ACTION LEVELS FOR AIRBORNE URANIUM IN THE WORKPLACE: CHEMICAL AND RADIOLOGICAL ASSESSMENTS

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ABSTRACT

A method is described for deriving two levels of action, an investigation level (IL) and an immediate action level (IAL), for different forms and mixtures of the natural uranium (U) isotopes ^{234}U, ^{235}U, and ^{238}U in air in the workplace. An IL indicates the need to confirm the validity of moderately elevated measurements of airborne U and adequacy of confinement controls and determine whether work limitations are appropriate. An IAL indicates that safeguards should be put into place immediately, including removal of workers from further exposure until conditions are acceptable. Derivations of ILs and IALs are based on latest radiation protection guidance, information on chemical toxicity of U, and biokinetic models for U. An action level (IL or IAL) is the more restrictive of two derived values, the action level based on U as a chemical hazard and the action level based on U as a radiation hazard.

Keywords: uranium, occupational exposure, inhalation, monitoring, bioassay, chemical toxicity, radiation protection

INTRODUCTION

Health risks associated with elevated intake of uranium (U) may be divided into two categories: chemical toxicity to tissues, primarily the kidneys; and radiogenic injury to lungs, bone, and other tissues that may result in an increased risk of cancer of these tissues. The relative significance of the chemical and radiation hazards from intake of the U isotopes ^{234}U, ^{235}U, and ^{238}U depends on the isotopic mixture and the chemical and physical form of U taken into the body. Chemical toxicity generally has been considered the overriding hazard for intake of relatively soluble U compounds with naturally occurring isotopic mixtures, based on studies on laboratory animals. This would also apply to intake of relatively soluble forms of depleted U, which has an even lower specific activity than natural U. The radiogenic risk (per unit mass of U taken into the body) increases with the level of ^{235}U enrichment. This is due mainly to an associated increase in the percentage of ^{234}U, which has a relatively high specific activity. For inhalation of relatively insoluble U compounds, the radiation dose to the lungs could become the prevailing consideration even for depleted U due to an increased residence time in the lungs and low fractional absorption of deposited U to blood.

Continuous air monitoring during work hours is often the primary method for monitoring and control of airborne U at fuel cycle facilities. This paper describes methods of interpreting air monitoring data for U and deriving investigation levels and immediate action levels for airborne U. The purposes of investigation and immediate action levels are to avoid chemical damage of U to the kidneys and limit the radiogenic cancer risk from U to an acceptable level. An investigation level (IL) indicates the need to confirm the validity of moderately elevated measurements and adequacy of confinement controls and determine whether work limitations are appropriate. An immediate action level (IAL) indicates that safeguards should be put into place immediately, including removal of workers from further exposure until conditions are found to be acceptable. Derivations of ILs and IALs are based on current primary radiological guidance of the International Commission on Radiological Protection (ICRP, 2008), current information on chemical toxicity of U, and recently updated biokinetic and dosimetric models (ICRP, 2015, 2016a, 2017). An action level (IL or IAL) is the more restrictive of two derived values, one determined from primary guidance for U as a chemical hazard and the other from primary guidance for U as a radiation hazard.

The reader is referred to the report ORNL/TM-2012/14 (Leggett et al., 2012) for a description of methods of derivation of action levels for a more comprehensive U monitoring scheme (e.g., including bioassay measurements) based on the general methods applied here but on earlier radiological guidance and biokinetic models (ICRP, 1991, 1994). That report also addresses some practical issues in U monitoring, a topic that is outside the scope of the present paper. The reader is also referred to ICRP Publication 130 (2015, pp. 98-99) for a discussion of potential limitations of air monitoring alone for control of intake of radionuclides by individual workers.

METHODS

Quantities and models used to calculate action levels

The purposes of ILs and IALs are to avoid chemical damage of U to the kidneys of workers and limit their radiogenic cancer risk from U to acceptable levels. The starting place for derivation of ILs and IALs is the selection of suitably cautious but practically achievable primary chemical and radiological guidance levels. The primary guidance for avoidance of

chemical effects is given in terms of a limiting concentration of U in the kidneys. The primary guidance for limitation of radiogenic cancer risk is given in terms of the effective dose as defined by the International Commission on Radiological Protection (ICRP 1991, 2008). The concentration of U in the kidneys and the effective dose are not measurable quantities. Biokinetic and dosimetric models, physical properties of U, reference characteristics of workers (e.g., daily air intake), and reference exposure scenarios are used to relate these non-measurable quantities to measurable ILs and IALs.

Reference primary guidance for U as a chemical hazard

The dominant adverse chemical effect of internally deposited U is nephrotoxicity (Voegtlin, C.; Hodge, H. C., eds., 1953; Spoor and Hursh, 1973; Stopps and Todd, 1982; Keith, et al., 2015). Consideration of chemical effects of U is limited here to avoidance of nephrotoxicity, assumed to occur when the renal U concentration exceeds a threshold.

Since the early 1950s a concentration of 3 μg U/g kidney has served as a primary guidance level for avoidance of chemical toxicity in workers exposed to U (Voegtlin, C.; Hodge, H. C., eds., 1953; ICRP, 1959; Spoor and Hursh, 1973; Stopps and Todd, 1982; U.S. Nuclear Regulatory Commission, 1991, 2010). This level represents a committee's judgment based primarily on results of animal experiments. Current information indicates that 3 μg U/g kidney is above the no-effects level but below a level with the serious effects of renal dysfunction. Subjects with intakes resulting in estimated peak concentrations near 3 μg U/g kidney have shown transient biochemical indicators of renal dysfunction but no acute illnesses or obvious long-term effects (U.S. National Research Council, 2008). Acutely exposed persons with estimated peak concentrations substantially exceeding 6 μg U/g kidney have shown protracted biochemical indicators of renal dysfunction and sometimes severe illness (U.S. National Research Council, 2008). Kathren and Burklin (2008) concluded from a review of the literature that there have been no reported human deaths attributable to chemical toxicity of U.

