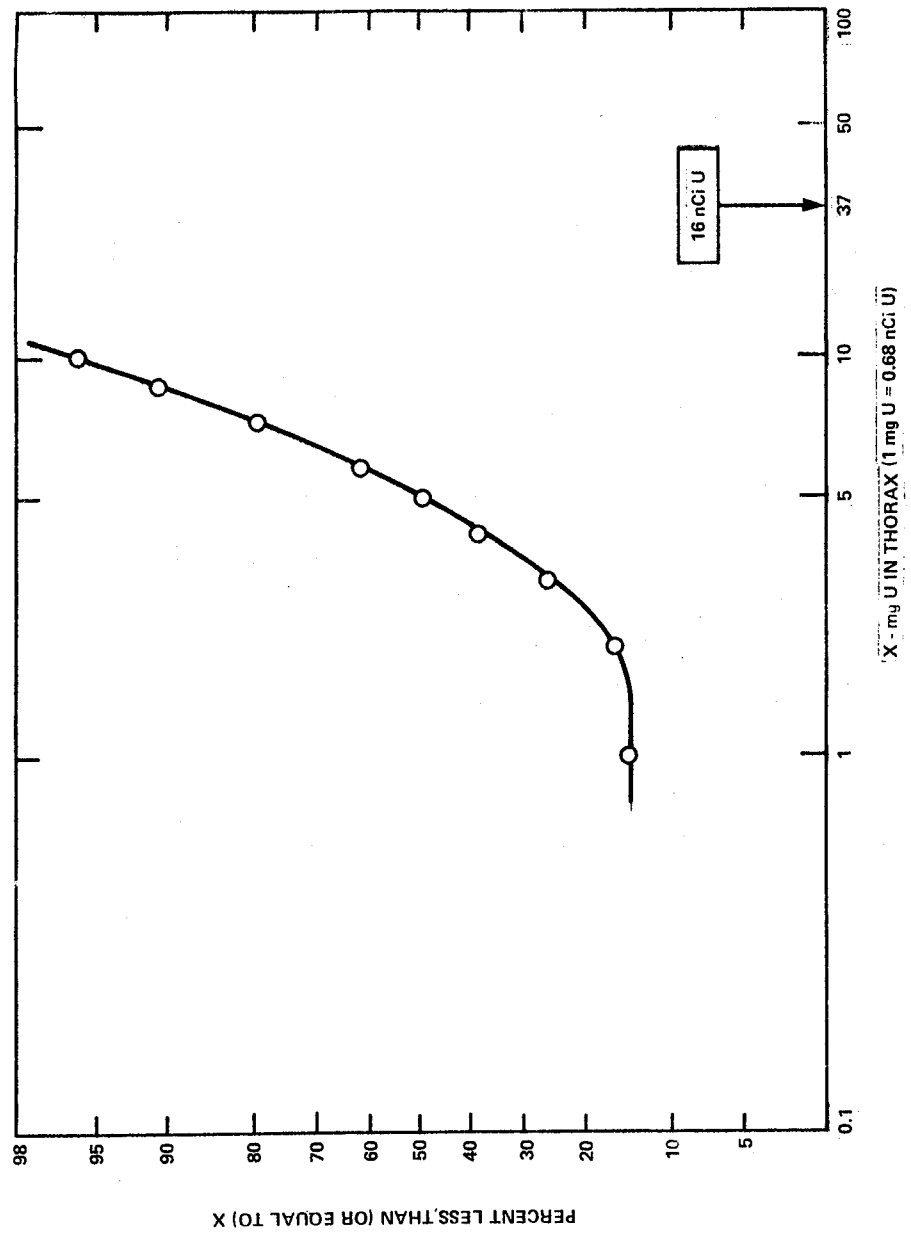

Figure S-2: Composite Frequency Distribution of Single In Vivo Lung Counts from Uranium Mill Workers

REFERENCES FOR SUMMARY

S-1. International Commission on Radiological Protection (ICRP), "Recommendations of the International Commission on Radiological Protection," ICRP-26, January 1977.*

S-2. ICRP, "Limits for Intakes of Radionuclides by Workers," ICRP-30, July 1978.*

S-3. P.E. Morrow et al., "Metabolic Fate and Evaluation of Injury in Rats and Dogs Following Exposure to the Hydrolysis Products of Uranium Hexafluoride," Department of Radiation Biology and Biophysics, University of Rochester, USNRC Report NUREG/CR-2268, December 1982.

S-4. H.B. Spitz et al., "Analysis of Uranium Urinalysis and In Vivo Measurement Results from Eleven Participating Uranium Mills," Battelle Pacific Northwest Laboratory, USNRC Report NUREG/CR-2955, 1984.

S-5. R.H. Knuth and A.C. George, "Uranium Mill Ore Dust Characterization," Environmental Measurements Laboratory, U.S. Department of Energy, EML-384, November 1980.

*ICRP publications are available from Pergamon Press, Fairview Park, Elmsford, NY 10523.

1. MODELS USED IN THIS STUDY

The models and the required data bases are not intended to represent reality beyond what is necessary for decisionmaking. However, Reference 1 has shown how the "catenary" type of modeling approach as used in this report may be used as an adequate approximation to systems (Ref. 2) incorporating recycling of radionuclides from organs back to blood provided the proper rate constants are used and compartments that recycle radionuclides are appropriately duplicated. The following sections explain how the rate constants and compartments were selected for the purposes of this report in order to obtain results consistent with recent research results on uranium mill workers.

1.1 RESPIRATORY TRACT DYNAMICS MODEL

The model developed by the Task Group on Lung Dynamics (TGLD) of the International Commission on Radiological Protection (ICRP) Committee II to describe the deposition and retention of inhaled radioactive material in the human respiratory tract is used in this study (Refs. 3 and 4). Information on lung deposition and clearance is provided in Tables 1-1 and 1-2.

TABLE 1-1

TGLD-ICRP Classification Nomenclature

TGLD	ICRP-10
Class Y - Avid retention, slow clearance, biological half-life more than 100 days	Nontransportable
Class W - Moderate retention, intermediate clearance, biological half-life from 10 to 100 days	Moderate Transportability
Class D - Minimal retention, rapid clearance, biological half-life less than 10 days	Transportable

TABLE 1-2

Constants for Use with TGLD Clearance Model

Region	Clearance Pathway	Class D	Class W	Class Y
NP	(a)	0.01 d/0.5	0.01 d/0.10	0.01 d/0.01
	(b)	0.01 d/0.5	0.4 d/0.90	0.4 d/0.99
TB	(c)	0.01 d/0.95	0.01 d/0.50	0.01 d/0.01
	(d)	0.20 d/0.05	0.20 d/0.50	0.20 d/0.99
P	(e)	0.5 d/0.80	50 d/0.15	500 d/0.05
	(f)	n.a.	1 d/0.40	1 d/0.40
	(g)	n.a.	50 d/0.40	500 d/0.40
	(h)	0.50 d/0.20	50 d/0.05	500 d/0.15
Lymph	(i)	0.5 d/1.00	50 d/1.00	1000 d/0.9

Note: The first value is the biological half-life; the second is the regional fraction. The lymphatic clearance for Class Y compounds indicates that a 90 percent regional fraction follows a 1000-day biological half-life. The remaining 10 percent is presumed to be permanently retained in the nodes and is reduced only by radioactive decay. The regions of the respiratory tract and pathways (a), (b), ..., (i) may be described as follows:

NP Nasopharyngeal Region

TB Tracheobronchial Region

P Pulmonary Region

(a) NP to Blood Pathway

(b) NP to GI Tract to Blood Pathway

(c) TB to Blood Pathway

(d) TB to GI Tract to Blood Pathway

(e) P to Blood Pathway

(f) P to GI Tract (rapid) to Blood Pathway

(g) P to GI Tract (delayed) to Blood Pathway

(h) P to Lymph Pathway

(i) Lymph Node to Blood Pathway

1.2 METABOLIC MODEL

The metabolic model used in this study is presented in Figure 1-1. The letters (a) through (i) in Figure 1-1 refer to respiratory tract clearance pathways. The fraction of the uranium that is not exhaled is deposited in the nasopharyngeal, tracheobronchial, and pulmonary regions of the respiratory tract. From the point of deposition, the uranium is divided into two parts--one part that is taken up by the blood directly and another part that is transferred to the GI tract prior to absorption and uptake into the blood. A fraction of the uranium deposited in the pulmonary lung is transferred to the lymph nodes from which it enters the blood.

In accordance with this model, 67 percent of the uranium entering the blood* is excreted in urine the first day without appreciable uptake by body tissues (Refs. 5 and 6). The uptake by kidney tissues is 11 percent, which is subsequently excreted (Refs. 6 and 7). The systemic uptake by all other organs is 22 percent; this uranium is subsequently released to the blood from which 67 percent is excreted each day, 11 percent is absorbed by the kidney and excreted, and 22 percent is reabsorbed by the system. This latter fraction, which is a little more than 4 percent of the original uptake in blood, is neglected in this analysis.

1.2.1 Retention Functions for Respiratory Tract

The complete list of constants and parameters used in this study may be found in Tables A-9 and A-10 of Appendix A. In Table A-11, these constants and parameters are compared to those used in ICRP-30 (Ref. 8). Although this study uses many of the parameters given by ICRP-30 and the TGLD, in this study the retention functions of uranium compounds in the pulmonary lung are based on new experimental data (Refs. 9, 10, 11, and 12) not available to the ICRP at

*The urinary excretion in the first 24 hours of that dose injected into blood is given in Reference 6 as from one-half to three-fourths of that injected. The fraction 0.8 is used in the section on uranium in Reference 6 to represent that amount excreted on the first day to that excreted over all time, i.e., 80 percent of the total excretion.

the time of the publication of ICRP-30. The retention times in the lung estimated for yellowcake and ore dust in these new studies are smaller than those assumed for uranium compounds in ICRP-30. As a consequence of this difference, for a given deposition of uranium in the lung, the metabolic model of ICRP-30 predicts a somewhat larger lung dose than is calculated from this model. Conversely, ALI values calculated from the ICRP-30 model are smaller than those given in this study since the lung dose per unit intake of uranium is larger for the ICRP-30 model.

1.2.1.1 Yellowcake

From in vitro solubility studies for yellowcake in simulated lung fluid, it may be concluded that yellowcake subjected to high-temperature drying has, with respect to retention in the lung, three components. The fractions having the indicated dissolution half-lives in the lung, as used in this analysis, are shown in Table 1-3.

TABLE 1-3

Fractional Composition and Lung Half-Life Values for Yellowcake and Ore Dust (in vitro studies)

	Fractional Composition	Dissolution Half-Life (days)
Yellowcake, High-Temperature Drying (Ref. 11)		
Short-Lived	0.17	0.125
Medium-Lived	0.19	5
Long-Lived	0.64	200
Yellowcake, Low-Temperature Drying (Refs. 9 and 12)		
Short-Lived	0.61	0.8
Medium-Lived	0.39	39
Ore Dust* (Ref. 9)	1.0	50

*As shown in Table A-10, ore dust is assumed to be composed of only one component with a medium elimination half-life (Class W).

1.2.1.2 Ore Dust

In vitro studies of the solubility in simulated lung fluid of the uranium compounds contained within ore dust are reported in Reference 9. The value of 50 days for the half-life of ore dust in the pulmonary lung used in this study was adopted from this reference.

1.2.2 Retention Functions for Kidney and System

The elimination constant for the kidney used in this study, which is based on a retention halftime of 15 days in kidney tissue, appears to be better supported by the data (Refs. 5 and 13) than the values selected in ICRP-30 based on Reference 14. The 15-day constant is based on data obtained from several studies of occupationally exposed adults and also from animal studies. In addition, a recent analysis of urinalysis data for 12 uranium mill workers indicated a mean observed half-life for uranium of 14.6 $\pm$ 4.3 days (Ref. 13). On the other hand, the elimination constant for the kidney adopted by ICRP-30 is supported only by data taken from one man who had been occupationally exposed and from data on adults who ingested (not inhaled) uranium in the course of a normal diet.

The elimination constant used for the body system in this study was taken from the first term of a two-term equation published in ICRP-30. The second term was rejected in this study since its use produced calculated results not in accord with the empirical bioassay data for uranium mill workers.

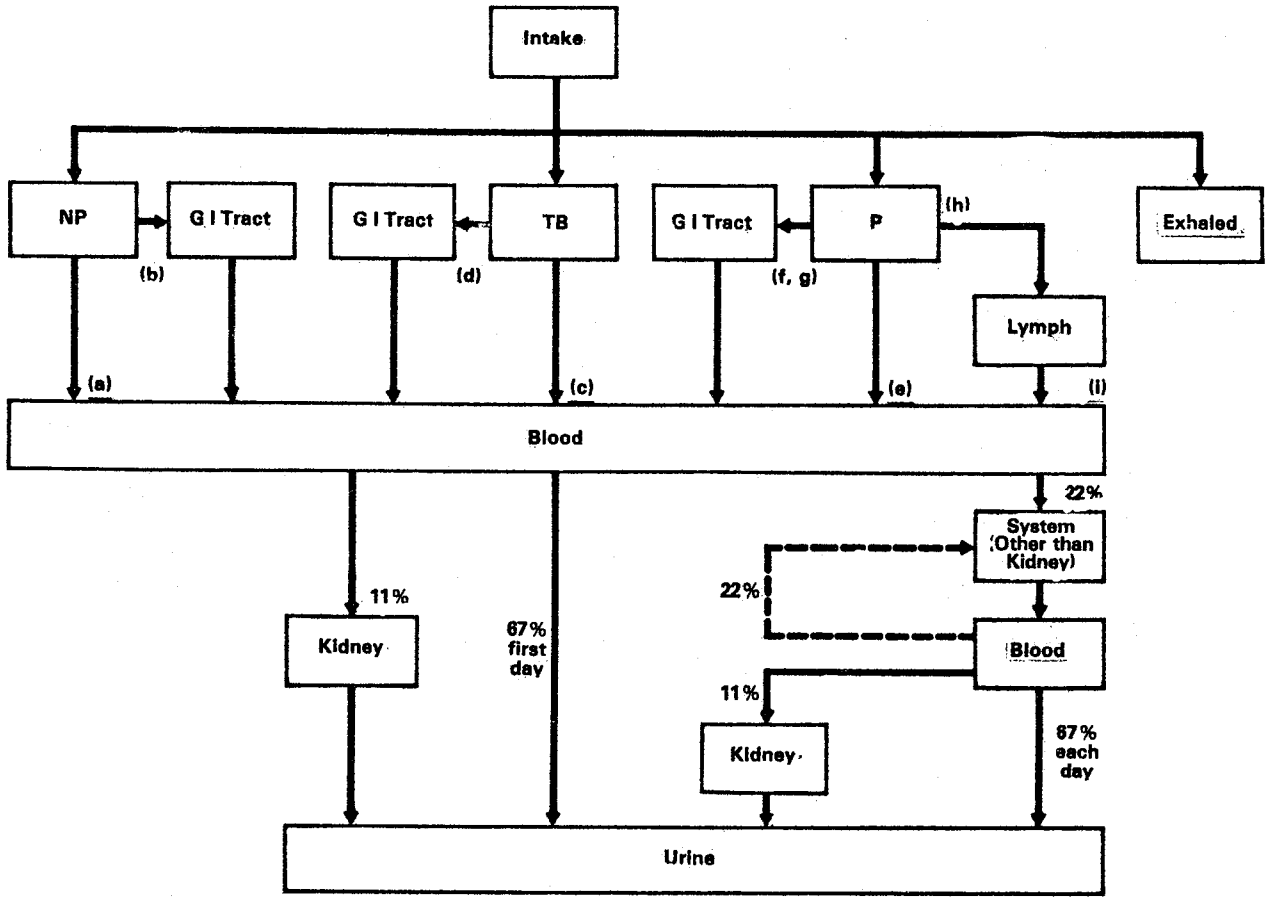

FIGURE 1-1: Metabolic Model for Inhaled Uranium in Urine

2. ORGAN AND SYSTEM BURDENS PER UNIT INTAKE FOLLOWING EXPOSURE TO YELLOWCAKE OR ORE DUST

The discussion in this chapter concerns the uranium content of the kidney, lung, and the balance of the system following exposure to yellowcake or ore dust. Calculational results per unit intake, using the metabolic and respiratory models described in Chapter 1, are presented. The results were obtained by using the calculational methods described in Appendix A. A computer program devised for this study is briefly described in Appendix B. The organ burdens are calculated for periods of time ranging from 1 day to that time corresponding to the establishment of a steady-state concentration of uranium in the organ under consideration. They are illustrated as functions of time in a series of graphs. Organ burdens for both single and continuous exposures were calculated for both yellowcake and ore dust.

2.1 RESULTS OF CALCULATIONS FOR KIDNEY BURDEN

As shown in Appendix A, the kidney burden calculations involve the sum of two contributions: (1) the blood-to-kidney contribution and (2) the blood-to-system-to-blood-to-kidney contribution. The latter contribution was calculated using an exponential term approximation of the power function reported in Reference 14.

2.1.1 Single Exposure

The kidney burden per unit intake as a function of time after a single exposure is shown in Figure 2-1 for (1) 1-μm-AMAD (Activity Median Aerodynamic Diameter) particles of yellowcake that have been subjected either to high- or low-temperature drying and (2) uranium ore dust that has size distributions of 1-μm AMAD and 10-μm AMAD.

2.1.2 Continuous Exposure

The kidney burden per unit rate of intake as a function of time during continuous exposure to yellowcake (dried at high and low temperature) or to

uranium ore dust (1-μm AMAD and 10-μm AMAD) is shown in Figure 2-2. The calculated equilibrium values, in micrograms of uranium per microgram of uranium inhaled daily, are:

Yellowcake, Dried at High Temperature	0.52
Yellowcake, Dried at Low Temperature	0.85
Ore Dust, 1-μm AMAD	0.39
Ore Dust, 10-μm AMAD	0.45

These numbers provide the estimated quantity in micrograms of uranium maintained in the kidney tissues per microgram of uranium inhaled daily.

The detailed mathematical analysis undertaken in this study considers the sum of the individual contributions of uranium to kidney along each TGLD pathway. A complete discussion of the method is given in Appendix A. The results indicate that, of all the many possible metabolic pathways along which inhaled yellowcake or ore dust can be translocated from the respiratory tract to the system or to the kidney, only three to five pathways are usually of major significance. These always include the three pathways (a), (c), and (e), which detour no uranium through the system but translocate it directly via the blood to the kidney (see Figure 1-1).

The values for the kidney burden per unit intake calculated in this study are larger than those that can be calculated from the data given in Supplement 1 to ICRP-30 for several reasons. First, the model used in ICRP-30 (Ref. 8) has no metabolic transfer pathway from the system to the kidneys as is used in this study. Second, and of greater importance, the approximations to retention half-time for uranium in the kidneys used by ICRP-30 (see Section A.2.4 and Table A-10 of Appendix A), the sum of two exponential functions with half-lives of 6 and 1500 days, are different from those used in this study.

2.2 RESULTS OF CALCULATIONS FOR SYSTEMIC BURDEN

As will be seen in Chapter 4, the systemic burden (excluding the kidney burden) following a single exposure is not used in the calculations of the urinary uranium concentration. Therefore, this section considers only continuous exposure conditions.

The calculated values of systemic burden, in micrograms of uranium per microgram of uranium inhaled daily, after equilibrium has been attained are:

Yellowcake, Dried at High Temperature	0.93
Yellowcake, Dried at Low Temperature	1.85
Ore Dust, 1-μm AMAD	0.67
Ore Dust, 10-μm AMAD	0.81

These numbers provide the estimated quantity in micrograms of uranium maintained in the systemic organs (other than the kidney) per microgram of uranium inhaled daily. These values are illustrated in Figure 2-3.

2.3 RESULTS OF CALCULATIONS FOR LUNG BURDEN

2.3.1 Single Exposure

Figure 2-4 illustrates the burden of uranium retained in the pulmonary lung (P) per unit intake of uranium to the respiratory tract, P/I. The fraction of the intake, I, that deposits in the pulmonary lung will be identical for either type of yellowcake since the particle sizes of both low- and high-fired yellowcake are assumed to be the same (1-μm AMAD). However, as shown in Table 1-3, the rates of elimination for each compound are considerably different. Table 1-3 indicates that about two-thirds of the inhaled yellowcake dried at high temperature and deposited in the pulmonary lung is eliminated with a half-life of 200 days. However, about one-third of the deposited yellowcake dried at low temperature is eliminated from the lung with a half-life of 39 days. Because of the longer retention time in the lung of the insoluble (Class Y) uranium compound contained in yellowcake dried at high temperature, the resulting lung burden persists much longer.

2.3.2 Continuous Exposure

The lung burden per unit intake rate, P/I', during continuous exposure to yellowcake (dried at high or low temperature) or to ore dust is given in Figure 2-5. The calculated equilibrium values, in micrograms of uranium per microgram of uranium inhaled daily, are:

Yellowcake, Dried at High Temperature	22.3
Yellowcake, Dried at Low Temperature	2.8
Ore Dust, 1-μm AMAD	8.7
Ore Dust, 10-μm AMAD	3.5

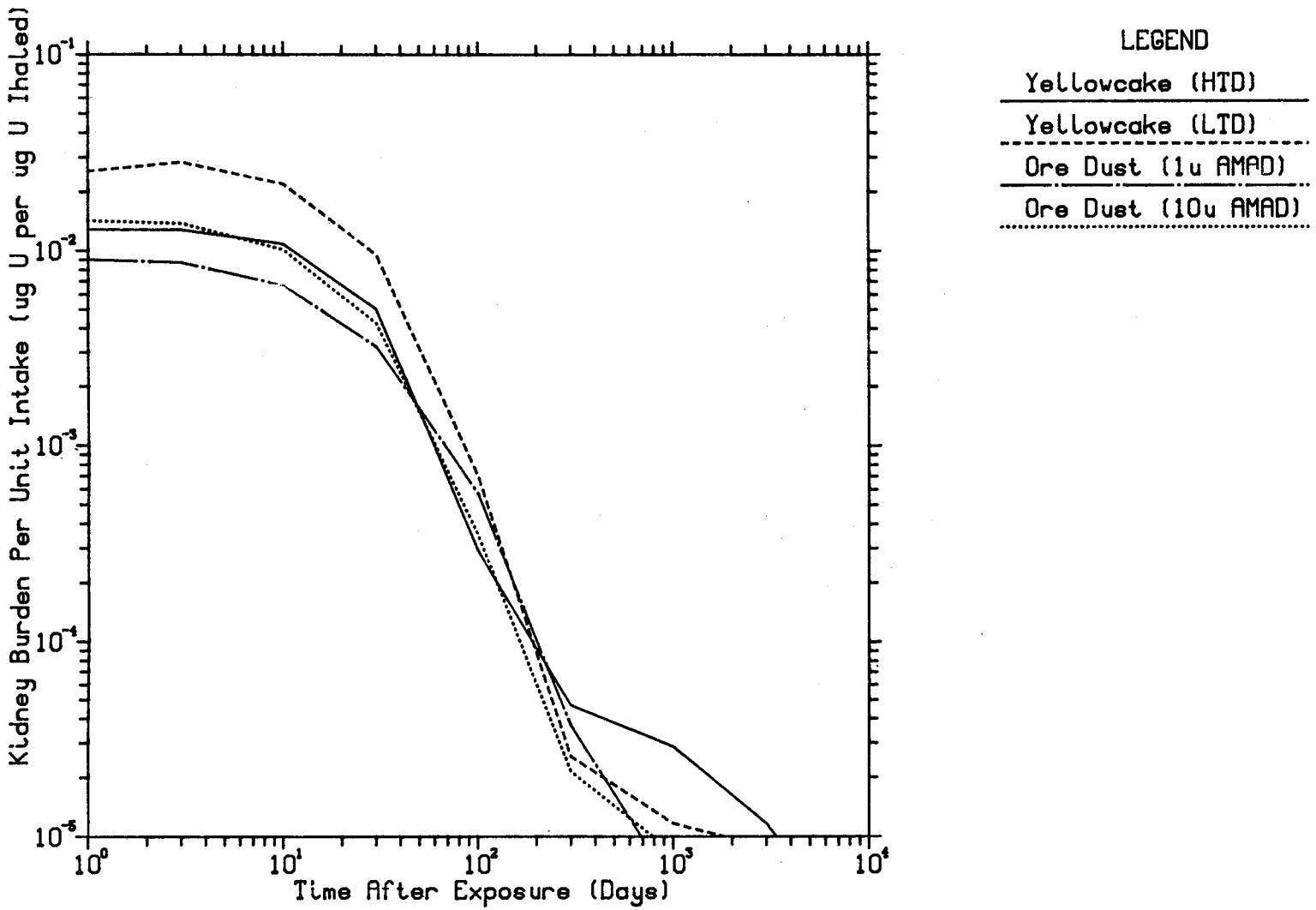

FIGURE 2-1: Kidney Burden per Unit Intake of Uranium Following Single Exposure to Yellowcake or Ore Dust

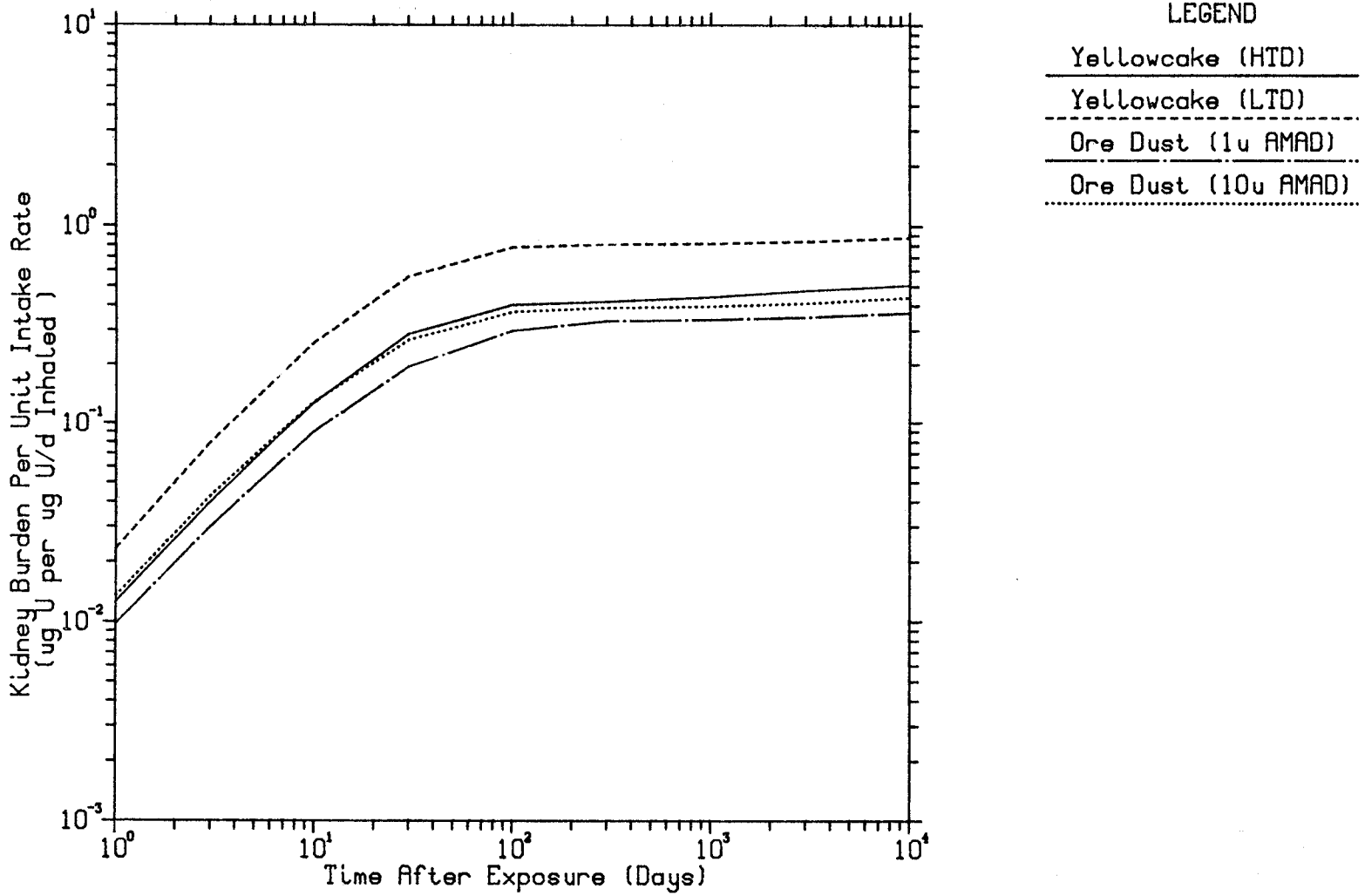

FIGURE 2-2: Kidney Burden per Unit Intake Rate of Uranium During Continuous Exposure to Yellowcake or Ore Dust

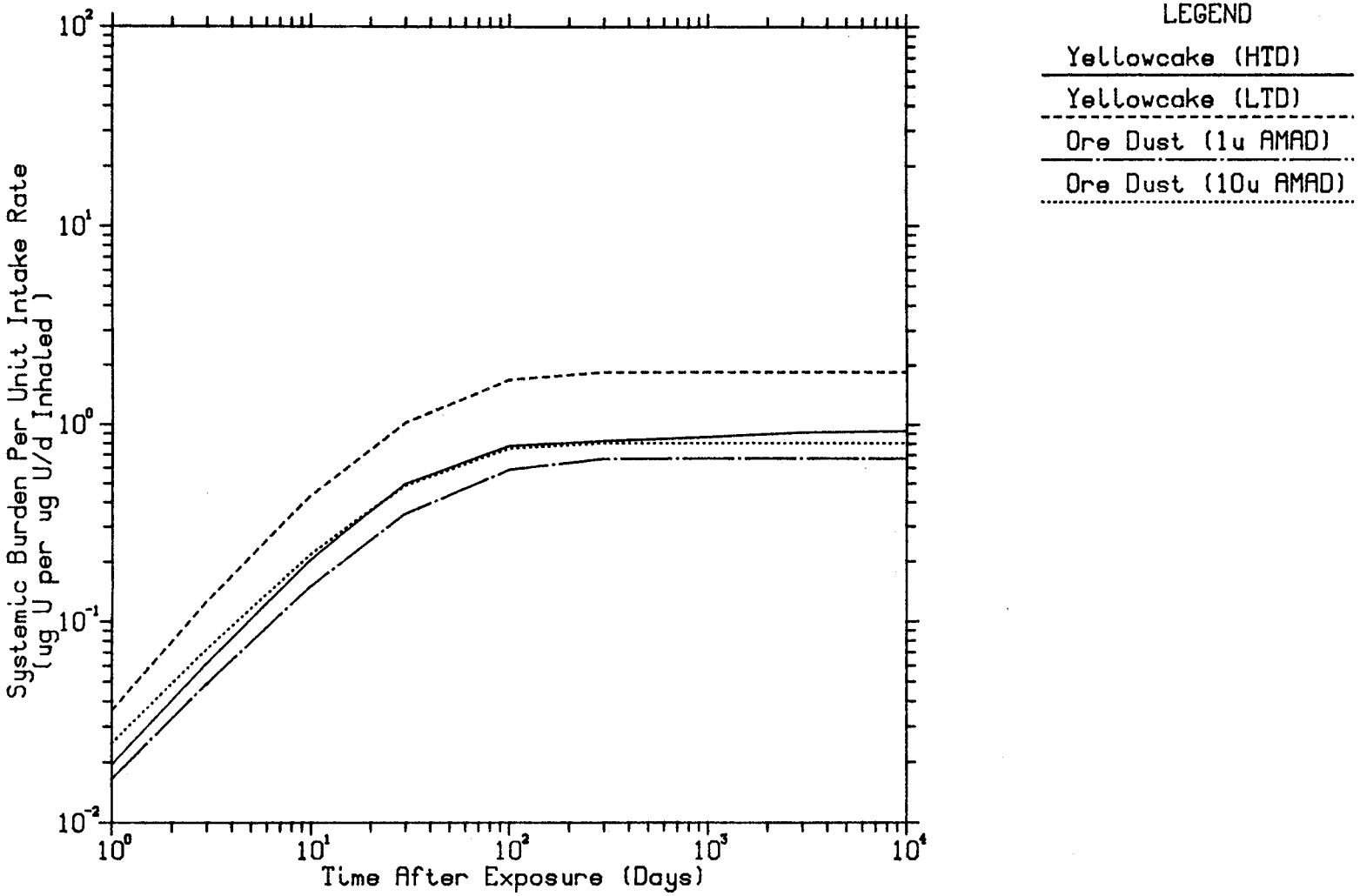

FIGURE 2-3: Systemic Burden per Unit Intake Rate of Uranium During Continuous Exposure to Yellowcake or Ore Dust

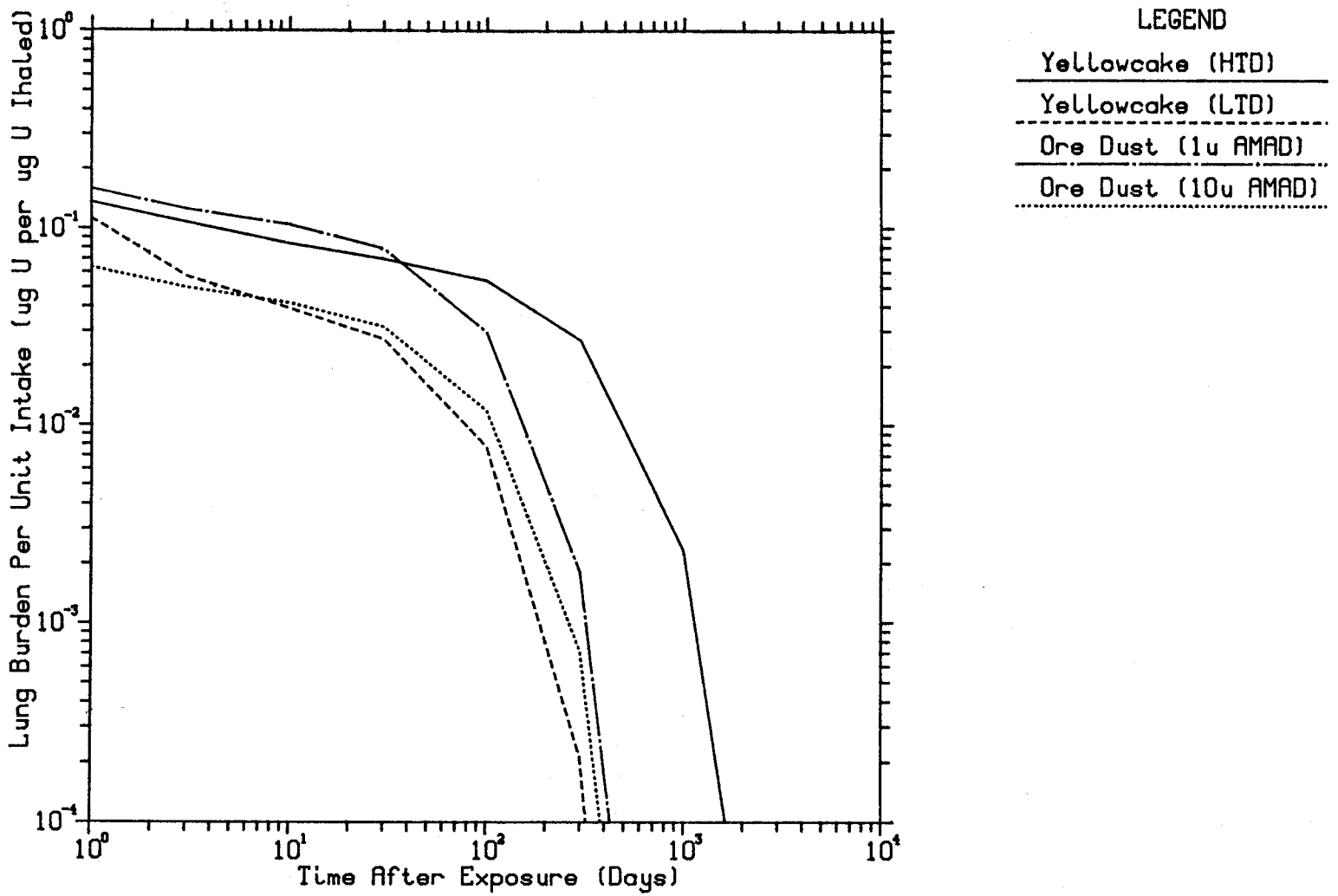

FIGURE 2-4: Lung Burden per Unit Intake of Uranium Following Single Exposure to Yellowcake or Ore Dust

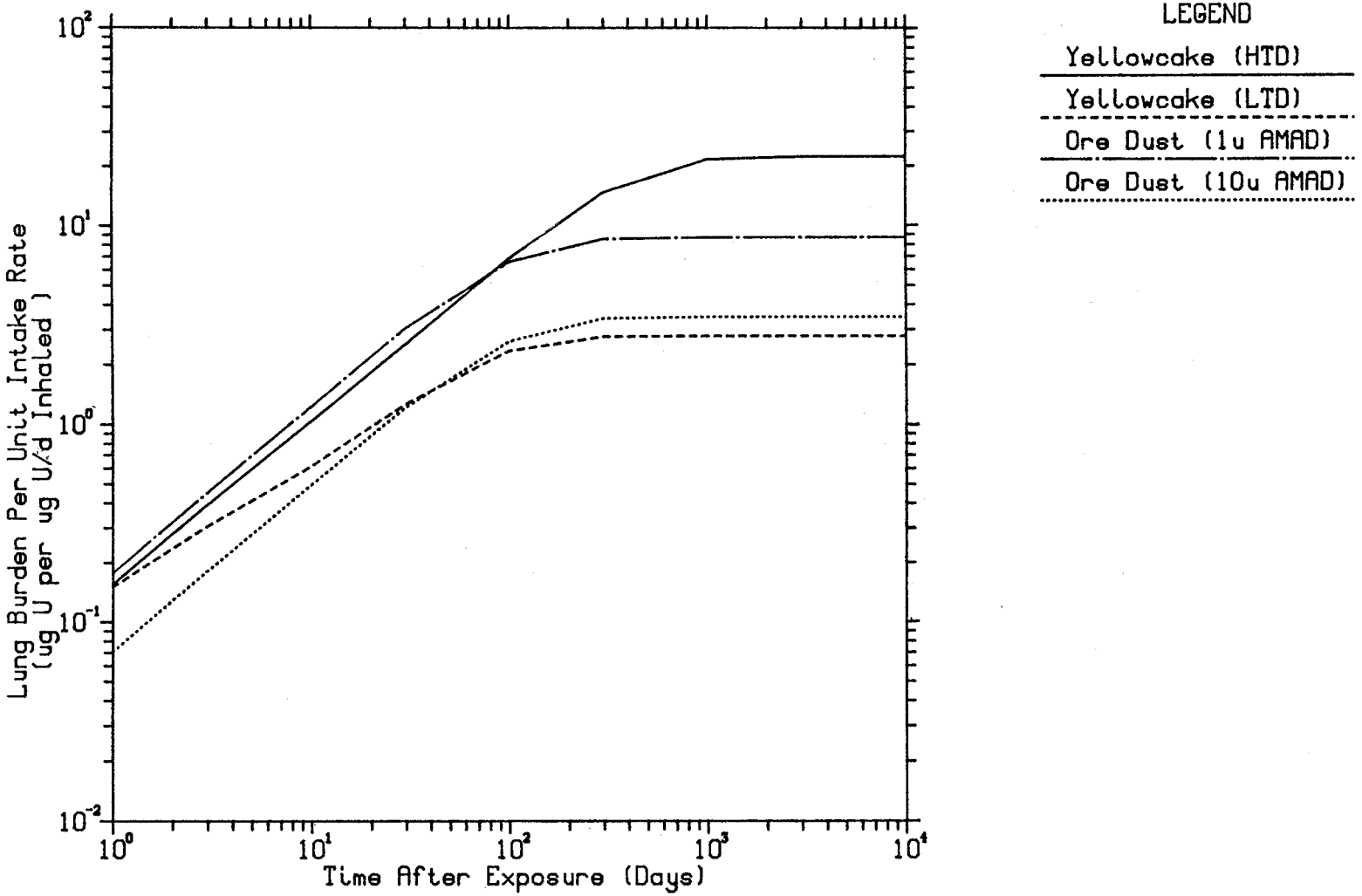

FIGURE 2-5: Lung Burden per Unit Intake Rate of Uranium During Continuous Exposure to Yellowcake or Ore Dust

3. INTAKE CRITERIA FOR INHALATION EXPOSURES

Health risks from inhaled uranium may result from either radiological or chemical toxicity mechanisms, operating either separately or jointly. In this chapter, intake criteria are derived for the control of these two types of risk. These intake criteria are subsequently used with the organ and system burden data per unit intake (or intake rate) given in Chapter 2 to derive urinary uranium concentration information. The information collected in this chapter is intended to answer the following questions:

1. Which is most likely to produce biological damage to a worker after an inhalation exposure to yellowcake or to ore dust, radiological or chemical toxicity?

