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Analysis of Radiation Exposures on or Near Uranium Mill Tailings Piles

Keith J. Schiager[1]

Potential radiation exposures from abandoned uranium mill tailings piles may be predicted in a general manner using minimal input data. If the average radium concentration in the tailings C_{Ra} is known, the external gamma exposure rate over the tailings can be estimated from: $X\ (\mu R/h) \cong 2.5\ C_{Ra}\ (pCi/g)$. The radon emanation rate can also be estimated as: $\phi\ (pCi\ Rn/m^2\text{–}s) \cong 1.6\ C_{Ra}\ (pCi/g)$. The reductions of exposure rates that can be achieved by covering the tailings with earth or concrete also are discussed. Radon progeny inhalation exposures depend upon the dispersion rate of radon in the atmosphere and the time available for progeny ingrowth. Meteorological data for the site are required for making reliable predictions of inhalation exposures. It is shown, however, that contributions to the average annual outdoor radon progeny concentrations exceeding 0.003 WL are very unlikely on or near any tailings pile. The methods used to analyze potential radiation exposures are illustrated by a case study on one abandoned tailings pile.

Uranium mill tailings piles are a source of potential radiation exposure to persons in the immediate vicinity. During the period of active use, exposures are primarily confined to mill personnel and are classified as occupational. For the purpose of preparing environmental reports, however, mill operators need to predict exposure rates that would occur both during use and also after stabilization. The analytical methods presented herein may be helpful in preparing such environmental reports.

Abandoned tailings piles present some special problems in addition to those encountered with active piles. If left unstabilized, an abandoned pile serves as a continuing source of environmental contamination as a result of wind and water erosion. The cost of stabilization, however, may be a significant economic burden if required of an owner who cannot realize an associated land-use benefit. Furthermore, even a stabilized pile represents a long-term net cost to the community if it cannot be used in some productive manner; the actual cost depends, of course, on the location of the pile and its potential for development.

The construction of enclosed buildings on, or immediately adjacent to, tailings piles is not thoroughly considered in this analysis; such use is not usually an acceptable option. However, data on the effectiveness of concrete slabs for reducing exposures are included since some potential uses of tailings may involve concrete surfacing. These data also can be applied in the analysis of exposures in structures already built over tailings.

Basic principles

The analytical methods presented in this discussion, and the kinds and sources of data required to support the analysis, were determined by the following basic principles.

Short-term stabilization versus long-term risk

At the present time, there is no proven method that is economically feasible for permanently eliminating the possibility of radiation exposures from radium-bearing tailings left on the earth's surface. The half-life of radium-226 is more than 1600 years, and typical uranium mill tailings contain radium concentrations approximately 100 times greater than ordinary Colorado soil (*1,2*). To reduce the radiation exposure potential to a level comparable to the normal background would require a decay time

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of more than 10 000 years. If the thorium-230 precursor of radium-226, with a half-life of 80 000 years, is present in significant quantities, the time element of the argument would be extended accordingly. No human institution, government or private, can effectively guarantee control over any parcel of land for thousands of years.

Any form of control or stabilization, whether by productive development or by nonproductive access restrictions, can be considered valid for only one or two generations. Consequently, any decision on a potential utilization of a tailings site should be based upon the careful appraisal of both the predictable radiation exposures and the expected benefits of the alternative choices over the time period of the anticipated utilization.

Radiation exposure sources

Radium and its decay products can produce radiation exposures through three basic routes; each potential exposure route must be considered independently.

1. Ingestion. Radium may be leached from tailings and enter surface waters or subsurface aquifers. The radium may subsequently be ingested directly with the water or transferred to humans through foods. The obvious preventive measure is to prevent leaching of the tailings. Whether to be used productively or not, a tailings pile should be contoured and covered in a manner that will minimize both leaching and erosion. In general, the risk of radium ingestion will be reduced in direct proportion to the thickness and durability of the cover material used for stabilization. The risk of contamination of water with radium is primarily dependent upon local variables, e.g. topography, soil characteristics, proximity of surface waters and subsurface aquifers, climate, etc. The risk of ingestion cannot be generalized as readily as can the other exposure risks and, consequently, is not considered further here.

2. Inhalation. Radium decays to radon, a noble gas that diffuses readily in air, as well as through many apparently solid materials. The radon that is produced in the uranium decay series is radon-222 which has a half-life of 3.8 days, or a mean lifetime of 5.5 days. During this mean lifetime, a radon atom may be transported hundreds of miles through the atmosphere. However, it would diffuse only a few feet through earth or tailings, and only a few inches through good concrete, during its lifetime.

The inhalation exposure of greatest importance is produced by the short-lived decay products of radon, rather than by the gas itself. Following its decay as radon, an atom progresses through four additional decays in a mean time of 74 minutes, emitting 2 alpha and 2 beta particles in the process. Most of the gamma rays arising from the radium decay series also originate from these short-lived progeny. Inhaled radon progeny atoms can deposit as solid particles in the respiratory tract. Completion of their decay sequence at or near the site of deposition produces a highly localized radiation dose to the respiratory epithelium, particularly due to the short-range alpha particles.

Concentrations of radon progeny in air are commonly expressed in units of working levels (WL)[2]. One WL is equivalent to the radon progeny that would be present in equilibrium with a radon concentration of 100 pCi/liter. Equilibrium in air between radon and its progeny is rarely approached, however, except outdoors at some distance above the ground. Even outdoors, therefore, it is necessary to determine radon progeny concentrations, as opposed to radon only.

3. External. Most of the radon produced by decay of radium is trapped in solid particles. In typical tailings, the "emanating power" (i.e. the fraction of the radon that is free to diffuse) is approximately 20 percent (*1*). The remaining radon (80 percent), plus all of the associated decay products, provide a source of gamma rays from within the tailings.

In contrast with ingestion or inhalation exposures, external gamma rays expose the entire body, including the gonads, blood-forming organs, and other sensitive tissues. However,

[2] One WL is defined as any combination of radon progeny in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy during decay to lead-210.

this source of exposure can be reduced and controlled much more easily than can the emanation of radon. The feasibility of reducing gamma exposure rates essentially to normal background levels is presented in a following section.

Annual averages

All of the radiation protection guides for the general public are based upon averages over a period of 1 year or longer. For each type of variable exposure, therefore, it is necessary to determine long-term averages rather than relying upon single measurements or peak values. The evaluation of long-term average exposures must include consideration of reasonable annual occupancy factors as well as the variability of the exposure rates. Any radiation exposure situation that involves less than 24 hours/day and 365 days/year of exposure time must be evaluated on the basis of the maximum potential exposure to any individual and the predicted average exposure to a population group.

Simplifying assumptions and approximations

In keeping with the proposed applications of the data and methods which follow, namely to permit reasonably accurate exposure estimates to be made for alternative uses of tailings locations, certain approximations are used to simplify the calculations. Sufficient background information and data are included, however, to support the simplifications. In view of the numerous environmental variables that affect the potential radiation exposures, the use of simplifying assumptions is believed to be justified. The accuracy of the exposure predictions depends much more heavily on the validity of the data introduced into the calculations than it does on the analytical approximations.