Guilmette and coworkers (2004) reviewed information on renal toxicity of U as part of the Capstone health risk assessment study of military uses of depleted U. They concluded that: U concentrations ≤ 2.2 μg U/g kidney will not result in detectable effects; concentrations > 2.2 μg U/g kidney but ≤ 6.4 μg U/g kidney may result in transient indicators of renal dysfunction without overt symptoms of illness; concentrations > 6.4 μg U/g kidney but ≤ 18 μg U/g kidney may result in protracted symptoms of renal dysfunction and possibly illness; and concentrations >18 μg U/g kidney are likely to result in severe clinical symptoms of renal dysfunction. These conclusions refer to peak concentrations following brief exposure to U. The authors also reviewed twenty-seven cases of human U exposures reported in the scientific literature and listed transient effects in the kidney in eight cases. The peak kidney concentration for those eight cases, apparently calculated by these authors or the original investigators using selected biokinetic models, ranged from 1 to 6 μg U/g kidney. In a ninth case, a biochemical indicator of renal dysfunction persisted for three weeks, and the estimated peak kidney concentration was 3 μg U/g kidney.

By contrast to the no-effects level of 2.2 μg U/g kidney proposed by those authors, a U.S. National Research Council committee recently concluded that transient adverse renal effects of U including proteinuria and glucosuria may occur at peak kidney concentrations as low as 1.0 μg U/g kidney (U.S. National Research Council , 2008).

In a cohort of Gulf War veterans with embedded fragments of depleted U (DU) metal resulting from "friendly fire" incidents, U concentrations in urine measured every two years since 1993 persistently range from 10 to over 500 times normal levels (Squibb, et al., 2005). This indicates that the embedded DU fragments are gradually releasing U to blood in these subjects. The biokinetic model for systemic U applied in the present paper was used to estimate kidney U concentrations in these veterans based on their urinary U excretion through about 2001 (Squibb, et al., 2005). Estimated kidney concentrations exceeded 0.1 μg U/g kidney in several veterans and ≥ 0.6 μg U/g kidney in two cases. Subtle changes in measures of renal proximal tubule function have been evident in some of the veterans, but no clinical evidence of decreased renal function has been observed in this cohort (Squibb, et al., 2005).

Mild renal injury with transient elevation in urinary biochemical indices may occur in chronically exposed animals at renal U concentrations of a few tenths of a microgram U per gram kidney ((Leggett, 1989; Foulkes, 1990; McDiarmid, et al., 2009). Return of the biochemical indices to normal during chronic exposure may reflect a kind of acquired tolerance to U associated with structural changes in the luminal surfaces of regenerated kidney tubule cells (Leggett, 1989). Several reviewers have suggested that the traditional chemical guidance level of 3 μg U/g kidney should be reduced, particularly for chronic exposures (Morrow, et al., 1982; Wrenn, et al., 1985; Morrow, 1984; Leggett, 1989; SuLu and Fu-Yao, 1990; Foulkes, 1990). Guidance values in the range 0.3–1 μg U/g kidney were proposed.

Established methods for assigning limits for exposure to hazardous chemicals were considered in the selection of the reference primary guidance levels for the chemical toxicity of U. These include consideration of a no-observed-adverse-effect level (NOAEL) and a lowest-observed-adverse-effect level (LOAEL) as applied by U.S. federal agencies (Chou and Pohl, 2005). Changes in the renal proximal tubular function, including the presence of urinary casts (Luessenhop, et al., 1958), were considered the LOAEL indicators. The data summarized in this section seem consistent with the conclusion that the LOAEL in the form of transient adverse renal effects of U including proteinuria and glucosuria) may occur at peak kidney concentrations as low as 1.0 μg U/g kidney.

The concentration 1.0 μg U/g kidney is adopted here as the reference primary guidance level for prevention of chemical toxicity. This value is used to derive immediate action levels in terms of measurable quantities such as the concentration of U in air or the concentration of U in urine. The equilibrium value 0.3 μg U/g kidney is used to derive investigation levels in terms of measurable quantities.

Reference primary guidance for U as a radiation hazard

To place all ionizing radiations on a common scale regarding their potential health detriment, the ICRP uses quantities called the equivalent dose and the effective dose. The equivalent dose is the absorbed dose averaged over an organ or tissue and multiplied by a radiation weighting factor that reflects the relative biological effectiveness of the type of radiation causing the dose. The effective dose is a weighted sum of equivalent doses to radiosensitive tissues, with the tissue weighting factor representing the relative contribution of that tissue to the total detriment for the case of uniform irradiation of the whole body.

ICRP Publication 60 (1991) and its replacement, ICRP Publication 103 (2008), both limit the effective dose (50-y integral) to 0.02 Sv per year (i.e., from intake during a 1 y period)

averaged over defined periods of five years and 0.05 Sv in any single year. The value 0.02 Sv rather than 0.05 Sv is intended for planning purposes, even for 1 y periods.

An annual effective dose of 0.02 Sv is adopted here as the reference primary guidance level for control of radiation effects from intake of U. This value is used to derive radiologically based investigation levels. An annual effective dose of 0.05 Sv is used to derive radiologically based immediate action levels.

Generic investigation levels and immediate action levels

Table 1 summarizes generic investigation and immediate action levels and the actions that should be taken at each level. These levels are generic in the sense that they are defined in terms of the primary guidance levels given earlier rather than in terms of specific measurable quantities, which are derived in a later section.

