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A Handbook for the Determination of Radon Attenuation Through Cover Materials

Prepared by V. C. Rogers, K. K. Nielson

Rogers and Associates Engineering Corporation

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Prepared by
V. C. Rogers, K. K. Nielson

Rogers and Associates Engineering Corporation
P.O. Box 330
Salt Lake City, UT 84110

Under Subcontract to
Pacific Northwest Laboratory
Richland, WA 99352

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ABSTRACT

Radon emissions from bare and covered uranium mill tailings can be estimated by diffusion theory if appropriate diffusion coefficients are known.

The mathematical bases for the diffusion theory expressions are herein presented, as is a general survey of previous and present research, as well as technological developments associated with radon transport through tailings cover systems.

Research is presently being conducted to define more clearly the influences of moisture, porosity, pore size distribution and other factors, on the attenuative properties of cover materials. The results of these present investigations will be incorporated in a subsequent addendum to this handbook.

The radon fluxes or cover thicknesses can be calculated by hand or by available computer programs. The equations and procedure for the hand calculations is in direct support of the methodology contained in Appendix P of the Generic Environmental Impact Statement on Uranium Milling. Several examples are given to demonstrate the methodology.

For most practical cases, the effect of the radon in the cover material can be neglected, if the radium concentration in the cover is at background levels.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Radon emissions from uranium mill tailings have long been recognized as a major potential health hazard. During the milling of uranium ore, the ore is crushed to facilitate processing and a negligible fraction of radium, the parent of radon, is removed. Consequently, the accessibility of radon to the environment is generally increased.

An important feature of any uranium mill tailings management program is the proper long-term stabilization of the tailings to adequately reduce radon emissions. The generally accepted means of achieving stabilization is to cover the tailings with earthen materials, sometimes supplemented by layers of manmade materials. It is therefore important to accurately determine the radon attenuating properties of cover materials and cover systems. This handbook provides the basis, the methodology, and the standardized procedures for calculating the radon attenuation provided by cover systems placed over uranium mill tailings impoundments, based on currently available data. Research is presently being conducted to define more clearly the influences of moisture, porosity, pore size distribution and other factors on the attenuative properties of cover materials. The results of these investigations will be incorporated in a subsequent addendum to this handbook.

1.1 ORGANIZATION OF HANDBOOK

This handbook addresses the following four main topics important in radon attenuation cover design effectiveness evaluations:

1. An identification of current research and development activities relating to radon transport through materials.

2. A complete foundation for the calculation of radon transport and attenuation through cover materials.

3. Documentation of the relevant expressions contained in Appendix P of the Final Generic Environmental Impact Statement on Uranium Milling.(1)

4. A concise set of procedures for calculating cover thicknesses required to satisfy the design criterion using both exact and approximate expressions.

The identification of research and development activities is presented in the following section of this chapter. Chapter 2 contains the mathematical basis for calculating radon attenuation through cover materials, including the documentation of relevant expressions in Appendix P of Reference 1. The procedures for calculating the required cover thickness are given in Chapter 3, along with several examples, and Chapter 4 contains the conclusions, summary and a procedural check list for calculating adequate cover thicknesses.

1.2 BACKGROUND AND PREVIOUS WORK

Radon does not combine readily with other elements because it is a chemically inert gas. The principal isotope of radon, ^{222}Rn, is generated from the radioactive decay of ^{226}Ra and is a decay daughter in the ^{238}U decay series as shown in Figure 1.1. The half-life of radon, $T_{1/2}$, is 3.8 days which allows the radon to migrate considerable distances before decaying. Furthermore, the generation of ^{222}Rn continues at its current rate for many thousands of years due to the relatively long half-lives of ^{226}Ra, and its parent, ^{230}Th, which are both present in the tailings.

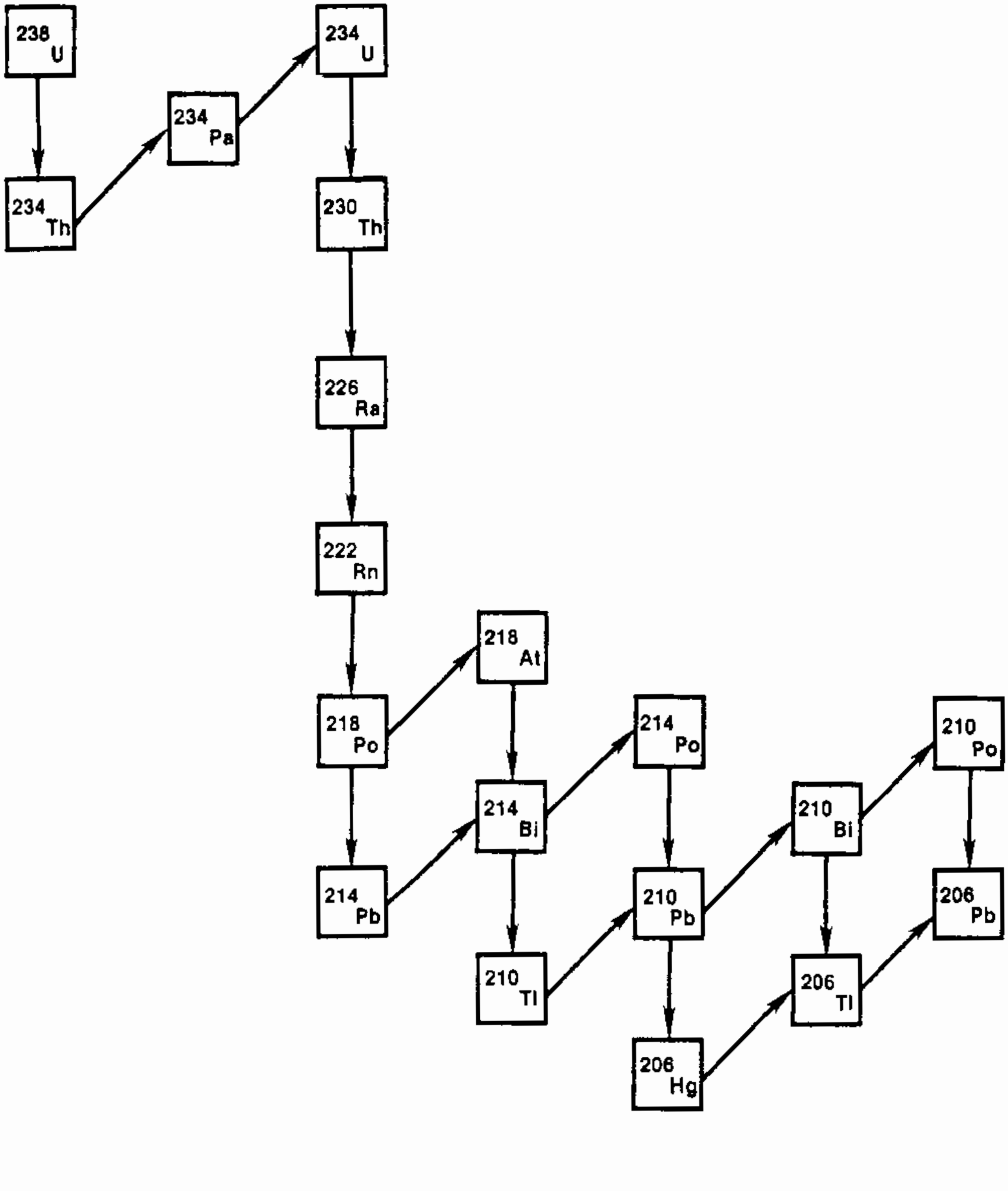

FIGURE 1.1 ^{238}U DECAY SCHEME

The calculation of the thicknesses of cover materials required to attenuate radon flux to near-background levels is generally based upon diffusion theory. The effectiveness of a particular cover material in attenuating radon release depends upon that material's ability to restrict the diffusion long enough so that, before the radon can completely penetrate the material, it will decay to a solid daughter product and will consequently remain trapped in the material. The parameter that characterizes this material property is called the diffusion coefficient.

Researchers have long been interested in the diffusion and transport of radon through porous materials. Early studies of radon in the natural environment(2-11) have been supplemented by research dealing specifically with the diffusion and transport of radon produced in uranium mill tailings(9, 12-14) and ore minerals.(15,16) In particular, References 8 and 17 contain excellent reviews of the general topic, and Reference 18 contains a comprehensive bibliography on the effects of radon moisture on emanation and diffusion.

Among the first major studies concerned with the diffusion of radon from uranium mill tailings are those reported in References 12-14. These studies were based on experiments with the diffusion of radon through tailings, soil and concrete. Measurements made during these experiments were compared with diffusion theory modeling and from the comparison, diffusion coefficients were deduced. In other laboratory experiments, (19,20) the diffusion of radon through various tailings and cover materials was measured. Diffusion coefficients were deduced from both radon fluxes and from radon gas concentration profiles.

Two recent field tests(21,22) using uranium tailings materials also have yielded information associated with the diffusion coefficient. In one test(21) surface radon fluxes were measured for various thicknesses of a cover material placed over a small plot of tailings. The diffusion coefficient obtained from a least-squares fit of the flux data was consistent with the laboratory measurement of similar material.(21) In the other field measurement(22) the diffusion coefficient was deduced from in-site borehole logging of the ^{226}Ra and ^{222}Rn concentrations in acidic and alkaline tailings.

In Reference 20, it was found that the diffusion coefficients for a wide variety of materials could be approximated by the following simple correlation involving moisture and the diffusion coefficient of radon in air:

$$D_e = D^o_{air}\, p \exp(-0.261M) \ , \tag{1-1}$$

where

D_e = effective bulk diffusion coefficient (cm^2/s)

D^o_{air} = diffusion coefficient of radon in air (0.106 cm^2/sec)

p = total porosity of material

M = weight-percent of moisture in the porous material, (i.e., grams water per gram wet sample)

The same data were used in Reference 23 to obtain a correlation similar in form to other correlations of gaseous diffusion through porous materials.(24)

The correlation based upon the air-filled porosity, p_a, is:

$$D_e = 0.74\ D^o_{air}\ p_a^{\ 2.16} + D_w\ \theta \tag{1-2}$$

where

θ = volume fraction of moisture

p_a = air filled porosity = $p - \theta$

D_w = diffusion coefficient in water-filled pores (assumed to be 6.6x10^{-6}cm^2/sec)

The radon transport through synthetic materials can also be described with diffusion theory with a material diffusion coefficient characterizing the diffusion. For these materials the porosity is unity. Diffusion coefficients for several synthetic materials are presented in Reference 25.

The same authors also reported preliminary results(19) with a clay-gravel aggregate that has a low air-filled porosity. Initial results with the aggregate suggested further development(19,25) and work is continuing in this area.

Other recent laboratory efforts have been focusing on diffusion coefficient measurements using small samples.(25-30)* In some of the methods, the effects the diffusion coefficient have upon a transient release of radon are measured. In others,(29,30)* two steady-state measurements are used to obtain a value for the diffusion coefficient. These methods generally yield diffusion coefficients that are smaller for the same conditions than those obtained from flux measurements on a large sample.

The radon flux reduction capability of synthetic materials has also been studied by several researchers. The primary concern with synthetic materials is their ability to maintain their integrity for the lengthy period of time that is required. Asphalt emulsions have been developed as radon sealants and initial results from the most recent field test are promising.(31,32) The Bureau of Mines has been studying foams, epoxy sealants and other materials as radon barriers for worked-out mine stopes.(33) Additionally, several materials have been identified as effective for the short-term reduction of radon in active mines.

The radon-attenuating properties of additional synthetic-materials are reported in References 19, 25, 26 and 34. Materials such as asphalt, EPDM rubber, Polyethylene sheets, Polycarbonate sheets, and Mylar are characterized by diffusion coefficients of less than 10^{-6} cm^2/sec.(25)

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*(Ref.30) Private communication between W. Silker (PNL) and V.C. Rogers (RAE), 1981.

2. MATHEMATICAL BASIS OF RADON DIFFUSION THROUGH COVERS

The physical processes by which radon can be transported from one point to another are both numerous and complex. In general these processes may be categorized into the two general groupings, of microscopic transport processes and macroscopic transport processes.

Macroscopic transport accounts for those transport processes in which radon atoms become intimately associated with their surrounding medium which itself is undergoing transport. For example the absorption of radon in ground water and subsequent flow of that water is a macroscopic radon transport process. In the overall movement of radon in containment systems, macroscopic processes can be important, but they are usually identified and evaluated separately. A recent evaluation(35) has shown that the macroscopic transport from diurnal atmospheric pressure variations is negligible when averaged over long periods.

In this handbook only microscopic transport of radon will be considered. Microscopic transport of radon is the set of processes by which individual free atoms of radon move as a consequence of momentum, thermal or mass gradients imposed upon the spatial radon distribution. Molecular diffusion of radon is one type of microscopic transport process.

If the spatial distribution of radon atoms existing within a containment volume exhibits a variation in concentration, a net flow of individual radon atoms will arise to reduce the concentration gradient. This particular microscopic transport process is generally referred to as simple molecular diffusion and is described mathematically by Fick's law of diffusion.

If a temperature or momentum gradient exists within a containment volume which includes radon, then a microscopic transport flow of radon will arise to minimize these gradients also. However, microscopic transport of radon arising from thermal or momentum gradients is generally negligible for long times in uranium tailings cover systems, and may therefore be ignored.

Only the microscopic transport of radon through a multiregion porous media system such as a covered tailings pile, as described mathematically by Fick's law of diffusion, will be considered in this handbook. Other transport mechamisms, such as advection, can often be accommodated by a suitable selection of the numerical value of the diffusion coefficient and thereby use the same mathematical formalism.

