APPENDIX J - Discussion of the Respiratory Tract Models, Computer Dosimetry Models and Uranium Transport Through the Kidney

J.1 Introduction

Material may enter the body through inhalation, ingestion, absorption through a wound in the skin, and fragment impaction (injection). Inhalation is one of the more important routes of exposure for intake of DU on the battlefield.

The behavior of inhaled DU particles in the respiratory tract and their alternative fates of either deposition in the various regions of the respiratory tract or exhalation depends upon the chemical composition and the physical behavior of the aerosol particles under the specific physiological and anatomical conditions of the exposed individual.

For purposes of health protection reasonable predictions are made using available biokinetic and mathematical models and data employing certain simplifying assumptions concerning biological and physical factors associated with the exposed individual and the aerosol particles.

The radiological dose calculations were performed using LUDEP Ver. 2.06. The ICRP-66 respiratory tract model was used in this dose assessment. The ICRP-30 biokinetic model was used in this dose assessment. The ICRP-69 biokinetic model would result in about a 1 percent increase in the dose. The ICRP-30 models were used to estimate the DU concentration in the kidney.

J.2 Natural Uranium Balance in Man

Uranium is present in trace quantities throughout the environment. As a result, man ingests about 2 μg of U_{Nat} each day in foodstuffs and fluids. A similar quantity is excreted each day in the feces and urine. The uranium balance for Reference Man is as follows (ICRP-23):

Intake:

Food and fluids:	1.9 μg/d
Inhalation:	7×10^{-3} μg/d

Losses:

Feces:	1.4 μg/d - 1.8 μg/d
Urine:	0.05 μg/d - 0.5 μg/d
Other (hair):	0.02 μg/d

The range of intake and losses has been observed to vary over several orders of magnitude, depending upon the uranium concentration in foods and in the water supply.

J.3 Respiratory Tract Models

In 1959, the ICRP published ICRP-2, Permissible Dose for Internal Radiation. The respiratory tract model used was very simple. In 1966, the ICRP Task Group on Lung Dynamics published their report on deposition and retention models for dosimetry of the human respiratory tract (Health Physics, Volume 12, No. 2, 1966). This model improved the ICRP-2 model.

In 1979, the ICRP published ICRP-30. The models contained in ICRP-30 form the bases for the radiation protection guidance to Federal agencies (52 FR 2822) and are implemented by the NRC standards in 10 CFR Part 20. The ICRP-30 respiratory tract model improved the ICRP-2 and the Task Group on Lung Dynamics' models.

In 1994, the ICRP published ICRP-66 that greatly improved the ICRP-30 model.

Air is taken into the respiratory tract through the nose and mouth. The ICRP-30 respiratory tract model may be broken into two functional parts: (1) inhalation and deposition of material into the three respiratory tract regions (N-P, T-B and P), and (2) retention and translocation of material by each of the compartments of the respiratory tract. Major anatomical structures are identified for the upper and lower portions of the respiratory tract as follows.

J.3.1 Upper Respiratory Tract

- Nose/Mouth
- Pharnyx
- Trachea
- Bronchi
- Bronchioles
- Terminal Bronchioles

J.3.2 Lower (Deep) Respiratory Tract

- Alveoli
- Alveolar Ducts
- Alveolar Sacs

J.3.3 Deposition

Inhaled particles are deposited in the respiratory tract as a result of physical and chemical properties of the particles and anatomical and physiological factors of the individual. Aerodynamic size, solubility, surface area, particle shape, hydroscopicity, intercrystalline forces, and electrical charges are important physical characteristics of particles that influence deposition patterns in the respiratory tract. Physical factors determine the extent to which

sedimentation, impaction, diffusion, interception, and electrostatic precipitation cause inhaled particles to be deposited in the respiratory tract.

According to the ICRP-30 model, the initial deposition of material into either the N-P, T-B, or P regions of the respiratory tract is a function of the particle size distribution of the inhaled material. This particle size distribution is represented by an AMAD, expressed in μ or μm. The ICRP-30 respiratory tract model assumes that the material inhaled is in the form of a lognormally distributed aerosol with an AMAD of 1 μm and a σ_g of less than 4.5 μm, unless specific information is available.

When a 1 μm AMAD aerosol is assumed, then penetration to the deep lung occurs and there will be an increase in the fractional deposition in the P region. Insoluble DU particles deposited in the respiratory bronchioles and alveoli will be cleared much more slowly, and, therefore, would be expected to deliver a higher radiation dose to the lung from alpha radiation. The use of a 5 μm AMAD aerosol implies increased thoracic (T-B) deposition and decreased fractional deposition in the deep lung. The choice of the 5 μm AMAD aerosol may not be conservative for considerations of either chemical toxicity or radiological dose to the respiratory tract for particle distribution less than 0.2 μm AMAD. (See Tables J-7 through J-18 for DCFs for 1 μm and 5 μm aerosols.) The 5 μm AMAD aerosol will deposit more mass in the ciliated airways of the T-B region of the respiratory tract, where they will be rapidly cleared from the respiratory tract by the mucociliary ladder and swallowed, leading to indirect ingestion exposure via the GI tract.

For mouth breathing at a BR (or ventilation rate) of 1.8 m^3/hr (30 L/min), approximately 20 percent of 5 μm AED particles and 70 percent of 10 μm AED particles are deposited before the inspired air reaches the larynx located in the N-P region. For nose breathing at a BR (or ventilation rate) of 1.8 m^3/hr, 70 percent of 5 μm AED particles and 100 percent of 10 μm AED particles are trapped in the nose (located in the N-P region). For both mouth and nose breathing, the number of particles deposited in the head (N-P) region increase when the average BR (or ventilation rate) increases. The particle size having the greater deposition in the alveolar (P) region during mouth breathing is about 3 μm AED, with about 50 percent of these particles being captured in the alveolar (P) region. During nose breathing, size of the particle for maximum deposition is reduced to about 2.5 μm AED, with about 25 percent of the particles being retained in the respiratory tract.

Because of particle size and selective deposition in the T-B region, particles greater than 10 μm AED generally do not reach the alveolar (P) region, and particles in the 2 μm to 10 μm AED range will reach the alveolar (P) region in reduced numbers. Deposition in the alveolar (P) region depends on particle size, BR (or ventilation rate), and tidal volume.

The major differences in the deposition of DU particles occur between nose breathing and mouth breathing. When DU aerosols are inhaled through the nose, the relatively efficient filtration action of the N-P region prevents the passage of particles with an AED larger than 10 μm to the lung. This action markedly limits the P region deposition of particles between

2-μm and 10-μm AED. An active person breathing at 15 breaths per minute with a tidal volume of 1.45 L would be expected to deposit in the deep lung about 35 percent, 25 percent, 10 percent, and essentially 0 percent of inhaled particles with an AED equal to 0.2 μm, 1 μm, 5 μm, and 10 μm, respectively, during nasal breathing. Deposition in the T-B region would be expected to be about 2 percent, 3 percent, 6 percent and 0 percent, respectively, for these same particle sizes.

Mouth breathing markedly alters the deposition of inhaled particles in humans, in that larger particles can enter both the T-B region and the P region. The deposition in the deep lung would be expected to increase to about 35 percent, 30 percent, 55 percent, and 10 percent, respectively, for inhaled particles with an AED equal to 0.2 μm, 1 μm, 5 μm and 10 μm for a reference worker breathing via mouth at 15 breaths per minute, with a tidal volume of 1.45 L.

When the BR (or ventilation rate) increases to > 2 m^3/hr, healthy military personnel may switch to oro-nasal breathing; therefore, it may be unrealistic to consider an individual to be a pure nose or mouth breather.

The IAEA in its Technical Report Series Publication No. 142 provides regional deposition estimates for monodispersed particles. These can be applied when the aerosol is not lognormally distributed and the particle size distribution is known.

J.3.4 Clearance

Two competing mechanisms, physical clearance and dissolution-absorption, are responsible for the removal of deposited particles or their constituents from all regions of the respiratory tract. Physical clearance may involve particles that have been phagocytized by macrophages. Particles that deposit on the mucous lining of the conducting airways can be rapidly cleared from the respiratory tract as a result of ciliary action that moves the mucous to the oropharynx to be swallowed. (This is known as indirect ingestion.)

It is important to distinguish between dissolution and absorption in the respiratory tract. Dissolution includes the net result of processes in cells and body fluids that cause constituents of particles to dissociate. Constituents of particles may leach from the particles. As a result of dissolution or leaching, constituents of the particles are available for absorption into the lymphatic or circulatory systems, for metabolism or for chemical reactions with or absorption into tissue constituents.

The apparent dissolution of small particles in the respiratory tract depends on the surface-to-mass ratio of the particles as well as their chemical form.

Absorption refers to transport phenomena that cause a net transfer of material to the lymphatic or circulatory systems. The absorbed material may be translocated to other body organs, or

excreted in urine and feces. Depending on the solubility of the DU, about 82 percent to 99 percent of the material in the GI tract will be excreted in the feces.

The fate of material deposited in the respiratory tract can be cleared to the GI tract or the lymph (nodes) tissue or retained within organs of the body.

Dissolution-absorption is a continuous process that leads to the removal of particles or their constituents from the alveolar (P) region. The physical clearance of particles from the P region takes place via two processes: (1) mucociliary clearance, and (2) transport from the respiratory tract to associated lymph nodes. Because lymph (nodes) tissue represent traps for particles cleared from the respiratory tract, particles will accumulate to high concentrations in the lymph nodes. Particles pass slowly through the lymph nodes, enter the systemic/circulatory system, and then become trapped in the reticulo-endothelial system of organs of the kidney, liver, spleen, and the skeleton (or bone).

Of the recognized factors that influence the clearance of particles from the respiratory tract and the dose patterns, smoking and pre-existing lung disease are the two most significant.

J.3.5 Retention

Once deposited, the retention of inhaled uranium or DU in the respiratory tract and the metabolic “fate” of that uranium or DU is determined by the transportability, including

solubility of the particular chemical/physical form of uranium or DU. The solubility of oxides decreases when produced at high temperatures. Higher temperatures produce dense particles with relatively small surface-to-volume ratios. Uranium or DU deposited into the respiratory tract may be either absorbed into the bloodstream or transferred via various clearance mechanisms to the GI tract.

Figure J-1 illustrates how respiratory tract retention is a function of particle size distribution versus time (days) post acute intake. It is clear that the retention and excretion of uranium or DU are highly dependent upon the initial pattern of deposition. The interpretation of bioassay results (for example, nasal swabs, early fecal samples, urine samples) is, therefore, also quite dependent upon particle size distribution.

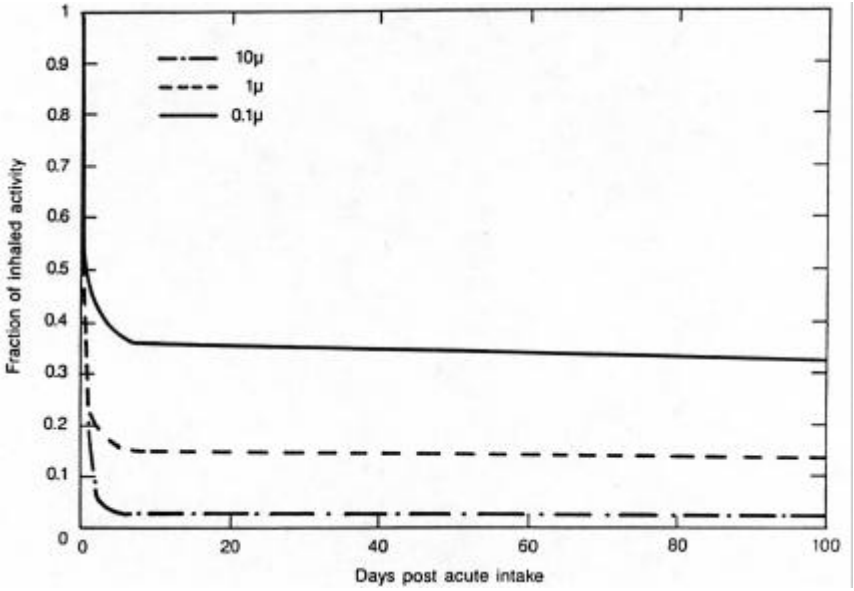


Figure J-1. Respiratory Tract Retention vs. Particle Size.

The ICRP has established in ICRP-30 three respiratory tract "clearance classes" which describe the behavior of deposited material in the respiratory tract. In ICRP-66, the ICRP established the absorption type to replace the ICRP-30 respiratory tract clearance classes. The ICRP-30 classes and ICRP-66 absorption types are based on the biological clearance half times (T_b) from the P region of the respiratory tract as follows:

Respiratory Tract Clearance Class/ Absorption Type	Clearance Half-Time from P Region (days)
Y (years)(S)	> 100
W (weeks)(M)	10 - 100
D (days)(F)	< 10

Figure J-2 (ICRP-30) shows the deposition of material in the three respiratory tract regions as a function of AMAD. Generally, the smaller the AMAD, the more material is deposited in the P region, and less material is deposited in the N-P region. The fraction of material deposited in the T-B region is more or less constant over the range of 0.2 μm to 10 μm AMAD.

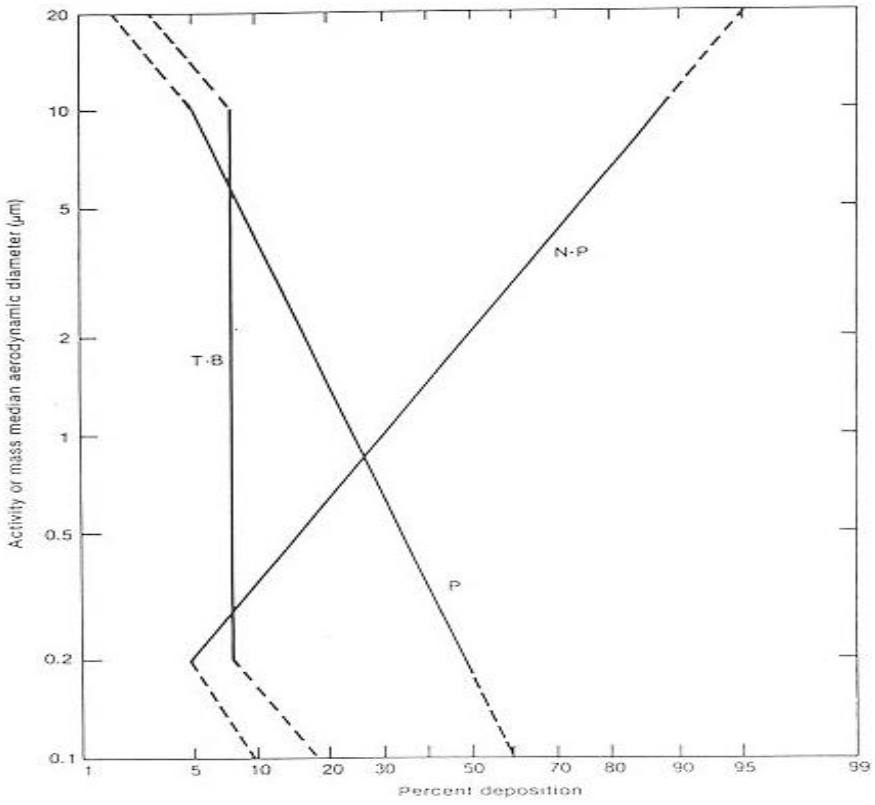
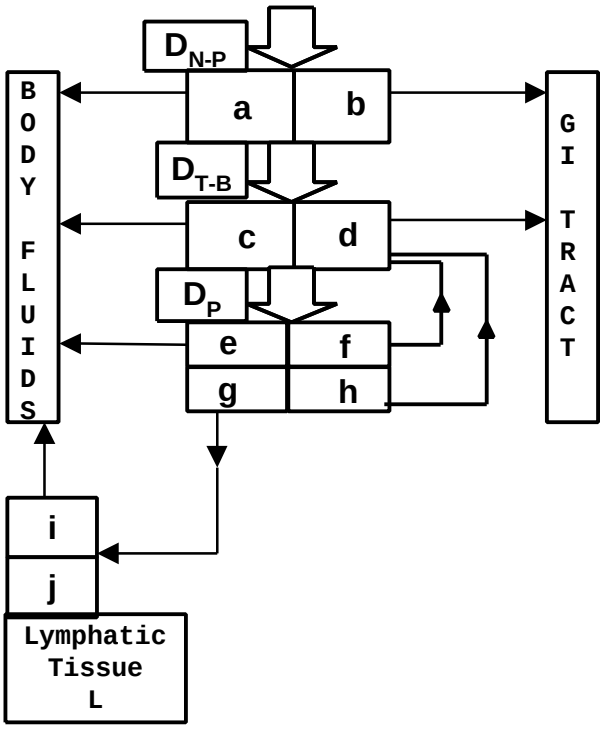


Figure J-2. Deposition Fractions in the Regions of ICRP-30 Respiratory Tract Model.

As seen in Figure J-3, each clearance class dictates compartmental fractions (F) and T_b for each of the pathways by which material is translocated from the compartments of the ICRP-30 respiratory tract model.



Region	Compartment	Class					
		D		W		Y	
		T	F	T	F	T	F
N-P (D_{N-P} =0.30)	a	0.01	0.5	0.01	0.1	0.01	0.01
	b	0.01	0.5	0.40	0.9	0.40	0.99
T-B (D_{T-B} =0.08)	c	0.01	0.95	0.01	0.5	0.01	0.01
	d	0.2	0.05	0.2	0.5	0.2	0.99
P (D_P =0.25)	e	0.5	0.8	50	0.15	500	0.05
	f	n.a.	n.a.	1.0	0.4	1.0	0.4
	g	n.a.	n.a.	50	0.4	500	0.4
	h	0.5	0.2	50	0.05	500	0.15
L	i	0.5	1.0	50	1.0	1000	0.9
	j	n.a.	n.a.	n.a.	n.a.	∞	0.1

Figure J-3. ICRP-30 Respiratory Tract Model Clearance Pathways (or regions) from Various Deposition Sites and Clearance Half-Times (T) and Compartmental Fractions (F).

Table J-1 describes the ICRP-30 respiratory tract model compartments.

Table J-1. Description of the Respiratory Tract Compartments

a: N-P Region	Absorbed to Body Fluids
b: N-P Region	Swallowed to GI Tract
c: T-B Region	Absorbed to Body Fluids
d: T-B Region	Swallowed to GI Tract
e: P Region	Absorbed to Body Fluids
f: P Region	Rapidly Cleared to Compartment d
g: P Region	Slowly Cleared to Compartment d
h: P Region	Cleared to Pulmonary Lymph Nodes
I: L Region	Absorbed to Body Fluids
j: L Region	That Does Not Clear

Reference: ICRP-30.