Table 1. Gamma-ray emission and exposure data for radium (*1, 4*)

Number of photons per radium decay	2.184
Total photon energy per radium decay	1.80 MeV
Mean photon energy	.824 MeV
Flux at 1 meter from a 1 curie point source:	
Photon flux	6.4×10^5 photons/cm^2−s
Energy flux	5.3×10^5 MeV/cm^2−s
Fluence-to-exposure conversions:	
Photon fluence	2 300 photons/cm^2−μR
Energy fluence	1 900 MeV/cm^2−μR
Gamma-ray exposure constant (for a source sealed in 0.5 mm platinum)	.84 R/h at 1 m from 1 Ci

Both customary and metric units are used throughout the presentation depending on common usage for the quantity involved. Although all quantities were converted to metric units for purposes of calculation, many customary units were retained in the figures and text for the convenience of readers.

External gamma-ray exposures

Most tailings sites are sufficiently large that they may be treated as slabs of infinite area for purposes of calculating gamma-ray exposures directly over the surface. The unscattered flux of gamma rays reaching a point near the surface of an infinite slab source can be expressed as (*3*):

$$\Phi = S/2\mu \, [1 - E_2 \, (\mu x)]$$

where: Φ = primary gamma-ray flux (photons/cm^2-s)

S = gamma-ray emission rate (photons/cm^3-s)

μ = linear attenuation coefficient in the slab material (cm^{-1})

x = slab thickness (cm)

$E_2(\mu x)$ = second order exponential integral

$$= \mu x \int_{\mu x}^{\infty} e^{-u} u^{-2} \, du$$

The radium decay series produces gamma rays over a broad range of energies and relative emission rates. The linear attenuation coefficient, μ, is also energy dependent. Thus, a precise calculation of the unscattered photon flux above the slab would require a summation of the contributions of the gamma rays of each energy. It is possible, however, to obtain reasonably good results using values that have been appropriately averaged for the entire energy spectrum. Some appropriate numerical values are shown in table 1. A graph of the function $[1 - E_2(\mu x)]$ versus μx is shown in figure 1.

Data pertaining to both source terms and shielding functions are listed in table 2. The activity concentration shown for tailings (C_{Ra}

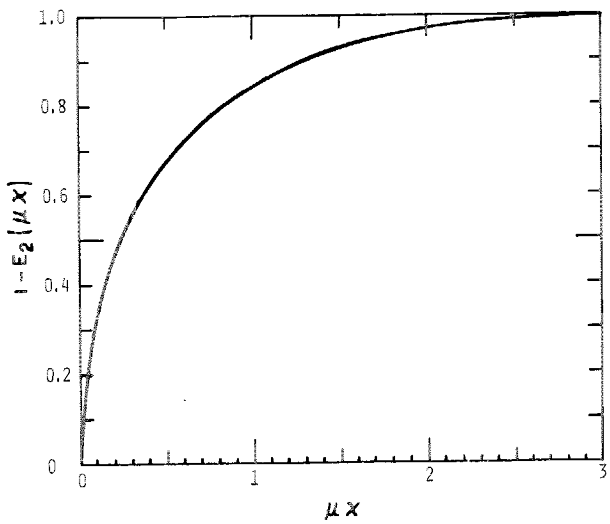

Figure 1. Plot of the function 1-E_2 (μx) versus μx

Table 2. Exposure rate variables for environmental radium and radon (values are typical or reasonable averages) (1)

Variable	Tailings (dry packed)	Earth (moist packed)	Concrete (ordinary)
Radium concentration, C_{Ra} (pCi/g)	250	2	2
Density, ρ(g/cm^3)	1.6	1.6	2.35
Attenuation coefficient, μ(cm^{-1})	.11	.11	.16
Tenth value layer ($I_X = 0.1\ I_0$)	—	13 inches	9 inches
Porosity (fraction void)	.36	.25	.06
Diffusion coefficient, D(cm^2/s)	5×10^{-2}	5×10^{-2}	2×10^{-5}
Relaxation length, ($C_X = C_0/e$)	1.5 m	1.5 m	5 cm

= 250 pCi/g) is considered typical for the sand portion, although actual concentrations may range from 130 to 300 pCi/g. The radium concentrations shown for earth and concrete are approximations only; actual values generally are in the range of 0 to 10 pCi/g.

Based upon the data contained in tables 1 and 2, one can calculate the emission rate of the unscattered photons:

$$S = (C_{Ra}\ \text{pCi/g})\ (0.037\ \text{dis/s-pCi})\ (1.6\ \text{g/cm}^3)\ (2.184\ \text{photons/dis}) = 0.13\ C_{Ra}\ \text{photons/cm}^3\text{-s}$$

where C_{RA} = concentration of radium in the tailings (pCi/g)

For values of μx greater than 3, the function $[1 - E_2(\mu x)]$ is essentially equal to 1 and the unscattered flux will be the same as that from an infinitely thick slab:

$$\Phi = S/2\mu = (0.13\ C_{Ra}\ \text{photons/cm}^3\text{-s})/2(0.11\ \text{cm}^{-1}) = 0.59\ C_{Ra}\ \text{photons/cm}^2\text{-s}$$

The contribution of the unscattered flux to the exposure rate is then calculated to be:

$$X = (0.59\ C_{Ra}\ \text{photons/cm}^2\text{-s})\ (3600\ \text{s/h})/(2300\ \text{photons/cm}^2\text{-}\mu\text{R}) = 0.92\ C_{Ra}\ \mu\text{R/h}$$

The total exposure rate over the slab, however, is only partially due to unscattered gamma rays. Scattered gamma rays contribute more to the exposure rate over the slab than the primary photons do. It is necessary, therefore, to incorporate a "buildup factor" into the calculations to account for the exposure contribution from the scattered radiation.

Buildup factors can be, and have been, calculated on a theoretical basis, but this approach requires sophisticated data and computerized analyses. The more common approach is to determine the buildup factor empirically by finding the function that best fits the experimental data. Most buildup factors reported in the literature (3,4) are applicable to slabs of shielding materials, rather than to slab sources. The following buildup factor is proposed for use in calculations involving tailings piles since it fits the available experimental data quite well:

$$B = e^{\mu x/1+\mu x}$$

Since the value of μ varies from approximately 0.11 cm^{-1} in dry tailings to 0.16 cm^{-1} in concrete, the value of B increases very slowly for x greater than 60 cm, or 24 inches. The values of $[1 - E_2(\mu x)]$ and of B need be determined only if one is concerned with shallow slabs of tailings. For such situations, the graph shown in figure 2 can be used to determine the fraction of the maximum exposure rate that would be produced over the slab. Because of the steep slope of the curve for slab thicknesses of only a few inches, the determination of the slab thickness is crucial for predicting exposure rates over thin layers of tailings.