2.1 DIFFUSION THROUGH ONE AND TWO REGIONS

The general diffusion equation for the long-term steady state condition is derived from the steady state equation of continuity where, for a particular infinitesimal volume in the tailings or cover material, the radon generation rate equals the loss rate from leakage and decay:

$$\nabla \cdot \overline{J} + p\lambda C = Q \ , \qquad (2\text{-}1)$$

where

$\overline{J}$ = radon flux from the porous material (pCi/m^2s)

$\nabla \cdot \overline{J}$ = radon leakage from the infinitesimal volume (pCi/m^3s)

p = total porosity of the material

λ = decay constant of radon ($2.1 \times 10^{-6} sec^{-1}$)

C = radon concentration in the total pore space (pCi/m^3)

Q = radon source term (pCi/m^3s)

The first term in the left-hand side of Eq 2-1 represents the loss by leakage from the infinitesimal volume and the second term is the loss by radioactive decay in the volume. The source term in the volume is generally calculated from the following expression:

$$Q = R\rho_b E\lambda \ , \tag{2-2}$$

where

R = ^{226}Ra content of the dry material (pCi/g)

ρ_b = dry bulk density of the material (g/m^3)

E = emanating power

The emanating power is the fraction of radon that escapes the mineral grains and enters the pore space following its production.

In diffusion theory it is assumed that the flux is proportional to the concentration gradient, as given by Fick's law. For a one-dimensional system this is:

$$J(x) = -D_e \frac{dC}{dx} \ ,$$

Where D_e is the effective bulk radon diffusion coefficient relating the gradient of the radon concentration in the pore space to the total radon flux J of the porous material. Because the ratio D_e/p often appears in the diffusion expressions, it can be related to radon attenuation measurements. It is known as the diffusion coefficient of the porous medium, D*, but will not be used in the expressions involving the diffusion coefficient in this report. It is only used in the Table of diffusion coefficients, Table 3.1. From this point on, D in the text is meant to represent the effective bulk diffusion coefficient even if the subscript e is omitted. The diffusion coefficient can be determined experimentally for particular materials by measuring the radon attenuation through the material and relating the resulting attenuation to the diffusion theory expression. Radon flux measurements(12,19,20) have been used to deduce D_e, as have radon concentration measurements in the soil gas of the material(7,20) and the time-dependent break-point of radon migrating through the material.(25,26,28) With Fick's Law, Eq 2-1 becomes, for a one-dimensional problem:

$$D_e \frac{d^2C}{dx^2} - p\lambda C + R\rho_b E\lambda = 0 \qquad (2\text{-}3)$$

Radon diffusion has also been described(23) by Eq 2-3 using the air-filled porosity for p, and Eq 1-2 for D_e.

2.2 GENERAL SOLUTION AND BOUNDARY CONDITIONS

The general solution to Eq 2-3, assuming constant coefficients, is

$$C(x) = A\exp(bx) + B\exp(-bx) + S\ , \qquad (2\text{-}4)$$

where

$$b = (\lambda p/D_e)^{1/2} \qquad (2\text{-}5)$$

$$S = R\rho_b E/p$$

A, B = integration constants

The associated radon flux, obtained from Eqs 2-2 and 2-4 is

$$J = -D_e\, b\, [A\exp(bx) - B\exp(-bx)] \qquad (2\text{-}6)$$

The integration constants A and B are determined from the boundary conditions of the problem.

The boundary conditions used to evaluate the constants, as shown in Figure 2.1, are:

1.	$J(0) = 0$	the flux is zero at the origin
2.	$C_i(x_i) = C_{i+1}(x_i)$	the concentration is continuous across a media interface at x_i
3.	$J_i(x_i) = J_{i+1}(x_i)$	the radon flux is continuous across a media interface at x_i
4.	$C_n(x_n) = C_a$	the concentration at the surface of the top layer (medium n) is equal to a specified value

2.3 SOLUTION FOR RADON FLUX ACROSS THE SURFACE OF BARE TAILINGS

Application of boundary condition 1 to Eq 2-6 yields A = B, so that Eq 2-4 becomes

$$C(x) = A[\exp(b_0 x) + \exp(-b_0 x)] + R\rho_b E/p_0$$

where the zero subscript indicates that the parameter is that value for tailings. Application of boundary condition 4 for $C_a = 0$ at the top surface of the tailings, $x = x_0$, yields

$$A = \frac{-R\rho_b E}{p_0[\exp(b_0 x_0) + \exp(-b_0 x_0)]}$$

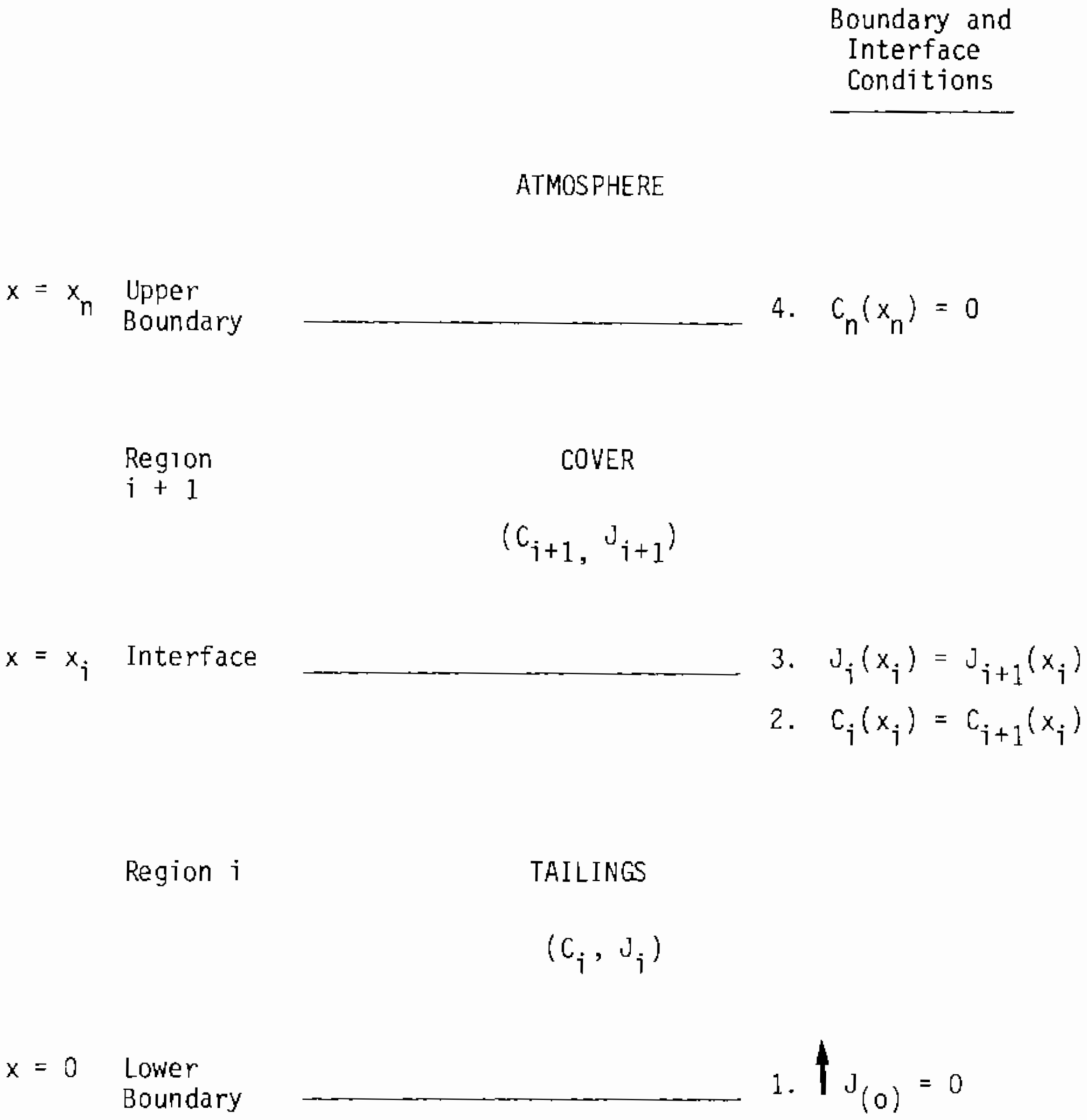

FIGURE 2.1 BOUNDARY AND INTERFACE CONDITIONS FOR SOLVING THE DIFFUSION EQUATIONS

then

$$C(x) = \frac{R\rho_b E}{p_o} [1 - \frac{\exp(b_o x) + \exp(-b_o x)}{\exp(b_o x_o) + \exp(-b_o x_o)}] \tag{2-7}$$

and

$$J(x) = R\rho_b E \left(\frac{\lambda D_o}{p_o}\right)^{\frac{1}{2}} \frac{[\exp(b_o x) - \exp(-b_o x)]}{[\exp(b_o x_o) + \exp(-b_o x_o)]} \tag{2-8}$$

Finally, the flux at the surface of the bare tailings is given by:

$$J(x_o) = J_o = R\rho_b E \left(\frac{\lambda D_o}{p_o}\right)^{\frac{1}{2}} \tanh \left(\sqrt{\frac{\lambda p_o}{D_o}}\ x_o\right) \tag{2-9}$$

$$J_o = b_o D_o S_o \tanh (b_o x_o) \tag{2-10}$$

where, as stated previously, D_o is the D_e for the tailings.

2.4 SOLUTION FOR COVERED TAILINGS

The solution of the diffusion equation for a two-region problem applies to a tailings pile covered with a homogeneous material. For simplicity the source term in the cover is assumed to be zero, C_a at the surface of the cover is also assumed to be zero, and the origin is assumed to be at the interface.

Application of the boundary conditions yields the following set of equations:

$$\begin{array}{lllll}
A_o \exp(-2b_o x_o) & -B_o & & & = 0 \\
A_o & +B_o & -A_1 & -B_1 & = -S_o \\
A_o & -B_o & -A_1 \left(\frac{D_1 b_1}{D_o b_o}\right) & + B_1 \left(\frac{D_1 b_1}{D_o b_o}\right) & = 0 \\
 & & A_1 & + B_1 \exp(-2b_1 x_1) & = 0
\end{array} \qquad (2\text{-}11)$$

Solution of Eqs 2-11 for A and B constants gives

$$A_1 = \frac{J_o}{b_o D_o \tanh(b_o x_o)[1 - \exp(2b_1 x_1)] - b_1 D_1 [1 + \exp(2b_i x_i)]} \qquad (2\text{-}12)$$

$$B_1 = -A_1 \exp(2b_1 x_1) \qquad (2\text{-}13)$$

Substitution of Eqs 2-12 and 2-13 into Eq 2-6 for the flux in the cover (region 1), yields:

$$J_1(x) = \frac{J_o [\exp(b_1 x) + \exp(2b_1 x_1 - b_1 x)]}{\left(\frac{D_o b_o}{D_1 b_1}\right)[\exp(2b_1 x_1) - 1] \tanh(b_o x_o) + [1 + \exp(2b_1 x_1)]} \qquad (2\text{-}14)$$

where Eq 2-10 has also been utilized.

The flux at the surface of the cover is given by substituting $x = x_1$ into Eq 2-14.

$$J_1(x_1) = \frac{2J_o \exp(-b_1 x_1)}{[1 + \left(\frac{D_o b_o}{D_1 b_1}\right) \tanh(b_o x_o)] + [1 - \left(\frac{D_o b_o}{D_1 b_1}\right) \tanh(b_o x_o)] \exp(-2b_1 x_1)} \qquad (2\text{-}15)$$

It is of interest to examine the behavior of $J_1(x_1)$ under various conditions. For $D_o b_o$ equal to $D_1 b_1$, and for sufficiently thick tailings such that tanh $(b_o x_o)$ is approximately unity, then Eq 2-15 becomes:

$$J_1(x_1) = J_o \exp(-b_1 x_1) \tag{2-16}$$

which is the simple exponential attenuation shown by curve A in Figure 2.2. However, if $D_o b_o << D_i b_i$, Eq 2-15 becomes:

$$J_1(x_1) = \frac{2J_o \exp(-b_1 x_1)}{1 + \exp(-2b_1 x_1)} \tag{2-17}$$

For small x_1, the value of $J_1(x_1)$ is approximately equal to J_o as shown by curve B in Figure 2.2, before the cover flux begins to decrease. This effect has been observed in laboratory measurements of radon fluxes from covered tailings.(20) At large x_1, Eq 2-17 becomes:

$$J_1(x_1 \text{ large}) = 2J_o \exp(-b_1 x_1), \tag{2-18}$$

so that J_1 decreases exponentially in the same manner as in Eq 2-16 but retains twice the magnitude which is shown by curve B in Figure 2.2. This is also observable(20) in laboratory measurements.

2.5 MULTIREGION SOLUTION

The mathematical solutions for three(9) and four(36) region systems have been presented previously. The diffusion solutions for the radon concentration and flux in a general multiregion system have recently been developed. The following presentation is based upon Reference 37.