Each major region of the respiratory tract is subdivided into compartments (see Figure J-3 and Table J-1). In the N-P region, material that is deposited in compartment a is available for absorption into body fluids, while that deposited in compartment b is eventually swallowed and thus transferred to the GI tract. In the T-B region, material that is deposited in compartment c is absorbed into body fluids, while that deposited in compartment d represents material that is being moved upward by ciliary action, out of the respiratory tract, and into the GI tract. In the P region, material from compartments f and g also enters compartment d and is moved upward by ciliary action, out of the respiratory tract, and into the GI tract; material from compartment f is cleared rapidly from the respiratory tract, and material from compartment g progresses very slowly. Material in compartment e of the P region is absorbed into body fluid, and material in compartment h is removed by lymphatic drainage. Lymphatic (L) tissue or lymph nodes is divided into two compartments (i and j), with material leaving compartment i entering body

fluids. Compartment j represents material that is retained in the L tissue or lymph nodes. This applies to Class Y material to 10 percent of the L tissue burden.

Material is cleared directly from the respiratory tract to body fluids via compartments a, c, e and i. Material is cleared directly from the respiratory tract to the GI tract via compartments b and d.

In ICRP-30, the dose to the respiratory tract includes the nuclear transformations that take place in compartments c through j, averaged over a mass of 1000 grams.

Insoluble uranium or DU oxides (DUO_2 and DU_3O_8) are retained in the respiratory tract or cleared by mechanical processes including lymphatic drainage, transport by phagocytes, and mucociliary transport in the ciliated airways to the GI tract.

Figure J-4 illustrates how the retention of uranium or DU material in the respiratory tract varies with clearance class. The dramatic differences in clearance patterns have obvious implications for interpretation of in-vivo counting and other bioassay results. Note that the overall retention in the first day or so is controlled by the rapid clearance of material from the N-P and T-B regions of the respiratory tract. This graph may be used for U-234, U-235, U-236, U-238, or DU since the clearance of the material from the respiratory tract is dominated by biological rather than radioactive properties.

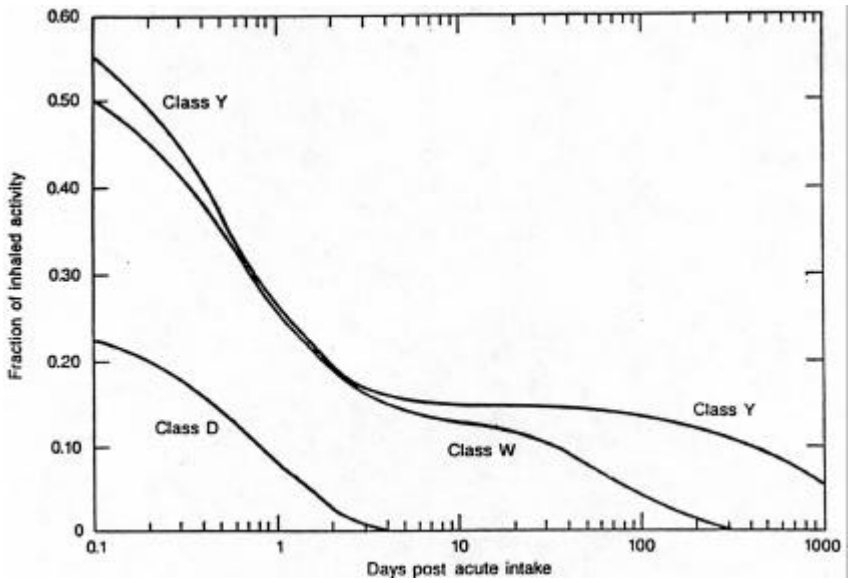


Figure J-4. Uranium Respiratory Track Retention of 1 μm AMAD Aerosol.

Figure J-3 illustrates the ICRP-30 respiratory tract model, and Figure J-6 illustrates the ICRP-66 respiratory tract model. Figures J-6 and J-9 illustrate pathways by which inhaled uranium or DU reaches the organs of interest and then is excreted via urine and feces.

The ICRP-66, published in 1994 and ICRP-71, published in 1996, update the ICRP-30 human respiratory tract model and identify the anatomical regions of the respiratory tract for dosimetric purposes. Figures J-6 through J-8 show the ICRP-66 modeled fractional deposition of an inhaled aerosol in each of these regions. The anatomical regions of the respiratory tract are as follows:

- Extrathoracic Region (ET) consisting of the anterior nose (ET_1) and the posterior nasopharyngeal region, larynx, pharynx, and mouth (ET_2).

- Bronchial Region (BB) consisting of the tracheobronchial region from which deposited material is cleared by ciliary action.
- Bronchiolar Region (bb) consisting of the bronchioles and terminal bronchioles from which deposited material is also cleared by ciliary actions.
- Alveolar-Interstitial Region (AI) consisting of the respiratory bronchioles, alveolar ducts and sacs with their alveoli, and the interstitial connective tissue.

The following definitions are provided to clarify the abbreviations used in Figures J-5 and J-6:

- LN_{ET} - Lymphatics and lymph nodes that drain the extra-thoracic region.
- LN_{TH} - Lymphatics and lymph nodes that drain the thoracic region.
- BB_{seq} - Compartment representing prolonged retention in airway walls of a small fraction of the particles deposited in the bronchial region.
- bb_{seq} - Compartment representing prolonged retention in airway walls of a small fraction of the particles deposited in the bronchiolar region.
- ET_{seq} - Compartment representing prolonged retention in airway tissue of a small fraction of particles deposited in the nasal passages.

For this assessment, it was assumed that 70 percent of the inspired air is taken in via the mouth; the dose per unit intake of 5 μm aerosol into the respiratory tract will be higher with a 3 m^3/hr BR (or ventilation rate) than for the 1.2 m^3/hr or 1.7 m^3/hr BR (or ventilation rate).

The ICRP-66 absorption rate Types F, M, and S are related to the ICRP-30 inhalation clearance Classes D, W, and Y, respectively.[3] The ICRP-30 respiratory tract clearance Classes D, W, or Y are respiratory tract parameters that define the overall respiratory clearance. The ICRP-66 absorption Types F, M, and S are parameters that relate only to absorption into body fluids. Lung retention given by the Type M and Type S parameters is greater than for Class W and Class Y, respectively.

The inhalation absorption rates for DU oxides are identified as Type F (fast), Type M (moderate) and Type S (slow) as discussed in ICRP-66 and ICRP-71. These absorption rates are summarized as follows:

- For Type F, there is rapid absorption (within 10 minutes) of 100 percent of the DU residue deposited in BB, bb and AI and 50 percent of the DU oxide deposited in ET_2. The remaining 50 percent of the materiel in ET_2 is cleared to the GI tract. For nose breathing, there is rapid absorption of about 25 percent of that deposited in ET and 50 percent for mouth breathing.
- For Type M, about 10 percent is absorbed at 10 minutes and 90 percent at 140 days. There is rapid absorption of about 10 percent of the uranium or DU residue that is deposited in BB and bb and 5 percent of the DU residue deposited in ET_2. About 70 percent of the uranium or DU residue in AI reaches the body fluids eventually. For nose breathing, approximately 2.5 percent of that deposited in ET is rapidly absorbed and 5 percent for mouth breathing.

- For Type S, there is little absorption of uranium or DU residue. About 0.1 percent absorbed at 10 minutes and 99.9 percent at 7,000 days, there is little absorption from the ET, BB and bb regions. Approximately 10 percent of the uranium or DU residue that is deposited in AI reaches the body fluids eventually.

The new ICRP-66 respiratory tract model provides more detailed anatomy and physiology of the respiratory tract. The respiratory tract is divided into two extrathoracic compartments (ET_1 and ET_2), which together make up the N-P region in the ICRP-30 respiratory tract model. There are also compartments containing the BB and bb, which make up the T-B region, and an AI compartment, which makes up the P region. Although there is not a lymphatic region of the respiratory tract there is lymphatic tissue (L) associated with all regions of the respiratory tract. The lymph passes through lymph nodes that filter the lymph that passes through them thereby collecting some of the DU.

For a 1 μm AMAD aerosol, about 25 percent of the DU inhaled will be deposited in the respiratory tract while the remaining 75 percent is exhaled (ICRP-30). The amount of DU deposited in the respiratory tract (about 80 percent of the 25 percent or 20 percent of the total inhaled) is removed and transported to the pharynx by the normal bronchial mucociliary clearance mechanism, which results in most of the DU being excreted via the GI tract. Only a small fraction of the DU enters the bloodstream via the intestinal absorption. The absorption factors or GI transfer coefficient for uranium or DU, as it passes through the GI tract after clearance from the respiratory system, is 0.02 or 2 percent for Classes D and W (or Type F and

Type M, respectively) and 0.002 or 0.2 percent for Class Y (or Type S). The absorption is assumed to take place in the small intestine.

Fifty percent of the pulmonary deposit clears rapidly and fifty percent clears after several hundred days. A small percentage of the amount deposited in the respiratory tract (12 percent of the 20 percent remaining in the respiratory tract or about 3 percent of amount inhaled) is retained by lymph nodes for very long times and 4 percent enters the bloodstream. About 10 percent is solubilized and goes to the blood where it is excreted or deposited in the kidney, liver, skeleton, and other organs. Of the original DU that enters the body via inhalation, about 1 percent makes its way to the kidney. Ninety percent of this 1 percent or about 0.9 percent of the DU deposited in the respiratory tract is excreted in urine. Table J-2 summarizes the disposition of inhaled 1 μm AMAD DU aerosols in the respiratory tract (ICRP-30). (The values in the second column have been rounded to approximate values.)

Table J-2. Disposition of Inhaled Uranium or DU
1 μm AMAD Aerosols

Location	Percentage of Particles Inhaled	Percentage of Amount Deposited in the Respiratory Tract
Initially Retained in Respiratory Tract	25%	
• Cleared from respiratory tract by bronchial mucociliary clearance mechanism	~20%	80%
• Deposited in Respiratory Tract		
To lymph nodes	~3%	12%
To blood and then to kidneys	~1%	4%

Figure J-5 identifies the anatomical regions of the respiratory tract. The lymphatic tissues (LN) are associated with both the extrathoracic (LN_{ET}) and thoracic (LN_{TH}) airways. However, all four regions of the respiratory tract contain lymphatic tissue.

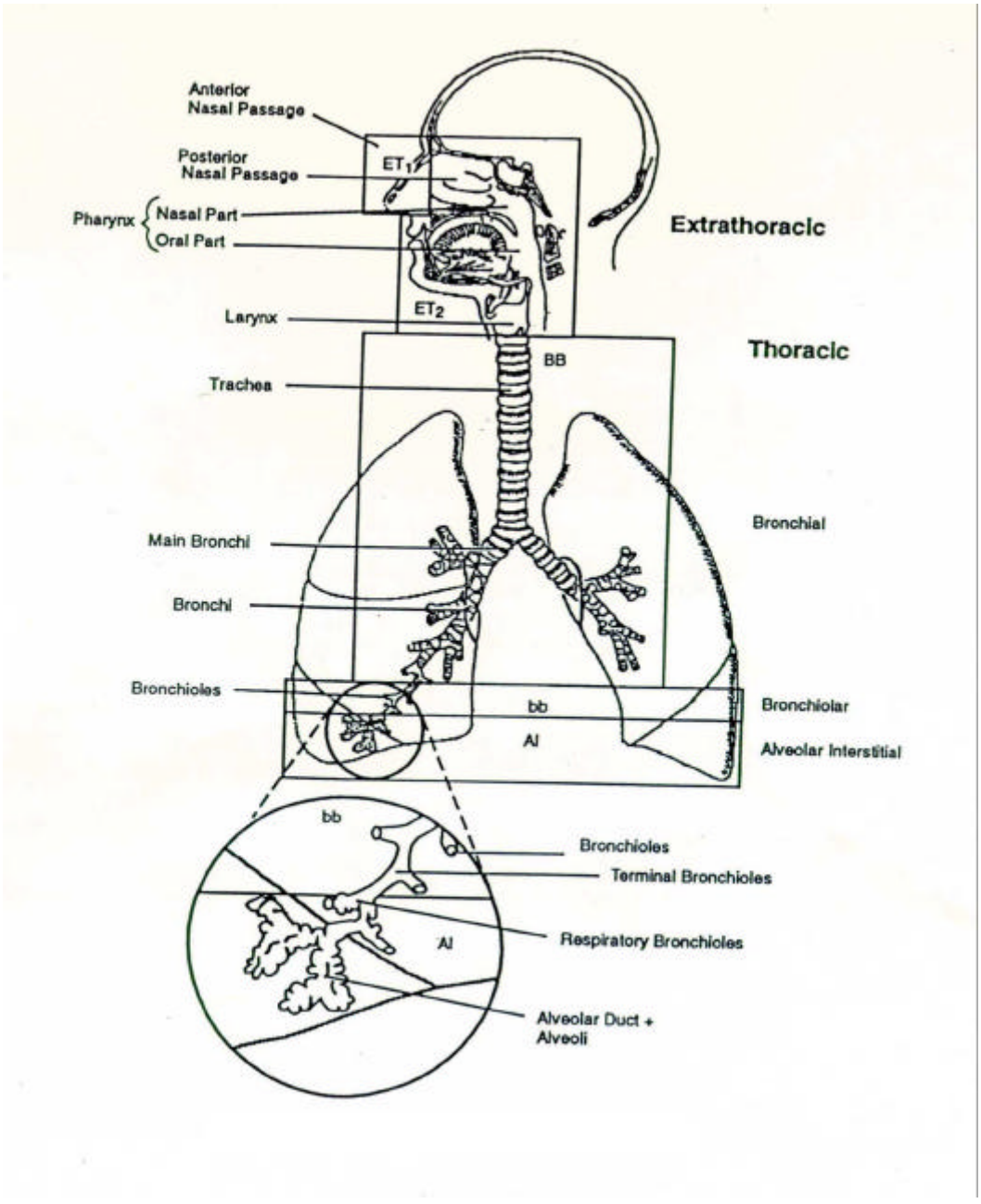


Figure J-5. Anatomical Regions of the Respiratory Tract. Reference: ICRP-66, ICRP-68, and ICRP-71.

Figure J-6 provides a compartment model representing time-dependent particle transport from each of the respiratory tract regions and the clearance rate. The clearance rates shown alongside arrows are in units of (1/day) between compartments.

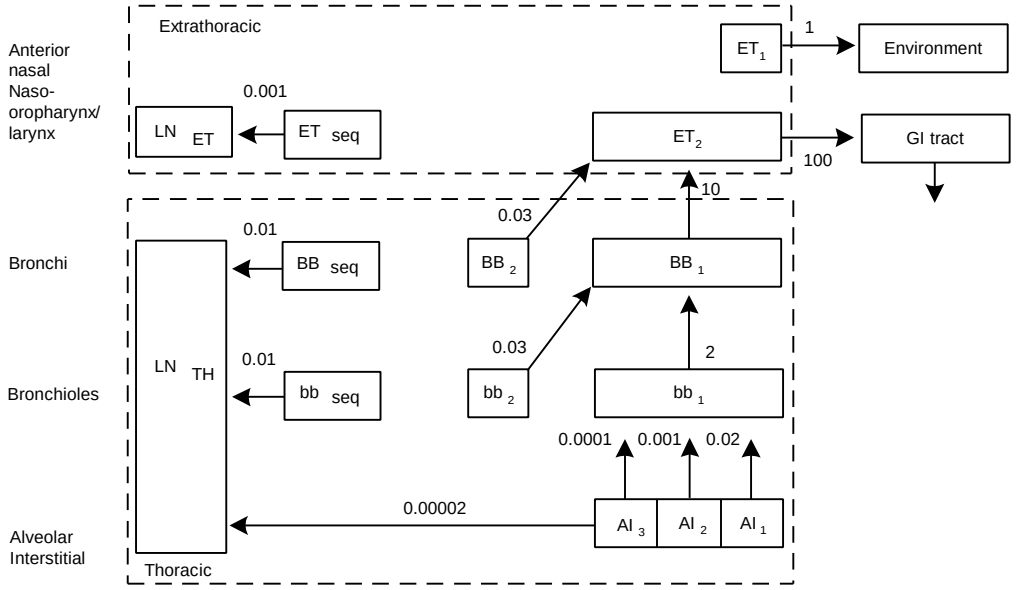


Figure J-6. Compartment Model Representing Time-Dependent Particle Transport from each Respiratory Tract Region. References: ICRP-66, ICRP-68, and ICRP-71.

Figure J-7, extracted from ICRP-66, illustrates values of regional deposition that are given by the recommended model for an adult male (nose breather) engaged in light work [with an assumed average BR (or ventilation rate) of 1.2 m^3/hr].

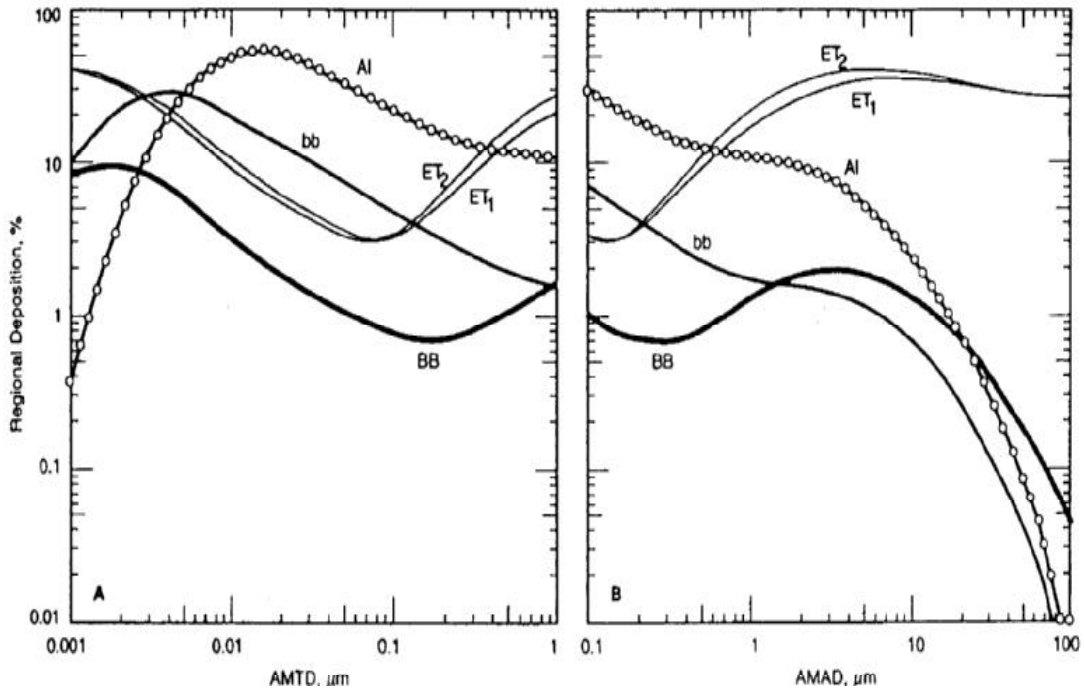


Figure J-7. Fractional deposition in each region of respiratory tract for a reference worker (normal nose breather) shown as functions of the activity median thermodynamic diameter (AMTD) and the AMAD. Deposition is expressed as a fraction of the activity present in the volume of ambient air that is inspired, and activity is assumed to be lognormally distributed as a function of particle size (for particles of density 3.0 g/cm^3 and shape factor of 1.5). References: ICRP-66 and ICRP-71.

