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**BIOASSAY AT URANIUM MILLS: A DISCUSSION OF NUCLEAR REGULATORY
COMMISSION REGULATORY GUIDE 6.22**

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BIOASSAY AT URANIUM MILLS: A DISCUSSION OF NUCLEAR REGULATORY
COMMISSION REGULATORY GUIDE 8.22

ABSTRACT

This report is a study of Nuclear Regulatory Commission (NRC) requirements for bioassay at uranium mills, using the AERIN Code developed at Lawrence Livermore Laboratory. It demonstrates that the minimum levels of detection required by the NRC in urinalysis and in *in vivo* lung counts are reasonable and that the frequency of sampling is adequate.

INTRODUCTION

Nuclear Regulatory Commission (NRC) Regulatory Guide 8.22 establishes regulations on the type and frequency of bioassays for workers exposed to inhaling natural uranium (U-nat) at ore-processing mills. The chemical compounds of uranium encountered in mill processing are uranium dioxide (UO_2), the ore, and uranium oxide (U_3O_8), the product of the mill process. Uranium dioxide is relatively insoluble in the lungs and is generally treated as Y solubility class in the International Commission on Radiological Protection (ICRP) Lung Model dynamics.¹ On the other hand, U_3O_8 is relatively soluble and is generally treated as W-class material.²

Only two bioassay methods are mentioned in the guide, namely, urinalysis and *in vivo* lung counting. Minimum detection limits are specified as 5 $\mu\text{g/l}$ or less for urinalysis and 9 nCi or less for *in vivo* lung counting.

It is the purpose of this paper to study the frequency of sampling and the minimum detection limits as they apply to dose commitment to the lung and bone and to chemical toxicity to the kidney.

The AERIN Code,³ discussed in Appendix A, is used to estimate the internal dose and organ burdens for inhalation of D-, W-, and Y-class natural uranium of 1-, 5-, and 10- μm Activity Mean Aerodynamic Diameter (AMAD) particle sizes. The study focuses primarily on acute exposures with bioassay sampling periods of 15, 30, 100, and 200 days, corresponding to 2-week, 1-month, 3-month, and 6-month intervals. Some discussion is included on long-term chronic exposures and the internal dose and organ burdens that might escape detection at the minimum detection levels required for bioassay samples.

METHODS

Runs of the AERIN Code were made for both acute and chronic inhalation exposure to natural uranium dust. The runs were made for three particle sizes: 1-, 5-, and 10- μm AMAD of solubility classes D, W, and Y as described in the ICRP Lung Model.¹

For acute exposure, a single inhalation of 10 nCi was assumed for input data. For the chronic case, 0.728 nCi was assumed inhaled each day, five days a week, 50 weeks a year (equivalent to a steady state of 0.500 nCi/day every date of the year, for code input).

The specific activity of natural uranium was taken as 0.677 pCi/ μ g and the sum of effective energy (ΣEF) in the bone and lung as 4.60 MeV/disintegration, as derived in Appendix B.

The fraction of U-nat moving from the blood after inhalation to the kidney was assumed to be 0.11, and the biological half-life in the kidney was taken as 15 days.⁴ For bone, the fraction of U-nat moving from the blood to the bone was assumed to be 0.33.² The biological half-life in the bone was taken as 300 days.²

The elimination rate for U-nat through urine as used in the code is

$$U(t) = 0.1 A_0 t^{-1.5} \text{ pCi/day},^5 \quad (1)$$

where t is time in days, A_0 represents the systemic burden at $t = 1$, and $t > 1$ day. For day 1,

$$U(t) = 0.56 A_1 \text{ pCi/day}, \quad (2)$$

where A_1 represents the activity entering the blood during day 1 (see Appendix C). On day 1, $A_0 = A_1$.

As long as uranium deposits remain in any of the naso-pharynx (NP), tracheo-bronchial (TB), pulmonary (PL), or pulmonary lymph (LY) regions, there is a daily contribution from these regions to the blood. Thus there is always a "day 1" component in the blood. As shown in Appendix C, the uranium content in the urine at any time can be represented by the expression

$$U(t) = \sum_{i=1}^t 0.1 A_0 (t + 1 - i)^{-1.5} + 0.46 A_1 \text{ pCi/day}. \quad (3)$$

The computer program calculates the term $\sum 0.1 A_0 (t + 1 - i)^{-1.5}$, but it is necessary to calculate the term $0.46 A_1$ by hand and add it to the value printed out to find the true urine activity.