2.5.1 General Multilayer Expression

The configuration and coordinate system used in the present development

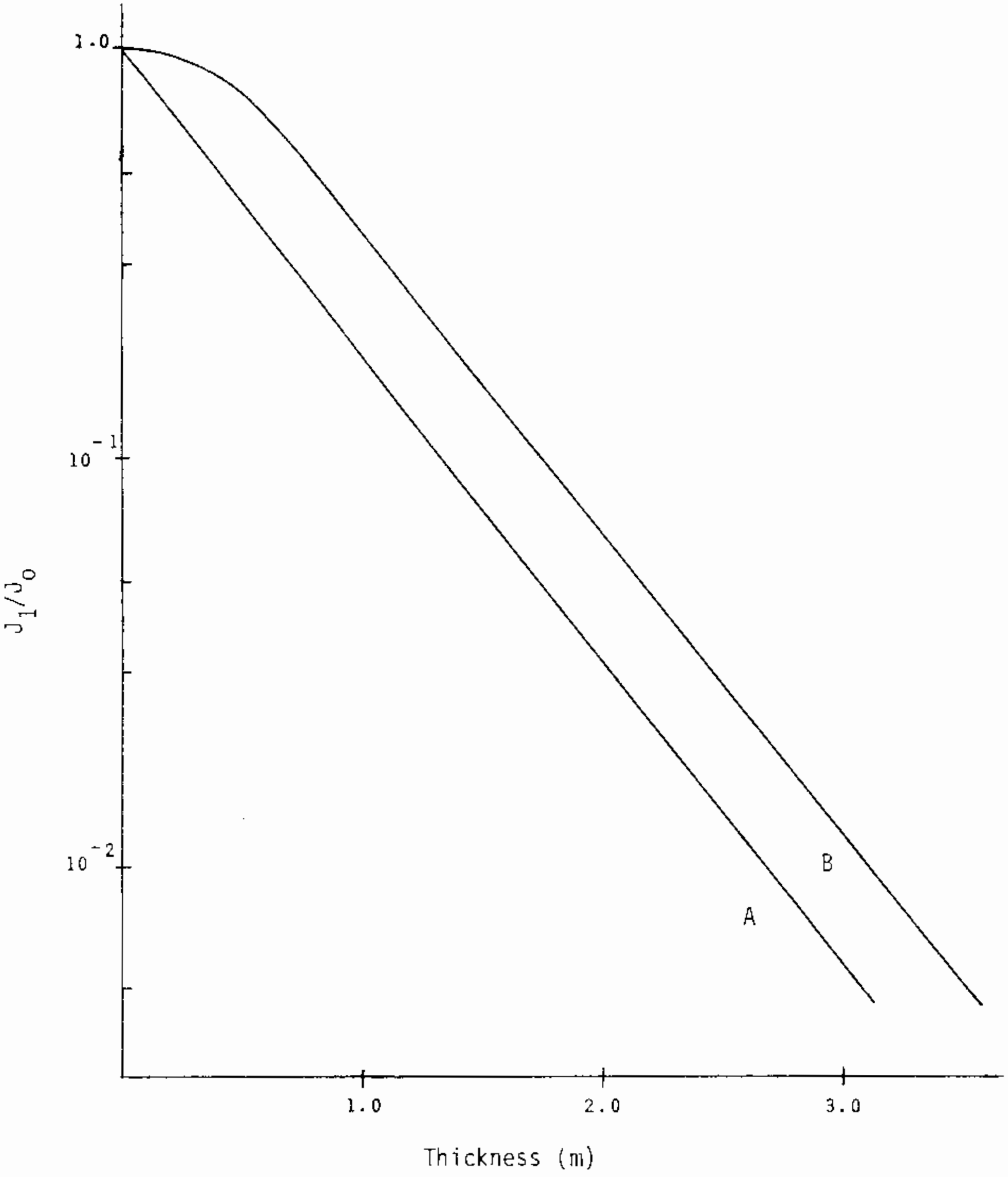

FIGURE 2.2 COVER SURFACE RADON FLUX FOR VARIOUS THICKNESSES AND PARAMETERS
Curve A ($D_o b_o = D_1 b_1$)
Curve B ($D_o b_o << D_1 b_1$)

of radon transport through a multilayer system is given in Figure 2.3. With each of the layers in the system is associated a thickness, d_i, a diffusion coefficient, D_i, and air-filled porosity, p_i, and a radon source, Q_i.

The general solution of Eq 2-1 for the radon concentration in the interval $x_{i-1} \leqslant x \leqslant x_i$, as given by Eq 2-4, is repeated with the present nomenclature,

$$C_i(x) = A_i \exp(b_i x) + B_i \exp(-b_i x) + S_i \tag{2-19}$$

for

$$x_{i-1} \leqslant x \leqslant x_i, \; i = 1 \text{ to } n$$

and

$$x_i = x_{i-1} + d_i$$

where

$C_i(x)$ = radon concentration at x in the i^{th} layer

x = the vertical distance from the bottom of the tailings system

b_i = $(p_i \lambda / D_i)^{\frac{1}{2}}$

d_i = layer thickness

D_i = the average effective radon diffusion coefficient (D_e) within the i^{th} layer

p_i = the average total porosity within the i^{th} layer

Q_i = the average volumetric ^{222}Rn source within the i^{th}layer

S_i = $Q_i / p_i \lambda$

The associated radon flux J_i, is given by Eq 2-6 and is repeated here:

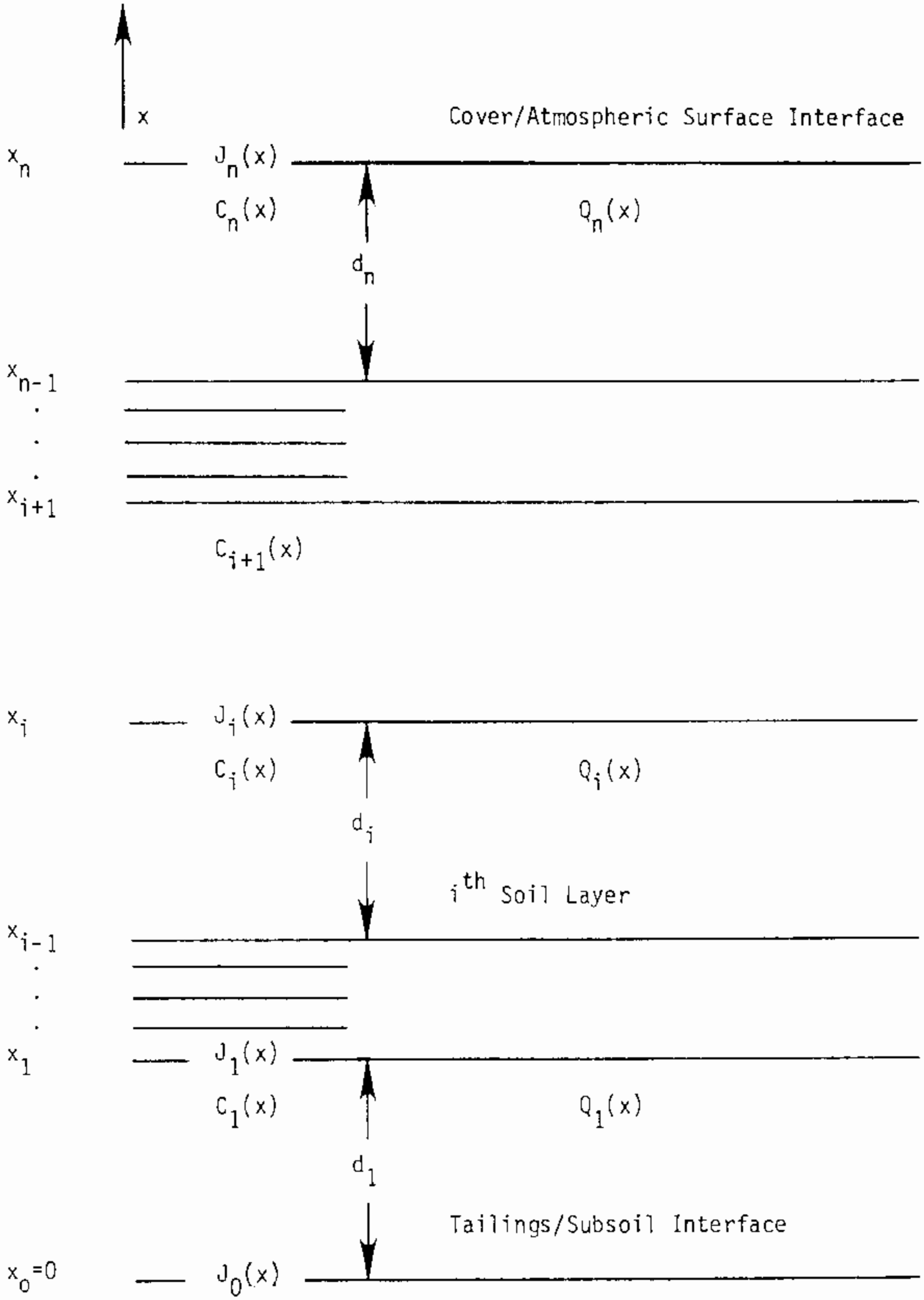

FIGURE 2.3 MULTILAYERED TAILINGS-COVER SYSTEM

$$J_i(x) = -D_i b_i \, [A_i \exp(b_i x) - B_i \exp(-b_i x)] \tag{2-20}$$

The A_i and B_i constants are determined by the boundary conditions for each layer.

As boundary conditions for each layer, the concentration, C(x), and flux, J(x), are assumed to be continuous across the layer interface as before, so that

$$C_i(x_i) = C_{i+1}(x_i) \tag{2-21}$$

$$-D_i \frac{dC_i(x_i)}{dx} = -D_{i+1} \frac{dC_{i+1}(x_i)}{dx} \tag{2-22}$$

for i = 1, 2, . . . n-1.

At the bottom boundary of the tailings system (i.e., $x_0 = 0$) it is assumed that the radon flux is a known constant, J_0, where

$$-D_1 \frac{dC_1(0)}{dx} = J_0 \tag{2-23}$$

and at the top boundary of the tailings system (i.e., x_n at the soil-air interface) it is assumed that the radon concentration is a known constant where,

$$C_n(x_n) = C_a \tag{2-24}$$

Imposing the boundary conditions as defined by Eq 2-21 upon Eq 2-19 provides the following relation for continuity of the concentration at the $x = x_i$ interface:

$$A_i \exp(b_i x_i) + B_i \exp(-b_i x_i) + S_i = A_{i+1} \exp(b_{i+1} x_i) + B_{i+1} \exp(-b_{i+1} x_i) + S_{i+1} \tag{2-25}$$

Equation 2-22 imposed upon Eq 2-20 requires, for flux continuity at the same interface ($x = x_i$), that

$$-D_i b_i \, [A_i \exp(b_i x_i) - B_i \exp(-b_i x_i)] =$$

$$-D_{i+1} b_{i+1} \, [A_{i+1} \exp(b_{i+1} x_i) - B_{i+1} \exp(-b_{i+1} x_i)] \qquad (2\text{-}26)$$

Equation 2-23 imposed upon 2-20 provides the following condition for the flux at the bottom layer:

$$A_1 = B_1 - J_o/(D_1 b_1) \qquad (2\text{-}27)$$

Finally, Eq 2-24 imposed upon Eq 2-19 gives the following condition for radon concentration at the soil-air surface:

$$A_n \exp(b_n x_n) + B_n \exp(-b_n x_n) + S_n = C_a \qquad (2\text{-}28)$$

Equations 2-25 through 2-28 constitute a complete set of equations for determining the constants, A_i and B_i. An equivalent matrix equation for this system of equations is shown in Figure 2.4.

The matrix equation representing the system of equations in Figure 2.4 has the general form:

$$MX = N \qquad (2\text{-}29)$$

which has the solution,

$$X = M^{-1}N \qquad (2\text{-}30)$$

where M^{-1} is the inverse of the coefficient matrix M. However, the determination of the inverse of this coefficient matrix is usually cumbersome, time consuming and subject to computational round-off errors. A simpler solution

$$\begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 & \cdots & 0 \\ e^{b_1x_1} & e^{-b_1x_1} & -e^{b_2x_1} & -e^{-b_2x_1} & 0 & 0 & \cdots & 0 \\ D_1b_1e^{b_1x_1} & -D_1b_1e^{-b_1x_1} & -D_2b_2e^{b_2x_1} & D_2b_2e^{-b_2x_1} & 0 & 0 & \cdots & 0 \\ 0 & 0 & e^{b_2x_2} & e^{-b_2x_2} & -e^{b_3x_2} & -e^{-b_3x_2} & \cdots & 0 \\ 0 & 0 & D_2b_2e^{b_2x_2} & -D_2b_2e^{-b_2x_2} & -D_3b_3e^{b_3x_2} & D_3b_3e^{-b_3x_2} & \cdots & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdots & \cdot \\ 0 & 0 & 0 & 0 & 0 & \cdots & e^{b_nx_n} & e^{-b_nx_n} \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \\ A_2 \\ B_2 \\ A_3 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ B_n \end{bmatrix} = \begin{bmatrix} J_0/D_1b_1 \\ S_2-S_1 \\ 0 \\ S_3-S_2 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ C_a-S_n \end{bmatrix}$$

FIGURE 2.4 MATRIX REPRESENTATION OF EQUATIONS FOR DETERMINING THE CONSTANTS A_i AND B_i

scheme is to transform this matrix into an equivalent triangular matrix which can then be readily solved in reverse order (i.e., B_n, A_n, B_{n-1}, . . . B_1, A_1) for the constants.(37)

The modified form of the resulting matrix(37) is shown in Figure 2.5. The definition of the terms used in the elements of the modified matrix in Figure 2.5 are as follows:

$$R_{i+1,i} = -\tfrac{1}{2}[1-(\frac{D_{i+1}b_{i+1}}{D_i b_i})^{\frac{1}{2}}] = -\tfrac{1}{2}[1-(\frac{D_{i+1}p_{i+1}}{D_i p_i})^{\frac{1}{2}}] \qquad (2\text{-}31)$$

$$\overline{R}_{i+1,i} = -\tfrac{1}{2}[1+(\frac{D_{i+1}b_{i+1}}{D_i b_i})^{\frac{1}{2}}] = -\tfrac{1}{2}[1+(\frac{D_{i+1}p_{i+1}}{D_i p_i})^{\frac{1}{2}}] \qquad (2\text{-}32)$$

$$T_i = (S_{i+1}-S_i)e^{-b_i x_i} = \frac{1}{\lambda}[\frac{Q_{i+1}}{p_{i+1}} - \frac{Q_i}{p_i}]\exp(-b_i x_i) \qquad (2\text{-}33)$$

$$U_i = \tfrac{1}{2}(S_{i+1}-S_i)\exp(b_i x_i) = \frac{1}{2\lambda}[\frac{Q_{i+1}}{p_{i+1}} - \frac{Q_i}{p_i}]\exp(b_i x_i) \qquad (2\text{-}34)$$

for i = 1, 2, . . . n-1.