Figure J-8 shows the corresponding values calculated for an adult male "mouth breather" who is assumed to take 60 percent of inspired air through his mouth. The habitual "mouth breather" inhales occasionally through the nose and mouth simultaneously.

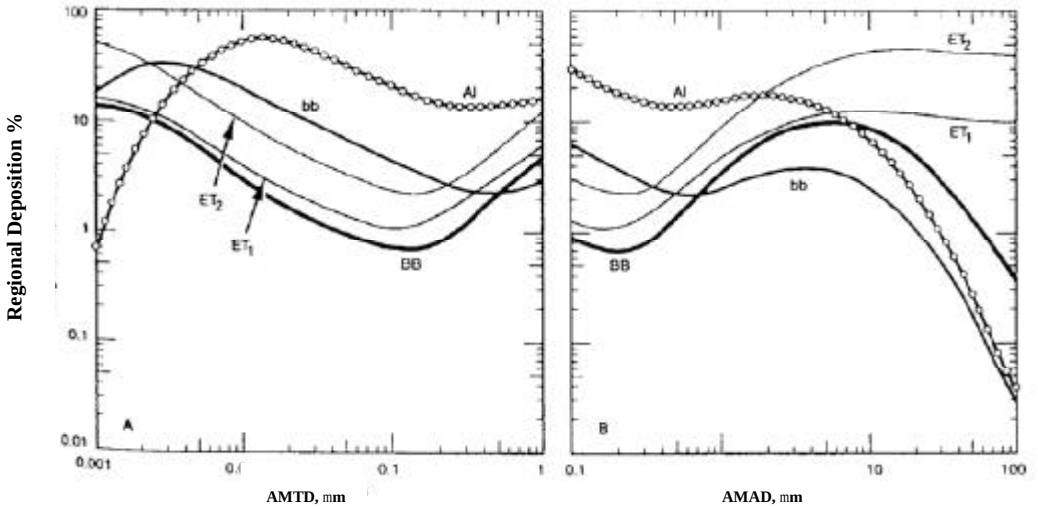


Figure J-8. Fractional deposition in each region of the respiratory tract for a reference worker (mouth breather) shown as functions of the AMTD and the AMAD. Deposition is expressed as a fraction of the activity present in the volume of ambient air that is inspired and is actually assumed to be lognormally distributed as a function of particle size (for particles of density 3.0 g/m^3 and shape factor of 1.5). References: ICRP-66 and ICRP-71.

Early behavior of uranium or DU in human circulation is represented reasonably well by treating plasma as being uniformly mixed (ICRP-69 and ICRP-78). The soft tissue component (STO) is where there is a relative rapid exchange of material with plasma.

Compartment STO serves two purposes: (1) to help maintain the amount of uranium or DU in the plasma, and (2) to help depict an early buildup and decline of uranium or DU in soft tissue other than liver and kidneys. Compartment STO will receive about 30 percent of the uranium or DU leaving the plasma. The assumed removal half-time from STO to plasma is 2 hours.

Figure J-9 provides a diagram of the ICRP-67, ICRP-69 and ICRP-78 biokinetic model for uranium or DU.

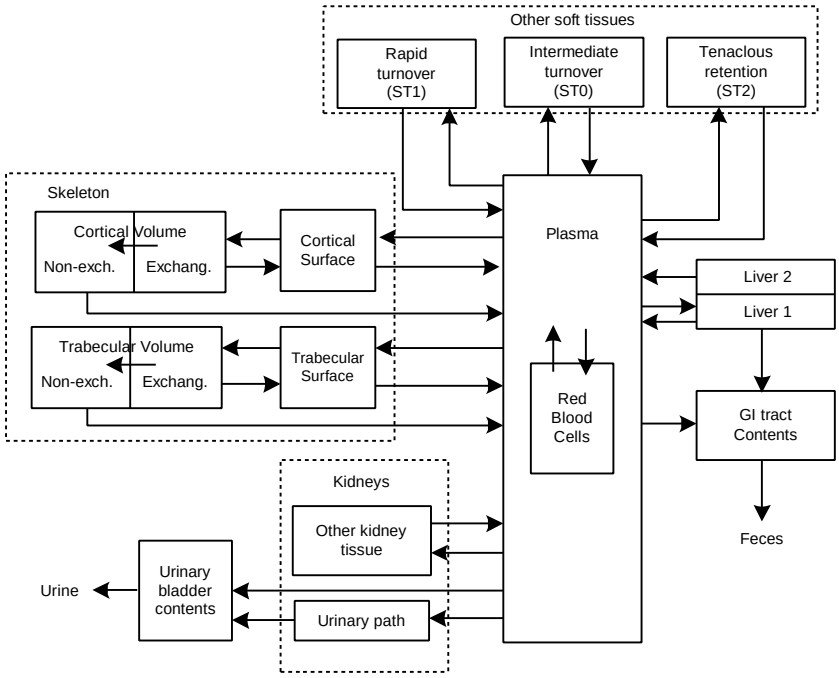


Figure J-9. Diagram of the Biokinetic Model for Strontium, Radium, and Uranium. References: ICRP-67, ICRP-69 and ICRP-78.

In addition to compartment STO, two other soft tissue compartments are used to describe the uptake and retention by soft tissue such as the liver and kidney. These are referred to as intermediate (ST_1) and slow (ST_2) turnover compartments. The ICRP-67, ICRP-69 and ICRP-78 discusses these transfer compartments and rate functions in more detail. ICRP-69 and ICRP-78 provide transfer rates for the various compartments.

Once the uranium or DU is solubilized in the blood, the kidney will effectively excrete approximately 90 percent of the DU in urine over the next three days[44]. Renal excretion of uranium or DU, like that of other heavy metals, is determined by such factors as the filterability of circulating chemical complexes and the ability of the filtered chemical complexes or their

decomposition products to be reabsorbed or secreted in the kidney tubules. The ICRP-30 biokinetic model was used in the dose assessment in this report (see Figure J-13). However, there is about a 1 percent difference between the calculated dose from the biokinetic models described in ICRP-30, ICRP-69 and ICRP-78. The ICRP-69 biokinetic model used in conjunction with the LUDEP ver 2.06 computer code resulted in a slightly higher (≅ 1 percent) dose.

Models that describe the distribution, retention, and elimination/excretion are required to evaluate and estimate the exposure of an individual following intake(s) of DU residue. These models are divided into three separate but interlinked biokinetic models: (1) the respiratory tract model, (2) the GI model, and (3) the blood or systemic model. The ICRP-30 biokinetic model is considered to be a "once-through" model, whereas, the ICRP-69 and ICRP-78 biokinetic model is a "recycle" model (see Figure J-9).

DU entering the blood is rapidly taken up by tissues/organs or eliminated/excreted in urine. The transfer of inhaled uranium or DU into blood directly from the respiratory tract is the predominate pathway for soluble Class D (or Type F) and moderately soluble Class W (or Type M) DUO_3. There is no significant pathway to blood for insoluble DUO_2 and DU_3O_8 Class Y (or Type S). DU in tissues/organs is recycled or returned to blood for subsequent re-distribution or elimination/excretion. There may be small components of elimination/excretion other than urine, but these will be negligible. Any fecal excretion of uranium or DU comes

directly from ingested uranium or DU or indirectly from inhaled insoluble DU that is cleared through the GI tract.

The ICRP discusses the "recycle" model for uranium or DU in ICRP-67 and ICRP-69. In the "recycle" model, there will be about 29.2 percent of the uranium or DU transferred to the kidney. This is a factor of 2.423 (29.2/12.052) greater than the "once-through" model. There will be about 7.6 percent transferred to bone. This is a factor of 0.631 (7.6/12.052) less than the "once-through" model. There will be about 1.5 percent transferred to soft tissue. This is a factor of 0.1245 (1.5/12.052) less than the "once-through" model. About 62 percent of the uranium or DU is directly excreted in the urine. When compared to the "once-through" model, there will be a factor 1.15 (62/54) greater of direct excretion of uranium or DU in the urine.

Using parameters from ICRP-66, an adult exposed to an airborne mass concentration of a contaminant of 1 mg/m^3 of 5 μm AMAD aerosol of soluble Class D (or Type F) uranium will have an uptake rate to blood between 1.3 mg/hr to 1.8 mg/hr.

Figure J-10 provides a schematic representation of routes of entry, metabolic pathways, possible elimination pathways, and bioassay samples for internally deposited radionuclides. In some cases, biopsy samples of particular tissues may be necessary such as bone or tissue from a wound.

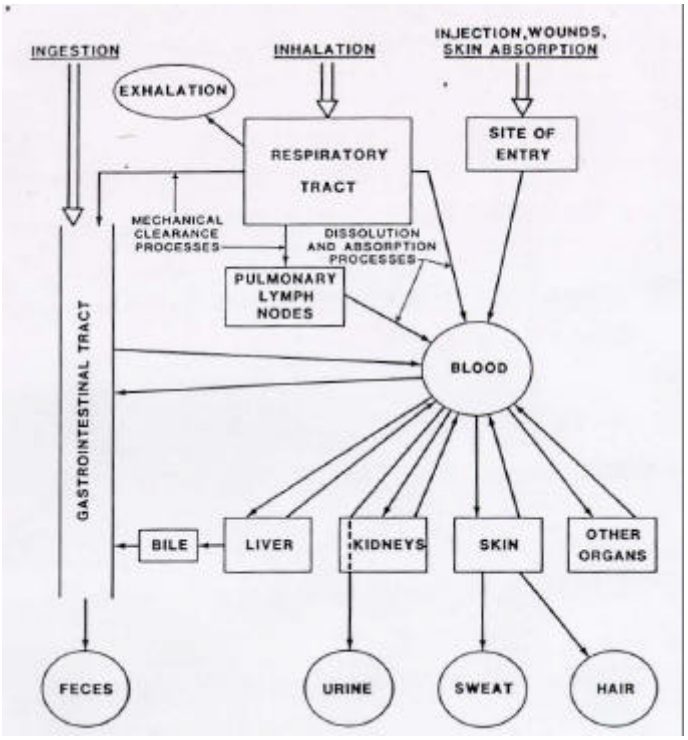


Figure J-10. Schematic Representation of Routes of Entry, Metabolic Pathways and Possible Bioassay Sampling for Internally Deposited Radionuclides. Reference: NCRP Report No. 87.

The new human respiratory tract model, which is described in ICRP-66, generally updates the model used in ICRP-30 for the occupational worker. This new model is broader in scope, having been designed not only to evaluate secondary limits on intake of radionuclides by inhalation for a worker, but also to:

- Provide for modeling of the respiratory tract retention and excretion characteristics in an individual case and the resulting respiratory tract and systemic organ doses based on bioassay data.

- Take into account factors such as cigarette smoking and lung disease that influence respiratory tract particle retention.
- Enable knowledge of the dissolution and absorption behavior of specific materials to be used in the calculation of the respiratory tract dose, systemic absorption, and excretion of the materials.
- Apply explicitly to age-dependent and sex of members of a population.
- Calculate biologically meaningful doses in a manner that is consistent with the morphological, physiological, and radiobiological characteristics of the various tissues of the respiratory tract.

The ICRP-30 respiratory tract model consists of two parts:

- A particle deposition/retention model
- A particle transport model

The ICRP-66 respiratory tract model consists of three parts:

- A particle deposition model
- A particle transport model
- A particle absorption model

The ICRP-66 respiratory tract model is different from the ICRP-30 respiratory tract model. The ICRP-30 model calculates only the average dose to the respiratory tract. The ICRP-66 model takes into account the differences in radiosensitivity of the respiratory tract tissues and the wide range of doses they may receive. Therefore, using the ICRP-66 model makes it possible to calculate doses to the specific tissues in the respiratory tract.

The reference adult worker is assumed to spend about 5.5 hrs or 69 percent of an 8-hr work day at light exercise and 2.5 hrs or 31 percent sitting, giving a mean BR (or ventilation rate) of 1.2 m^3/hr (20 L/min).

The adult worker who does manual labor spends about 7 hrs or 87.5 percent of an 8-hr work day at light exercise and 1 hr or 12.5 percent at heavy exercise, giving a mean BR (or ventilation rate) of 1.688 m^3/hr (28 L/min).

Soldiers in the OSAGWI Level I Scenarios were assumed to have a BR (or ventilation rate) of 3 m^3/hr (50 L/min) at 100 percent heavy exercise for their exposure duration. They were also considered to be mouth breathers.

Soldiers in the OSAGWI Levels II and III Scenarios were assumed to have BRs (or ventilation rates) of 3 m^3/hr (50 L/min) for their exposure duration. Welders and armor removers were considered to be mouth breathers. All others were considered nose breathers.

Material deposited in the respiratory tract are cleared by three routes:

- Into the blood by absorption
- To the GI tract via the pharynx
- To regional LN via the lymphatic system

The rates at which deposited material are cleared by each route, in general, depend on:

- The location of the material in the respiratory tract
- The physical and chemical form of the material
- The time since deposition of the material

The modeled aerosol inhalability and BRs (or ventilation rates) determine the intake of a contaminant for a given exposure and are used with the deposition model to determine the regional deposition of particles in the respiratory tract. The resulting total deposition in each region of the respiratory tract is represented by an algebraic formula, expressed in terms of particle size, BRs (or ventilation rates), lung volumes, and scaling factors for airway dimensions (see Appendix D).

Table J-2 summarizes the dimensions of respiratory tract target tissues. For each source/target combination, ICRP-66 provides absorbed fractions for alpha, beta and electrons in each case as

a function of energy. The absorbed fraction is used in the calculation of the dose to the various tissues of the respiratory tract.

Table J-2. Summary of Dimensions of Respiratory Tract Target Tissues

Respiratory Tract Tissue	Target Cells	Mucous Thickness (μm)	Mass of Target Tissue (gm)	Depth of Target Cell Nuclei (μm)	Epithelial Thickness (μm)
ET_1	Basal	-	0.02	40.50	50
ET_2	Basal	15	0.45	40.50	50
BB_s	Secretory	5	0.87	10.40	55
BB_b	Basal	5	0.43	35.50	55
bb	Secretory	2	2.0	4.12	15

Note: BB_s is the mass of the bronchial epithelium through which secretory cell nuclei are distributed, and BB_b is that for the basal cell nuclei.
Reference: ICRP-66

When calculating the CEDE from inhaled and indirectly ingested DU, the following general observations can be made using the LUDEP:

- For soluble fractions Class D (or Type F) of alpha and beta emitters, the new respiratory tract model (ICRP-66) tends to predict lower effective doses per unit intake than the older respiratory tract model (ICRP-30).
- For moderately soluble fractions Class W (or Type M), the new respiratory tract model (ICRP-66) tends to predict effective doses that are similar to those calculated using the older respiratory tract model (ICRP-30).
- For insoluble fractions Class Y (or Type S), the new respiratory tract model (ICRP-66) tends to predict effective doses that are two-to-nine fold lower than the corresponding values calculated using the older respiratory tract model (ICRP-30).

J.4 Computer Dosimetry Models

J.4.1 Lung Dose Evaluation Program

The National Radiological Protection Board (United Kingdom) developed the LUDEP software package (NRPB-SR-287, LUDEP ver 2.0). The LUDEP computer code allows the user to calculate doses and dose rates to regions of the respiratory tract and to other body organs from intakes of radionuclides, using the ICRP-66 model[7] of the human respiratory tract. In the absence of particle size data, the ICRP recommends modeling exposures for both 1 μm and 5 μm particles for environmental (or general public) and workplace considerations, respectively[7].

For the dose estimates in this report, the following parameters were used: BR (or ventilation rate) of 3 m^3/hr, 5 μm AMAD aerosol and heavy exercise. The LUDEP code uses the biokinetic model presented in ICRP-30[5] and the retention and excretion functions presented in ICRP-54. The organ or tissue weighting factors and quality or radiation weighting factors were taken from ICRP-26. (See Appendices G and H, respectively.)

The LUDEP code also allows the user to input the particle size of an airborne concentration or intake. LUDEP allows the user to input the characteristic aerosol AMAD (or AMTD) for a given airborne concentration or inhalation intake. The particle size(s) used in the LUDEP calculations was chosen based on the particle size which gave the most conservative dose

(highest dose based on particle size) for the range of particle sizes as presented in Table-14, Part III. (See Appendix D for a discussion of inhalability and respirability of airborne particles.) In addition, consideration was given to the isotopic composition of the uranium isotopes in DOD DU. Also, consideration was given to a 10-year equilibrium of U-235 and U-238 progeny, which includes the very short-lived beta-emitting progeny (which make a negligible contribution to the total dose). The code contains the ICRP-30 uranium biokinetic model and calculates doses to target organs.

When an inhalation intake of DU is entered into LUDEP along with the particle size, BR (or ventilation rate), type (or route) of breathing, type of exercise and isotopic composition, the computer program uses these parameters in the dose calculation. Features include options for calculating bioassay quantities (urinary/fecal excretion and lung/whole body retention) and for estimating intakes from bioassay measurements.

The metabolic and excretion models available in LUDEP are:

- ICRP-30, GI model
- ICRP-30, General systemic model
- ICRP-30, Uranium biokinetic model
- ICRP-54, Uranium excretion model and retention functions
- ICRP-66, Respiratory tract model

LUDEP uses the Q and organ/tissue weighting factors published in ICRP-26 or W_R and organ/tissue weighting factors published in ICRP-60 (see Appendix G and Appendix H). The bone dosimetry model is a "recycling" model with initial uptake onto bone surfaces, transfer from bone surface to bone volume, and "recycling" from bone and other tissues to plasma.

