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RADON AND TUNNELS

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Abstract

Radon activity may be a source of radiation exposure in the SSC main ring tunnel. Typical radon activity concentrations for rock and soil are calculated. The effects of mitigation by tunnel sealing, lining and ventilating are discussed.

I. Introduction

Radon is a naturally occuring noble gas (Z=86) all of whose isotopes are radioactive. Because of its chemical inertness it does not bond to the surface of material, in marked contrast to its heavy metal daughters. From a health physics point of view, the main hazard is the alpha radiation dose to the lungs. This dose is mainly due to direct radiation from inhaled dust particles on which the radon daughter nuclides' ions have become attached. Nero and Nazaroff[1] state: "Exposures of the lung to the decay products of ^{222}Rn and ^{220}Rn contribute approximately half of the average total effective dose equivalent of 2 mSv (0.2 rem) per year suffered by the general population from naturally occurring radionuclides. Most of the radon-daughter exposure occurs indoors, where substantial variability in time-averaged exposures to the daughters is observed, ranging from rates more than a factor of 10 lower to a factor of 50 or more higher than average, even among the general population. This variability arises partly from different equilibrium factors, but is caused mainly by the difference in indoor radon concentration from one building to another. Furthermore, although the indoor radon concentration is definitely affected by the ventilation rate, the major cause of the variability in radon concentration from one building to another appears to be differences in the rate at which radon enters the indoor atmosphere from its various sources." The same should be true for tunnels. The radon concentration in an unlined rock tunnel will govern the dose received by workers replacing or repairing equipment in the tunnel. Dagenais [2] quotes Department of Energy Order 5480.1A, Chapter 11, p. 3, as listing a concentration guide for radon gas in air under controlled conditions of 100 pCi/ℓ (units: 1 Ci = 1 curie = 3.7×10^{10} Bq, where 1 Bq = 1 becquerel = 1 disintegration/second = 1 s^{-1}. 1 liter = 1 ℓ = 10^{-3} m^3. Therefore, 100 pCi/ℓ = 3.7 Bq/ℓ = 3.7×10^3 Bq/m^3, or 1 Bq m^{-3} = 0.027027 ... pCi/ℓ).

It is the purpose of this note to estimate the likely radon concentrations in tunnels, with and without substantial ventilation. In the SSC, the tunnel is not occupied under operating conditions; it is likely that ventilation would be required only prior to and during occupation of the tunnel by work crews. Ventilation applied to the entire tunnel can be expensive. Peterson and Theilacker [3], indicate that power expenditures of the order of megawatts (MW) can be achieved in cooling and dehumidifying tunnel air on a continuous basis. Using outside air directly for ventilation purposes produces problems of condensation of moisture in the tunnel, with attendant problems with corrosion and increased likelihood of electrical breakdown. Therefore it is of interest to examine the case in which the radon concentration is allowed to build up to equilibrium levels in the absence of ventilation, and then examine the time constants associated with subsequent ventilation. The release rates will also be a concern, since they will govern dose to the general public at the site boundaries.

The porosity ϵ of rock, soil, or building materials is the ratio of void space volume due to pores to the total bulk volume of the material. This pore space is connected to a certain degree, so that radon in the pore space can diffuse through the material. The release of radon from a porous material is thus due to Ra alpha decay driving the recoiling Rn atom into a pore space, from whence it diffuses (or is forced by a pressure gradient) into the surrounding environment.

In what follows, the diffusion equation for radon is reviewed following the treatment by Nazaroff, Moed and Sextro [4] (NMS) and solved for the case of cylindrical geometry, which is taken to approximate the shape of a tunnel. Ventilation is then discussed in terms of the model of Dagenais. A brief discussion of the venting problem concludes the report.

II. Radon Diffusion

Notation (units):

$C_{\rm Rn}$ = concentration $(\rm m^{-3})$ = number of radon atoms/volume

$\lambda_{\rm Rn}$ = decay constant of Rn = 2.0982×10^{-6} s^{-1} for ^{222}Rn; for ^{220}Rn, the decay constant is 1.247×10^{-2} s^{-1}.

$I_{\rm Rn} = C_{\rm Rn}\lambda_{\rm Rn}$ = activity concentration of Rn (Bq m^{-3}).

f = emanation fraction, emanation ratio or emanation coefficient. $f = (0.005 - 0.40)$ for rock, with an "average" value of around 0.085 given by NMS [4]. For soil $f = (0.05 - 0.7)$ with a representative value of 0.4 for very dry soil, or around 0.2 for representative soil moisture.

ρ_g = density of solid grains in rock or soil; $\rho_g = (2.5 - 3.0) \times 10^3$ kg m^{-3} with a typical value for continental rock minerals of $\rho_g = 2.65 \times 10^3$ kg m^{-3}.

ϵ = porosity = (effective pore space volume)/(total volume). A typical value for silt with a sizeable clay fraction is 0.5. In reservoir rocks this may vary from 0.20 near surface to less than 0.05 at depth.

A_{Ra} = radium activity concentration in bulk material (Bq kg^{-1}).

D_0 = diffusion coeffcient of radon in open air. $D_0 = 1.2 \times 10^{-5}$ m^2 s^{-1}.

D_e = effective or interstitial diffusion coefficient in the pores of the material. $D_e = (0.7 - 5) \times 10^{-6}$ m^2 s^{-1} for dry soil, with a typical value of 2×10^{-6} m^2 s$^-$1. For mud with high moisture content, D_e is of the order of 10^{-10} m^2 s^{-1}, essentially impervious to radon.