The modified matrix is in a sufficiently simplified form for easy upper triangulation and backward solving for the coefficients A_i and B_i. With each of these coefficients known, the radon concentration is known within each layer and is given by:

$$C_i(x) = A_i\exp(b_i x_i) + B_i\exp(-b_i x_i) + \frac{Q_i}{p_i\lambda} \qquad (2\text{-}35)$$

for i = 1, 2, . . . n-1 and $x_i \leqslant x \leqslant x_{i+1}$. The related radon flux within that same layer is given by:

$$\begin{bmatrix}
1 & -1 & 0 & 0 & 0 & \cdots & -J_0/(D_1\, b_1) \\
1 & e^{-2b_1x_1} & -e^{(b_2-b_1)x_1} & -e^{-(b_2+b_1)x_1} & 0 & \cdots & T_1 \\
0 & 1 & R_{21}e^{(b_2+b_1)x_1} & \bar{R}_{21}e^{-(b_2-b_1)x_1} & 0 & \cdots & U_1 \\
0 & 0 & 1 & e^{-2b_2x_2} & -e^{(b_3-b_2)x_2} & \cdots & T_2 \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdots & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdots & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdots & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdots & \cdot \\
0 & 0 & 0 & 0 \;\cdots & 1 & e^{-2b_nx_n} & (C_a-S_n)e^{-b_nx_n}
\end{bmatrix}$$

FIGURE 2.5 MODIFIED MATRIX

$$J_i(x) = -D_i \frac{dC_i}{dx} = -D_i b_i \,[A_i \exp(b_i x) - B_i \exp(-b_i x)] \qquad (2\text{-}36)$$

2.5.2 Numerical Solution for Multilayer Systems

RAECO (acronym for Radon Attenuation Effectiveness and Cost Optimization) is a FORTRAN computer program which determines the radon fluxes and concentrations in a multilayer uranium tailings and cover system and then minimizes the cost associated with a specified uranium tailings cover system for given constraints on the maximum ground surface radon flux and/or the cover thickness.

A logic flow diagram for the code is shown in Figure 2.6. First, the migration of radon is determined for the specified cover characteristics and the radon concentrations (C), the radon fluxes (J), and the exponential constants are calculated. Then input of all pertinent cover cost data is made and the direct and support cover layer costs are generated. The cost optimization is performed yielding adjusted values (d) for the layer thicknesses. Layer thickness constraints are then imposed and new layer thickness values (d) are determined if necessary. The radon migration calculations are then repeated for each J and C with the adjusted cover layer thicknesses, and the resulting surface flux, J_s, is tested against the specified criterion, J_c. If this criterion is satisfied, the code proceeds to calculate the minimum costs for the cover system and the total remedial action. If the flux criterion is not satisfied, appropriate layer thicknesses are adjusted within the specified constraints, radon migration calculations are repeated, and the surface radon flux is again tested against the flux criterion. This process is repeated until all criteria are satisfied. The code then outputs all radon attenuation data and optimum cost information pertinent to the cover system

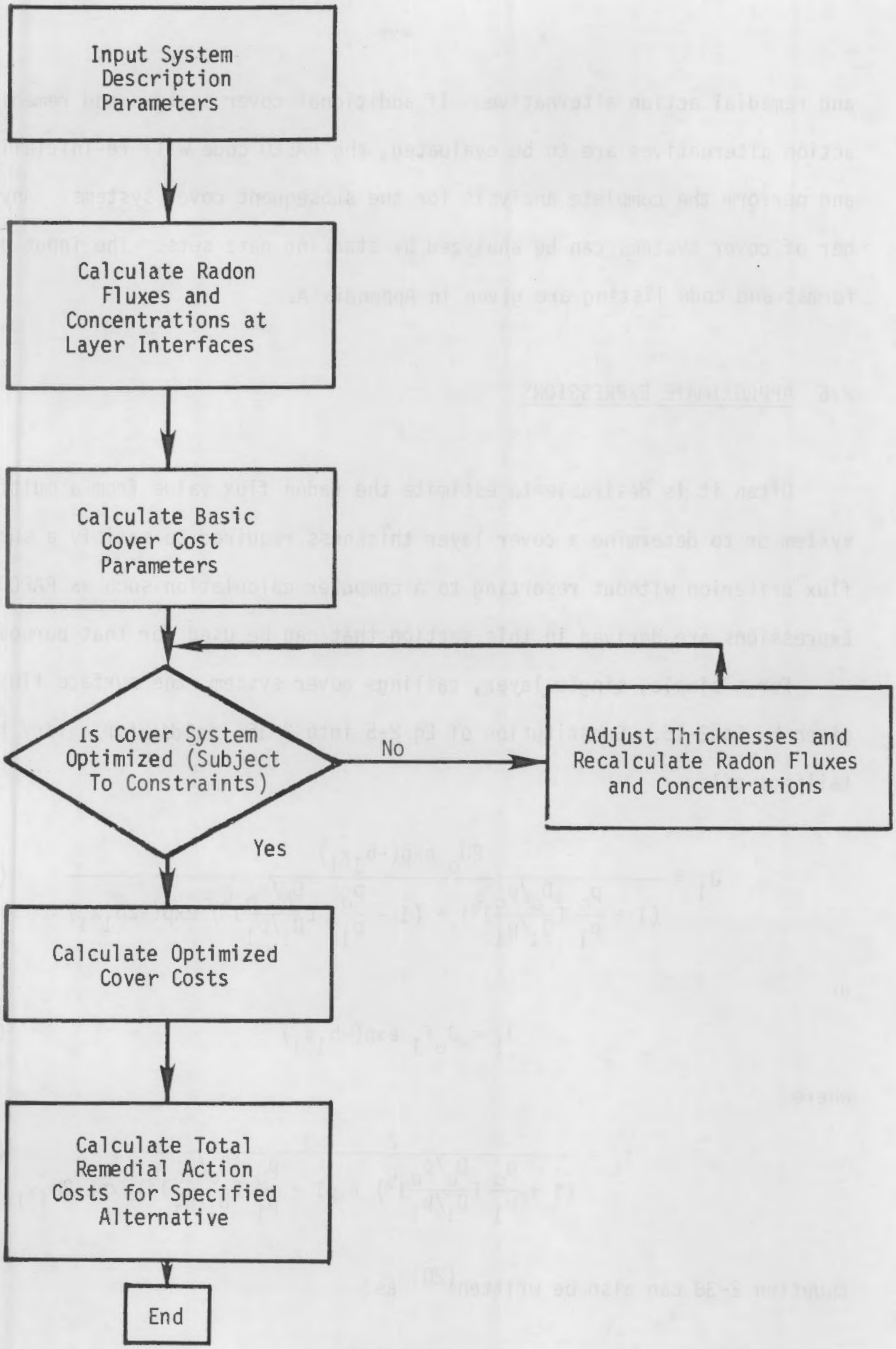

FIGURE 2.6 MAJOR COMPONENTS OF RAECO MODEL

and remedial action alternative. If additional cover systems and remedial action alternatives are to be evaluated, the RAECO code will re-initialize and perform the complete analysis for the subsequent cover systems. Any number of cover systems can be analyzed by stacking data sets. The input data format and code listing are given in Appendix A.

2.6 APPROXIMATE EXPRESSIONS

Often it is desirable to estimate the radon flux value from a multilayer system or to determine a cover layer thickness required to satisfy a surface flux criterion without resorting to a computer calculation such as RAECO. Expressions are derived in this section that can be used for that purpose.

For a simple, single-layer, tailings cover system, the surface flux is given by Eq 2-15. Substitution of Eq 2-5 into 2-15 yields, for a very thick tailings pile,

$$J_1 = \frac{2J_o \exp(-b_1x_1)}{\left(1 + \frac{p_o}{p_1}\left[\frac{D_o/p_o}{D_1/p_1}\right]^{\frac{1}{2}}\right) + \left(1 - \frac{p_o}{p_1}\left[\frac{D_o/p_o}{D_1/p_1}\right]^{\frac{1}{2}}\right)\exp(-2b_1x_1)} \qquad (2\text{-}37)$$

or

$$J_1 = J_of_1 \exp(-b_1x_1) \qquad (2\text{-}38)$$

where

$$f_1 = \frac{2}{\left(1 + \frac{p_o}{p_1}\left[\frac{D_o/p_o}{D_1/p_1}\right]^{\frac{1}{2}}\right) + \left(1 - \frac{p_o}{p_1}\left[\frac{D_o/p_o}{D_1/p_1}\right]^{\frac{1}{2}}\right)\exp(-2b_1x_1)} \qquad (2\text{-}39)$$

Equation 2-38 can also be written(20) as:

$$J_1 = J_o \exp(-a_1x_1) \qquad (2\text{-}40)$$

where

$$a_1 = b_1/\sqrt{h} = \sqrt{\frac{\lambda p_1}{D_1 h}} \tag{2-41}$$

Comparison of Eqs 2-38 and 2-41 gives the following relationship for h:

$$h = [1 - \frac{1}{b_1 x_1} \ln f\ ]^{-2} \tag{2-42}$$

Although h is generally a function of x, and the tailings and cover parameters, it can often be approximated by a constant average value because h is a very slowly varying function of the cover thickness and it approaches unity as the cover thickness becomes large.

Often the allowable surface flux is specified and it is the cover thickness that needs to be determined. The value of x_1 for a specified flux can be obtained by rearranging Eq 2-37 as follows:

$$x_1 = \sqrt{\frac{D_1}{p_1\lambda}}\ [\ \ln\ (\frac{2J_o}{J_1})\ - \ln\ [(1 + \frac{p_o}{p_1}\ [\frac{D_o/p_o}{D_1/p_1}]^{\frac{1}{2}}) + (1 - \frac{p_o}{p_1}\ [\frac{D_o/p_o}{D_1/p_1}]^{\frac{1}{2}})\exp(-2b_1x_1))]] \tag{2-43}$$

Most covers of interest exhibit a high degree of attenuation so that the last term in the second natural logarithm is very small. To a high degree of accuracy, the term $\exp(-2b_1x_1)$ may be replaced by $(J_1/J_o)^2$, so that Eq 2-43 becomes:

$$x_1 = \sqrt{\frac{D_1}{p_1\lambda}}\ [\ln\ (\frac{2J_o}{J_1})\ - \ln\ [(1 + \frac{p_o}{p_1}\ [\frac{D_o/p_o}{D_1/p_1}]^{\frac{1}{2}}) + (1 - \frac{p_o}{p_1}\ [\frac{D_o/p_o}{D_1/p_1}]^{\frac{1}{2}})\ (\frac{J_1}{J_o})^2]] \tag{2-44}$$

Often the diffusion coefficients for a proposed tailings and cover system are not known. For the purpose of estimating a cover thickness, Eqs 1-1 or 1-2 can be used to approximate the diffusion coefficients. If Eq 1-1 is used, then Eq 2-44 becomes:

$$x_1 = 2.28 \exp(-0.13\, M_1) \left\{ \ln(\frac{2J_o}{J_1}) - \ln[(1 + \frac{p_o}{p_1} \exp(0.13(M_1 - M_o))) + (1 - \frac{p_o}{p_1} \exp(0.13(M_1 - M_o)))(\frac{J_1}{J_o})^2] \right\} \qquad (2\text{-}45)$$

where

M_o = weight-percentage of moisture in tailings

M_1 = weight-percentage of moisture in soil cover

If the flux attenuation is greater than a factor of ten ($J_o/J_1 > 10$), Eq 2-45 can be written as,

$$x_1 = 2.28 \exp(-0.13\, M_1)[\ln(2J_o/J_1) - \ln[1 + \frac{p_o}{p_1} \exp(0.13(M_1 - M_o))]] \qquad (2\text{-}46)$$

For calculations involving composite covers, an approximate expression can be obtained from the following considerations. The general expressions for the flux in the i^{th} and $i\text{-}1^{th}$ cover layers are given by:

$$J_i = J(x_i) = -D_i b_i [A_i \exp(b_i x_i) - B_i \exp(-b_i x_i)]$$

$$J_{i-1} = J(x_{i-1}) = -D_i b_i [A_i \exp(b_i x_{i-1}) - B_i \exp(-b_i x_{i-1})]$$

It should be noted that for i = 1, J_{i-1} is not equal to the bare flux expression J_o.

Forming the ratio J_i/J_{i-1} yields

$$\frac{J_i}{J_{i-1}} = f_i \exp(-b_i d_i) \tag{2-47}$$

where

$$f_i \frac{(A_i/B_i) \exp(2b_i x_i) - 1}{(A_i/B_i) \exp(2b_i x_{i-1}) - 1} \quad i \geqslant 2 \tag{2-48}$$

$$d_i = x_i - x_{i-1}$$

Taking the product of Eq 2-47 for i = 2 to n gives

$$\frac{J_n}{J_1} = (\prod_{i=2}^{n} f_i) \exp(-\sum_{i=2}^{n} b_i d_i) \tag{2-49}$$

Now, J_1 can be expressed in the following form

$$J_1 = J_o f_1 \exp(-b_1 d_1) \tag{2-50}$$

where

$$f_1 = -D_1 b_1 A_1 [(A_1/B_1) - 1] \tag{2-51}$$

so that Eq 2-49 becomes:

$$J_n = J_o (\prod_{i=1}^{n} f_i) \exp(-\sum_{i=1}^{n} b_i d_i) \tag{2-52}$$

where f_i is defined in Eqs 2-48 and 2-51.