In the absence of a computer program, such as LUDEP, intake may be calculated from the following equation:

$$I = BR * C * t * RF$$

Where:

I	=	Intake (mg)
BR	=	Breathing Rate (m^3/hr)
C	=	Airborne Mass Concentration (mg/m^3)
t	=	Exposure Duration (hour)
RF	=	Respirable Fraction

Tables J-3, J-3a J-3b and J-3c and Tables J-4, J-4a, J-4b and J-4c summarize the LUDEP ver 2.06 computer model input parameters for 1 μm aerosol and a 5 μm AMAD aerosol and the input parameters for a respiratory tract clearance classification of Y, W and D (or Types S, M, and F), respectively[3].

Table J-3. ICRP-66 Default Physiological Parameters for the Adult Male Assumed for Dose Calculations Using the LUDEP Computer Model (1 μm AMAD Aerosol)

ICRP Default Parameters	
Exposure	User Defined
Subject	Adult Male
Activity	Heavy Exercise
Type	Mouth Breather
Dispersion	Polydispersion
Percent Time in Different Activities	
Sleep	0.00%
Sitting	0.00%
Light Exercise	0.0%
Heavy Exercise	100%
Physiological Parameters	
Functional Residual Capacity	3301 cm^3
Extra-thoracic Dead Space	50 cm^3
Bronchial Dead Space	49 cm^3
Bronchiolar Dead Space	47 cm^3
Height	176 cm
Tracheal Diameter	1.650 cm
First Bronchiolar Diameter	0.165 cm
Activity-Related Parameters	
Ventilation Rate	3.00 m^3/hr
Respiratory Frequency	26.0/min
Tidal Volume	1923 cm^3
Volumetric FR	1667 cm^3/s
Fraction Breathed Through Nose	0.30

Table J-3a. Aerosol Parameters and Resulting Regional Lung Deposition Fractions Calculated by LUDEP for a 1 μm AMAD Aerosol of DU_3O_8

Aerosol Size Parameters			
AMAD		1.00 μm	
AMTD		0.3812 μm	
σ_g		2.44	
Density		8.30 g/cm^3	
Shape Factor		1.50	
Deposition (calculated from LUDEP)			
Region	Delayed	Normal + seq	FS%
ET_1	---	4.18%	---
ET_2	---	9.73%	---
BB	3.02%	3.14%	49.08
bb	1.36%	1.37%	49.88
AI	---	15.54%	---
Total 38.33%			

Table J-3b. Aerosol Parameters and Resulting Regional Lung Deposition Fractions Calculated by LUDEP for a 1 μm AMAD Aerosol of DUO_2

Aerosol Size Parameters			
AMAD		1.00 μm	
AMTD		0.3219 μm	
σ_g		2.42	
Density		10.97 g/cm^3	
Shape Factor		1.50	
Deposition (calculated from LUDEP)			
Region	Delayed	Normal + seq	FS%
ET_1	---	4.19%	---
ET_2	---	9.76%	---
BB	3.05%	3.10%	49.55
bb	1.46%	1.46%	49.97
AI	---	16.60%	---
Total 39.62%			

Table J-3c. Aerosol Parameters and Resulting Regional Lung Deposition Fractions Calculated by LUDEP for a 1 μm AMAD Aerosol of DUO_3

Aerosol Size Parameters			
AMAD		1.00 μm	
AMTD		0.4115 μm	
σ_g		2.45	
Density		7.3 g/cm^3	
Shape Factor		1.50	
Deposition (calculated from LUDEP)			
Region	Delayed	Normal + seq	FS%
ET_1	---	4.18%	---
ET_2	---	9.71%	---
BB	3.00%	3.16%	48.74
bb	1.32%	1.33%	49.79
AI	---	15.11%	---
Total 37.82%			

Table J-4. ICRP-66 Default Physiological Parameters for the Adult Male Assumed for Dose Calculations Using the LUDEP Computer Model (5 μm AMAD Aerosol)

ICRP Default Parameters	
Exposure	User Defined
Subject	Adult Male
Activity	Heavy Exercise
Type	Mouth Breather
Dispersion	Polydispersion
Percent Time in Different Activities	
Sleep	0.00%
Sitting	0.00%
Light Exercise	0.0%
Heavy Exercise	100%
Physiological Parameters	
Functional Residual Capacity	3301 cm^3
Extra-thoracic Dead Space	50 cm^3
Bronchial Dead Space	49 cm^3
Bronchiolar Dead Space	47 cm^3
Height	176 cm
Tracheal Diameter	1.650 cm
First Bronchiolar Diameter	0.165 cm
Activity-Related Parameters	
Ventilation Rate	3.00 m^3/hr
Respiratory Frequency	26.0/min
Tidal Volume	1923 cm^3
Volumetric FR	1667 cm^3/s
Fraction Breathed Through Nose	0.30

Table J-4a. Aerosol Parameters and Resulting Lung Deposition Fractions Calculated by LUDEP for a 5 μm AMAD Aerosol of DU_3O_8.

Aerosol Size Parameters			
AMAD		5.00 μm	
AMTD		2.0766 μm	
σ_g		2.50	
Density		8.30 g/cm^3	
Shape Factor		1.50	
Deposition (calculated from LUDEP)			
Region	Delayed	Normal + seq	FS%
ET_1	---	9.50%	---
ET_2	---	36.91%	---
BB	6.40%	8.31%	43.49
bb	1.56%	1.63%	48.86
AI	---	9.25%	---
Total 73.56%			

Table J-4b. Aerosol Parameters and Resulting Lung Deposition Fractions Calculated by LUDEP for a 5 μm AMAD Aerosol of DUO_2

Aerosol Size Parameters			
AMAD		5.00 μm	
AMTD		1.796 μm	
σ_g		2.49	
Density		10.97 g/cm^3	
Shape Factor		1.50	
Deposition (calculated from LUDEP)			
Region	Delayed	Normal + seq	FS%
ET_1	---	9.50%	---
ET_2	---	36.91%	---
BB	6.74%	7.97%	45.81
Bb	1.59%	1.61%	49.59
AI	---	9.31%	---
Total 73.63%			

Table J-4c. Aerosol Parameters and Resulting Lung Deposition Fractions Calculated by LUDEP for a 5 μm AMAD Aerosol of DUO_3

Aerosol Size Parameters			
AMAD		5.00 μm	
AMTD		2.2208 μm	
σ_g		2.50	
Density		7.3 g/cm^3	
Shape Factor		1.50	
Deposition (calculated from LUDEP)			
Region	Delayed	Normal + seq	FS%
ET_1	---	9.50%	---
ET_2	---	36.91%	---
BB	6.19%	8.51%	42.10
bb	1.54%	1.65%	48.22
AI	---	9.23%	---
Total 73.53%			

See Appendix F for a discussion of calculational methodologies.

Table J-5 compares the fraction of a 1 μm AMAD DU aerosol that is deposited in the respiratory tract for ICRP-30 and ICRP-66 models according to region.

Table J-5. Fraction of 1 μm AMAD DU Aerosol Deposited in the Respiratory Tract

ICRP-30 Model	ICRP-66 Model
N-P - 0.30	ET_1 - 0.1489
	ET_2 - 0.1897
T-B - 0.08	BB - 0.0129
	bb - 0.0195
P - 0.25	AI - 0.1148
Total: 0.63	**Total**: 0.4858

Particles that are deposited in ET_1 are not transferred to blood. Therefore, about 33.7 percent of the 1 μm particles deposited in the respiratory tract according to ICRP-66 respiratory tract model are transferred to blood. For 5 μm particles, about 51.1 percent that is deposited in the respiratory tract are transferred to blood.

Table J-6 compares the fraction of 1 μm AMAD DU aerosol that are transferred from the respiratory tract to the blood according to ICRP-30 solubility and ICRP-66 absorption type of the DU aerosol.

Table J-6. Fraction of 1 μm AMAD DU Particles Transferred From the Respiratory Tract to Blood

ICRP-30 Model	ICRP-66 Model
Class D - 0.4791	Type F - 0.2439
Class W - 0.1292	Type M - 0.0998
Class Y - 0.0548	Type S - 0.0136

Tables J-7, J-8, and J-9 summarize data for a unit inhalation intake (1 mg) of 100 percent Class Y (or Type S), Class W (or Type M), and Class D (or Type F) for various BRs (or ventilation rates), nose breather, and 1 μm AMAD aerosol. About 85 percent to 89 percent of the dose is from U-238 for a 1 μm AMAD aerosol. For mixtures of different classes of uranium or DU compounds, appropriate percentages of the respiratory class must be used and then the results have to be added for the specific BR (or ventilation rate).

Table J-7. 1 mg Inhalation Intake/Dose of DU
Nose Breather (100% Class Y); 1 μm AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	2.18E-3	6E-6	1.65E-3	6E-6	2.12E-3
U-235	2E-3	2.15E-4	2E-3	2.13E-4	2E-3	2.13E-4
U-236	3E-6	1.01E-5	3E-6	1.07E-5	3E-6	9.97E-6
U-238	0.998	1.23E-2	0.998	1.58E-2	0.998	1.45E-2
Total	1	1.47E-2	1	1.66E-2	1	1.68E-2

Table J-8. 1 mg Inhalation Intake/Dose of DU
Nose Breather (100% Class W); 1 um AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	5.47E-4	6E-6	6.01E-4	6^E-6	8.99E-4
U-235	2E-3	5.59E-5	2E-3	6.03E-5	2^E-3	8.73E-5
U-236	3E-6	2.61E-6	3E-6	2.83E-6	3^E-6	4.13E-6
U-238	0.998	4.01E-3	0.998	4.27E-3	0.998	6.06E-3
Total	1	4.62E-3	1	4.94E-3	1	7.05E-3

Table J-9. 1 mg Inhalation Intake/Dose of DU
Nose Breather (100% Class D); 1 um AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	5.62E-5	6E-6	5.64E-5	6^E-6	5.85E-5
U-235	2E-3	6.00E-6	2E-3	6.03E-6	2^E-3	6.25E-7
U-236	3E-6	2.70E-7	3E-6	2.77E-7	3^E-6	2.87E-8
U-238	0.998	4.49E-4	0.998	4.50E-4	0.998	4.67E-4
Total	1	5.11E-4	1	5.13E-4	1	5.26E-4

Tables J-10, J-11, and J-12 summarize data for a unit inhalation intake (1 mg) of 100 percent Class Y (or Type S), Class W (or Type M), and Class D (or Type F) for various BRs (or ventilation rates), nose breather, and 5 μm AMAD aerosol. About 85 percent to 89 percent of the dose is from U-238 for a 5 μm AMAD aerosol. For mixtures of different classes of uranium or DU compounds, appropriate percentages of the respiratory clearance class must be used and then the results have to be added for the specific BR (or ventilation rate).

Table J-10. 1 mg Inhalation Intake/Dose of DU
Nose Breather (100% Class Y); 5 μm AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	7.82E-4	6E-6	1.02E-3	6E-6	2.17E-3
U-235	2E-3	7.91E-5	2E-3	1.00E-4	2E-3	2.08E-4
U-236	3E-6	3.70E-6	3E-6	4.73E-6	3E-6	9.88E-6
U-238	9.98E-1	5.71E-3	9.98E-1	7.09E-3	9.98E-1	1.44E-2
Total	1	6.57E-3	1	8.21E-3	1	1.68E-2

Table J-11. 1 mg Inhalation Intake/Dose of DU
Nose Breather (100% Class W); 5 μm AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	6.00E-5	6E-6	9.19E-5	6E-6	1.28E-3
U-235	2E-3	5.79E-6	2E-3	8.57E-6	2E-3	1.20E-4
U-236	3E-6	2.76E-7	3E-6	4.14E-7	3E-6	5.73E-6
U-238	9.98E-1	4.08E-4	9.98E-1	5.92E-4	9.98E-1	8.09E-3
Total	1	4.74E-4	1	6.93E-4	1	9.50E-3

Table J-12. 1 mg Inhalation Intake/Dose of DU
Nose Breather (100% Class D); 5 μm AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	5.90E-5	6E-6	6.36E-5	6E-6	8.30E-5
U-235	2E-3	6.31E-6	2E-3	6.80E-6	2E-3	8.86E-6
U-236	3E-6	2.89E-7	3E-6	3.12E-7	3E-6	4.07E-7
U-238	9.98E-1	4.72E-4	9.98E-1	5.08E-4	9.98E-1	6.62E-4
Total	1	5.38E-4	1	5.79E-4	1	7.54E-4

Tables J-13, J-14 and J-15 summarize data for a unit inhalation intake (1 mg) of 100 percent Class Y (or Type S), Class W (or Type M), and Class D (or Type F) for various BRs (or ventilation rates), mouth breather, and 1 μm AMAD aerosol. About 85 percent to 89 percent of the dose is from U-238 for a 1 μm AMAD aerosol. Appropriate percentages of the respiratory clearance class must be used and then the results have to be added for the specific BR (or ventilation rate).

Table J-13. 1 mg Inhalation Intake/Dose of DU
Mouth Breather (100% Class Y); 1 μm AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	2.33^{E}-3	6E-6	2.42E-3	6E-6	2.42E-3
U-235	2E-3	2.40^{E}-4	2E-3	2.38E-4	2E-3	2.43E-4
U-236	3E-6	1.11^{E}-5	3E-6	1.11E-5	3E-6	1.14E-5
U-238	0.998	1.75^{E}-2	0.998	1.73E-2	0.998	1.74E-2
Total	1	2.01E-2	1	2.00E-2	1	2.01E-2

Table J-14. 1 mg Inhalation Intake/Dose of DU
Mouth Breather (100% Class W); 1 μm AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	8.65E-4	6E-6	9.11E-4	6E-6	1.06E-3
U-235	2E-3	8.69E-5	2E-3	9.04E-5	2E-3	1.03E-4
U-236	3E-6	4.08E-6	3E-6	4.26E-6	3E-6	4.87E-6
U-238	0.998	6.18E-3	0.998	6.37E-3	0.998	7.11E-3
Total	1	7.14E-3	1	7.37E-3	1	8.28E-3

Table J-15. 1 mg Inhalation Intake/Dose of DU
Mouth Breather (100% Class D); 1 μm AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	5.81E-5	6E-6	5.82E-5	6E-6	5.96E-5
U-235	2E-3	6.18E-6	2E-3	6.22E-6	2E-3	6.38E-6
U-236	3E-6	2.76E-7	3E-6	2.85E-7	3E-6	2.92E-7
U-238	0.998	4.64E-4	0.998	4.64E-4	0.998	4.75E-4
Total	1	5.29E-4	1	5.29E-4	1	5.41E-4

Tables J-16, J-17 and J-18 summarize data for a unit inhalation intake (1 mg) of 100 percent Class Y (or Type S), Class W (or Type M), and Class D (or Type F) for various BRs (or ventilation rates), mouth breather, and 5 μm AMAD aerosol. About 85 percent to 89 percent of the dose is from U-238 for a 5 μm AMAD aerosol. Appropriate percentages of the respiratory clearance class must be used, and then the results have to be added for the specific BR (or ventilation) rate.

Table J-16. 1 mg Inhalation Intake/Dose of DU for a Mouth Breather 100% Class Y; 5 μm AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	2.52E-3	6E-6	2.63E-3	6E-6	2.83E-3
U-235	2E-3	2.50E-4	2E-3	2.58E-4	2E-3	2.71E-4
U-236	3E-6	1.18E-6	3E-6	1.22E-5	3E-6	1.29E-5
U-238	9.98E-1	1.78E-2	9.98E-1	1.82E-2	9.98E-1	1.87E-2
Total	1	2.06E-2	1	2.11E-2	1	2.18E-2

Table J-17. 1 mg Inhalation Intake/Dose of DU for a Mouth Breather (100% Class W) 5 μm AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	2.16E-4	6E-6	2.40E-4	6E-6	1.68E-3
U-235	2E-3	2.12E-5	2E-3	2.24E-5	2E-3	1.57E-4
U-236	3E-6	9.79E-7	3E-6	1.08E-6	3E-6	7.52E-6
U-238	9.98E-1	1.42E-3	9.98E-1	1.54E-3	9.98E-1	1.06E-4
Total	1	1.66E-3	1	1.80E-3	1	1.25E-2

Table J-18. 1 mg Inhalation Intake/Dose of DU for a Mouth Breather (100% Class D); 5 μm AMAD Aerosol

Isotope	Breathing Rate 1.2 m^3/hr		Breathing Rate 1.688 m^3/hr		Breathing Rate 3.0 m^3/hr	
	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)	Intake (mg)	Dose (rem)
U-234	6E-6	8.70E-5	6E-6	8.96E-5	6E-6	9.38E-5
U-235	2E-3	9.43E-6	2E-3	9.56E-6	2E-3	1.00E-5
U-236	3E-6	4.26E-8	3E-6	4.39E-7	3E-6	4.59E-7
U-238	9.98E-1	6.94E-4	9.98E-1	7.14E-4	9.98E-1	7.47E-4
Total	1	7.81E-4	1	8.14E-4	1	8.52E-4

Updates to the LUDEP computer program are expected to include:

- ICRP-67, ICRP-69 and ICRP-78, generic alkaline earth biokinetic model
- ICRP-69, Uranium excretion model
- ICRP-71, Inhalation dose coefficients for uranium
- Contributions from radioactive decay products
- Method for estimating intakes from radiobioassay results

J.4.2 Radiological Bioassay and Dosimetry Program

The RBD software package was developed for the U.S. Army by Oak Ridge National Laboratory (ORNL) to demonstrate compliance with Federal radiation protection guidance (ORNL/TM-11858, 1993). The software package was designed to run interactively on a personal computer. The RBD consists of a database module to manage bioassay data and a computational module that incorporates algorithms for estimating radionuclide intakes from either acute or chronic exposures. These calculated results are based on the measurement of the worker's rate of excretion of the radionuclide or the retained material in the body using the approach contained in ICRP-30 and the radiation quality and tissue weighting factors in ICRP-26. The RBD estimates an intake using a separate file for each radionuclide containing parametric representations of the retention and excretion functions. These files also contain dose-per-unit intake coefficients used to compute the CDE. Computed results derived from bioassay data (estimates of intake and CDE) are stored in separate databases, and the bioassay

measurements used to compute a given result can be identified. A report file is generated containing the CEDE for each individual.