2. What is the maximum quantity of uranium that can be inhaled under either single or chronic exposure conditions without exceeding the limiting criteria for chemical toxicity?

3. What is the maximum quantity of uranium that can be inhaled under either single or chronic exposure conditions without exceeding the limiting dose criteria for radiological toxicity?

3.1 INTAKE CRITERIA BASED ON CHEMICAL TOXICITY

After a single inhalation exposure to uranium, the respiratory and GI tracts receive the initial radiation dose. But translocation of soluble uranium compounds from these tracts can also produce chemical toxicity damage to the kidney or radiological toxicity damage to the bone and other organs.

If a concentration exceeding about 3 μg U/g of kidney tissue (the nephrotoxic limit, see Refs. 15 and 16) is maintained for a sufficiently long period, kidney damage may occur. This limit for uranium corresponds to a constant organ burden of 930 μg U for a 310-gram kidney tissue mass (Ref. 17). In practice, inhalation exposures are not constant, and equilibrium conditions in kidney tissue are not likely to be achieved. However, it is evident that if workers are exposed to large enough concentrations of soluble uranium in air for a sufficiently long period of time, the kidney burden will rise above 930 μg U. The length of time that such conditions may be allowed to exist must be chosen arbitrarily because there is an insufficient data base for this decision. It

is known that on a cellular level in the kidney the presence of a sufficient quantity of uranium results in cell death (Ref. 5). Prolonged conditions of this nature could have serious consequences. However, there is evidence that recovery is complete if the kidney burden is allowed to fall below the apparent threshold concentration of 3 μg U/g of kidney tissue soon enough. The time above 930 μg that could be allowed before serious damage occurs is not known but is likely to depend on how far above 930 μg the burden rises. Despite this lack of knowledge, a decision must be made for purposes of control. Therefore, a period of 8 weeks is arbitrarily selected as that maximum period of time during which the concentration of uranium in the kidneys could be allowed to equal (or exceed) 3 μg U/g of kidney tissue.

3.1.1 Intake from Single Exposure

The single intake (I) of yellowcake or ore dust that will just produce the nephrotoxic limit 56 days after a single exposure can be calculated from the following expression:

$$I = \frac{930\ \mu g\ U}{K(56)/I}$$

where K(56)/I is the kidney burden in μg U on the 56th day (8th week) following an acute exposure per μg of U inhaled . For example: K(56)/I, taken from Figure 2-1, is 1.7×10^{-3} for yellowcake dried at high temperature; the value for I is 5.5×10^{5}. Explicitly, if an intake of 5.5×10^{5} μg U (0.37 μCi U) contained in high-temperature-dried (HTD) yellowcake is inhaled in a very short period of time, the kidney burden will diminish to 930 μg U 56 days later (to the extent that the single exposure model in this study is correct for the affected worker). In like manner, the single intakes of uranium in ore dust and low-temperature-dried (LTD) yellowcake that will produce the nephrotoxic limit 56 days after exposure are tabulated below.

Uranium Compound Inhaled	K(56)/I (Fig. 2-1)	Uranium Intake* (μg U)
Yellowcake (HTD)	1.7×10^{-3}	5.5×10^{5}
Yellowcake (LTD)	3.5×10^{-3}	2.6×10^{5}
Ore Dust (1-μm AMAD)	1.5×10^{-3}	6.2×10^{5}
Ore Dust (10-μm AMAD)	1.5×10^{-3}	6.2×10^{5}

These intake values, and others that follow, are used subsequently in this report in the development of bioassay program recommendations.

3.1.2 Intake from Continuous Exposure

The continuous intake rate (I') of yellowcake or ore dust that will maintain the nephrotoxic limit of 930 μg U in kidney tissue, i.e., at equilibrium when the intake rate of natural uranium to the kidney is equal to the rate of loss of natural uranium from the kidney, is given by the following equation:

$$I' = \frac{930\ \mu g\ U}{K(Equil)/I'}$$

The values of K(Equil)/I', obtained from Figure 2-2, are listed below with the corresponding calculated value of uranium intake rate (in μg U/d) for the compounds in this study.

Uranium Compound Inhaled	K(Equil)/I' (Fig. 2-2)	Uranium Intake Rate** (μg U/d)
Yellowcake (HTD)	0.52	1788
Yellowcake (LTD)	0.85	1094
Ore Dust (1-μm AMAD)	0.39	2385
Ore Dust (10-μm AMAD)	0.45	2067

*An intake resulting in 930 μg U kidney burden at 8 weeks.

**An intake rate resulting in 930 μg U kidney burden at equilibrium.

3.2 INTAKE CRITERIA BASED ON RADIOLOGICAL TOXICITY

The intake values developed in this section are based on the methodology of the ICRP in Part 1, Section 2.1, of ICRP-30. The ICRP states that these limits are "intended to prevent non-stochastic effects and to limit the occurrence of stochastic effects to an acceptable level."

3.2.1 Intake from Single Exposure

The single intake values listed below for uranium contained in yellowcake or in ore dust are the corresponding Annual Limit on Intake (ALI) values calculated in Appendix C of this report. For single intakes of these magnitudes, the expected lifetime risk to a uranium mill worker is assumed to be no greater than the risk normally experienced in any single workyear as a result of continuous exposure at the derived air concentration (DAC) level.

The numerical values for a single intake of uranium based on radiological toxicity are listed below along with the corresponding values of the ALI from which they were derived. The ALI values, in μCi U/yr, were converted to gravimetric units using the specific activity for natural uranium of 6.77×10^{-7} Ci/g.

Uranium Compound Inhaled	Annual Limits on Intake (ALI) (μCi U)	(μg U)
Yellowcake (HTD)	0.106	1.6×10^5 s
Yellowcake (LTD)	1.85	2.7×10^6 s
Ore Dust (1-μm AMAD)	0.031*	4.6×10^4 ns
Ore Dust (10-μm AMAD)	0.054*	8.0×10^4 ns

ns - based on nonstochastic limit to the bone surfaces
s - based on stochastic limit

3.2.2 Intake from Continuous Exposure

For each uranium compound discussed below, an ALI of natural uranium was calculated according to the methods of ICRP-30 as described in Appendix C of

*These ALI values pertain only to the uranium inhaled, not to the intake of the daughters.

this report. The values below were calculated from the ALI assuming 250 workdays in the workyear as recommended in ICRP-30.

Uranium Compound Inhaled	Limits on Continuous Intake Rates of Natural Uranium	
	μCi U/yr	μg/d
Yellowcake (HTD)	0.106	626 s
Yellowcake (LTD)	1.85	10,931 s
Ore Dust (1-μm AMAD)	0.031*	182 ns
Ore Dust (10-μm AMAD)	0.054*	320 ns

ns - based on nonstochastic limit to the bone surfaces
s - based on stochastic limit

3.3 LIMITING INTAKE CRITERIA

3.3.1 Intakes from Single Exposure

In order to establish intake criteria for single exposure to yellowcake or ore dust, intake values reported in Sections 3.1 and 3.2 are compared below. The limiting intake is the smaller of these two values.

Uranium Compound Inhaled	Limits of Intake of Uranium		
	Chem. Toxic (μg U)	Radio. Toxic (μg U)	Intake Limited by
Yellowcake (HTD)	5.5×10^5	$\underline{1.6 \times 10^5}$	Radiotoxicity
Yellowcake (LTD)	$\underline{2.6 \times 10^5}$	2.7×10^6	Chem. toxicity
Ore Dust (1-μm AMAD)	6.2×10^5	$\underline{4.6 \times 10^4}$	Radiotoxicity
Ore Dust (10-μm AMAD)	6.2×10^5	$\underline{8.0 \times 10^4}$	Radiotoxicity

The intake values underlined above are considered to be an acceptable basis for the bioassay program recommendations developed in this study.

*These ALI values pertain only to the uranium inhaled, not to the intake of the daughters.

3.3.2 Intake from Continuous Exposure

Values of continuous intake reported in Sections 3.1 and 3.2 are compared below. The limiting intake rate is the smaller of these two values.

Uranium Compound Inhaled	Intake Rate of Uranium: Chem. Toxic (μg U/d)	Intake Rate of Uranium: Radio. Toxic (μg U/d)	Intake Rate Limited by
Yellowcake (HTD)	1788	626	Radiotoxicity
Yellowcake (LTD)	1094	10,931	Chem. toxicity
Ore Dust (1-μm AMAD)	2385	182	Radiotoxicity
Ore Dust (10-μm AMAD)	2067	320	Radiotoxicity

The intake rate values underlined above are considered to be a suitable basis for the bioassay program recommendations developed in this study.

4. FINAL RESULTS--CALCULATION OF URINARY URANIUM CONCENTRATION

4.1 YELLOWCAKE DRIED AT HIGH TEMPERATURE

4.1.1 Following Single Exposure

After the first day, to obtain the urinary uranium concentration as a function of time following a single exposure, it is necessary to take the sum of the following two components: (1) the contribution from uranium stored in kidney tissues, which is assumed to be transferred to urine in accordance with an exponential retention function (15-day half-life) and (2) the contribution from uranium stored in the system other than the kidney, which is assumed to be released to the blood in accordance with a power function ($t^{-0.39}$), (Ref. 14), from which 67 percent is excreted directly in urine.

In this section, the kidney burden per unit intake data given for single exposure conditions in Chapter 2 are used to derive the first component described above. The second component is then derived from the intake using a mathematical procedure described subsequently in this section. The two components are then added as shown in Figure 4-1.

4.1.1.1 Uranium Released from Kidney Tissues

The equation for the urinary uranium concentration, $X_K(t)$, due to the kidney burden, K(t),* is:

$$X_K(t) = \lambda_K[K(t)/I]I/1.4 \qquad (4\text{-}1)$$
$$= 3.3 \times 10^{-2}\ I[K(t)/I]$$

where

λ_K = kidney elimination constant = $\frac{0.693}{15} d^{-1}$

*K(t) includes contributions from two sources: (1) blood to kidney and (2) blood to system to blood to kidney (see Fig. 1-1).

I = intake of interest, μg U

K(t)/I = kidney burden per unit intake (Fig. 2-1), μg U per μg U inhaled

1.4 = the urinary excretion rate for reference man, 1/d

The single exposure criterion developed in Section 3.3.1 is an intake of 1.6×10^5 μg U. With this value of I, Equation 4-1 reduces to

$$X_K(t) = 5.3 \times 10^3 \, [K(t)/I] \qquad (4\text{-}2)$$

Values of $X_K(t)$ calculated for yellowcake dried at high temperature appear in Figure 4-1 under the designation "Kidney Pathways."

4.1.1.2 Uranium Released from Systemic Tissues (Other Than Kidney) and Excreted Directly in Urine

The calculation of this component involves the use of a power function. (Here it was not necessary to use the exponential term approximation.) The equation employed (Eq. 4-3 below) includes a term for the quantity of uranium to which the power function is to be applied. This quantity is designated ΦI where Φ is the fraction of I (the quantity inhaled) that is deposited in the system soon after the single exposure. The calculational method is given immediately below rather than in Appendix A because it is not included as a method requiring the use of a computer. The systemic burden $q_s(t)$, after the first day following exposure, is given by the following retention function:

$$q_s(t) = \Phi I t^x \qquad (4\text{-}3)$$

where x has the value of -0.39 as given in Reference 14, and t is the time after exposure. The first derivative of Equation 4-3 gives the uranium excretion rate

$$-\frac{dq_s(t)}{dt} = 0.39\Phi I t^{-1.39} \qquad t > 1$$

According to the metabolic model used in this study (Fig. 1-1), uranium is released from the system into the blood each day, and 67 percent is transferred directly from the blood into the urine without being incorporated in tissue. Assuming an excretion rate of 1.4 l/d, the urinary uranium concentration due to the systemic burden (excluding the kidney), X_S, is given by

$$X_S = \frac{0.67(0.39)}{1.4}\Phi I t^{-1.39} \qquad t > 1$$

or

$$X_S = 0.19\Phi I t^{-1.39} \qquad t > 1 \qquad (4\text{-}4)$$

I is known from Chapter 3 to have a value of 1.6×10^5 μg U. The calculation of Φ was performed as described below.

The fraction Φ was calculated separately for the TGLD pathways (a), (b), (c), (d), (e), and (h) for that fraction of I considered to be Class D and for (a), (b), (c), and (d) for that fraction of I considered to be Class Y (see Table 1-3). These values were then summed to obtain Φ for Equation 4-4. The pathways included are those contributing significantly to the early systemic burden.

For a given pathway, Φ is the product of the following factors: the overall "deposition fraction" in the appropriate region (NP, TB, P) of the respiratory tract; the "regional fraction" for the individual pathway (the regional fraction distributes the deposition fraction between all pathways assigned to the region); the "composition fraction," i.e., the fraction of I that is Class D or Class Y; for pathways (b) and (d) only, the fractional uptake from the GI tract to blood for Class D, W, or Y; and the fractional uptake from the blood to the system. The symbols and values used in this report for these fractions are given in Table A-9 of Appendix A. In Table 4-1, Φ is shown, in calculational detail, to have a value of 0.035.

Substituting $I = 1.6 \times 10^5$ μg and $\phi = 0.035$ in Equation 4-4,

$$X_S(t) = 1.05 \times 10^3\ t^{-1.39} \qquad t > 1 \qquad (4\text{-}5)$$

TABLE 4-1

Calculation of Φ for Single Exposure to
High-Temperature-Dried Yellowcake*

Class/Pathway, Region	f_{Region}	$R_{Class, Pathway}$	F	$f_{1, Class}$	f_s	Product
D/(a), NP	0.3	0.5	0.36	-	0.22	0.012
D/(b), NP	0.3	0.5	0.36	0.05	0.22	0.0006
D/(c), TB	0.08	0.95	0.36	-	0.22	0.006
D/(d), TB	0.08	0.05	0.36	0.05	0.22	0.00002
D/(e), P	0.2	0.8	0.36	-	0.22	0.013
D/(h), P	0.2	0.2	0.36	-	0.22	0.003
Y/(a), NP	0.3	0.01	0.64	-	0.22	0.0004
Y/(b), NP	0.3	0.99	0.64	0.002	0.22	0.0001
Y/(c), TB	0.08	0.01	0.64	-	0.22	0.0001
Y/(d), TB	0.08	0.99	0.64	0.002	0.22	0.00002
				Sum	(Φ)	0.035

*ϕ is the fraction of mass inhaled that is deposited in the system soon after exposure.

Values of $X_S(t)$ calculated for yellowcake dried at high temperature appear in Figure 4-1 under the designation "Systemic Pathways."

The sum of the contributions of both pathways to the total urinary uranium concentration, X_T, is shown as a solid line in Figure 4-1. This curve provides the urinary uranium concentration as a function of time following a single exposure equal to 1 ALI.

4.1.2 During Continuous Exposure

During continuous exposure to airborne high-temperature-dried yellowcake, the magnitude of the urinary uranium concentration is the sum of two principal contributions: (1) uranium stored in kidney tissues, which is assumed to be transferred directly to urine in accordance with an exponential retention

function (15-day half-life) and (2) the contribution from uranium stored in the system other than the kidney, which is assumed to be released to the blood in accordance with a power function ($t^{-1.39}$), from which 67 percent is excreted directly into urine.* In this section, the kidney burdens calculated for continuous exposure conditions in Chapter 2 are used to derive the first contribution to the urinary concentration described above. The second contribution is then derived using an approximation of the power function model as originally proposed by Adams and Spoor (Ref. 14) and subsequently used in ICRP-30 (Ref. 8). The approximation (exponential) was used because of analytical difficulties associated with the power function at times preceding equilibrium. Values of K(t)/I', the kidney burden per unit intake rate, appear in Figure 2-2 for the first contributor; values of S(t)/I', the systemic burden per unit intake rate, appear in Figure 2-3 for the second contributor.

4.1.2.1 Uranium Released from Kidney Tissues

In the first case, the urinary uranium concentration is given by

$$X_K(t) = \lambda_K K(t)/1.4$$
$$= 3.3 \times 10^{-2}\ K(t) \qquad (4\text{-}6)$$

or

$$X_K(t) = 3.3 \times 10^{-2}\ I'[K(t)/I'] \qquad (4\text{-}7)$$

The constant 1.4 l/d is the daily urinary volume excretion of the reference man. K(t) is the kidney burden as a function of time. λ_K is the kidney elimination constant, $\frac{0.693}{15}$ d^{-1}. I' is the intake rate of interest. The value of interest for the intake, I', is the continuous exposure criterion developed in Section 3.3.2, 626 μg U/d. Substituting into the equation above gives

$$X_K(t) = 20.7K(t)/I' \qquad (4\text{-}8)$$

---

*In making this statement, it is assumed that specimens are obtained more than 24 hours after the exposure to airborne uranium is temporarily terminated, thus avoiding the uranium that is excreted the first day without deposition in the organs.

Values of $X_K(t)$ calculated for yellowcake dried at high temperature appear in Figures 4-2 and 4-3 under the designation "Kidney Pathways."

4.1.2.2 Uranium Released from Systemic Tissues and Excreted Directly in Urine

In the second case, the urinary uranium concentration due to the systemic burden (excluding the kidney) is given by

$$X_S(t) = 0.67\lambda_S S(t)/1.4 = 0.48\lambda_S S(t) \qquad (4\text{-}9)$$

where S(t) is the systemic burden.

The exponential equation given in Equation 4-10 is used in ICRP-30 (Ref. 8) to approximate the power function term used in the retention equation for uranium in bone that was developed by Adams and Spoor (Ref. 14).

$$t^{-0.39} = 0.8 \exp\frac{-0.693t}{20} + 0.092 \exp\frac{-0.693t}{5000} \qquad (4\text{-}10)$$

In this study, only the first term of Equation 4-10 is used as the major component for estimating excretion from the system. The second term was omitted because its use would produce calculated results not in accord with empirical data for uranium mill workers, which do not show any evidence of long-term excretion of uranium (Ref. 13).

Thus,

$$X_S(t) = 0.48[0.8\lambda_{1S}]S(t)$$

Substitution of 0.693/20 for λ_{1S} gives

$$X_S(t) = 1.33 \times 10^{-2}\ S(t) = 1.33 \times 10^{-2}\ I'[S(t)/I'] \qquad (4\text{-}11)$$

Values of S(t)/I' appear in Figure 2-3. Using the value of 626 µg/d for I' gives

$$X_S(t) = 8.3\ \frac{S(t)}{I'} \qquad (4\text{-}12)$$

Note that Figures 4-2 and 4-3 each contain a curve entitled "Systemic Pathways." The curve in Figure 4-2 labeled "X_S - Systemic Pathways (One Exponent Term)" was calculated using only the first exponent term of the Adams and Spoor approximation to the systemic burden retention curve. The curve in Figure 4-3 labeled "X_S - Systemic Pathways (Two Exponent Terms)" was calculated using both of the exponent terms given by Adams and Spoor (Ref. 14).

The shape of the X_T curve in Figure 4-3 is primarily determined by the contributions of uranium by the system. Because of the 5000-day half-life for uranium in the Adams-Spoor approximation (second exponent term in Eq. 4-10), more uranium accumulates in the system than when only the first exponential term is used to approximate the retention (Eq. 4-11). According to Equation 4-9, this larger systemic accumulation will therefore result in significantly greater values of X_S than are shown in Figure 4-2. To be conservative, the urinary uranium concentration expected from continuous occupational exposure to uranium contained in airborne yellowcake dried at high temperature at the limiting intake should therefore be estimated from Figure 4-2 rather than Figure 4-3.

4.2 YELLOWCAKE DRIED AT LOW TEMPERATURE

The procedures described in Section 4.1 are repeated here with a few differences in the values of the parameters as noted below.

4.2.1 Following Single Exposure

4.2.1.1 Uranium Released from Kidney Tissues

The contribution of the total urinary uranium concentration contributed by the kidneys, $X_K(t)$, is described by Equation 4-1 as

$$X_K(t) = 3.3 \times 10^{-2} \, I[K(t)/I]$$

Values of K(t)/I are obtained from the curve in Figure 2-1 for yellowcake dried at low temperature. The value of I that is of interest, 2.6×10^5 µg U,

is obtained from Section 3.3.1. When this value of I is substituted in the equation above,

$$X_K(t) = 8.6 \times 10^3 \, [K(t)/I]$$

4.2.1.2 Uranium Released from Systemic Tissues and Excreted Directly in Urine

That fractional part of the total urinary uranium concentration contributed by the systemic tissues, $X_S(t)$, is described by Equation 4-4 as

$$X_S(t) = 0.19\phi I t^{-1.39}$$

Using the procedure shown in Table 4-1, it can be shown that the value for Φ is 0.057. From Section 3.3.1, I is 2.6×10^5 µg U. Substituting these values,

$$X_S(t) = 2.81 \times 10^3 \, t^{-1.39}$$

The urinary uranium concentration due to contributions from both kidney and systemic pathways is shown in Figure 4-4.

4.2.2 <u>During Continuous Exposure</u>

4.2.2.1 Uranium Released from Kidney Tissues

The fractional part of the total urinary uranium concentration contributed by the kidneys, $X_K(t)$, is described by Equation 4-7,

$$X_K(t) = 3.3 \times 10^{-2} \, I'[K(t)/I']$$

Values of K(t)/I' are obtained from the appropriate curve in Figure 2-2. The value of interest for the intake, I', is the continuous exposure criterion developed in Section 3.3.2, 1094 µg U/d. Substituting this value into the equation above gives

$$X_K(t) = 36.1[K(t)/I']$$

4.2.2.2 Uranium Released from Systemic Tissues and Excreted Directly in Urine

The fractional part of the total urinary uranium concentration contributed by the systemic tissues, $X_S(t)$, is described by Equation 4-11,

$$X_S(t) = 1.33 \times 10^{-2}\ I'[S(t)/I']$$

Substituting the value given above for I', 1094 μg U/d, gives

$$X_S(t) = 14.6[S(t)/I']$$

Values of S(t)/I' are obtained from Figure 2-3.

The total urinary uranium concentration is the sum of the contributions of uranium from both kidney and systemic pathways as illustrated in Figures 4-5 and 4-6.

$$X_T(t) = X_K(t) + X_S(t)$$

4.3 ORE DUST

The procedures described in Section 4.1 are repeated here with a few differences in the values of the parameters as noted below.

4.3.1 Following Single Exposure

4.3.1.1 Uranium Released from Kidney Tissues

The fractional part of the total urinary uranium concentration contributed by the kidneys, $X_K(t)$, is described by Equation 4-1 as

$$X_K(t) = 3.3 \times 10^{-2}\ I[K(t)/I]$$

The values of K(t)/I for ore dust are obtained from the curves in Figure 2-1. The values of I given in Section 3.3.1 are 4.6×10^4 and 8.0×10^4 μg U for size distributions 1-μm and 10-μm AMAD, respectively. When these values of I are substituted into the equation above,

$$X_K(t) = 1.5 \times 10^3 \, [K(t)/I] \text{ for 1-μm AMAD}$$
$$X_K(t) = 2.6 \times 10^3 \, [K(t)/I] \text{ for 10-μm AMAD}$$

4.3.1.2 Uranium Released from Systemic Tissues and Excreted Directly in Urine

The fractional part of the total urinary uranium concentration contributed directly by the systemic tissues, $X_S(t)$, is described by Equation 4-4 as

$$X_S(t) = 0.19\Phi I t^{-1.39} \qquad t > 1$$

Using the procedure shown in Table 4-1, it can be shown that the value for Φ is 0.0165 for 1-μm-AMAD particles and 0.021 for 10-μm-AMAD particles. Using these values and the values of I given above, $X_S(t)$ can be expressed as

$$X_S(t) = 144t^{-1.39} \text{ for 1-μm-AMAD particles}$$

$$X_S(t) = 320t^{-1.39} \text{ for 10-μm-AMAD particles}$$

The total urinary uranium concentrations, summing the kidney and systemic pathways, are shown in Figure 4-7 for 1-μm-AMAD and in Figure 4-8 for 10-μm-AMAD particle sizes.

4.3.2 <u>During Continuous Exposure</u>

4.3.2.1 Uranium Released from Kidney Tissues

The fractional part of the urinary uranium concentration that is contributed by the kidneys, $X_K(t)$, is described by Equation 4-7 as

$$X_K(t) = 3.3 \times 10^{-2} \, I'[K(t)/I']$$

Values of K(t)/I' are obtained from the appropriate curve in Figure 2-2. The appropriate values for the intake, I', are the continuous exposure criteria developed in Section 3.3.2: 182 μg U/d for 1-μm-AMAD particles of ore dust and 320 μg U/d for 10-μm-AMAD particles. Substituting these values into the equation above gives

$$X_K(t) = 6.0[K(t)/I'] \text{ at 1-μm AMAD and}$$
$$X_K(t) = 10.6[K(t)/I'] \text{ at 10-μm AMAD}$$

4.3.2.2 Uranium Released from Systemic Tissues and Excreted Directly in Urine

The fractional part of the urinary uranium concentration that is contributed by the systemic tissues, $X_S(t)$, is described by Equation 4-11 as

$$X_S(t) = 1.33 \times 10^{-2}\ I'[S(t)/I']$$

Substituting the values given above for I', 182 μg U/d and 320 μg U/d, gives

$$X_S(t) = 2.4[S(t)/I'] \text{ at 1-μm AMAD and}$$
$$X_S(t) = 4.3[S(t)/I'] \text{ at 10-μm AMAD}$$

Values of S(t)/I' are obtained from Figure 2-3.

The total urinary uranium concentrations illustrated in Figures 4-9 through 4-12 are determined by the sum of the contributions of uranium along both the kidney and systemic pathways, i.e.,

$$X_T(t) = X_K(t) + X_S(t)$$

4.3.3 Particle Size Distributions

From measurements of particle size distribution using a cascade impactor, the Environmental Measurements Laboratory concluded that a 10-μm-AMAD parameter for ore dust much more closely approximates the actual size of airborne dust during processing at uranium mills than the 1-μm-AMAD parameter (Ref. 18).

4.4 IMPLICATIONS FOR BIOASSAY PROGRAMS

The recommendations for a urinalysis program that are provided in this section are based on the important assumption that the air sampling program conducted at the affected mill normally provides sufficient and sufficiently representative data for the monitoring and control of airborne uranium. Under these conditions, routine urinalysis is a secondary check on the effectiveness of the primary method of monitoring, i.e., air sampling. If for any reason the air sampling program is inadequate and reliance for the monitoring function must be placed on urinalysis instead, the bioassay program recommended here would not be acceptable.

The principal value of this internal dosimetry model as it is to be used in the development of a standardized bioassay program for uranium mills is the guidance it provides for two difficult decisions regarding urinalysis: (1) action points and (2) frequency. In this section, recommendations on these subjects are made, based on analytical results previously presented.

4.4.1 Action Points

Bioassay results should be used to detect either of two undesirable situations: (1) significantly large single exposures or (2) gradual unfavorable trends. In either event, corrective action in the workplace may be indicated. Thus, it is essential that each set of bioassay results be carefully examined by a qualified individual. In looking for single exposures and trends, it is also essential to compare present results for each worker with results obtained previously for that person. The data should be displayed in a manner that permits this type of examination.

For example, assume that the urinalysis result for a worker is 40 µg/l. It is unlikely that the significance of this result will be understood apart from an examination of previous results. If the last three results are 15, 20, and 30 µg/l, it is clear that an unfavorable trend is developing and that corrective action may be necessary to reverse it.* If the last three results

*For this example, it is assumed that the bioassay method for uranium has a zero standard deviation and no bias.

are 5, 10, and 7 μg/l, it is evident that an unusual exposure has occurred and that the conditions surrounding it may still exist. Again, corrective action may be indicated. If the last three results are 40, 35, and 45 μg/l, a quasi-equilibrium condition that may have already been investigated and accepted is indicated.

Not every increase in urinary uranium is sufficiently large to require corrective action or even an investigation. Thus, in the establishment of a standardized bioassay program, it is necessary to select criteria or action points above which corrective action is required. The action points selected for the purposes of this study are the equilibrium values under continuous exposure conditions, obtained from the model, which may be rounded to 60 μg/l for yellowcake dried at low temperature, 20 μg/l for yellowcake dried at high temperature, 10 μg/l for 10-μm-AMAD ore dust, and 5 μg/l for 1-μm-AMAD ore dust. These action points are applicable to both continuous and single exposure conditions.

4.4.2 Action Points for Combined Exposures

Although some mill workers may be exposed only to yellowcake or only to ore dust during a bioassay period, many may be exposed to both. In such cases, the urinary uranium concentration is likely to be attributable to both types of material, and the appropriate action point lies somewhere between the action point for ore dust and the action point for yellowcake. The most straightforward procedure for estimating the appropriate action point involves the use of intake estimates that are required by NRC regulations (§ 20.103 of 10 CFR Part 20) and are therefore already available to the mill health physicist. The following equation may be used for this purpose:

$$\text{Action Point} = \frac{1}{\frac{f_{yc}}{AP_{yc}} + \frac{f_{od}}{AP_{od}}}$$

where

f_{yc} = fraction of total uranium intake contributed by yellowcake

AP_{yc} = appropriate action point for type of yellowcake inhaled

f_{od} = fraction of total uranium intake contributed by ore dust

AP_{od} = appropriate action point for type of ore dust inhaled

Note that the sum of f_{yc} and f_{od} is unity.

4.4.3 Frequency

The maximum time interval for specimen collection is dependent on the magnitude of the action point and the rate at which uranium is excreted following a single exposure. After the action point is determined on the basis of continuous exposure conditions, it is desirable to use the same action point for single exposures. Use of the same action point for both types of exposure conditions is very convenient and is necessary because the exposure conditions are not always known. Application of the action point to the single exposure case essentially dictates the maximum time interval. First, it is assumed that the single exposure occurs immediately following collection of the previous specimen. Second, it is assumed that the exposure involves an intake equal to the limiting intake derived in Chapter 3 (so that smaller intakes do not necessarily trigger corrective action). Third, the elapsed time needed for this intake to produce a urinary uranium concentration equal to the action point is determined. This time establishes the maximum time interval. (Of course a longer or shorter time could be selected, but then the action point would have to be changed to a value different from the continuous exposure action point.) The maximum time intervals determined using this procedure are shown along with their respective action points in Table 4-2.

The maximum time intervals shown in Table 4-2 are subject to simplification. Workers at a given mill are most likely to be exposed either to a combination of low-temperature-dried yellowcake and 10-μm-AMAD ore dust or to a combination of high-temperature-dried yellowcake and 10-μm-AMAD ore dust. In either case, a maximum time interval of 40 days is acceptable. If practicable, the interval between specimen collections should be less than 40 days.

TABLE 4-2

Action Points and Maximum Time Intervals
for Specimen Collection
(Based on Constant, Continuous Intake Rate)

Form	Limiting Intake Rate (μg U/d)	Action Point (μg U/l)	Maximum Time Interval (days)
Yellowcake, LTD	1094	60	40
Yellowcake, HTD	626	20	40
Ore Dust, 10-μm AMAD	320	10	37
Ore Dust, 1-μm AMAD	182	5	36

4.5 URINARY URANIUM CONCENTRATION FOR UNIT INTAKE OF YELLOWCAKE OR ORE DUST

The discussion that precedes this section is concerned with the derivation and significance of the urinary uranium concentrations that result from either single or continuous inhalation exposures when the intake of uranium is limited so as not to exceed the nephrotoxic limit for kidney or the radiological risk criteria established by the ICRP. In most cases encountered in routine occupational exposure at uranium mills, the uranium intake will not be as large as these limiting intakes, and therefore the expected urinary uranium concentrations will be correspondingly smaller. Occasionally, as a result of an acute exposure, the single intake values will be larger than those given in this study, and it may be informative to estimate the uranium intake using these values.

4.5.1 Following Single Exposure

The urinary uranium concentration per unit intake of uranium following a single exposure to yellowcake or ore dust is given in Figure 4-13. The following example may be used to illustrate the use of this figure. Assume a worker who is exposed exclusively to high-temperature-dried yellowcake submits bioassay specimens every 40 days. Assume the following results appear in this

worker's bioassay records: 13, 10, 5, 12, 10, 130 μg/l. These results indicate that a significant single exposure has occurred, raising questions as to why the exposure occurred and whether the intake limits were exceeded. Addressing the latter question, assume that it is not possible to establish the time of the exposure. Under these conditions, it is necessary to assume that the exposure took place immediately after collection of the last 10-μg/l specimen. Figure 4-13 indicates that at 40 days after exposure the urinary uranium concentration per unit intake is 1.3×10^{-4} μg/l per μg inhaled. An estimate of the intake is obtained (1) by subtracting the "background" concentration of about 10 μg/l (average), leaving 120 μg/l to be associated with the single exposure and (2) dividing this value by 1.3×10^{-4} μg/l per μg inhaled. The result is 9.2×10^{5} μg, which would be the intake if all of the many assumptions made in the development of the model were in fact applicable to this worker. From Chapter 3, the intake associated with 1 ALI is 1.6×10^{5} μg, and this analysis therefore indicates that the exposure exceeded the ICRP-recommended limit. (The limiting value for chemical damage to the kidney, Chapter 3, is 5.5×10^{5} μg; this value was also exceeded.)