Equation 2-52 is readily transformed to

$$J_n = J_o \prod_{i=1}^{n} \exp(-a_i d_i) \qquad (2\text{-}53)$$

where

$$a_i = b_i/\sqrt{h_i}$$

$$h_i = [1 - \frac{1}{b_i d_i} \ln f_i]^{-2}$$

Equations 2-52 and 2-53 define the radon flux for the n^{th} layer exactly, assuming only the absence of radium in the cover layers and the usual boundary conditions. However, to use these equations in their present form requires some additional information about the parameters A_i and B_i. If these are known, then A_n and B_n can be used directly in Eq 2-20 to obtain J_n. The purpose of obtaining Eqs 2-52 and 2-53 is to demonstrate the attenuation provided by a multiple-layer cover system can be expressed in the form of the product of the attenuations for each layer. Thus, the flux J_m can be approximated from the surface flux from an m-1 cover layer system by:

$$J_m = J_{m-1} \exp(-a_m x_m) \qquad (2\text{-}54)$$

This approach treats the system as an effective source layer, consisting of the tailings and the m-1 cover layers; and the top one-layer cover, the m^{th} layer. With this approximation either Eq 2-38 or 2-40 can be used to obtain the surface flux. However, the appropriate value of D/p for the effective source must be determined. The influence is assumed to be proportional to the attenuation through the succeeding layers. Furthermore, the direct influence of the i^{th} layer upon the attenuation in the m^{th} layer is assumed to be of the form $[1 - \exp(-a_i d_i)]$, so that the contribution D_i/p_i to the corresponding parameter D_{sm}/p_{sm} in the effective source is

$$\frac{D_i}{p_i} [1 - \exp(-a_i d_i)] \exp(-\sum_{j=i+1}^{m-1} a_j d_j)$$

Summing over all layers up to m-1 yields:

$$\frac{D_{sm}}{p_{sm}} = \sum_{i=0}^{m-1} \frac{D_i}{p_i} [1 - \exp(-a_i d_i)] \exp\ (-\sum_{j=i+1}^{m-1} a_j d_j) \qquad (2\text{-}55)$$

This expression is exact in when all D_i/p_i are equal. Additionally, the parameter a_i can be replaced by b_i with little loss of accuracy. With these definitions, Eqs 2-38 and 2-41 become

$$J_m = J_{m-1}\ f_m \exp(-b_m d_m) \qquad (2\text{-}56)$$

$$f_m = \frac{2}{[1 + (\frac{D_{sm}/p_{sm}}{D_m/p_m})^{\frac{1}{2}}] + [1 - (\frac{D_{sm}/p_{sm}}{D_m/p_m})^{\frac{1}{2}}] \exp(-2b_m x_m)} \qquad (2\text{-}57)$$

$$J_m = J_{m-1} \exp(-a_m d_m) \qquad (2\text{-}58)$$

$$a_m = b_m/\sqrt{h_m} = b_m(1 - \frac{\ell n f_m}{b_m d_m}) \qquad (2\text{-}59)$$

In order to determine J_m to a high degree of accuracy, J_{m-1} must be known. Equation 2-56 or 2-58 can be used to obtain J_{m-1} in a similar manner. Therefore, the most appropriate use of the above equations is to determine D_{S2}/p_{S2} and J_2, then, using J_2, obtain D_{S3}/p_{S3} and J_3, and so on until J_m is calculated. This procedure is demonstrated by an example given in Section 3.4.

3. APPLICATION OF CALCULATION METHODS

The procedures for determining the cover thickness required over uranium mill tailings to meet flux criteria are presented in this chapter. Briefly, the major items are as follows:

1. Definition of Source Term - determine the values of parameters defining the radon generation and diffusion out of the tailings.
2. Cover Materials Characterization - select candidate cover materials and estimate their porosities, moisture characteristics and diffusion coefficients.
3. Initial System Configuration - establish an initial cover design for analysis. For single-layer systems, provisions are made for determining the cover thickness.
4. System Cover Surface Flux and Thickness Determination - perform radon flux calculations and adjust cover system design as necessary.

3.1 SOURCE TERM DEFINITION

Characterization of the source term is the first major step in performing the design analysis of an adequate cover system. As given by Eq 2-2 or 2-45, the key parameters for the source term are the radium concentration, the dry bulk density and the emanating power.

Values for the radium concentration, R, of tailings can be measured directly from tailings samples by the radon equilibrium method, by direct gamma spectroscopy, or by chemical separations and subsequent alpha spectroscopy. If a radium analysis is not available, it can be estimated quite accurately from the uranium concentration of the ore as specified by the ore grade, using the following equation:

$$R = K_a G \tag{3-1}$$

where

$G =$ ore grade (wt% U_3O_8)

$K_a = 2800$ pCi (^{226}Ra) per gram soil/(wt% U_3O_8)

This equation presumes equilibrium between the uranium and radium in the ore and all radium being contained in the tailings.

The bulk density, ρ_b, of the solid tailings material is a relatively easy measurement to perform. In the absence of measured data a typical value of 1.6 g/cm^3 can be used for the bulk dry density.

The emanating power, E, for uranium tailings is the fraction of the radon generated that is free to diffuse in the pore spaces. It has been shown recently(38) that E varies with moisture. However, for most practical applications(20) with uranium tailings, a value of 0.2 is a good estimate of E.

3.2 DIFFUSION COEFFICIENTS

If Eq 2-3 is divided by the porosity, p, it can be viewed as a rate balance per volume of pore space instead of a volume of material space; accordingly, the parameter D_e/p, is the diffusion coefficient of the fluid in the pore space. When presenting values for the diffusion coefficient, the D_e/p is often used.(8,20) A tabulation of several values of D_e/p is given in Table 3.1. In general, D_e/p decreases dramatically with the moisture content of the diffusing medium. One correlation indicating this decrease is given in Eq 1-1. The correlation, and the data

TABLE 3.1

BULK DIFFUSION COEFFICIENTS FOR RADON IN VARIOUS MEDIA

Medium		Moisture Content (%)	D_e/p (cm^2/sec)	Source
Air		0	1.0 E-1	Ref 8
Water		100	1.1 E-5	Ref 8
Sand				Ref 8
Building Sand		4	5.4 E-2	
Fine Quartz		0	6.8 E-2	
Fine Quartz		8.1	5.0 E-2	
Fine Quartz		17	5.0 E-3	
Soils				Ref 8
Granodiorite			4.5 E-2	
Yucca Flats			3.6 E-2	
Granite			1.5 E-2	
Loams			8.0 E-3	
Varved Clays			7.D E-3	
Mud		37.2	5.7 E-6	
Powder River	#1	5	2.3 E-2	Ref 20
	#1	9	2.2 E-2	
	#1	17	2.6 E-4	
	#1	30	8.2 E-5	
	#2	6	2.7 E-2	
	#2	6	2.3 E-2	
Shirley Basin	#1	5	9.3 E-3	Ref 20
	#1	12	1.8 E-2	
	#1	20	1.7 E-4	
	#2	8	2.3 E-2	
	#2	15	4.6 E-3	
Ambrosia Lake	#1	10	5.3 E-2	Ref 20
	#1	20	6.4 E-3	
	#2	2	3.5 E-2	
	#2	6	2.0 E-2	
Wyoming General	#1	11	8.3 E-3	Ref 20
	#2	1	8.8 E-3	
Concrete (5% porosity)			3.4 E-4	Ref 12
Concrete (18% porosity)			2.0 E-4	Ref 9
Concrete (1% porosity)			1.0 E-2	Ref 9

used to obtain the correlation,(20) are shown in Figure 3.1. The same data, plus other data points, used to obtain the correlation given by Eq 1-2, are presented in Figure 3.2. The latter correlation has a form similar to other correlations of gaseous diffusion in porous materials. The moisture content of soil covers is usually more readily available than the information required to estimate the air porosity of the material, so that the former correlation will be used in the examples given later in this chapter.

As stated previously, it is desired that values of D_e/p be measured experimentally for a given material at its ambient moisture level and expected degree of compaction. Alternatively, D_e/p can be estimated solely from the moisture content and porosity of the material, because the large variation (four orders of magnitude) in D_e/p with moisture content obscures the much smaller effects on the value of D_e/p from other soil properties. Hence, one of the more important characteristics of cover soils is their ability to retain moisture.

Although soils contain widely varying proportions of the three particle size categories, sand (50-2,000 μm), silt (2-5D μm), and clay (<2 μm), they are generally referred to in terms of the predominant particle size fraction, i.e., clay soils contain greater than 40% clay-sized particles. Because the small clay particles contain various proportions of clay minerals, there is a great diversity of clays in nature; however, thay all generally have pronounced absorption and adsorption of moisture. Because clays, particularly montmorillonite, can retain significant amounts of moisture for extended periods of time, they are effective in attenuating radon; however, they must be protected from the surface effects of cracking and erosion. As an example of the water retention properties of clay, laboratory measurements of individual heavy clay types have measured hygroscopic water concentrations of 15 to 20%. The hygroscopic water is held as a very thin film and requires the application of greater than

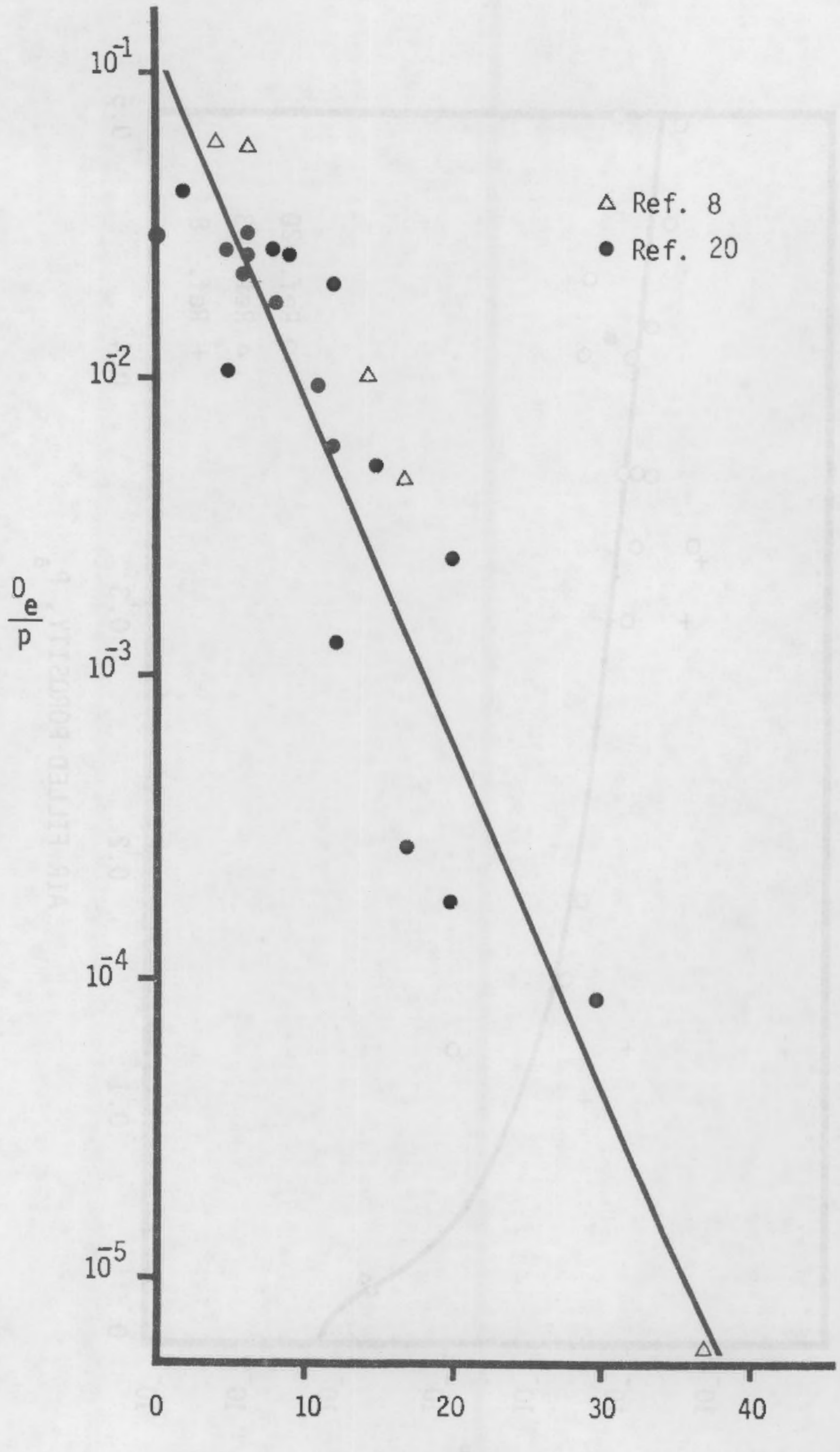

FIGURE 3.1 MOISTURE DEPENDENCE OF THE DIFFUSION COEFFICIENT

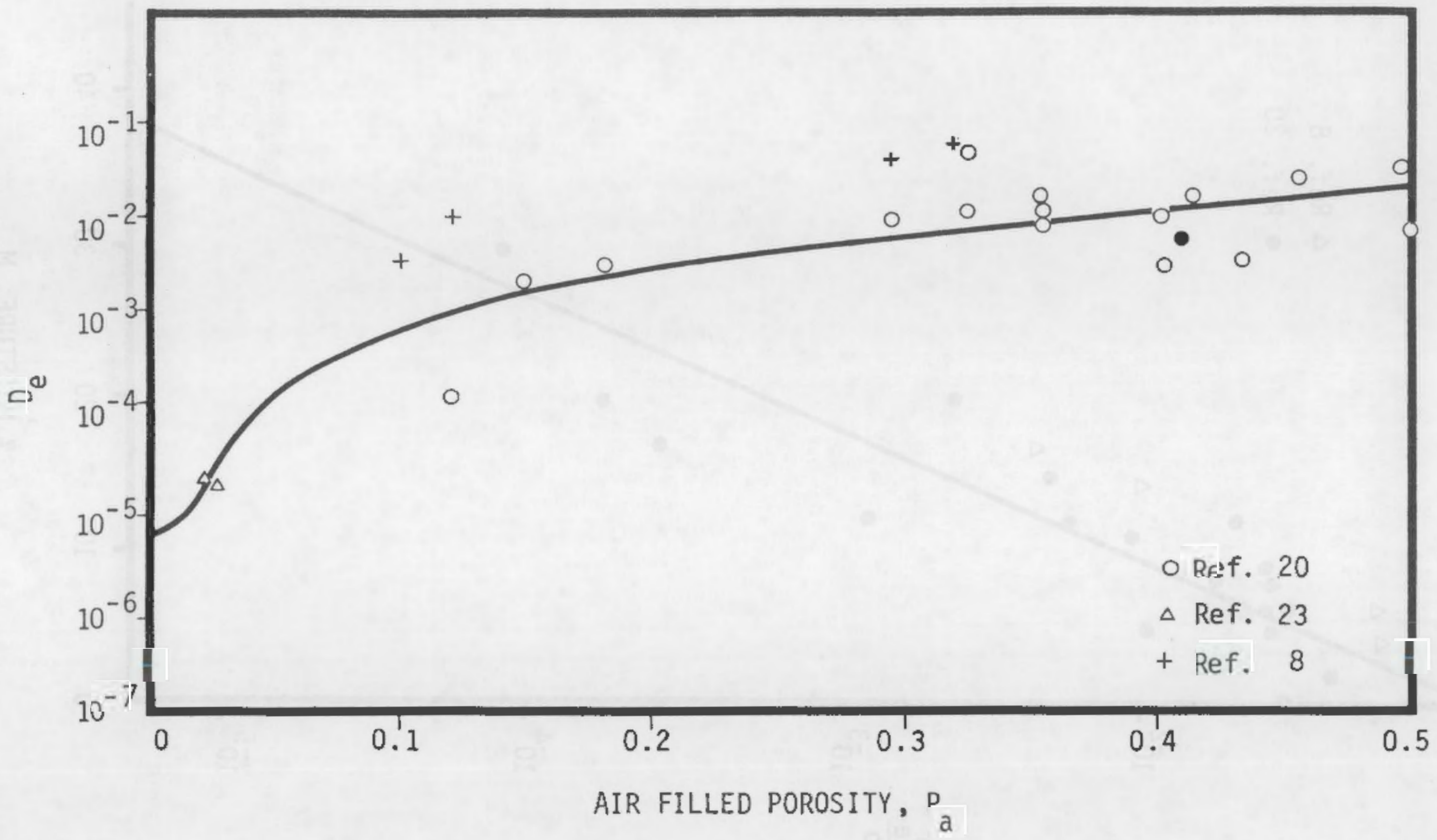

FIGURE 3.2 DIFFUSION COEFFICIENT AS A FUNCTION OF AIR FILLED POROSITY

30 to 10,000 bars pressure to remove it.(39)

A survey of available drilling log information from ten sites in the uranium milling regions in Wyoming, Colorado, New Mexico and Utah yielded ambient moisture concentrations of near-surface clay soils ranging from 9 to 12%, although a few isolated, undisturbed values exceeded 12%. For non-clay soils the survey indicated moisture concentrations ranging from 6 to 10%.