J.4.3 Code for Internal Dosimetry

The PNNL developed the CINDY software package (PNL-7493, 1992) to provide the capabilities to calculate organ dose equivalents and effective dose equivalents using the approach contained in ICRP-30 and the organ tissue and radiation quality factors contained in ICRP-26. The code assists in the interpretation of bioassay data, the evaluation of doses from intake or bioassay measurements data, and the preparation of reports. Flexible biokinetic models are used to estimate organ doses and committed effective doses for any time period specified and for acute or chronic intakes.

Some of the metabolic and excretion models available in CINDY are—

- ICRP-30, respiratory tract model
- ICRP-30, GI model
- ICRP-30, general systemic model
- Wrenn-Lipsztein uranium model
- Fisher modified Wrenn-Lipsztein uranium model
- ICRP-54, uranium excretion model

CINDY uses the Q and tissue or organ weighting factors published in ICRP-26. The bone dosimetry classification is "volume".

J.5 Modeling the Behavior of Uranium and DU in the Human Body

The key to estimating the amount of DU that has been internalized requires an understanding of the behavior of uranium or DU in the human body. Biokinetic models of uranium or DU metabolism are the only link between bioassay results and estimates of organ depositions or doses. Such models are used for estimating intakes or doses. The predicted absorption of DU to body fluid (or blood) is about four times greater for Class Y than Type S, and predicted fecal excretion is nearly two-fold greater for Class Y than Type S.

The models discussed in this Appendix are very simple representations of the complex behavior of uranium or DU that is taken into the body. Care should be used when dealing with the models, particularly when they are being applied to dose reconstruction for specific intake incidents. Values need to be adjusted to simulate actual exposure scenarios.

The behavior of uranium or DU in the body may be understood by describing the body as a series of mathematical compartments among which material is transferred. Inhaled material is deposited in the respiratory tract where it is either retained or transferred into the bloodstream or GI tract. Material deposited in the GI tract [through either ingestion (direct), secondary ingestion (hand-to-mouth), or transfer from the respiratory tract (indirect ingestion)] may be

absorbed into the bloodstream or be excreted. Finally, material transferred into the bloodstream (from the respiratory tract, GI tract, direct ingestion, or recycling) is either transferred to various organs or excreted via the urine and feces (see Figures J-9 and J-13).

The behavior (distribution and retention) of uranium or DU in these three major compartments [respiratory tract, GI tract, and systemic (blood and internal organs) circulation] is a function of the chemical and physical form of the uranium or DU. A knowledge of the chemical and physical forms present is critical to estimating the amount of DU that has been internalized and the resultant organ uptake of DU.

Although uranium is an actinide, it chemically acts as an alkaline earth element in the body, because it follows the movement of calcium (Ca) in the human body. However, it exhibits different rates of transfer from that of Ca due to discrimination by biological membranes and bone minerals. The biokinetic parameter values (transfer rates) for uranium or DU are provided in ICRP-69 and ICRP-78.

Table J-19 summarizes an example of the CEDE and individual organ CDE using the ICRP-26 organ weighting factors for an inhalation intake of 41 mg of 5 μm AMAD DU aerosol that is 17 percent Class W (or Type M) and 83 percent Class Y (or Type S).

Table J-19. An Example of the CEDE and Individual Organ Dose Equivalent from an Inhalation Intake of 41 mg of DU Using LUDEP (ver. 2.06)

Assuming 83% of the 41 mg (34 mg) Intake is Class Y or Slow Absorption							
	DOSE EQUIVALENT (rem)						
ORGAN	U-238	U-236	U-235	U-234	Total CDE (rem)	ICRP-26 Organ Weighting Factors	Effective Dose Equivalent (EDE) [W_T * CDE (rem)**
Breasts	4.35E-5	1.55E-8	1.96E-6	3.17E-6	4.86E-5	0.15	7.29E-6
Lungs	5.29E+0	3.64E-3	7.66E-2	8.01E-1	6.17E+0	0.12	7.40E-1
Gonads	2.65E-5	1.54E-8	4.63E-7	3.15E-6	3.01E-5	0.25	7.53E-6
Bone Marrow	7.16E-4	4.13E-7	9.91E-6	8.43E-5	8.11E-4	0.12	9.73E-5
Bone Surface	1.05E-2	6.46E-6	1.42E-4	1.32E-3	1.19E-2	0.03	3.58E-4
Thyroid	3.20E-5	1.54E-8	9.40E-7	3.15E-6	3.61E-5	0.03	1.08E-6
Remainder*	7.92E-3	3.87E-6	9.34E-5	7.89E-4	8.81E-3	0.30	2.64E-3
					Total EDE for Class Y or Slow Absorption =		**7.43E-1**
Assuming 17% of the 41 mg (7 mg) Intake is Class W or Moderate Absorption							
	DOSE EQUIVALENT (rem)						
ORGAN	U-238	U-236	U-235	U-234	Total CDE (rem)	ICRP-26 Organ Weighting Factors	Effective Dose Equivalent (EDE) [W_T * CDE (rem)
Breasts	5.47E-5	3.35E-8	7.76E-7	6.83E-6	6.23E-5	0.15	9.35E-6
Lungs	6.06^{E}-1	4.31E-4	8.98E-3	9.64E-2	7.11E-1	0.12	8.54E-2
Gonads	5.45^{E}-5	3.35E-8	7.61E-7	6.83E-6	6.21E-5	0.25	1.55E-5
Bone Marrow	1.63^{E}-3	9.51E-7	2.10E-5	1.94E-4	1.84E-3	0.12	2.21E-4
Bone Surface	2.41^{E}-2	1.49E-5	3.24E-4	3.04E-3	2.75E-2	0.03	8.25E-4
Thyroid	5.45^{E}-5	3.35E-8	7.64E-7	6.83E-6	6.22E-5	0.03	1.86E-6
Remainder*	1.06E-2	6.37E-6	1.39E-4	1.30E-3	1.20E-2	0.30	3.60E-3
					Total EDE for Class W or Moderate Absorption =		**9.00E-2**
					CEDE 83% Class Y and 17% Class W =		**0.83 rem**

*Remainder organs include: kidneys, small intestine wall, lower large intestine wall, upper large intestine wall, and stomach.

**The assumptions used in these calculations are BR of 3.0 m^3/hr, 5 μm AMAD aerosol, and the individual is a mouth breather.

Table J-20 summarizes an example of the CEDE and individual organ CDE using the ICRP-60 organ weighting factors for an inhalation intake of 41 mg of 5 μm AMAD DU aerosol that is 17 percent Class W (or Type M) and 83 percent Class Y (or Type S).

Table J-20. An Example of the CEDE and Individual Organ Dose Equivalent from an Inhalation Intake of 41 mg of DU Using LUDEP (ver. 2.06)

Assuming 83% of the 41 mg (34 mg) Intake is Class "Y" or Slow Absorption							
	DOSE EQUIVALENT (rem)						
ORGAN	U-238	U-236	U-235	U-234	Total CDE (rem)	ICRP-60 Organ Weighting Factors	Effective Dose Equivalent (EDE) [W_T * CDE] (rem)
Breasts	4.35E-05	1.55E-08	1.96E-06	3.17E-06	4.86E-05	0.05	2.43E-06
Stomach wall	8.71E-05	3.17E-08	1.60E-06	6.47E-06	9.52E-05	0.12	1.14E-05
Liver	4.09E-05	1.57E-08	1.76E-06	3.20E-06	4.58E-05	0.05	2.29E-06
Lungs	5.29E+00	3.64E-03	8.57E-02	8.01E-01	6.18E+00	0.12	7.41E-01
Gonads	2.65E-05	1.54E-08	4.63E-07	3.15E-06	3.01E-05	0.2	6.03E-06
Bone marrow	7.16E-04	4.13E-07	9.91E-06	8.43E-05	8.11E-04	0.12	9.73E-05
Bone surfaces	1.05E-02	6.46E-06	1.42E-04	1.32E-03	1.19E-02	0.01	1.19E-04
Skin	2.86E-05	1.54E-08	6.29E-07	3.15E-06	3.24E-05	0.01	3.24E-07
Thyroid	3.20E-05	1.54E-08	9.40E-07	3.15E-06	3.61E-05	0.05	1.80E-06
Urinary bladder wall	2.54E-05	1.54E-08	3.74E-07	3.14E-06	2.90E-05	0.05	1.45E-06
Colon	1.49E-03	4.65E-07	1.25E-05	9.50E-05	1.60E-03	0.12	1.92E-04
Oesophagus	4.71E-05	1.55E-08	2.26E-06	3.16E-06	5.26E-05	0.05	2.63E-06
Remainder*	1.35E-03	8.55E-07	1.92E-05	1.74E-04	1.54E-03	0.05	7.72E-05
Breasts	5.47E-05	3.35E-08	7.76E-07	6.83E-06	6.23E-05	0.05	3.12E-06
Stomach wall	6.36E-05	3.63E-08	8.38E-07	7.41E-06	7.19E-05	0.12	8.63E-06
Liver	5.47E-05	3.35E-08	7.78E-07	6.83E-06	6.23E-05	0.05	3.12E-06
Lungs	6.06E-01	4.31E-04	8.98E-03	9.64E-02	7.11E-01	0.12	8.54E-02
Gonads	5.45E-05	3.35E-08	7.61E-07	6.83E-06	6.21E-05	0.2	1.24E-05
Bone marrow	1.57E-03	9.51E-07	2.10E-05	1.94E-04	1.78E-03	0.12	2.14E-04
Bone surfaces	2.41E-02	1.49E-05	3.24E-04	3.04E-03	2.75E-02	0.01	2.75E-04
Skin	5.44E-05	3.35E-08	7.50E-07	6.83E-06	6.20E-05	0.01	6.20E-07
Total EDE for Class "Y" or Slow Absorption =							**7.42E-01**

Table J-20. An Example of the CEDE and Individual Organ Dose Equivalent from an Inhalation Intake of 41 mg of DU Using LUDEP (ver. 2.06) (con't.)

Assuming 17% of the 41 mg (7 mg) Intake is Class "W" or Moderate Absorption							
	DOSE EQUIVALENT (rem)						
ORGAN	U-238	U-236	U-235	U-234	Total CDE (rem)	ICRP-60 Organ Weighting Factors	Effective Dose Equivalent (EDE) [W_T * CDE] (rem)
Thyroid	5.45E-05	3.35E-08	7.64E-07	6.83E-06	6.22E-05	0.05	3.11E-06
Urinary bladder wall	5.43^{E}-05	3.35E-08	7.44E-07	6.83E-06	6.19E-05	0.05	3.09E-06
Colon	2.96^{E}-04	1.08E-07	2.74E-06	2.20E-05	3.21E-04	0.12	3.85E-05
Oesophagus	5.48E-05	3.35E-08	7.88E-07	6.83E-06	6.25E-05	0.05	3.12E-06
Remainder*	1.96E-04	1.22E-07	2.69E-06	2.48E-05	2.24E-04	0.05	1.12E-05
Total EDE for Class "W" or Moderate Absorption =							**8.59E-02**
CEDE 83% Class "Y" and 17% Class "W" =							**0.83 rem**

*Remainder organs include adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, and uterus

**The assumptions used in thee calculations are BR of 3.0 m^3/hr, 5 μm AMAD particle size, and mouth breather.

J.6 Calculation and Comparison of Inhalation Dose Conversion Factors for DU

The inhalation DCFs for aerosols of 1 μm AMAD and 5 μm AMAD having a solubility of 83 percent Class Y (or Type S) and 17 percent Class W (or Type M) as calculated for a nose breather and for a month breather having a BR of 3.0 m^3/hr (50 L/min) are provided below.

- The equation for calculation of the DCF is:

DCF = (rem/mg * fraction of Class D) + (rem/mg * fraction of Class W) + (rem/mg * fraction of Class Y)

Where:

- Rem/mg is from the LUDEP calculation. [LUDEP takes into consideration the DU isotopic mixture of uranium, particle size, BR, type of exercise, type (or route) of breathing and the solubility class.]
- Fraction of class is the fractional amount of each of the respiratory tract clearance classes.

- **Summary Comparison of DCFs for Inhalation of DU**

Nose (1 μm AMAD) 83% Y + 17% W

$(1.68 \times 10^{-2}$ rem/mg * 0.83) + $(7.05 \times 10^{-3}$ rem/mg * 0.17) = 1.51×10^{-2} rem/mg

Nose (5 μm AMAD) 83% Y + 17% W

$(1.68 \times 10^{-2} * 0.83) + (9.50 \times 10^{-3} * 0.17) = 1.56 \times 10^{-2}$ rem/mg

Mouth (1 μm AMAD) 83% Y + 17% W

$(2.01 \times 10^{-2} * 0.83) + (8.28 \times 10^{-3} * 0.17) = 1.81 \times 10^{-2}$ rem/mg

Mouth (5 μm AMAD) 83% Y + 17% W

$(2.18 \times 10^{-2} \times 0.83) + (1.25 \times 10^{-2} * 0.17) = 2.02 \times 10^{-2}$ rem/mg

J.7 ICRP-30 Gastrointestinal Tract Model

The GI tract model is divided into four compartments: the stomach (ST), the small intestine (SI), the upper large intestine (ULI), and the lower large intestine (LLI).

Material is assumed to be transferred from ST→SI at a fractional rate of 2/day, from SI→ULI at a fractional rate of 6/day, from ULI→LLI at a fractional rate of 1.88/day, and from LLI→feces at a fractional rate of 1/day.

The absorption of ingested material to blood occurs in SI. The absorption to blood is described in terms of a fraction f_1. With the long radiological half time (T_p) of uranium or DU, the fraction f_1 of the ingested material moves from SI→blood, and the fraction $1 - f_1$ moves from SI→ULI and eventually is excreted in the feces.

The GI tract transfer coefficient rate from SI to blood is the following:

$$6 * f_1/(1 - f_1)/d$$

Table J-22 summarizes the transfer of uranium or DU through the GI tract.

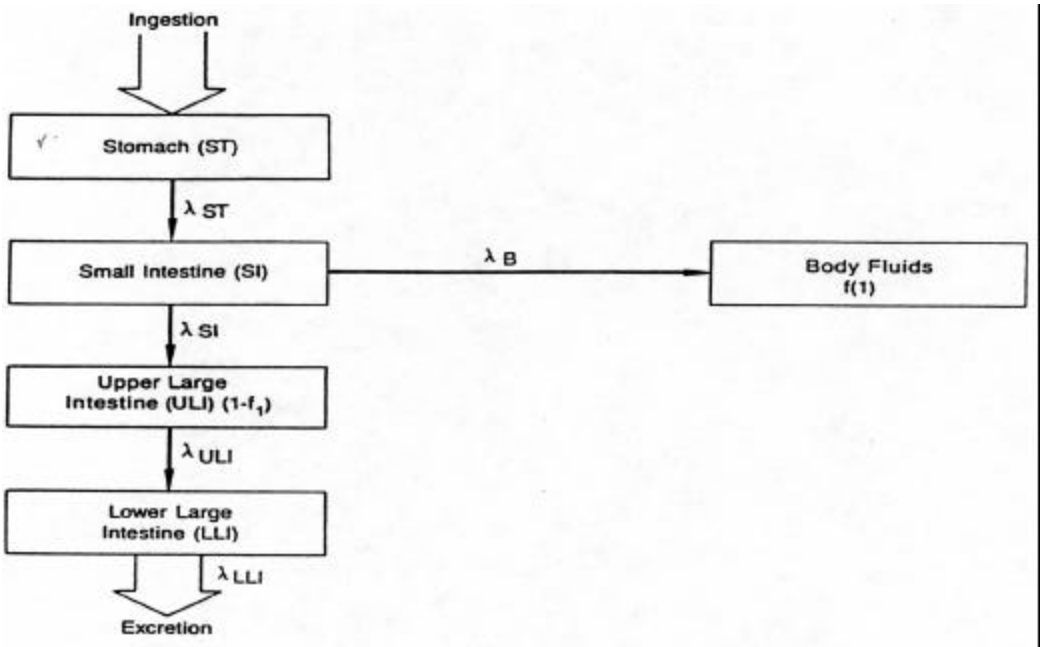
Table J-22. Transfer of Uranium or DU Through the GI Tract

Respiratory Tract Clearance Class/Absorption Type	Fraction of Uranium or DU Transferred to Blood from GI Tract (f_1)	SI→ULI ($1 - f_1$)	SI→Blood (d^{-1}) [$6 * f_1/(1 - f_1)/d$]
D (F)	0.02	0.98	0.12
W (M)	0.02	0.98	0.12
Y (S)	0.002	0.998	0.012

Absorption of uranium or DU from the GI tract is minimal (2 percent) for Class D (or Type F) and Class W (or Type M) uranium or DU and almost negligible (0.2 percent) for Class Y (or Type S) uranium or DU (ICRP-68, ICRP-69 and ICRP-71).

Figure J-11 shows the GI tract model recommended in ICRP-30. Uranium or DU entering the GI tract from either the respiratory tract or directly from ingestion is either excreted via feces or is absorbed from the GI tract into the bloodstream.

Inspection of the respiratory tract and GI tract models reveal a number of predicted features, which affect the management of an internal dose-monitoring program. It is worth noting that, for almost all clearance classes and particle sizes, a large fraction of inhaled material will appear in the feces within the first week or so after intake.



Section of GI tract	Mass of walls* (g)	Mass of contents* (g)	Mean residence time (day)	λ day⁻¹
Stomach (ST)	150	250	1/24	24
Small Intestine (SI)	640	400	4/24	6
Upper large Intestine (ULI)	210	220	13/24	1.85
Lower Large Intestine (LLI)	160	135	24/24	1

Figure J-11. ICRP-30 GI Tract Model.

By coupling this GI tract model to the previously discussed respiratory tract model, one can derive retention functions, which predict the quantity of material in the feces as a function of time after intake. Figure J-12 shows the predicted fecal excretion pattern based on ICRP-30 models after an acute intake. Figure J-12 may be used for either uranium (U-234, U-235, U-236, U-238) or DU.