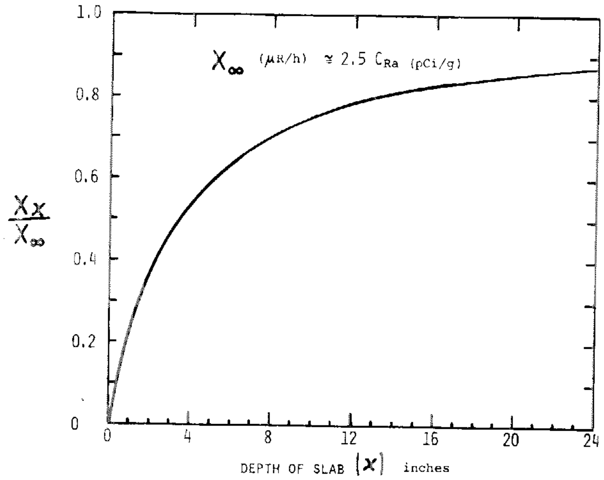

Figure 2. Fractional contribution to gamma exposure rate at surface depth of infinite slab of earth (or tailings) containing radium

For any situation involving tailings depths of more than 1 or 2 feet, the value of μx becomes very large, and the external exposure rate over the tailings can be calculated as follows:

$$X\ (\mu R/h) = 0.92\ e\ C_{Ra}\ (pCi/g) = 2.5\ C_{Ra}\ (pCi/g)$$

The relationship calculated above is in excellent agreement with a simplified formula presented by Hultqvist (*5*) for determining the dose rate above soils containing radium:

$$D\ (mrads/yr)\ \text{in air} = 18.4 \times 10^{12}\ S\ (g\ Ra/g\ soil)$$

This formula, when converted to the units used in this paper, becomes:

$$X\ (\mu R/h) = \frac{18.4\ (g\text{-}mrad/pCi\text{-}yr)\ C_{Ra}\ (pCi/g)\ 10^3\ (\mu R/mR)}{8766\ (h/yr)\ (0.877\ rad/R)} = 2.4\ C_{Ra}\ (pCi/g)$$

It should be pointed out here that accurate measurements of external gamma-ray exposure rates in the environment are not generally obtained with portable survey instruments. Most instruments are calibrated against point sources exhibiting only the primary photon energy spectrum. Because of the energy dependence of most survey instruments, they tend to over-

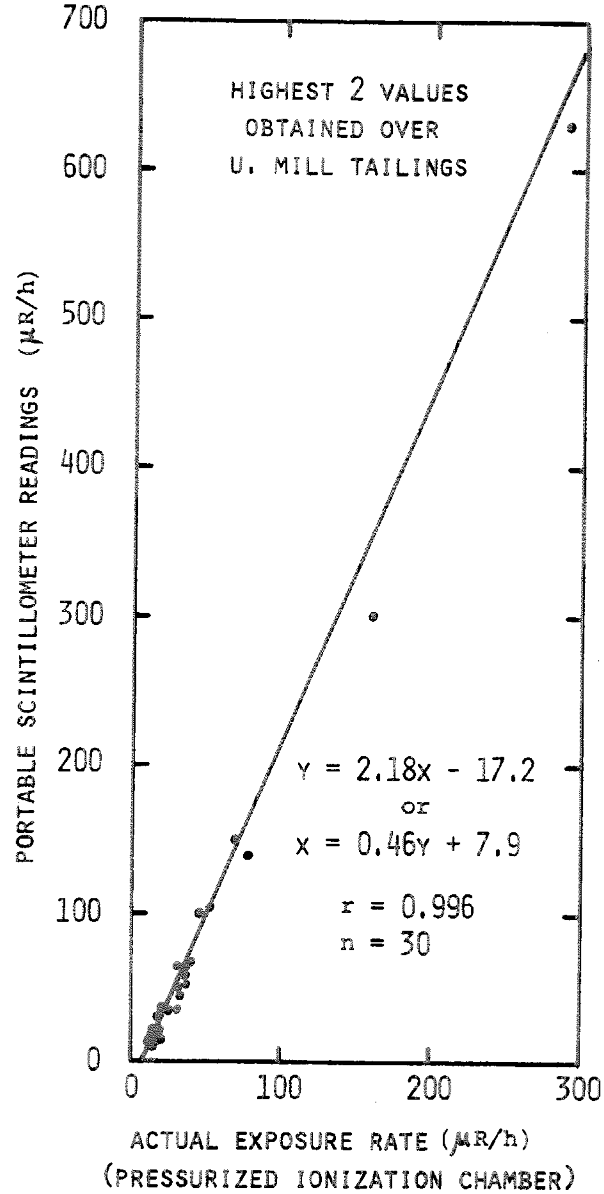

Figure 3. Scintillometer readings versus gamma exposure rate measured with a pressurized ionization chamber at identical locations

respond to scattered radiation, which comprises 60 to 70 percent of the total in the environment. Figure 3 shows a calibration curve for a scintillation crystal (NaI) survey meter that was calibrated to read the correct exposure rate when exposed to a point source of radium. In general, readings obtained over tailings locations were more than double the true exposure rate, as determined with a pressurized ionization chamber. Although this calibration applies only to one specific instrument, calibration curves for many other instruments are similar.

Gamma-ray exposures from tailings can be reduced to levels comparable to the natural background by covering with earth to a depth of approximately 2 feet. The reduction factors that can be achieved with various thicknesses of earth or concrete can be determined from the graph in figure 4.

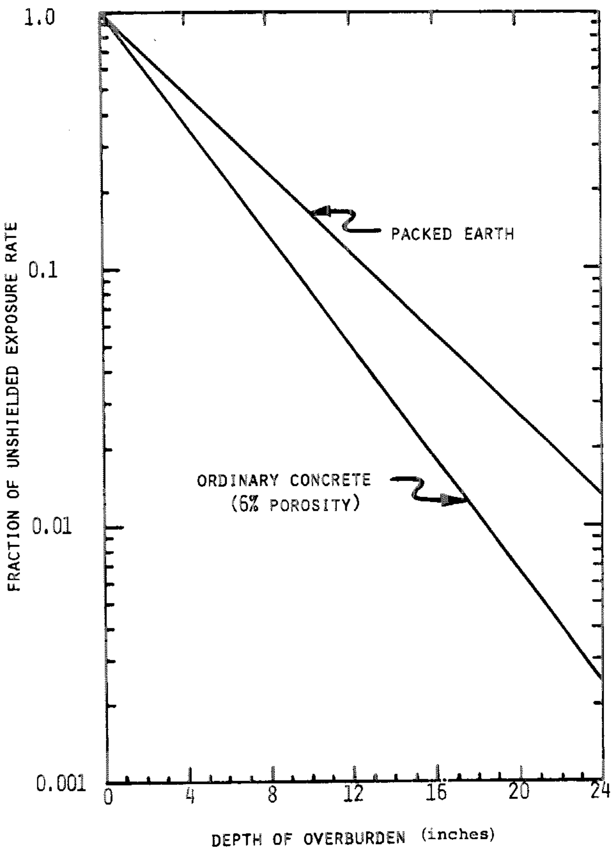

Figure 4. Reduction of gamma exposure rate resulting from earth or concrete shielding (2)