As part of the technology projects for the Inactive Uranium Mill Tailings Remedial Action Program, the above data have recently been correlated with soil-type, annual precipitation and annual evaporation.(40) The following simple, preliminary correlation is useful in estimating average ambient soil moistures at depths of about ten feet:

$$M = 3.2\, P_r^{\frac{1}{2}} - 0.03\, E_v + S, \qquad (3\text{-}2)$$

where

M = soil moisture (wt%)
P_r = annual precipitation (in)
E_v = annual lake evaporation (in)
S = soil index
= 2.9 for clay soils
= -1.0 for sandy soils

Research on the moisture dependence of the diffusion coefficient is currently being conducted at Battelle Pacific Northwest Labortories and at RAE Corporation for both the Department of Energy and the Nuclear Regulatory Commission.

3.3 SURFACE FLUX AND COVER THICKNESS DETERMINATION

After values for the diffusion coefficients and porosities of the tailings and cover materials are determined, the radon flux from the bare tailings is calculated using Eq 2-9; and the surface flux from the covered tailings is calculated with Eq 2-15. Figure 3.3 contains the results of cover calculations for a bare tailings flux of $J_o = 280$ pCi/m^{2}s. Various soil moistures are used to obtain the curves in the figure. The cover moisture is the dominant parameter affecting the radon attenuation. When the flux attenuation is specified and the cover thickness must be determined, Eq 2-44 or 2-45 is used. Because the bare tailings flux can be expressed explicitly as a function of ore grade using Eq 3-1, and the parameters E and M_o, the resulting form for Eq 2-45 with $p_o = p_1$, $\rho_b = 1.6$ g/cm^3, $J_1 = 2$ pCi/m^{2}s, and $E = 0.2$, is:

$$x_1 = 2.28 \exp(-0.13\ M_1)\ [\ \ln[4{,}200\ G\ \ \exp(-0.13\ M_o)]$$

$$-\ln[1 + \exp(0.13\ (M_1 - M_o)) + \frac{1 - \exp(0.13\ (M_1 - M_o))}{[(2{,}100\ G)\ \ \exp(-0.13\ M_o)]^2}]] \qquad (3\text{-}3)$$

Results of this expression are tabulated in Tables B.1 - B.11 in Appendix B for G from 0.05 - 0.30, M_o from 3 to 15%, and M_1 from 5 to 15%. The ranges of these parameters are compatible for ambient soils of the western United States milling and mining regions. The D_e/p values are also given in the tables so that they may be useful even if the moisture correlation of Eq 1-1 is modified, or other moisture correlations are used for D_e/p. Once the correct D_e/p has been determined for the tailings and cover soil, then the tables give the correct thicknesses.

The sensitivity of the cover thickness to variations in ore grade, tailings

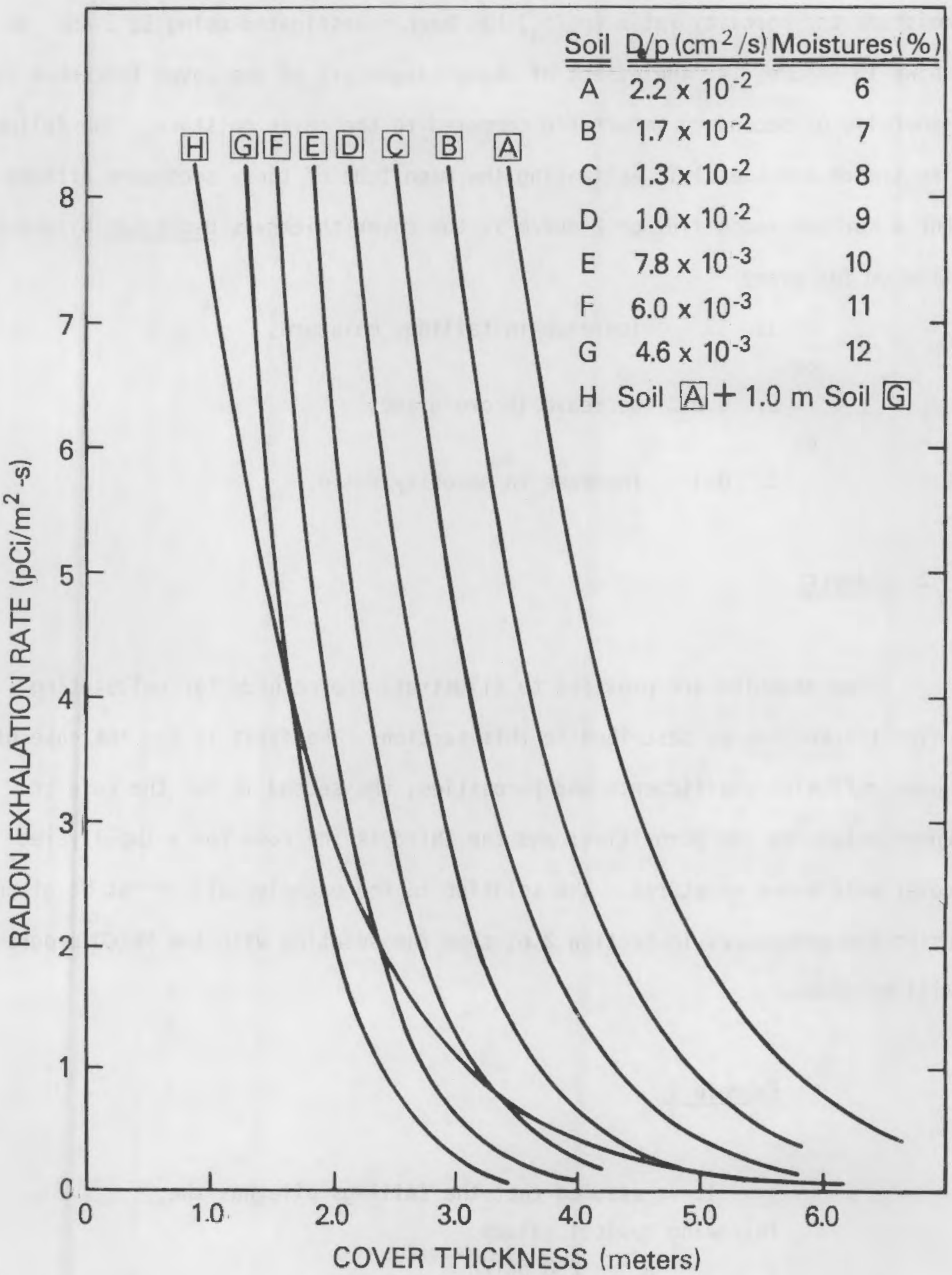

FIGURE 3.3 EFFECT OF SOIL THICKNESS ON RADON EXHALATION RATE

moisture and porosity ratio (p_o/p_1) has been investigated using Eq 2-45. As shown in Figure 3.4, the effect of these parameters on the cover thickness is generally of secondary importance compared to the cover moisture. The following trends are useful in estimating the magnitude of these secondary effects. For a surface radon flux of 2 pCi/m^{2}s, the cover thickness decreases by about five cm for every

1. 1% increase in tailings moisture,

or

2. 0.01% decrease in ore grade,

or

3. 0.1 increase in porosity ratio.

3.4 EXAMPLES

Three examples are provided to illustrate the methods for calculating cover thicknesses as described in this section. The first is for the case of known diffusion coefficients and porosities; the second is for the case of known moistures and porosities; and the third is the case for a two-layered cover with known moistures. The solution to the examples will first be given using the procedures in Section 2.6, then the solution with the RAECO program will be given.

Example 1

It is assumed that the tailings pile has the following typical values:

$R = 280$ pCi/g

$\rho_b = 1.6$ g/cm^3

$E = 0.2$

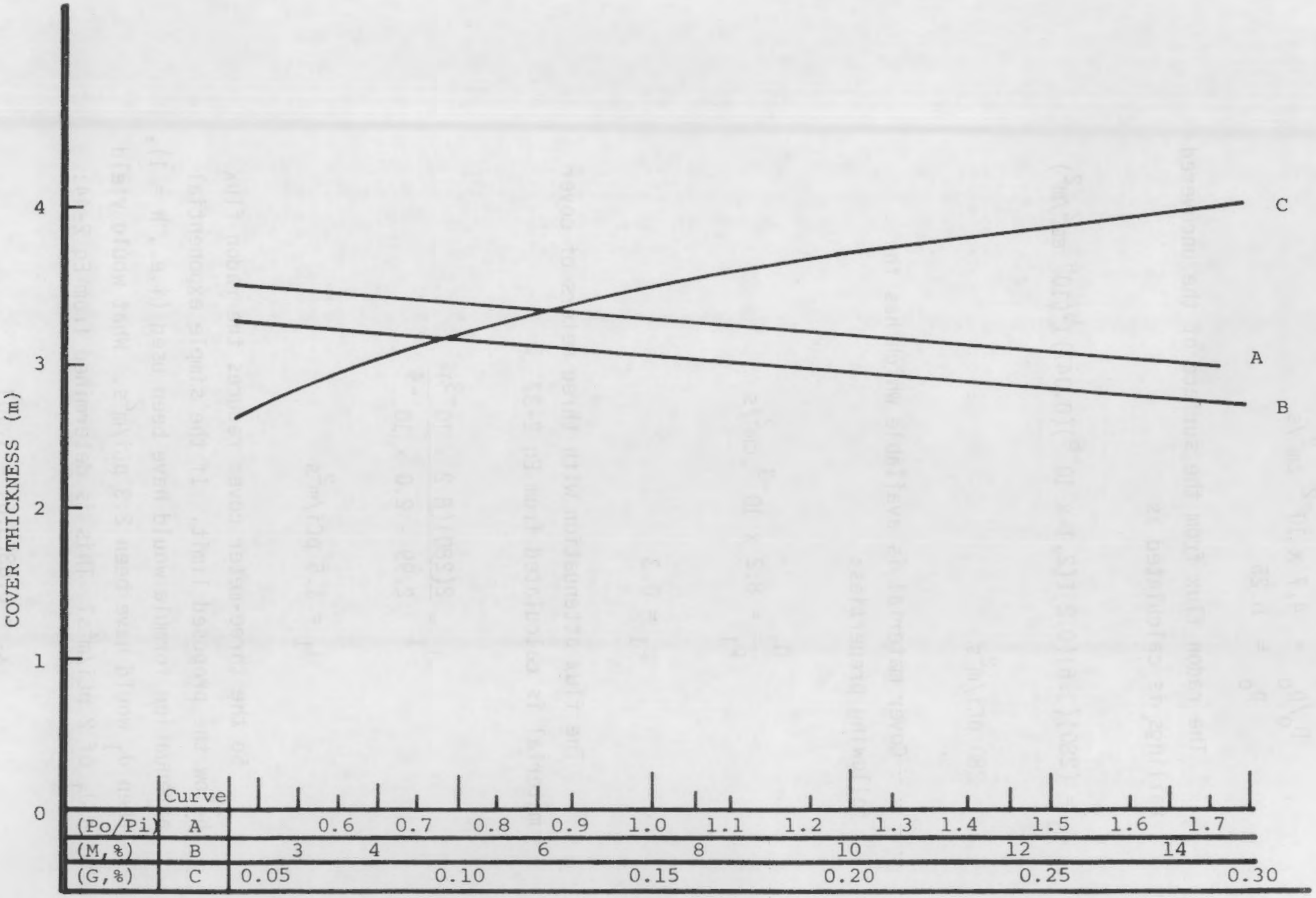

FIGURE 3.4 TAILINGS COVER THICKNESS VARIATION WITH POROSITY RATIO, TAILINGS MOISTURE AND ORE GRADE

$$D_o/p_o = 4.7 \times 10^{-2}\ \text{cm}^2/\text{s}$$
$$p_o = 0.25$$

The radon flux from the surface of the uncovered tailings is calculated as

$$J_o = (280)(1.6)(0.2)[(2.1 \times 10^{-6})(0.047)]^{\frac{1}{2}}(10^4\ \text{cm}^2/\text{m}^2)$$

$$= 280\ \text{pCi/m}^2\text{s}$$

Cover material is available which has the following properties:

$$\frac{D_1}{p_1} = 8.2 \times 10^{-3}\ \text{cm}^2/\text{s}$$

$$p_1 = 0.3$$

The flux attenuation with three meters of cover material is calculated from Eq 2-37

$$J_1 = \frac{2(280)(8.2 \times 10^{-3})}{2.99 - 2.0 \times 10^{-4}}$$

$$J_1 = 1.5\ \text{pCi/m}^2\text{s}$$

So the three-meter cover reduces the radon flux below the proposed limit. If the simple exponential attenuation formula would have been used (i.e., $h = 1$), then J_1 would have been 2.3 pCi/m^{2}s. What would yield a J_1 of 2 pCi/m^{2}s? This is determined from Eq 2-44:

$$x_1 = 0.63[5.64 - 1.10]$$

$$x_1 = 2.8\ \text{m}$$

Example 2

What thickness of 10% moisture cover soil will attenuate the radon flux from an 8% moisture tailings pile to a value of 2 pCi/m^{2}s? The porosities are the same, and all other tailings parameters are given previously.