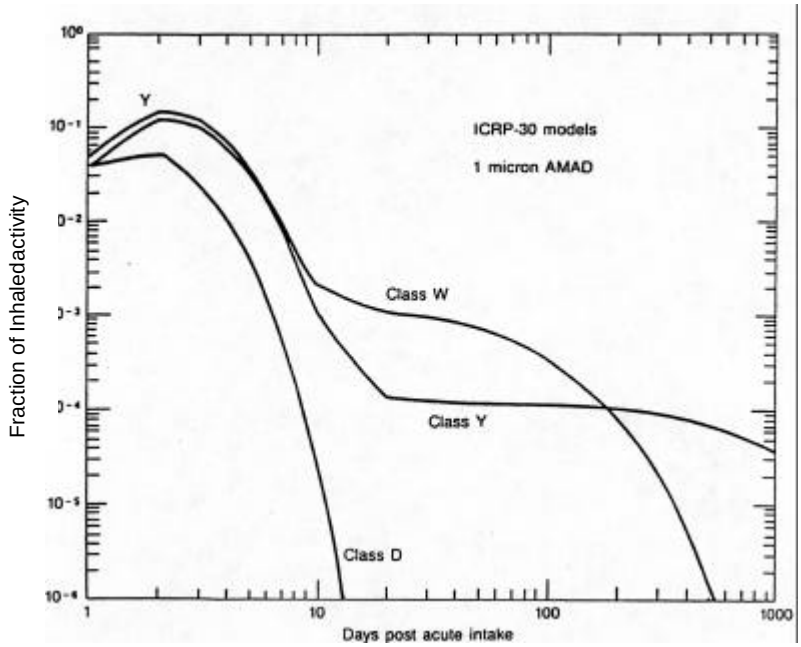


Figure J-12. Fecal Excretion-Acute Inhalation.

Table J-23 summarizes the CEDE from an ingestion intake of 1 mg (100 percent insoluble) of DU. The ingestion DCFs for the uranium isotopes and progeny that are in secular equilibrium were obtained from IAEA Safety Series 115.

Table J-23. 1 mg Ingestion Intake/Dose of DU
(100% Insoluble)

Isotope	Intake (mg)	Dose (rem)
U-234	6E-6	1.15E-6
U-235	2E-3	6.77E-7
U-236	3E-6	5.69E-9
U-238	0.998	1.43E-5
Total	1	1.61E-5

Table J-24 summarizes the CEDE from an ingestion intake of 1 mg (100 percent soluble) of DU. The ingestion DCFs for the uranium isotopes and progeny that are in secular equilibrium were obtained from IAEA Safety Series 115.

Table J-24. 1 mg Ingestion Intake/Dose of DU
(100% Soluble)

Isotope	Intake (mg)	Dose (rem)
U-234	6E-6	6.79E-6
U-235	2E-3	1.28E-6
U-236	3E-6	5.70E-5
U-238	0.998	5.87E-5
Total	1	1.24E-4

- Summary Comparison of DCFs for Ingestion of DU

$(1.61 \times 10^{-5}$ rem/mg * 0.83) + $(1.24 \times 10^{-4}$ rem/mg * 0.17) = 3.44×10^{-5} rem/mg

J.8 Systemic Retention and Excretion of Uranium

Understanding and predicting the behavior of uranium or DU deposited into systemic distribution (bloodstream and organs) play a critical role in assessing doses from intakes of uranium or DU. The behavior of uranium or DU in the body, and subsequent excretion patterns, are complex and are still the subject of on-going research.

A detailed review of models used to predict systemic uranium or DU behavior is beyond the scope of this Appendix. A brief discussion of ICRP-10 and ICRP-30 metabolic models follows in Sections J-9 and J-10, respectively.

J-9 ICRP-10 Retention and Excretion Functions for Uranium

The ICRP recommended the following systemic uptake retention power function for uranium in ICRP-10:

$$R_{(t)} = 0.2\ t^{-0.5} \text{ for values of t greater than 1 day post-intake.}$$

$R_{(t)}$ represents the fraction of the initial uptake to systemic distribution, which is present in the system at any day, t, after intake. Since this is an uptake retention power function, the value of the $R_{(t)}$ at t = 0 is, by definition, 1.0.

A related fractional excretion function is also presented:

$$Y_{(t)} = 0.8 \text{ for } t = 1 \text{ day}$$

$$Y_{(t)} = 0.1\ t^{-1.5} \text{ for } t > 1 \text{ day}$$

Since this fractional excretion function is simply the first derivation of the uptake retention function, it represents the instantaneous fraction of the initial uptake, which is excreted at any time greater than 1 day.

Note that, with the possible exception of Class D (or Type F) materials, these functions must be coupled with those of the respiratory tract model in order to interpret bioassay results from inhalation intakes.

J.10 ICRP-30 Systemic Retention Model for Uranium

The corresponding retention functions are as follows:

$$R(\text{bone}) = 0.2\ e^{-0.693\ t/20} + 0.023\ e^{-0.693\ t/5000}$$

$$R(\text{kidney}) = 0.12\ e^{-0.693\ t/6} + 5.2\text{E-}4\ e^{-0.693\ t/1500}$$

$$R(\text{other}) = 0.12\ e^{-0.693\ t/6} + 5.2\text{E-}4\ e^{-0.693\ t/1500}$$

This ICRP-30 retention model is a very simplistic representation of the behavior of uranium or DU in the body. It does not, for example, explicitly recognize any recycling of uranium or DU from organs back to the transfer compartment. However, the retention functions of ICRP-30 are “effective” uptake retention functions, that is, they were developed to fit observed retention and excretion data. The behavior described by these functions must therefore include all of the complexities of distribution within the body, including "recycling".

J-11 ICRP 30 Generic Biokinetic Model for Uranium

Figure J-13 provides a ICRP-30 schematic of a generic biokinetic model.

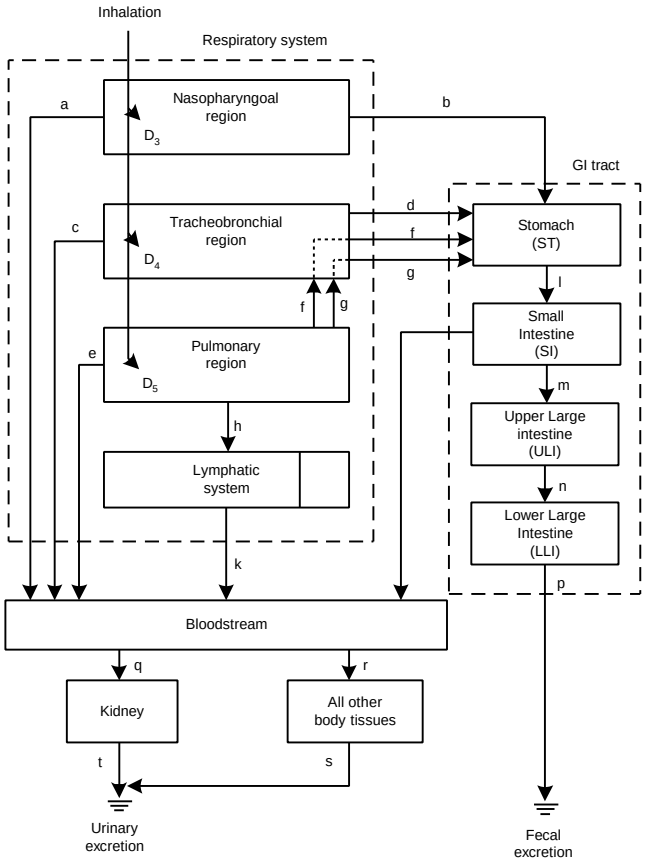
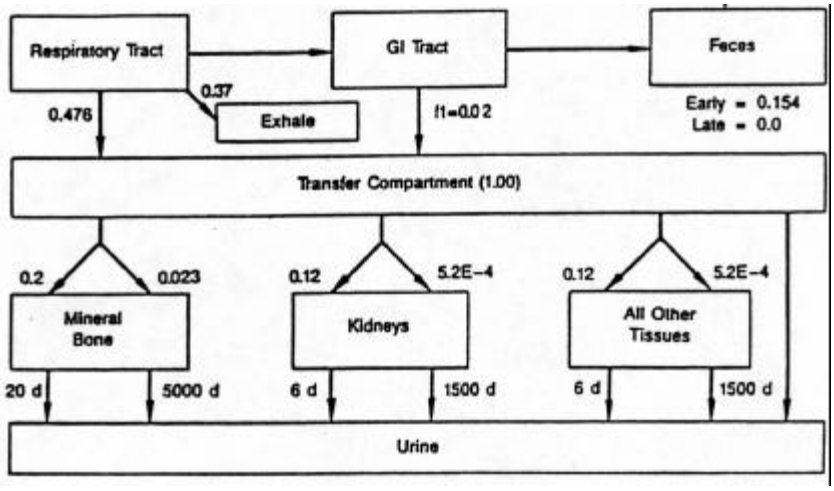


Figure J-13. Schematic Diagram of the ICRP-30 Biokinetic Model.

Figures J-14 and J-15 represent the ICRP-30 biokinetic model for respiratory Classes D, W and Y implied by the retention functions for uranium or DU and statements of ICRP-30 and ICRP-54. According to this "once through" model, for uranium or DU entering the bloodstream (or “transfer compartment”), about 22.3 percent goes to bone where it is assumed

to be uniformly distributed throughout the volume of mineral bone. About 12.052 percent of the uranium or DU goes to the kidneys, about 12.052 percent goes to "all other tissues of the body," and the remainder (about 54 percent) goes "directly to urinary excretion."

CLASS D
Chemical Form = UF_6, UO_2F_2, $UO_2 (NO_3)_2$



CLASS W
Chemical Form = UO_3, UF_4, UCl_4

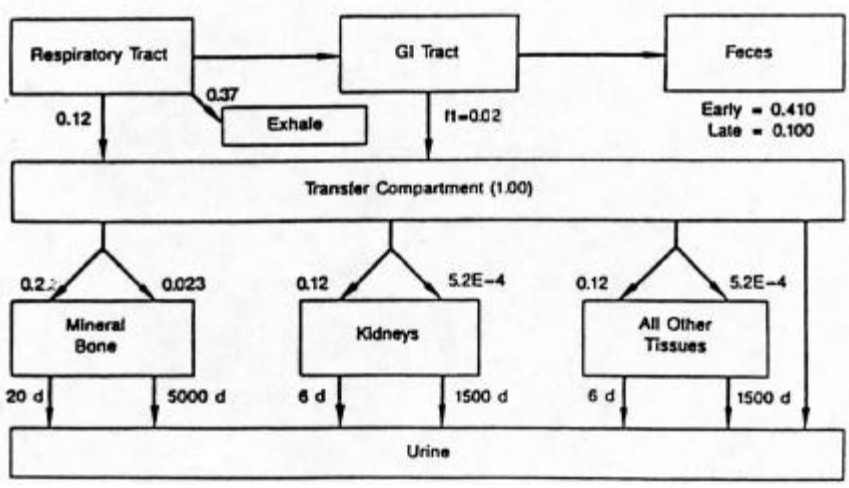


Figure J-14. ICRP-30 Metabolic Models – Class D and Class W.

CLASS Y
Chemical Form – UO_2, U_3O_8

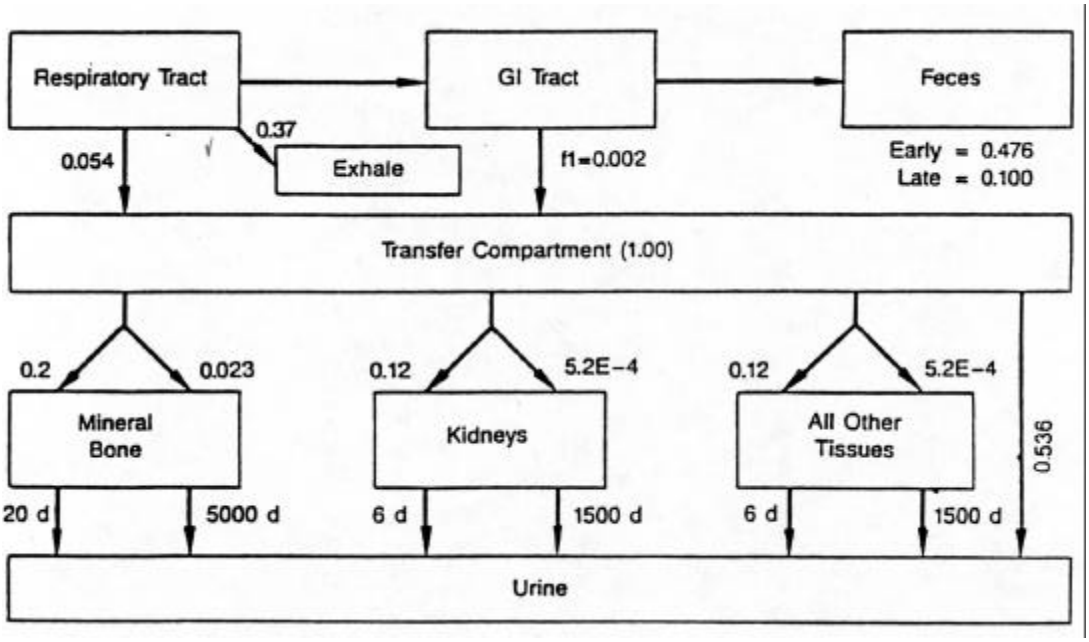


Figure J-15. ICRP-30 Metabolic Model – Class Y.

Coupling the respiratory tract model with different systemic retention functions will, of course, give different predicted excretion patterns and correspondingly different estimates of intake. All other things being equal, the ICRP-10 function will result in higher estimates of intake (from about 3 days to 100 days) because the predicted fractional excretion is lower than that of ICRP-30.

The fractional uptake retention functions presented in ICRP-10 and ICRP-30 are compared in Figure J-16. These curves represent the fraction of an acute uptake by blood that is retained on any day post acute intake.

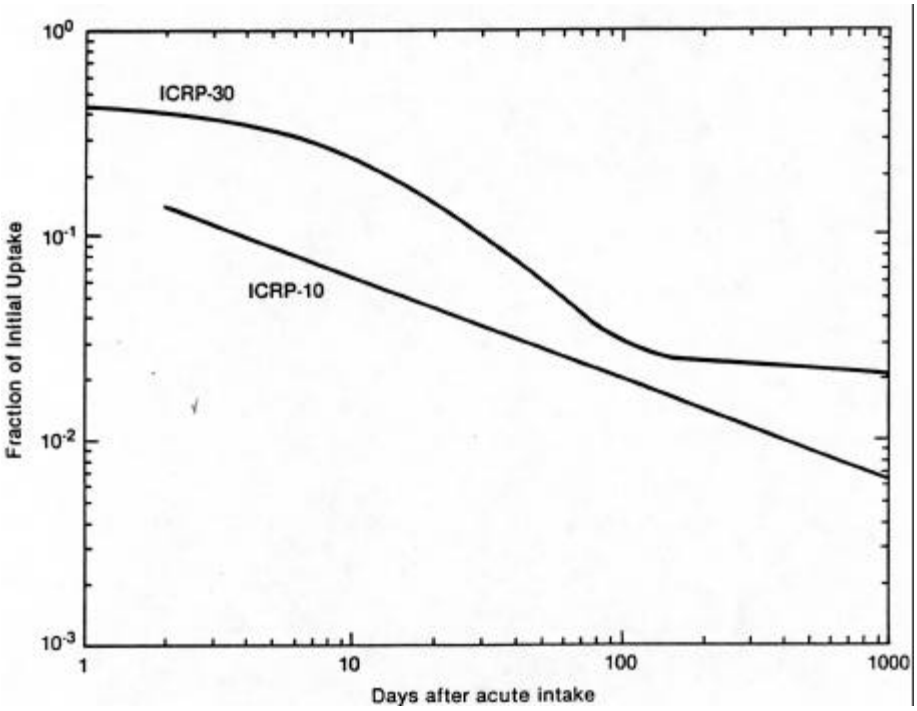


Figure J-16. Fractional Uranium Uptake Retention Functions.

The corresponding uptake fractional excretion functions seen in Figure J-17 represent the fraction of the acute uptake, which is excreted at any day after intake. Note that these fractional excretion functions give "instantaneous" excretion rates, not incremental "24-hour" excretion rates.

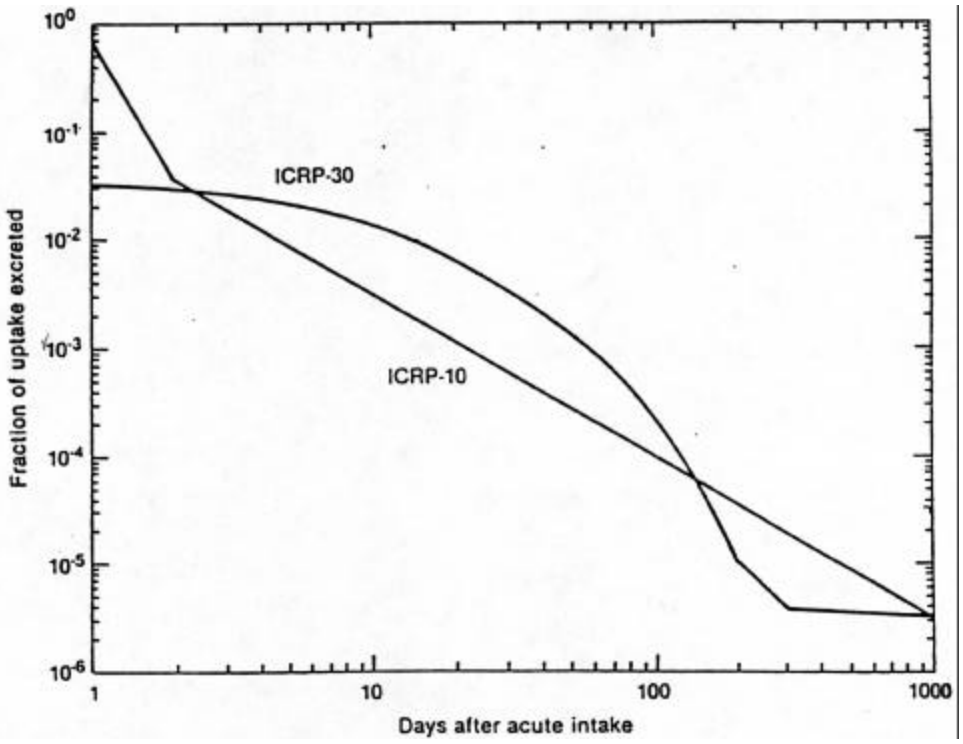


Figure J-17. Fractional Uranium Urinary Excretion Functions.

The distribution and retention of uranium as presented in ICRP-54 assumes that the uranium or DU entering the transfer compartment (blood) is dependent on solubility or respiratory tract clearance class as presented in Table J-6. Fifty-four (54) percent of the uranium or DU is directly excreted in the urine. Twenty (20) percent and 2.3 percent (or 22.3 percent) are transferred to mineral bone and retained there with biological half-times (T_b) of 20 days and 5000 days, respectively. Twelve (12) percent and 0.052 percent (or 12.052 percent) are transferred to the kidneys and retained there with T_b of 6 days and 1500 days, respectively. Twelve (12) percent and 0.052 percent (or 12.052 percent) are transferred to all other tissues of the body and retained there with T_b of 6 days and 1500 days, respectively.