D = bulk diffusion coefficient = ϵD_e (m^2 s^{-1})

J_{Rn} = magnitude of the activity flux density (Bq m^2 s^{-1})

$$\vec{J}_{\mathrm{Rn}} = I_{\mathrm{Rn}} \vec{v}_{\mathrm{air}} - D \nabla I_{\mathrm{Rn}} , \tag{1}$$

where the first term on the right-hand side (RHS) is due to the motion of the air with velocity $\vec{v}_{\mathrm{air}}$ and the second term is the diffusive flux density for the bulk material, or the geometric diffusive radon activity flux density:

$$\vec{J}^{dG}_{\mathrm{Rn}} = - D \nabla I_{\mathrm{Rn}} .$$

The diffusion through the pores is given by the effective diffusion coefficient D_e, so

$$\vec{J}^{d}_{\mathrm{Rn}} = - D_e \nabla I_{\mathrm{Rn}} ; \tag{2}$$

since $D = \epsilon D_e$

$$\vec{J}^{dG}_{\mathrm{Rn}} = \epsilon \vec{J}^{d}_{\mathrm{Rn}} \tag{3}$$

G = volumetric generation rate of radon in pore space (Bq m^{-3} s^{-1}).

$G = f \ \rho_s A_{\mathrm{Ra}} \lambda_{\mathrm{Rn}} \frac{1-\epsilon}{\epsilon}$

$\ell = (D_e/\lambda_{\mathrm{Rn}})^{1/2}$ diffusion length for radon in material (m).

The local change with time in numbers of radon atoms is given by the rate of generation due to decay of the radium parents, the decay rate into daughters, and the rate of diffusion of radon from elsewhere. Corresponding terms would apply for the numbers per unit volume, the radon concentrations. Thus, one could multiply through by λ_{Rn} to write the equation in terms of the activity concentration I_{Rn}. The increase in activity concentration due to diffusion is, by the divergence theorem,

$$\oint\!\!\oint \vec{J} \cdot (-d\vec{S}) = -\int\!\!\int\!\!\int (\nabla \cdot \vec{J})\, dV \,, \tag{4}$$

where the infinitesimal area vector over the closed surface spanning the volume is directed outward. The increase in the activity per volume is then

$$-\nabla \cdot \vec{J}^{\,d}_{\mathrm{Rn}} = + D_e \nabla^2 I_{\mathrm{Rn}} \,, \tag{5}$$

where D_e is taken as constant.

The total diffusion equation for the activity concentration in the pores is then

$$\partial_t I_{\mathrm{Rn}} = D_e \nabla^2 I_{\mathrm{Rn}} - \lambda_{\mathrm{Rn}} I_{\mathrm{Rn}} + G \,, \tag{6}$$

where the terms on the RHS correspond to the diffusion term, loss rate due to radon decay and generation rate due to radium decay and radon recoil into the pore space.

As an example, consider the case of "all outdoors" modeled as an infinite half space with typical soil values for the parameters. If ventilation of uncovered soil reduces the radon concentration at the surface to zero, then the steady-state equation for the radon activity concentration in the soil half space (z positive down) is

$$-\frac{G}{\lambda_{\mathrm{Rn}}} = \left(\frac{D_e}{\lambda_{\mathrm{Rn}}}\right) \frac{d^2}{dz^2} (I_{\mathrm{Rn}}) - I_{\mathrm{Rn}} \,. \tag{7}$$

The solution to the homogeneous equation

$$\frac{d^2}{dr^2}(I_{\mathrm{Rn}}) - I_{\mathrm{Rn}} = 0 \tag{8}$$

is $I_{\mathrm{Rn}} = I_1 e^{-r}$ where $r = z/l$ and $\ell = (D_e/\lambda_{\mathrm{Rn\,p}})^{1/2}$ is the diffusion length. The particular (constant) solution is $I_{\mathrm{Rn\,p}} = G/\lambda_{\mathrm{Rn}} = I_\infty$.

The solution that goes to zero at the surface is then

$$I_{\mathrm{Rn}}(z) = I_\infty(1 - e^{-z/l}) \tag{9}$$

The bulk flux density at $z = 0$ in this case, following NMS, is:

$$\begin{aligned} J^{dG}_{\mathrm{Rn}} &= -\epsilon D_e \frac{d}{dz}\left[I_{\mathrm{Rn}}(z)\right]_{z=0} = -\frac{\epsilon D_e}{l} I_\infty \\ J^{dG}_{\mathrm{Rn}} &= -\epsilon\, \lambda_{\mathrm{Rn}}\, l\, I_\infty = -(D_e \lambda_{\mathrm{Rn}})^{1/2} \rho_s\, f\, A_{\mathrm{Ra}}\,(1-\epsilon) \end{aligned} \tag{10}$$

where the minus sign means the flux is out of the surface (toward negative z). NMS proposed typical values for the case of ^{222}Rn emanating from soil of $D_e = 2 \times 10^{-6}$ m^2 s^{-1}, $\rho_g = 2.65 \times 10^3$ kg m^{-3}, $f = 0.2$, $A_{\mathrm{Ra}} = 30$ Bq kg^{-1} and $\epsilon = 0.5$, which yields $J^{dG}_{\mathrm{Rn}} = 0.016$ Bq m^{-2} s^{-1}. The corresponding value of $I_\infty = 1.55 \times 10^4$ Bq m^{-3} = 419 pCi/ℓ at depth. The mean worldwide flux [4] is roughly 0.015 Bq m^{-2} s^{-1}.

The isotopes ^{222}Rn, ^{220}Rn, ^{219}Rn and ^{224}Rn are decay products from the naturally occurring radioactive chains originating with ^{238}U, ^{232}Th, ^{235}U, and ^{232}Th respectively. The molar flux of ^{220}Rn is about 60 times less than the value for ^{222}Rn. Because of its longer half life (smaller decay constant) the diffusion length of ^{222}Rn is about 80 times that of ^{220}Rn. ^{222}Rn is therefore the isotope that forms most of the radon concentration in enclosed spaces. The equations used thus far could be used separately for each radon isotope.