Radon emanation

The rate of radon emanation from a thick slab of uranium mill tailings is primarily dependent on the radium concentration and the fraction of the radon that escapes from the solid particles and is free to diffuse. The radon flux expected at the surface of a slab of dry tailings is shown in figure 5 as a function of slab thickness. The shape of the curve is similar to that which describes the gamma-ray flux; the most notable difference is the scale for the depth of tailings. A slab of 6 to 10 feet in depth is required to produce the maximum radon flux. The relationship between the maximum radon flux and the radium concentration is:

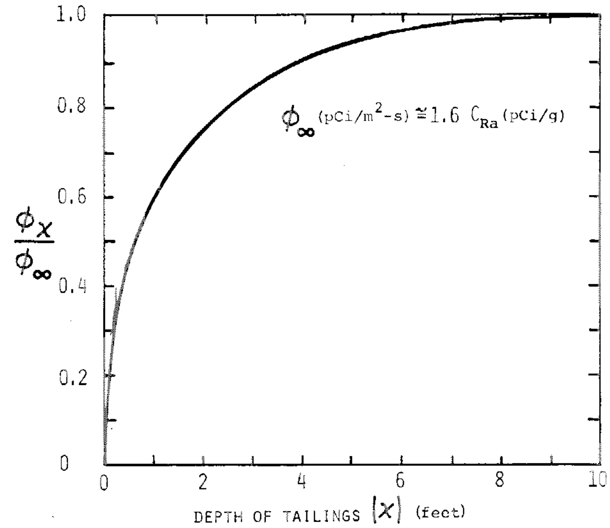

Figure 5. Fractional radon emanation rate versus depth of bare tailings (*1*)

$$\frac{\Phi_\infty \ (\text{pCi Rn/m}^2\text{-s})}{C_{Ra} \ (\text{pCi Ra/g})} = 1.6$$

$$\text{or } \Phi_\infty \ (\text{pCi/m}^2\text{-s}) = 1.6 \ C_{Ra} \ (\text{pCi/g})$$

For tailings depths of only a few feet, the flux can be predicted as a fraction (Φ_x/Φ_∞) of the flux for a slab of infinite thickness, as shown in figure 5.

Radon emanation cannot be stopped as readily with earth as can gamma rays. As shown in table 2, the "relaxation length" (the distance required to reduce the radon concentration by a factor of *e*) is approximately 1.5 meters of earth, or approximately 10 times greater than the thickness required to reduce the gamma-ray exposure rate by the same factor. Consequently, the thickness of earth cover required to reduce the radon flux to a level equivalent to the normal background would be approximately 20 feet. On the other hand, the diffusion coefficient for radon in concrete is approximately three orders of magnitude smaller than it is in earth. The

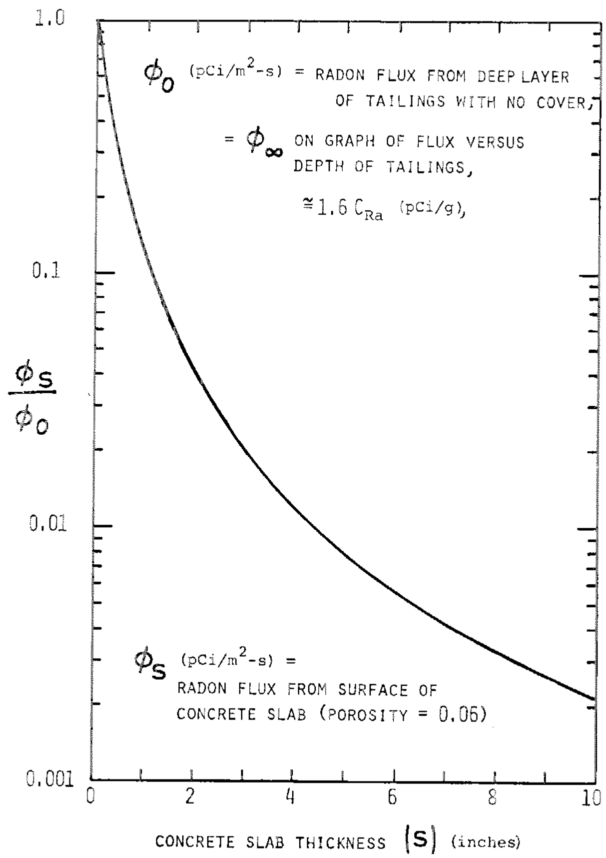

Figure 6. Fractional radon emanation rate through concrete slab placed over a thick layer of tailings versus slab thickness (*1*)

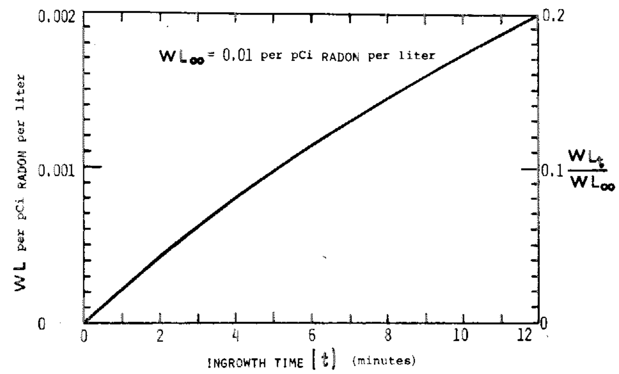

Figure 7. Ingrowth rate of radon progeny from radon-222 (in units of working levels, WL)

relaxation length is correspondingly shorter (5 cm or 2 inches), indicating the potential of using concrete slabs to reduce radon diffusion, as shown in figure 6.

Radon progeny ingrowth

The concentration of radon in the atmosphere depends upon the rate of dispersion as well as upon the rate of emanation into the atmosphere. The actual inhalation exposure, however, is determined by the concentration of radon progeny which is also dependent upon the mean "age" of the radon. Evans (*6*) has presented a detailed but concise analysis of the behavior of radon progeny. The radon progeny concentration per unit concentration of radon, for ingrowth times up to 12 minutes, starting with radon contamination only, is shown in figure 7.

For typical tailings piles of several hundred meters in width, and typical wind speeds of a few meters per second, the transit time over the tailings is rarely more than a few minutes. Thus, the ingrowth of radon progeny in the immediate vicinity of the pile can seldom exceed 10 percent of its equilibrium value, or 0.001 WL per pCi of radon per liter. The maximum concentration of radon progeny, under most meteorological conditions, would occur just beyond the edge of the pile; further downwind, the dilution of the radon in the atmosphere more than compensates for the subsequent ingrowth of the progeny.

In the special situation in which buildings are located immediately adjacent to a tailings pile, the indoor radon concentration in such buildings would be in equilibrium with that found outdoors. The residence time of the air indoors would be long enough, however, for the radon progeny to reach a significant fraction of the equilibrium concentration. It is highly likely that the radon progeny concentration in a building adjacent to, but not on, a tailings pile would be higher than the maximum outdoor concentration. Such situations obviously require more detailed evaluations.