4.5.2 Following Continuous Exposure

The urinary uranium concentration per unit intake rate of uranium during continuous exposure to yellowcake or to ore dust is given in Figure 4-14. For a worker whose urinalysis results are relatively constant, an estimate of the average daily rate of intake can be made by dividing the average urinary uranium concentration by the equilibrium value from the appropriate curve. These curves may also be useful for new workers. For example, assume that a specimen is collected 40 days after beginning exposure to low-temperature-dried yellowcake and that the result is 48 μg/l (below the action point for equilibrium conditions). At 40 days the curve indicates 3.5×10^{-2} μg/l per μg/d. The intake rate estimate is obtained by dividing this number into 48 μg/l, yielding 1371 μg/d. According to Section 3.3.2, this rate of intake is too large for adequate kidney protection, and corrective action is indicated.

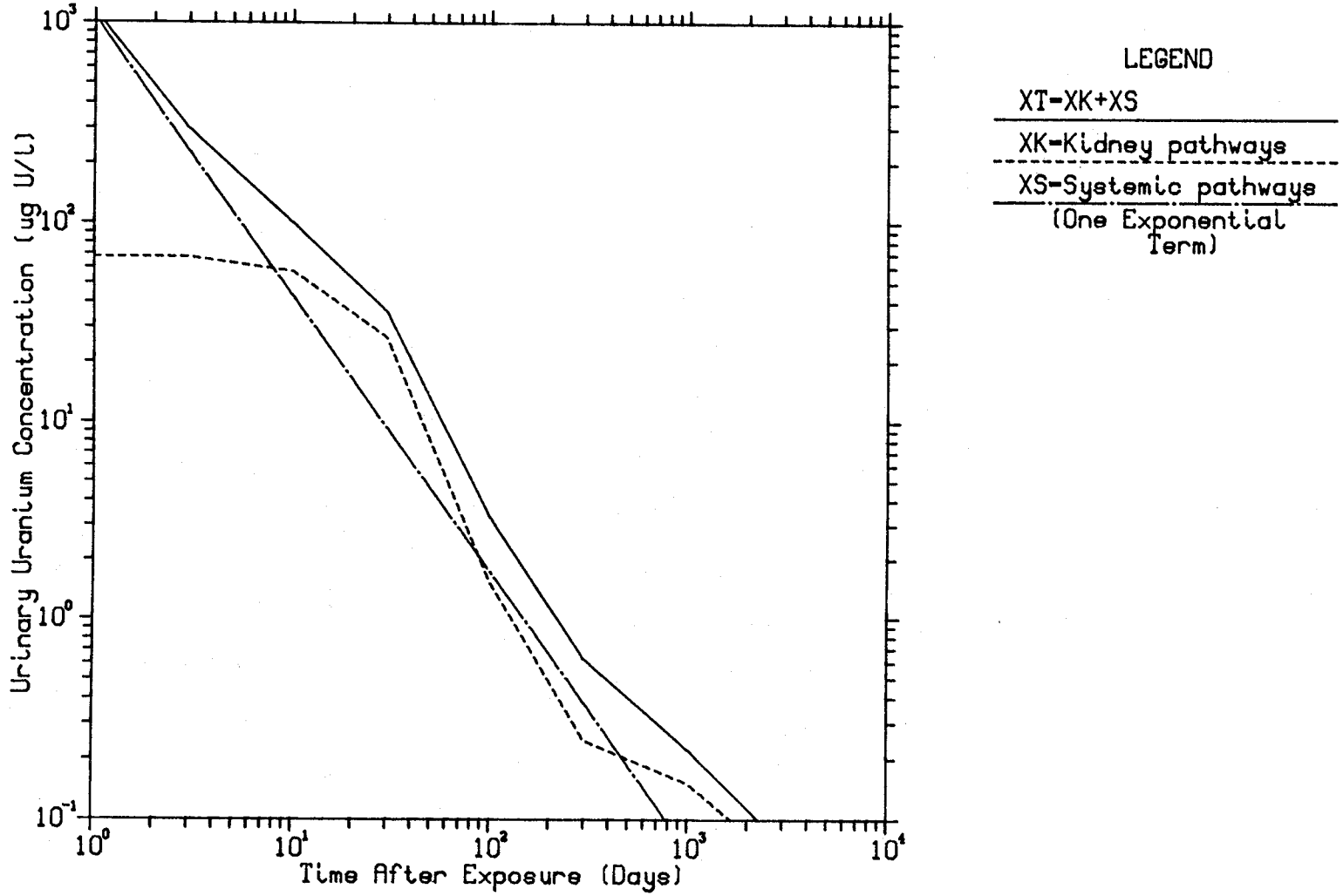

FIGURE 4-1: Urinary Uranium Concentration Following Single Exposure to Uranium Contained in Yellowcake Dried at High Temperature (Intake - 160000 µg U - 1 ALI)

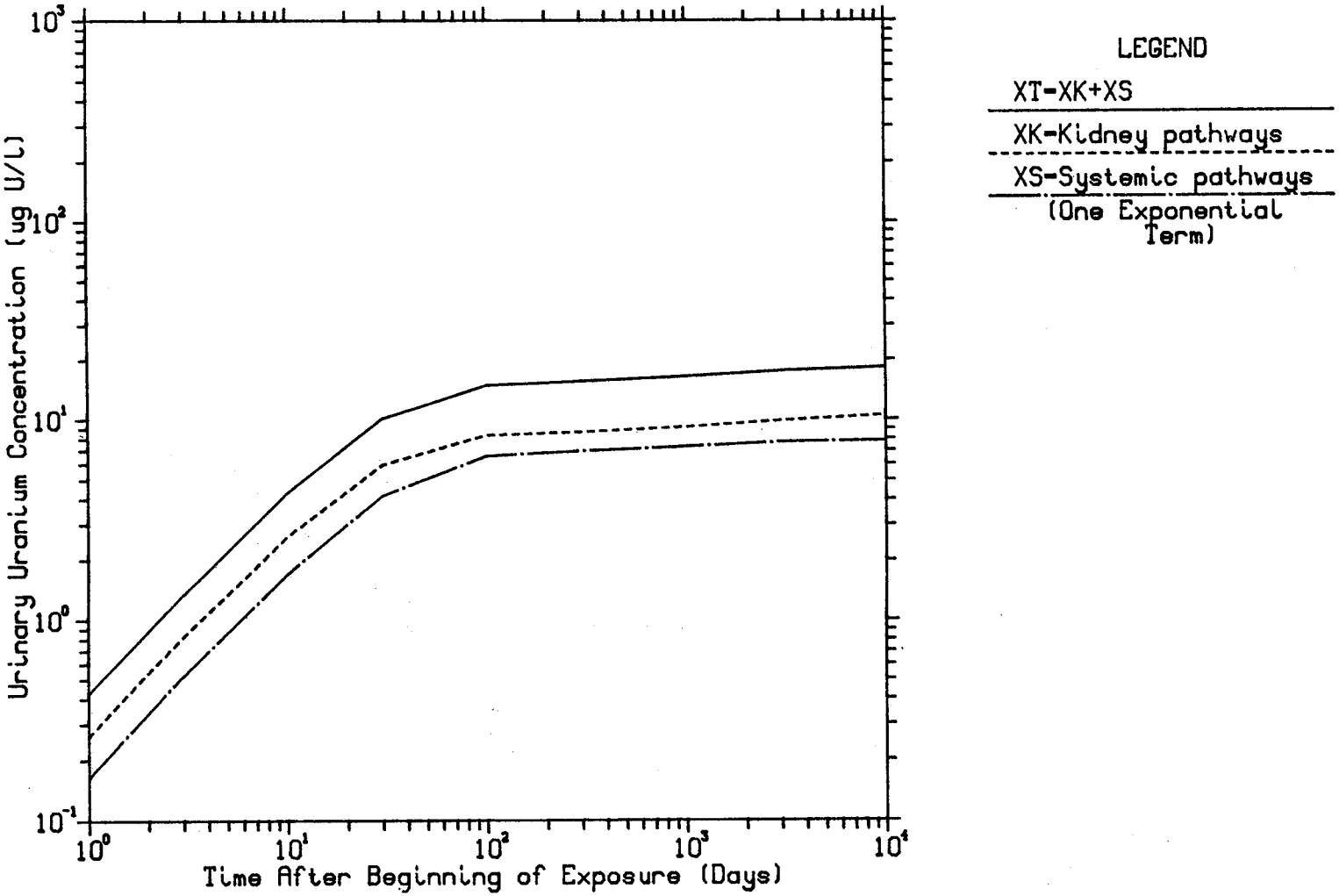

FIGURE 4-2: Urinary Uranium Concentration During Continuous Exposure to Uranium Contained in Yellowcake Dried at High Temperature (Intake Rate - 626 µg U/d Resulting in 1 ALI/yr)

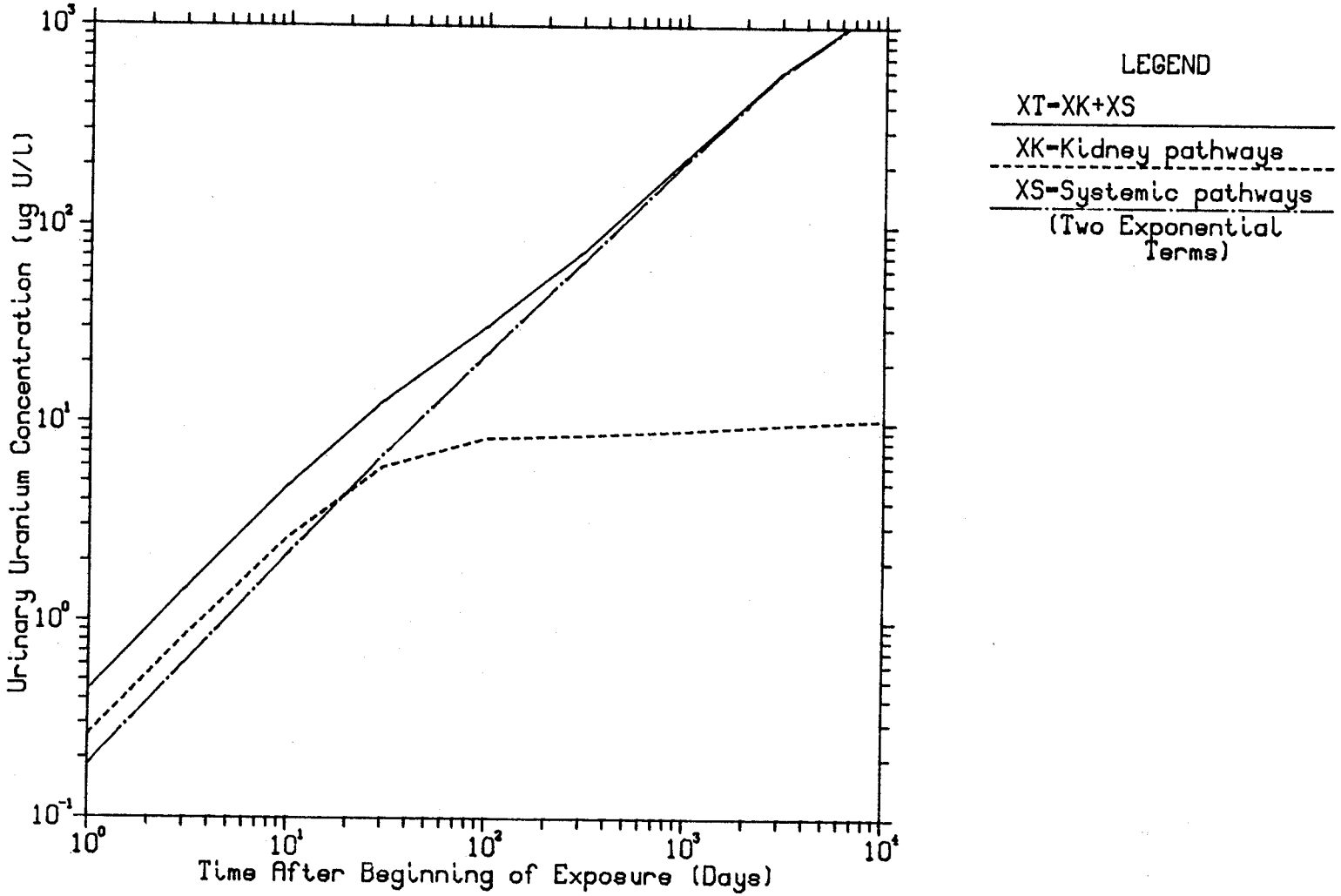

FIGURE 4-3: Urinary Uranium Concentration During Continuous Exposure to Uranium Contained in Yellowcake Dried at High Temperature (Intake Rate - 626 µg U/d Resulting in 1 ALI/yr)

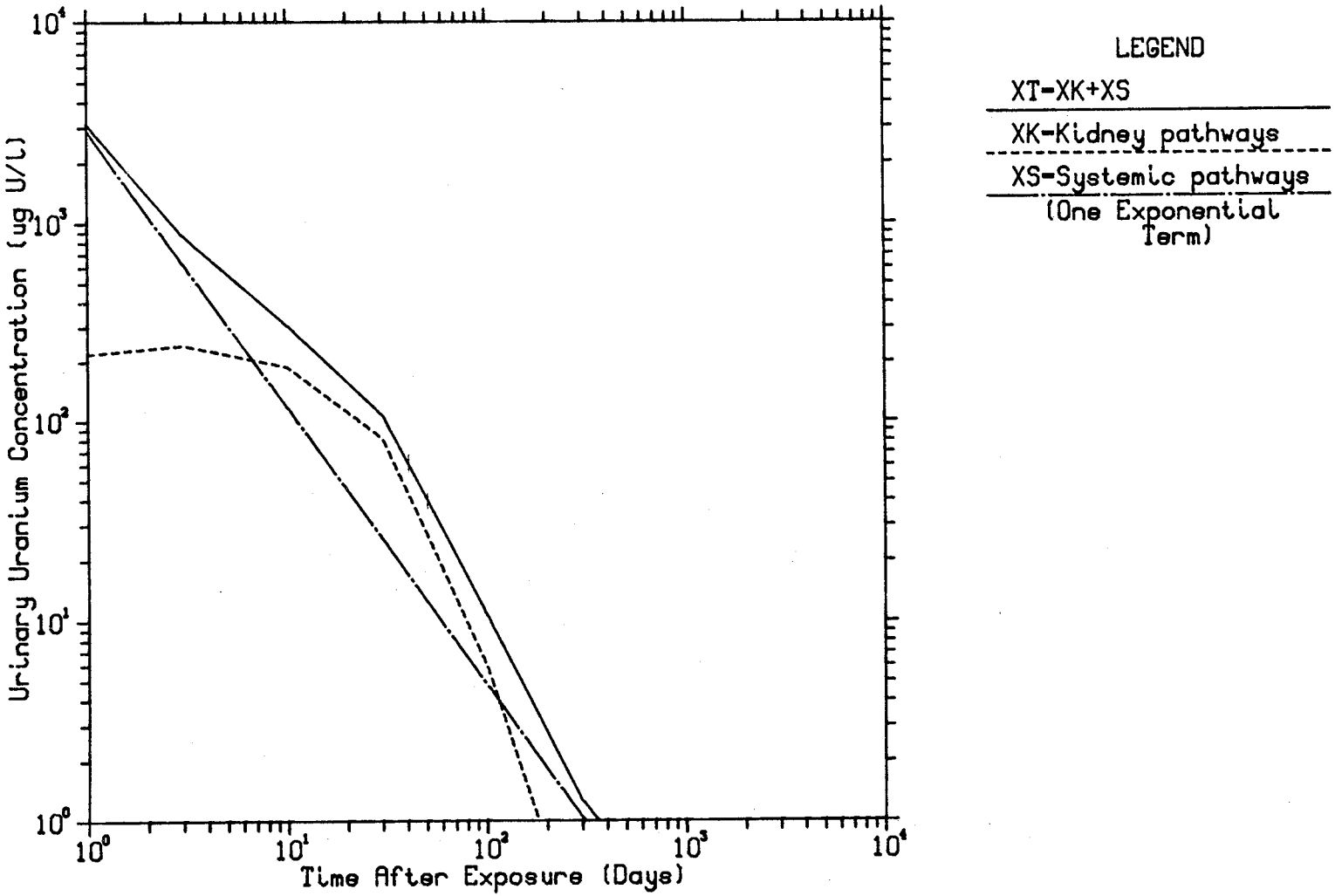

FIGURE 4-4: Urinary Uranium Concentration Following Single Exposure to Uranium Contained in Yellowcake Dried at Low Temperature (Intake - 260000 µg)

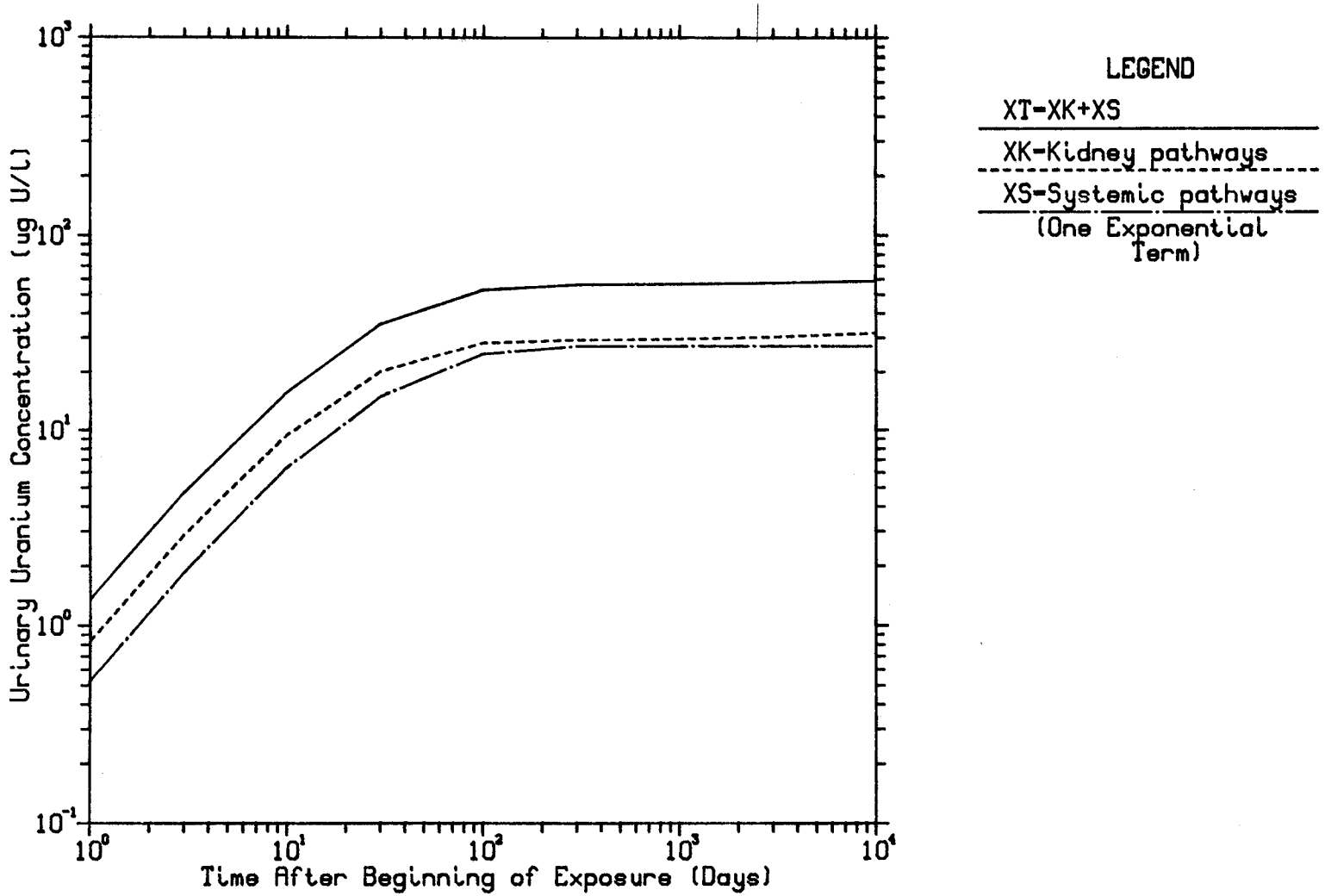

FIGURE 4-5: Urinary Uranium Concentration During Continuous Exposure to Uranium Contained in Yellowcake Dried at Low Temperature (Intake Rate - 1094 µg U/d)

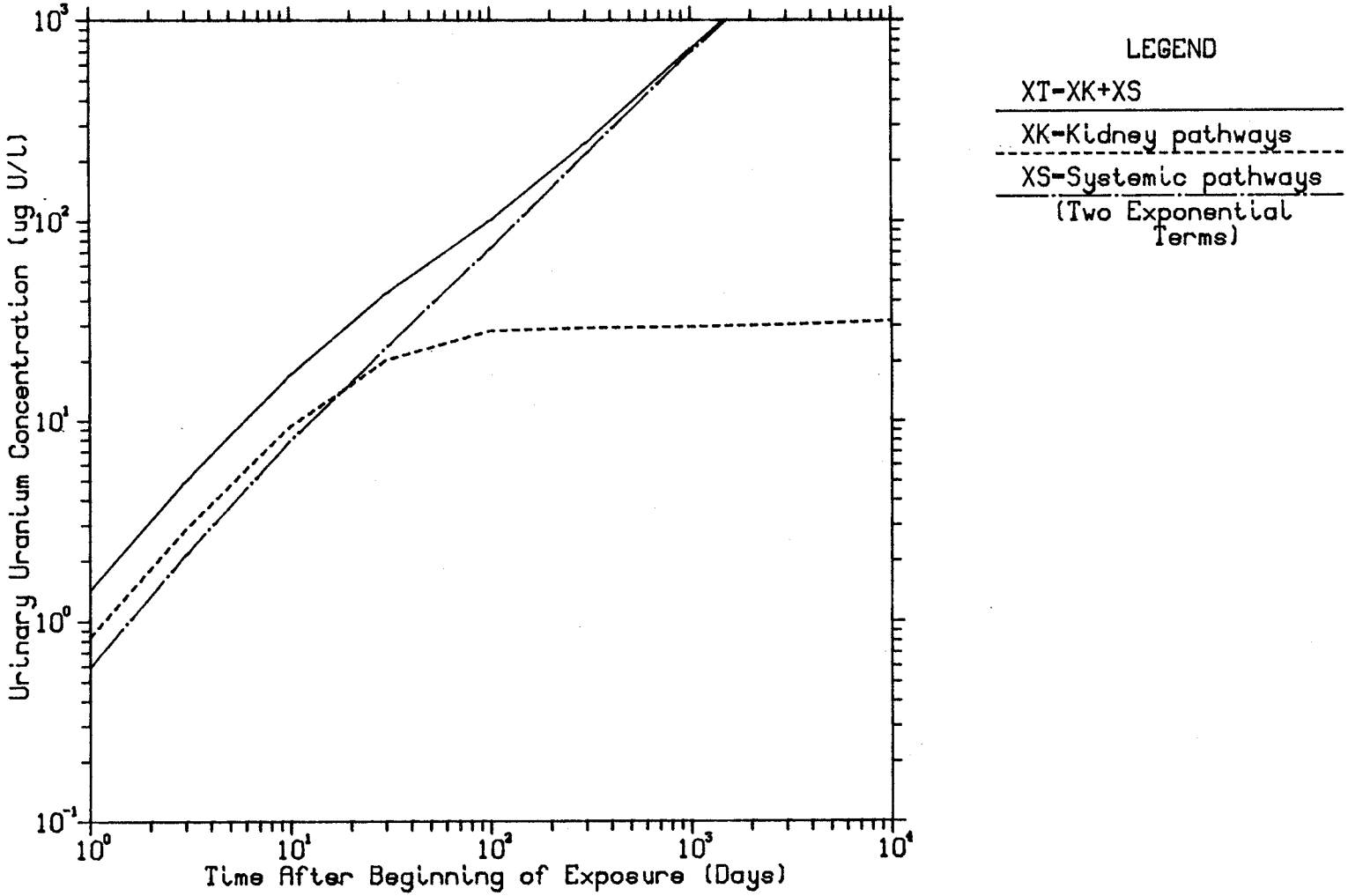

FIGURE 4-6: Urinary Uranium Concentration During Continuous Exposure to Uranium Contained in Yellowcake Dried at Low Temperature (Intake Rate - 1094 µg U/d)

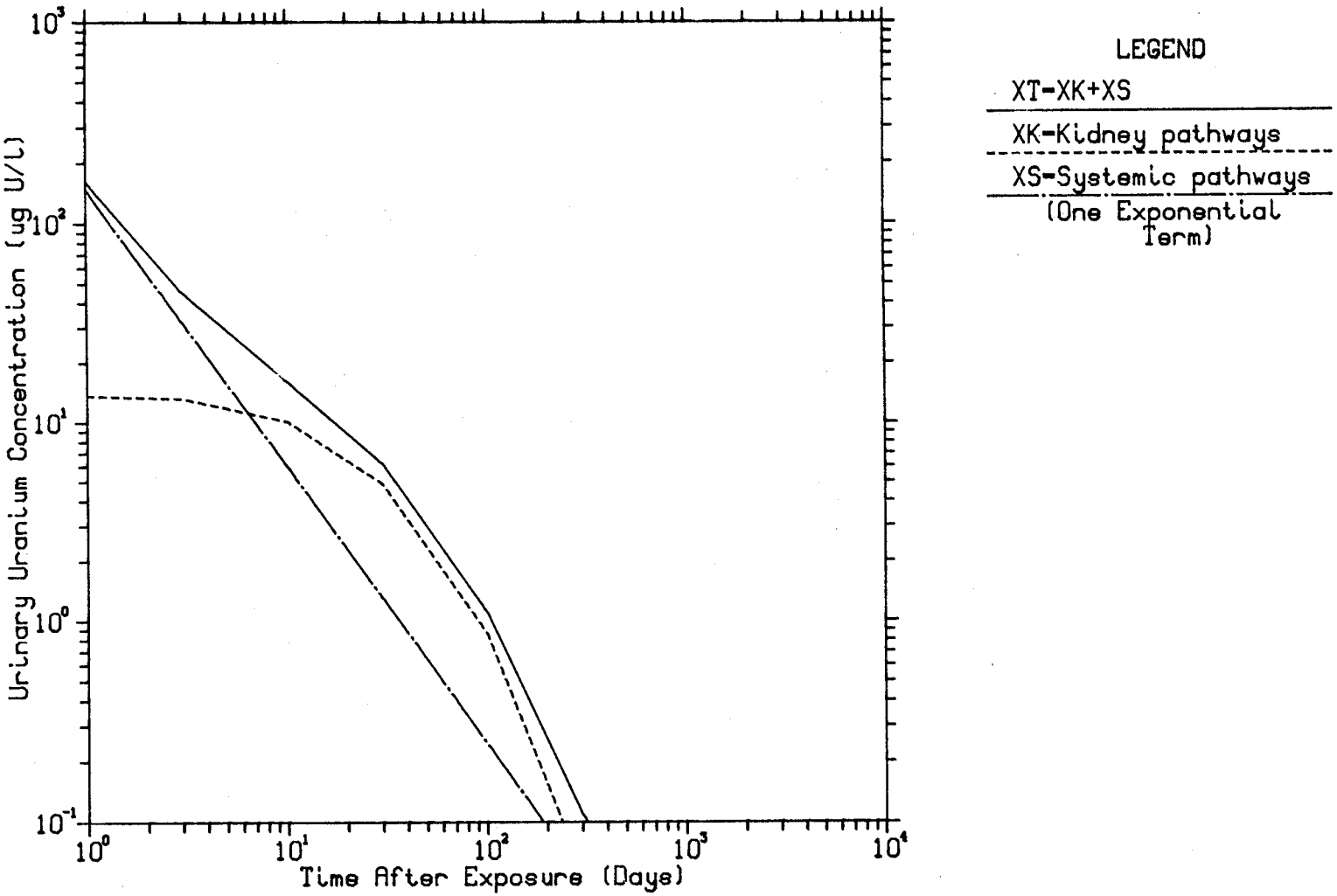

FIGURE 4-7: Urinary Uranium Concentration Following Single Exposure to Uranium Contained in 1-μm-AMAD Particles of Ore Dust (Intake - 46000 μg U - ALI)

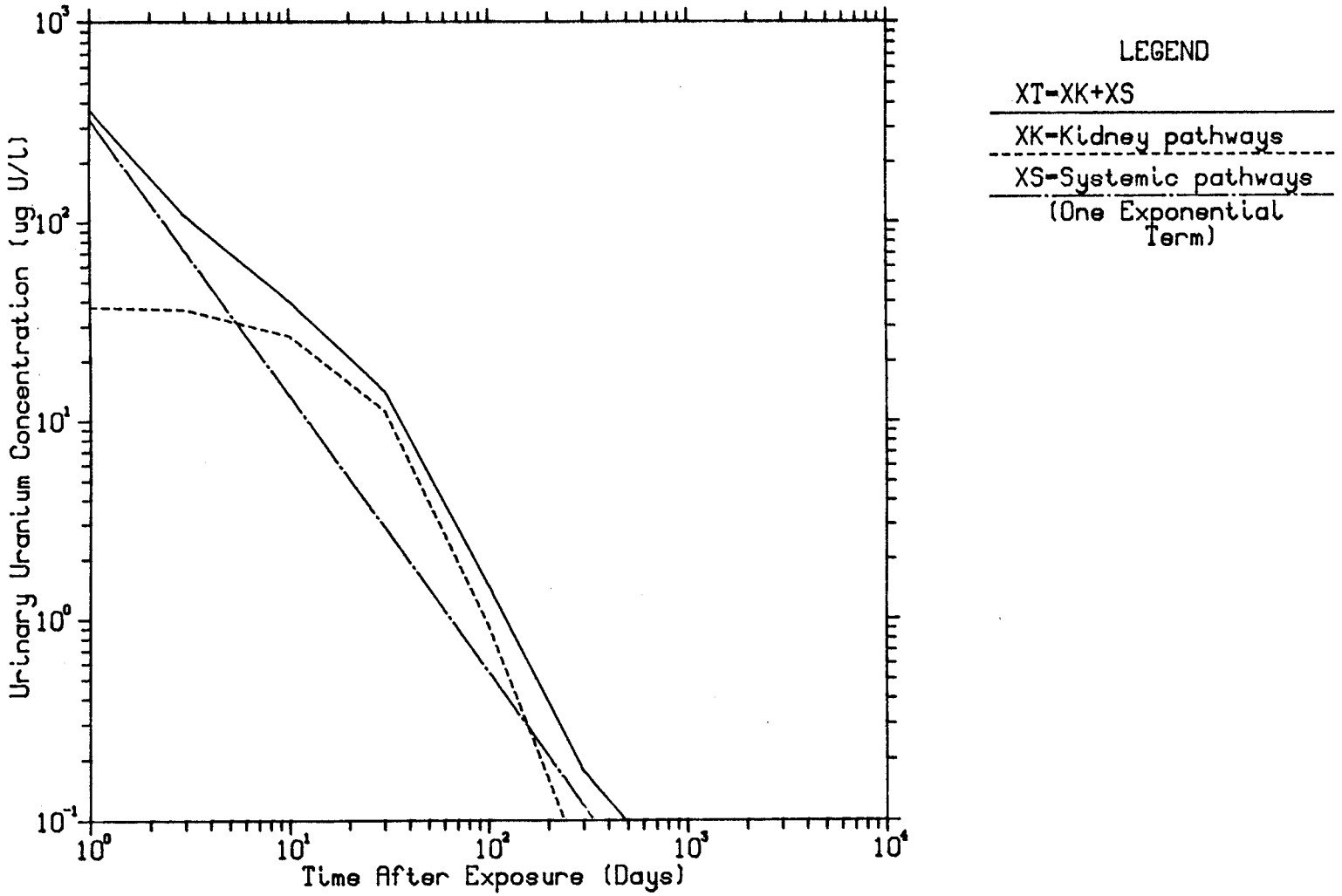

FIGURE 4-8: Urinary Uranium Concentration Following Single Exposure to Uranium Contained in 10-μm-AMAD Particles of Ore Dust (Intake - 80000 μg U - ALI)

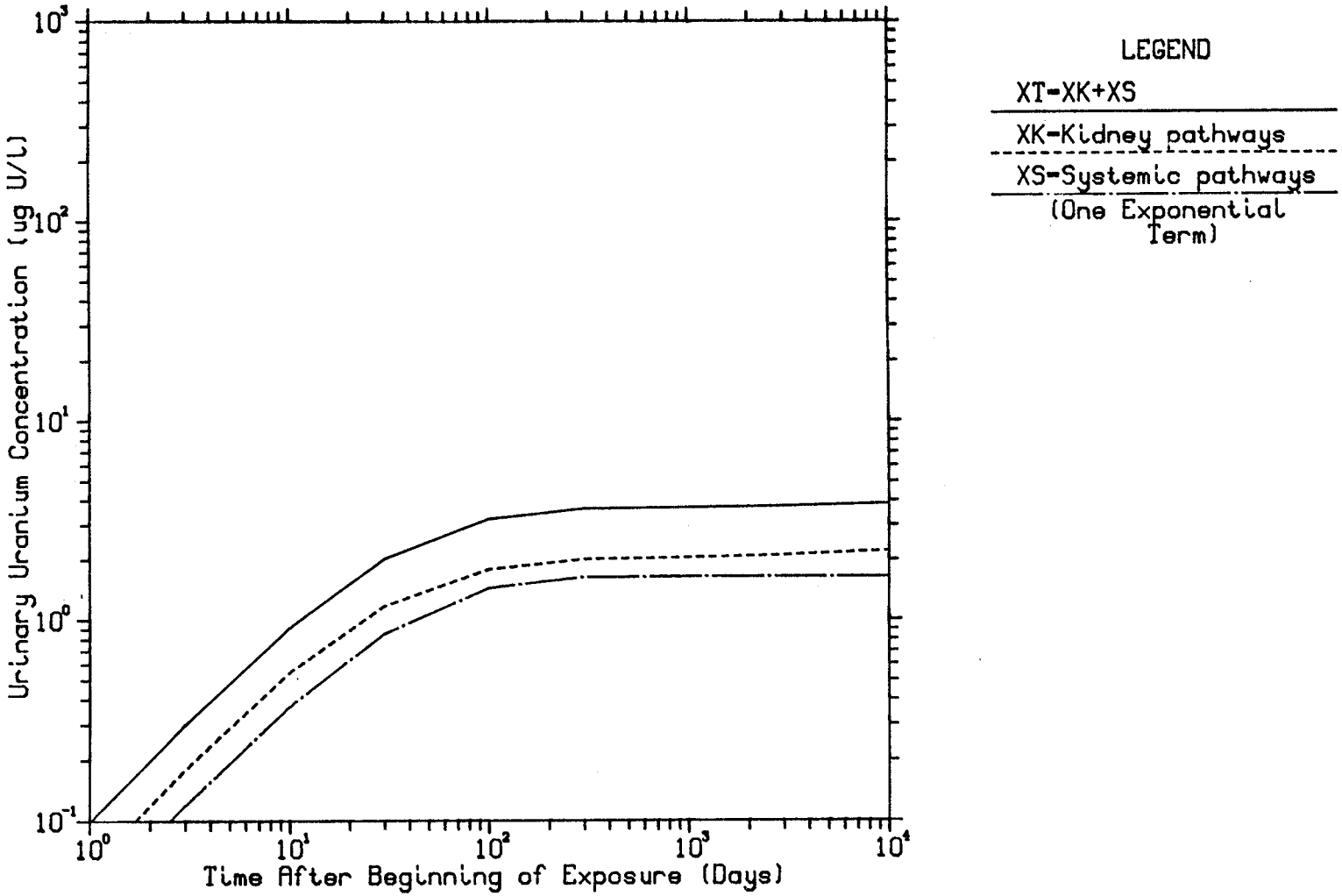

FIGURE 4-9: Urinary Uranium Concentration During Continuous Exposure to Uranium Contained in 1-μm-AMAD Particles of Ore Dust (Intake Rate - 182 μg U/d Resulting in 1 ALI/yr)