Table 1. Generic criteria for investigation levels and immediate action levels

Type of information	Interpretation	Actions
Monitoring data and biokinetic models indicate that for current levels of exposure: (a) The kidney concentration will never exceed 0.3 μg U/g kidney. (b) The annual effective dose will never exceed 0.02 Sv.	U confinement is adequate.	No corrective actions needed.
Monitoring data and biokinetic models indicate one or both of the following for current levels of exposure: (a) The kidney concentration has exceeded or will eventually exceed 0.3 μg U/g kidney at current levels of exposure. (b) The annual effective dose has exceeded or will eventually exceed 0.02 Sv at current levels of exposure.	Investigation level (IL). U confinement or respiratory controls may not provide an adequate margin of safety.	1. Confirm results (e.g., repeat latest urinalysis and increase frequency of urine sampling). 2. Reassess model predictions. Where feasible, replace idealized exposure scenarios with worker-specific scenarios. 3. Identify cause of elevated monitoring data and initiate additional control measures if initial results are confirmed. 4. If monitoring data are found to be anomalous, improve sampling and measurement procedures. 5. If elevated exposure to a worker is confirmed, determine whether other workers may have been exposed. 6. Consider work assignment limitations for workers with elevated U intake.
Monitoring data and biokinetic models indicate either of these situations for current exposures: (a) The kidney concentration has exceeded or will eventually exceed 1.0 μg U/g kidney at current levels of exposure. (b) The annual effective dose has exceeded or will eventually exceed 0.05 Sv at current levels of exposure.	Immediate action level (IAL). U confinement, respiratory protection, or monitoring program not acceptable.	1. Take the actions indicated above for an IL. 2. Immediately remove from further exposure any workers estimated to have a kidney U concentration approaching or exceeding 1.0 μg U/g kidney or annual effective dose that might exceed 0.05 Sv. 3. Continue operations only if source of elevated U is clearly identified and corrected, or if clearly established that the incorrect monitoring data led to false alarm. 4. Analyze bioassay samples weekly or more frequently for workers in affected area.

Biokinetic models

The biokinetic models applied here are those currently recommended by the ICRP: the updated Human Respiratory Tract Model (HRTM) (ICRP, 2015), the Human Alimentary Tract Model (HATM) (ICRP, 2006), and the biokinetic model for systemic (absorbed) U (ICRP, 1995, 2017). The HRTM describes the deposition and retention of inhaled material in the respiratory tract and its subsequent clearance from the respiratory tract to blood or the alimentary tract. The HATM is used to describe the movement of swallowed or endogenously secreted material through the alimentary tract and the rate and extent of absorption of the radionuclide from the alimentary tract to blood. The systemic model is used to describe the time-dependent retention, distribution, and excretion of the radionuclide after its absorption to blood.

The reader is referred to ICRP reports indicated above for descriptions of the HATM and the biokinetic model for systemic U, both of which were adopted several years ago and remain unchanged. The HRTM was introduced in ICRP Publication 66 (1994a) and revised recently in Publication 130 (ICRP, 2015). The updated version of the HRTM is summarized below.

The compartments of the HRTM and the paths of mechanical clearance of deposited particles are shown in Figure 1. Reference values for particle transport rate constants are shown beside the arrows and are in units of d^{-1}. The rates of particle transport are assumed to be independent of particle size.

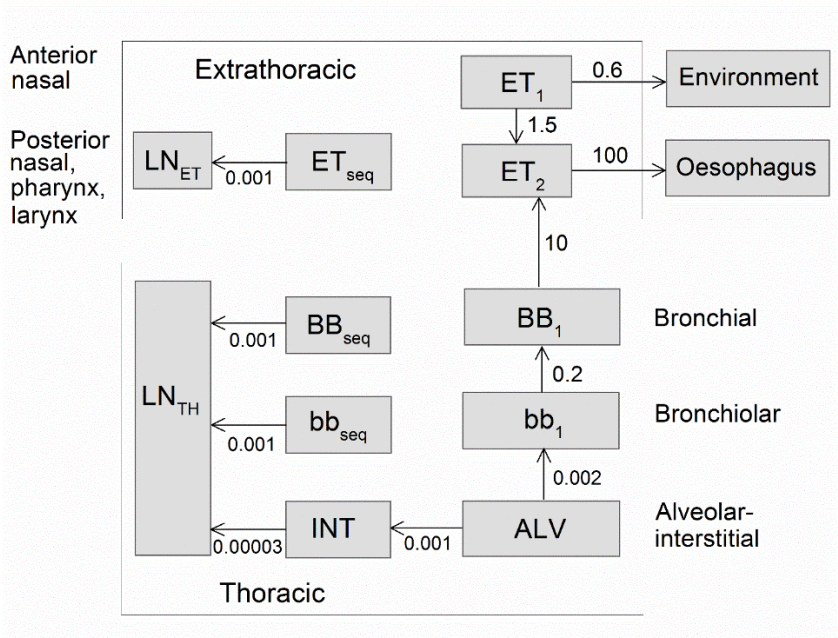

Figure 1. Structure of the updated Human Respiratory Tract Model (HRTM) (ICRP, 2015). Numbers next to arrows are particle transport rates (d^{-1}) along indicated paths. Abbreviations: ET = extrathoracic; BB = bronchi; bb = bronchioles; LN = lymph nodes; ALV = alveolar; INT = interstitial; TH = thoracic; seq = sequestered**.**

Particle transport is in competition with the dissolution of particles, which determines the rate of absorption of the contained radionuclide to blood. Dissolution models used in conjunction with the particle transport model are described below. Absorption to blood is assumed to occur from all respiratory compartments except the anterior nasal passages (ET_1 in Figure 1). This is in addition to activity that is absorbed from the alimentary tract after it is escalated from the lungs and swallowed.

The dissolution rate depends on the chemical and physical form of the inhaled element. Dissolved activity generally is assumed to be immediately absorbed to blood, although the HRTM allows for binding of dissolved activity to tissues of the respiratory tract and gradual absorption of bound activity to blood when indicated by specific information.

The most general form of the dissolution-absorption model within the HRTM is shown in Figure 2. This is a first-order model designed to depict a time-dependent rate of absorption to blood. This model applies to each compartment of the respiratory tract from which absorption occurs. All the deposit in a region of the respiratory tract is assigned to a compartment representing an initial state, i.e., an initial rate of dissolution of inhaled particles. Material in the initial state dissolves at the rate s_p but is simultaneously transformed in undissolved form at the rate s_{pt} to a material with a different dissolution rate s_t. A fraction f_b of activity dissolved from particles either in the initial state or the transformed state enters a respiratory tissue compartment called "Bound material" (f_b is assumed to be zero for U), and a fraction $1-f_b$ goes directly to blood. Activity transfers from the bound state to blood at the rate s_b.