Atmospheric dispersion

The method used to calculate the concentration and mean age of radon in the atmosphere is shown in figure 8. The method is based on one important assumption: that the lateral extent of the area source (tailings), upwind

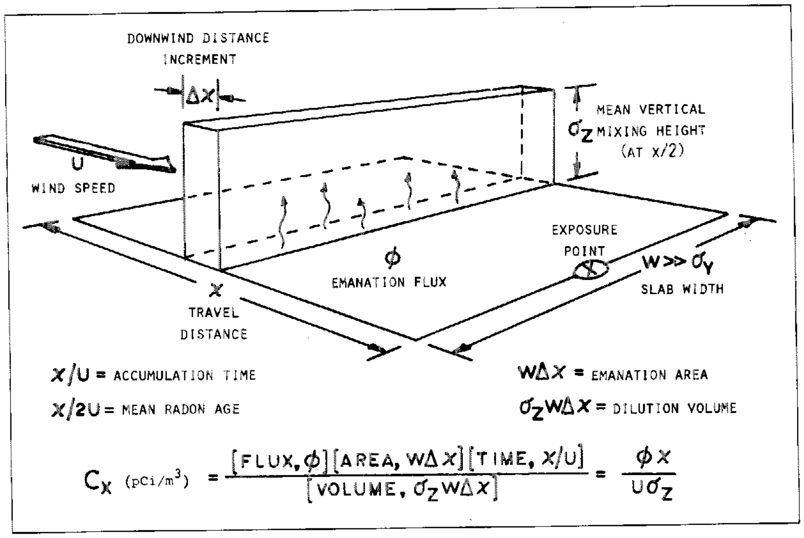

Figure 8. Atmospheric dilution diagram for radon emanating from a large slab source, e.g., a tailings pile

from the point where the concentration is to be determined, is large compared to the horizontal dispersion coefficient for the assumed meteorological condition. This assumption will always be satisfied if the width of the upwinding tailings area, w, is of the same order of magnitude as the travel distance in the direction of the wind, x.

Horizontal and vertical dispersion coefficients, σ_y and σ_z, represent the mean mixing distances, for various meteorological conditions, as functions of the downwind travel distance (7). For the stated assumption, i.e. $w >> \sigma_y$, the actual value of σ_y is not required for the analysis to be made here. However, the value of σ_z is crucial; values of σ_z for x in the range of 100 to 1000 meters are plotted in figure 9.

Consider a thin section of air extending across the tailings slab in a direction normal to the wind. The area of this section of air at the slab surface is $w\Delta x$, where Δx is a small increment of distance in the direction of the wind, and w is the width of the slab. The height of this section of air is assumed to be the mean vertical mixing height, σ_z, at the mean travel distance, x/2.

The total distance in the direction of the wind, from the upwind edge of the source area to the point where the concentration is to be determined, is defined as x. At a wind speed of u, the total time available for accumulation of radon in the section of air is x/u; the mean radon age is x/2u.

The radon concentration is calculated as follows:

$$C_{Ra}\ (pCi/m^3) = \frac{[\phi\ (pCi/m^2\text{-}s)]\ [w\Delta x\ (m^2)]\ [x/u\ (s)]}{[w\Delta x\sigma_z\ (m^3)]}$$

$$= \phi x/u\sigma_z\ (pCi/m^3)$$

$$= 10^{-3}\ \phi x/u\sigma_z\ (pCi/liter)$$

The preceding calculation applies strictly to instantaneous conditions and to locations on or immediately adjacent to a tailings pile. The concentration at a distance, d, further downwind from the tailings pile, may be estimated from:

$$C_{Rn}\ (\text{at } x+d) = C_{Rn}\ (\text{at } x)\ \frac{\sigma_y\sigma_z\ (\text{at } x)}{\sigma_y\sigma_z\ (\text{at } x+d)}$$

In this case, the mean travel time, or the mean age of the radon, would be (d+x/2)u. Beyond the range for which this calculation is valid, the radon concentration will be too low to be of much interest.

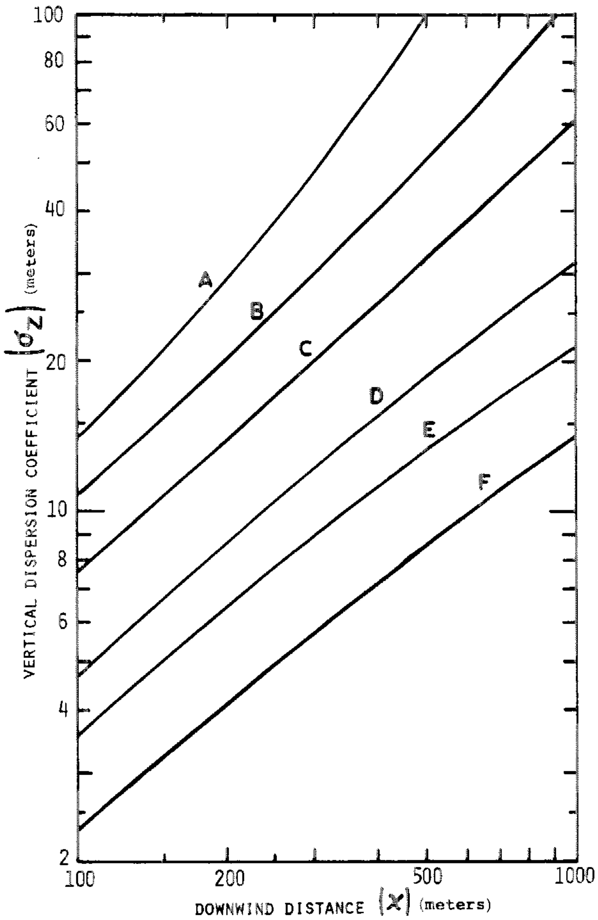

Figure 9. Vertical dispersion coefficients by atmospheric stability classes (after Pasquill and Gifford) (7)

Case study—the Vitro site

The data and computations which follow are presented as a case study to illustrate procedures for predicting radiation exposures that might be encountered as a result of commercial development of a uranium mill tailings pile. This case was selected because it involved a specific proposal by the Silvex Corporation of Salt Lake City to construct an automobile race track on the site of the abandoned tailings pile of the Vitro Chemical Corporation near Salt Lake City. The average radium concentration in this pile has been estimated to be 290 pCi/g.

The general layout of the tailings pile from the Vitro mill, and the location of the proposed Silvex Speedway, is shown in figure 10. The general wind pattern, as reported by Shearer and Sill (*8*), is shown on the site plan. The prevailing wind, occurring approximately half of the time, is from the south-southeast. The most frequent wind direction is from the northwest; it is referred to as the "Salt Lake City" wind, and occurs about 20 percent of the time. A "morning" wind from the south occurs somewhat less frequently.

The estimated distribution of tailings over the 93-acre site is listed in table 3. The source terms for calculating potential radiation exposures are contained in table 4. The gamma-ray exposure rate of 1.1 mR/h over the bare tailings was measured with CaF_2:Dy thermoluminescent dosimeters (*8*). The source used in the calibration of these dosimeters was not specified. The radon emanation rates were calculated in the manner previously presented.

Exposure calculations

The specific assumptions used in the calculation of radon and radon progeny concentrations also are shown in figure 10. The most important exposure location was assumed to be the proposed track. Since the largest source of radon lies to the southwest of the track, the SSE prevailing wind was assumed. The radon flux in the upwind area (cross-hatched) was assumed to be 350 pCi/m^2-s.