Suppose now we want to find the maximum annual undetected absorbed dose to the lung from a single acute inhalation of Y-class U-nat of a given particle size if urine sampling is done semiannually (at 200-day intervals). The minimum detection level for U-nat in the urine, 5 μ g/l, corresponds to 4.7 pCi/day (5 μ g/l $\times$ 1.4 l/day $\times$ 0.677 pCi/ μ g; the specific activity value is derived in Appendix B). We find the predicted urine

activity from the computer printout for day 200 and add to it the value calculated for $0.46 A_1$ (see Appendix C for an example). We then take the minimum detection level for U-nat in the urine (4.7 pCi/day) and divide it by the predicted value to obtain a scaling factor which can be applied to all of the other data printed out.

These calculations of absorbed dose to the lung and bone were converted to dose equivalents as shown in Appendix D. For maximum kidney burden, total kidney mass of 300 g was assumed.

We can find a scaling factor for the minimum detection limit for lung burden (9 nCi) in the same manner to determine what doses could be received without detection if an *in vivo* lung count were made annually. (This is done for Y-class U-Nat only; urinalysis is an adequate protective bioassay for D- and W-class material, as will be discussed.)

For chronic exposure, a constant intake was assumed until equilibrium organ burdens were established and a constant urine activity was observed. A scaling factor, found by using the equilibrium concentration in the urine, was applied to the equilibrium organ burdens from the computer printout to get the organ burden and annual absorbed dose that would result.

RESULTS AND DISCUSSION

ACUTE EXPOSURE

Tables 1-3 show the maximum dose equivalents for the lung and bone and the maximum specific organ burden in the kidney that might not be detected at a minimum uranium detection in the urine of 5 $\mu\text{g/l}$. An acute inhalation exposure is assumed.

The total inhalation entries represent the total amount necessary to give 5 $\mu\text{g/l}$ activity in the urine at the indicated interval after exposure. For example, if one were exposed to 5 μm AMAD natural uranium of W solubility class, it would take an intake of 23.4 nCi to give 5 $\mu\text{g/l}$ in the urine 30 days after the inhalation exposure (Table 2). Such an exposure would result in a maximum annual dose equivalent of 0.48 rem to the lung and 0.60 rem to the bone. The maximum specific kidney burden would be 1.4 $\mu\text{g/g}$.

It is apparent in Tables 1-3 that the kidney is the critical organ for D- and W-class material, but the lung is the critical organ for

TABLE 1. Annual dose equivalents to lung and bone and maximum kidney burden from a single inhalation of D-class natural uranium.

Urine sampling interval	Organ	Particle size (AMAD ^a), μ m			Unit
		1	5	10	
15 days	Total inhalation needed to obtain 5 μ g/l	5.6	4.6	4.7	nCi
	Lung	0.004	0.002	0.001	rem
	Bone	0.50	0.51	0.52	rem
	Kidney	1.24	1.31	1.33	μ g/g
30 days	Total inhalation needed to obtain 5 μ g/l	16.2	13.2	13.3	nCi
	Lung	0.011	0.004	0.003	rem
	Bone	1.44	1.47	1.47	rem
	Kidney	3.60	3.74	3.80	μ g/g
100 days	Total inhalation needed to obtain 5 μ g/l	100	80.9	81.6	nCi
	Lung	0.068	0.027	0.018	rem
	Bone	8.95	8.99	9.00	rem
	Kidney	22.3	23.0	23.2	μ g/g
200 days	Total inhalation needed to obtain 5 μ g/l	285	229	231	nCi
	Lung	0.19	0.078	0.052	rem
	Bone	25.4	25.5	25.5	rem
	Kidney	63.4	65.0	65.7	μ g/g

^aActivity Mean Aerodynamic Diameter.

TABLE 2. Annual dose equivalents to lung and bone and maximum kidney burden from a single inhalation of W-class natural uranium.