Thus, systemic body retention, which is a sum of exponential function for uranium or DU can be represented by:

$$R_{(t)} = 5.4\times10^{-1} \exp\left(-0.693\frac{t}{0.25}\right) + 2.4\times10^{-1} \exp\left(-0.693\frac{t}{6}\right) + 2.0\times10^{-1} \exp\left(0.693\frac{6}{20}\right) + 1.0\times10^{-3} \exp\left(-0.693\frac{t}{1500}\right) + 2.3\times10^{-2} \exp\left(-0.693\frac{t}{5000}\right)$$

Intake limits of the more soluble Class D compounds are controlled by consideration of the chemical toxicity. Intake limits of the insoluble Class Y compounds are controlled by the radiation dose rather than chemical toxicity. However, there are data suggesting that DUO_2 (a Class Y compound) can act as a moderately soluble Class W (or Type M) compound.

The DU compounds initially formed on the battlefield due to fire or impact have been found to be DUO_2 and DU_3O_8. The solubility of these compounds due to fire has been found to be primarily Class Y (or Type S). The solubility of these compounds formed due to impact has been found to be also primarily Class Y (or Type S); however, there is a greater percentage of the soluble compound present in this type of event.

J.12 Prediction of Excretion Rates for Uranium

The systemic retention functions are commonly coupled with the respiratory tract model and used to predict the rates of excretion from intakes. The NRC[10] uses the retention function and

respiratory tract model of ICRP-30 to predict excretion and to derive reference levels and bioassay frequencies.

This Appendix presents predictions of excretion based on the ICRP-30 respiratory tract model coupled to the ICRP-30 systemic retention model for uranium or DU. In doing so, it is recognized that the systemic models of ICRP-30 were not necessarily intended to be used to predict excretion patterns or to estimate intake from bioassay results. The use of such models produces estimates of intake, which are sufficiently accurate to be used to establish reference levels and bioassay frequencies.

Great care should be used in extending such use to estimates of intake and the resultant dose for individuals. When practicable, every attempt should be made to match the model and/or model parameters to the individual and actual excretion rates observed to perform a dose reconstruction for that individual.

Figure J-18 shows the predicted urine excretion rates for an acute inhalation intake of Class D (or Type F), W (or Type M), and Y (or Type S), 1-μm AMAD uranium or DU aerosol. The daily fractional urinary excretion values have been divided by 1.4 L/day to account for the average daily urine volume of male workers on any day post acute intake.

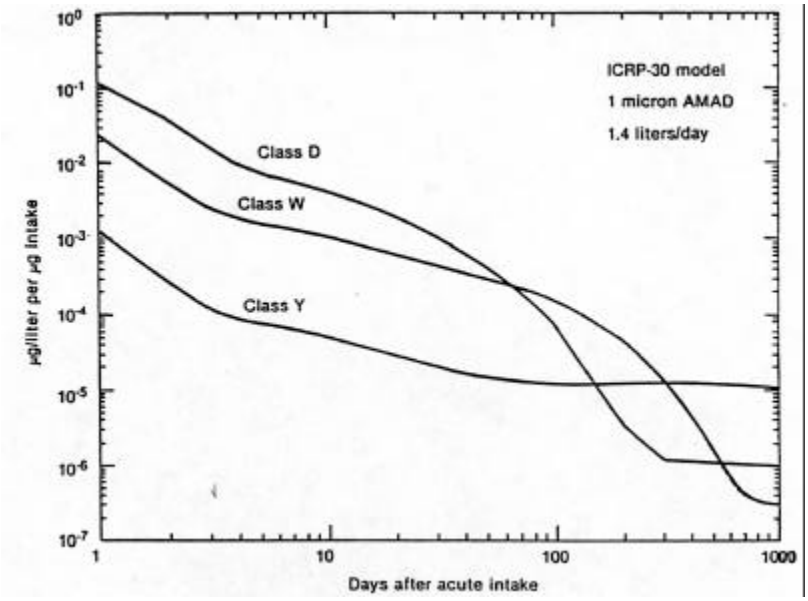


Figure J-18. Urinary Uranium Excretion Function Following Acute Intake.

J.13 ICRP-30 Metabolic Model for Uranium in Kidney

The quantity of uranium or DU present in the kidney is of interest because of chemical toxicity considerations. In the following figures, the ICRP-30 respiratory tract model has been coupled to the ICRP-30 retention function for the kidneys to derive kidney intake retention functions.

Figures J-14 and J-15 show that the parameters which control the ICRP-30 kidney retention model for uranium or DU are the fractional uptake from the blood (about 0.12) and the T_b in the kidney (6 days) or biological elimination constant (λ_b) 0.116/day and 0.00052 (1,500 days) or λ_b 0.00046/day, respectively. Uranium is removed from the renal tubules to the urinary bladder with a T_b of 7 days or an elimination constant of 0.1 per day. In comparison, ICRP-10

used a fractional uptake of 0.11, and a T_b in the kidney of 15 days. Thus, the only significant difference in the models is the T_b of uranium or DU in the kidney.

The use of the ICRP-30 metabolic model is sufficiently accurate to establish reference levels and bioassay frequencies. Once again, the use of the ICRP-30 model for individual dose reconstruction should be done with great care.

Figure J-19 shows the predicted kidney burden based on the ICRP-30 model as a function of time after a single acute intake of 1 μm, Class D (or Type F), W (or Type M), or Y (or Type S) aerosol.

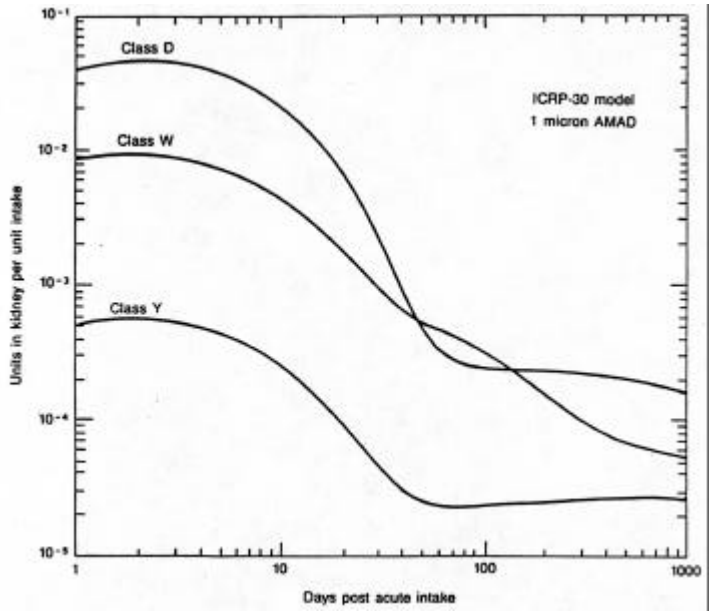


Figure J-19. Kidney Intake Retention Function – Acute Uranium or DU Intake.

The pathway for the removal of uranium or DU from the body is via the feces or transfer in the kidneys from the blood into urine. The functional unit of the kidney is the nephron, a structure that starts with the glomerulus where fluids and toxicants are removed from the blood, extends through a long tubular system in which the content and concentration of the fluid is adjusted, and ends with urine being passed into a collecting system that leads to the bladder.

Figure J-20 provides a diagram of the kidney and nephron.

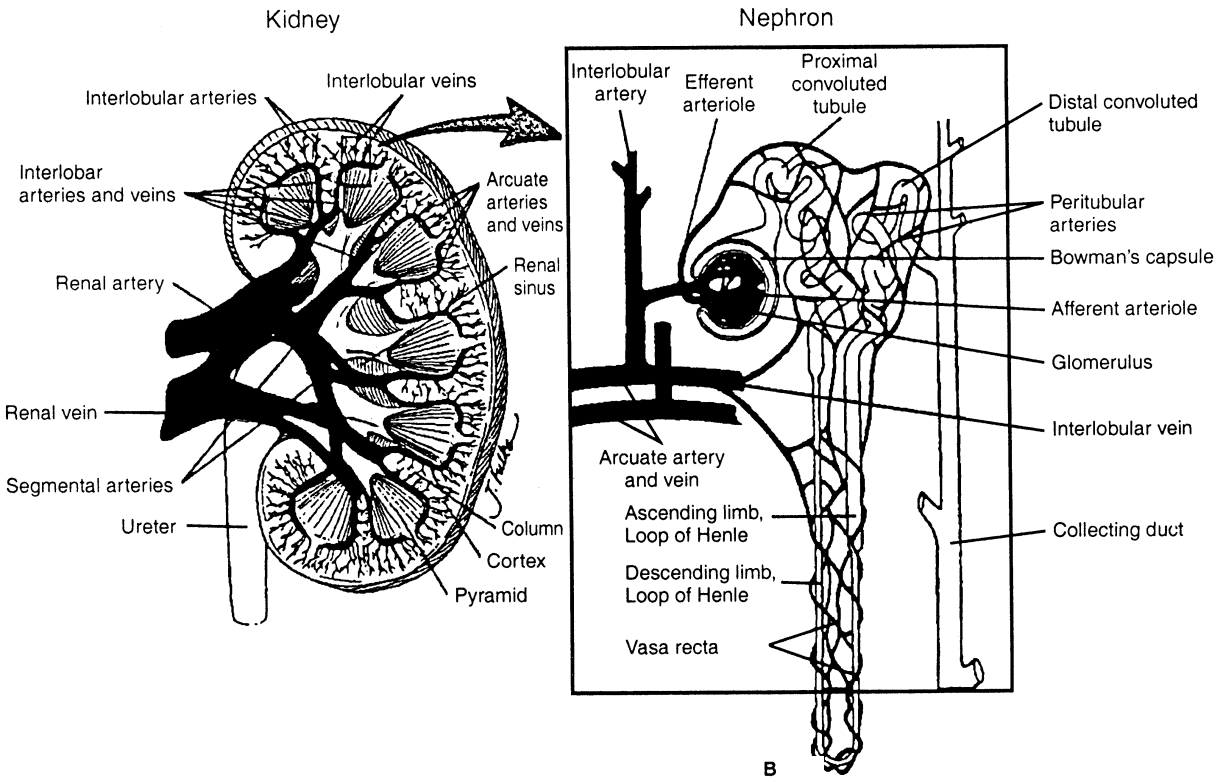


Figure J-20. Human Kidney and Nephron (National Defense Research Institute, 1998)

In the glomerulus, blood is filtered through a porous membrane so that a water solution of small molecules enters the tubular system and the relatively large blood cells and proteins remain in the blood.

One of the symptoms of kidney damage is the appearance of blood and/or protein in the urine. The tissue damage is usually localized in the proximal convoluted tubule. There is evidence in humans and animals of repair to damaged renal tubular epithelial tissue. The likelihood of developing delayed renal disease from DU exposure if there has been no acute toxicity is not observed or supported by medical evidence[3]. To date neither renal tubular dysfunction nor glomerular damage has been observed among Gulf War veterans, even among veterans with embedded DU fragments, McDiarmid et al., (1999 and 2000).

It should be noted that to date the VA has not observed any indications of either renal tubular dysfunction or glomerular damage among Gulf War Veterans, who would have inhaled DU while in a vehicle that had been perforated by DU munition(s).

J.14 ICRP-30 Metabolic Model for Uranium in Bone

According to the ICRP-30 metabolic model, the fraction 0.223 of the uranium or DU reaching the transfer compartment is estimated to go to mineral bone, where 0.20 is retained with a 20 days T_b, and 0.023 is retained with a 5000 days T_b. All of the long-lived isotopes of uranium (U-234, U-235, U-236, U-238 and DU) are assumed to be uniformly deposited

throughout the volume of mineral bone. Since this uranium or DU is distributed evenly within the mass of trabecular and cortical bone (1 and 4 kg, respectively), it is assumed that 20 percent of the uranium or DU goes to trabecular bone and 80 percent goes to cortical bone. Figure J-21 reflects this assumed distribution of uranium or DU in the bone.

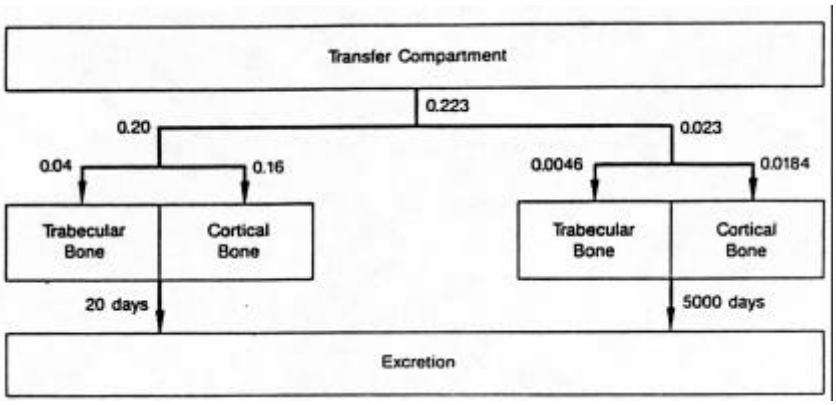


Figure J-21. ICRP-30 Uranium Bone Metabolic Model.

J.15 Application of Retention/Excretion Functions for Uranium

The incremental urine excretion functions used in this Appendix to predict systemic uranium or DU behavior may also be used to establish estimates of intake and dose. Each of the following intake estimators follows directly from the excretion functions previously discussed in this Appendix.

Figure J-22 shows the estimated intake as a function of "days post-acute intake" for a given urine sample result. The estimate of intake is derived as follows:

$$I = \frac{E_t * 1.4}{IRF}$$

Where:

I	=	The initial quantity of material or material inhaled (units)
E_t	=	The concentration of material or material observed in a urine sample collected on day, t, post-intake (units/liter)
IRF	=	The incremental intake retention function (that is, the fraction of the intake which would be expected to be excreted during day, t, post intake).
1.4	=	Reference Man urinary excretion rate in "L/day".

In this case, E is set to 1 unit/L, and the IRF is taken directly from Figure J-22. Although the Y axis of Figure J-22 (and similar figures) is expressed as "µg of uranium intake per µg/L", note that the curves could be expressed, for example, as "dpm of intake per dpm/L."

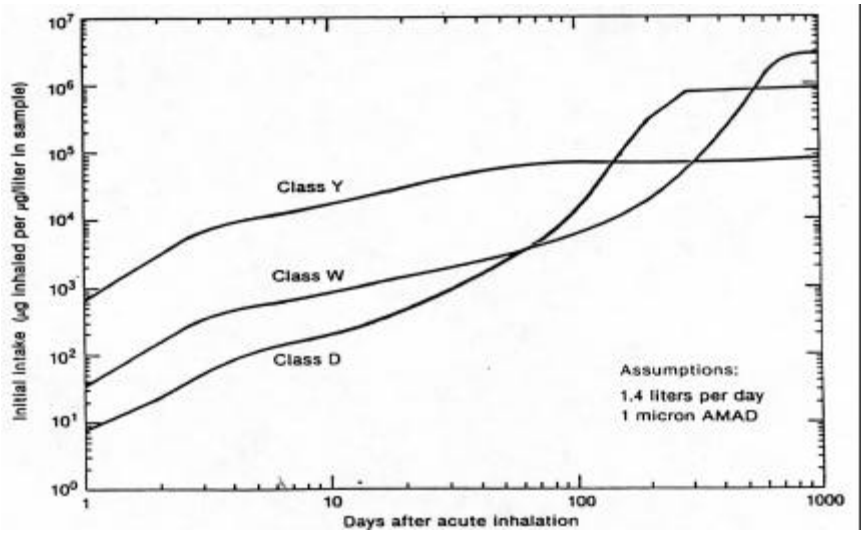


Figure J-22. Uranium Urine Intake Estimator – Acute Inhalation.

J.16 Chemical Toxicity of Uranium

One can relate the quantity of uranium or DU observed in the urine to the quantity of uranium or DU presumed to be deposited in the kidney. This "kidney-concentration" may then be compared to the ICRP guideline of 3 μg of U/g of kidney, Spoor and Hursh, (1973). The work of Morrow et al., as described in BEIR IV, has cast some doubt on the validity of the conclusion that 3 μg U/g of kidney is the threshold level of nephrotoxicity, NRC, (1988). The renal threshold concentration of uranium that results in significant damage is a matter of controversy and estimates range from ≤ 1 to 3 μg U/g of kidney. Based on the 1959 guidance of the ICRP, the threshold value for nephrotoxicity used in this report is 3 μg DU/g of kidney. Less than 1 percent of the original intake of DU by inhalation of a 1 μm AMAD aerosol makes its way to the kidney, where it might affect the function of the kidney (ICRP-71).

Figure J-23 shows the ratio of the mass of uranium in the kidneys to the mass observed in the urine as a function of days post-acute intake. The curves have been normalized to an assumed daily urine output rate of 1.4 L/day. Figure J-23 has been derived from the curves of Figure J-18 in a manner similar to that discussed for interpretation of urine samples. The curves, for all practical purposes, are identical from about day 3 to approximately 100 days post-intake.