Because of a lack of specific meteorological data, three atmospheric stability conditions (B, D, and F), and three wind speeds for each stability class, were assumed. A frequency of occurrence, based upon generalizations from other locations, was assigned to each meteorological condition. Since the calculations were made only for the prevailing wind direction, the frequencies of occurrence were selected to produce a total of 100 percent, although the actual frequencies for this wind direction would be only 50 percent of the total. For the indicated wind direction, the mean source distance, x, is 1400 feet (460 meters).

The intermediate results obtained from the atmospheric dispersion and concentration calculations are shown in table 5. The calculated average radon concentration, for the stated assumptions, turned out to be 6.8 pCi/liter, com-

Table 3. Estimated distribution of tailings on old Vitro mill site

Area	Quantity of tailings				
	Acres	M (tons)	M (cubic yards)	Average depth (feet)	Exposed area (m^2)
Silvex proposal:					
Track	[a] 13.5	0.33	0.13	14	21 000
North parking	[a] 10.3	.27	.11	5.5	42 000
South parking	[a] 10.1	.26	.10	5.5	41 000
Subtotal	33.9	0.86	[b] 0.34	8.9	104 000
Other:					
Vacant (north)	12.5	.16 (Vacant (north) and South frontage together)	.06	3.1	72 000
South frontage	5.2				
M & R	41.4	.48	.20	3.1	167 000
Total	[b] 93	[b] 1.5	0.6	5.2	343 000

[a] Areas determined from architect's drawings for Silvex Speedway. All other numbers are estimates derived from (a) and (b) and from personal observations.
[b] Personal communication from Mr. Robert J. Catlin, USAEC, April 11, 1973.

Table 4. Radiation exposure source terms for Vitro mill site

Site area [a]	Average tailings depth (feet)	Exposed area (m^2)	Bare tailings exposures		Assumed earth cover	Covered tailings	
			Radon (pCi/m^2–s)	Gamma (mR/h)		Radon (pCi/m^2–s)	Gamma (mR/h)
Vacant (north)	3.1	51 000	380	1.1	1 foot earth	350	0.1
North parking	5.5	42 000	435	1.1	2 feet earth	360	.01
Track:							
Bowl	0	—	—	—	none	0	.01
Grandstands	14	—	—	—	2 feet earth + 9 inches concrete	<1	.01
Surroundings	14	21 000	455	1.1	2 feet earth	380	.01
South parking	5.5	41 000	435	1.1	2 feet earth	360	.01
South frontage	3.1	21 000	380	1.1	2 feet earth	310	.01
M & R	3.1	167 000	380	1.1	1 foot earth	350	.1

[a] Designated areas are as shown in figure 10.

Table 5. Calculations of average concentrations of radon and progeny

Radon flux, ϕ: 350 pCi/m^2–s
Source distance, X: 1400 feet or 460 m

Atmospheric stability class: Vertical dispersion coefficient, σ_Z (at $X/2$):	B, good dispersion 23 m			D, neutral 9.5 m			F, near stagnant 4.5 m		
Wind speed, μ: (miles per hour)	6.7	13.4	20.0	4.5	9.0	13.5	2.2	4.5	6.7
(m/s)	3.0	6.0	9.0	2.0	4.0	6.0	1.0	2.0	3.0
Frequency of occurrence (assumed), f:	.10	.10	.05	.20	.20	.20	.05	.05	.05
Radon concentration:									
$C_i = (10^{-3})\phi x/u\sigma_Z$: (pCi/liter)	2.3	1.2	.80	8.5	4.2	2.8	36	18	12
Contribution to annual average, $C_f = fC_i$: (pCi/liter)	.23	.12	.04	1.7	.84	.56	1.8	.90	.60
Radon progeny concentration:									
Ingrowth time, x/2u: (s)	77	38	26	115	58	38	230	115	77
(min)	1.3	.6	.4	1.9	1.0	.4	3.8	1.9	1.3
Progeny ingrowth fraction,									
WL per pCi Rn/liter: [$\times 10^4$]	2.8	1.3	1.0	4.0	2.2	1.0	7.6	4.0	2.8
$WL_i = (WL\text{–}1/pCi)C_i$: [$\times 10^4$]	6.4	1.6	.8	34	9.2	2.8	270	72	33
Contribution to annual average, $WL_f = fWL_i$: [$\times 10^4$]	.64	.16	.05	6.8	1.8	.56	14	3.6	1.7

Annual averages (calculated from above assumptions):
Radon, C(average) = ΣC_f = 6.8 pCi/liter
Radon progeny, WL(average) = Σ WL_f = 0.0029 WL
Average radon progeny ingrowth = 0.0029/6.8 = 0.00043, or 4 percent of equilibrium.

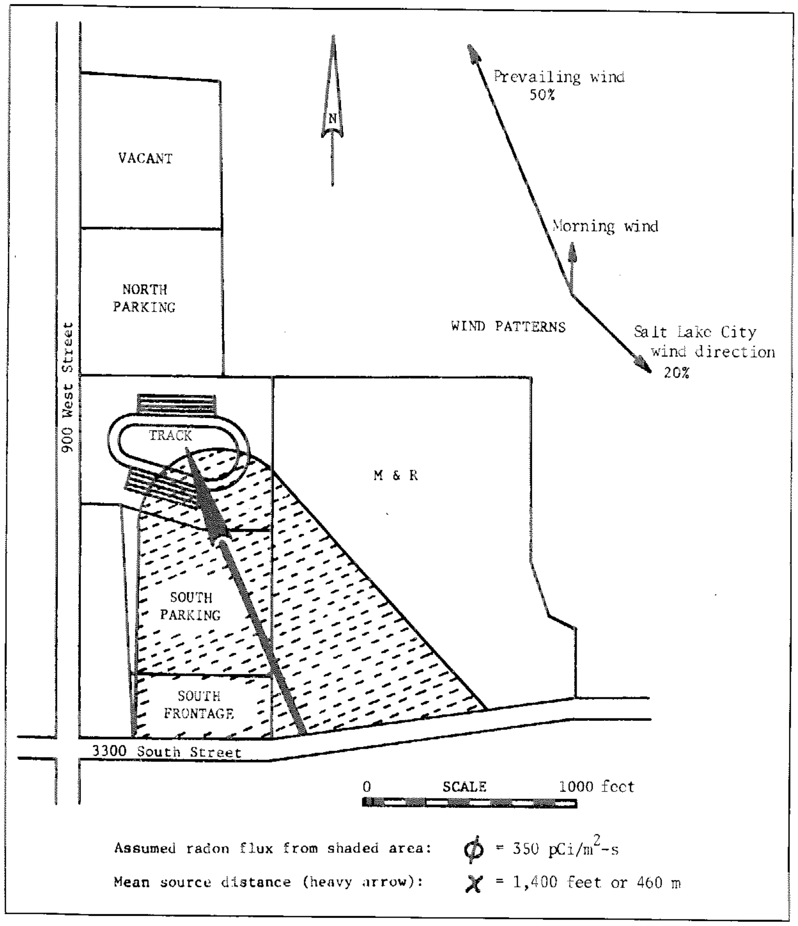

Figure 10. Radon source geometry for prevailing wind at proposed Silvex Speedway

pared with a measured value (*8*) of 10 pCi/liter. The calculated average concentration of radon progeny is 0.0029 WL.