Because of the difficulties of specifying the dose due to the mixture of radon isotopes [5] the notion of a "working level" (WL) was introduced; 1 WL = concentration of radon daughter products that emit 1.3×10^5 MeV of α radiation in a liter of air. According to Dagenais [2], this concentration is about 100 pCi/ℓ of the mixture of naturally occurring radon isotopes.

We now focus our attention on a tunnel of radius a in an infinite porous medium. In cylindrical coordinates,

$$\nabla^2 = \partial_R^2 + \frac{1}{R}\,\partial_R + \frac{1}{R^2}\,\partial_\phi^2 + \partial_z^2$$

where the abbreviated notation for partial derivatives (with respect to the subscript) has been employed. For cylindrical symmetry, $I_{\rm Rn}$ depends only on R; the diffusion equation becomes

$$D_e\left(\frac{d^2}{dR^2} + \frac{1}{R}\frac{d}{dR}\right) I_{\rm Rn} - \lambda_{\rm Rn} I_{\rm Rn} = -G\,. \tag{11}$$

Let $r = R/l$, so that $l\ d/dR = d/dr = D_r$ in terms of the diffusion length $\ell = (D_e/\lambda_{\rm Rn})^{1/2}$. Let $F = I_{\rm Rn}$ for the sake of simplicity; the diffusion equation is then

$$\left(D_r^2 + \frac{1}{r}\,D_r - 1\right) F = -\frac{G}{\lambda_{\rm Rn}} = \text{constant}\,. \tag{12}$$

The equation

$$z^2 D_z^2 w + z D_z w - (z^2 + \nu^2) w \ = \ 0 \tag{13}$$

has solutions $I_{\pm\nu}(z)$ and $K_\nu(z)$, the exponential-like Bessel functions [6]. If we rewrite (13) as

$$\left(D_z^2 + \frac{1}{z} - 1 + \frac{\nu^2}{z^2}\right) w = 0 \tag{14}$$

and note that $\nu = 0$, we see that the solution to the homogeneous equation for F is a linear combintion of I_0 and K_0:

$$F = A\, I_0 + B\, K_0\,.$$

I_0 and K_0 have the following asymptotic behavior:

$$\begin{aligned}
&I_\nu(z)\underset{z\to 0}{\longrightarrow} \frac{(\frac{1}{2}z)^\nu}{\Gamma(\nu+1)} \quad , \quad \text{so} \qquad I_0(z=0) = 1 \\
&K_0(z)\underset{z\to\infty}{\longrightarrow} 0 \\
&I_0(z)\underset{z\to\infty}{\longrightarrow} \infty \\
&K_0(z)\underset{z\to 0}{\longrightarrow} -\ \ln(z)
\end{aligned} \tag{15}$$

so K_0 is irregular at the origin and regular at infinity, and the reverse is true for I_0.

Inside the tunnel, $A_{\mathrm{Ra}} = 0$ so $G = 0$ and

$$\left(D_r^2 + \frac{1}{r}D_r - 1\right)F = 0 \quad for \quad 0 \le r \le \frac{a}{l}\,, \tag{16}$$

with interior solution $F_i = C_1 I_0(r)$.

Outside the tunnel,

$$\left(D_r^2 + \frac{1}{r}D_r - 1\right)F_0 = -\frac{G}{\lambda_{\mathrm{Rn}}}\,, \tag{17}$$

so the homogeneous solution is $F_{H0} = C_2 K_0(r)$ and the particular solution is

$F_{0p} = G/\lambda_{\mathrm{Rn}} =$ constant. For $K_0(r) > 0$, $C_2 < 0$ and the outside solution is

$$F_0(r) = \frac{G}{\lambda_{\mathrm{Rn}}} - |C_2| K_0(r) . \tag{18}$$

With the requirement that the radon activity concentration flux

$$\begin{aligned} \vec{J}^{\,d}_{\mathrm{Rn}} &= -D_e \nabla F = -D_e \left(\hat{R}\,\partial_R + \frac{\hat{\phi}}{R}\partial_\phi + \hat{z}\partial_z \right) F \\ &= -\hat{R}(D_e l)\left[\partial_r F(r)\right] , \end{aligned} \tag{19}$$

be continuous at the wall, then

$$C_1 \partial_r \left[I_0(r)\right]_{r=a/l} = -|C_2| \partial_r \left[K_0(r)\right]_{r=a/l} . \tag{20}$$

Matching the activity concentrations and their fluxes at the tunnel wall gives two linear equations in two unknowns that can be used to find the coefficients C_1 and C_2 for given a, l and G:

$$D_r\left[I_r(r)\right] = I_1(r) \quad \text{and} \quad D_r\left[K_0(r)\right] = -K_1(r) \tag{21}$$

from [6]. In terms of quantities evaluated at $r_0 = a/l$

$$\frac{C_1}{|C_2|} = \frac{K_1(r_0)}{I_1(r_0)} \tag{22}$$

and

$$\frac{G}{\lambda_{\mathrm{Rn}}} \frac{1}{|C_2|} = K_0(r_0) + I_0(r_0) \frac{K_1(r_0)}{I_1(r_0)} ,$$

or

$$\frac{|C_2|}{(G/\lambda_{\mathrm{Rn}})} = \frac{1}{K_0 + I_0(K_1/I_1)}$$

$$\frac{C_1}{(G/\lambda_{\mathrm{Rn}})} = \frac{K_1/I_1}{K_0 + I_0(K_1/I_1)}. \tag{23}$$

The concentration of radon at the center of the tunnel $I_{\mathrm{Rn}}(r = 0) = C_1$, which is given in terms of $I_\infty = G/\lambda_{\mathrm{Rn}}$ in Table I, for a tunnel radius of $a = 1.524$ m = 5.00 ft. For a diffusion length of about a meter, $D_e = l^2\lambda_{\mathrm{Rn}} = 2.1 \times 10^{-6}$ m^2 s^{-1}, a value typical of soil or extremely porous rock. At the other extreme, *NN* [1] quote a value of $\ell = 0.15$ m for red brick, corresponding to a value of $D_e = 4.7 \times 10^{-8}$ m^2 s^{-1}. Some concretes have similar values [1].