Urine sampling interval	Organ	Particle size (AMAD ^a), μm			Unit
		1	5	10	
15 days	Total inhalation needed to obtain 5 $\mu\text{g/l}$	11.4	13.5	15.1	nCi
	Lung	0.47	0.28	0.21	rem
	Bone	0.24	0.35	0.40	rem
	Kidney	0.42	0.83	0.98	$\mu\text{g/g}$
30 days	Total inhalation needed to obtain 5 $\mu\text{g/l}$	15.5	23.4	29.0	nCi
	Lung	0.64	0.48	0.40	rem
	Bone	0.32	0.60	0.76	rem
	Kidney	0.57	1.40	1.90	$\mu\text{g/g}$
100 days	Total inhalation needed to obtain 5 $\mu\text{g/l}$	33.5	60.1	82.8	nCi
	Lung	1.4	1.2	1.1	rem
	Bone	0.70	1.6	2.2	rem
	Kidney	1.2	3.7	5.4	$\mu\text{g/g}$
200 days	Total inhalation needed to obtain 5 $\mu\text{g/l}$	90.3	163	225	nCi
	Lung	3.7	3.4	3.1	rem
	Bone	1.9	4.2	5.9	rem
	Kidney	3.3	9.9	14.6	$\mu\text{g/g}$

^aActivity Mean Aerodynamic Diameter.

TABLE 3. Annual dose equivalents to lung and bone and maximum kidney burden from a single inhalation of Y-class natural uranium.

Urine sampling interval	Organ	Particle size (AMAD ^a), μ m			Unit
		1	5	10	
15 days	Total inhalation needed to obtain 5 μ g/l	261	231	239	nCi
	Lung	42.3	18.7	12.9	rem
	Bone	0.52	0.46	0.48	rem
	Kidney	1.25	1.11	1.15	μ g/g
30 days	Total inhalation needed to obtain 5 μ g/l	339	430	498	nCi
	Lung	54.9	34.8	26.9	rem
	Bone	0.48	0.85	0.99	rem
	Kidney	0.67	1.91	2.39	μ g/g
100 days	Total inhalation needed to obtain 5 μ g/l	379	685	954	nCi
	Lung	61.4	55.5	51.5	rem
	Bone	0.54	1.35	1.90	rem
	Kidney	0.75	3.04	4.58	μ g/g
200 days	Total inhalation needed to obtain 5 μ g/l	376	725	1056	nCi
	Lung	60.9	58.7	57.0	rem
	Bone	0.53	1.43	2.10	rem
	Kidney	0.75	3.22	5.07	μ g/g

^aActivity Mean Aerodynamic Diameter.

Y-class material. The critical organ has the highest fraction of the maximum permissible organ burden as given in the federal radiation protection guides mentioned in Appendix B. Thus, urinalysis in itself does not provide an adequate protective bioassay method where Y-class material is present. *In vivo* lung counts are necessary.

Even when D- and W-class materials are involved, the frequency of collecting and analyzing urine content has to be chosen with care. Table 4 shows the maximum time that can elapse between collection periods to prevent the specific kidney burden from exceeding 3 $\mu\text{g/g}$ (1 kidney burden²).

TABLE 4. Maximum time, days, between urine sampling to keep the specific kidney burden $\leq 3 \mu\text{g/g}$ after acute inhalation exposure.

Particle size (AMAD ^a), μm	Solubility class	
	D	W
1	26	189
5	25	81
10	25	56

^aActivity Mean Aerodynamic Diameter.

Therefore, urinalysis should be performed at least every three weeks for D-class material, and at least every six weeks for W-class.

For Y-class solubility, the maximum time that may elapse between *in vivo* lung counts is 283 days if the annual dose equivalent to the lung is to be $\leq 15 \text{ rem/year}$ (1 lung burden²) and the minimum detection level by *in vivo* lung counting is 9 nCi (see Table 5). If only an annual count were made at a minimum detection level of 9 nCi, an annual dose equivalent of 16.8 rem could exist without being detected. These values were calculated using the biological half-life in the lung for 60% of the deposited material as 500 days.¹ If the biological half-life were shorter, then the annual dose equivalent to the lung would be larger. Table 5 shows the effect of biological half-life on the annual dose equivalent to the lung for an annual *in vivo* count with a minimum detection level of 9 nCi.