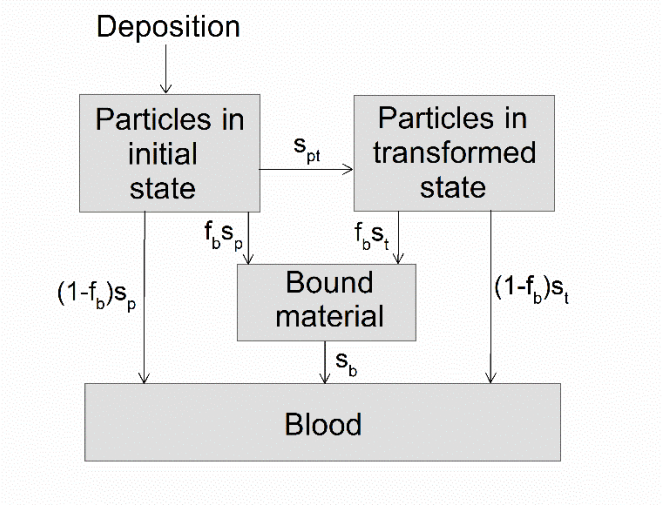

Figure 2. Model within the HRTM describing time-dependent absorption to blood.

In ICRP's applications of the original version of the HRTM, inhaled particulate material generally was assigned to one of three generic absorption types: Type F, representing fast dissolution and a high level of absorption to blood; Type M, representing a moderate rate of dissolution and an intermediate level of absorption to blood; and Type S, representing slow dissolution and a low level of absorption to blood. The absorption types recommended for use in the updated HRTM differ from those associated with the original HRTM in two main ways: (1) In the original HRTM, the absorption parameter values representing Type F, M, or S were completely generic, i.e., independent of the element. With the updated HRTM, generic sets of absorption parameter values indicated in Figure 2 are still provided for Types

F, M, and S, but element-specific parameter values are used in place of generic values when supported by available data, as is the case for U. (2) For several frequently studied elements including U, additional element-specific absorption types have been introduced. For U, the ICRP has introduced Type F/M with dissolution rates intermediate to those of Types F and M, and Type M/S with dissolution rates intermediate to those of Types M and S (ICRP, 2017). Parameter values for Type F/M are based on collective inhalation data for $UO_2(NO_3)_2$, UO_4, ADU (ammonium diuranate), and UO_3. Parameter values for Type M/S are based on collective inhalation data for U_3O_8 and UO_2. The absorption parameter values of the updated HRTM for U of Type F, F/M, M, M/S, and S are listed in Table 2. ICRP Publication 137 (2017) also addresses a special form of U called uranium aluminide, but that form is not considered here.

Table 2. In the updated HRTM (ICRP, 2015), absorption parameter values for different forms (Absorption Types) of inhaled U (ICRP, 2017).

Parameter	Symbol	Type				
		F	F/M[a]	M	M/S[b]	S
Fraction dissolved rapidly	f_r	1	0.8	0.2	0.03	0.01
Rapid dissolution rate (d^{-1})	s_r	10	1	3	1	3
Slow dissolution rate (d^{-1})	s_s	None	0.01	0.005	0.0005	0.0001
Absorption from alimentary tract	f_A	0.02	0.016	0.004	0.0006	0.0002

[a] $UO_2(NO_3)_2$, UO_4, ADU, UO_3
[b] U_3O_8, UO_2

Other models and assumptions used here to derive ILs and IALs

Particle size
The methods of derivation of action levels described here may be applied to any particle size. The assumed particle size of airborne U is 5 μm AMAD, the default value for occupational intake recommended in ICRP Publication 68 (1994b) and in the ICRP's updated series of reports on occupational intake of radionuclides (ICRP, 2015, 2016b, 2017).

Effective dose coefficients and peak kidney content
The following values based on the biokinetic models listed above are required in the development of action levels for airborne U for the forms of U described here (Types F, F/M, M, M/S, and S as defined in Table 2): (1) effective dose coefficients for inhalation of each U isotope, assuming particle size 5 μm AMAD; and (2) peak concentrations of U in the kidneys for the same exposure cases, assuming chronic intake of 1 μg U / d. These values are listed in Tables 3 and 4, respectively.

Table 3. Effective dose coefficients[a] for inhalation of U isotopes (particle size 5 µm AMAD).		
Isotope	Type	Effective dose Coefficient (Sv Bq^{-1})
^{234}U	F	2.5×10^{-7}
	F/M	4.1×10^{-7}
	M	1.4×10^{-6}
	M/S	5.5×10^{-6}
	S	1.3×10^{-5}
^{235}U	F	2.3×10^{-7}
	F/M	3.8×10^{-7}
	M	1.3×10^{-6}
	M/S	5.1×10^{-6}
	S	1.2×10^{-5}
^{238}U	F	2.2×10^{-7}
	F/M	3.6×10^{-7}
	M	1.2×10^{-6}
	M/S	4.8×10^{-6}
	S	1.2×10^{-5}
[a]Based on the ICRP's updated dosimetry system (ICRP, 2016a).		

Table 4. Model predictions of the peak U concentration in the kidneys for chronic inhalation of 1 Bq U d^{-1} (particle size 5 µm AMAD).	
Type	**Peak kidney concentration (µg g^{-1})**
F	0.0015
F/M	0.00081
M	0.00056
M/S	0.00027
S	0.00018[a]
[a]U concentration in kidneys predicted to continually increase well past normal work age for chronic exposure to airborne U of Type S. Listed value based on exposure for 50 y.	

Exposure patterns

The ILs and IALs derived here are based on chronic intake of airborne U at a constant rate for 8 hours a day, 5 days a week. For computational convenience, calculations are based on continuous intake 24 hours a day and 7 days each week at a rate that produces the intended total intake per workweek. For example, if it is assumed that total intake during each 8-h workday is 1 µg, then the weekly intake would be 5 workdays/wk × 1 µg/workday = 5 µg/wk, and the intake rate based on the convenient assumption of continuous exposure would be (5 µg/wk) / (7 d/wk) = 0.714 µg/d.

Isotopic mixtures

The isotopic mixtures of U considered here are depleted, natural, and ^{235}U-enriched U.