The answer can be obtained using Eq 2-46 once J_o is determined.

$$\frac{D_o}{p_o} = 0.106 \exp(-0.261(8))$$

$$\frac{D_o}{p_o} = 0.013 \text{ cm}^2/\text{sec}$$

$$J_o = (280)(1.6)(0.2)[(2.1 \times 10^{-6})(0.013)]^{\frac{1}{2}} \times 10^4$$

J_o = 149 pCi/m^{2}s, and

$$x_1 = (0.62)(5.00 - 0.832)$$

$$x_1 = 2.6 \text{ m}$$

Example 3

The tailings pile described in Example 2 is to be covered with one meter of a good quality clay capable of retaining 12% moisture and sufficient overburden at 6% moisture to achieve a surface flux of 2 pCi/m^{2}s. What thickness of overburden should be used? Assume equal porosities for all materials.

First, determine the diffusion coefficients:

tailings $\frac{D_o}{p_o} = 0.013 \text{ cm}^2/\text{s}$

clay $\frac{D_1}{p_1} = 0.0046 \text{ cm}^2/\text{s}$

overburden $\frac{D_2}{p_2} = 0.022 \text{ cm}^2/\text{s}$

Then, calculate the attenuation through the clay component using Eqs 2-38 and 2-39.

$$J_1 = (149) \left[\frac{2}{2.682 - (0.682)(0.014)}\right] (0.119)$$

$$J_1 = 13 \text{ pCi/m}^2\text{s}.$$

Now, determine the diffusion coefficient for the source term to the overburden (the source is now the tailings and clay) using Eq 2-55.

$$\frac{Ds_2}{ps_2} = \frac{D_o}{p_o} \exp(-a_1x_1) + \frac{D_1}{p_1} [1 - \exp(-a_1x_1)]$$

$$\frac{Ds_2}{ps_2} = (0.013)(0.088) + (0.0046)(1 - 0.088)$$

$$\frac{Ds_2}{ps_2} = 0.0053 \text{ cm}^2/\text{s}$$

This expression is substituted for D_o/p_o, and J_1 = 13 is substituted for J_o in Eq 2-44.

$$x_2 = (1.02)[2.56 - \ln[0.491 + (1 - 0.491)(0.024)]]$$

$$x_2 = 2.3 \text{ m} = \text{overburden thickness}$$

So the total cover thickness is 3.2 m.

3.5 EXAMPLE CALCULATIONS WITH RAECO

The parameters specified in Section 3.4 were used to construct the input to the RAECO program as specified in Appendix A. Table 3.2 contains the input data set for the three examples.

The calculation for Example 1, shown in Table 3.3, specifies a cover thickness of 2.8 m in order to achieve surface flux of 2 pCi/m^{2}s from the tailings.

The results of the Example 2 calculations are shown in Table 3.4. A cover thickness of 2.6 m is sufficient to give a surface radon flux of 2 pCi/m^{2}s from the tailings.

The multilayer cover example calculations, shown in Table 3.5, yield an overburden thickness of 2.35 m, which is just slightly greater than the 2.3 m thickness calculated by the procedure given in Section 2.6, but still well within acceptable uncertainty limits.

3.6 COVER SOURCE CONSIDERATIONS

The example calculations of the previous section did not consider any surface radon flux contribution from radium in the covers. The cover source term was set equal to zero. For soil cover materials containing background values of radium, the effect of the radon from the covers is very small and

TABLE 3.2

INPUT DATA SET FOR RAECO CALCULATIONS OF EXAMPLE PROBLEMS

```
 URANIUM MILL TAILINGS GEIS, APPENDIX P -EX. 1
2,0.,.0,0,0.,0.001
500.,0.01175,0.25,1.882E-3
283.574,0.00246,0.3,0.
```

```
URANIUM MILL TAILINGS GEIS, APPENDIX P -EX. 2
2,0.,.0,0,0.,0.001
500.,0.00325,0.25,1.882E-4
260.,.002338,0.3,0.
```

```
URANIUM MILL TAILINGS GEIS, APPENDIX P -EX.3
3,0.,0.,0,0.,.001
500.,0.00325,0.25,1.882E-4
100.,0.00138,0.3,0.
235.,0.0066,0.3,0.
```

TABLE 3.3

RAECO CALCULATION OF EXAMPLE 1

```
*****    URANIUM MILL TAILINGS GEIS, APPENDIX P -EX. 1




 **********  I N P U T   P A R A M E T E R S         **********

NUMBER OF LAYERS = 2
INITIAL RADON FLUX =  .000     PCI/SQM*SEC
SURFACE RADON CONCENTRATION =  .000     PCI/LITER
COST FLAG = 0
FLUX CRITERIA FOR OPTIMIZATION =  .000     PCI/SQM*SEC
ACC = 1.000-003
LAYER        THICKNESS        DIFF COEFF        POROSITY         SOURCE
               (CM)          (SQCM/SEC)                       (PCI/CC*SEC)
  1          .5000+003        .1175-001        .2500+000        .1882-003
  2          .2838+003        .2460-002        .3000+000        .0000



*****  R E S U L T S   O F   R A D O N   D I F F U S I O N   C A L C U L A T I O N *****


      LAYER   THICKNESS        EXIT FLUX          EXIT CONC.         EFF
                (CM)         (PCI/SQM*SEC)          (PCI/L)

        1        500.          .9391+002         .2386+006        .0000
        2        284.          .2005+001         .0000            .0000
```

TABLE 3.4

RAECO CALCULATION OF EXAMPLE 2

```
*****   URANIUM MILL TAILINGS GEIS, APPENDIX P -EX. 2




 **********  I N P U T   P A R A M E T E R S         **********

NUMBER OF LAYERS = 2
INITIAL RADON FLUX =  .000     PCI/SQM*SEC
SURFACE RADON CONCENTRATION =  .000     PCI/LITER
COST FLAG = 0
FLUX CRITERIA FOR OPTIMIZATION =  .000     PCI/SQM*SEC
ACC = 1.000-003
LAYER        THICKNESS        DIFF COEFF        POROSITY        SOURCE
               (CM)          (SQCM/SEC)                       (PCI/CC*SEC)
  1           .5000+003       .3250-002        .2500+000        .1882-003
  2           .2600+003       .2338-002        .3000+000        .0000



***** R E S U L T S   O F   R A D O N   D I F F U S I O N   C A L C U L A T I O N *****


      LAYER   THICKNESS        EXIT FLUX           EXIT CONC.        EFF
                (CM)        (PCI/SQM*SEC)           (PCI/L)

        1       500.          .7120+002          .1855+006          .0000
        2       260.          .1996+001          .0000              .0000
```

TABLE 3.5

RAECO CALCULATION OF EXAMPLE 3

```
*****   URANIUM MILL TAILINGS GEIS, APPENDIX P -EX.3




 **********  I N P U T   P A R A M E T E R S         **********

NUMBER OF LAYERS = 3
INITIAL RADON FLUX =  .000     PCI/SQM*SEC
SURFACE RADON CONCENTRATION =  .000     PCI/LITER
COST FLAG = 0
FLUX CRITERIA FOR OPTIMIZATION =  .000     PCI/SQM*SEC
ACC = 1.000-003
LAYER        THICKNESS         DIFF COEFF        POROSITY         SOURCE
               (CM)           (SQCM/SEC)                        (PCI/CC*SEC)
  1          .5000+003         .3250-002        .2500+000         .1882-003
  2          .1000+003         .1380-002        .3000+000         .0000
  3          .2350+003         .6600-002        .3000+000         .0000



***** R E S U L T S   O F   R A D O N   D I F F U S I O N   C A L C U L A T I O N *****



      LAYER   THICKNESS       EXIT FLUX          EXIT CONC.         EFF
                 (CM)      (PCI/SQM*SEC)          (PCI/L)

        1        500.        .6196+002         .2080+006          .0000
        2        100.        .1006+002         .1529+005          .0000
        3        235.        .2007+001         .0000              .0000
```

is approximately additive, so that the component of the radon flux from radium in the cover material does not appreciably alter the component of the radon flux from radium in the tailings. Furthermore, the linearity assumption for tailings plus cover fluxes is conservative, that is, the surface flux due only to the tailings is slightly less with a cover source term than without the cover source term. For example, the radon flux from radium in the cover specified in Example 2 is 0.82 pCi/m^2s, as determined by a RAECO calculation. A RAECO calculation of the total surface radon flux from radium in both the tailings and the cover is 2.80 pCi/m^2s. Subtracting the cover contribution of 0.82 pCi/m^2s from the total flux yields a value of 1.98 pCi/m^2s of the total surface flux that is attributed to the tailings. This is in excellent agreement with, but is slightly less than, the surface flux of 2.00 pCi/m^2s previously calculated assuming no radium in the cover materials.

4. SUMMARY AND CONCLUSIONS

The radon releases from bare and covered tailings can be estimated using diffusion theory, if appropriate diffusion coefficients are used. The procedures for calculating the thickness of an adequate cover system are straightforward and the calculations can be performed by hand or by computer programs such as the RAECO code. A procedural checklist for the hand calculations is given in Table 4.1.

As shown in the table, first the values for all pertinent parameters must be determined, then an initial tailings-cover system configuration must be developed and finally the surface flux and cover thickness calculations are performed. Multilayer covers require a cyclical calculation starting with the lowest layer and proceeding to the top layer.

A site-specific example (41) of this procedure is now presented.

The values used for computing the bare tailings flux for the Hansen Project facility are as follows:

$$R = 231.8 \text{ pCi/g}$$

$$p = 1.6 \text{ g/cm}^3$$

$$E = 0.2$$

$$D_o/p_o = 0.01314 \text{ cm}^2\text{/s}$$

The value of $D_o/p_o = 0.01314$ cm^2/s was obtained from Eq 4-1 based on a tailings residual moisture of 8%. Substitution of the above values into Eq 4-3 yields

TABLE 4.1

PROCEDURAL CHECKLIST FOR CALCULATING ADEQUATE COVER THICKNESS

1.	DETERMINE THE REQUIRED COVER THICKNESS	If desired, the required cover thickness can be obtained from the tables in Appendix B given the ore grade and the tailings and cover moistures.	
2.	DETERMINE SOURCE TERM PARAMETERS, R, E, ρ_b, p_o, D_o	Default values, R = 2,800 G, E = 0.2, ρ_b = 1.6, p_o = 0.35	$D_o/p_o = 0.106 \exp(-0.261\ M_o)$
3.	DETERMINE COVER MATERIAL PARAMETERS, D_i, p_i	Default value, p_i = 0.35	$D_i/p_i = 0.106 \exp(-0.261\ M_1)$
4.	CALCULATE BARE TAILINGS FLUX AND COVER ATTENUATION PARAMETER		$J_o = R\rho_b E\ (\lambda D_o/p_o)^{1/2}$ $b_1 = (\lambda p_1/D_1)^{1/2}$
5.	CALCULATE SURFACE FLUX OR COVER THICKNESS		$J_1 = \dfrac{2J_o \exp(-b_1 x_1)}{(1 + \frac{p_o}{p_1} [\frac{D_o/p_o}{D_1/p_1}]^{1/2}) + (1 - \frac{p_o}{p_1} [\frac{D_o/p_o}{D_1/p_1}]^{1/2}) \exp(-2b_1 x_1)}$ $x_1 = b_1 \{\ln (\frac{2J_o}{J_1}) - \ln [(1 + \frac{p_o}{p_1} [\frac{D_o/p_o}{D_1/p_1}]^{1/2})$ $+ (1 - \frac{p_o}{p_1} [\frac{D_o/p_o}{D_1/p_1}]^{1/2}) (\frac{J_1}{J_o})^2]\}$
6.		If multiple layer cover, calculate effective key parameters source D/p.	$a_i = b_i/\sqrt{h_i}$ $\dfrac{D_{sm}}{p_{sm}} = \sum_{i=o}^{m-1} \dfrac{D_i}{p_i} [1 - \exp(-a_i x_i)] \exp(-\sum_{j=i+1}^{m-1} a_j x_j)$
7.		If multiple layers are in the cover, calculate Item 5 for the first cover layer, then calculate Item 6 for the second cover layer, then calculate Item 5 for the second cover layer, and so on until Item 5 is calculated for the top layer.	

$$J_o = (231.8\ \text{pCi/g})(1.6\ \text{g/cm}^3)(0.2) \times (2.1\text{x}10^{-6}\ \text{s}^{-1}\text{x}0.01314\ \text{cm}^2/\text{s})^{\frac{1}{2}}$$
$$\times\ 10^4\text{cm}^2/\text{m}^2 = 123.2\ \ \text{pCi/m}^2\text{s}$$

Equation 4-3 assumes effectively infinite depth of tailings. A factor given by tanh $[x_o\sqrt{\lambda p_o/D_o}\ ]$, where x_o the depth of tailings, is used to account for finite depth of tailings. However, in cases where the average depth of tailings is three meters or more, the factor is effectively unity.

The cover system consists of three feet of compacted clay, 6.5 feet of random fill or overburden, and one-half foot of topsoil. The long-term moisture content of the clay is estimated to be 12.3% and the topsoil and the overburden will maintain a moisture concentration of 10.5%. Equation 4-5 is used to estimate the radon flux from the surface of the clay cover.