TABLE 5. Annual dose equivalent to the lung relative to biological half-life, after acute inhalation exposure (when *in vivo* lung counts are made annually).

Biological half-life, days	Dose equivalent, rem/year
700	15.5
600	16.0
500	16.8
400	18.0
300	20.2

Thus, to ensure a lung dose of ≤ 15 rem/year from exposure to Y-class U-nat, semiannual (six-month) *in vivo* counts will be necessary.

CHRONIC EXPOSURE

Consider now the continuous inhalation of U-nat at a low concentration. After a more or less constant intake of uranium by inhalation, equilibrium will be established for the uranium deposited in the various organs in the body. This means that the amount of material in the organs will remain at some constant level as long as the intake continues. The time to reach equilibrium is dependent primarily on the biological half-life of the material in the organ. The equilibrium level is dependent not only on the biological half-life but also on the intake rate, particle size, solubility, and fractional distribution from the blood to the organ during transport through the blood stream. Table 6 lists the time of continuous intake required to reach 99% of equilibrium in the organs listed.

If one assumes a continuous inhalation exposure until an equilibrium concentration is achieved in the urine and if the level of intake is just sufficient to produce an equilibrium urine concentration of 5 $\mu\text{g/l}$, what will be the annual dose equivalents to the lung and bone and the specific kidney burden? These values are given in Table 7.

TABLE 6. Time to reach 99% of equilibrium in the organs from a continuous inhalation of uranium.

Organ	Solubility class			Particle size (AMAD ^a), μ m
	D	W	Y	
Lung	3-4 days	300-350 days	9-10 years	b
Bone	5-6 years ^b	5-6 years ^b	20-21 years	1
			19-20 years	5
			19 years	10
Kidney	100 days ^b	300-350 days	19-20 years	1
		250-300 days	18-19 years	5
		200-250 days	17-18 years	10

^aActivity Mean Aerodynamic Diameter.

^bValues are the same for all particle sizes.

TABLE 7. Annual dose equivalents to lung and bone and specific kidney burden for chronic inhalation (assuming equilibrium urine concentration of 5 μ g/l).

Organ	Particle size (AMAD ^a), μ m	Solubility class			Unit
		D	W	Y	
Lung	1	0.0034	0.84	20.4	rem
	5	0.0014	0.35	16.0	rem
	10	0.0009	0.24	13.6	rem
Bone	0.81 rem for all particle sizes and solubility classes				
Kidney	0.077 μ g/g for all particle sizes and solubility classes				

These data show that for long-term chronic exposure to D-class U-nat, the bone is the critical organ. For W-class U-nat, the lung or the bone is the critical organ, depending on particle size. For Y-class, the lung is the critical organ.

Although the bone is the critical organ for D-class U-nat, this annual dose equivalent will not be reached until at least five years of inhalation have accumulated (Table 6); urinalysis would detect the intake long before this occurred. Activity in the kidney would also be revealed by urinalysis before it reached 1 kidney burden, as Table 7 shows. Similarly, chronic inhalation of W-class material would be detected by routine urine sampling.

Because it is already necessary to perform semiannual lung counts (to assure ≤ 15 rem/year from acute exposures), it is assumed that the deposit in the lung from chronic exposure would be detected at one of these counts long before equilibrium would be established (see Table 6). An equilibrium level of 9 nCi in the lung will deliver a dose equivalent rate of 12.9 rem/year.

CONCLUSIONS

For a single inhalation exposure to natural uranium, the kidney is the critical organ for D-class and W-class materials. For Y-class U-nat, the lung is the critical organ.

With the NRC minimum detection limit of 5 $\mu\text{g/l}$ of natural uranium in the urine, urinalysis on a worker should be performed at least every three weeks if the uranium taken into the body is of D-class solubility. This should assure detection of an intake before it exceeds 1 kidney burden. The NRC Regulatory Guide 8.22 recommends that workers be sampled every two weeks.