At least two potential sources of error in the theoretical analysis of radon exposures should be noted:

(1) Errors in the assumed meteorological conditions. Although the mean wind speed used in the calculations (9 miles per hour) is essentially the same as that observed during the period of the radon measurements (*8*), the assumed dispersion conditions may not be adequately representative. Also, the use of only the prevailing wind direction in the calculations tends to produce an overestimate of the average radon concentration.

(2) Errors in the assumed radon flux. The radon emanation rate used in the calculations was based upon experimental data obtained with dry tailings. The radon flux can be lowered significantly if the tailings are soaked and/or covered with standing water.

Although the numerical values used in the calculations were carried to two or three figures, the resulting exposure estimates should be interpreted as valid only to one significant figure, with an estimated overall accuracy of approximately a factor of two.

Occupancy factors

Radiation protection guides for the general public are always based on annual averages and not on instantaneous peak values. In the case of the proposed Silvex Speedway, the automobile racing season would be limited to about 5 months—primarily by the temperature range that is acceptable to spectators in outdoor grandstands. For the foreseeable future, the track proposed to schedule events no more than three nights a week; however, it is possible that it might eventually be used as many as six evenings each week. In addition, a few special events, e.g. snowmobile racing, could be scheduled during the winter. The maximum number of track use days could conceivably be 150 per year.

The average time that most spectators will remain at any sporting event is generally 4 hours or less. Consequently, the maximum public attendance time at the track might be as high as 600 hours, although the average exposure time would obviously be much less. A full-time employee at the track would be exposed a maximum of 2000 hours per year, although fewer hours would be more likely.

Enclosed structures

The most significant type of radiation exposure produced by uranium mill tailings, and the most difficult and costly to control, is the exposure to airborne radon progeny in enclosed spaces. If a structure is built in direct contact with tailings, it is possible for radon to diffuse directly from the tailings into the structure. If a structure is merely situated in an environment containing abnormally high atmospheric radon concentrations, the indoor concentration of radon will be essentially equal to the outdoor concentration.

The critical factor in determining the indoor radon progeny concentration, in addition to ascertaining the concentration of the radon, is the assessment of the mean residence time of the radon in the indoor atmosphere. In private homes, the typical air residence time falls in the range of 20 to 60 minutes. In commercial structures, the average time for one complete air exchange is frequently less than 20 minutes.

In the case of the proposed Silvex Speedway, the only enclosed areas would be the snack bars, the rest rooms, a press box and a club house. Each of these structures would have to be designed in a manner that would minimize the buildup of radon and progeny. The direct diffusion of radon into these structures from tailings beneath them could be minimized by using extra thick concrete floor slabs, or even multilayered floors with radon barriers between the layers.

Even with radon barriers in the floors, the indoor radon concentrations would be in equilibrium with the outdoor concentrations. During occupancy, ingrowth of radon progeny might have to be minimized by reducing the mean air residence time indoors to a few minutes, or by continually recirculating and filtering the air. These precautions would be needed for the benefit of track employees who would be spending much more time indoors than the race spectators. However, since the situation could be evaluated prior to construction, the radon progeny exposures could be controlled appropriately.

Radiation dose limits and population risk

There is no recognized radioactivity concentration guide (RCG) for radon alone, nor is there a radiation protection guide (RPG) for the general population for the type of radiation exposure of concern here. However, there are three acceptable sources of recommended exposure limits from which inferences may be drawn. Each of the recommended exposure limits is based upon the dose to the respiratory tract from the alpha particles emitted by the short-lived progeny, but each is restricted to occupational exposures or to a special situation.

The ICRP (*9*) recommends a limit for continuous occupational exposure of 10 pCi of radon per liter of air, including all of the daughter products ordinarily found in unfiltered air. Depending upon the degree of equilibrium, this limit would be equivalent to 0.03 to 0.1 WL. The ICRP further recommends that the average permissible limit for the population at large should not exceed one-thirtieth of the continuous occupational value. Although the phrase "populations at large" is not precisely defined, the continuous public exposure limit recommended by the ICRP could be as low as 0.001 to 0.003 WL.

In connection with the anticipated remedial action program for buildings in Grand Junction, Colo. (where tailings had been used as construction fill), exposure guidelines were set by the U.S. Surgeon General (*10*). The Surgeon General's guidelines state that for an annual average exposure of less than 0.001 WL, no corrective action is indicated. This limit, of course, was set only for a preexisting exposure condition and is not directly applicable to a preplanned situation. However, if this limit is reduced by another factor of three to account for a general, as opposed to a limited, population, the annual average exposure limit would be equivalent to the ICRP value, or 0.003 WL.

The third exposure limit from which an inference may be drawn is that recommended by the Federal Radiation Council (*11*) and subsequently adopted by the U.S. Department of Labor. This limit applies to uranium miners and is expressed as an annual exposure limit of 4 WL-months per year. Since one month of occupational exposure consists of 173 hours, this is equal to an exposure-time product of 692 WL-hours per year. If this limit is reduced by the factor of 30 recommended by the ICRP, the resulting limit for the general population becomes, by inference, about 23 WL-hours per year. If this number is divided by 8766 hours/year, the average annual exposure limit would also be 0.003 WL.

Whether or not the occupational exposure limit for radon progeny inhalation should be reduced for the general population by the same factor as is applied to other kinds of radiation exposure is a matter of conjecture. In a comprehensive analysis of the incidence of lung cancer among uranium miners, Lundin et al. (*12*) found no indication of additional risk among miners having a cumulative exposure of less than 120 WL-months. Spread out over a nominal 70-year lifetime, rather than the 30 years used in deriving the occupational limit, the equivalent continuous exposure rate would be 0.03 WL. Radon progeny inhalation may, in fact, be one type of exposure for which there is a practical, if not theoretical, threshold for somatic biological effects.

Since all of the recommended exposure limits are for exposures in addition to natural background radiation, the natural concentrations of radon and its progeny must be considered. Eisenbud (*13*) states that "the average concentrations of radon in outdoor air may be taken to be in the range of 0.1 to 0.5 pCi/liter and the radon concentration inside buildings is somewhat higher and in round numbers may be taken as 0.5 pCi/liter on the average." In a study of radon in ground level air at Cincinnati, Ohio, Cox et al. (*14*) found that monthly average concentrations ranged from 0.1 to 1.5 pCi/liter during an 8-year period. Radon progeny concentrations in outdoor air, measured in Colorado, are typically in the range of 0.001 to 0.01 WL, with a mean of about 0.004 WL.