The quantity that depends on the details of the radioelement distribution in the material is the emanation coefficient f. Diffusion coefficients for ^{40}Ar for solid grains of rock forming minerals are found to be in the range $10^{-31} - 10^{-69}$ m^2 s^{-1}; the corresponding radon diffusion lengths are in the range $10^{-13} - 10^{-32}$ m [4]. Therefore, radon diffusion through crystalline material can be neglected. Because the precursors of radium cause radiation damage in the crystal (halos) and because radionuclides are commonly found in accessory minerals (e.g., zircon) or at grain boundaries, radon can readily escape from the mineral grains into the pore space, and diffuse from there. The large values of f for soil (around 0.3–0.4) relative to rock (around 0.085) are due to this.

The effective diffusion coefficients D_e for crystalline rock are very small, even less than the $D_e = 10^{-10}$ m^2 s^{-1} characteristic of saturated soil or rock. Most of the diffusion in granite and massive carbonates occurs along fractures in the rock. This process is much more difficult to characterize than the more uniform diffusion in well sorted terrigenous clastics and soils, for which D_e has values similar to that quoted earlier. Also, the process of pressurized flow is much more important in the case of media with a linear fracture density of more than a few centimeters.

To summarize this section, it is clear that radon activity can range from negligible values in unfractured crystalline rock to significant exposure levels in dry porous material. The effect of concrete slab shielding [1] shows that a 10 cm thick slab can cut the transmitted radon flux to 2–4% of the unshielded case. Even with a 1 cm gap for every meter of slab, the flux penetration rate is still calculated to be only 25% of maximum [1]. The effect of lining and/or sealing the tunnel can be quite significant in reducing the radon activity, subject to certain conditions on performance. Franklin, Bates, Holub and their coworkers have done considerable work on the measurement and mitigation of radon in mines [8]. Their conclusions may be summarized as follows: two-coat sealing of tunnels with e.g., latex, can reduce influx on the order of 50–75%, however, any cracks or gaps may episodically release more concentrated radon from pore reservoirs. Sealed-off underpressured bulkheads are used as radon barriers by the mining industry. Shotcrete (gunite) as usually used is so porous as to be a negligible hindrance to radon diffusion.

Marked effects due to the superposed velocity flow field of the air are important in radon levels in houses and mines [1, 4, 7]. Pressures of only a few Pa (n m^{-2}) can produce large differences in radon concentrations within structures by bringing in radon from reservoirs in the vicinity. Overpressuring structures has a marked effect in reducing radon inflow rate. In regions of fracturing, this type of radon source may be dominant and extensive grouting may be useful in reducing the inflow rate. If the problem is acute enough, local bulkheading and pumps may have to be installed to control this effect. In the SSC, fracturing significant enough to be of structural concern or allowing significant water inflow would cause the affected region to be fully lined with reinforced concrete. This would also serve as an effective radon barrier (see above).

III. Fluxes and Concentrations

The diffusive flux density of radon activity of bulk material was found to be

$$\vec{J} = -\epsilon D_e \nabla I_{\mathrm{Rn}}\,, \tag{24}$$

with peak values at depth of

$$J = \epsilon\, l\, \lambda_{\mathrm{Rn}}\, I_\infty = \epsilon (D_e \lambda_{\mathrm{Rn}})^{1/2} I_\infty \tag{25}$$

where

$$I_\infty = G/\lambda_{\mathrm{Rn}} = f \rho_g \left(\frac{1-\epsilon}{\epsilon}\right) A_{\mathrm{Ra}} \tag{26}$$

is the limiting radon activity per volume at depth. In the previous section we found typical values for soil of $J = 0.016$ Bq m^{-2} s^{-1} and $I_\infty = 1.55 \times 10^4$ Bq m^{-3} = 419 pCi/ℓ for soil. For rock with $\epsilon = 0.10$, $f = 0.01$, $\rho_g = 2.65 \times 10^3$ kg m^{-3}, $A_{\mathrm{Ra}} = 30$ Bq kg^{-1}, and $D_e = 10^{-6}$ m^2 s^{-1}, then $I_\infty = 7.16 \times 10^3$ Bq m^{-3} = 193 pCi/ℓ and $J = 1.04 \times 10^{-3}$ Bq m^{-2} s^{-1}.

Consider a simple model of cylindrical tunnel of radius R and length z, with a constant concentration of radon at equilibrium between that supplied by the flux of I_{Rn} through the wall and the rate of loss of I_{Rn} via decay ($I_{\mathrm{Rn}}\lambda_{\mathrm{Rn}}$). Assuming that the flux into the cylindrical cavity is given by $\vec{J}_{\mathrm{wall}} = -\hat{R}\, J$ (Fig. 1) and the outward area infinitesimal $d\vec{a} = \hat{R}\, Rz\, d\phi$, then the activity introduced into the tunnel per time will be $-\int\int \vec{J}_{\mathrm{wall}} \cdot d\vec{a} = 2\pi z R J$. The rate of change of activity per volume with time is then

$$\frac{2\pi z R}{\pi R^2 z} = \frac{2J}{R}\,. \tag{27}$$

The equilibrium activity concentration of radon is then $I_{\mathrm{Rn}} = 2J/(R\lambda_{\mathrm{Rn}})$. As an example, for a tunnel of radius 1.524 m (5 ft) and a flux in of 0.01524 Bq m^{-2} s^{-1}

(about the world average for soil) then $I_{Rn} = 0.952 \times 10^4$ Bq m^{-3} = 257 pCi/ℓ, about two and a half times the established WL. Multiplying this figure by the ratio of the actual radon activity to 30 Bq kg^{-1} would give the anticipated activity concentration for dry porous material. Values of A_{Ra} double or triple those used here may be encountered in the range of rock types found on the sites on the BQL.