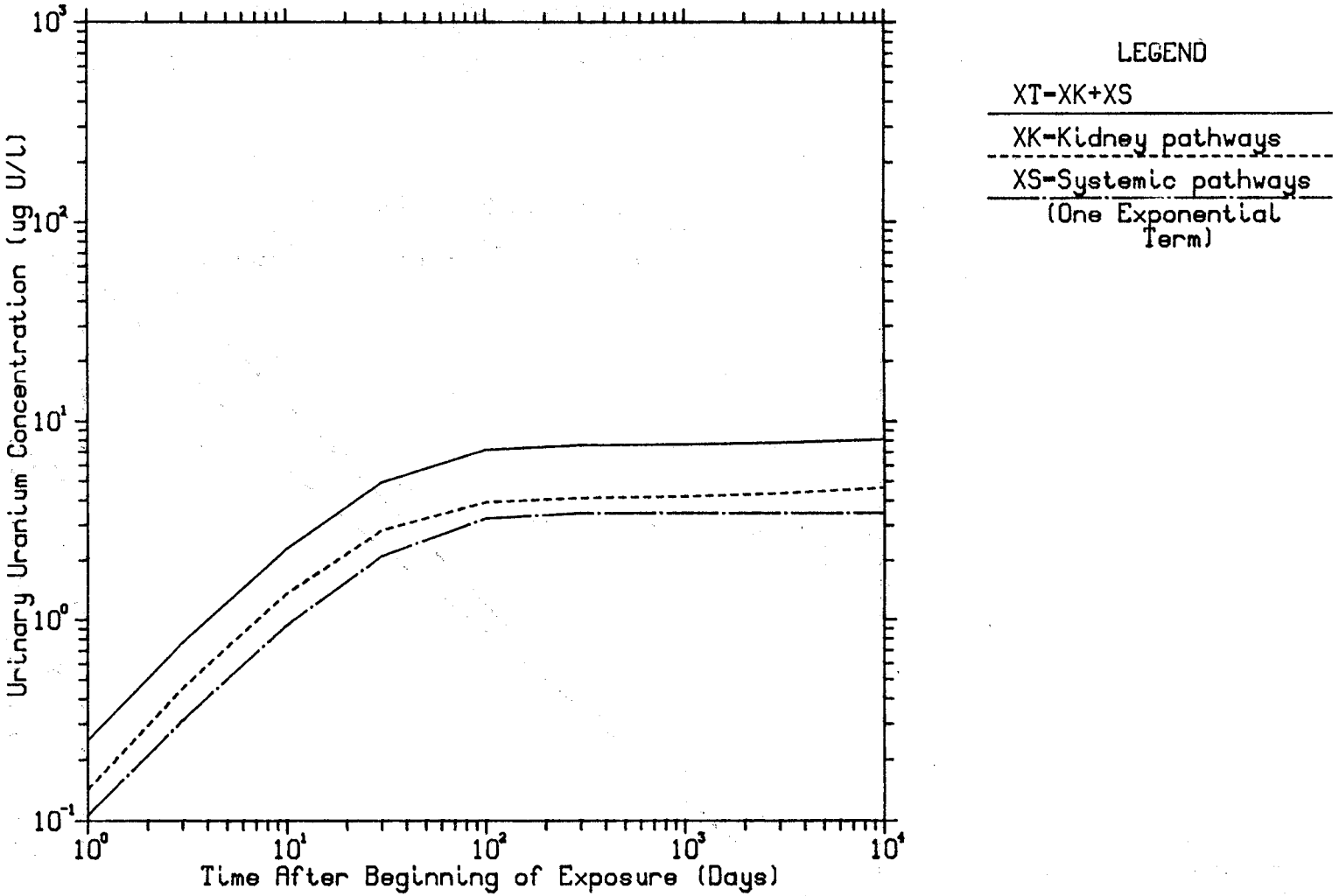

FIGURE 4-10: Urinary Uranium Concentration During Continuous Exposure to Uranium Contained in 10-µm-AMAD Particles of Ore Dust (Intake Rate - 320 µg U/d Resulting in 1 ALI/yr)

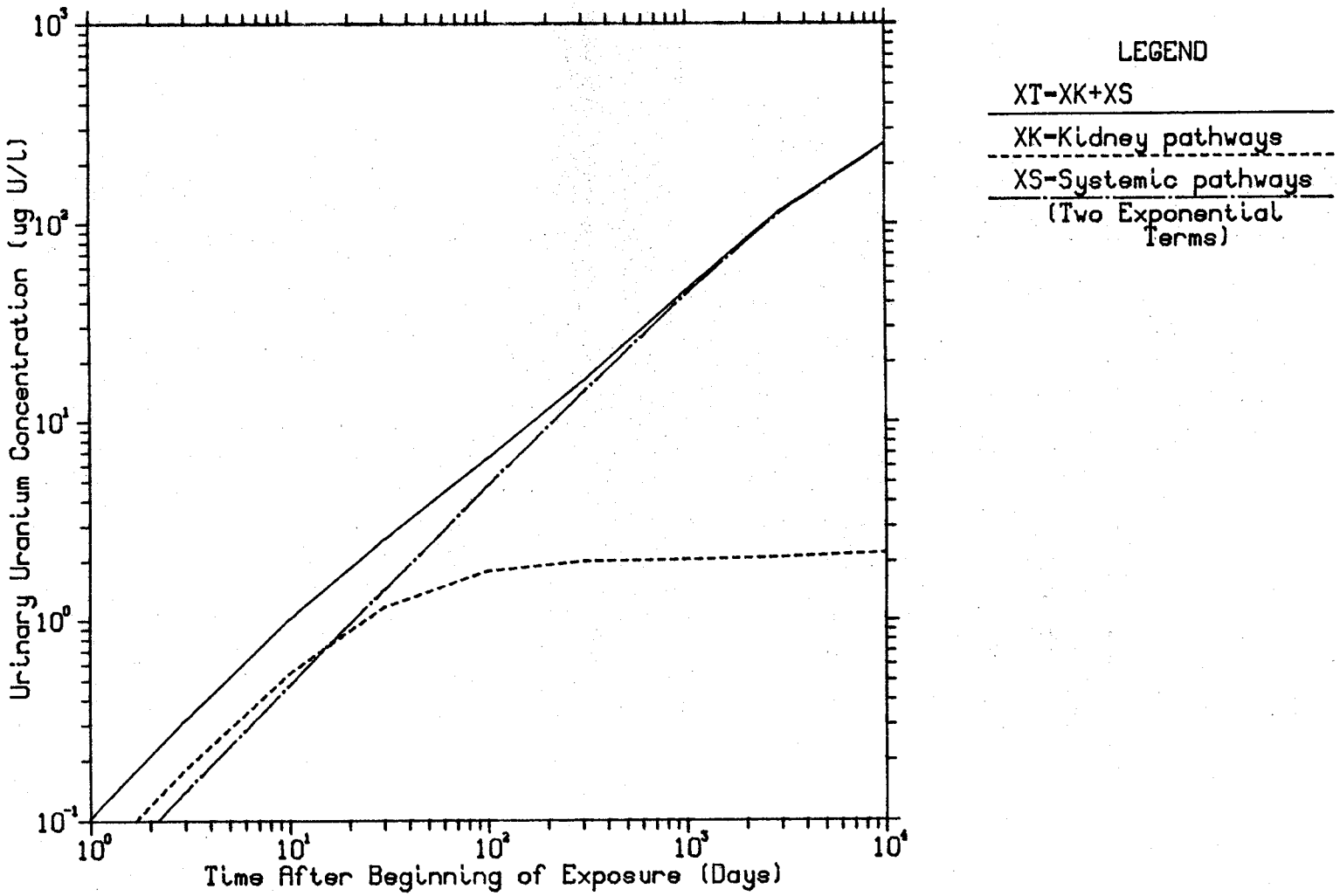

FIGURE 4-11: Urinary Uranium Concentration During Continuous Exposure to Uranium Contained in 1-μm-AMAD Particles of Ore Dust (Intake Rate - 182 μg U/d Resulting in 1 ALI/yr)

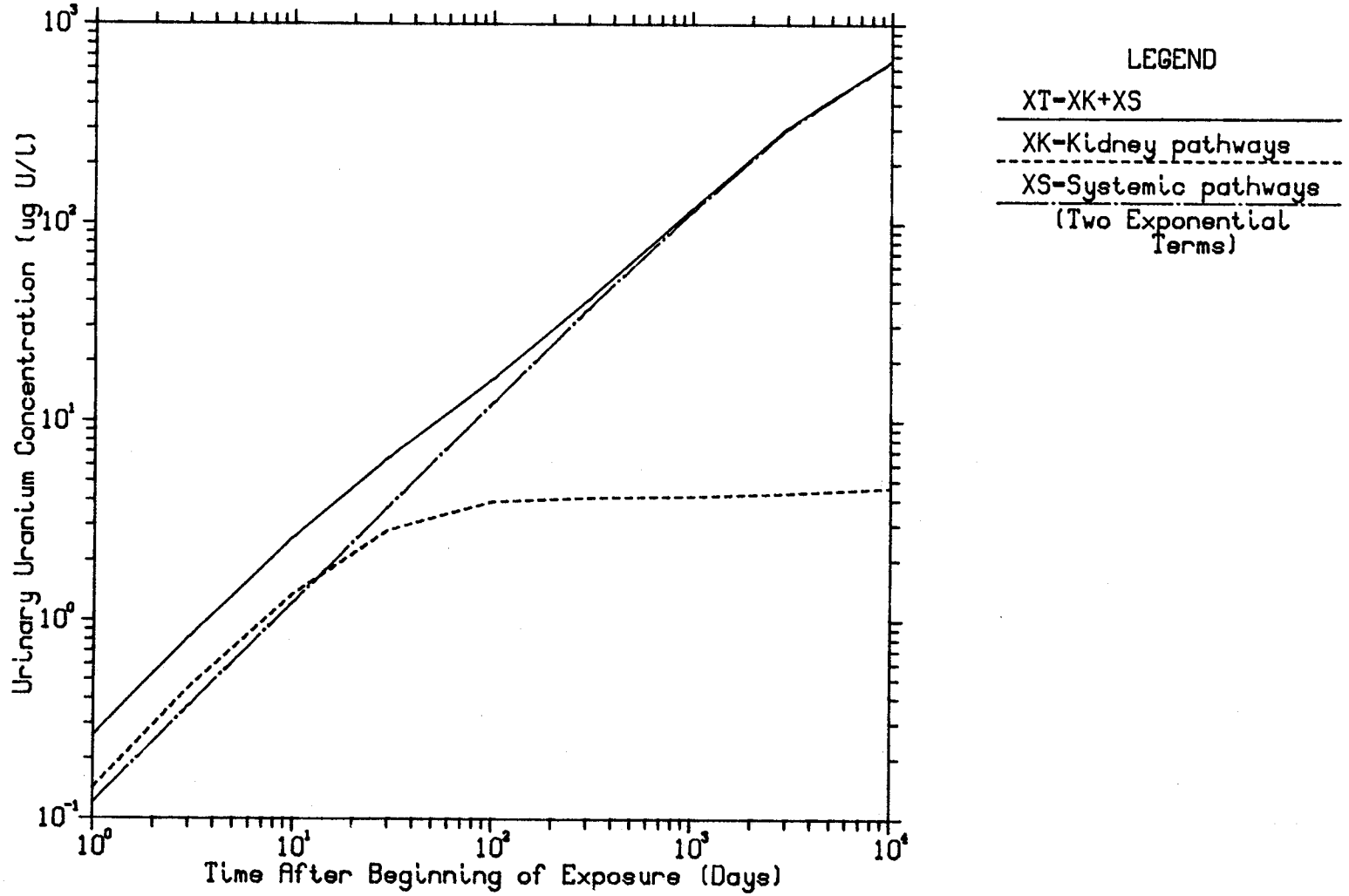

FIGURE 4-12: Urinary Uranium Concentration During Continuous Exposure to Uranium Contained in 10-μm-AMAD Particles of Ore Dust (Intake Rate - 320 μg U/d Resulting in 1 ALI/yr)

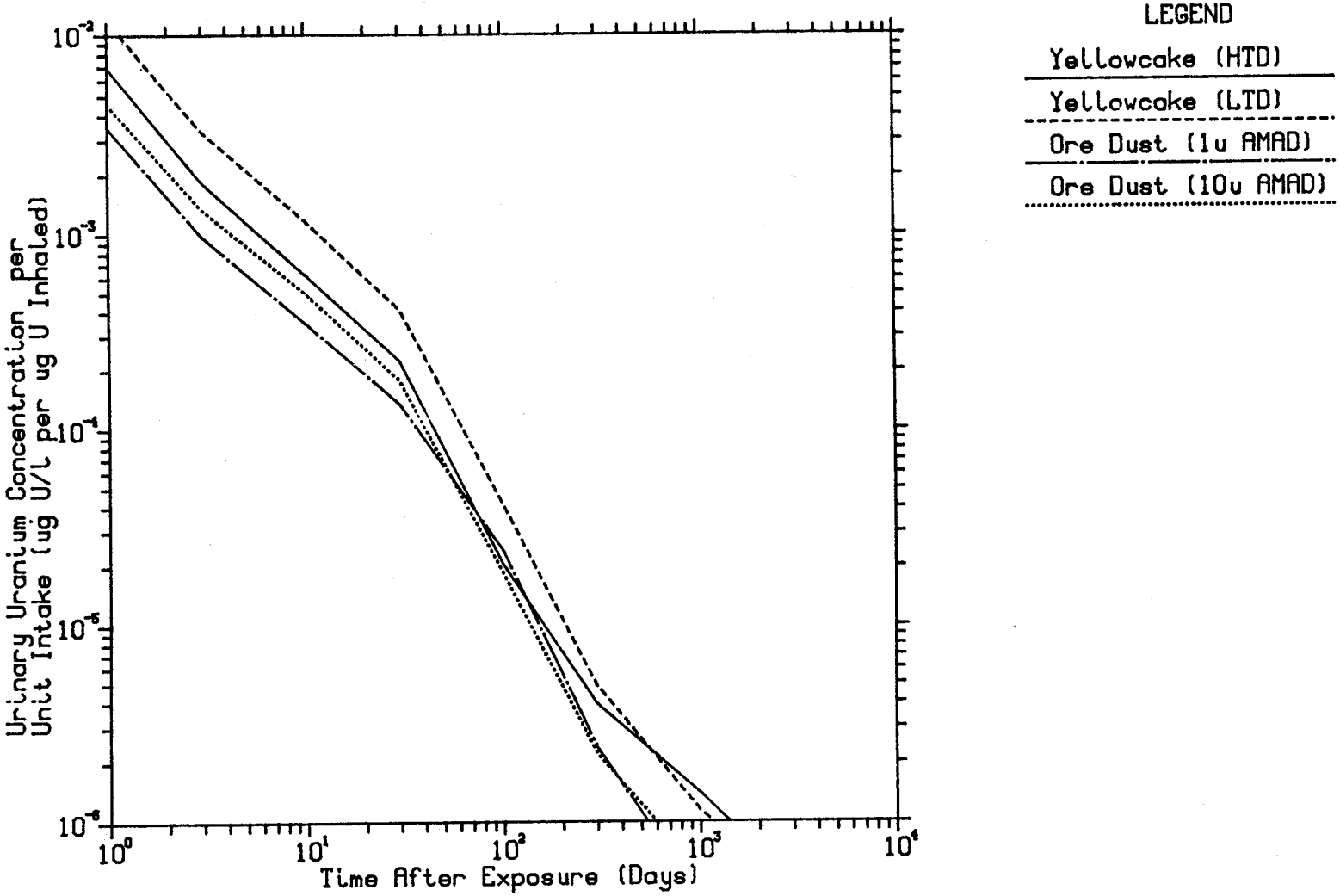

FIGURE 4-13: Urinary Uranium Concentration per Unit Intake of Uranium Following Single Exposure to Yellowcake or Ore Dust

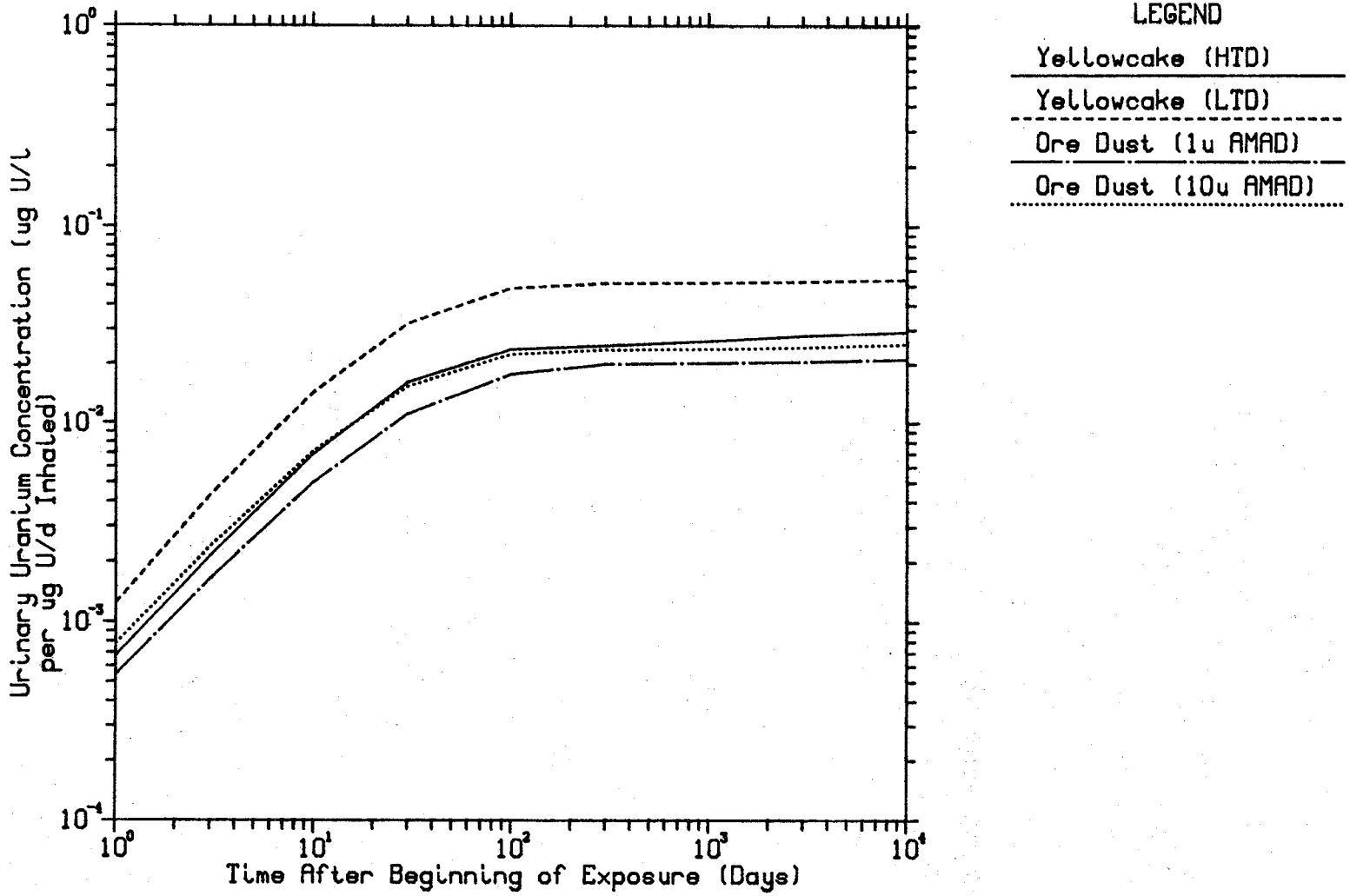

FIGURE 4-14: Urinary Uranium Concentration per Unit Intake Rate of Uranium During Continuous Exposure to Airborne Yellowcake or Ore Dust

5. FINAL RESULTS--CALCULATIONS FOR LUNG BURDEN

The calculational procedures used for determining the lung burden upon which the lung dose estimates in this study are based are given in Section A.1.2 of Appendix A. The results of the calculations, the pulmonary (P) lung burden per unit intake (or intake rate) of uranium, P(t)/I or P(t)/I', are given in Figures 2-4 and 2-5, respectively. In this chapter, the limiting intakes of yellowcake or ore dust (I or I') given in Section 3.3 are combined with the ratios P(t)/I and P(t)/I' to give the time-varying values of the lung burden resulting from such single or continuous inhalation exposures (see Figs. 5-1 and 5-2).

If the lung burden of uranium after an inhalation exposure is sufficiently large, in vivo counting techniques may be necessary. For in vivo counting measurements, the photon emissions from Th-234 (gamma rays at 63 and 93 keV) or U-235 (gamma rays at 186 keV) are used to determine the presence and quantity of U-238 or U-235 from which the quantity of natural uranium can be calculated. For these measurements, it is frequently assumed that Th-234 is in secular equilibrium with the parent U-238 and that these two nuclides are released from the lung at the same rate. Any uranium present on the surface of the subject can be detected by its 16-17 keV x-ray. These x-ray photons are almost completely absorbed by the overlying tissue when the uranium is deposited in the lung. For a dual-crystal Phoswich detector system, which is commonly employed for in vivo lung scans, lung burdens less than 3-8 milligrams (2-5 nCi) of natural uranium are considered undetectable (Refs. 19 and 20). Because of background radiation, some portable onsite in vivo counting facilities may not be able to attain measurement sensitivities as low as do laboratory facilities. A detection limit of 3 nCi has been adopted for purposes of this analysis.

In the discussions that follow, the residual lung burden of uranium in those individuals subjected to lung scans is considered as resulting only from inhalation. If a residual lung burden of uranium is present prior to an inhalation exposure as discussed below, this "background" should be subtracted from the measured values before using Figures 5-1 and 5-2 to evaluate recent exposures.

5.1 YELLOWCAKE DRIED AT HIGH TEMPERATURE

5.1.1 Following Single Exposure

Following a single exposure of 1.6×10^5 μg U (108 nCi) contained in airborne yellowcake dried at high temperature (the limiting intake given in Chapter 3), the uranium lung burden can, according to the model, be detected from the time of exposure up to about 300 days after exposure (Fig. 5-1) using in vivo lung scan techniques. This indicates the usefulness of in vivo counting for workers exposed to this material.

5.1.2 During Continuous Exposure

The lung burden of uranium in yellowcake dried at high temperature during continuous exposure to the limiting intake rate of 626 μg U/d is barely detectable about 1 quarter-year after the beginning of exposure, but after about 1 year is readily detected using current in vivo techniques (Fig. 5-2). Again, the usefulness of in vivo measurements is indicated.

5.2 YELLOWCAKE DRIED AT LOW TEMPERATURE

5.2.1 Following Single Exposure

Although chemical toxicity is the limiting risk for the inhalation of yellowcake dried at low temperature, a sufficiently large exposure may involve an excessive radiological risk as well as potential kidney damage. To permit an evaluation of in vivo counting as a protective measure against this risk, the curve for this type of material in Figure 5-1 is based on 1 ALI (2.7×10^6 μg U) rather than the chemical toxicity limit. An exposure of 1 ALI would, according to the model, remain detectable by in vivo techniques for about 180 days. To the extent that the model would be correct for the affected worker, in vivo counting would be an effective method for obtaining better information regarding the lung burden than urinalysis provides.

5.2.2 During Continuous Exposure

The lung burden predicted by the model during continuous exposure to low-temperature-dried yellowcake is shown as a function of time in Figure 5-2. This figure indicates that exposure at the rate of 1 ALI/yr would become detectable using in vivo measurement techniques. It should be noted that the curve for low-temperature-dried yellowcake in Figure 5-2 is based on an intake rate of 10,931 μg U/d, the radiological toxicity limit, rather than 1094 μg U/d, the chemical toxicity limit. It should be recalled that the purpose here is to evaluate the in vivo measurement technique as a radiological protective measure when the chemical toxicity limit has been exceeded by a large factor.

5.3 ORE DUST (10-μm AMAD)

5.3.1 Following Single Exposure

According to Figure 5-1, reliable detection of the lung burden, which results from the limiting intake of 8×10^4 μg U (54 nCi) in a single exposure, is not possible when using current in vivo techniques. For workers exposed only to ore dust, any uranium detected by lung scan techniques should be interpreted as requiring corrective action.

5.3.2 During Continuous Exposure

According to Figure 5-2, reliable detection of the lung burden that results from continuous inhalation at the limiting intake rate, 320 μg U/d, is not possible when using current in vivo techniques. For workers exposed only to ore dust, corrective action is indicated if uranium is detected by lung scan techniques.

5.4 IMPLICATIONS OF IN VIVO MEASUREMENTS FOR BIOASSAY PROGRAM

The recommendations for in vivo measurements given in this section are based on the important assumption that the air sampling program conducted at the affected mill normally provides sufficient and sufficiently representative data for the monitoring and control of airborne uranium. It is also

assumed that the urinalysis program normally provides an adequate check on the effectiveness of the air sampling program. Under these conditions, in vivo measurements are a tertiary safety measure used primarily in cases of high exposure to obtain the best possible information about the lung burden and dose commitment. If for any reason the air sampling program is inadequate to the extent that reliance for the monitoring function must be placed on in vivo measurements instead, the recommendations made here would not be applicable. In like manner, if for any reason the urinalysis program is inadequate to the extent that reliance for checking the air sampling program must be placed on in vivo measurements, these recommendations would not be applicable.

From Chapter 4 it is evident that, for any worker for whom the model is representative, urinalysis performed at 40-day or shorter intervals will provide a warning of excessive exposures to airborne uranium within uranium mills. In the case of ore dust, the warning capability could be considered marginal, but excessive exposures to uranium as contained in ore dust are highly unlikely. Thus, there would appear to be little or no justification in the case of uranium mill workers for routine in vivo measurements.

However, it is clear that virtually every worker's experience will differ in one or more respects from the model, perhaps significantly and possibly in a manner that underestimates the risk. For this reason, it is important to perform confirmatory in vivo measurements for workers whose urinary uranium concentrations are sufficiently large. The selection of concentration criteria that would qualify as "sufficiently large" is a matter of judgment, depending heavily on measurement detection limitations and type of exposure. Although most of the uranium would be expected to be eliminated from the body within a few months following a single exposure, an intake of 1 ALI, if detectable, is considered sufficiently large to justify confirmatory in vivo measurement to ensure that the lung burden and other radiological risks are not greatly in excess of those indicated by the model. When the worker is subjected to a single exposure, an in vivo measurement should be performed (1) if the trend of bioassay results indicates that the measured urinary uranium concentration exceeds the concentration predicted by the model to be associated with an intake of 1 ALI and (2) if this measured urinalysis result can be adequately verified by additional bioassay samples. Where an intake of 1 ALI is not

detectable, it is necessary to base the in vivo criterion on the intake required to attain the detection limit, which is assumed in this study to be 3 nCi of natural uranium.

This 1-ALI intake criterion is also applicable to continuous exposure conditions (for an intake rate of 1 ALI per year). In Table 4-2, the urinary uranium action points that are recommended are based on 1 ALI per year. When these concentrations are exceeded, it is expected that corrective action will quickly be successful in reversing the upward trend. If a worker's urinary uranium concentration steadily increases until the action-point level is exceeded, it is anticipated that corrective action would be promptly completed. Thus, the urinary uranium concentration associated with an intake rate of 1 ALI per year has been selected as the criterion for in vivo measurements. When the worker is subjected to continuous exposure conditions, an in vivo measurement should be performed (1) if the trend of previous bioassay results indicates an increasing urinary uranium concentration resulting from chronic exposure conditions, (2) if a measured concentration exceeds the concentration predicted by the model to be associated with an intake rate of 1 ALI per year, and (3) if measured urinalysis results can be adequately verified by additional bioassay samples.

Since the purpose of this section is to examine the utility of in vivo measurements at uranium mills and since in vivo measurements are not normally used to estimate the kidney burden, chemical toxicity is not considered in this section. For low-temperature-dried yellowcake, the single intake and continuous intake rates used are those based on the ALI rather than on chemical toxicity.

It is recognized that some workers are exposed only to ore dust or only to yellowcake while others are exposed to both. Recommendations are given in this section for each type of exposure.

5.4.1 Workers Exposed Only to Ore Dust

In this section, it is assumed that the particle size for ore dust is 10-μm AMAD. This assumption is in keeping with analytical results obtained for the NRC by the Environmental Measurements Laboratory (Ref. 18).

5.4.1.1 Single Exposure

The urinary uranium action point given in Table 4-2 for ore dust is 10 μg/l. This concentration is predicted by the model to occur approximately 40 days following exposure to an intake of 1 ALI. If in vivo detection limits would permit, an in vivo measurement should be performed when 10 μg/l at 40 days after exposure is exceeded. However, Figure 2-4 indicates that at 40 days the lung burden is 2.5×10^{-2} μg U per μg U inhaled, and Section 3.3.1 indicates that there are 8×10^{4} μg U per ALI for 10-μm-AMAD ore dust. Using these numbers, it can be shown that the lung burden at 40 days following a 1-ALI exposure is only 1.4 nCi, which is generally undetectable using in vivo techniques. Thus, the criterion for performing a confirmatory in vivo measurement must be based on the detection capabilities of the equipment.

If it is assumed that a 3-nCi lung burden is detectable and that this burden is measured at 40 days after exposure, the minimum detectable intake is 2.2 ALIs. The corresponding urinary uranium concentration would be 22 μg/l at 40 days. Therefore, for a worker who has been exposed only to ore dust during the previous bioassay period, an in vivo measurement should be performed if (1) an examination of the worker's urinalysis history indicates that a single exposure has occurred during the previous bioassay period and (2) the increase in the worker's urinary uranium concentration above the average or background concentration exceeds 22 μg/l at 40 days after exposure.

Should the time interval between the exposure and the collection of the specimen be other than 40 days, an appropriate criterion (other than 22 μg/l) should be calculated. The procedure for this determination is straightforward. The intake to be associated with the criterion is 2.2 ALIs or 1.8×10^{5} μg U. Use Figure 4-13 to determine the urinary uranium concentration per unit intake for the time interval of interest. Take the product of these numbers to obtain the criterion.

5.4.1.2 Continuous Exposure

As may be seen in Figure 5-2, the model shows that a worker being exposed continuously to ore dust at the rate of 1 ALI per year would, at equilibrium, have a lung burden of only 0.75 nCi of uranium--undetectable by in vivo techniques. Thus, the criterion again must be based on equipment capability. Assuming a 3-nCi detection limit, the annual intake for a worker would have to be 4.0 ALIs, or 1280 µg/d, in order to be detected. From Figure 4-14, the equilibrium urinary uranium concentration in µg U/l per µg U/d inhaled is 2.6×10^{-2} for ore dust. The product of this number and 1280 µg/d is about 33 µg/l, which should be the criterion. Therefore, if previous urinalysis results indicate, after correction for excretion due to any significant single exposure, that the urinary uranium resulting from chronic exposure conditions exceeds 33 µg/l, a second confirmatory specimen should be collected promptly. If the confirmatory specimen also exceeds 33 µg/l, an in vivo measurement should be performed.

5.4.2 Workers Exposed Only to High-Temperature-Dried Yellowcake

5.4.2.1 Single Exposure

A single exposure to high-temperature-dried yellowcake of 1 ALI (1.6×10^5 µg) would, according to the model, produce a urinary uranium concentration of about 20 µg/l at 40 days after exposure. This estimate may be obtained using Figure 4-13. This concentration would, of course, be in addition to the worker's average or background concentration. According to Figure 5-1, the lung burden at that time would probably be detectable at 7 nCi. If a verified additional concentration exceeds 20 µg/l and there is reason to believe that a single exposure has occurred, an in vivo measurement should also be performed.

If the time interval between the exposure and the collection of the specimen is other than 40 days, Figure 4-13 should be used to calculate the appropriate criterion.

5.4.2.2 Continuous Exposure

The equilibrium urinary uranium concentration per unit intake rate associated by the model with high-temperature-dried yellowcake is 2.8×10^{-2} µg U/l per µg U/d inhaled (Fig. 4-14). The intake rate associated with 1 ALI per year is 626 µg/d (Section 3.3.2). Thus the concentration at equilibrium under such conditions of exposure would be about 18 µg/l. (This result also appears in Fig. 4-2.) This concentration was rounded to 20 µg/l in establishing the action point for this material, and 20 µg/l is used as the in vivo criterion here. The equilibrium lung burden (Fig. 5-2) would probably be detectable at about 9.5 nCi. If previous urinalysis results indicate that a significant single exposure has not occurred, i.e., that the urinary uranium is the result of chronic conditions, and if the concentration exceeds 20 µg/l, a second confirmatory specimen should be collected promptly. If the confirmatory specimen also exceeds 20 µg/l, an in vivo measurement should be performed.

5.4.3 Workers Exposed Only to Low-Temperature-Dried Yellowcake

5.4.3.1 Single Exposure

A 1-ALI single exposure (2.7×10^6 µg U) would, according to the model, produce a urinary uranium concentration of about 621 µg/l at 40 days after exposure (Fig. 4-13). The model would also predict a lung burden of about 36 nCi at that time (Fig. 5-1), which would be readily detectable using in vivo equipment. If a verified urinalysis result above 600 µg/l should occur, an in vivo measurement should be made. For time periods other than 40 days, Figure 4-13 should be consulted.

5.4.3.2 Continuous Exposure

The urinary uranium action point for continuous exposure to low-temperature-dried yellowcake for protection against chemical toxicity is 60 µg/l (Chapter 4). A value larger by about an order of magnitude would be indicated for radiological considerations (Section 3.3.2). It does not seem likely that chronic conditions under which a worker's urinary uranium concentration would be allowed to gradually climb to a value as large as 600 µg/l could ever exist.

For continuous exposure conditions, it therefore appears that routine in vivo measurements would not serve a useful purpose for workers exposed only to yellowcake dried at low temperature.

5.4.4 Workers Exposed to Ore Dust and High-Temperature-Dried Yellowcake

During a given bioassay period a mill worker's duties may bring him or her into contact with both airborne ore dust and yellowcake. Both of these materials may then contribute to the urinary uranium concentration observed at the end of the bioassay period. Such circumstances may complicate the decision as to whether an in vivo measurement is necessary. The criteria selected earlier in this section are

Single Exposure	
Ore Dust	22 µg/l
High-Temperature-Dried Yellowcake	20 µg/l

Continuous Exposure	
Ore Dust	33 µg/l
High-Temperature-Dried Yellowcake	20 µg/l

In this section, recommendations are made regarding the management of this problem.

5.4.4.1 Single Exposure

If an ore-dust/yellowcake worker has a verified urinalysis result greater than 20 µg/l above his or her background and if a review of previous results indicates that a single exposure has occurred, an in vivo measurement should be performed.

5.4.4.2 Continuous Exposure

If an ore-dust/yellowcake worker has a urinalysis result greater than 33 µg/l as a result of uranium buildup in the body from continuous exposure, an in vivo measurement should be performed since the buildup could be the

result of uranium in the lung that should then be measurable. If the urinalysis result is between 20 and 33 µg/l, uranium intake records (required by § 20.103 of 10 CFR Part 20) should be consulted to estimate the fraction of the intake that was contributed during the bioassay period by yellowcake (f_{yc}) and the fraction contributed by ore dust (f_{od}). Then the appropriate criterion can be calculated from the equation

$$\text{Criterion} = \frac{1}{\frac{f_{yc}}{20} + \frac{f_{od}}{33}}$$

where the sum of f_{yc} and f_{od} is unity.

The sum of f_{yc} and f_{od} must be unity. If there is no convincing information to assist in assigning values to these fractions, 0.5 may be used for each. If the investigation doesn't provide any convincing information as to where the exposure occurred and the result exceeds 20 µg/l, an in vivo measurement should be performed.

5.4.5 Workers Exposed to Ore Dust and Low-Temperature-Dried Yellowcake

The in vivo criteria selected earlier in this section are

Single Exposure	
Ore Dust	22 µg/l
Low-Temperature-Dried Yellowcake	621 µg/l
Continuous Exposure	
Ore Dust	33 µg/l
Low-Temperature-Dried Yellowcake	600 µg/l

The 600-µg/l value, as explained in Section 5.4.3, is not a recommended in vivo criterion but is given here for information purposes only.

5.4.5.1 Single Exposure

If an ore-dust/yellowcake worker has a verified urinalysis result greater than 22 µg/l above his or her background and if a review of previous results

indicates that a single exposure has occurred, an attempt should be made to find out whether the exposure occurred in the ore-dust area or in the yellowcake area. If there is reason to believe that the intake was ore dust, an in vivo measurement should be performed. If there is reason to believe that no ore dust is implicated and low-temperature-dried yellowcake appears to be the source of the deposition, an in vivo measurement should be performed if the concentration exceeds 621 μg/l above background. If there is evidence that two single intakes occurred, one in each area, the following equation may be used to calculate the criterion value:

$$\text{Criterion} = \frac{1}{\frac{f_{yc}}{621} + \frac{f_{od}}{22}}$$

where f_{yc} and f_{od} are as defined in the immediately preceding section. If there is no convincing information to assist in assigning values to these fractions, 0.5 may be used for each, in which case the criterion is approximately 43 μg/l. If the investigation doesn't provide any convincing information as to where the exposure occurred and the result exceeds 22 μg/l, an in vivo measurement should be performed.