- U is assumed to contain 0.0057% ^{234}U, 0.72% ^{235}U, and 99.2743% ^{238}U by mass, corresponding to 50.45% ^{234}U, 2.20% ^{235}U, and 47.35% ^{238}U by activity based on specific activities of ^{234}U, ^{235}U, and ^{238}U listed in Table 5.
- Depleted U is assumed to contain 0.0005% ^{234}U, 0.25% ^{235}U, and 99.7495% ^{238}U by mass, corresponding to 8.39% ^{234}U, 1.45% ^{235}U, and 90.16% ^{238}U by activity based on specific activities of these isotopes.
- Enriched U refers to any level of ^{235}U enrichment. The ^{238}U content of "X% ^{235}U-enriched U" is calculated as 100% minus X minus a ^{234}U content calculated as described below.

The ^{234}U content of enriched U is assumed here to be related to the ^{235}U content by the function

$$\%^{234}U = 0.0015 + 0.0058E + 0.000054E^2 \qquad \text{Eq. 1}$$

where E = $\%^{235}$U by mass. Equation 1 was derived as a curve fit to measurements of ^{234}U in U enriched by the gaseous diffusion technique (R. Leggett, unpublished data). The equation is reasonably consistent with limited data on the ^{234}U content of uranium enriched by the gas centrifuge method (Bush et al., 2001). Equation 1 can be used together with the specific activities of ^{234}U, ^{235}U, and ^{238}U to derive the following expression for the specific activity, SpA, of depleted, natural, or enriched U:

$$SpA = 15{,}980 + 14{,}130\mathrm{E} + 125.3E^2 \text{ Bq/g.} \quad \text{Eq. 2}$$

Equation 2 agrees closely with an expression given by Rich et al. (1988) for the specific activity of U enriched by gaseous diffusion.

Table 5. Specific activities of U isotopes

U isotope	Specific activity (Bq/g)
^{234}U	2.32×10^8
^{235}U	8.01×10^4
^{238}U	1.25×10^4

Reference characteristics of workers

Derivations of ILs and IALs are based on characteristics of a reference adult male (ICRP 2002). The derived values differ little if characteristics of a reference adult female or sex-averaged characteristics are applied. The assumed breathing rate is 1.2 m^3 h^{-1}. Derivations involving chronic exposure are based on exposure to a fixed concentration of U in air for 2000 h y^{-1}, giving an annual air intake 2400 m^3. The volume of urine excreted daily is assumed to be 1.6 L and the mass of faeces excreted daily is assumed to be 150 g.

RESULTS

Derivation of IL and IAL for airborne U for a well characterized exposure

The method of derivation of an IL or IAL for a well characterized form of airborne U is illustrated by the following hypothetical exposure scenario. A conservative assumption is that there is no absence from work during the year. Suppose workers are chronically exposed to depleted U in air, the airborne particles are found to be moderately soluble in simulated lung fluid indicative of Type M material, and the measured particle size is of the order of the ICRP's default value of 5 μm AMAD. As indicated in Table 4, the equilibrium concentration of U in the kidneys based on continuous inhalation at the rate 1 μg U/d (equivalent to about 1.4 μg U per 8-h work day) is 0.00056 μg U/g kidney for Type M particles of size 5 μm AMAD. The annual intake eventually leading to the IL of 0.3 μg U/g kidney is calculated as:

$$(365\ \text{d} \times 1\ \mu\text{g}\ d^{-1} \times 0.3\ \mu\text{g}\ g^{-1}) \,/\, 0.00056\ \mu\text{g}\ g^{-1} = 195{,}536\ \mu\text{g U.} \quad \text{Eq. 3}$$

The concentration of U in air corresponding to this intake is derived by dividing 195,536 μg by the reference value for occupational intake of air in a year:

$$195{,}536\ \mu\text{g} \,/ 2400\ m^3 = 81\ \mu\text{g}/m^3. \qquad \text{Eq. 4}$$

Thus, the chemically based IL for airborne U in this example is 81 μg m^{-3}. By the same method it can be shown that the chemically based IL would be 30 μg m^{-3} for Type F, 56 μg m^{-3} for Type F/M, 167 μg m^{-3} for Type M/S, and 253 μg m^{-3} for Type S uranium assuming a particle size of 5 μm AMAD.

For comparison, the radiologically based IL in μg m^{-3} for chronic exposure to airborne depleted U, Type M, 5 μm AMAD is calculated as [(0.02 Sv / E) / 2400 m^3] / SpA(DU), where E is the effective dose coefficient for Type M depleted U with the reference isotopic composition given in Section 2 and SpA(DU) is the specific activity of that isotopic mixture. The value E is derived as a linear combination of the effective dose coefficients given in Table 1 for ^{234}U (1.4 x 10^{-6} Sv/Bq), ^{235}U (1.3 x 10^{-6} Sv/Bq), and ^{238}U (1.2 x 10^{-6} Sv/Bq) of Type M and particle size 5 μm AMAD:

$$\text{E} = 0.0839 \times (1.4 \times 10^{-6}\ \text{Sv/Bq}) + 0.0145 \times (1.3 \times 10^{-6}\ \text{Sv/Bq}) + 0.9016 \times (1.2 \times 10^{-6}\ \text{Sv/Bq}) = 1.22 \times 10^{-6}\ \text{Sv/Bq} \qquad \text{Eq. 5}$$

where 0.0839, 0.0145, and 0.9016 are the reference fractions listed earlier of total activity in depleted U represented by ^{234}U, ^{235}U, and ^{238}U, respectively. Thus, the radiologically based IL for the air concentration of this form of U is

$$[0.02\ \text{Sv} \,/\, 1.22 \times 10^{-6}\ \text{Sv/Bq}] \,/\, 2400\ m^3 = 6.8\ \text{Bq}/m^3. \quad \text{Eq. 6}$$

Based on the reference mass composition of depleted U listed earlier and the specific activities listed in Table 5, the specific activity SpA(DU) of depleted U is 1.383 x 10^4 Bq/g. Therefore, the radiologically based IL of 6.8 Bq/m^3 derived above is equivalent to

$$6.8\ \text{Bq}\ m^{-3} / 1.383 \times 10^4\ \text{Bq/g} = 0.000492\ \text{g} \,/\, m^3 = 492\ \mu\text{g} \,/\, m^3. \qquad \text{Eq. 7}$$

The chemically based value of 81 μg m^{-3} derived earlier is more restrictive than the radiologically based value and therefore is the IL for this exposure situation.