However, the activity concentration in the tunnel is unlikely to be as high as the $(1 - 3) \times 10^4$ Bq m^{-3} (250–750 pCi/ℓ) that this implies, for the following reasons:

1) Where the tunnel is in porous material it will either be lined (basin sediments, AZ) or sealed with latex or epoxy (air-slaking shale, CO; sandstones, MI; epiclastics, NC; Taylor marl, TX; fracture and/or shear zones, any site). As discussed above, this can reduce the value of I_{Rn} in the tunnel to a few percent of I_∞.

2) The actual values of the diffusion coefficient for massive rock are much smaller than the values used above, so that for tunnels in unfractured rocks like the massive carbonates in IL, TN, and TX and the high quality granite and diorite in AZ and NC the actual activity concentration of tunnel radons may be a factor of ten or so lower than the value of I_∞ calculated above for rock, 7155 Bq m^{-3} (193 pCi/ℓ).

Because of the heterogeneity of the formations and the position of the water table, several sections of tunnel would need to be lined or sealed if constructed at the NC or MI sites. There is no reason based on literature information to anticipate problems with radon at any of the other sites, although it would be desirable to monitor radon activity concentrations in tunnels as close to the conditions of the site areas as feasible.

For a variety of reasons, including the possibility of radon buildup, it would be desirable to ventilate at least a section of the tunnel during its occupancy by people working on equipment stored within the tunnel. Using the model of activity flux above, with an activity concentration independent of position within the tunnel, the expression for I_{Rn} is

$$D_t I_{\mathrm{Rn}} = S - \lambda_{\mathrm{Rn}} I_{\mathrm{Rn}} - \lambda_v I_{\mathrm{Rn}}\,, \tag{28}$$

where the activity source term $S = 2\ J/R$ and λ_v is the effective "decay" coefficient for the removal of radon by ventilation.

As an example, if half the radon in the tunnel were removed by ventilation in a time $T_{v\,1/2} = 1$ h $= 3600$ s, then $\lambda_v = (\ln 2)/T_{v\,1/2} = 1.925 \times 10^{-4}$ s^{-1}, which is a factor of a hundred larger than λ_{Rn}. Therefore ventilation would dominate decay as a removal mechanism for the radon itself. Equations similar to (28) could be written for each of the daughter products in order to compute the working levels, but because of their much shorter half lives, ventilation is much less effective in reducing the activity concentrations once they are produced.

The solution to the homogeneous equation corresponding to (28)

$$D_t I_{\mathrm{Rn}} + (\lambda_{\mathrm{Rn}} + \lambda_v) I_{\mathrm{Rn}} = 0 \tag{29}$$

is $I_{\mathrm{Rn}} = I_0 e^{-(\lambda_{\mathrm{Rn}}+\lambda_v)t}$ and a particular solution to (28) is $I_1 = S/(\lambda_{\mathrm{Rn}} + \lambda_v)$ so that as $t \to \infty$, $I_{\mathrm{Rn}} \to I_1$. At $t = 0$, $I_{\mathrm{Rn}} = I_{\mathrm{max}} = I_1 + I_0$, the value of the activity concentration before ventilation starts. Thus, $I_0 = I_{\mathrm{max}} - I_1$. At equilibrium, $D_t I_{\mathrm{Rn}} = 0$ when $I_{\mathrm{Rn}} = I_1$. The time to reach any particular activity concentration can be found by inverting the solution

$$\exp\left[(-t)(\lambda_{\mathrm{Rn}} + \lambda_v)\right] = \frac{I_{\mathrm{Rn}} - I_1}{I_0} = \frac{I_{\mathrm{Rn}} - I_1}{I_{\mathrm{max}} - I_1} \tag{30}$$

or

$$t = \frac{1}{(\lambda_{\mathrm{Rn}} + \lambda_v)} \ln\left(\frac{I_{\mathrm{max}} - I_1}{I_{\mathrm{Rn}} - I_1}\right). \tag{31}$$

For example, to dilute a given concentration by a factor of two requires (with mixing) a complete "room change" of air, so that with thorough mixing the time for inflow of an amount of air equal to the affected tunnel volume is $T_{v\,1/2} = \ln 2/\lambda_v$. For ventilation rates of a room change per hour or less and $I_1 << I_{\mathrm{max}}$, this would be the approximate time given by (31). The airspeed is given by the volume to area ratio divided by $T_{v\,1/2}$: $v = V/AT_{v\,1/2}$. Because of the effect of wall friction, actual air speeds will be down to about 2/3 to 1/2 this value. For the tunnel with $z = 4.0$ km and $T_{v\,1/2} = 3600$ s, this estimate gives $v = z/2T_{1/2} = 0.55$ m/s, a desirable plume speed.

For $J = 0.01524$ Bq m^{-2}s^{-1}, $R = 1.524$ m, $S = 2J/R = 0.02$ Bq m^{-3}s^{-1}; for $\lambda_v + \lambda_{\mathrm{Rn}} = 1.946 \times 10^{-4}$ s^{-1}, $I_1 = S/(\lambda_{\mathrm{Rn}} + \lambda_v) = 103$ Bq m^{-3} and $I_{\mathrm{max}} = 9520$ Bq m^{-3} (257 pCi/l). The time to reduce this activity concentration to

$I_{\mathrm{Rn}} = 3700$ Bq m^{-3} (100 pCi/l) is then

$$t = 5139 \text{ s } \ln(9417/3597) = 4946 \text{ s} = 1.37 \text{ h}.$$

Therefore, even if the tunnel had a significant radon activity concentration, ventilation for a room charge and half would be sufficient to meet exposure standards.