5.4.5.2 Continuous Exposure

If an ore-dust/yellowcake worker has a urinalysis result greater than 33 μg/l and if a review of previous results indicates that a single exposure has not occurred, uranium intake records (required by § 20.103 of 10 CFR Part 20) should be consulted in an effort to determine the extent to which the additional concentration is due to ore dust. If the ore-dust uranium intake estimate during the previous bioassay period was greater than 7.8×10^4 μg, an in vivo measurement should be performed.*

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*This intake limit was derived as follows: Let I μg be the cumulative intake, X $\frac{\mu g}{l}$ be the urinary uranium concentration, t days be the number of working days in the bioassay period, and r $\frac{\mu g/l}{\mu g/d}$ be the excretion constant. Then $I = Xt/r$. When X = 33 $\frac{\mu g}{l}$, t = 40 days, and $r = 1.7 \times 10^{-2}$ $\frac{\mu g/l}{\mu g/d}$ (Fig. 4-14), the limiting value of I is 7.8×10^4 μg.

5.4.6 Action Points, In Vivo Measurements

Any corrective action needed in the workplace, as well as the need for protein urea testing, would presumably be triggered by high urinalysis results. However, in the case of uranium mill workers, the action points for in vivo measurements are based on other measures (principally work restrictions) that may be taken directly for the protection of the affected worker's health. In any discussion of work restrictions for personnel exposed in connection with NRC-licensed activities, it is well to point out that NRC regulations are written in a manner that will avoid career interference. For example, during a calendar quarter a worker may be involved in an accident that causes an intake of natural uranium exceeding the limit given in 10 CFR Part 20. The regulations prohibit any additional intake of natural uranium during that calendar quarter, but the affected worker may resume his or her duties at the beginning of the next quarter without additional restrictions because of the residual organ burden or dose commitment.

Although not required by regulations, it is common practice among employers to impose work restrictions when in vivo measurements indicate a lung burden (alpha emitters) exceeding 16 nCi.* The affected worker is assigned duties that do not involve radiation or inhalation exposures until subsequent in vivo measurements indicate that the lung burden is well below 16 nCi. Thus, 16 nCi is a very commonly used in vivo action point.

Although not required by regulations, the following discussion may be of interest to those who would prefer to use action points based on new ICRP recommendations (Refs. 8 and 22) and the new lung solubility data presented in this report. Figure 5-2 presents equilibrium lung burdens for intakes of 1 ALI per year. These lung burdens are the new counterparts to the old 16-nCi criterion. They are

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*This quantity of an alpha emitter, if maintained continuously in the pulmonary lung, will deliver an annual dose equivalent of 15 rems to the lung tissues according to ICRP recommendations first issued in 1960 (Ref. 21). Fifteen rems per year is the dose criterion on which the Maximum Permissible Concentrations (MPCs) were based, i.e., for radioactive materials having the lung as the critical organ. The MPCs for uranium are presently in effect in 10 CFR Part 20.

Low-Temperature-Dried Yellowcake	21 nCi U
High-Temperature-Dried Yellowcake	10 nCi U
Ore Dust (10-μm AMAD)	0.8 nCi U

These values are based on stochastic risks for yellowcake and on nonstochastic risks for ore dust (bone dose). The yellowcake values are directly usable as in vivo criteria. The case of ore dust is more difficult since a lung burden of uranium as small as 0.8 nCi cannot be reliably detected using present in vivo techniques. For a worker exposed only to ore dust, any uranium detected through in vivo techniques would be a matter of concern.

With regard to combined exposures, it should be noted that a determination as to the type of material involved is to be made immediately following a high urinalysis result. This determination is necessary for the decision as to whether in vivo counting is to be performed. Thus, in many cases of combined exposure the lung-burden criteria given above may be used directly. If it is determined that there was appreciable exposure to both ore dust and yellowcake, the fractional intakes (f_{yc} and f_{od} as defined above) can be used with the equation in Section 5.4.5 and elsewhere to calculate an appropriate criterion. An example may be instructive.

Assume that a worker exposed to ore dust and high-temperature-dried yellowcake has a urinalysis result of 28 μg/l and a review of the worker's bioassay history indicates that there was a relatively steady and gradual increase to this level with no significant single exposure involved. This result would require an investigation of the cause with possible corrective action. It would also necessitate a decision as to whether an in vivo measurement should be made. This decision would require use of the equation. Assume that intake records reveal that f_{yc} is about 80 percent of the intake and f_{od} is about 20 percent. Then

$$\text{Criterion} = \frac{1}{\frac{0.8}{20} + \frac{0.2}{33}} = 22 \frac{\mu g}{l}$$

which is lower than the 28 μg/l result so that a measurement is required.

Assume that the subsequent in vivo result is 5 nCi. The equation would be used again with the same values of f_{yc} and f_{od} and with the appropriate lung-burden criteria shown above to evaluate the desirability of work restrictions.

$$\text{Criterion} = \frac{1}{\frac{0.8}{10} + \frac{0.2}{0.8}} = 3.0 \text{ nCi}$$

which is lower than the 5-nCi result. Although not a regulatory requirement, past experience suggests that many employers might preclude further exposure to airborne uranium until subsequent bioassay results provided some assurance that the lung burden had fallen below 3.0 nCi. An important value of the in vivo measurement in this example is assurance that for this worker the model did not seriously underestimate the risk.

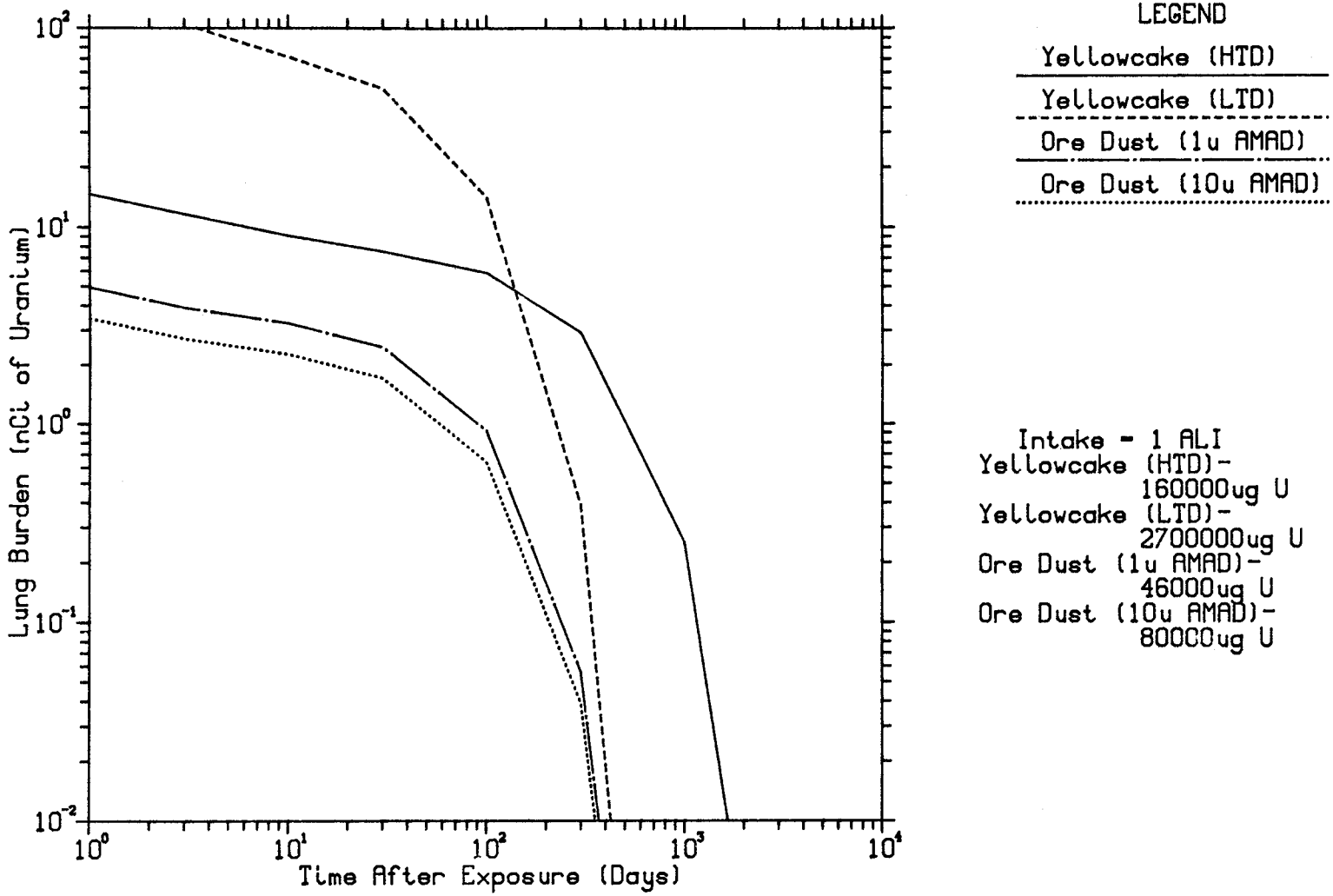

FIGURE 5-1: Lung Burden After Single Exposure to Uranium Contained in Yellowcake or in Ore Dust

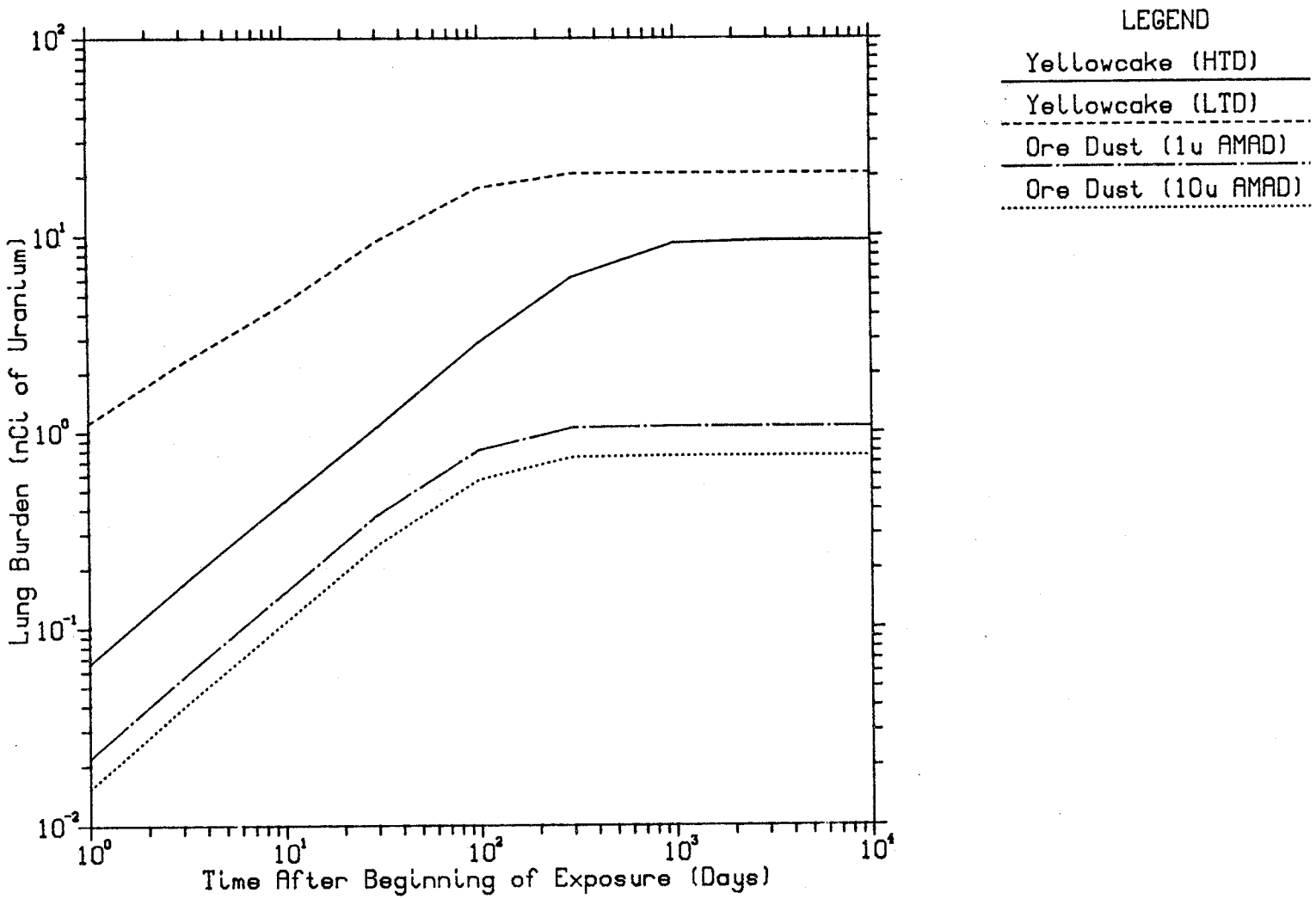

FIGURE 5-2: Lung Burden During Continuous Exposure to Uranium Contained in Yellowcake or in Ore Dust (Intake Rate - 1 ALI per year) [Note in text that the yellowcake values in this figure are based on radiological toxicity alone.]

6. COMPARISON OF ACTION LEVELS AND BIOASSAY FREQUENCIES IN REGULATORY GUIDE 8.22 TO THOSE IN NUREG-0874

This report presents the development of a model that permits analytical estimates regarding the behavior of uranium following inhalation by uranium mill workers. Regulatory guidance, however, is not established through NUREG-series reports. Therefore, the results of this study, along with other current information, were used to formulate a bioassay program for uranium mills (and applicable portions of uranium conversion facilities) that is acceptable to the NRC as guidance for its licensees. The details of this program are given in Regulatory Guide 8.22, "Bioassay at Uranium Mills." This section compares action levels and bioassay frequencies reflected in the regulatory guide and in this report and discusses how the corresponding values in these documents are consistent with each other.

The action levels and frequencies found in Regulatory Guide 8.22 and in NUREG-0874 are reproduced in Tables 6-1 and 6-2. As indicated in Table 6-1, the minimum acceptable action level for yellowcake used in the guide, 15 μg U/l, is smaller than values predicted by the model of NUREG-0874. The guide uses the larger values for ore dust because of the simplicity of using one number for the action level rather than three numbers as given in NUREG-0874. This selection is justified since the silica contained in ore dust is a greater hazard to workers than the radiological hazard. If concentrations of airborne silica are properly controlled (5 to 100 times more restrictive than the airborne limit for uranium (Ref. 23)), the urinary uranium concentrations should be well below the value for the action level given in Table 6-1. Finally, because of the statistical uncertainties associated with the current techniques used for analysis of urinary uranium, an action level of 10 μg U/l is frequently not clearly distinguished from a value of 15 μg U/l. In a recent study jointly funded by the NRC and the Department of Energy (Ref. 24), Battelle's Pacific Northwest Laboratory (PNL) determined the fraction of bioassay laboratories in a sample population from the United States that could attain bioassay criteria for uranium, 5.0 μg/l, as published in a draft of ANSI N13.30, "Performance Criteria for Radiobioassay" (Ref. 25). Only 50 percent of these laboratories could meet this acceptable minimum detectable amount for uranium.

TABLE 6-1

Comparison of Action Levels and Frequencies for Urinalysis

	NUREG-0874		Regulatory Guide 8.22	
	Maximum Frequency* (d)	Action Levels (μg U/l)	Acceptable Frequency (d)	Acceptable Action Levels (μg U/l)
Yellowcake (LTD)	40	60	30	15 to 35
Yellowcake (HTD)	40	20	30	15 to 35
Ore Dust (10-μm AMAD)	37	10	30	15 to 35

TABLE 6-2

Comparison of Action Levels Leading to In Vivo Lung Count

	Action Levels in NUREG-0874 (μg U/l)		Action Levels in Regulatory Guide 8.22 (μg U/l or μCi-h/ml)
	Single Exposure	Continuous Exposure	Single or Continuous Exposure
Yellowcake (LTD)	100	600	Based on intake**
Yellowcake (HTD)	20	20	130 μg/l for any single sample; 35 μg/l for 2 consecutive samples**
Ore Dust (10-μm AMAD)	22	33	130 μg/l for any single sample; 35 μg/l for 2 consecutive samples**

*This time interval is the upper limit recommended by this report for the frequency of bioassay sampling.

**The regulatory guide also requires that in vivo lung-counting measurements be performed if air monitoring results or exposure calculations indicate that the exposure (intake) could exceed 520×10^{-10} μCi-h/ml.

In vivo counting levels in Table 6-2 were set higher for the regulatory guide for reasons summarized in Table 6-3. A most important consideration in reducing the frequency of routine in vivo counting is the experience of the industry and a conclusion of Reference 13 that the large volume of expensive in vivo counts shows no significant indications of lung depositions under routine operating conditions. Also, the variability of in vivo measurements was large enough in field measurements so that routine in vivo counting programs would not be expected to add significantly to the control of inhalation exposure under routine operating conditions.

However, both Reference 13 and Dr. Christopher Pomroy* of the Canadian Radiation Protection Bureau have recommended that in vivo counting be part of a uranium mill bioassay program to protect against the rare, but possible, accidental inhalation of large amounts of material containing a substantial proportion of uranium in the form of Class W or Class Y material. Both the model in Reference 13 and that cited by Dr. Pomroy show that a single intake of Class Y material equivalent to 1 ALI or more could give such low urinary excretion levels that they could go undetected by urinalyses (because of the limited detection capabilities of current analytical methods used in routine bioassay programs). On the other hand, after the unusual event of an incident involving large enough quantities of high-temperature-dried yellowcake or ore dusts that could produce either the urinary excretion levels in Table 6-2 (right column) or the measured integrated air concentration-time exposures in the footnote of Table 6-2, in vivo counting in a whole-body counting facility specially equipped for uranium lung counting should be available as part of the bioassay program. These special in vivo counts serve two purposes: (1) to guard against the unlikely, but possible, contingency that large intakes of uranium of Class W or Class Y transportability might go undetected and (2) to provide early data useful in evaluating any high accidental exposures, their long-term uptake and excretion trends, and ultimately the relevant estimates of intake and dose commitment that may be necessary for medical or regulatory purposes.

*Presentation at a public hearing of Committee BEIR IV, National Academy of Sciences, Washington, DC, 1985.

TABLE 6-3

Rationale for Numerical Action Levels and Frequencies
Given in Regulatory Guide 8.22

In the discussion below, C2, C4(b)(c), C4(d), and C4(e) refer to the corresponding sections given in Regulatory Guide 8.22.

C2 - 40×10^{-10} μCi-h/ml and 520×10^{-10} μCi-h/ml - taken from proposed Regulatory Guide 8.22, published for comment in 1978 (Ref. 26).

C4(b)(c) - 5 μg/l LLD for uranium. This level is recommended in draft ANSI N13.30 (Ref. 25) as well as in the independent example calculation in Appendix A to Regulatory Guide 8.22 that is taken from actual laboratory data.

C4(d) - 35 μg/l in two monthly samples

1. Below this action level for a small intake of uranium, in vivo measurements have been found to be unreliable (Ref. 13).

2. Public comments on the proposed Regulatory Guide 8.22 indicated that four consecutive specimens at 30 μg/l may indicate kidney damage.

3. This excretion level is very unlikely to occur for high-fired yellowcake unless a large lung burden is present to continuously feed uranium to system; this is very unlikely to occur (Ref. 13).

4. 35 μg/l is the model excretion rate in this document at 1 month for an inhalation of 1 ALI of yellowcake dried at high temperature at the beginning of the month. (See Fig. 4-1.)

5. Only 2.5 percent of the samples in a population of urine samples from mills would exceed 35 μg/l; less than 1 percent would exceed 50 μg/l, even if all the frequency distribution were attributed to measurement error. (See Fig. S-1.)

6. The 35 μg/l value is very close to the upper 95 percent confidence band for the single sample urinary levels (median of only 4.4 μg/l and a standard geometric deviation, $Sg = \overset{\times}{\div} 2.3$).

7. An average value of the 35 μg/l has been adopted in the Canadian standard (Ref. 27).

C4(e) - 130 μg/l for any specimen

1. Some consideration was given to adding conservatism to the value of 130 μg/l in Table 1 of Reference 26. Some additional (although questionable) indicators of kidney damage were found in the experiments described in Reference 28. This reference recommends, as action levels, 100 μg/l during the first 24 hours after exposure and only 1 μg/l for a "Monday

TABLE 6-3 (Continued)

morning" excretion rate. Renal-urinary uranium relationships depend on the concentration of UO_2^{++} and reversible complexes in the kidney and not on the form of uranium exposure, according to Reference 28.

2. Also, 100 µg/l may be indicative of 1 ALI if the material happens to be Class D rather than Class W. (See Fig. 4-4.)

3. However, two consecutive monthly urinary uranium samples below 150 µg U/l are considered to be protective of workers in the Canadian standard (Ref. 27).

4. Therefore, since it is extremely improbable that a confirmed sample (two measurements) would fall between 100 and 130 µg/l, the difference between these values was deemed insignificant. The action level of 130 µg/l was retained as a reasonable consensus of the single sample action level of Table 1 of Regulatory Guide 8.22.

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*ICRP publications are available from Pergamon Press, Fairview Park, Elmsford, NY 10523.

**Copies may be available from K. R. Heid, Chairman, Battelle Pacific Northwest Laboratory, P.O. Box 999, Richland, WA 99352.

APPENDIX A
EQUATIONS FOR ORGAN AND SYSTEMIC BURDEN CALCULATIONS

A large number of equations (138) are used in this analysis to calculate organ and systemic burdens. Therefore, the following somewhat unusual method has been developed to present their derivation in a concise manner:

1. A simplified system of symbols is employed to present the derivation of eight basic differential equations, and each equation is assigned a number;

2. The symbols used in the equations--primary symbols as well as superscripts and subscripts--are tabulated;

3. Tables showing, for each equation used, the type of differential equation by number and the actual symbol for each constant appearing in the simplified version of the equations are given; and

4. A table describing each constant and listing its symbol and numerical value is given.

This information can be used in a straightforward manner to reproduce the calculations performed in this study as illustrated in Section A.3 of this appendix.

A.1 GENERAL SOLUTIONS FOR DIFFERENTIAL EQUATIONS

In this study, all the organs of the body except those of the respiratory tract are represented by a single compartment. The respiratory tract is subdivided into four separate compartments: the nasopharyngeal, tracheobronchial, pulmonary lung, and lymph. Any one of the eight types of differential equations listed below may be considered to describe the rate of accumulation of matter in any single compartment of an interconnected multicompartment system. In the text, each of these eight types of equations is uniquely identified by the alphanumeric designation shown below.

In this analysis, solutions are required for eight general types of differential equations:

Type IA	One-Compartment Model, Single Exposure
Type IB	One-Compartment Model, Continuous Exposure
Type IIA	Two-Compartment Model, Single Exposure
Type IIB	Two-Compartment Model, Continuous Exposure
Type IIIA	Three-Compartment Model, Single Exposure
Type IIIB	Three-Compartment Model, Continuous Exposure
Type IVA	Four-Compartment Model, Single Exposure
Type IVB	Four-Compartment Model, Continuous Exposure

All these equations are first-order linear differential equations. Derivations and solutions are indicated in this section.

A.1.1 Single Exposure

A.1.1.1 Type IA

Let $b_1(t)$ be the burden in 1 at time t, and let λ_1 be the elimination constant from 1. Let c_1 be the initial fixed amount of nuclide deposited in 1.* Then

$$b_1(t) = c_1 e^{-\lambda_1 t} \qquad \text{(A-1)}$$

A.1.1.2 Type IIA

Let $b_2(t)$ be the burden in compartment 2 at time t, and let λ_2 be the elimination constant from compartment 2. Let b_1 be the source of b_2, and let c_2 be the fractional uptake by compartment 2 so that the rate of uptake in compartment 2 is $c_2\lambda_1 b_1$. The rate of elimination from compartment 2 is $\lambda_2 b_2$. The rate of change is

$$\frac{db_2}{dt} = c_2\lambda_1 b_1 - \lambda_2 b_2$$

*Constants c_1, c_2, etc., are discussed in Section A.3 of this appendix.

Substituting from Equation A-1,

$$\frac{db_2}{dt} = c_1c_2\lambda_1e^{-\lambda_1t} - \lambda_2b_2$$

Using an integration factor of e^{λ_2t} and multiplying by dt,

$$e^{\lambda_2t}db_2 + e^{\lambda_2t}\lambda_2b_2dt = c_1c_2\lambda_1(e^{\lambda_2t})(e^{-\lambda_1t})dt$$

Note that the terms to the left of the equal sign are equivalent to the first derivative of $e^{\lambda_2t}b_2$* so that

$$d(e^{\lambda_2t}b_2) = c_1c_2\lambda_1e^{(\lambda_2 - \lambda_1)t}dt$$

Integrating both sides,

$$e^{\lambda_2t}b_2 = c_1c_2\lambda_1\int e^{(\lambda_2 - \lambda_1)t}dt$$

$$= c_1c_2\frac{\lambda_1}{\lambda_2 - \lambda_1)}e^{(\lambda_2 - \lambda_1)t} + H$$

Using initial conditions of $b_2 = 0$ when $t = 0$, this equation has the following solution:

$$b_2(t) = c_1c_2\frac{\lambda_1}{(\lambda_2 - \lambda_1)}(e^{-\lambda_1t} - e^{-\lambda_2t}) \qquad (A\text{-}2)$$

The expression for $b_2(t)$ becomes indeterminant for $\lambda_1 = \lambda_2$. The limiting value can, however, be obtained using L'Hospital's rule. Consider the expression

$$f(\lambda_i, \lambda_j, t) = \frac{e^{-\lambda_it} - e^{-\lambda_jt}}{\lambda_i - \lambda_j}$$

*This mathematical maneuver is repeated, but not explained, in each subsequent equation derivation.

in the limit as $\lambda_i \to \lambda_j$. Letting $\delta = \lambda_i - \lambda_j$, the limit becomes

$$\lim_{\lambda_i \to \lambda_j} f(\lambda_i, \lambda_j, t) = \lim_{\delta \to o} \frac{e^{-(\lambda_j + \delta)t} - e^{-\lambda_j t}}{\delta}$$

Differentiating both numerator and denominator with respect to δ, as specified by L'Hospital's rule, the limit reduces to

$$\lim_{\lambda_i \to \lambda_j} \frac{e^{-\lambda_i t} - e^{-\lambda_j t}}{\lambda_i - \lambda_j} = -te^{-\lambda_j t} \qquad \text{(A-3)}$$

Substituting into Equation A-2,

$$b_2(t) = c_1 c_2 \lambda_i t e^{-\lambda_j t} \qquad \text{(A-4)}$$

in the limit of $\lambda_1 \to \lambda_2 = \lambda$.

A.1.1.3 Type IIIA

Let $b_3(t)$ be the burden in compartment 3 at t, and let λ_3 be the elimination constant from compartment 3. Let b_2 be the source of b_3, and let c_3 be the fractional uptake in compartment 3 so that the rate of uptake in compartment 3 is $c_3\lambda_2 b_2$. The rate of elimination from compartment 3 is $\lambda_3 b_3$. The rate of change is

$$\frac{db_3}{dt} = c_3\lambda_2 b_2 - \lambda_3 b_3$$

Substituting from Equation A-2,

$$\frac{db_3}{dt} = c_1 c_2 c_3 \frac{\lambda_1 \lambda_2}{(\lambda_2 - \lambda_1)}(e^{-\lambda_1 t} - e^{-\lambda_2 t}) - \lambda_3 b_3$$

Using an integration factor of $e^{\lambda_3 t}$,

$$e^{\lambda_3 t}db_3 + \lambda_3 b_3 e^{\lambda_3 t}dt = c_1c_2c_3\frac{\lambda_1\lambda_2}{(\lambda_2 - \lambda_1)}(e^{-\lambda_1 t} - e^{-\lambda_2 t})e^{\lambda_3 t}dt$$

Note that

$$d(e^{\lambda_3 t}b_3) = c_1c_2c_3\frac{\lambda_1\lambda_2}{(\lambda_2 - \lambda_1)}(e^{-\lambda_1 t} - e^{-\lambda_2 t})e^{\lambda_3 t}dt$$

So that, integrating both sides,

$$e^{\lambda_3 t}b_3 = c_1c_2c_3\frac{\lambda_1\lambda_2}{(\lambda_2 - \lambda_1)}$$

$$[\int e^{(\lambda_3 - \lambda_1)t}dt - \int e^{(\lambda_3 - \lambda_2)t}dt]$$

$$= c_1c_2c_3\frac{\lambda_1\lambda_2}{(\lambda_2 - \lambda_1)}$$

$$[\frac{1}{(\lambda_3 - \lambda_1)}e^{(\lambda_3 - \lambda_1)t} - \frac{1}{(\lambda_3 - \lambda_2)}e^{(\lambda_3 - \lambda_2)t}] + H$$

Using initial conditions of $b_3 = 0$ when $t = 0$, this equation has the following solution:

$$b_3(t) = c_1c_2c_3\frac{\lambda_1\lambda_2}{(\lambda_2 - \lambda_1)}[\frac{1}{(\lambda_3 - \lambda_1)}(e^{-\lambda_1 t} - e^{-\lambda_3 t})$$

$$- \frac{1}{(\lambda_3 - \lambda_2)}(e^{-\lambda_2 t} - e^{-\lambda_3 t})] \qquad \text{(A-5)}$$

This expression is indeterminant when any two of the elimination constants are equal. The cases $\lambda_1 = \lambda_3$ and $\lambda_2 = \lambda_3$ are readily solved using the limiting expression given in Equation A-3 above, but the case $\lambda_1 = \lambda_2$ is slightly more complicated. Equation A-4 can be rewritten

$$b_3(t) = \frac{C_1C_2C_3\lambda_1\lambda_2}{(\lambda_3 - \lambda_1)(\lambda_3 - \lambda_2)} \left[e^{-\lambda_3 t} + \frac{\lambda_3(e^{-\lambda_1 t} - e^{-\lambda_2 t})}{\lambda_2 - \lambda_1} + \frac{\lambda_4 e^{-\lambda_2 t} - \lambda_2 e^{-\lambda_1 t}}{\lambda_2 - \lambda_1}\right]$$

Taking the limit of both sides as $\lambda_2 \to \lambda_1$,

$$\lim_{\lambda_2 \to \lambda_1} b_3(t) = \frac{C_1C_2C_3\lambda_1^2}{(\lambda_3 - \lambda_1)^2} \left[e^{-\lambda_3 t} + \lim_{\lambda_2 \to \lambda_1} \frac{\lambda_3(e^{-\lambda_1 t} - e^{-\lambda_2 t})}{\lambda_2 - \lambda_1} + \lim_{\lambda_2 \to \lambda_1} \frac{\lambda_1 e^{-\lambda_2 t} - \lambda_2 e^{-\lambda_1 t}}{\lambda_2 - \lambda_1}\right]$$

Applying Equation A-3 once again, the middle term in the brackets reduces to $\lambda_3 t\, e^{-\lambda_1 t}$. The final term can also be evaluated using L'Hospital's rule.

$$\lim_{\lambda_2 \to \lambda_1} \frac{\lambda_i e^{-\lambda_j t} - \lambda_j e^{-\lambda_i t}}{\lambda_j - \lambda_i} = \lim_{\delta \to o} \frac{\lambda_i e^{-(\lambda_i + \delta)t} - (\lambda_i + \delta)e^{-\lambda_i t}}{\delta}$$

$$= -(\lambda_i t + 1)e^{-\lambda_i t}, \qquad \text{(A-6)}$$

from which it follows that

$$\lim_{\lambda_2 \to \lambda_1} b_3(t) = \frac{C_1C_2C_3\lambda_1^2}{(\lambda_3 - \lambda_1)^2} \left[e^{-\lambda_3 t} - e^{-\lambda_1 t} + (\lambda_3 - \lambda_1)te^{-\lambda_1 t}\right] \qquad \text{(A-7)}$$

A.1.1.4 Type IVA

Let $b_4(t)$ be the burden in compartment 4 at t, and let λ_4 be the elimination constant from compartment 4. Let b_3 be the source of b_4, and let c_4 be the fractional uptake in compartment 4 so that the rate of uptake in compartment 4 is $c_4\lambda_3 b_3$. The rate of elimination from compartment 4 is $\lambda_4 b_4$. The rate of change is

$$\frac{db_4}{dt} = c_4\lambda_3 b_3 - \lambda_4 b_4$$

Substituting from Equation A-3,

$$\frac{db_4}{dt} = c_1c_2c_3c_4\frac{\lambda_1\lambda_2\lambda_3}{(\lambda_2 - \lambda_1)}\left[\frac{1}{(\lambda_3 - \lambda_1)}(e^{-\lambda_1 t} - e^{-\lambda_3 t})\right.$$

$$\left. - \frac{1}{(\lambda_3 - \lambda_2)}(e^{-\lambda_2 t} - e^{-\lambda_3 t})\right] - \lambda_4 b_4$$

Using an integration factor of $e^{\lambda_4 t}$,

$$e^{\lambda_4 t}db_4 + \lambda_4 b_4 e^{\lambda_4 t}dt = c_1c_2c_3c_4e^{\lambda_4 t}\frac{\lambda_1\lambda_2\lambda_3}{(\lambda_2 - \lambda_1)}$$

$$\left[\frac{1}{(\lambda_3 - \lambda_1)}(e^{-\lambda_1 t} - e^{-\lambda_3 t})\right.$$

$$\left. - \frac{1}{(\lambda_3 - \lambda_2)}(e^{-\lambda_2 t} - e^{-\lambda_3 t})\right]dt$$

Note that

$$d(e^{\lambda_4 t}b_4) = c_1c_2c_3c_4\frac{\lambda_1\lambda_2\lambda_3}{(\lambda_2 - \lambda_1)}$$

$$\left[\frac{1}{(\lambda_3 - \lambda_1)}(e^{(\lambda_4 - \lambda_1)t} - e^{(\lambda_4 - \lambda_3)t})\right.$$

$$\left. - \frac{1}{(\lambda_3 - \lambda_2)}(e^{(\lambda_4 - \lambda_2)t} - e^{(\lambda_4 - \lambda_3)t})\right]dt$$

So that, integrating both sides,

$$e^{\lambda_4 t} b_4 = c_1 c_2 c_3 c_4 \frac{\lambda_1 \lambda_2 \lambda_3}{(\lambda_2 - \lambda_1)}$$

$$\left[\frac{1}{(\lambda_3 - \lambda_1)} \left(\int e^{(\lambda_4 - \lambda_1)t} dt - \int e^{(\lambda_4 - \lambda_3)t} dt\right)\right.$$

$$\left. - \frac{1}{(\lambda_3 - \lambda_2)} \left(\int e^{(\lambda_4 - \lambda_2)t} dt - \int e^{(\lambda_4 - \lambda_3)t} dt\right)\right]$$

$$= c_1 c_2 c_3 c_4 \frac{\lambda_1 \lambda_2 \lambda_3}{(\lambda_2 - \lambda_1)} \left[\frac{1}{(\lambda_3 - \lambda_1)} \left(\frac{1}{(\lambda_4 - \lambda_1)}\right.\right.$$

$$\left. e^{(\lambda_4 - \lambda_1)t} - \frac{1}{(\lambda_4 - \lambda_3)} e^{(\lambda_4 - \lambda_3)t}\right)$$

$$- \frac{1}{(\lambda_3 - \lambda_2)} \left(\frac{1}{(\lambda_4 - \lambda_2)} e^{(\lambda_4 - \lambda_2)t}\right.$$

$$\left.\left. - \frac{1}{(\lambda_4 - \lambda_3)} e^{(\lambda_4 - \lambda_3)t}\right)\right] + H$$

Using initial conditions of $b_4 = 0$ when $t = 0$, this equation has the following solution:

$$b_4(t) = c_1 c_2 c_3 c_4 \lambda_1 \lambda_2 \lambda_3 \left[\frac{1}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)(\lambda_4 - \lambda_1)} \left(e^{-\lambda_1 t} - e^{-\lambda_4 t}\right)\right.$$

$$- \frac{1}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)(\lambda_4 - \lambda_2)} \left(e^{-\lambda_2 t} - e^{-\lambda_4 t}\right)$$

$$\left. + \frac{1}{(\lambda_3 - \lambda_2)(\lambda_3 - \lambda_1)(\lambda_4 - \lambda_3)} \left(e^{-\lambda_3 t} - e^{-\lambda_4 t}\right)\right] \qquad \text{(A-8)}$$

For cases in which any pair of elimination constants are equal, $b_4(t)$ can be evaluated using Equations A-3 and A-6.