Conversion of all of the calculated exposures and inferred exposure limits to common units of WL-hours per year permits the following comparisons:

Naturally occurring radon progeny, outdoors:
$0.004 \text{ WL} \times 8766 \text{ h/yr} = 35 \text{ WL-h/yr}$

Occupational exposure limit for uranium miners:
$4 \text{ WL-mo/yr} \times 173 \text{ h/mo} = 692 \text{ WL-h/yr}$

Inferred population exposure limit (in addition to natural background):
$0.003 \text{ WL} \times 8766 \text{ h/yr} = 26 \text{ WL-h/yr}$

Full-time race track employees (maximum):
$0.003 \text{ WL} \times 2000 \text{ h/yr} = 6 \text{ WL-h/yr}$

Individual spectators (maximum):
$0.003 \text{ WL} \times 600 \text{ h/yr} = 2 \text{ WL-h/yr}$

At present there is no consensus on the appropriate conversion of working-level-months to man-rems or any other acceptable units of population dose commitment. However, it can be pointed out that if the track were to be completed as proposed, a few full-time employees would receive an exposure increment of 17 percent above the normal background exposure, corresponding to 1 percent of the occupational exposure limit, or 23 percent of the population exposure limit. A few thousand members of the general public could receive a maximum additional exposure of 6 percent over the natural background or about 8 percent of the inferred population exposure limit.

Conclusions

For a depth of tailings of more than 1 or 2 feet thick, the gamma exposure rate over the tailings can be estimated from:

$$X\ (\mu R/h) \cong 2.5\ C_{Ra}\ (pCi/g)$$

Since C_{Ra} refers to a uniform concentration of radium in the tailings, it is essential that the value of C_{Ra} used in the above calculation be representative of the pile as a whole. Nonuniformity of the radium concentration would produce variations in measured exposure rates over the pile, but would have minimal effects on long-term average exposures.

The gamma-ray exposure rate over a tailings pile can be reduced to essentially that of the normal background by a cover of 2 feet of packed earth.

The radon emanation rate from the surface of a dry, bare tailings pile several feet thick can be estimated from:

$$\phi_{\infty}\ (pCi/Rn/m^2\text{-}s) \cong 1.6\ C_{Ra}\ (pCi\ Ra/g)$$

Air concentrations of radon will be highest at the downwind edge of the pile. Earth covering will not be very effective for reducing radon emanation; 2 feet of earth would only reduce the radon flux to about three-fourths of its initial value.

The air concentration of radon progeny, the determinant factor for inhalation exposures, depends upon both the concentration and the mean age of the radon. For typical piles and wind conditions, the ingrowth of radon progeny near the pile will rarely reach 10 percent of equilibrium with the maximum radon concentration. It is also unlikely that the outdoor radon progeny concentration, on or near any tailings pile, would exceed an annual average of 0.003 WL in addition to natural background.

All of the radon and radon progeny concentrations presented in this paper were calculated on the basis of very conservative assumptions. To the extent possible, the calculations should be verified and refined. Air sampling for radon progeny concentrations, even for a relatively short time period, would provide some experimental evidence of actual conditions. A refinement of the theoretical analysis could also be made by using actual meteorological data for the local area instead of the assumed conditions used in the preceding calculations.

Enclosed structures should not be constructed on, or adjacent to, tailings piles without valid assurances that the occupancy factors will be quite low. Even then, special attention must be given to construction plans, and especially to ventilation, to assure low indoor air residence times during the periods of occupancy.

Until a permanent solution is found to the problem of abandoned uranium mill tailings, any plans for stabilization or utilization must be regarded as valid for only a short time period, e.g. 25–50 years. Although denial of all public access to a tailings pile may be a convenient and expedient action for a regulatory agency (*15–17*), it has not been conclusively demonstrated to be in the best public interest in all cases. If a productive use is proposed for an abandoned tailings location, a detailed analysis should be made of the potential radiation exposures involved. It is apparent that, in some circumstances, the radiation exposure risk would be extremely low and might well be completely offset by the benefits to be derived from productive use.

REFERENCES

(*1*) CULOT, M. V. J., H. E. OLSON and K. J. SCHIAGER. Radon progeny control in buildings, final report on EPA grant #R01-EC-00153 and AEC contract #AT(11-1)-2273. Colorado State University, Fort Collins, Colo. (May 1973).

(*2*) THROCKMORTON, C. R. Environmental gamma-ray flex analysis. Dissertation, Colorado State University, Fort Collins, Colo. (1973).

(*3*) MORGAN, K. Z. and J. E. TURNER. Principles of radiation protection. John Wiley and Sons, New York, N.Y. (1967).

(*4*) BUREAU OF RADIOLOGICAL HEALTH. Radiological health handbook, PHS Publication No. 2016. Department of Health, Education, and Welfare, Washington, D.C. (1970).

(5) EISENBUD, M. Environmental radioactivity, 2nd edition, quoting B. Hultqvist in studies on naturally occurring ionizing radiation. Kungliga Svenska Velenskapsakademiens Handlingar (1956). Academic Press, New York, N.Y. (1973) p. 189.

(6) EVANS, R. D. Engineers guide to the elementary behavior of radon daughters. Health Phys 17:229–252 (1969).

(7) TURNER, D. B. Workbook of atmospheric dispersion estimates. PHS Publication No. 999–AP–26. Department of Health, Education, and Welfare, Washington, D.C. (1967).

(8) SHEARER, Jr., S. D., and C. W. SILL. Evaluation of atmospheric radon in the vicinity of uranium mill tailings. Health Phys 17:77–88 (1969).

(9) INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. Report of Committee II on permissible dose for internal radiation, ICRP Publication No. 2 and Publication No. 6. Pergamon Press, New York, N.Y. (1969), (1962).

(10) SURGEON GENERAL, PUBLIC HEALTH SERVICE. Surgeon General's guidelines. Use of uranium mill tailings for constructive purposes. Hearings before the Subcommittee on Raw Materials of the Joint Committee on Atomic Energy, October 28 and 29, 1971 (1971) pp. 52–54.

(11) FEDERAL RADIATION COUNCIL. Radiation protection guidance for federal agencies, Federal Register, Vol. 34, No. 10 (1969) p. 576.

(12) LUNDIN, F. E., J. K. WAGONER and V. E. ARCHER. Radon daughter exposure and respiratory cancer quantitative and temporal aspects. NIOSH-NIEHS Joint Monograph No. 1, Department of Health, Education, and Walfare, Washington, D.C. (1971).

(13) EISENBUD, M. Environmental radioactivity, 2nd edition, Academic Press, New York, N.Y. (1973).

(14) COX, W. M., R. L. BLANCHARD and B. KAHN. Relation of radon concentration in the atmosphere to total moisture detention in soil and atmospheric thermal stability. Symposium, Radionuclides in the Environment, American Chemical Society, Washington, D.C. (1970).

(15) COLORADO DEPARTMENT OF HEALTH. Rules and regulations pertaining to radiation control; part VIII—regulations requiring stabilization of uranium and thorium mill tailings piles (radiation regulation no. 2, adopted December 12, 1966) Denver, Colo. (1970).

(16) ENVIRONMENTAL PROTECTION AGENCY. Model tailings regulation. Presented at the Seventh Session, Conference on the Colorado River Basin, February 15–16, 1972, EPA Region VIII, Denver, Colo.

(17) U.S. ATOMIC ENERGY COMMISSION. Fuels and materials guide: stabilization, maintenance and long term control of uranium mill tailings retention systems. Regulatory guide 3.11, directorate of regutory standards, USAEC, Washington, D.C. (draft—January 1973).