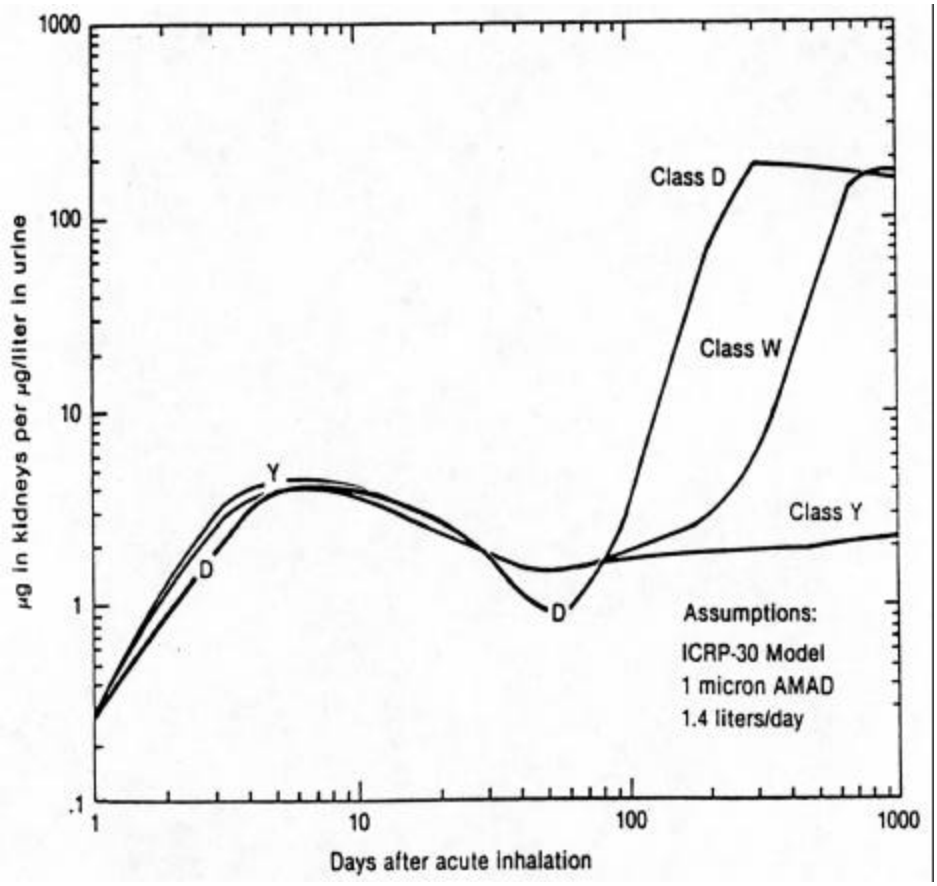


Figure J-23. Ratio of Uranium in Kidney to Urine Concentration – Acute Inhalation.

In some circumstances, the estimation of the fraction of inhaled uranium or DU, which reaches the kidneys, may be useful. This quantity of a 1 µm AMAD aerosol may be estimated using the ICRP-30 respiratory tract clearance Classes D, W, and Y and "once-through" biokinetic model (see Figures J-2 and J-3) as outlined below:

Class D:

Compartment & Pathway	Deposition * Compartmental Fraction(s)	Transferred Fraction	Biological Half-Times
a→ blood	(0.30 * 0.50)	= 0.15	(0.01 days)
b→GI→ blood	(0.30 * 0.50 * 0.02)	= 0.003	(0.01 days→GI)
c→ blood	(0.08 * 0.95)	= 0.076	(0.01 days)
d→GI→ blood	(0.08 * 0.05 * 0.02)	= 0.00008	(0.20 days→GI)
e→ blood	(0.25 * 0.80)	= 0.20	(0.50 days)
h→L→i→ blood	(0.25 * 0.20)	= 0.05	(0.50→0.50 days)
	Total	= 0.4791	

The fraction of the initial intake reaching the kidney is:

$$[0.4791 * (0.12 + 0.00052)] = 0.0577 \text{ or } 6\%$$

Class W:

Compartment & Pathway	Deposition * Compartmental Fraction(s)	Transferred Fraction	Biological Half-Times
a→blood	(0.30 * 0.1)	= 0.03	(0.01 days)
b→GI→blood	(0.30 * 0.9 *0.02)	= 0.0054	(0.40 days→GI)
c→blood	(0.08 * 0.5)	= 0.04	(0.01 days)
d→GI→blood	(0.08 * 0.5 * 0.02)	= 0.0008	(0.20 days→GI)
e→blood	(0.25 * 0.15)	= 0.038	(50 days)
f→d→GI→blood	(0.25 * 0.4 * 0.02)	= 0.002	(1→0.20 days→GI)
h→L→I→blood	(0.25 * 0.05)	= 0.013	(0.50→0.50 days)
	Total	= 0.1292	

The fraction of the initial intake reaching the kidney is:

$$[0.1292 * (0.12 + 0.00052)] = 0.0156 \text{ or } 1.6\%$$

Class Y:

Compartment & Pathway	Deposition * Compartmental Fraction(s)	Transferred Fraction	Biological Half-Times
a→blood	(0.30 * 0.01)	= 0.003	(0.01 days)
b→GI→blood	(0.30 * 0.99 *0.002)	= 0.00059	(0.40 days→GI)
c→blood	(0.08 * 0.01)	= 0.0008	(0.01 days)
d→GI→blood	(0.08 * 0.99 * 0.002)	= 0.00016	(0.20 days→GI)
e→blood	(0.25 * 0.05)	= 0.0125	(500 days)
f→d→GI→blood	(0.25 * 0.40 * 0.002)	= 0.0002	(1→0.2 days→GI)
h→L→i→blood	(0.25 * 0.15)	= 0.0375	(500→1000 days)
	Total	= 0.0548	

The fraction of the initial intake reaching the kidney is:

$$[0.0548 * (0.12 + 0.00052)] = 0.0066 \text{ or } 0.7\%$$

As an example, the upper-bound intake of DU was determined to be 41 mg of DU. The upper-bound value for Class D (or Type F) or soluble DU was determined to be 43 percent, and the lower-bound value for Class Y (or Type S) or insoluble DU was determined to be 57 percent.

The amount of 1 μm AMAD aerosol of Class D (or Type F) DU reaching the kidney is:

$$41 \text{ mg} * 0.43 * 0.0577 = 1 \text{ mg}$$

The amount of 1 μm AMAD aerosol of Class Y (or Type S) DU reaching the kidney is:

41 mg * 0.57 * 0.0066 = 0.15 mg

Therefore, for a 41 mg intake of 1 μm AMAD DU aerosol that is 43 percent Class D (or Type F) and 57 percent Class Y (or Type S), the upper-bound amount of DU reaching the kidney is 1 mg + 0.15 mg for a total of ≅ **1.2 mg** or 1.2 x 10^3 μg DU per 310 grams of kidney results in a concentration of 3.9 μg DU/g of kidney.

The amount of DU that passes through the kidney from an upper-bound intake of 41 mg of 1 μm AMAD aerosol, which is 17 percent Class W (or Type M) and 83 percent Class Y (or Type S) is—

- Class W (or Type M) -

41 mg * 0.17 * 0.0156 = 0.108 mg

- Class Y (or Type S) –

41 mg * 0.83 * 0.0066 = 0.2246 mg

Therefore, for a 41 mg intake of 1 μm AMAD DU aerosol that is 17 percent Class W (or Type M) and 83 percent Class Y (or Type S), the amount of DU passing through the kidney is

0.108 mg + 0.2246 mg for a total of ≅ **0.33 mg or 3.3 x 10^2** μg DU/310 grams of kidney resulting in a concentration of 1.1 μg DU/g of kidney.

According to the ICRP-30 respiratory tract model, the fraction of an inhaled Class D (or Type F), 5 μm AMAD aerosol that will be absorbed directly into the transfer compartment (body fluid) is (see Figures J-2 and J-3)—

Class D:

Compartment & Pathway	Deposition * Compartmental Fraction(s)	Transferred Fraction	Biological Half-Times
a→ blood	(0.70 * 0.50)	= 0.35	(0.01 days)
b→GI→ blood	(0.70 * 0.50 * 0.02)	= 0.007	(0.01 days→GI)
c→ blood	(0.08 * 0.95)	= 0.076	(0.01 days)
d→GI→ blood	(0.08 * 0.05 * 0.02)	= 0.00008	(0.20 days→GI)
e→ blood	(0.10 * 0.80)	= 0.08	(0.50 days)
h→L→i→ blood	(0.10 * 0.2 * 1.0)	= 0.02	(0.50→0.50 days)
	Total	= 0.5331	

The fraction of the initial intake reaching the kidney is—

$$[0.5331 * (0.12 + 0.00052)] = 0.0642 \text{ or } 6.4\%$$

According to the ICRP-30 respiratory tract model, the fraction of an inhaled Class W (or Type M), 5 μm AMAD aerosol that will be absorbed directly into the transfer compartment (body fluid) is (see Figures J-2 and J-3)—

Class W:

Compartment & Pathway	Deposition * Compartmental Fraction(s)	Transferred Fraction	Biological Half-Times
a→blood	(0.70 * 0.10)	= 0.07	(0.01 days)
b→GI→blood	(0.70 * 0.90 *0.02)	= 0.0126	(0.40 days→GI)
c→blood	(0.08 * 0.50)	= 0.04	(0.01 days)
d→GI→blood	(0.08 * 0.50 * 0.02)	= 0.0008	(0.20 days→GI)
e→blood	(0.10 * 0.15)	= 0.015	(50 days)
f→d→GI→blood	(0.10 * 0.40 * 0.02)	= 0.0008	(1→0.20 days→GI)
h→L→i→blood	(0.10 * 0.05 * 1.0)	= 0.005	(0.50→0.50 days)
	Total	= 0.1442	

The fraction of the initial intake reaching the kidney is—

$$[0.1442 * (0.12 + 0.00052)] = 0.0174 \text{ or } 1.7\%$$

According to the ICRP-30 respiratory tract model, the fraction of an inhaled Class Y (or Type S), 5 μm AMAD aerosol that will be absorbed directly into the transfer compartment (body fluid) is (see Figures J-2 and J-3)—

Class Y:

Compartment & Pathway	Deposition * Compartmental Fraction(s)	Transferred Fraction	Biological Half-Times
a→blood	(0.70 * 0.01)	= 0.007	(0.01 days)
b→GI→blood	(0.70 * 0.99 *0.002)	= 0.0014	(0.40 days→GI)
c→blood	(0.08 * 0.01)	= 0.0008	(0.01 days)
d→GI→blood	(0.08 * 0.99 * 0.002)	= 0.00016	(0.20 days→GI)
e→blood	(0.10 * 0.05)	= 0.005	(500 days)
f→d→GI→blood	(0.10 * 0.40 * 0.002)	= 0.00008	(1→0.2 days→GI)
h→L→i→blood	(0.10 * 0.15 * 0.90)	= 0.0135	(500→1000 days)
	Total	= 0.0279	

The fraction of the initial intake reaching the kidney is—

$$[0.0279 * (0.12 + 0.00052)] = 0.0034 \text{ or } 0.34\%$$

The amount of uranium or DU that passes through the kidney from an upper-bound intake of 41 mg of 5 μm AMAD aerosol that is 43 percent Class D (or Type F) and 57 percent Class Y (or Type S) is—

- Class D (or Type F) -

$$41 \text{ mg} * 0.43 * 0.0642 = 1.13 \text{ mg}$$

- Class Y (or Type S) -

$$41 \text{ mg} * 0.57 * 0.0034 = 0.0795 \text{ mg}$$

Therefore, for a 41 mg intake of 5 μm AMAD aerosol that is 43 percent Class D (or Type F) and 57 percent Class Y (or Type S), the upper-bound amount of DU reaching the kidney is 1.13 mg + 0.0795 mg for a total of ≅ **1.2 mg** or 1.2×10^3 μg DU/310 grams of kidney resulting in a concentration of 3.9 μg DU/g of kidney.

The total lower-bound Class D (or Type F) DU is 0 percent. The Class W (or Type M) is 17 percent and the upper-bound value for Class Y (or Type S) is 83 percent; therefore, the amount of DU that passes through the kidney from an upper-bound intake of 41 mg of 5 μm AMAD aerosol, which is 17 percent Class W (or Type M) and 83 percent Class Y (or Type S) is—

- Class W (or Type M) -

$$41 \text{ mg} * 0.17 * 0.0174 = 0.12 \text{ mg}$$

- Class Y (or Type S) -

$$41 \text{ mg} * 0.83 * 0.0034 = 0.12 \text{ mg}$$

Therefore, for a 41 mg intake of 5 μm AMAD DU aerosol that is 17 percent Class W (or Type M) and 83 percent Class Y (or Type S), the amount of DU passing through the kidney is 0.12 mg + 0.12 mg for a total of ≅ **0.24 mg** or 2.4 x 10^2 μg DU/310 grams of kidney resulting in a concentration of 0.77 μg DU/g of kidney.

Table 25 summarizes the fraction of 1 μm AMAD and 5 μm AMAD aerosols that are transferred from the respiratory tract to blood and then transferred from the respiratory tract via the blood to the kidney.

Table 25. Fraction of 1 μm AMAD and 5 μm AMAD DU Aerosols Transferred to Blood and to Kidney

Class	1 μm AMAD		5 μm AMAD	
	f_b	f_t*	f_b	f_t*
D	0.4791	0.0575	0.5331	0.0640
W	0.1292	0.0155	0.1442	0.0173
Y	0.0548	0.0066	0.0279	0.0033

* $f_t = f_b * 0.12$

The amount of DU that is inhaled which reaches the kidney is calculated as follows:

$$K_y = I * \sum_{Class}^{D,W,Y} (f_b * f_k)$$

Where:

K_y = Mass of DU in the kidney (mg)

I = Intake of DU (mg)

f_b = Fraction transferred from respiratory tract to blood (related to particle size and solubility)

f_k = Fraction transferred from blood to kidney (0.12)

For example, an acute intake of 79 mg of a 5 μm AMAD Class D (or Type F) aerosol will result in what mass of DU going to the kidneys and what concentration of DU in the kidney.

$$K_y = 79 \text{ mg} * 0.5331 * 0.12 = 5.1 \text{ mg}$$

The mass of the kidneys in Reference Man is 310 grams, so this amount, 5.1 mg in the kidney, represents about (5.1×10^3 μg/310 grams) or 16.5 μg/g of kidney.

For example, an acute intake of 79 mg of a 5 μm AMAD aerosol which is 17 percent Class W (or Type M) and 83 percent Class Y (or Type S), what is the mass of DU going to the kidney and the concentration of DU in the kidneys—

$$K_y = (79 \text{ mg} * 0.17 * 0.1442 * 0.12) + (79 \text{ mg} * 0.85 * 0.0279 * 0.12)$$

$$= 0.454 \text{ mg}$$

Kidney concentration:

$$0.454 \text{ mg} * 1 \times 10^3 \text{ µg/mg} \div 310\text{g} = 1.46 \text{ µg DU/g of kidney}$$

The daily removal rate of DU from the kidney is calculated as follows:

$$R = \lambda_b * K_y$$

Where:

R	=	Rate of removal from the kidney (mg/day)
λ_b	=	Biological elimination constant ($0.693/T_b$), T_b = 6 days
K_y	=	Mass of DU in the kidney (mg)

Therefore, the rate of removal of 0.454 mg of DU from the kidney per day is—

$$R = 0.116/\text{day} * 0.454 \text{ mg} = 0.0524 \text{ mg/day}$$

The methodology for estimating the amount of DU reaching the kidney may be used for different intakes and various classes of inhaled DU.

For example, the amount of DU that passes through the kidney from an inhalation intake of 79 mg of DU, having a particle size distribution of 5 μm AMAD aerosol which is 60 percent Class Y (or Type S), 20 percent Class W (or Type M), and 20 percent Class D (or Type F), is--

$$(0.60 * 79 * 0.0034) + (0.20 * 79 * 0.0174) + (0.20 * 79 * 0.0642) = 1.45 \text{ mg}$$

Therefore, for a 79 mg intake of 5 μm AMAD aerosol for the example above, the amount of DU passing through the kidney is **1.45 mg** or 1.45×10^3 μg DU/310 grams of kidney resulting in a concentration of ≅ 4.7 μg DU/g of kidney.

The values for Reference Man (ICRP-23) are based on the ICRP-30 respiratory tract model and biokinetic model for uranium or DU. Approximately 53 percent of inhaled 5 μm AMAD aerosol Class D (or Type F) is taken up into the bloodstream and 12.052 percent of that goes to the kidney.

A concentration of 3 μg of uranium/g of kidney tissue has been used as a guideline for controlling and monitoring uranium exposure on the basis of uranium's chemical toxicity, Spoor and Hursh, (1973). [The selection of the 3 μg of U/g of kidney is based on the radiological limit established in 1959 by the ICRP (ICRP-2). The ICRP value for the whole body content (or body burden) was 0.005 μCi of uranium, and the fraction, at that time assumed to be in the 300-gram kidney, was 0.065. Thus, $0.005/0.33 \times 10^{-6} * 0.065/300 = 3.3$ μg/g of kidney. The value of 3.3 μg/g of kidney was rounded to 3 μg/g of kidney]. Reference

Man (ICRP-23) has a kidney mass of 310 g; therefore, this concentration (3 μg U/g of kidney) translates into a total mass of 0.97 mg or about 1 mg of uranium or DU in the kidney. This guideline of 3 μg DU/g of kidney should be updated to reflect current knowledge.

See Appendix K for a discussion of the NRC, OSHA, ACGIH, DOE and Health Physics Society inhalation exposure limits for uranium. These inhalation limits (based on exposure to an airborne concentration) have been established for health and safety practices at uranium production facilities, and their relevance to a retrospective evaluation of a battlefield situation is questionable.

The ICRP (ICRP-6) established a recommended limit for an acute inhalation intake of 2.5 mg of soluble Class D (or Type F) uranium inhaled in any one day or an average ingestion over 2 days, which should not exceed 150 mg of soluble uranium Class D (or Type F). This value is based on an airborne mass concentration of 0.2 mg uranium per cubic meter.

Lawrence derived acute inhalation intake limits for uranium of 15 mg and 80 mg for Class D (or Type F) and Class W (or Type M), respectively. These values derived by Lawrence were based on not exceeding a kidney burden of 3 μg U/g of kidney after a single acute inhalation incidence of uranium or DU, LA-10246-MS, (1984).

The technical literature indicates that moderately soluble DUO_3 is more likely to remain in the respiratory tract (lung) and associated lymph nodes for weeks and is classed as a D or W (or

Type F or M) compound[3]. The relatively insoluble compounds DUO_2 and DU_3O_8 may remain in the respiratory tract (lung) for years and are classed as Y (or Type S) compounds.[5] DUO_2 and DU_3O_8 are produced during the perforation of a hard target; they are also produced in fires involving DU munitions. In contrast with the technical literature, various lung solubility studies conducted as a result of Army DU munition tests indicate that a range of DU solubility exists for these two compounds. Only DUO_2 and DU_3O_8 have been observed from either hard-target tests or fires. However, because DUO_3 has been found in some of the range studies and is considered to be the most soluble of the three DU oxides, it was chosen to model the soluble fraction.

The DU residue produced following a 120mm DU penetrator perforating a tank will result in an upper-bound acute inhalation and indirect ingestion intake of 79 mg of 17 percent moderately soluble Class W (or Type M) and 83 percent insoluble DU oxides Class Y (or Type S) for a single perforation of an Abrams tank and a 2-minute exposure. The estimated lower-bound acute inhalation and indirect ingestion intake is 9 mg of 17 percent moderately soluble Class W (or Type M) and 83 percent insoluble DU oxides Class Y (or Type S) for a single perforation of an Abrams tank and a 2-minute exposure. (See Appendix O for a discussion of the uncertainties associated with the use of the median intake value.)