A.1.2 Continuous Exposure

A.1.2.1 Type IB

Let $B_1(t)$ be the burden in compartment 1 at time t, and let λ_1 be the elimination constant from compartment 1. Let the rate of deposition in compartment 1 be C_1. The rate of elimination from compartment 1 is $\lambda_1 B_1$. The rate of change is

$$\frac{dB_1}{dt} = C_1 - \lambda_1 B_1$$

Using an integration factor of $e^{\lambda_1 t}$,

$$e^{\lambda_1 t} dB_1 + \lambda_1 B_1 e^{\lambda_1 t} dt = C_1 e^{\lambda_1 t} dt$$

Note that

$$d(e^{\lambda_1 t} B_1) = C_1 e^{\lambda_1 t} dt$$

So that, integrating both sides,

$$e^{\lambda_1 t} B_1 = C_1 \lambda_1 e^{\lambda_1 t} + H$$

Using initial conditions of $B_1 = 0$ when $t = 0$, this equation has the following solution:

$$B_1(t) = C_1(1 - e^{-\lambda_1 t}) \qquad \text{(A-9)}$$

A.1.2.2 Type IIB

Let $B_2(t)$ be the burden in compartment 2 at t, and let λ_2 be the elimination constant from compartment 2. Let B_1 be the source of B_2, and let C_2 be the fractional uptake for compartment 2 so that the rate of uptake in compartment 2 is $C_2\lambda_1B_1$. The rate of elimination from compartment 2 is λ_2B_2. The rate of change is

$$\frac{dB_2}{dt} = C_2\lambda_1B_1 - \lambda_2B_2$$

Substituting from Equation A-9,

$$\frac{dB_2}{dt} = C_1C_2(1 - e^{-\lambda_1 t}) - \lambda_2B_2$$

Using an integration factor of $e^{\lambda_2 t}$,

$$e^{\lambda_2 t}dB_2 + \lambda_2B_2e^{\lambda_2 t}dt = C_1C_2e^{\lambda_2 t}(1 - e^{-\lambda_1 t})dt$$

Note that

$$d(e^{\lambda_2 t}B_2) = C_1C_2e^{\lambda_2 t}(1 - e^{-\lambda_1 t})dt$$

So that, integrating both sides,

$$e^{\lambda_2 t}B_2 = C_1C_2[\int e^{\lambda_2 t}dt - \int e^{(\lambda_2 - \lambda_1)t}dt]$$

$$= C_1C_2[\frac{e^{\lambda_2 t}}{\lambda_2} - \frac{e^{(\lambda_2 - \lambda_1)t}}{\lambda_2 - \lambda_1}] + H$$

Using initial conditions of $B_2 = 0$ when $t = 0$, this equation has the following solution:

$$B_2(t) = C_1C_2\frac{1}{\lambda_2(\lambda_2 - \lambda_1)}$$

$$[\lambda_2(1 - e^{-\lambda_1 t}) - \lambda_1(1 - e^{-\lambda_2 t})] \qquad \text{(A-10)}$$

In the limit where $\lambda_2 \to \lambda_1$, the solution is again obtained by L'Hospital's rule.

$$\lim_{\lambda_2 \to \lambda_1} B_2(t) = \lim_{\lambda_2 \to \lambda_1} \{\frac{C_1C_2\ (\lambda_2 - \lambda_1)}{\lambda_2(\lambda_2 - \lambda_1)} + C_1C_2\ \frac{\lambda^1 e^{-\lambda_2 t} - \lambda_2 e^{-\lambda_1 t}}{(\lambda_2 - \lambda_1)\lambda_2}\}$$

$$= \frac{C_1C_2}{\lambda_1}\ [1 - (\lambda_1 t + 1)e^{-\lambda_1 t}] \text{ for } \lambda_1 = \lambda_2 \qquad \text{(A-11)}$$

where the second term in the limit has been evaluated using Equation A-6. The same approach can be used to evaluate the expressions derived below, for cases of more than two compartments, in the limit where any two of the elimination constants are equal.

A.1.2.3 Type IIIB

Let $B_3(t)$ be the burden in compartment 3 at t, and let λ_3 be the elimination constant from compartment 3. Let B_2 be the source of B_3, and let C_3 be the fractional uptake in compartment 3 so that the rate of uptake in compartment 3 is $C_3\lambda_2B_2$. The rate of elimination from compartment 3 is λ_3B_3. The rate of change is

$$\frac{dB_3}{dt} = C_3\lambda_2B_2 - \lambda_3B_3$$

Substituting from Equation A-10,

$$\frac{dB_3}{dt} = C_1C_2C_3(\lambda_2 - \lambda_1)^{-1}[\lambda_2(1 - e^{-\lambda_1 t}) - \lambda_1(1 - e^{-\lambda_2 t})] - \lambda_3B_3$$

Using an integration factor of $e^{\lambda_3 t}$,

$$e^{\lambda_3 t} dB_3 + \lambda_3 B_3 e^{\lambda_3 t} dt = C_1 C_2 C_3 e^{\lambda_3 t} (\lambda_2 - \lambda_1)^{-1}$$

$$[\lambda_2 (1 - e^{-\lambda_1 t}) - \lambda_1 (1 - e^{-\lambda_2 t})] dt$$

Note that

$$d(e^{\lambda_3 t} B_3) = C_1 C_2 C_3 e^{\lambda_3 t} (\lambda_2 - \lambda_1)^{-1}$$

$$[\lambda_2 (1 - e^{-\lambda_1 t}) - \lambda_1 (1 - e^{-\lambda_2 t})] dt$$

So that, integrating both sides,

$$e^{\lambda_3 t} B_3 = C_1 C_2 C_3 \{ \frac{\lambda_2}{(\lambda_2 - \lambda_1)} [\int e^{\lambda_3 t} dt - \int e^{(\lambda_3 - \lambda_1) t} dt]$$

$$- \frac{\lambda_1}{(\lambda_2 - \lambda_1)} [\int e^{\lambda_3 t} dt - \int e^{(\lambda_3 - \lambda_2) t} dt] \}$$

$$= C_1 C_2 C_3 \{ \frac{\lambda_2}{(\lambda_2 - \lambda_1)} [\frac{e^{\lambda_3 t}}{\lambda_3} - e \frac{(\lambda_3 - \lambda_1) t}{(\lambda_3 - \lambda_1)}]$$

$$- \frac{\lambda_1}{(\lambda_2 - \lambda_1)} [\frac{e^{\lambda_3 t}}{\lambda_3} - e \frac{(\lambda_3 - \lambda_2) t}{(\lambda_3 - \lambda_2)}] \} + H$$

Using initial conditions of $B_3 = 0$ when $t = 0$, this equation has the following solution:

$$B_3(t) = C_1C_2C_3[\frac{1}{\lambda_3}(1 - e^{-\lambda_3 t})$$

$$- \frac{\lambda_2}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)}(e^{-\lambda_1 t} - e^{-\lambda_3 t})$$

$$+ \frac{\lambda_1}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)}(e^{-\lambda_2 t} - e^{-\lambda_3 t})] \quad \text{(A-12)}$$

A.1.2.4 Type IVB

Let $B_4(t)$ be the burden in compartment 4 at t, and let λ_4 be the elimination constant from compartment 4. Let B_3 be the source of B_4, and let C_4 be the fractional uptake in compartment 4 so that the rate of uptake in compartment 4 is $C_4\lambda_3B_3$. The rate of elimination from compartment 4 is λ_4B_4. The rate of change is

$$\frac{dB_4}{dt} = C_4\lambda_3B_3 - \lambda_4B_4$$

Substituting from Equation A-12,

$$\frac{dB_4}{dt} = C_1C_2C_3C_4[(1 - e^{-\lambda_3 t}) - \frac{\lambda_2\lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)}(e^{-\lambda_1 t} - e^{-\lambda_3 t})$$

$$+ \frac{\lambda_1\lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)}(e^{-\lambda_2 t} - e^{-\lambda_3 t})] - \lambda_4B_4$$

Using an integration factor of $e^{\lambda_4 t}$,

$$e^{\lambda_4 t}dB_4 + \lambda_4B_4e^{\lambda_4 t}dt = C_1C_2C_3C_4e^{\lambda_4 t}[(1 - e^{-\lambda_3 t})$$

$$- \frac{\lambda_2\lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)}(e^{-\lambda_1 t} - e^{-\lambda_3 t})$$

$$+ \frac{\lambda_1\lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)}(e^{-\lambda_2 t} - e^{-\lambda_3 t})]dt$$

Note that

$$d(e^{\lambda_4 t}B_4) = C_1C_2C_3C_4e^{\lambda_4 t}[(1 - e^{-\lambda_3 t}) - \frac{\lambda_2\lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)}$$

$$(e^{-\lambda_1 t} - e^{-\lambda_3 t}) + \frac{\lambda_1\lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)}(e^{-\lambda_2 t} - e^{-\lambda_3 t})]dt$$

So that, integrating both sides,

$$e^{\lambda_4 t}B_4 = C_1C_2C_3C_4\{\int e^{\lambda_4 t}dt - \int e^{(\lambda_4 - \lambda_3)t}dt - \frac{\lambda_2\lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)}$$

$$[\int e^{(\lambda_4 - \lambda_1)t}dt - \int e^{(\lambda_4 - \lambda_3)t}dt] + \frac{\lambda_1\lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)}$$

$$[\int e^{(\lambda_4 - \lambda_2)t}dt - \int e^{(\lambda_4 - \lambda_3)t}dt]\}$$

$$= C_1C_2C_3C_4\{\frac{1}{\lambda_4}e^{\lambda_4 t} - \frac{1}{(\lambda_4 - \lambda_3)}e^{(\lambda_4 - \lambda_3)t}$$

$$- \frac{\lambda_2\lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)}[\frac{1}{(\lambda_4 - \lambda_1)}e^{(\lambda_4 - \lambda_1)t}$$

$$- \frac{1}{(\lambda_4 - \lambda_3)}e^{(\lambda_4 - \lambda_3)t}] + \frac{\lambda_1\lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)}$$

$$[\frac{1}{(\lambda_4 - \lambda_2)}e^{(\lambda_4 - \lambda_2)t} - \frac{1}{(\lambda_4 - \lambda_3)}e^{(\lambda_4 - \lambda_3)t}]\} + H$$

Using initial conditions of $B_4 = 0$ when $t = 0$, this equation has the following solution:

$$B_4(t) = C_1C_2C_3C_4\{\frac{1}{\lambda_4}(1 - e^{-\lambda_4 t})$$

$$- [\frac{1}{(\lambda_4 - \lambda_3)} + \frac{\lambda_3\lambda_2(\lambda_3 - \lambda_2) - \lambda_3\lambda_1(\lambda_3 - \lambda_1)}{(\lambda_4 - \lambda_3)(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)(\lambda_3 - \lambda_2)}] (e^{-\lambda_3 t} - e^{-\lambda_4 t})$$

$$+ \frac{\lambda_3\lambda_1}{(\lambda_4 - \lambda_2)(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)} (e^{-\lambda_2 t} - e^{-\lambda_4 t})$$

$$- \frac{\lambda_3\lambda_2}{(\lambda_4 - \lambda_1)(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)} (e^{-\lambda_1 t} - e^{-\lambda_4 t})\} \qquad \text{(A-13)}$$

A.1.3 Selection of Constants

A.1.3.1 Single Exposure

1. c_1 is all the initial deposition in compartment 1 or a specified fraction of this initial deposition. The initial deposition is the product of the total intake and the deposition fraction for compartment 1. If the ICRP Task Group on Lung Dynamics (TGLD) model is being used, this product must be multiplied by the regional fraction in order to isolate that part of the initial deposition that will follow a given pathway in the body. Other multiplication factors may be needed to fractionate the initial deposition. For example, the toxic substance may be composed of materials with two or more different retention functions, requiring a separate calculation for each component. In such cases, the initial deposition must be multiplied by a composition fraction. As another example, the pathway being treated may take a fraction of the toxic substance through

a barrier such as the absorbing cells of the GI tract without accumulation; in such cases, this uptake fraction must also be used as a multiplying factor.

2. c_2 is the fractional uptake of the toxic substance by 2.

3. c_3 is the fractional uptake of the toxic substance by 3.

4. c_4 is the fractional uptake of the toxic substance by 4.

A.1.3.2 Continuous Exposure

C_i (where i = 1, 2, 3, or 4) in the continuous exposure equations is equivalent to c_i in the single exposure equations with one exception. In C_i, the rate of intake is used rather than the intake.

A.1.3.3 Elimination Constants

The mathematical difference in two elimination constants often appears in the denominator in the equations derived above. Where two such constants are equal, a special derivation must be performed (see Sections F.1.e and F.2.c of Appendix B in Ref. A-1).

A.2 SPECIFIC EQUATIONS, EQUATION SYMBOLS, AND CONSTANT VALUES

A.2.1 Equation Symbols

The basic equation symbols used in this analysis are shown in Table A-1. The symbols are used in a wide variety of combinations, including subscripts and superscripts, but are usually self-explanatory. The symbols used for constants and parameters are defined in Table A-9. Table A-1 includes nine anatomical symbols not directly defined in Table A-9: NP, TB, P, K, S, L, B, G, r. The first six of these, when used as basic symbols rather than as subscripts or superscripts, are used to denote the uranium burden. For example,

K(t) is the uranium kidney burden at time t. However, these symbols are also used as subscripts or superscripts to identify the organ for which a constant or parameter is to be used. For example, λ_K is the elimination constant for uranium in the kidney. Of the symbols mentioned above, B (blood) and G (GI tract) are used as subscripts and superscripts to identify pathways taken by uranium in the body. B indicates direct deposition in the blood, TGLD pathways (a), (c), and (e). G indicates GI tract pathways (b), (d), (f), and (g). The symbol r is used to identify direct pathways to the kidney that do not involve interim systemic deposition.

Since the analysis is complex, the symbol structure also becomes complex. However, familiarity with the individual symbols should make their use in combination understandable. For example, $K_{r,G}^{P(f)}(t)$ defines that part of the kidney burden at t that has arrived at the kidney via the pathway specified by the subscripts and superscripts (see Fig. 1-1). The r states that this uranium arrived in the kidney without first being deposited in some other systemic organ. The G states that the uranium was temporarily detained in the GI tract. The P states that the uranium was initially deposited in the pulmonary region of the lung, and (f) identifies the TGLD pathway followed by the uranium. With these identifying symbols, the correct constants and parameters can be chosen to calculate the value of $K_{r,G}^{P(f)}(t)$.

As another example, the symbol $K_{S,B}^{NP,Y}(t)$ is used for that part of the kidney burden that (1) was initially deposited as Class Y material in the nasopharyngeal region, (2) was absorbed directly into the blood, (3) was deposited in the system, and (4) was released again to the blood for final deposition in the kidney. Any departures from the use of this system of symbols are clearly explained in footnotes.

A.2.2 Equations for Calculating Organ Burdens Following Inhalation Exposure

A.2.2.1 Kidney-Burden Equations (Single or Continuous Exposure)

A.2.2.1.1 Kidney Burden Following Exposure to Yellowcake Dried at High Temperature

In accordance with the metabolic model in Section 1.2 of Chapter 1 of this document, inhaled uranium reaches the kidney directly via the respiratory tract and via the respiratory tract after interim systemic deposition. Thus

$$K(t) = K_r(t) + K_S(t)$$

$$K(t) \quad \begin{cases} K_r(t) = K_{r,B}(t) + K_{r,G}(t) + K_{r,L}(t) \\ K_S(t) = K_{S,B}(t) + K_{S,G}(t) + K_{S,L}(t) \end{cases}$$

$K_r(t)$ is constructed from three subequations that represent those contributions of uranium directly to the kidney from the respiratory tract. Equations for the underlined kidney-burden components appear in Table A-3 for single exposures and for continuous exposure conditions.

$$K_r(t) \quad \begin{cases} K_{r,B}(t) = K^{P}_{r,B}(t) + K^{NP}_{r,B}(t) + K^{TB}_{r,B}(t) \\ K_{r,G}(t) = K^{P}_{r,G}(t) + K^{NP}_{r,G}(t) + K^{TB}_{r,G}(t) \\ K_{r,L}(t) = \underline{K}^{1L}_{r,L}(t) + \underline{K}^{2L}_{r,L}(t) + \underline{K}^{3L}_{r,L}(t)^{*} \end{cases}$$

---

*As shown in Table A-9 for high-temperature-dried yellowcake, the lymph compartment (L) is assumed to contain short (1L), medium (2L), and long (3L) lived components. Note that all of this uranium is initially deposited in P.

The first two subterms in $K_r(t)$ above may be further subdivided as follows:

$$K_{r,B}(t) \begin{cases} K^{P}_{r,B}(t) = \underline{K}^{1P}_{r,B}(t) + \underline{K}^{2P}_{r,B}(t) + \underline{K}^{3P}_{r,B}(t)* \\ K^{NP}_{r,B}(t) = \underline{K}^{NP,D}_{r,B}(t) + \underline{K}^{NP,Y}_{r,B}(t)** \\ K^{TB}_{r,B}(t) = \underline{K}^{TB,D}_{r,B}(t) + \underline{K}^{TB,Y}_{r,B}(t)** \end{cases}$$

$$K_{r,G}(t) \begin{cases} K^{P}_{r,G}(t) = \underline{K}^{P(f)}_{r,G}(t) + \underline{K}^{P(g)}_{r,G}(t)*** \\ K^{NP}_{r,G}(t) = \underline{K}^{NP,D}_{r,G}(t) + \underline{K}^{NP,Y}_{r,G}(t) \\ K^{TB}_{r,G}(t) = \underline{K}^{TB,D}_{r,G}(t) + \underline{K}^{TB,Y}_{r,G}(t) \end{cases}$$

$K_S(t)$ is also constructed from three subequations that represent those contributions of uranium to the kidney from the respiratory tract, but <u>indirectly</u> through the body system.

$$K_S(t) \begin{cases} K_{S,B}(t) = K^{P}_{S,B}(t) + K^{NP}_{S,B}(t) + K^{TB}_{S,B}(t) \\ K_{S,G}(t) = K^{P}_{S,G}(t) + K^{NP}_{S,G}(t) + K^{TB}_{S,G}(t) \\ K_{S,L}(t) = \underline{K}^{1L}_{S,L}(t) + \underline{K}^{2L}_{S,L}(t) + \underline{K}^{3L}_{S,L}(t) \end{cases}$$

---

* As shown in Table A-9, 1P, 2P, and 3P refer to the three components of high-temperature-dried yellowcake deposited in the pulmonary compartment.

** For the NP and TB regions, the three yellowcake components measured for the P region do not apply. For NP and TB, the two more soluble components (Table A-9) are called Class D, and the long-half-life component is called Class Y.

***Class Y only, two pathways. Regional fractions are zero for Class D.

The first two subequations may be further subdivided as follows:

$$K_{S,B}(t) \begin{cases} K^{P}_{S,B}(t) = \underline{K}^{1P}_{S,B}(t) + \underline{K}^{2P}_{S,B}(t) + \underline{K}^{3P}_{S,B}(t) \\ K^{NP}_{S,B}(t) = \underline{K}^{NP,D}_{S,B}(t) + \underline{K}^{NP,Y}_{S,B}(t) \\ K^{TB}_{S,B}(t) = \underline{K}^{TB,D}_{S,B}(t) + \underline{K}^{TB,Y}_{S,B}(t) \end{cases}$$

$$K_{S,G}(t) \begin{cases} K^{P}_{S,G}(t) = \underline{K}^{P(f)}_{S,G}(t) + \underline{K}^{P(g)}_{S,G}(t) \\ K^{NP}_{S,G}(t) = \underline{K}^{NP,D}_{S,G}(t) + \underline{K}^{NP,Y}_{S,G}(t) \\ K^{TB}_{S,G}(t) = \underline{K}^{TB,D}_{S,G}(t) + \underline{K}^{TB,Y}_{S,G}(t) \end{cases}$$

Equations and constants for the underlined kidney-burden components are specified in Table A-2, both for single exposures and for continuous exposure conditions. Section A.3 illustrates how these equations and constants are used to calculate each individual kidney-burden contribution to the total kidney burden.

In column 1 of Table A-2, K is used to represent the organ in which accumulation occurs, in this case the kidney. A particular metabolic pathway that uranium follows in reaching the kidney is indicated by subscripts and superscripts, which represent metabolic compartments (or subcompartments, e.g., 1P, 2P, or 3P) in this study (except D, W, Y). The accumulation of uranium in the kidney along any particular metabolic pathway is represented by one of the basic equations given in this appendix. The appropriate equation is shown in column 2 or 3. Under the term "Constants" in Table A-2 appear the simplified constant symbols defined in Table A-1. Under these symbols, the actual symbols for each equation are given. The meaning of each actual symbol may be obtained in Table A-9, which also provides the numerical values used in this study.

A.2.2.1.2 Kidney Burden Following Exposure to Yellowcake Dried at Low Temperature

As in the case of high-temperature-dried yellowcake, uranium in low-temperature-dried yellowcake reaches the kidney directly via the respiratory tract and via the respiratory tract plus interim systemic deposition. Thus, the system of equations shown in the preceding section is for the most part applicable also to low-temperature-dried yellowcake. The differences may be described as follows: As indicated in Table 1-3 of Chapter 1, there is no long-lived component in the case of low-temperature drying. Therefore, the burden component terms with 3L and 3P superscripts disappear while those terms with Y superscripts are changed so that they have W superscripts. The medium-half-life component is much longer (39 days rather than 5 days) and must be classified as Class W rather than Class D. With these changes, the equation for the kidney burden becomes

$$K(t) = K_r(t) + K_S(t)$$

$$K(t) \begin{cases} K_r(t) = K_{r,B}(t) + K_{r,G}(t) + K_{r,L}(t) \\ K_S(t) = K_{S,B}(t) + K_{S,G}(t) + K_{S,L}(t) \end{cases}$$

$K_r(t)$ is constructed from three subequations that represent those contributions of uranium <u>directly</u> to the kidney from the respiratory tract.

$$K_r(t) \begin{cases} K_{r,B}(t) = K^{P}_{r,B}(t) + K^{NP}_{r,B}(t) + K^{TB}_{r,B}(t) \\ K_{r,G}(t) = K^{P}_{r,G}(t) + K^{NP}_{r,G}(t) + K^{TB}_{r,G}(t) \\ K_{r,L}(t) = \underline{K}^{1L}_{r,L}(t) + \underline{K}^{2L}_{r,L}(t) \end{cases}$$

The first two subterms in $K_r(t)$ above may be further subdivided as follows:

$$K_{r,B}(t) \begin{cases} K^{P}_{r,B}(t) = \underline{K}^{1P}_{r,B}(t) + \underline{K}^{2P}_{r,B}(t) \\ K^{NP}_{r,B}(t) = \underline{K}^{NP,D}_{r,B}(t) + \underline{K}^{NP,W}_{r,B}(t) \\ K^{TB}_{r,B}(t) = \underline{K}^{TB,D}_{r,B}(t) + \underline{K}^{TB,W}_{r,B}(t) \end{cases}$$

$$K_{r,G}(t) \begin{cases} K^{P}_{r,G}(t) = \underline{K}^{P(f)}_{r,G}(t) + \underline{K}^{P(g)}_{r,G}(t)* \\ K^{NP}_{r,G}(t) = \underline{K}^{NP,D}_{r,G}(t) + \underline{K}^{NP,W}_{r,G}(t) \\ K^{TB}_{r,G}(t) = \underline{K}^{TB,D}_{r,G}(t) + \underline{K}^{TB,W}_{r,G}(t) \end{cases}$$

$K_S(t)$ is also constructed from three subequations that represent those contributions of uranium to the kidney from the respiratory tract but <u>indirectly</u> through the body system.

$$K_S(t) \begin{cases} K_{S,B}(t) = K^{P}_{S,B}(t) + K^{NP}_{S,B}(t) + K^{TB}_{S,B}(t) \\ K_{S,G}(t) = K^{P}_{S,G}(t) + K^{NP}_{S,G}(t) + K^{TB}_{S,G}(t) \\ K_{S,L}(t) = \underline{K}^{1L}_{S,L}(t) + \underline{K}^{2L}_{S,L}(t) \end{cases}$$

The first two subequations may be further subdivided as follows:

$$K_{S,B}(t) \begin{cases} K^{P}_{S,B}(t) = \underline{K}^{1P}_{S,B}(t) + \underline{K}^{2P}_{S,B}(t) \\ K^{NP}_{S,B}(t) = \underline{K}^{NP,D}_{S,B}(t) + \underline{K}^{NP,W}_{S,B}(t) \\ K^{TB}_{S,B}(t) = \underline{K}^{TB,D}_{S,B}(t) + \underline{K}^{TB,W}_{S,B}(t) \end{cases}$$

*Class W only. Regional fractions are zero for Class D.

$$K_{S,G}(t) \begin{cases} K^{P}_{S,G}(t) = \underline{K}^{P(f)}_{S,G}(t) + \underline{K}^{P(g)}_{S,G}(t) \\ K^{NP}_{S,G}(t) = \underline{K}^{NP,D}_{S,G}(t) + \underline{K}^{NP,W}_{S,G}(t) \\ K^{TB}_{S,G}(t) = \underline{K}^{TB,D}_{S,G}(t) + \underline{K}^{TB,W}_{S,G}(t) \end{cases}$$

Equations for the underlined kidney-burden components appear in Table A-3, both for single exposures and for continuous exposure conditions. Explanations of the constant symbols are given in Table A-9, along with the numerical values used in this study.

A.2.2.1.3 Kidney Burden Following Exposure to Ore Dust

In accordance with this analysis, inhaled uranium reaches the kidney directly via the respiratory tract and via the respiratory tract plus interim systemic deposition. Thus,

$$K(t) = K_r(t) + K_S(t)$$

$$K(t) \begin{cases} K_r(t) = K_{r,B}(t) + K_{r,G}(t) + K_{r,L}(t) \\ K_S(t) = K_{S,B}(t) + K_{S,G}(t) + K_{S,L}(t) \end{cases}$$

The terms $K_r(t)$ and $K_S(t)$ may be further subdivided as follows:

$$K_r(t) \begin{cases} K_{r,B}(t) = \underline{K}^{P(e)}_{r,B}(t) + \underline{K}^{NP,W}_{r,B}(t) + \underline{K}^{TB,W}_{r,B}(t) \\ K_{r,G}(t) = K^{P(f,g)}_{r,G}(t) + \underline{K}^{NP,W}_{r,G}(t) + \underline{K}^{TB,W}_{r,G}(t) \\ \qquad K^{P(f,g)}_{r,G}(t) = \underline{K}^{P(f)}_{r,G}(t) + \underline{K}^{P(g)}_{r,G}(t) \\ K_{r,L}(t) = \underline{K}^{P(h)}_{r,L}(t) \end{cases}$$

$$K_S(t) \begin{cases} K_{S,B}(t) = \underline{K}^{P(e)}_{S,B}(t) + \underline{K}^{NP,W}_{S,B}(t) + \underline{K}^{TB,W}_{S,B}(t) \\ K_{S,G}(t) = K^{P(f,g)}_{S,G}(t) + \underline{K}^{NP,W}_{S,G}(t) + \underline{K}^{TB,W}_{S,G}(t) \\ \qquad K^{P(f,g)}_{S,G}(t) = \underline{K}^{P(f)}_{S,G}(t) + \underline{K}^{P(g)}_{S,G}(t) \\ K_{S,L}(t) = \underline{K}^{P(h)}_{S,L}(t) \end{cases}$$

Equations for the underlined kidney-burden components appear in Table A-4, both for single exposures and for continuous exposure conditions.

A.2.2.2 Systemic-Burden Equations (Continuous Exposure)*

The bases used for the calculations are:

- Metabolic Model - The metabolic model shown in Figure 1-1 and the discussion in Chapter 1 also apply to this calculation.

- Fractional Composition and Retention Functions for the Pulmonary Lung - Table A-9 should be consulted for these values.

- Equation Symbols - The discussion in Section A.2.1 is applicable here; the symbol S is also used in this analysis to refer to the systemic uranium burden. The other subscripts, superscripts, and symbols for constants remain the same.

A.2.2.2.1 Systemic Burden Following Exposure to Yellowcake Dried at High Temperature

In accordance with this analysis, inhaled uranium reaches the system via the NP, TB, and P regions of the respiratory tract. The system of equations describing the systemic burden is given below.

*Calculation of the systemic burden following a single exposure is discussed in Section 4.1.1.2 of Chapter 4.

$$S(t) = S_B(t) + S_G(t) + S_L(t)$$

$$S(t) \begin{cases} S_B(t) = S_B^P(t) + S_B^{NP}(t) + S_B^{TB}(t) \\ S_G(t) = S_G^P(t) + S_G^{NP}(t) + S_G^{TB}(t) \\ S_L(t) = \underline{S}_L^{1P(h)}(t) + \underline{S}_L^{2P(h)}(t) + \underline{S}_L^{3P(h)}(t) \end{cases}$$

The first two subterms in the expression for S(t) above can be further subdivided as follows:

$$S_B(t) \begin{cases} S_B^P(t) = \underline{S}_B^{1P}(t) + \underline{S}_B^{2P}(t) + \underline{S}_B^{3P}(t) \\ S_B^{NP}(t) = \underline{S}_B^{NP,D}(t) + \underline{S}_B^{NP,Y}(t) \\ S_B^{TB}(t) = \underline{S}_B^{TB,D}(t) + \underline{S}_B^{TB,Y}(t) \end{cases}$$

$$S_G(t) \begin{cases} S_G^P(t) = \underline{S}_G^{P(f)}(t) + \underline{S}_G^{P(g)}(t) \\ S_G^{NP}(t) = \underline{S}_G^{NP,D}(t) + \underline{S}_G^{NP,Y}(t) \\ S_G^{TB}(t) = \underline{S}_G^{TB,D}(t) + \underline{S}_G^{TB,Y}(t) \end{cases}$$

Equations for the underlined system-burden components appear in Table A-5 for continuous exposure conditions.

A.2.2.2.2 Systemic Burden Following Exposure to Yellowcake Dried at Low Temperature

As in the case of high-temperature-dried yellowcake, uranium in low-temperature-dried yellowcake reaches the system via the NP, TB, and P regions

of the respiratory tract. The system of equations shown in Section A.2.2.2.1 for yellowcake dried at high temperature is for the most part applicable also to low-temperature-dried yellowcake. The differences may be described as follows: As indicated in Table A-9, there is no long-lived component in the case of low-temperature drying. Therefore, the burden component equations with 3L and 3P superscripts disappear while those terms with Y superscripts are changed so that they have W superscripts.

The medium-half-life component is much longer (39 days rather than 5 days) and must be classified as Class W rather than Class D. With these changes, the equation for the system becomes

$$S(t) = S_B(t) + S_G(t) + S_L(t)$$

$$S(t) \quad \begin{cases} S_B(t) = S_B^P(t) + S_B^{NP}(t) + S_B^{TB}(t) \\ S_G(t) = S_G^P(t) + S_G^{NP}(t) + S_G^{TB}(t) \\ S_L(t) = \underline{S}_L^{1P(h)}(t) + \underline{S}_L^{2P(h)}(t) \end{cases}$$

The first two subterms in the expression for S(t) above can be further subdivided as follows:

$$S_B(t) \quad \begin{cases} S_B^P(t) = \underline{S}_B^{1P}(t) + \underline{S}_B^{2P}(t) \\ S_B^{NP}(t) = \underline{S}_B^{NP,D}(t) + \underline{S}_B^{NP,W}(t) \\ S_B^{TB}(t) = \underline{S}_B^{TB,D}(t) + \underline{S}_B^{TB,W}(t) \end{cases}$$

$$S_G(t) \quad \begin{cases} S_G^P(t) = \underline{S}_G^{P(f)}(t) + \underline{S}_G^{P(g)}(t) \\ S_G^{NP}(t) = \underline{S}_G^{NP,D}(t) + \underline{S}_G^{NP,W}(t) \\ S_G^{TB}(t) = \underline{S}_G^{TB,D}(t) + \underline{S}_G^{TB,W}(t) \end{cases}$$

Equations for the underlined system-burden components appear in Table A-6 for continuous exposure conditions.

A.2.2.2.3 Systemic Burden Following Exposure to Ore Dust

In accordance with this analysis, inhaled uranium reaches the system via the NP, TB, and P regions of the respiratory tract. The system of equations describing the systemic burden is given below.

$$S(t) = S_B(t) + S_G(t) + S_L(t)$$

$$S(t) \begin{cases} S_B(t) = \underline{S}_B^{P(e)}(t) + \underline{S}_B^{NP,W}(t) + \underline{S}_B^{TB,W}(t) \\ S_G(t) = S_G^P(t) + \underline{S}_G^{NP,W}(t) + \underline{S}_G^{TB,W}(t) \\ S_G^P(t) = \underline{S}_G^{P(f)}(t) + \underline{S}_G^{P(g)}(t) \\ S_L(t) = \underline{S}_L^{P(h)}(t) \end{cases}$$

Equations for the S values underlined above appear in Table A-7.

A.2.2.3 Lung-Burden Equations

Presented in this section are the calculational procedures used for determining the lung burden upon which lung dose estimates in this study are based. The lung-burden equations may be found in Table A-8, which includes equations for single and continuous exposure to high- and low-temperature-dried yellowcake and to ore dust. The construction of this table is explained below.

For each type of exposure and for each type of material P(t), the uranium burden in the pulmonary lung as a function of time may be given by

$$P(t) = \sum_{i=(e)}^{(h)} P_i(t)$$

where (e), (f), (g), and (h) are TGLD pathways. It is necessary to calculate the subburden associated with each pathway because different retention functions are involved and because it is necessary to also calculate the subsequent burden in other organs. The individual equations for the summation are

$$P_{(e)}(t) = \underline{P}^{1P}_{(e)}(t) + \underline{P}^{2P}_{(e)}(t) + \underline{P}^{3P}_{(e)}(t)$$

$$P_{(f)}(t) = \underline{P}^{1P}_{(f)}(t) + \underline{P}^{2P}_{(f)}(t) + \underline{P}^{3P}_{(f)}(t)$$

$$P_{(g)}(t) = \underline{P}^{1P}_{(g)}(t) + \underline{P}^{2P}_{(g)}(t) + \underline{P}^{3P}_{(g)}(t)$$

$$P_{(h)}(t) = \underline{P}^{1P}_{(h)}(t) + \underline{P}^{2P}_{(h)}(t) + \underline{P}^{3P}_{(h)}(t)$$

The superscripts 1P, 2P, and 3P refer to the three components of high-temperature-dried yellowcake (see Table A-9), each of which has a different dissolution rate. In the case of low-temperature drying, only two components are considered, and the symbols with 3P superscripts are ignored. For ore dust, only one component is used, and therefore the summation equation shown above is applicable without superscripts.

All the equations used for these lung-burden calculations appear in Table A-8. In each case, the table specifies the type of differential equation used, which may be obtained from Section A.1, and the actual constants to be employed in the equation. For the constants as indicated in the table, symbol explanations and values are given in Tables A-1 and A-9.

A.2.3 Numerical Values for Constants

Numerical values for the constants and parameters used in this study are listed in Table A-9. Exponential retention functions are used for the regions of the respiratory tract, for the lymph nodes, and for the kidney. A power function retention model is frequently used for systemic uranium. However, for calculational simplification, this function is usually represented in this report by the sum of two exponentials as developed by Adams and Spoor (Ref. A-2) or by only the first term of this approximation.

The retention functions and the fractional composition fractions used for yellowcake and ore dust deposited in the pulmonary lung are listed in Table A-9. From in vitro solubility studies for yellowcake in simulated lung fluid (Refs. A-3, A-4, and A-5), it may be concluded that yellowcake subjected to high-temperature drying has, with respect to retention in the lung, three components.

In vitro studies of the solubility of the uranium contained in ore dust in simulated lung fluid are also reported (Ref. A-3). From this study, a value of 50 days was adopted in this analysis for the half-life of 100 percent of the ore-dust uranium in the pulmonary lung.

A.2.4 Comparison to Model Parameters of ICRP-30

A comparison of the constants and parameters used in this study to those used in ICRP-30 is provided in Table A-10. Most of these values as used in this study were taken directly from the TGLD model or from ICRP-30 without modification or with only minor changes (such as the values for f_P and f_K in Table A-10). As used in this study, the constant f_S refers to that fraction of material instantaneously entering the blood and then transferred to all body tissues except the kidney.

The most significant differences between the parameters used in this study and those used in ICRP-30 are differences in values used for the organ elimination constants. As discussed above, the selection of elimination constants for the pulmonary lung in this study is based on new experimental data. The elimination constant for the kidney used in this study, which is based on a retention halftime of 15 days in kidney tissue, appears to be better supported by previously published data (Refs. A-6 and A-7) than the value selected in ICRP-30 based on the paper by Adams and Spoor (Ref. A-2). The 15-day constant is based on data obtained from several studies of occupationally exposed adults and also from animal studies. On the other hand, the elimination constant for kidney adopted by ICRP-30 is supported only by data taken from one man who had been occupationally exposed and from data on adults who ingested (not inhaled) uranium in the course of a normal diet.

The elimination constant used for the body system in this study is identical to the first constant for bone selected by ICRP-30. The second elimination constant was rejected in this study because its use produced calculated results not in accord with the empirical bioassay data for uranium mill workers (Ref. A-7).