The methods used in the above example to derive a radiologically based action level for depleted U of known solubility and particle size can be generalized to any form of airborne U of known solubility, isotopic composition, and particle size. The following equation is used to derive a radiologically based IL, R μg U / m^3:

$$R = (0.02\ \text{Sv} \times 10^6\ \mu\text{g/g}) \,/\, [2400\ m^3 \times ((F4 \times E4 \times S4) + (F5 \times E5 \times S5) + (F8 \times E8 \times S8))] \quad \text{Eq. 8}$$

where 0.02 Sv is the primary reference guidance level for radiologically based ILs; F4, F5, and F8 are mass fractions of ^{234}U, ^{235}U, and ^{238}U, respectively, in the material; E4, E5, and E8 are effective dose coefficients (Sv/Bq) for ^{234}U, ^{235}U, and ^{238}U, respectively, each derived on the basis of the solubility and particle size distribution of the material; S4, S5, and S8 are the specific activities of ^{234}U, ^{235}U, and ^{238}U, respectively; and 2400 m^3 is the reference occupational annual air intake.

Equation 8 was used to calculate radiologically based ILs for airborne U (averages over a 1-y period) in μg U / m^3, for depleted U, natural U, or ^{235}U enriched U of Type F, F/M, M, M/S, or S, assuming a particle size of 5 μm AMAD. Effective dose coefficients E4, E5, and E8 for these absorption types are listed in Table 3. Results of the analysis are summarized in Table 6 for all absorption types and shown graphically in Figure 3 for three absorption types. The chemically based ILs are derived from the equilibrium concentrations of U in the kidneys indicated in Table 4 for continuous inhalation of U at the constant rate of 1 μg/d. The method of calculation of the chemically based ILs was described above. Recall that a chemically based action level is independent of the isotopic mixture of ^{234}U, ^{235}U, and ^{238}U.

Table 6. For depleted, natural, or ^{235}U-enriched uranium in air, Investigation Levels (µg m^{-3}) for different Absorption Types.					
Mass % ^{235}U	Type				
	F	F/M	M	M/S	S
Investigation Level based solely on radiological guidance (µg m^{-3})					
0.25	1851	1130	336	84.6	34.6
0.72	1350	824	244	61.6	25.4
1.0	1162	709	210	53.0	21.9
1.5	929	567	167	42.3	17.6
2.0	773	471	139	35.2	14.7
3.0	576	351	103	26.2	11.0
4.0	458	279	82.0	20.8	8.7
5.0	379	231	67.8	17.2	7.2
7.0	280	171	50.0	12.7	5.4
10	199	121	35.5	9.0	3.8
15	131	80.0	23.5	6.0	2.5
20	96.3	58.7	17.2	4.4	1.9
25	74.9	45.7	13.4	3.4	1.4
30	60.6	37.0	10.8	2.8	1.2
35	50.4	30.8	9.0	2.3	0.97
40	42.8	26.1	7.7	2.0	0.82
45	37.0	22.5	6.6	1.7	0.97
50	32.3	19.7	5.8	1.5	0.82
55	28.5	17.4	5.1	1.3	0.71
60	25.4	15.5	4.5	1.2	0.62
65	22.8	13.9	4.1	1.0	0.55
70	20.7	12.6	3.7	0.94	0.49
75	18.8	11.5	3.4	0.85	0.44
80	17.2	10.5	3.1	0.78	0.40
85	15.8	9.6	2.8	0.72	0.36
90	14.5	8.9	2.6	0.66	0.33
93	13.8	8.4	2.5	0.63	0.30
95	13.4	8.2	2.4	0.61	0.28
97	13.0	7.9	2.3	0.59	0.27
Investigation Level based solely on chemical guidance (µg m^{-3})					
All mixtures	30	56	81	167	253
^{235}U content above which radiological guidance is limiting					
Mass %^{235}U	53%[a]	21%[a]	4.1%[a]	b	b

[a]Investigation Level is determined by chemical guidance for lower ^{235}U content and by radiological guidance for higher ^{235}U content.
[b]Radiological guidance is always more restrictive than chemical guidance for this Absorption Type.

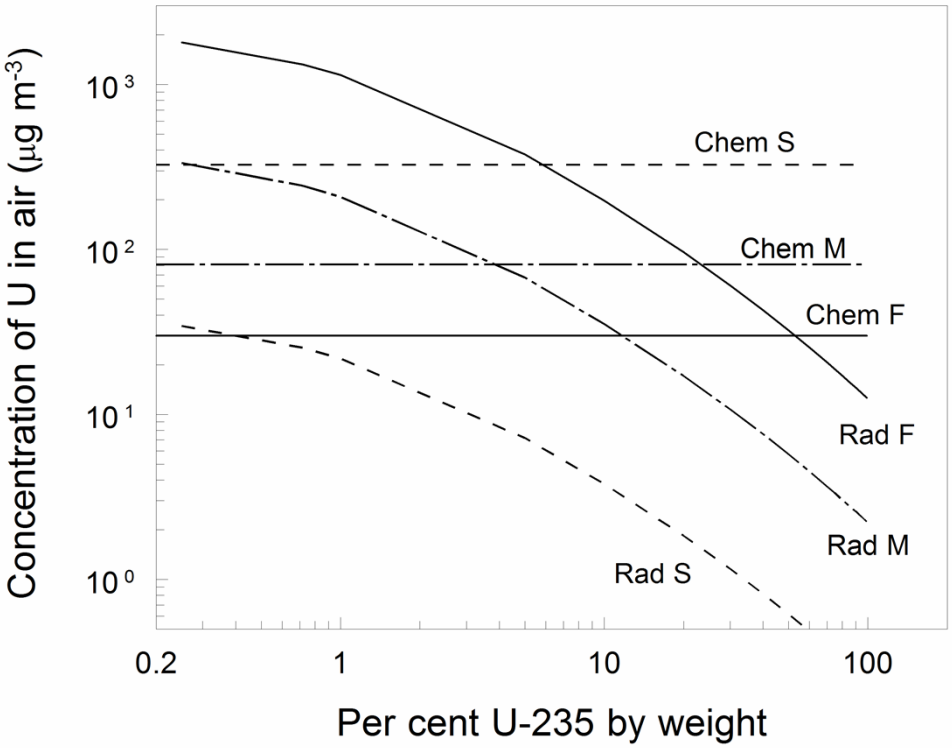

Figure 3. Graphs used to determine Investigation Levels (ILs) for the concentration of U in air. The cases considered are depleted, natural, or ^{235}U-enriched U of Type F, M, or S (5 µm AMAD). The IL for Type X (X = F, M, or S) and a given isotopic composition is determined by the lower of the curves Chem X (chemically based IL) and Rad X (radiologically based IL) at their points of intersection with a vertical line through the ^{235}U content (horizontal axis).