For W-class soluble material the period of urinalysis could be extended to once every six weeks. However, the NRC makes no distinction between sampling frequencies for D- and W-solubility classes of the uranium compounds.

For Y-class material, with a minimum detection limit of 9 nCi, *in vivo* lung counts should be made on potentially exposed workers once every six months to detect less than 1 lung burden. However, if only annual *in vivo* lung counts are made, as the NRC recommends, the maximum possible deposit would be only about 1.1 lung burdens. It is very unlikely that an acute exposure that would deposit 1.1 lung burdens would go undetected. Air samples and body surface contamination would give indications of exposures of this magnitude. Proper environmental monitoring procedures therefore could reduce the need for semiannual lung counting.

This study indicates that the NRC is conservative in its requirement of two-week intervals for urinalysis for transportable (D- and W-class) compounds of uranium. Although the NRC requirement of annual lung counts for nontransportable (Y-class) compounds is not as conservative, the worst possible case would result in a lung burden only 10% greater than the maximum permissible lung burden, and the probability of this going undetected by other means is very slight. Therefore, the requirement of annual lung counts is reasonable.

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APPENDIX A

The AERIN Code

The AERIN Code,³ developed at LLL, computes for various organs of the body the burden of radioactivity and absorbed dose that result from the inhalation of a radionuclide; it plots these data vs. time. In addition, it predicts the amount of activity excreted in the urine and feces as a function of time.

The code uses the ICRP task group's model¹ on lung dynamics as a basis for the computations.

Particle size can be selected by the operator from a table of 13 diameters, ranging from 0.01 to 50.00 μm AMAD, or he has the option to alter the table if he chooses.

Solubility class Y, W, or D may be selected. The inhalation intake can be a single acute exposure, a series of exposures occurring at varying times and in varying amounts, or a chronic exposure.

Options are also available to alter the transport fractions and the biological half-lives in the various organ compartments if one chooses not to use the ICRP lung model.

The urine excretion function is the familiar Langham expression for plutonium ($0.002 t^{-0.74}$); however, the option is available to change the fractional constant and the exponent if one chooses, as was done in this case for uranium ($0.1 t^{-1.5}$).

A schematic representation of the AERIN Code model follows.

Fig. A1. AERIN Code model.

APPENDIX B

Definition of a Curie of Natural Uranium and Its Application in Internal Dose Calculations for Bone and Lung

Originally, a curie of natural uranium meant the sum of 3.7×10^{10} disintegrations/second (dis/s) from ^{238}U plus 3.7×10^{10} dis/s from ^{234}U plus 1.7×10^9 dis/s from ^{235}U . One curie of natural uranium was equivalent to 3000 kg. This special definition of the curie was used to establish the maximum permissible concentration (MPC) in air and water for natural uranium prior to 1976 and was published in 10 CFR 20 Appendix B, in DOE Appendix 0524 Annex A, and in other federal radiation protection guides.

Natural uranium is composed of 0.0057 at.% ^{234}U , 0.7196 at.% ^{235}U , and 99.276 at.% ^{238}U . The latest half-life values for these isotopes as given by the LLL Nuclear Chemistry Division are 2.45×10^5 years for ^{234}U , 7.04×10^8 years for ^{235}U , and 4.47×10^9 years for ^{238}U . The specific activity per atom is the radioactive decay constant $\times$ number of atoms/number of atoms ($\lambda N/N$) or simply λ ; thus, for ^{234}U ,

$$\frac{\lambda N}{N} = \frac{\ln 2}{(2.45 \times 10^5 \text{ years}) \left(365.25 \frac{\text{days}}{\text{year}}\right) \left(1440 \frac{\text{minutes (min)}}{\text{day}}\right)} = 5.38 \times 10^{-12} \text{ dis/min per atom,} \quad (\text{B1})$$

for ^{235}U ,

$$\frac{\lambda N}{N} = \frac{\ln 2}{(7.04 \times 10^8) (365.25) (1440)} = 1.87 \times 10^{-15} \text{ dis/min per atom,} \quad (\text{B2})$$

and for ^{238}U ,

$$\frac{\lambda N}{N} = \frac{\ln 2}{(4.47 \times 10^9) (365.25) (1440)} = 2.95 \times 10^{-16} \text{ dis/min per atom.} \quad (\text{B3})$$