A.3 EXAMPLE CALCULATION

A.3.1 Kidney Burden

In this example, the accumulation of uranium in the kidney is calculated at any time (after day 1) along a single metabolic pathway because of a single exposure to yellowcake dried at high temperature. The uranium is deposited in the NP region of the respiratory tract, is transferred to the GI tract where a fraction is absorbed into the blood, and is subsequently deposited in the kidney. Only the Class D component of the inhaled uranium is considered. The symbol $K_{r,G}^{NP,D}(t)$ represents this burden; the symbol may be found as the tenth entry in column 1 of Table A-2. Column 2 indicates that an equation of the Type IIA (see Eq. A-2) is to be used, i.e.,

$$b_2(t) = c_1 c_2 \frac{\lambda_1}{(\lambda_2 - \lambda_1)}(e^{-\lambda_1 t} - e^{-\lambda_2 t})$$

The accumulation in the kidney, $K_{r,G}^{NP,D}(t)$, is represented in this equation by the symbol b_2. No accumulation is assumed to occur in either the GI tract or in the blood; therefore, a two-compartment model is adequate to describe the kidney burden.

Columns 4 and 5 contain the elimination constants that are to be substituted for the simplified constants above. Thus,

$$\lambda_1 = \lambda_{NP(b)} \quad \text{and} \quad \lambda_2 = \lambda_K$$

In the equation above, the constants c_1 and c_2 should also be replaced by their equivalents in the dosimetry model, as given in columns 8 and 9, i.e.,

$$c_1 = (F_1 + F_2) f_{1D} R_{D(b)} f_{NP} I \quad \text{and} \quad c_2 = f_K$$

For the parameters used in the simplified Type IIA equation, make the following numerical substitutions from Table A-9:

1. $c_1c_2\lambda_1 = [(F_1 + F_2)f_{1D}R_{D(b)}f_{NP}I](f_K)\lambda_{NP(b)}$

$= (0.17 + 0.19)(0.05)(0.5)(0.3)(0.11)(69.3)I$

$= 0.0206I$ and

2. $\lambda_1 = \lambda_{NP(b)} = 69.3$

$\lambda_2 = \lambda_K = 0.0462$

$(\lambda_2 - \lambda_1) = (0.0462 - 69.3) = -69.25$

These calculated values are then substituted into the simplified equation for $b_2(t)$ to give the desired accumulation of uranium in the kidney as a function of time.

$$\frac{K_{r,G}^{NP,D}(t)}{I} = \frac{0.0206}{-69.25}(e^{-69.3t} - e^{-0.0462t})$$

$$= 2.97 \times 10^{-4}(e^{-0.0462t} - e^{-69.3t})$$

A.3.2 Organ Burdens for System and Lung

The calculation of the uranium burden in the system (Section A.2.2.2) or in the lung (Section A.2.2.3) that results in a unit intake is executed in a manner similar to the calculations for the kidney burden given above. The constants to be used in the initial equations are expressed in symbolic form in Tables A-5 through A-7 for the system and in Table A-8 for the lung. Conversion of the symbolic values of the constants to numerical values requires the use of Table A-9 as was the case for the kidney-burden calculation described above.

TABLE A-1

Equation Symbols

Symbol	Explanation
NP	Nasopharyngeal Region
TB	Tracheobronchial Region
P	Pulmonary Region
K	Kidney
r	Nonsystemic
S	System (other than kidney)
L	Lymph Nodes
B	Blood (non-GI tract)
G	Gastrointestinal Tract
X	Urinary Uranium Concentration
I	Intake, Quantity Inhaled During a Single Exposure*
I'	Intake Rate, Quantity Inhaled Per Day*
D	Class D Material (retention for days)
W	Class W Material (retention for weeks)
Y	Class Y Material (retention for years)
(a)	NP to Blood Pathway
(b)	NP to GI Tract to Blood Pathway
(c)	TB to Blood Pathway
(d)	TB to GI Tract to Blood Pathway
(e)	P to Blood Pathway
(f)	P to GI Tract (rapid) to Blood Pathway
(g)	P to GI Tract (delayed) to Blood Pathway
(h)	P to Lymph Pathway
(i)	Lymph Node to Blood Pathway
R	Regional Fraction
F	Composition Fraction
f	Deposition or Uptake Fraction
λ	Elimination Constant (d^{-1})

*Although the symbol I is always used in the "Constants" column in the tables that follow, it should be understood that in the case of continuous exposure I' is to be substituted.

TABLE A-2

Equations: Single or Continuous Exposure, High-Temperature Drying, Kidney Burden

Burden Component*	Type Equation		Constants							
	Single Exposure	Continuous Exposure	λ_1	λ_2	λ_3	λ_4	C_1	C_2	C_3	C_4
$K_{r,B}^{1P}(t)$	IIA	IIB	λ_{1P}	λ_K	-	-	$F_1 R_{D(e)} f_P I$	f_K	-	-
$K_{r,B}^{2P}(t)$	IIA	IIB	λ_{2P}	λ_K	-	-	$F_2 R_{D(e)} f_P I$	f_K	-	-
$K_{r,B}^{3P}(t)$	IIA	IIB	λ_{3P}	λ_K	-	-	$F_3 R_{Y(e)} f_P I$	f_K	-	-
$K_{r,B}^{NP,D}(t)$	IIA	IIB	$\lambda_{NP(a)}$	λ_K	-	-	$(F_1 + F_2) R_{D(a)} f_{NP} I$	f_K	-	-
$K_{r,B}^{NP,Y}(t)$	IIA	IIB	$\lambda_{NP(a)}$	λ_K	-	-	$F_3 R_{Y(a)} f_{NP} I$	f_K	-	-
$K_{r,B}^{TB,D}(t)$	IIA	IIB	$\lambda_{TB(c)}$	λ_K	-	-	$(F_1 + F_2) R_{D(c)} f_{TB} I$	f_K	-	-
$K_{r,B}^{TB,Y}(t)$	IIA	IIB	$\lambda_{TB(c)}$	λ_K	-	-	$F_3 R_{Y(c)} f_{TB} I$	f_K	-	-
$K_{r,G}^{P(f)}(t)$	IIA	IIB	$\lambda_{P(f)}$	λ_K	-	-	$F_3 f_{1Y} R_{Y(f)} f_p I$	f_K	-	-
$K_{r,G}^{P(g)}(t)$	IIA	IIB	λ_{3P}	λ_K	-	-	$F_3 f_{1Y} R_{Y(g)} f_P I$	f_K	-	-
$K_{r,G}^{NP,D}(t)$	IIA	IIB	$\lambda_{NP(b)}$	λ_K	-	-	$(F_1 + F_2) f_{1D} R_{D(b)} f_{NP} I$	f_K	-	-
$K_{r,G}^{NP,Y}(t)$	IIA	IIB	$\lambda_{NP(b)}^{Y}$	λ_K	-	-	$F_3 f_{1Y} R_{Y(b)} f_{NP} I$	f_K	-	-
$K_{r,G}^{TB,D}(t)$	IIA	IIB	$\lambda_{TB(d)}$	λ_K	-	-	$(F_1 + F_2) f_{1D} R_{D(d)} f_{TB} I$	f_K	-	-
$K_{r,G}^{TB,Y}(t)$	IIA	IIB	$\lambda_{TB(d)}$	λ_K	-	-	$F_3 f_{1Y} R_{Y(d)} f_{TB} I$	f_K	-	-

*The burden component shown in this table is represented by "b" or "B" in the derivation of equations.

TABLE A-2 (Continued)

Burden Component*	Type Equation: Single Exposure	Type Equation: Continuous Exposure	Constants: λ_1	λ_2	λ_3	λ_4	C_1	C_2	C_3	C_4
$K_{r,L}^{1P(h)}(t)$	IIIA	IIIB	λ_{1P}	λ_L^D	λ_K	-	$F_1 R_{D(h)} f_P I$	f_L	f_K	-
$K_{r,L}^{2P(h)}(t)$	IIIA	IIIB	λ_{2P}	λ_L^D	λ_K	-	$F_2 R_{D(h)} f_P I$	f_L	f_K	-
$K_{r,L}^{3P(h)}(t)$	IIIA	IIIB	λ_{3P}	λ_L^Y	λ_K	-	$F_3 R_{Y(h)} f_P I$	f_L	f_K	-
$K_{S,B}^{1P}(t)$**	IIIA	IIIB	λ_{1P}	λ_{1S}	λ_K	-	$0.8F_1 R_{D(e)} f_P I$	f_S	f_K	-
$K_{S,B}^{2P}(t)$**	IIIA	IIIB	λ_{2P}	λ_{1S}	λ_K	-	$0.8F_2 R_{D(e)} f_P I$	f_S	f_K	-
$K_{S,B}^{3P}(t)$**	IIIA	IIIB	λ_{3P}	λ_{1S}	λ_K	-	$0.8F_3 R_{Y(e)} f_P I$	f_S	f_K	-
$K_{S,B}^{NP,D}(t)$**	IIIA	IIIB	$\lambda_{NP(a)}$	λ_{1S}	λ_K	-	$0.8(F_1 + F_2) R_{D(a)} f_{NP} I$	f_S	f_K	-
$K_{S,B}^{NP,Y}(t)$**	IIIA	IIIB	$\lambda_{NP(a)}$	λ_{1S}	λ_K	-	$0.8F_3 R_{Y(a)} f_{NP} I$	f_S	f_K	-
$K_{S,B}^{TB,D}(t)$**	IIIA	IIIB	$\lambda_{TB(c)}$	λ_{1S}	λ_K	-	$0.8(F_1 + F_2) R_{D(c)} f_{TB} I$	f_S	f_K	-
$K_{S,B}^{TB,Y}(t)$**	IIIA	IIIB	$\lambda_{TB(c)}$	λ_{1S}	λ_K	-	$0.8F_3 R_{Y(c)} f_{TB} I$	f_S	f_K	-
$K_{S,G}^{P(f)}(t)$**	IIIA	IIIB	$\lambda_{P(f)}$	λ_{1S}	λ_K	-	$0.8F_3 f_{1Y} R_{Y(f)} f_P I$	f_S	f_K	-
$K_{S,G}^{P(g)}(t)$**	IIIA	IIIB	λ_{3P}	λ_{1S}	λ_K	-	$0.8F_3 f_{1Y} R_{Y(g)} f_P I$	f_S	f_K	-

**Option: The burden component may be the sum of two equations, the equation shown in the table plus the same equation with λ_{2S} substituted for λ_{1S} and 0.09 substituted for 0.8.

TABLE A-2 (Continued)

Burden Component*	Type Equation: Single Exposure	Type Equation: Continuous Exposure	Constants: λ_1	λ_2	λ_3	λ_4	C_1	C_2	C_3	C_4
$K_{S,G}^{NP,D}(t)$**	IIIA	IIIB	$\lambda_{NP(b)}$	λ_{1S}	λ_K	-	$0.8(F_1 + F_2)f_{1D}R_{D(b)}f_{NP}I$	f_S	f_K	-
$K_{S,G}^{NP,Y}(t)$**	IIIA	IIIB	$\lambda_{NP(b)}^{Y}$	λ_{1S}	λ_K	-	$0.8F_3f_{1Y}R_{Y(b)}f_{NP}I$	f_S	f_K	-
$K_{S,G}^{TB,D}(t)$**	IIIA	IIIB	$\lambda_{TB(d)}$	λ_{1S}	λ_K	-	$0.8(F_1 + F_2)f_{1D}R_{D(d)}f_{TB}I$	f_S	f_K	-
$K_{S,G}^{TB,Y}(t)$**	IIIA	IIIB	$\lambda_{TB(d)}$	λ_{1S}	λ_K	-	$0.8F_3f_{1Y}R_{Y(d)}f_{TB}I$	f_S	f_K	-
$K_{S,L}^{1P(h)}(t)$**	IVA	IVB	λ_{1P}	λ_L^D	λ_{1S}	λ_K	$0.8F_1R_{D(h)}f_PI$	f_L	f_S	f_K
$K_{S,L}^{2P(h)}(t)$**	IVA	IVB	λ_{2P}	λ_L^D	λ_{1S}	λ_K	$0.8F_2R_{D(h)}f_PI$	f_L	f_S	f_K
$K_{S,L}^{3P(h)}(t)$**	IVA	IVB	λ_{3P}	λ_L^Y	λ_{1S}	λ_K	$0.8F_3R_{Y(h)}f_PI$	f_L	f_S	f_K

TABLE A-3

Equations: Single or Continuous Exposure, Low-Temperature Drying, Kidney Burden

Burden Component *	Type Equation		Constants							
	Single Exposure	Continuous Exposure	λ_1	λ_2	λ_3	λ_4	C_1	C_2	C_3	C_4
$K_{r,B}^{1P}(t)$	IIA	IIB	λ_{1P}^{LT}	λ_K	-	-	$F_1^{LT}R_{D(e)}f_P^I$	f_K	-	-
$K_{r,B}^{2P}(t)$	IIA	IIB	λ_{2P}^{LT}	λ_K	-	-	$F_2^{LT}R_{W(e)}f_P^I$	f_K	-	-
$K_{r,B}^{NP,D}(t)$	IIA	IIB	$\lambda_{NP(a)}$	λ_K	-	-	$F_1^{LT}R_{D(a)}f_{NP}^I$	f_K	-	-
$K_{r,B}^{NP,W}(t)$	IIA	IIB	$\lambda_{NP(a)}$	λ_K	-	-	$F_2^{LT}R_{W(a)}f_{NP}^I$	f_K	-	-
$K_{r,B}^{TB,D}(t)$	IIA	IIB	$\lambda_{TB(c)}$	λ_K	-	-	$F_1^{LT}R_{D(c)}f_{TB}^I$	f_K	-	-
$K_{r,B}^{TB,W}(t)$	IIA	IIB	$\lambda_{TB(c)}$	λ_K	-	-	$F_2^{LT}R_{W(c)}f_{TB}^I$	f_K	-	-
$K_{r,G}^{P(f)}(t)$	IIA	IIB	$\lambda_{P(f)}$	λ_K	-	-	$F_2^{LT}f_{1W}R_{W(f)}f_P^I$	f_K	-	-
$K_{r,G}^{P(g)}(t)$	IIA	IIB	λ_{2P}^{LT}	λ_K	-	-	$F_2^{LT}f_{1W}R_{W(g)}f_P^I$	f_K	-	-
$K_{r,G}^{NP,D}(t)$	IIA	IIB	$\lambda_{NP(b)}$	λ_K	-	-	$F_1^{LT}f_{1D}R_{D(b)}f_{NP}^I$	f_K	-	-
$K_{r,G}^{NP,W}(t)$	IIA	IIB	$\lambda_{NP(b)}$	λ_K	-	-	$F_2^{LT}f_{1W}R_{W(b)}f_{NP}^I$	f_K	-	-
$K_{r,G}^{TB,D}(t)$	IIA	IIB	$\lambda_{TB(d)}$	λ_K	-	-	$F_1^{LT}f_{1D}R_{D(d)}f_{TB}^I$	f_K	-	-
$K_{r,G}^{TB,W}(t)$	IIA	IIB	$\lambda_{TB(d)}$	λ_K	-	-	$F_2^{LT}f_{1W}R_{W(d)}f_{TB}^I$	f_K	-	-
$K_{r,L}^{1P(h)}(t)$	IIIA	IIIB	λ_{1P}^{LT}	λ_L^D	λ_K	-	$F_1^{LT}R_{D(h)}f_P^I$	f_L	f_K	-

*The burden component shown in this table is represented by "b" or "B" in the derivation of equations.

TABLE A-3 (Continued)

Burden Component*	Type Equation: Single Exposure	Type Equation: Continuous Exposure	Constants: λ_1	λ_2	λ_3	λ_4	C_1	C_2	C_3	C_4
$K_{r,L}^{2P(h)}(t)$	IIIA	IIIB	λ_{2P}^{LT}	λ_L^W	λ_K	-	$F_2^{LT}R_{W(h)}f_P I$	f_L	f_K	-
$K_{S,B}^{1P}(t)$**	IIIA	IIIB	λ_{1P}^{LT}	λ_{1S}	λ_K	-	$0.8F_1^{LT}R_{D(e)}f_P I$	f_S	f_K	-
$K_{S,B}^{2P}(t)$**	IIIA	IIIB	λ_{2P}^{LT}	λ_{1S}	λ_K	-	$0.8F_2^{LT}R_{W(e)}f_P I$	f_S	f_K	-
$K_{S,B}^{NP,D}(t)$**	IIIA	IIIB	$\lambda_{NP(a)}$	λ_{1S}	λ_K	-	$0.8F_1^{LT}R_{D(a)}f_{NP} I$	f_S	f_K	-
$K_{S,B}^{NP,W}(t)$**	IIIA	IIIB	$\lambda_{NP(a)}$	λ_{1S}	λ_K	-	$0.8F_2^{LT}R_{W(a)}f_{NP} I$	f_S	f_K	-
$K_{S,B}^{TB,D}(t)$**	IIIA	IIIB	$\lambda_{TB(c)}$	λ_{1S}	λ_K	-	$0.8F_1^{LT}R_{D(c)}f_{TB} I$	f_S	f_K	-
$K_{S,B}^{TB,W}(t)$**	IIIA	IIIB	$\lambda_{TB(c)}$	λ_{1S}	λ_K	-	$0.8F_2^{LT}R_{W(c)}f_{TB} I$	f_S	f_K	-
$K_{S,G}^{P(f)}(t)$**	IIIA	IIIB	$\lambda_{P(f)}$	λ_{1S}	λ_K	-	$0.8F_2^{LT}f_{1W}R_{W(f)}f_P I$	f_S	f_K	-
$K_{S,G}^{P(g)}(t)$**	IIIA	IIIB	λ_{2P}^{LT}	λ_{1S}	λ_K	-	$0.8F_2^{LT}f_{1W}R_{W(g)}f_P I$	f_S	f_K	-
$K_{S,G}^{NP,D}(t)$**	IIIA	IIIB	$\lambda_{NP(b)}$	λ_{1S}	λ_K	-	$0.8F_1^{LT}f_{1D}R_{D(b)}f_{NP} I$	f_S	f_K	-
$K_{S,G}^{NP,W}(t)$**	IIIA	IIIB	$\lambda_{TB(d)}$	λ_{1S}	λ_K	-	$0.8F_2^{LT}f_{1W}R_{W(d)}f_{NP} I$	f_S	f_K	-
$K_{S,G}^{TB,D}(t)$**	IIIA	IIIB	$\lambda_{TB(d)}$	λ_{1S}	λ_K	-	$0.8F_1^{LT}f_{1D}R_{D(d)}f_{TB} I$	f_S	f_K	-

**Option: The burden component may be the sum of two equations, the equation shown in the table plus the same equation with λ_{2S} substituted for λ_{1S} and 0.09 substituted for 0.8.

TABLE A-3 (Continued)

Burden Component*	Type Equation: Single Exposure	Type Equation: Continuous Exposure	Constants: λ_1	λ_2	λ_3	λ_4	C_1	C_2	C_3	C_4
$K_{S,G}^{TB,W}(t)$**	IIIA	IIIB	$\lambda_{TB(d)}$	λ_{1S}	λ_K	-	$0.8F_2^{LT}f_{1W}R_{W(d)}f_{TB}I$	f_S	f_K	-
$K_{S,L}^{1L}(t)$**	IVA	IVB	λ_{1P}^{LT}	λ_L^D	λ_{1S}	λ_K	$0.8F_1^{LT}R_{D(h)}f_PI$	f_L	f_S	f_K
$K_{S,L}^{2L}(t)$**	IVA	IVB	λ_{2P}^{LT}	λ_L^W	λ_{1S}	λ_K	$0.8F_2^{LT}R_{W(h)}f_PI$	f_L	f_S	f_K

TABLE A-4

Equations: Single or Continuous Exposure to Ore Dust, Kidney Burden

Burden Component*	Type Equation		Constants							
	Single Exposure	Continuous Exposure	λ_1	λ_2	λ_3	λ_4	C_1	C_2	C_3	C_4
$K_{r,B}^{P(e)}(t)$	IIA	IIB	$\lambda_{P(e)}$	λ_K	-	-	$R_{W(e)}f_P I$	f_K	-	-
$K_{r,B}^{NP,W}(t)$	IIA	IIB	$\lambda_{NP(a)}$	λ_K	-	-	$R_{W(a)}f_{NP} I$	f_K	-	-
$K_{r,B}^{TB,W}(t)$	IIA	IIB	$\lambda_{TB(c)}$	λ_K	-	-	$R_{W(c)}f_{TB} I$	f_K	-	-
$K_{r,G}^{P(f)}(t)$	IIA	IIB	$\lambda_{P(f)}$	λ_K	-	-	$f_{1W}R_{W(f)}f_P I$	f_K	-	-
$K_{r,G}^{P(g)}(t)$	IIA	IIB	$\lambda_{P(g)}$	λ_K	-	-	$f_{1W}R_{W(g)}f_P I$	f_K	-	-
$K_{r,G}^{NP,W}(t)$	IIA	IIB	$\lambda_{NP(b)}$	λ_K	-	-	$f_{1W}R_{W(b)}f_{NP} I$	f_K	-	-
$K_{r,G}^{TB,W}(t)$	IIA	IIB	$\lambda_{TB(d)}$	λ_K	-	-	$f_{1W}R_{W(d)}f_{TB} I$	f_K	-	-
$K_{r,L}^{P(h)}(t)$	IIIA	IIIB	$\lambda_{P(h)}$	λ_L^W	λ_K	-	$R_{W(h)}f_P I$	f_L	f_K	-
$K_{S,B}^{P(e)}(t)$**	IIIA	IIIB	$\lambda_{P(e)}$	λ_{1S}	λ_K	-	$0.8R_{W(e)}f_P I$	f_S	f_K	-
$K_{S,B}^{NP,W}(t)$**	IIIA	IIIB	$\lambda_{NP(a)}$	λ_{1S}	λ_K	-	$0.8R_{W(a)}f_{NP} I$	f_S	f_K	-

*The burden component shown in this table is represented by "b" or "B" in the derivation of equations.

**Option: The burden component may be the sum of two equations, the equation shown in the table plus the same equation with λ_{2S} substitution for λ_{1S} and 0.09 substituted for 0.8.

TABLE A-4 (Continued)

Burden Component*	Type Equation: Single Exposure	Type Equation: Continuous Exposure	Constants: λ_1	λ_2	λ_3	λ_4	C_1	C_2	C_3	C_4
$K_{S,B}^{TB,W}(t)$**	IIIA	IIIB	$\lambda_{TB(c)}$	λ_{1S}	λ_K	-	$0.8R_{W(c)}f_{TB}I$	f_S	f_K	-
$K_{S,G}^{P(f)}(t)$**	IIIA	IIIB	$\lambda_{P(f)}$	λ_{1S}	λ_K	-	$0.8f_{1W}R_{W(f)}f_PI$	f_S	f_K	-
$K_{S,G}^{P(g)}(t)$**	IIIA	IIIB	$\lambda_{P(g)}$	λ_{1S}	λ_K	-	$0.8f_{1W}R_{W(g)}f_PI$	f_S	f_K	-
$K_{S,G}^{NP,W}(t)$**	IIIA	IIIB	$\lambda_{NP(b)}$	λ_{1S}	λ_K	-	$0.8f_{1W}R_{W(b)}f_{NP}I$	f_S	f_K	-
$K_{S,G}^{TB,W}(t)$**	IIIA	IIIB	$\lambda_{TB(d)}$	λ_{1S}	λ_K	-	$0.8f_{1W}R_{W(d)}f_{TB}I$	f_S	f_K	-
$K_{S,L}^{P(h)}(t)$**	IVA	IVB	$\lambda_{P(h)}$	λ_L^W	λ_{1S}	λ_K	$0.8R_{W(h)}f_PI$	f_L	f_S	f_K

TABLE A-5

Equations: Continuous Exposure, High-Temperature Drying, Systemic Burden

Burden Component *,**	Type Equation	Constants λ_1	λ_2	λ_3	C_1	C_2	C_3
$S_B^{1P}(t)$	IIB	λ_{1P}	λ_{1S}	-	$0.8F_1R_{D(e)}f_PI'$	f_S	-
$S_B^{2P}(t)$	IIB	λ_{2P}	λ_{1S}	-	$0.8F_2R_{D(e)}f_PI'$	f_S	-
$S_B^{3P}(t)$	IIB	λ_{3P}	λ_{1S}	-	$0.8F_3R_{Y(e)}f_PI'$	f_S	-
$S_B^{NP,D}(t)$	IIB	$\lambda_{NP(a)}$	λ_{1S}	-	$0.8(F_1 + F_2)R_{D(a)}f_{NP}I'$	f_S	-
$S_B^{NP,Y}(t)$	IIB	$\lambda_{NP(a)}$	λ_{1S}	-	$0.8F_3R_{Y(a)}f_{NP}I'$	f_S	-
$S_B^{TB,D}(t)$	IIB	$\lambda_{TB(c)}$	λ_{1S}	-	$0.8(F_1 + F_2)R_{D(c)}f_{TB}I'$	f_S	-
$S_B^{TB,Y}(t)$	IIB	$\lambda_{TB(c)}$	λ_{1S}	-	$0.8F_3R_{Y(c)}f_{TB}I'$	f_S	-
$S_G^{P(f)}(t)$	IIB	$\lambda_{P(f)}$	λ_{1S}	-	$0.8F_3f_{1Y}R_{Y(f)}f_PI'$	fS	-
$S_G^{P(g)}(t)$	IIB	λ_{3P}	λ_{1S}	-	$0.8F_3f_{1Y}R_{Y(g)}f_PI'$	f_S	-
$S_G^{NP,D}(t)$	IIB	$\lambda_{NP(b)}$	λ_{1S}	-	$0.8(F_1 + F_2)f_{1D}R_{D(b)}f_{NP}I'$	f_S	-
$S_G^{NP,Y}(t)$	IIB	$\lambda^{Y}_{NP(b)}$	λ_{1S}	-	$0.8F_3f_{1Y}R_{Y(b)}f_{NP}I'$	f_S	-

*The burden component shown in this table is represented by "b" or "B" in the derivation of equations.

**Option: The burden component may be the sum of two equations, the equation shown in the table plus the same equation with λ_{2S} substituted for λ_{1S} and 0.09 substituted for 0.8.

TABLE A-5 (Continued)

Burden Component*,**	Type Equation	Constants					
		λ_1	λ_2	λ_3	C_1	C_2	C_3
$S_G^{TB,D}(t)$	IIB	$\lambda_{TB(d)}$	λ_{1S}	-	$0.8(F_1 + F_2)f_{1D}R_{D(d)}f_{TB}I'$	f_S	-
$S_G^{TB,Y}(t)$	IIB	$\lambda_{TB(d)}$	λ_{1S}	-	$0.8F_3f_{1Y}R_{Y(d)}f_{TB}I'$	f_S	-
$S_L^{1P(h)}(t)$	IIIB	λ_{1P}	λ_L^D	λ_{1S}	$0.8F_1R_{D(h)}f_PI'$	f_L	f_S
$S_L^{2P(h)}(t)$	IIIB	λ_{2P}	λ_L^D	λ_{1S}	$0.8F_2R_{D(h)}f_PI'$	f_L	f_S
$S_L^{3P(h)}(t)$	IIIB	λ_{3P}	λ_L^Y	λ_{1S}	$0.8F_3R_{Y(h)}f_PI'$	f_L	f_S

TABLE A-6

Equations: Continuous Exposure, Low-Temperature Drying, Systemic Burden

Burden Component*,**	Type Equation	Constants λ_1	λ_2	λ_3	C_1	C_2	C_3
$S_B^{1P}(t)$	IIB	λ_{1P}^{LT}	λ_{1S}	-	$0.8F_1^{LT}R_{D(e)}f_P I'$	f_S	-
$S_B^{2P}(t)$	IIB	λ_{2P}^{LT}	λ_{1S}	-	$0.8F_2^{LT}R_{D(e)}f_P I'$	f_S	-
$S_B^{NP,D}(t)$	IIB	$\lambda_{NP(a)}$	λ_{1S}	-	$0.8F_1^{LT}R_{D(a)}f_{NP} I'$	f_S	-
$S_B^{NP,W}(t)$	IIB	$\lambda_{NP(a)}$	λ_{1S}	-	$0.8F_2^{LT}R_{W(a)}f_{NP} I'$	f_S	-
$S_B^{TB,D}(t)$	IIB	$\lambda_{TB(c)}$	λ_{1S}	-	$0.8F_1^{LT}R_{D(c)}f_{TB} I'$	f_S	-
$S_B^{TB,W}(t)$	IIB	$\lambda_{TB(c)}$	λ_{1S}	-	$0.8F_2^{LT}R_{W(c)}f_{TB} I'$	f_S	-
$S_G^{P(f)}(t)$	IIB	$\lambda_{P(f)}$	λ_{1S}	-	$0.8F_2^{LT}f_{1W}R_{W(f)}f_P I'$	f_S	-
$S_G^{P(g)}(t)$	IIB	λ_{2P}^{LT}	$\lambda 1S$	-	$0.8F_2^{LT}f_{1W}R_{W(g)}f_P I'$	f_S	-
$S_G^{NP,D}(t)$	IIB	$\lambda_{NP(b)}^{D}$	$\lambda 1S$	-	$0.8F_1^{LT}f_{1D}R_{D(b)}f_{NP} I'$	f_S	-
$S_G^{NP,W}(t)$	IIB	$\lambda_{NP(b)}^{W}$	$\lambda 1S$	-	$0.8F_2^{LT}f_{1W}R_{W(b)}f_{NP} I'$	f_S	-
$S_G^{TB,D}(t)$	IIB	$\lambda_{TB(d)}$	λ_{1S}	-	$0.8F_1^{LT}f_{1D}R_{D(d)}f_{TB} I'$	f_S	-
$S_G^{TB,W}(t)$	IIB	$\lambda_{TB(d)}$	λ_{1S}	-	$0.8F_2^{LT}f_{1W}R_{W(d)}f_{TB} I'$	f_S	-
$S_L^{1P(h)}(t)$	IIIB	λ_{1P}^{LT}	λ_L^D	λ_{1S}	$0.8F_1^{LT}R_{D(h)}f_P I'$	f_L	f_S
$S_L^{2P(h)}(t)$	IIIB	λ_{2P}^{LT}	λ_L^W	λ_{1S}	$0.8F_2^{LT}R_{W(h)}f_P I'$	f_L	f_S

*The burden component shown in this table is represented by "b" or "B" in the derivation of equations.

**Option: The burden component may be the sum of two equations, the equation shown in the table plus the same equation with λ_{2S} substituted for λ_{1S} and 0.09 substituted for 0.8.

TABLE A-7

Equations: Continuous Exposure to Ore Dust, Systemic Burden

Burden Component*,**	Type Equation	Constants					
		λ_1	λ_2	λ_3	C_1	C_2	C_3
$S_B^{P(e)}(t)$	IIB	$\lambda_{P(e)}$	λ_{1S}	-	$0.8R_{W(e)}f_P I'$	f_S	-
$S_B^{NP,W}(t)$	IIB	$\lambda_{NP(a)}$	λ_{1S}	-	$0.8R_{W(a)}f_{NP}I'$	f_S	-
$S_B^{TB,W}(t)$	IIB	$\lambda_{TB(c)}$	λ_{1S}	-	$0.8R_{W(c)}f_{TB}I'$	f_S	-
$S_G^{P(f)}(t)$	IIB	$\lambda_{P(f)}$	λ_{1S}	-	$0.8f_{1W}R_{W(f)}f_P I'$	f_S	-
$S_G^{P(g)}(t)$	IIB	$\lambda_{P(g)}$	λ_{1S}	-	$0.8f_{1W}R_{W(g)}f_P I'$	f_S	-
$S_G^{NP,W}(t)$	IIB	$\lambda_{NP(b)}$	λ_{1S}	-	$0.8f_{1W}R_{W(b)}f_{NP}I'$	f_S	-
$S_G^{TB,W}(t)$	IIB	$\lambda_{TB(d)}$	λ_{1S}	-	$0.8f_{1W}R_{W(d)}f_{TB}I'$	f_S	-
$S_L^{P(h)}(t)$	IIIB	$\lambda_{P(h)}$	λ_L^W	λ_{1S}	$0.8R_{W(h)}f_P I'$	f_L	f_S

*The burden component shown in this table is represented by "b" or "B" in the derivation of equations.

**Option: The burden component may be the sum of two equations, the equation shown in the table plus the same equation with λ_{2S} substituted for λ_{1S} and 0.09 substituted for 0.8.

TABLE A-8

Equations: Single or Continuous Exposure, Lung Burden

Burden Component*	Type Equation: Single Exposure	Type Equation: Continuous Exposure	Constants: λ_1	Constants: C_1**
A. High-Temperature-Dried Yellowcake				
$P^{1P}_{(e)}(t)$	IA	IB	λ_{1P}	$F_1R_{D(e)}f_PI$
$P^{2P}_{(e)}(t)$	IA	IB	λ_{2P}	$F_2R_{D(e)}f_PI$
$P^{3P}_{(e)}(t)$	IA	IB	λ_{3P}	$F_3R_{Y(e)}f_PI$
$P^{1P}_{(f)}(t)$	IA	IB	λ_{1P}	***$F_1R_{D(f)}f_PI$
$P^{2P}_{(f)}(t)$	IA	IB	λ_{2P}	***$F_2R_{D(f)}f_PI$
$P^{3P}_{(f)}(t)$	IA	IB	$\lambda_{P(f)}$	$F_3R_{Y(f)}f_PI$
$P^{1P}_{(g)}(t)$	IA	IB	λ_{1P}	***$F_1R_{D(g)}f_PI$
$P^{2P}_{(g)}(t)$	IA	IB	λ_{2P}	***$F_2R_{D(g)}f_PI$
$P^{3P}_{(g)}(t)$	IA	IB	λ_{3P}	$F_3R_{Y(g)}f_PI$
$P^{1P}_{(h)}(t)$	IA	IB	λ_{1P}	$F_1R_{D(h)}f_PI$
$P^{2P}_{(h)}(t)$	IA	IB	λ_{2P}	$F_2R_{D(h)}f_PI$
$P^{3P}_{(h)}(t)$	IA	IB	λ_{3P}	$F_3R_{Y(h)}f_PI$

*The burden component shown in this table is represented by "b" or "B" in the derivation of equations.