In order to examine the fenceline concentrations of the expelled radon consider the (over) simplified model where the tunnel air is expelled through a stack to form a plume which is the frustrum of a cone, with a radius R near the stack the same as the tunnel radius (1.524 m) and the radius at the boundary of the service sector (fenceline) the same as the height of the stack, here taken as 15.24 m (Fig. 2).

The volume of a unit thickness at each end of the cone will be proportional to the areas. Even disregarding the decay of the radon flux as the plume passes through the canonical outline, the concentration of particles moving at constant (wind) speed will be decreased by the area ratio of the top to the bottom of the cone, here 10^{-2}. The activity concentration I_{Rn} in the air expelled by the stack will be less than half the corresponding value in the tunnel at any time t. Reducing this by a further factor of 100 converts a level of 2 WL in the tunnel to 10^{-2} WL or 1 pCi/l outside the fenceline. For comparison, the average concentrations in outdoor air are in the range (0.1–0.5) pCi/l and show wide daily variability [7]. More sophisticated (Gaussian) plume models would show considerably greater reduction. Even with the close boundaries of the sector service areas, the released radon activity (an episodic event) seems a negligible hazard.

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Table 1

Radon Concentrations in Center of Tunnel

r_0	$\ell = a/r_0$ (m)	C_1/I_∞
1.0	1.524	0.6019074
1.5	1.016	0.416082
2.0	0.762	0.279731
5.0	0.305	0.0202683
10.0	0.152	1.867×10^{-5}

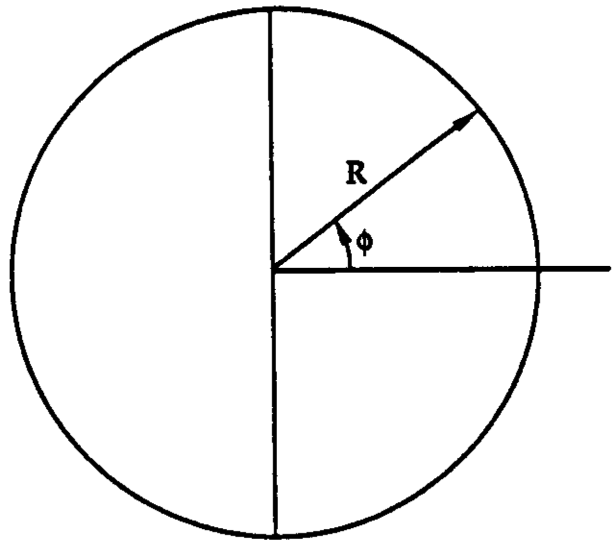

FIG. 1.

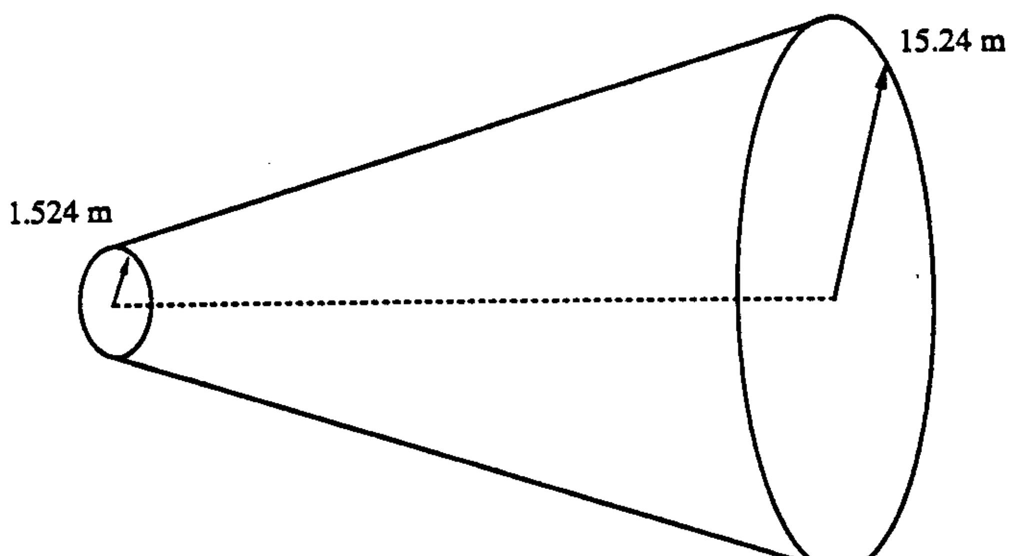

FIG. 2.

Radon Contributions from the Mining Industry

Bates, Robert C., 1977
Rock sealant restricts falling barometer effect:
Mining Engineering, Dec. 1977, p. 38-39
"These analyses demonstrate that radon contamination resulting from a change in barometric pressure is reduced by a rock [sealant] coating. This, however, is not the major fact to be kept in mind. More important is that, despite the imperfection in the coatings, the radon concentration in the mine atmosphere was reduced through the use of coatings by more than 70% from an average of 480 to 140 [pCi/L]."

Bates, Robert C., 1977
Sealants restrict barometric pressure effects:
Mining Engineering, 29(12); 38-39

Bates, Robert C., 1980
Time dependent radon loss from small samples:
Health Physics, 39: 799-801
In connection with a study of the effect of moisture on the radon emanation coefficient in small uranium ore samples, the question arose about the time needed to reach a steady-state flux of radon from a sample after opening of its sealed storage and counting can. It was felt intuitively that the time required to reach equilibrium would depend on the pore-filling fluid and the diffusion coefficient. No evaluation of this effect was found in the literature. A previously developed analytical code was used with a cylindrical model 9.2 cm long and 3.843 cm in radius, 0.2 porosity, 1E-7 cm^2 permeability, 300 K, and pore-fluid viscosity of 1.8E-4 g/cm-s. The periods required to reach a steady-state flux were computed to be 0.25, 1.25, 10.0, 70.0, and >100.0 hours, respectively, for diffusion coefficients of 1E-2, 1E-3, 1E-4, 1E-5, and 1E-6 cm^2/s.