The activity in 1 g of natural uranium would therefore be

$$\Sigma (\text{Specific activity} \times \text{Relative atomic abundance} \times N \text{ in 1 g of U-nat.}) \quad (B4)$$

The number of atoms in 1 g of natural uranium is

$$\frac{(5.7 \times 10^{-5})^{234}}{6.0255 \times 10^{23}} N + \frac{(7.196 \times 10^{-3})^{235}}{6.0255 \times 10^{23}} N + \frac{(0.99276)^{238}}{6.0255 \times 10^{23}} N = 1 \text{ g.} \quad (B5)$$

$$N = 2.5 \times 10^{21} \text{ atoms/g of U-nat.}$$

Therefore, for ^{234}U ,

$$(5.38 \times 10^{-12} \text{ dis/min}) (5.7 \times 10^{-5}) (2.5 \times 10^{21}) \\ = 7.8 \times 10^5 \text{ dis/min,} \quad (B6)$$

^{235}U ,

$$(1.87 \times 10^{-15} \text{ dis/min}) (7.196 \times 10^{-3}) (2.5 \times 10^{21}) \\ = 3.4 \times 10^4 \text{ dis/min,} \quad (B7)$$

^{238}U ,

$$(2.95 \times 10^{-16} \text{ dis/min}) (9.9276) (2.5 \times 10^{21}) \\ = 7.4 \times 10^5 \text{ dis.} = 7.4 \times 10^5 \text{ dis/min,} \quad (B8)$$

$$\Sigma = 1.5 \times 10^6 \text{ dis/min per g,}$$

$$\text{or } 6.7 \times 10^5 \text{ pCi/g} = 0.67 \text{ pCi/}\mu\text{g.}$$

Thus it takes 1480 kgm of U-nat to make 1 curie instead of 3000 kg as defined previously.

As now defined in 10 CFR 20 Appendix B, 1 kg of U-nat is made up of 330.9 μCi of ^{238}U plus 330.9 μCi of ^{234}U plus 15.2 μCi of ^{235}U for a total of 677.0 μCi .

Thus the specific activity of U-nat by the new definition is 0.6770 $\mu\text{Ci}/\mu\text{g}$. According to the new definition then, it takes 1477 kg to make 1 Ci of U-nat. The MPC of both soluble and insoluble U-nat in air and water given in the current issue of 10 CFR 20 Appendix B reflect this new definition. These are, in $\mu\text{Ci}/\text{ml}$:

<u>Occupational workers</u>		<u>General public</u>	
<u>Air</u>	<u>Water</u>	<u>Air</u>	<u>Water</u>
10^{-10}	10^{-3}	5×10^{-12}	3×10^{-5}

From the report of ICRP Committee II,⁴ the SEF for the three isotopes in natural uranium deposited in the bone and lung are:

for ^{234}U , SEF = 4.9 MeV/dis,

^{235}U , SEF = 4.6 MeV/dis,

^{238}U , SEF = 4.3 MeV/dis.

To find the weighted average, we do the following:

$$\begin{aligned}
 & (330.9 \mu\text{Ci}/\text{kg}) (4.9 \text{ MeV}/\text{dis}) = 1621 (\mu\text{Ci-MeV})/(\text{kg-dis}) \\
 & + (330.9 \mu\text{Ci}/\text{kg}) (4.3 \text{ MeV}/\text{dis}) = 1423 \\
 & + \frac{(15.2 \mu\text{Ci}/\text{kg}) (4.6 \text{ MeV}/\text{dis}) = 699}{677.0 \mu\text{Ci}/\text{kg}} \quad \frac{3114 (\mu\text{Ci-MeV})/(\text{kg-dis})}{677}
 \end{aligned}$$

SEF in the bone and lung = $3114/677 = 4.60 \text{ MeV}/\text{dis}$.

APPENDIX C Uranium Activity in the Urine

The fractional distribution of the uranium as it enters the blood from the naso-pharynx, (NP), tracheo-bronchial (TB), pulmonary (PL), and pulmonary lymph (LY) regions is 0.11 to the kidney and 0.33 to the bone. This leaves 0.56 in the blood, which is eliminated in the urine during the first day.