**The symbol I is applicable for single exposures; I' is applicable for continuous exposure conditions.

***TGLD indicates regional fraction is NA; therefore, zero is assigned in this analysis to these terms.

TABLE A-8 (Continued)

Burden Component*	Type Equation: Single Exposure	Type Equation: Continuous Exposure	Constants: λ_1	Constants: C_1**
B. Low-Temperature-Dried Yellowcake				
$P^{1P}_{(e)}(t)$	IA	IB	λ^{LT}_{1P}	$F^{LT}_1 R_{D(e)} f_P I$
$P^{2P}_{(e)}(t)$	IA	IB	λ^{LT}_{2P}	$F^{LT}_2 R_{W(e)} f_P I$
$P^{1P}_{(f)}(t)$	IA	IB	λ^{LT}_{1P}	$***F^{LT}_1 R_{D(f)} f_P I$
$P^{2P}_{(f)}(t)$	IA	IB	$\lambda_{P(f)}$	$F^{LT}_2 R_{W(f)} f_P I$
$P^{1P}_{(g)}(t)$	IA	IB	λ^{LT}_{1P}	$***F^{LT}_1 R_{D(g)} f_P I$
$P^{2P}_{(g)}(t)$	IA	IB	λ^{LT}_{2P}	$F^{LT}_2 R_{W(g)} f_P I$
$P^{1P}_{(h)}(t)$	IA	IB	λ^{LT}_{1P}	$F^{LT}_1 R_{D(h)} f_P I$
$P^{2P}_{(h)}(t)$	IA	IB	λ^{LT}_{2P}	$F^{LT}_2 R_{W(h)} f_P I$
C. Ore Dust				
$P_{(e)}(t)$	IA	IB	$\lambda_{P(e)}$	$R_{W(e)} f_P I$
$P_{(f)}(t)$	IA	IB	$\lambda_{P(f)}$	$R_{W(f)} f_P I$
$P_{(g)}(t)$	IA	IB	$\lambda_{P(g)}$	$R_{W(g)} f_P I$
$P_{(h)}(t)$	IA	IB	$\lambda_{P(h)}$	$R_{W(h)} f_P I$

TABLE A-9

Constants and Parameters

Constant or Parameter	Symbol	Value
Regional Fraction, Class D, Pathway (a)	$R_{D(a)}$	0.5
Regional Fraction, Class D, Pathway (b)	$R_{D(b)}$	0.5
Regional Fraction, Class D, Pathway (c)	$R_{D(c)}$	0.95
Regional Fraction, Class D, Pathway (d)	$R_{D(d)}$	0.05
Regional Fraction, Class D, Pathway (e)	$R_{D(e)}$	0.8
Regional Fraction, Class D, Pathway (f)	$R_{D(f)}$	NA
Regional Fraction, Class D, Pathway (g)	$R_{D(g)}$	NA
Regional Fraction, Class D, Pathway (h)	$R_{D(h)}$	0.2
Regional Fraction, Class D, Pathway (i)	$R_{D(i)}$	1.0
Regional Fraction, Class W, Pathway (a)	$R_{W(a)}$	0.1
Regional Fraction, Class W, Pathway (b)	$R_{W(b)}$	0.9
Regional Fraction, Class W, Pathway (c)	$R_{W(c)}$	0.5
Regional Fraction, Class W, Pathway (d)	$R_{W(d)}$	0.5
Regional Fraction, Class W, Pathway (e)	$R_{W(e)}$	0.15
Regional Fraction, Class W, Pathway (f)	$R_{W(f)}$	0.4
Regional Fraction, Class W, Pathway (g)	$R_{W(g)}$	0.4
Regional Fraction, Class W, Pathway (h)	$R_{W(h)}$	0.05
Regional Fraction, Class W, Pathway (i)	$R_{W(i)}$	1.0
Regional Fraction, Class Y, Pathway (a)	$R_{Y(a)}$	0.01
Regional Fraction, Class Y, Pathway (b)	$R_{Y(b)}$	0.99
Regional Fraction, Class Y, Pathway (c)	$R_{Y(c)}$	0.01
Regional Fraction, Class Y, Pathway (d)	$R_{Y(d)}$	0.99
Regional Fraction, Class Y, Pathway (e)	$R_{Y(e)}$	0.05
Regional Fraction, Class Y, Pathway (f)	$R_{Y(f)}$	0.4
Regional Fraction, Class Y, Pathway (g)	$R_{Y(g)}$	0.4
Regional Fraction, Class Y, Pathway (h)	$R_{Y(h)}$	0.15
Regional Fraction, Class Y, Pathway (i)	$R_{Y(i)}$	0.9

TABLE A-9 (Continued)

Constant or Parameter	Symbol	Value	
		1 μm	10 μm
Deposition Fraction, Nasopharyngeal Region	f_{NP}	0.3	0.9
Deposition Fraction, Tracheobronchial Region	f_{TB}	0.08	0.02
Deposition Fraction, Pulmonary Region	f_P	0.2	0.08
Fractional Uptake, Blood to Kidney	f_K	0.11	
Fractional Uptake, Blood to System	f_S	0.22	
Fractional Uptake, Lymph to Lymph Nodes	f_L	1.0	
Fractional Uptake, Class D, GI Tract to Blood	f_{1D}	0.05	
Fractional Uptake, Class W, GI Tract to Blood	f_{1W}	0.05	
Fractional Uptake, Class Y, GI Tract to Blood	f_{1Y}	0.002	
For High-Temperature-Dried (Composition Fractions)			
Yellowcake Fraction with Short Half-Life	F_1	0.17	
Yellowcake Fraction with Medium Half-Life	F_2	0.19	
Yellowcake Fraction with Long Half-Life	F_3	0.64	
For Low-Temperature-Dried (Composition Fractions)			
Yellowcake Fraction with Short Half-Life	F_1^{LT}	0.61	
Yellowcake Fraction with Medium Half-Life	F_2^{LT}	0.39	
Intake, Single Exposure	I		
Intake Rate, Continuous Exposure	I'		

TABLE A-9 (Continued)

	Eliminated From	By-Path(s)	TGLD Class	Half-Life (Days)	Elimination Constant	Value
A.	High-Temperature-Dried Yellowcake					
1.	P	(e)(h)	D	0.125	λ_{1P}	5.54
		(e)(h)	D	5.0	λ_{2P}	0.139
		(e)(h)(g)	Y	200	λ_{3P}	3.5×10^{-3}
		(f)	Y	1	$\lambda_{P(f)}$	0.693
2.	NP	(a)	D,Y	0.01	$\lambda^{D}_{NP(a)} = \lambda^{Y}_{NP(a)} = \lambda_{NP(a)}$	69.3
		(b)	D	0.01	$\lambda^{D}_{NP(b)} = \lambda_{NP(b)}$	69.3
		(b)	Y	0.40	$= \lambda^{Y}_{NP(b)}$	1.7
3.	TB	(c)	D,Y	0.01	$\lambda^{D}_{TB(c)} = \lambda^{Y}_{TB(c)} = \lambda_{TB(c)}$	69.3
		(d)	D,Y	0.2	$\lambda^{D}_{TB(d)} = \lambda^{Y}_{TB(d)} = \lambda_{TB(d)}$	3.47

TABLE A-9 (Continued)

	Eliminated from	By-Path(s)	TGLD Class	Half-Life (Days)	Elimination Constant	Value
B.	Low-Temperature-Dried Yellowcake					
1.	P	(e)(h)(g)	D	0.8	λ_{1P}^{LT}	0.87
		(e)(h)(g)	W	39	λ_{2P}^{LT}	0.018
		(f)	W	1	$\lambda_{P(f)}$	0.693
2.	NP	(a)	D,W	0.01	$\lambda_{NP(a)}^{D} = \lambda_{NP(a)}^{W} = \lambda_{NP(a)}$	69.3
		(b)	D	0.01	$\lambda_{NP(b)}^{D} = \lambda_{NP(b)}$	69.3
		(b)	W	0.4	$\lambda_{NP(b)}^{W} = \lambda_{NP(b)}^{Y}$	1.7
3.	TB	(c)	D,W	0.01	$\lambda_{TB(c)}^{D} = \lambda_{TB(c)}^{W} = \lambda_{TB(c)}$	69.3
		(d)	D,W	0.2	$\lambda_{TB(d)}^{D} = \lambda_{TB(d)}^{W} = \lambda_{TB(d)}$	3.47
C.	Ore Dust					
	P	(e)(h)(g)	W	50	$\lambda_{P(e)} = \lambda_{P(h)} = \lambda_{P(g)}$	0.014
		(f)	W	1	$\lambda_{P(f)}$	0.693
	NP	(a)	W	0.01	$\lambda_{NP(a)}$	69.3
		(b)	W	0.4	$\lambda_{NP(b)}$	1.7

TABLE A-9 (Continued)

	Eliminated from	By-Path(s)	TGLD Class	Half-Life (Days)	Elimination Constant	Value
	TB	(c)	W	0.01	$\lambda_{TB(c)}$	69.3
		(d)	W	0.2	$\lambda_{TB(d)}$	3.47

Note: The other elimination constants from lymph nodes (lung), kidney, and system are identical for yellowcake or ore dust; they are given below.

	Eliminated from	Half-Life (Days)	Elimination Constant	Value
D.	Lymph Nodes	0.5	λ_L^D	1.4
		50	λ_L^W	0.014
		1000	λ_L^Y	7×10^{-4}
E.	Body System	20	λ_{1S}	0.035
		5000	λ_{2S}	1.4×10^{-4}
F.	Kidney	15	λ_K	0.0462

TABLE A-10

Comparison of Model Parameters in This Study to ICRP-30 Parameters
(Values of the Elimination Constants are given in days^{-1})

Model Parameter	NRC Study Reference	Model Parameters Used for This Study	ICRP-30
First Day Excretion	Ref. A-8	0.67	---
Regional Fractions	TGLD*	Same as ICRP-30	See Table A-9
Deposition Fractions	TGLD	f_P = 0.20, 0.08	f_P = 0.25
Uptake Fractions			
Systemic	Ref. A-9	f_S = 0.22	f_S = 0.34**
Kidney		f_K = 0.11	f_K = 0.12
GI Tract		Same as ICRP-30	See Table A-9
Elimination Constants (Organs)			
Systemic	Ref. A-2	λ_{1S} = 0.693/20 ---	λ_{1S} = 0.693/20 λ_{2S} = 0.693/5000
Kidney	Ref. A-6	λ_K = 0.693/15 ---	λ_K = 0.693/6 and 0.693/1500
Lymph	TGLD	Same as ICRP-30	See Table A-9
Elimination Constants (Respiratory Tract)			
From Lung:	Refs. A-3, A-5, and A-10	λ_{1P} = 0.693/0.125	λ_D = 0.693/0.5
Yellowcake, High Temp.		λ_{2P} = 0.693/5.0 $\lambda_{P(g)} = \lambda_{3P}$ = 0.693/200	--- λ_Y = 0.693/500
Yellowcake, Low Temp.	Same as above	λ_{1P}^{LT} = 0.693/0.8 λ_{2P}^{LT} = 0.693/39	λ_D = 0.693/0.5 λ_W = 0.693/50
Ore Dust	TGLD, Ref. A-3	Same as ICRP-30	
From NP Region	TGLD	Same as ICRP-30	
From TB Region	TGLD	Same as ICRP-30	

*Task Group on Lung Dynamics.

**For this study, the system is defined as all tissues other than kidney, and f_S = 0.22. Note that f_K is assumed to be 0.11 so that the total uptake fraction is 0.33. The systemic uptake fraction in ICRP-30 includes uptake by bone, 0.22, and by all other soft tissues (excluding the kidneys), 0.12.

REFERENCES FOR APPENDIX A

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A-4. Inhalation Toxicology Research Institute, Lovelace Biomedical and Environmental Research Institute, "Biological Characterization of Radiation Exposure and Dose Estimates for Inhaled Uranium Milling Effluents," USNRC Reports NUREG/CR-2832, December 1982, and NUREG/CR-3745, May 1984.

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A-8. P.E. Morrow et al., "Metabolic Fate and Evaluation of Injury in Rats and Dogs Following Exposure to the Hydrolysis Products of Uranium Hexafluoride," Department of Radiation Biology and Biophysics, University of Rochester, USNRC Report NUREG/CR-2268, December 1982.

A-9. International Commission on Radiological Protection (ICRP), "Supplement to the Report of Committee II on Permissible Dose for Internal Radiation," ICRP-6, 1964.

A-10. A.F. Eidson and J.A. Mewhinney, "In Vitro Dissolution of Uranium Product Samples from Four Uranium Mills," Lovelace Biomedical and Environmental Research Institute, USNRC Report NUREG/CR-0414, 1978.

APPENDIX B
COMPUTER PROGRAM UMIBIO DEVELOPED FOR NUREG-0874

The computer program UMIBIO (Uranium Mill Bioassay) calculates the burden of uranium in selected organs (K,S,P) and the urinary uranium concentration (X_T) at selected times following exposure, then plots these as a function of time using the proprietary software package, DISSPLA (Ref. B-1).

The program was written in FORTRAN 77 for an IBM 3081 computer and is modular in structure. The main program uses DATA statements to assign numerical values from Table A-9 to the constants and variables used in the calculations, including default values for some of the input variables. It then reads the input data according to the format shown in Table B-1. Calculations of the burdens of uranium in organs or in urine at various times following exposure are carried out by subroutine functions named for the equation types discussed in Section A.1 of Appendix A. Subroutine DISPLT generates the graphics output from these values.

Several adjustments to the program were necessary to prevent overflow, underflow, or division by zero. Division by zero can occur when any two elimination constants are assigned the same numerical value. To avoid this problem, the program automatically increments one of the constants by a small number, e, and proceeds with the calculations. For example, if

$$\lambda_1 = \lambda_2, \text{ set } \lambda_1 = (1 + e)\lambda_1$$

(e = 0.00027, an arbitrary value)

The error in such estimates is comparable to the size of 'e' (Refs. B-2 and B-3). Underflow or overflow, which can occur in the subroutine calculations involving exponential terms, is avoided by limiting values of λt to the largest (10^{88}) or smallest (10^{-87}) values handled by the IBM computer.

Input Description

The input required for UMIBIO is shown in Table B-1.

Record 1 is used to indicate whether the user wants to execute the program using the default values for the intakes (I or I') or to provide different values on the next input record.

Record 2 is included only if the value of ICHK on record 1 was "1." It contains user-specified uranium intake values.

Record 3 is used to indicate whether the user wants to execute the program using the default values for the composition fractions or to provide different values on the next record.

Record 4 is included only if the value of JCHK on record 3 was 1. It contains user-specified composition fractions.

Record 5 is used to choose the exposure type (single or continuous) and the number of exponential terms (one or two) to be used in calculating the systemic burdens.

Output Description

The figures used in this document were generated from this program. In addition to the graphics output, this program also generates a printed output (see sample portion of output at the end of this section). The complete printed output (not shown here) includes additional tables listing the accumulated uranium burdens for the system, kidney, and urine. The tables in the output entitled BURDEN COMPONENT list that part of the total uranium accumulated in an organ that is contributed by one of the metabolic pathways leading to the organ from the respiratory tract. For example, in the sample output (Table B-2), the listings under BURDEN COMPONENT # 1 correspond to the contributions of uranium (Class D) to the pulmonary lung due to the first entry, $P_{(e)}^{1P}$, in Table A-8 of Appendix A.

Computer Code Availability

Information regarding the availability of the computer program UMIBIO associated with this NUREG report is available from:

U.S. Nuclear Regulatory Commission
Information Technology Services Support Center
Mail Stop P-808
Washington, DC 20555
Telephone: (301)492-4160 or FTS 492-4160

TABLE B-1

UMIBIO Input Description

	COLUMNS	VARIABLE NAME	FORMAT	DESCRIPTION	DEFAULT VALUE
Record 1	1	ICHK	I1	0 = Use default intake values 1 = Next card contains new I values	N/A
Record 2	(include only if Card 1 contains a "1")				
	1-8	IDEF(1)	I8	Single intake for Yellowcake (HTD)	160,000
	9-16	IDEF(2)	I8	Single intake for Yellowcake (LTD)	260,000
	17-24	IDEF(3)	I8	Single intake for Ore Dust (1 AMAD)	46,000
	25-32	IDEF(4)	I8	Single intake for Ore Dust (10 AMAD)	80,000
	33-40	IDEF(5)	I8	Continuous intake for Yellowcake (HTD)	626
	41-48	IDEF(6)	I8	Continuous intake for Yellowcake (LTD)	1,094
	49-56	IDEF(7)	I8	Continuous intake for Ore Dust (1 AMAD)	182
	57-64	IDEF(8)	I8	Continuous intake for Ore Dust (10 AMAD)	320
Record 3	1	JCHK	I1	0 = Use default F1, F2, F3, FLT1, FLT2 values for composition fractions 1 = Next card will contain new F1, F2, F3, FLT1, FLT2 values	N/A
Record 4	(include only if Card 3 contains "1")				
	1-10	F1	F10.3	New F1 value for Yellowcake (HTD)	0.17
	11-20	F2	F10.3	New F2 value for Yellowcake (HTD)	0.19
	21-30	FLT1	F10.3	New F3 value for Yellowcake (HTD)	0.64
	31-40	FLT2	F10.3	New FLT1 value for Yellowcake (LTD)	0.61
	41-50	FLT3	F10.3	New FLT2 value for Yellowcake (LTD)	0.39
Record 5	1	IEXP	I1	1 = Single exposure 2 = Continuous exposure	N/A
	2	INEXP	I1	1 = One exponential term 2 = Two exponential terms	N/A

TABLE B-2

SAMPLE OF PRINTED OUTPUT

QUANTITY OF NATURAL URANIUM ACCUMULATED IN THE PULMONARY
PER UNIT INTAKE RATE - 626 ug U/d OF URANIUM
FROM A CONTINUOUS INHALATION EXPOSURE
TO PARTICLES OF YELLOWCAKE (HIGH TEMPERATURE DRIED)

TIME (DAYS) POST EXPOSURE	P(T) ug U INHALED	P/I(T) ug U PER ug U/d INHALED
1	97.1499	0.1552
3	246.1379	0.3932
10	651.0092	1.0400
30	1587.7492	2.5363
100	4277.7002	6.8334
300	9150.6322	14.6176
1000	13542.6589	21.6336
3000	13957.0788	22.2957
10000	13957.4571	22.2963
18263	13957.4571	22.2963
30000	13957.4571	22.2963
40000	13957.4571	22.2963
50000	13957.4571	22.2963

BURDEN COMPONENT # 1

3.0614	FOR TIME	1	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	3	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	10	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	30	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	100	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	300	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	1000	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	3000	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	10000	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	18263	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	30000	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	40000	DAYS -	POST	EXPOSURE
3.0735	FOR TIME	50000	DAYS -	POST	EXPOSURE

BURDEN COMPONENT # 2

17.7670	FOR TIME	1	DAYS -	POST	EXPOSURE
46.6832	FOR TIME	3	DAYS -	POST	EXPOSURE
102.8086	FOR TIME	10	DAYS -	POST	EXPOSURE
134.7938	FOR TIME	30	DAYS -	POST	EXPOSURE
136.9092	FOR TIME	100	DAYS -	POST	EXPOSURE
136.9094	FOR TIME	300	DAYS -	POST	EXPOSURE
136.9094	FOR TIME	1000	DAYS -	POST	EXPOSURE
136.9094	FOR TIME	3000	DAYS -	POST	EXPOSURE
136.9094	FOR TIME	10000	DAYS -	POST	EXPOSURE
136.9094	FOR TIME	18263	DAYS -	POST	EXPOSURE
136.9094	FOR TIME	30000	DAYS -	POST	EXPOSURE
136.9094	FOR TIME	40000	DAYS -	POST	EXPOSURE
136.9094	FOR TIME	50000	DAYS -	POST	EXPOSURE

REFERENCES FOR APPENDIX B

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APPENDIX C
STANDARDS FOR OCCUPATIONAL EXPOSURE

This appendix provides the detailed methodology used to calculate the radiological intake criteria for yellowcake and ore dust tabulated in Chapter 3 of this study and used to calculate the urinary uranium concentration as a function of time in subsequent chapters. The first part of this appendix explains the methodology for calculating the annual limit on intake (ALI) of a radionuclide as recommended in ICRP-30. The second part illustrates how these methods of ICRP-30 are used in this study to calculate the intake values listed in Chapter 3.

C.1 CALCULATION OF INTAKE VALUES ACCORDING TO ICRP-30

C.1.1 Calculation of ALI and Derived Air Concentration (DAC) Values

The ALI is defined in Section 4.7 of ICRP-30 as the greatest intake value that still satisfies both of the following expressions:

$$\text{ALI } \Sigma w_T(H_{50,T} \text{ per unit intake}) \leq 5 \text{ rems} \qquad \text{(C-1)}$$

$$\text{ALI}(H_{50,T} \text{ per unit intake}) \leq 50 \text{ rems} \qquad \text{(C-2)}$$

where

T = Tissue irradiated

$H_{50,T}$ = Dose equivalent (in rems) delivered to tissue (T) over a period of 50 years following exposure from all radiations originating in any source organ (S). $H_{50,T}$ per unit intake has dimensions of rem per μCi of nuclide inhaled.

w_T = Weighting factor used in ICRP-30. These factors weight each organ dose according to the organ's susceptibility. The sum of the weighted doses is called the effective dose equivalent (in rems).

An intake of radioactive material into the body is limited by Equation C-1 unless Equation C-2 overrides it because of the possibility of nonstochastic effects.

The DAC value for a radionuclide is related to the ALI by the following expression:

$$DAC = \frac{ALI\ (\mu Ci\ \text{inhaled per year})}{40\ \frac{hr}{wk} \times 50\ \frac{wk}{yr} \times 60\ \frac{min}{hr} \times 2 \times 10^4\ \frac{cc}{min}} \qquad (C\text{-}3)$$

In this report, DAC values are given in units of μCi/cc.

C.1.2 Calculation of Values for Dose Conversion Factors

The values of the committed dose equivalent, $H_{50,T}$, which are substituted into Equations C-1 and C-2 in order to calculate the ALI, are obtained from two sources. For lung, factors were calculated from values computed especially for this report by the Metabolism and Dosimetry Group, Biomedical Effects and Instrumentation Section, Health and Safety Research Division of the Oak Ridge National Laboratory, Oak Ridge, Tennessee.* These calculations for lung were necessary because the retention times and the lung deposition fraction for uranium in the pulmonary lung adopted in this study differed from those assumed in the ICRP-30 study (see Section A.2.4 of Appendix A for a discussion of these differences). For kidney and bone, factors were calculated from the data given in the supplement to Part 1 of ICRP-30. Since values of the committed dose equivalent in target organs per unit intake of uranium isotopes (Solubility Classes W and Y) are not explicitly listed for kidney and bone in the supplement, they were calculated for this study from the product of the number of transformations in the

*The ICRP code was used to perform dosimetric calculations. This code is described in Reference C-1.

source organs over a 50-year period, the specific effective energy (MeV per gram per transformation), and appropriate conversion factors. Because the supplement to Part 1 of ICRP-30 does not list dose conversion factors for uranium burdens in the other organs, the only organs considered in Equations C-1 and C-2 were lung, kidney, and bone. To simplify the calculations of dose conversion factors for natural uranium, this study assumed that half of the transformations in an organ are due to U-238 and the remainder to U-234. In order to approximate those transformations due to U-235 and its daughters, the values of the dose conversion factors in Table C-1 calculated on this basis were increased by 5 percent for kidney and bone. Values of dose conversion factors used in this study are listed in Tables C-1, C-2, and C-3.

TABLE C-1

$H_{50,T}$ per Unit Intake (rem/μCi) of Uranium Inhaled
(Body Organs Other Than Lung)

Radioactive Material	Class	Kidney	Bone Surface	Bone Marrow
	Basis: 1-μm-AMAD Ore-Dust Particles			
U-238	D	14.8	36.3	2.4
	W	4.5	7.0	-
	Y	1.6	-	-
U-234	D	16.7	40.7	2.6
	W	4.9	7.5	-
	Y	1.8	-	-
Natural Uranium	D	16.5	40.4	2.5
	W	4.9	7.6	-
	Y	1.8	-	-

TABLE C-2

$H_{50,T}$ per Unit Intake (rem/μCi) of Natural Uranium and Radionuclides in Secular Equilibrium with Uranium in Ore Dust*

Radioactive Material	Class	Lung	Kidney	Bone Surface	Bone Marrow
	Basis: 1-μm-AMAD Ore-Dust Particles				
U-Nat**	W	46	4.9	7.6	-
Th-230	Y	1110	-	3219	259
Ra-226	W	59	-	28	-
Po-210	W	48	14.4	-	-
	Basis: 10-μm-AMAD Ore-Dust Particles				
U-Nat***	W	18	6	9.4	-
Th-230	Y	444	-	1780	143
Ra-226	W	24	-	38	-
Po-210	W	19	19	-	-

*The solubility classification for oxides or hydroxides in ICRP-30 was selected in determining these values.

**Values are taken from Tables C-1 and C-3.

***Calculated from the values of the dose conversion factors at 1-μm AMAD using the method for conversion to the values at 10-μm AMAD given in Section 5.5 of ICRP-30.

TABLE C-3

Committed Dose Equivalent to Lung per Unit Intake of Natural Uranium (rem/μCi U Inhaled)

TGLD Class	Biological Half-Life(d) *	H_{50}, Lung Nat. Uranium **	Fraction U in This Class (μCi)	Lung Dose (rem/μCi)
		Yellowcake Dried at High Temperature		
D	0.13	0.38	0.17	0.07
D	5	6.94	0.19	1.32
Y	200	598	0.64	382.7
			Sum: 1.00	384.0
		Yellowcake Dried at Low Temperature		
D	0.8	1.29	0.61	0.79
W	39	35.8	0.39	13.96
			Sum: 1.00	15.00
		Ore Dust		
		Basis: 1-μm-AMAD Particles		
W	50	46.4	1.00	46
		Basis: 10-μm-AMAD Particles		
W	50	18.6	1.00	18

* Values taken from References C-2, C-3, and C-4.

**The ICRP code was used to perform dosimetric calculations. This code is described in Reference C-1. Dose conversion factors obtained from ORNL were multiplied by the ratio 0.20/0.25 to correct for differences in lung deposition fractions in the ICRP-30 model and the NRC model.

The way in which the dose conversion factors given in Table C-1 are used in this report can be illustrated by a sample calculation. For example, the dose to kidney due to the inhalation of one microcurie of the natural uranium contained within dust particles of yellowcake dried at high temperature (size distribution 1-μm AMAD) is calculated as

Composition Fractions from Table A-9			Dose Conversion Factors from Table C-1			Kidney Dose (rems)
Class D:	0.17	x	16.5 rem/μCi Natural Uranium	=		2.8
Class D:	0.19	x	16.5 rem/μCi Natural Uranium	=		3.1
Class Y:	0.64	x	1.8 rem/μCi Natural Uranium	=		1.2
Sum:	1.00 μCi of Natural Uranium gives					7.1 rems to kidney

Doses to other organs may also be calculated from the product of the composition fraction of the material in each solubility class (Table A-9) and the dose conversion factor for that solubility class.

Values of the dose conversion factor per unit intake of the radionuclides found in ore dust are summarized in Table C-2. The factors for Th-230, Ra-226, and Po-210 were taken directly from the supplement to Part I of ICRP-30. The values of the dose conversion factors at 10-μm AMAD in Table C-2 were calculated from the values given at 1-μm AMAD using the method given in Section 5.5 of ICRP-30. For example, to calculate the bone surface dose per unit intake of natural uranium that is contained in 10-μm-AMAD ore-dust particles, the following formula given in Section 5.5 Of ICRP-30 was used:

$$\frac{H_{50}(10\ \mu m)}{H_{50}(1\ \mu m)} = X_{NP} \times \frac{f_{NP}^{10}}{f_{NP}^{1}} + X_{TB} \times \frac{f_{TB}^{10}}{f_{TB}^{1}} + X_{P} \times \frac{f_{P}^{10}}{f_{P}^{1}}$$

where

X = fraction of committed dose equivalent in reference tissue (T) resulting from deposition in the NP, TB, or P regions of the respiratory tract.

The following quantities are needed to solve this equation for H_{50} (10 μm):

Quantity Required	Quantity is Found in
H_{50}(1-μm AMAD) = 7.6 rem/μCi U inhaled	Table C-1 of this study
$X_{NP}/X_{TB}/X_P$ = 0.33/0.16/0.51	Supplement 1 to ICRP-30
f_{NP}^{10}/f_{NP}^{1} = 0.9/0.3 = 3	Table A-9 of this study
f_{TB}^{10}/f_{TB}^{1} = 0.02/0.08 = 0.25	Table A-9 of this study
f_{P}^{10}/f_{P}^{1} = 0.08/0.20 = 0.4	Table A-9 of this study

Substituting these quantities into the ICRP-30 equation above,

H_{50}(10-μm AMAD) = [0.33(3) + 0.16(0.25) + 0.51(0.4)] 7.6 rem/μCi U*

= 1.23 x 7.6 = 9.4 rem/μCi U inhaled.

This value is listed in column 5 of Table C-2 under the heading of bone surface; it applies to a 10-μm-AMAD particle size of ore dust.

C.2 CALCULATION OF INTAKE VALUES FOR THIS STUDY

C.2.1 Yellowcake Dried at High Temperature

C.2.1.1 Calculation of ALI Value

To calculate the ALI_s that is limited by stochastic health effects,

a. Substitute numerical values for the parameters in Equation C-1:

- For w_T, substitute the values given in ICRP-30;

*This is the bone surface dose (from Table C-2) due to inhalation of 1 μCi of uranium in 1-μm-AMAD ore-dust particles.

- For the lung, substitute the dose conversion factor, H_L, taken directly from Table C-3;

- For the kidney and bone surfaces, substitute H_K and H_B, values of the committed dose equivalent for yellowcake calculated from the dose conversion factors given in Table C-1.

- For these substitutions, Equation C-1 is rewritten:

$$ALI_s[w_L H_L + w_K H_K + w_B H_B] = 5 \text{ rems} \qquad \text{(C-1)}$$

or

$$ALI_s[0.12(384) + 0.06(7.1) + 0.03(15.3)] = 5 \text{ rems} \qquad \text{(C-4)}$$

b. Solve Equation C-1 for ALI_s, which equals 0.106 μCi U/yr when stochastic effects limit the intake.

To calculate the ALI_{ns} that is limited by nonstochastic effects,

a. Substitute numerical values for the parameters in Equation C-2; use the same numerical values of H_L, H_K, and H_B that were used in Equation C-4.

b. Solve substituted Equation C-2 (repeated below) for the intake, ALI_{ns}. The ALI_{ns} values calculated in this way are tabulated below for those organs considered in ICRP-30.

$$ALI_{ns} = \frac{50 \text{ rems}}{H_{50,T} \text{ rem/μCi U inhaled}} \qquad \text{(C-2)}$$

ORGAN	$H_{50,T}$ rem/μCi	ALI_{ns} μCi U
Lung	384	0.130
Kidney	7.1	7.0
Bone	15.3	3.3

The ALI for a radionuclide is the largest value of intake that will satisfy both Equations C-1 and C-2. Select the largest value of intake above,

either an ALI_{ns} value or the ALI_s value that satisfies both Equations C-1 and C-2. Only one of the four values above meets this criterion, the ALI_s value of 0.106 μCi U/yr. This is the ALI selected in this study for yellowcake dried at high temperature.

C.2.1.2 Calculation of DAC Value

The DAC is obtained from the ALI_s value simply by dividing the quantity of air inhaled by a worker during a 250-day workyear, i.e., by 2.4 X 10^9 cc/yr, (ICRP-30) or

$$DAC = \frac{ALI\ (\mu Ci\ U/yr)}{2.4 \times 10^9\ (cc/yr)} \qquad (C\text{-}5)$$

$$= 0.106/2.4 \times 10^9$$

$$= 4.4 \times 10^{-11}\ \mu Ci\ U/cc$$

C.2.2 Yellowcake Dried at Low Temperature

C.2.2.1 Calculation of ALI Value

The ALI value for yellowcake dried at low temperature can be calculated in the same manner as was illustrated for yellowcake dried at high temperature. When the proper dose conversion factors and w_T values are substituted into Equations C-1 and C-2, it can be shown that the annual intake is limited to 1.81 μCi U by nonstochastic health effects that could be produced in bone surfaces.

$$ALI_{ns} = \frac{50\ rems}{27.6\ bone\ rem/\mu Ci} = 1.81\ \mu Ci\ U/yr$$

To exceed this intake value would increase the risk of health effects because of irradiation of the bone surfaces to a level considered unacceptable by the ICRP. On the other hand, it was shown in Section 3.1 of Chapter 3 that if the annual intake of uranium exceeds 0.185 μCi U (1094 μg U/d), nephrotoxic effects could occur. Consequently, for this study, the smaller value of 0.185 μCi U/yr is selected as the ALI for yellowcake dried at low temperature.

C.2.2.2 Calculation of DAC Value

The DAC value is calculated from the smaller ALI value above as

$$DAC = \frac{0.185\ \mu Ci\ U/yr}{2.4 \times 10^{9}\ cc/yr}$$

$$= 7.7 \times 10^{-11}\ \mu Ci\ U/cc$$

C.2.3 Ore Dust - 10-μm AMAD

C.2.3.1 Calculation of ALI Value

In order to calculate the ALI value for ore dust, it is first necessary to make several assumptions about the physical and chemical composition of the mixture of airborne radionuclides inhaled by a worker. For this study, it was assumed that uranium and its daughters that are contained in ore-dust particles are in secular equilibrium and that no Rn-222 escapes from these particles (Ref. C-5). In addition, each radionuclide in the ore dust was assumed to be in the chemical form of insoluble oxides (or hydroxides). The solubility classes of these oxides (or hydroxides) were taken to be those given in ICRP-30, i.e.,

Radioactive Material	Solubility Class
Uranium (natural)	W
Th-230	Y
Ra-226	W*
Po-210	W*

*No ALI value for Class Y is given in ICRP-30 for these radionuclides.

The following approach was adopted in this study for calculation of the ALI for ore dust. First, the ALI values for each nuclide are calculated separately. Then, using the method of the harmonic mean, these individual ALI values are combined into the ALI of the mixture. This ALI value of the mixture is used in conjunction with the internal dosimetry model to predict the urinary uranium concentrations given in Chapters 4 and 5 of this study.

The calculation of the ALI value for each radionuclide in ore dust is executed in the same manner as in the preceding calculations for yellowcake dried at either high or low temperatures. For the nuclides U-238, U-234, Ra-226, and Po-210, the intake must be controlled so as to limit stochastic health effects in body tissues. The ALI values are obtained by substitution of the dose conversion factors from Table C-2 and the w_T values from Equation C-4. Solving Equations C-1 and C-2 for the ALI when an ore dust of 10-μm-AMAD particle size is inhaled gives the following ALI values:

For Natural Uranium

$$ALI_{U,s}[0.12(18) + 0.06(6) + 0.03(9.4)] = 5 \text{ rems} \quad \text{(C-6)}$$

$$ALI_{U,s} = 1.79 \text{ μCi U}$$

$$ALI_{U,ns} = 50 \text{ rems}/18 \text{ lung rems}/\mu\text{Ci U} = 2.78 \text{ μCi U}$$

For Ra-226

$$ALI_{Ra,s}[0.12(24) + 0 + 0.03(38)] = 5 \text{ rems} \quad \text{(C-7)}$$

$$ALI_{Ra,s} = 1.24 \text{ μCi Ra}$$

$$ALI_{Ra,ns} = 50 \text{ rems}/38 \text{ lung rems}/\mu\text{Ci Ra} = 1.32 \text{ μCi Ra}$$

For Po-210

$$ALI_{Po,s}[0.12(19) + 0.06(19) + 0] = 5 \text{ rems} \quad \text{(C-8)}$$

$$ALI_{Po,s} = 1.46 \text{ μCi Po}$$

$$ALI_{Po,ns} = 50 \text{ rems}/19 \text{ lung rems}/\mu\text{Ci Po} = 2.63 \text{ μCi Po}$$

For Th-230

$$ALI_{Th,s}[0.12(444) + 0 + 0.03(1780) + 0.12(143)] = 5 \text{ rems} \quad \text{(C-9)}$$

$$ALI_{Th,s} = 0.040 \text{ μCi Th}$$

$$ALI_{Th,ns} = 50 \text{ rems}/1780 \text{ bone surface rems}/\mu\text{Ci Th} = 0.028 \text{ μCi Th}$$

The value selected for this study as the ALI for thorium is 0.028 μCi Th. If the larger value of intake were selected, the dose to the bone surfaces

would exceed 50 rems. However, in a calculation of the ALI for a mixture of nuclides, it is necessary to use ALIs all based on stochastic effects or all based on nonstochastic effects. Therefore, a value for Th-230 of 0.04 μCi is also used below.

The calculation of the ALI for a mixture of these radionuclides, each in secular equilibrium with the others, is performed by the method of the harmonic mean, i.e.,

$$\frac{1}{ALI_{mix}} = \frac{f_U}{ALI_U} + \frac{f_{Ra}}{ALI_{Ra}} + \frac{f_{Po}}{ALI_{Po}} + \frac{f_{Th}}{ALI_{Th}} \qquad \text{(C-10)}$$

where

f_X = fraction of the radioactivity in the form of nuclide X

Beta- or gamma-emitting radionuclides in secular equilibrium with the uranium in ore dust will make insignificant contributions to the sum of terms on the right-hand side of Equation C-10 because their ALI values are large in comparison to those calculated for the alpha-emitting radionuclides. When the appropriate ALI values from Equations C-6, C-7, C-8, and C-9 are substituted into Equation C-10, two ALI_{mix} values can be calculated.

For Stochastic Health Effects

$$\frac{1}{ALI^s_{mix}} = \frac{0.4}{1.79} + \frac{0.2}{1.24} + \frac{0.2}{1.46} + \frac{0.2}{0.04}$$

ALI^s_{mix} = 0.181 μCi (alpha) of ore-dust mixture

For Nonstochastic Health Effects

$$\frac{1}{ALI^{ns}_{mix}} = \frac{0.4}{2.78} + \frac{0.2}{1.32} + \frac{0.2}{2.63} + \frac{0.2}{0.028}$$

ALI^{ns}_{mix} = 0.133 μCi (alpha) of ore-dust mixture

Thus, it is evident that the ALI for the mixture is 0.133 μCi (alpha) of ore-dust mixture. This value agrees rather well with the ALI value calculated by the Atomic Energy of Canada Limited (Ref. C-6).

C.2.3.2 Calculation of DAC Value

The nonstochastic ALI value for the ore-dust mixture is used for calculating the DAC value of ore dust.

$$\text{DAC (mixture)} = \frac{0.133\ \mu\text{Ci (alpha)/yr of ore-dust mixture}}{2.4 \times 10^{9}\ \text{cc/yr air breathed}}$$

$$= 5.5 \times 10^{-11}\ \mu\text{Ci alpha/cc of ore-dust mixture}$$

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The internal dosimetry model developed in this study is useful for estimation of the urinary concentration of natural uranium excreted at various times after an inhalation exposure to yellowcake or to ore dust. According to this internal dosimetry model, the time interval between collections of bioassay samples following an inhalation exposure to airborne yellowcake (dried at high or low temperature) or to ore dust should be less than 40 days. In vivo thorax scanning techniques are shown to be sufficiently sensitive to confirm overexposures to natural uranium inhaled in yellowcake dried at high temperature, but not to yellowcake dried at low temperature or to ore dust. New experimental data, which illustrate the dependence of lung solubility on the thermal history of the inhaled yellowcake, are incorporated into the model. This study employs the Task Group Lung Model to represent the deposition of uranium into the respiratory tract and its clearance into the blood. The dosimetric model adopted in this study is that proposed by the International Commission for Radiological Protection in Publication 30.

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