Bates, Robert C., and John C. Edwards, 1978
Radon emanation relative to changing barometric pressure and physical constraints, in Conference on Uranium Mining Technology, Second, Reno, Nev., November 13-17, 1978:
Background is given on the various equations used to describe diffusion and convective flow of radon in porous media. Equations developed by the Bureau of Mines for modeling diffusion and Darcy flow through multilayered porpus media are described briefly and examples of their use are given. Cases evaluated include overpressurization, underpressurization, and cyclic pressurization of different-sized ore bodies. Another part of the analysis deals with the effect of pinholes on the effectiveness of a radon barrier coating.

Bates, Robert C., and John C. Edwards, 1981
The effectiveness of overpressure ventilation: a mathematical study, in Gomez, Manuel, ed., Radiation Hazards in Mining: Control, Measurement, and Medical Aspects, International Conference, Golden, Colo., October 4-9, 1981:
Golden, CO, Colorado School of Mines, Chap. 24, p. 149-154

Results are given of a mathematical study of overpressurization ventilation effects in underground uranium mines. The mathematics and computer codes make it possible to analyze many facets of transient and steady-state radon diffusion with Darcy flow. Rapid changes in radon flux occur after imposing a pressure differential across the model. Flux into the model mine drops to near zero and then increases to the steady state level, while the sink flux increases rapidly and then drops slightly to the steady-state level. Magnitudes of mine flux decreases and sink flux increases are dependent upon the distance from the mine to sink, permeability, and the amount of overpressure.

Bates, Robert C., and John C. Franklin, 1977
U. S. Bureau of Mines radiation control research, in Conference on Uranium Mining Technology, Reno, Nev., April 25-29, 1977:
Efforts by the Bureau of Mines to measure and reduce harmful concentrations of radioactive gas in uranium mines are discussed. Equipment has been developed for simultaneous monitoring of radon and radon daughters, temperature, relative humidity, absolute pressure, and air velocity. The effects of changes in weather conditions, ventilation, adn mining methods on the mine atmosphere can therefore be evaluated. Addition of water to the rock substantially increases the radon emanation from rock walls. Control methods being evaluated include overpressurization, cyclic ventilation, bulkheading, backfilling with tailings, and application of sealants to the mine rock.

Bates, R. C., and R. L. Rock, 1962
Estimating Daily Exposures of Underground Uranium Miners to Airborne Radon-Daughter Products:
U. S. Bur. Mines Rept. Investigations 6106, 22 p.

Droullard, R. F., T. H. Davis, E. E. Smith, and R. F. Holub, 1984
Radiation Hazard Test Facilities at the Denver Research Center:
U. S. Bur. Mines Inf. Circ. 8965, 22 p.
The Bureau of Mines has developed test facilities for use in a research program that deals with radiation hazards in mining. This report describes the radon test chamber located at the Denver Research Center and the Twilight experimental mine located near Uravan, CO.

Droullard, R. F., and R. F. Holub, 1977
Continuous Working-Level Measurements Using Alpha or Beta Detectors:
U. S. Bur. Mines Rept. Investigations 8237, 14 p.
The Bureau of Mines has investigated techniques of using gross alpha or beta detectors to continuously measure working levels. Both methods measure radioactive particulates collected on a filter paper using a constant airflow. Inherent-error studies indicate a value of about +/- 3 percent for the gross alpha method and about +/- 8 percent for the beta method in typical mine atmospheres. However, the beta method avoids problems associated with alpha detectors and is therefore more useful. Applications of these continuous working-level detectors

include work area monitoring of exposure levels in underground openings, such as mines and caves, and calibrating personal dosimeters exposed over extended time intervals.

Droullard, R. F., and R. F. Holub, 1985
Continuous Radiation Working-Level Detectors:
U. S. Bur. Mines Inf. Circ. 9029, 20 p.
The Bureau of Mines has used gross alpha and gross beta detectors to continuously measure radiation working levels for a number of years. During this time, improvements have been made in the design and performance of continuous working-level (CWL) detectors. This report discusses the improved designs and some of the operating principles and applications of CWL detectors in the measurement of radon daughter products in mines and dwellings.

Edwards, John C., and Robert C. Bates, 1980
Theoretical evaluation of radon emanation under a variety of conditions:
Health Physics, 39: 263-274

Franklin, John C., 1981
Control of radiation hazards in underground uranium mines, in Gomez, Manuel, ed., Radiation Hazards in Mining: Control, Measurement, and Medical Aspects, International Conference, Golden, Colo., October 4-9, 1981:
Golden, CO, Colorado School of Mines, Chap. 69, p. 441-446

Franklin, J. C., R. C. Bates, and J. L. Habberstad, 1975
Polymeric sealants may provide effective barriers to radon gas in uranium mines:
Engineering Mining Jour., 176(9): 116-118

Franklin, John C., and Randall F. Marquardt, 1976
Continuous radon gas survey of the Twilight Mine:
U. S. Bur. Mines, Metal-Nonmetal Health and Safety/Health Program, Tech. Prog. Rept. 93, 16 p.

Franklin, John C., Thomas O. Meyer, and Robert C. Bates, 1977
Barriers for Radon in Uranium Mines:
U. S. Bur. Mines Rept. Inv. 8259, 24 p.
Water-based epoxy sealants were examined during a 2-year period to determine their effectiveness as barriers to radon release in uranium mines. Radon emanation rates from uranium ore samples were monitored for extended periods in the laboratory before and after sealant application. Reduction of radon flux due to the coating of laboratory samples was approximately 80 percent. Test chambers in a dormant uranium mine were monitored to determine both short and long-term barrier effectiveness. These field studies of the sealants indicated radon flux reductions exceeding 50 percent relatively soon after application and nearly 75 percent about 1 year later. An unexpected compli-

cation to early monitoring in the form of a large radon emanation increase, believed due to added moisture, is discussed.