In Figure 3, the labels Rad X and Chem X, where X represents absorption Type F, M, or S, refer to radiologically (Rad) and chemically (Chem) based ILs, respectively, for inhalation of U of Type X. The IL for Type X and a given isotopic composition is determined by the lower of the curves Chem X and Rad X at their points of intersection with a vertical line drawn through the ^{235}U content on the horizontal axis.

The derivations listed in Table 6 indicate that the IL for airborne U of Type F is determined by the horizontal line representing a chemically based limit (30 µg m^{-3}) except for enriched U containing more than ~53% ^{235}U by mass, beyond which the enrichment-dependent radiologically based guidance is limiting. For Type F/M, the chemically based value (56 µg m^{-3}) is limiting up to a ^{235}U enrichment level of ~21%, beyond which radiological guidance is limiting. For Type M, the chemically based value (81 µg m^{-3}) is limiting up to a ^{235}U enrichment level of ~4.1%, beyond which radiological guidance is limiting. For Types M/S and S, radiological guidance is limiting regardless of the ^{235}U content.

Analogous derivations of IALs for depleted, natural, or enriched U in air are summarized in Table 7 for all five absorption types and in Figure 4 for Types F, M, and S. The methods of derivation of IALs for different mixtures of ^{234}U, ^{235}U, and ^{238}U are the same as described above for IL, with the limiting kidney concentration changed from 0.3 to 1.0 µg U/g kidney

and the limiting annual effective dose coefficient changed from 0.02 to 0.05 Sv. For these primary guidance values the derived chemically based limits are 101 μg m^{-3} for Type F, 188 μg m^{-3} for Type F/M, 272 μg m^{-3} for Type M, 563 μg m^{-3} for Type M/S, and 845 μg m^{-3} for Type S. The data in Table 7 indicate that the IAL for airborne U of Type F is determined by the horizontal line representing a chemically based limit except for enriched U containing more than ~42% ^{235}U by mass, beyond which the enrichment-dependent radiologically based guidance is limiting. For Type F/M, the chemically based value is limiting up to a ^{235}U enrichment level of ~16%, beyond which radiological guidance is limiting. For Type M, the chemically based value is limiting up to a ^{235}U enrichment level of ~2.8%, beyond which radiological guidance is limiting. For Types M/S and S, radiological guidance is limiting regardless of the ^{235}U content.

Default ILs and IALs for airborne U

Default action levels are also needed for situations in which the form of airborne U is poorly characterized. In this case action levels are based on cautious derivations of both the chemically and radiologically based action level. This is achieved in both cases by applying a worst-case assumption regarding the solubility of the airborne material. For the chemically based action level the worst case is that 100% of airborne U is highly soluble (Type F) material. For the radiologically based action levels the worst case is that 100% of airborne U is poorly soluble (Type S) material. If the percentage of ^{235}U by weight is known, but the solubility of the material is unknown, the lower of the curves Chem F and Rad S directly above the percentage of ^{235}U by weight should be used. If the percentage ^{235}U by weight is known only within a range of values, model predictions for the upper end of the range should be applied. The curves in Figures 3 and 4 indicate that a simplifying and reasonably cautious approach for determining ILs and IALs for unknown forms of airborne U is to assume that airborne U consists of Type S material.

Table 7. For depleted, natural, or ^{235}U-enriched uranium in air, Immediate Action Levels (µg m^{-3}) for different Absorption Types.					
Mass % ^{235}U	Type				
	F	F/M	M	M/S	S
Immediate Action Level based solely on radiological guidance (µg m^{-3})					
0.25	4628	2825	840	211	86.4
0.72	3376	2060	610	154	63.5
1	2905	1772	524	132	54.8
1.5	2322	1417	418	106	44.0
2	1931	1178	347	88.0	36.7
3	1440	878	258	65.6	27.5
4	1144	698	205	52.1	21.9
5	947	577	170	43.1	18.1
7	699	426	125	31.8	13.4
10	497	303	88.8	22.6	9.5
15	328	200	58.6	14.9	6.3
20	241	147	43.0	10.9	4.6
25	187	114	33.5	8.5	3.6
30	152	92.4	27.1	6.9	2.9
35	126	76.9	22.5	5.7	2.4
40	107	65.3	19.1	4.9	2.1
45	92.4	56.3	16.5	4.2	1.8
50	80.8	49.2	14.4	3.7	1.6
55	71.4	43.5	12.7	3.2	14
60	63.6	38.8	11.4	2.9	1.2
65	57.1	34.8	10.2	2.6	1.1
70	51.6	31.5	9.2	2.4	0.99
75	46.9	28.6	8.4	2.1	0.90
80	42.9	26.2	7.7	2.0	0.82
85	39.4	24.0	7.0	1.8	0.76
90	36.3	22.1	6.5	1.7	0.70
93	34.6	21.1	6.2	1.6	0.67
95	33.6	20.5	6.0	1.5	0.65
97	32.6	19.9	5.8	1.5	0.63
Immediate Action Level based solely on chemical guidance (µg m^{-3})					
µg m^{-3}	101	188	272	563	845
^{235}U content at which radiological and chemical guidance are equally limiting					
Mass %^{235}U	42%[a]	16%[a]	2.8%[a]	b	b
[a]Immediate Action Level is determined by chemical guidance for lower ^{235}U content and by radiological guidance for higher ^{235}U content. [b]Radiological guidance is always more restrictive than chemical guidance for this Absorption Type.					