The AERIN Code gives the daily urine elimination, based on the equation

$$U(t) = 0.1 A_0 t^{-1.5} \text{ pCi/day,} \quad (C1)$$

where t is in days and A_0 represents the systemic burden at day 1. To apply the AERIN Code to uranium excretion, we must set up an activity balance equation for day 1. Therefore, the amount in the urine is

$$U(1) = 0.1 A_0 (1)^{-1.5} + 0.46 A_1 \text{ pCi/day,} \quad (C2)$$

where A_1 is the activity entering the blood during day 1. Since $A_0 = A_1$ on day 1,

$$U(1) = 0.56 A_1 \text{ pCi/day.} \quad (C3)$$

For $t > 1$,

$$U(t) = 0.1 A_0 t^{-1.5} \text{ pCi/day.} \quad (C4)$$

Complexity arises, however, because new material is being added daily to the blood from deposits in the NP, TB, PL, and LY regions. As long as there are deposits in any one of these regions, there is a day 1 situation for the material added that day. It is therefore necessary to sum all the previous days' contribution to the systemic burden. Therefore, the urine output on any day may be given by

$$U(t) = \sum_{i=1}^t 0.1 A_0 (t + 1 - i)^{-1.5} + 0.46 A_1 \text{ pCi/day.} \quad (C5)$$

The computer program gives only the value of $\Sigma 0.1 A_0 (t + 1 - i)^{-1.5}$ and it is necessary to add the value of $0.46 A_1$ by hand to the computer printout to obtain the urine activity for that day. The value of A_1 is given by

$$A_1 = \lambda_{NP}(qNP) + \lambda_{TB}(qTB) + \lambda_{PL}(qPL) + \lambda_{LY}(qLY), \quad (C6)$$

where λ represents the biological decay constants of the material in NP, TB, etc., regions destined to go to the blood, and the q values are the quantity in activity units deposited in each region. This can best be explained by an example. From the computer printout we obtain the following values for $t = 30$ days:

Urine output indicated = 1.32 pCi/day

$qNP = 0.0$ pCi

$qTB = 0.0$ pCi

$qPL = 2.39$ pCi

$qLY = 32.7$ pCi.

The material is W class in the model so $\lambda_{PL} = \ln 2/50$ days and $\lambda_{LY} = \ln 2/50$ days, where 50 days is the biological half-life in the ICRP lung model, or

$$\lambda_{PL} = \lambda_{LY} = 0.0139/\text{day}.$$

Thus,

$$A_1 = 0 + 0 + 0.0139 (2.39 + 32.7) = 3.77 \text{ pCi/day}.$$

The true urine activity is

$$U(30) = 1.32 + 1.73 = 3.05 \text{ pCi/day}.$$

APPENDIX D

Absorbed Dose-Rate to the Bone and Lung from the Deposit of Natural Uranium: Conversion to Dose Equivalent

The internal absorbed dose-rate is expressed by the equation

$$\frac{d(AD)}{dt} = \frac{51.149 \times 10^{-3}}{m} q \Sigma EF \text{ rad/day,} \quad (D1)$$

where q is the quantity in μCi of U-nat in the organ of mass, m , in grams at time t , and ΣEF is in MeV/dis . From the ICRP Publication 19¹, m for the lung is 600 g and for the bone 5000 g. From Appendix B, $\Sigma EF = 4.60 \text{ MeV/dis}$. Therefore, for the bone, 1 μCi deposited in the skeleton gives

$$\frac{d(AD)}{dt} = \frac{(51.149 \times 10^{-3})(10^3)(4.60)}{5000} = 4.7 \times 10^{-2} \text{ rad/day}$$

and 1 μCi deposited in the lung gives

$$\frac{d(AD)}{dt} = 0.39 \text{ rad/day.}$$

Since we are dealing primarily with Alpha particles where the QF (Quality Factor) is 10 and $n = 5$ in the bone and 1 in the lung, the above values can be expressed in dose equivalent as

Bone = 2.4 rem/day per μCi , and

Lung = 3.9 rem/day per μCi .