Franklin, J. C., T. O. Meyer, R. W. McKibbin, and J. C. Kerkering, 1976
A continuous radon survey in an active uranium mine:
Mining Engineering, 30(6): 647-649

Franklin, J. C., C. S. Musulin, and R. C. Bates, 1980
Monitoring and control of radon hazards, in International Mine Ventilation Congress, 2d, Reno, Nev.:
Proceedings, p. 405-411

Franklin, John C., Lee T. Nazum, and Adare L. Hill, 1975
Polymeric Materials for Sealing Radon Gas Into the Walls of Uranium Mines:
U. S. Bur. Mines Rept. Investigations 8036, 26 p.
The Bureau of Mines conducted extensive laboratory and limited field tests to determine whether a polymeric material could effectively reduce the emanation rate of radon gas from uranium ore. In the laboratory 46 different single-coat materials and 14 two-coat applications were tested. The laboratory tests showed that up to 100 percent of the radon gas could be sealed into the rock. Materials tested in the laboratory were polyesters, furan resins, epoxies, latices, and totally inorganic coatings. From the laboratory work six different materials were selected for field testing. The first test was single-coat materials in five static chambers; the second test used two-coat applications in an open chamber. Both tests were conducted in the Dakota mine at Grants, N. M. During the second test, the emanation rate of radon was reduced up to 62 percent.

Franklin, J. C., R. J. Zawadski, T. O. Meyer, and A. L. Hill, 1976
Data-Acquisition System for Radon Monitoring:
U. S. Bur. Mines Rept. Investigations 8100, 19 p.
A data-acquisition system was designed by the Bureau of Mines to monitor five detectors with radon continuously flowing through each. These detectors could be monitored up to 12 times an hour, but were only monitored according to a preset time, thus allowing radon to be monitored continuously in a uranium mine. The counter can be set to monitor each detector for any period of time up to 16.5 minutes. This allows very low concentrations to be monitored longer to reduce statistical error. There would be no upper limit in radon concentration that could be monitored, but there would be a lower limit of 50 pCi/L. Each detector was calibrated in the laboratory by the Lucas flask method. Multiple samples were taken at two different concentrations, and the correction factors for each detector was determined by a least squares fit of the data. To verify the calibrations, a series of measurements at several concentrations (300 pCi/L) with the two-filter method was within 3 percent; thus, the total error would be this difference plus the two-filter error. At high concentrations the coeffi-

cient of variation ranged between 2.1 and 9.8 percent for the five different detector units.

Holub, R. F., 1984
Turbulent plateout of radon daughters:
Radiation Protection Dosimetry, 7(1-4): 155-158
CA 101:99840n

Holub, R. F., and P. J. Dallimore, 1981
Factors affecting radon transport and the concentration of radon in mines, in Gomez, Manuel, ed., Radiation Hazards in Mining: Control, Measurement, and Medical Aspects, International Conference, Golden, Colo., October 4-9, 1981:
Golden, CO, Colorado School of Mines, Chap. 154, p. 1022-1028.
"...The laboratory experiments performed involved measurements of diffusion and emanation coefficients, porosity and permeability of representative rock samples. Significant differences have been found when comparing the results of the laboratory permeability determinations to those of the mine determinations. Considerations of underlying principles, however, suggest that the diffusion and emanation coefficients are the same in laboratory and mine. It was also found that moisture content plays a dominant role in radon transport through rock...."

Holub, R. F., and R. F. Droullard, 1978
Radon Daughter Mixture Distributions in Uranium Mine Atmospheres:
U. S. Bur. Mines Rept. Investigations 8316, 20 p.
The Bureau of Mines has made a study of the magnitude of the variations of radon daughter mixtures, with the objective of determining whether these variations reflect the existing physical conditions in uranium mine atmospheres or if they are merely random or systematic errors. To accomplish this, many data have been plotted using a triangular graphing technique which shows that plateout affects Po-218 more than Pb-214 or Bi-214, and that it is impossible to find simple correlations between working level ratios, radon daughter mixtures, and age.

Holub, R. F., R. F. Droullard, T. B. Borak, W. C. Inkret, J. G. Morse, and J. F. Baxter, 1985
Radon-222 and Rn-222 progeny concentrations measured in an energy-efficient house equipped with a heat exchanger:
Health Physics, 49(2): 267-277

McVey, James R., John C. Franklin, and David M. Shaw, 1977
Portable instrument measures four ventilation parameters:
Mining Congress Jour., 63(4): 49-52
A four-parameter measurement system for accurate determination of relative humidity, temperature, mine pressure and ventilation velocity has been developed for use in the radon control research of the U. S. Bureau of Mines. The new unit is housed in a 17-by 20- by 8-in. suitcase weighing less than 15 pounds.

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Development and evaluation of radon sealants for uranium mines:
Livermore, Calif., Lawrence Livermore Lab., U. S. Bur. Mines Contract Rept. H0232047, 67 p.

Lindsay, D. B., G. L. Schroeder, and C. H. Summers, 1981
Polymeric wall sealant test for radon control in a uranium mine, in Gomez, Manuel, ed., Radiation Hazards in Mining: Control, Measurement, and Medical Aspects, International Conference, Golden, Colo., October 4-9, 1981:
Golden, CO, Colorado School of Mines, Chap. 118, p. 790-793

Schroeder, G. L., 1977
Falling barometer nullifies rock sealant effectiveness:
Mining Engineering, 29(6): 38-39

Strong, Kaye P., Desmond M. Levins, and Anthony G. Fane, 1981
Radon diffusion through uranium tailings and earth cover, in Gomez, Manuel, ed., Radiation Hazards in Mining: Control, Measurement, and Medical Aspects, International Conference, Golden, Colo., October 4-9, 1981:
Golden, CO, Colorado School of Mines, Chap. 107, p. 713-719