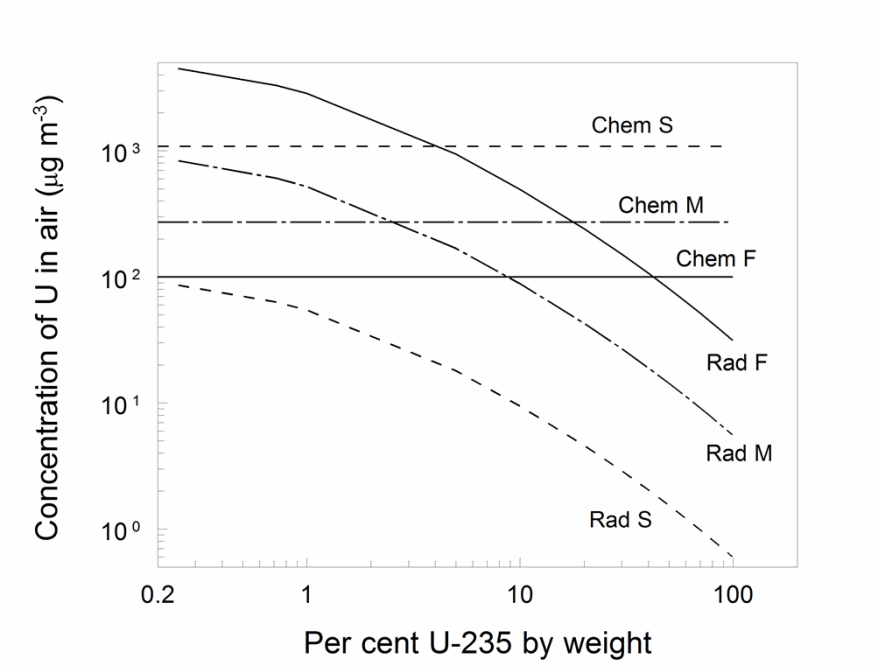

Figure 4. Graphs used to determine Immediate Action Levels (IALs) for the concentration of U in air. The cases considered are depleted, natural, or ^{235}U-enriched U of Type F, M, or S (5 µm AMAD). The IAL for Type X (X = F, M, or S) and a given isotopic composition is determined by the lower of the curves Chem X (chemically based IAL) and Rad X (radiologically based IAL) at their points of intersection with a vertical line through the ^{235}U content (horizontal axis).

SUMMARY AND CONCLUSIONS

Continuous measurement of airborne U typically is a key component of radiation monitoring programs at U fuel cycle facilities. An air monitoring program should include not only measurements of the mass and activity concentrations of airborne U but also its solubility, because inhalation of highly insoluble material may result in long-term retention of U in the lungs and elevated radiation dose to lung tissue.

This paper describes a method of setting action levels for U in the workplace based on interpretation of air monitoring data. The reader is referred to an earlier ORNL report (Leggett et al., 2012) for a description of a more comprehensive U monitoring scheme that supplements air monitoring with a bioassay program. The action levels derived in the 2012 report incorporate primary radiological guidance of ICRP Publication 60 (1991) and biokinetic and dosimetric models applied in ICRP Publication 68 (1994b). The action levels derived in the present paper are based on primary guidance of ICRP Publication 103 (2008) and updated biokinetic and dosimetry models of the ICRP (2015, 2016a, 2017). Thus, the action levels for airborne U listed in this paper update those in the 2012 report.

Two action points are addressed here: an investigation level (IL) and an immediate action level (IAL). An IL indicates the need to confirm the validity of recently moderately increased

measurements and the adequacy of confinement controls and determine whether work limitations are appropriate. An IAL indicates that safeguards should be put into place immediately, including removal of workers from further exposure until exposure conditions are found to be acceptable. Derivations of ILs and IALs are based on current radiation protection guidance, current information on chemical toxicity of U, reference characteristics of workers such as breathing rates, and the ICRP's latest biokinetic models for U. An IL or IAL is the more restrictive of two derived values, one determined from primary guidance for U as a chemical hazard and the other from primary guidance for U as a radiation hazard.

The models, methods, and assumptions applied in this paper have the following implications regarding ILs and IALs for airborne depleted, natural, or ^{235}U-enriched U:

- ILs and IALs derived from the chemical primary reference guidance level depend on the solubility but not the isotopic composition of the airborne material. The derived chemically based ILs are 30, 56, 81, 167, and 253 μg m^{-3} for Types F, F/M, M, M/S, and S, respectively. The derived IALs are 101, 188, 272, 563, and 845 μg m^{-3} for Types F, F/M, M, M/S, and S, respectively.
- ILs and IALs (μg m^{-3}) derived from the radiological primary reference guidance level vary with the isotopic composition as well as the solubility of the airborne material and become increasingly restrictive with increasin ^{235}U content, due primarily to increasing levels of accompanying ^{234}U.
- For Type F material, the chemical reference guidance is limiting for ^{235}U content up to about 53% ^{235}U by mass for the IL and up to about 42% ^{235}U by mass for the IAL, and radiological reference guidance is limiting for higher ^{235}U content.
- For Type F/M material, the chemical reference guidance is limiting for ^{235}U content up to about 21% ^{235}U by mass for the IL and up to about 16% ^{235}U by mass for the IAL, and radiological reference guidance is limiting for higher ^{235}U content.
- For Type M material, the chemical reference guidance is limiting for ^{235}U content up to about 4.1% ^{235}U by mass for the IL and up to about 2.8% ^{235}U by mass for the IAL, and the radiological reference guidance is limiting for higher ^{235}U content.
- For Type M/S or Type S material, the radiological reference guidance is limiting regardless of the isotopic composition of the material.

Default action levels are set for use in situations where the solubility of airborne U is poorly characterized. Default action levels are based on the worst-case assumptions regarding solubility of the inhaled material in the respiratory tract, i.e., that the material is Type F for derivation of the chemically based IL or IAL and Type S for derivation of the radiologically based IL or IAL. A simplifying and cautious approach for determining ILs and IALs for unknown forms of airborne U is to assume that airborne U consists of Type S material.

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