The following D/p values are computed from Eq 4-2:

$$D_0/p_0\ =\ 0.01314\ \text{cm}^2/\text{s (tailings, 8\% moisture)}$$

$$D_1/p_1\ =\ 0.0043\ \text{cm}^2/\text{s (clay layer, 12.3\% moisture)}\ ,$$

Using the above values, the previously calculated radon flux, and assuming the porosities are equal for all materials yields J_1=12 pCi/m^{2}s from Eq 4-5. Equation 4-5 can also be written as

$$J_1 = J_0 f\ \exp(-b_1x_1)$$

where

$$f = \frac{2}{(1 + \frac{p_o}{p_1} [\frac{D_o/p_o}{D_1/p_1}]^{\frac{1}{2}}) + (1 - \frac{p_o}{p_1} [\frac{D_o/p_o}{D_1\ p_1}]^{\frac{1}{2}})\ \exp(-2b_1x_1)}$$

The function f is useful in calculating the composite diffusion coefficient. This composite diffusion coefficient is computed by Eq 4-7. Thus, the composite D/p is computed as:

$$\frac{D_{s2}}{p_{s2}} = D_o/p_o\ [-\exp(-a_i x_i)] + D_i/p_i\ [1 - \exp(-a_i x_i)]$$

where

$D_o/p_o = 0.01314\ cm^2/s$

$D_1/p_1 = 0.0043\ cm^2/s$

$x_1 = 91.44\ cm$

$a_1 = [2.1 \times 10^{-6}\ s^{-1}/0.0043\ cm^2/s \times h]$

Now

$$h = [1 - \frac{1}{b_1x_1} \ln f]^{-2}$$

$$= [1 - \frac{1}{(0.0221) \times 91.44} \ln (0.7313)]^{-2}$$

$$= 0.75$$

and

$$a_1 = \left(\frac{2.1 \times 10^{-6}\ s^{-1}}{0.043\ cm^2/s \times 0.75}\right)^{½}$$

$$= 0.0255$$

Equation 4-7 now becomes:

$$\frac{D_{s2}}{p_{s2}} = 0.01314\ (0.0971) + 0.0043\ (1 - 0.0971) = 0.0052\ cm^2/s$$

Equation 4-6 yields the minimum required depth of overburden-topsoil in addition to the clay layer by using the following quantities:

$$D_o/p_o = 0.0052\ cm^2/s$$

$$p_o/p_1 = 1$$

$$J_1 = 2\ pCi/m^2s$$

$$J_o = 12\ pCi/m^2s$$

$$D_1/p_1 + 0.106\ \exp(-0.106 \times 10.5\%) = 0.0068\ cm^2/s$$

The moisture content of the overburden-topsoil is 10.5%, as mentioned previously. A value of x_1 = 105.3 cm or x_1 = 1.05 m of overburden-topsoil is obtained. Thus, the total cover needed to achieve the minimum radon flux of 2 pCi/m^2s is

0.92 m clay
+ 1.05 m overburden-topsoil
1.96 m total cover

It is also of interest to calculate the surface radon flux if seven feet of overburden-topsoil is placed over the three feet of clay.

Using Eq 4-5 with the values

$$J_o = 123.22 \text{ pCi/m}^2\text{s}$$

$$b_1 = \left[\frac{2.1 \times 10^{-6} \text{ s}^{-1}}{0.0068 \text{ cm}^2/\text{s}}\right]^{1/2}$$

D_o/p_o = 0.01314 cm^2/s (the diffusion coefficient of the tailings)

D_1/p_1 = 0.0068 cm^2/s (the diffusion coefficient of the sand-soil)

x_1 = 304.8 cm (i.e., 10 ft, the depth of cover),

then

$$J_1 = 0.5 \text{ pCi/m}^2\text{s}$$

The above calculations are performed by hand. If a suitable computer program is used such as RAECO, items 1-3 of Table 4.1 provide sufficient information to prepare a complete data set in the format given in Appendix A.

5. REFERENCES

1. Final Generic Environmental Impact Statement on Uranium Millings, U.S. NRC Report NUREG-0706, September 1980.

2. G.E. Harrison, "The Diffusion of Radon Gas Mixtures," University of Birmingham, 1938.

3. E.M. Kovach, "Meteorological Influences Upon the Radon-Content of Soil-Gas," Transaction, American Geophysical Union, 26, No. II, 1945.

4. B.J. Giletti and J.L. Kulp, "Radon Leakage from Radioactive Minerals," Columbia University, 1954.

5. S.L. Jaki and V.F. Hess, "A Study of the Distribution of Radon, Thoron, and Their Decay Products Above and Below the Ground," Fordham University, 1958.

6. H.B. Evans, "Factors Influencing Permeability and Diffusion of Radon in Synthetic Sandstones," University of Utah, 1959.

7. H.W. Kraner, G.L. Schroeder, and R.D. Evans, "Measurements of the Effects of Atmosheric Variables on Radon 222 Flux and Soil-Gas Concentration," The Natural Radiation Environment, J.A.S. Adams and W.M. Lowder, Eds., University of Chicago Press, 1964.

8. Allen B. Tanner, "Radon Migration in the Ground: A Review," The Natural Radiation Environment, J.A.S. Adams and W.M. Lowder, Eds., University of Chicago press, 1964.

9. H.W. Kraner, G.L. Schroeder, and R.D. Evans, "Annual Progress Report to AEC," MIT-952-4, 1967.

10. Wilkening, M.H. and J.E. Hand, "Radon Flux at the Earth-Air Interface," J. Geophys. Res. 65, 3367-3370, 1960.

11. Wilkening, M.H., W.E. Clements and D. Stanley, "Radon-222 Flux Measurements in Widely Separated Regions," The Natural Radioation Environment II, J.A.S. Adams and W.M. Lowder, Eds., The University of Chicago Press, 1975.

12. M.V.J. Culot, H.G. Olson, and K.J. Schiager, "Effective Diffusion Coefficient of Radon in Concrete Theory and Method for Field Measurements," Health Physics, 30, p. 263, March 1976.

13. K.J. Schiager, "Analysis of Radiation Exposures on or Near Uranium Mill Tailings Piles," Radiation Data and Reports, No. 7, July 1974.

14. M.V.J. Culot, H.G. Olson, and K.J. Schiager, "Radon Progeny Control in Buildings," Colorado State University, Fort Collins, Colorado, May 1973.

15. J.C. Franklin, et.al., "Effects of Moisture on Radon Emanation," U.S. Bureau of Mines Technical Progress Report 1978.

16. R.C. Bates and J.E. Edwards, "Radon Emanation Relative to Changing Barometric Pressure and Physical Constraints," Second Conference on Uranium Mining Technology, Reno, Nevada, November 1978.

17. A.B. Tanner, "Radon Migration in the Ground--A Supplementary Review," The Natural Radiation Environment II, J.A.S. Adams and W.M. Lowder, Eds., The University of Chicago Press, 1975.

18. K.K. Nielson, B.J. Thamer, K.M. Putzig, "The Effects of Moisture on Radon Emanation and Diffusion," Bureau of Mines Report, FBDU-315-1, January 1980.

19. P.J. Macbeth, et al., "Laboratory Research on Tailings Stabilization Methods and Their Effectiveness in Radiation Containment," Department of Energy Report GJT-21, April 1978.

20. V.C. Rogers, et al., "Characterization of Uranium Tailings Cover Materials for Radon Flux Reduction," NUREG/CR-1081, March 1980.

21. M.H. Momeni, et al., "Radiological Impact of Uranium Tailings and Alternatives for Their Management," Proceedings of the Health Physics Society 12th Mid-Year Topical Symposium, "Low-Level Radioactive Waste Management," U.S. EPA 520/3-79-002, February 1979.

22. W.B. Silker and P.G. Heasler, "Diffusion and Exhalation of Radon from Uranium Tailings," Battelle Pacific Northwest Laboratory, NUREG/CR-1138, PNL-3207, October 1979.

23. R.W. Nelson, G.W. Gee, and C.A. Oster, "Radon Control by Multilayer Earth Barriers," Symposium of Uranium Mill Tailings Management, Ft. Collins, Colorado, November 1980.

24. E. Buckingham, "Contributions to Our Knowledge of the Aeration of Soils," U.S. Department of Agr. Bur. Soils Bulletin, No. 25, 1904.

25. K.K. Nielson, et al., "Laboratory Measurements of Radon Diffusion Through Multilayered Cover Systems for Uranium Tailings," (In Preparation).

26. B.J. Thamer, et al., "Radon Diffusion and Cover Material Effectiveness for Uranium Tailings Stabilization," Ford, Bacon and Davis Report, FBDU-258, May 1980.

27. V.C. Rogers, et al., "A New Laboratory Technique for Measuring Diffusion Coefficients of Mill Tailings Covers," Trans. Am. Nuc. Soc., 34, 132, 1980.

28. R. Bates, "Time Dependent Rn-222 Loss from Small Samples," Health Physics 38, 1980.

29. B.L. Cohen, "Laboratory Measurements of Diffusion Constants for Mill Tailings Covers and Its Application," Trans. Amer. Nuc. Soc. 33, p. 173, 1979.

30. Reference deleted - see footnote on page 6.

31. P.L. Koehmstedt, J.N. Hartley, and D.K. Davis, "Use of Asphalt Emulsion Sealants to Contain Radon and Radium in Uranium Tailings," Pacific Northwest Laboratory Report, BNWL-2190, 1977.

32. J.N. Hartley, et al., "Application of Asphalt Emulsion to Uranium Mill Tailings," Symposium of Uranium Mill Tailings Management, Ft. Collins, Colorado, November 1980.

33. J.C. Franklin, et al., "Barriers for Radon in Uranium Mines," U.S. Bureau of Mines Report, RI-8259, 1977.

34. J. Pohl-Ruling, F. Stienhauser, and E. Pohl, "Investigation on the Suitability of Various Materials as Rn-222 Diffusion Barriers," Health Physics 39, p. 299, 1980.

35. Y.C. Yuan and C.J. Roberts, "Numerical Investigation of Radon Transport Through a Porous Medium," Trans. of the American Nuc, Soc., 38, p. 108, 1981.

36. K.K. Nielson and V.C. Rogers, "Radon Flux Through Multi-Layered Covers Over Uranium Mill Tailings," Trans. Amer. Nuc. Soc., 34, p. 131, 1980.

37. V.C. Rogers, G.M. Sandquist, and K.K. Nielson, "Radon Attenuation Effectiveness and Cost Optimization for Uranium Mill Tailings and Composite Covers," U.S. DOE Report, UMTRA-DOE/ACO 165, July 1981.

38. K.K. Nielson, et al., "Effects of Moisture on Radon Emanation and Diffusion," Ford, Bacon and Davis Report, FBDU-315-2 Report, July 1981.

39. R.N. Yong and B.P. Warkentin, Introduction to Soil Behavior, Macmillan, New York, 1966.

40. V.C. Rogers, "Ambient Soil Moistures in the Uranium Milling Region of the West," RAE Quarterly Progress Report to B-PNWL, March 1981.

41. Environmental Assessment Related to the Operation of Hansen Uranium Mill Project, NUREG-0749, January 1981.

APPENDIX A

INPUT DATA FORMAT FOR RAECO PROGRAM

All input data is free format. The following input is needed for program operation.

Card Set Number	Card Description
1	Site Designation Card - One card with up to 80 characters which designates the tailings cover system and run identification.
2	Boundary Conditions and Cost Control Parameters - One card containing six parameter values, each separated by commas in the following order: (1) N, Number of distinct Tailings cover layers: positive integer, presently limited to 99. (2) F01, Entrance radon flux to layer 1, pCi/m^{2}sec. (3) CN1, Surface radon concentration at top of system, pCi/l. (4) ICOST, Integer Cost Flag, ICOST = 0 if no cost or optimization is to be performed, 1 otherwise. (5) CRITJ, Surface Flux Constraint for optimization, pCi/m^{2}sec. CRITJ = 0 for no constraint. (6) ACC, Surface Flux Convergence Criterion, fraction.
3, 1-N	Individual Cover Layer Data Cards - One card for each tailings or cover layer. Each card is composed of four parameters: (1) DX, The layer thickness in cm.

Card Set Number	Card Description
	(2) D, Layer effective radon diffusion coefficient, cm^2/sec. (3) p, Layer porosity. (4) Q, Layer radon source term in pCi/cm^{3}sec.
4	Cost Control Alternative Flags and Tailings Area - One card composed of five numerical data fields each separated by commas in the following order: (1) ICF, Cost Alternative Flag, integer where ICF = 0 for cover costs only and 1 for total remedial action costs. (2) IOPT, Alternative Type Flag, integer, where IOPT = 0 for alternative in which tailings are not moved and 1 for moving alternative. (3) TAREA, Total area of tailings pile (acres). (4) DAREA, Total area of new tailings pile (acres) if IOPT = 1. (5) ITRAN, Cover Haul Cost Flag, integer, ITRAN = 0 if cover haul costs not specified separately and 1 if they are.
5	Tailings Cover Unit Costs - This card contains C131 or C521 unit costs for each cover layer each separated by a comma ($/yd3). (See Section 1.3 or 5.2 in Appendix B.) The layer costs appear on the card in order of ascending layer number.
6	Tailings Cover Spreading Unit Costs - This card contains unit costs for each cover layer, each separated by a comma ($/yd^3), in ascending order (see Section 1.3 or 5.2 in Appendix B).
6_a (OPTIONAL)	Cover Material Haul Unit Costs - This card is only needed if ITRAN = 1. It contains Section 4.3 (Appendix B) unit costs for each cover layer ($/ton).
6_b (OPTIONAL)	Cover Material Densities - This card is only needed if ITRAN = 1. It contains RHO, cover densities (gm/cm^3) to convert cover haul unit costs from tons to yd^3.
7	Cover Support Costs - This card gives site support costs in dollars. The format of this card depends upon the value of IOPT (moving or nonmoving alternative). If IOPT = 0, the parameters are: (1) Site Preparation (Section 1.1, Appendix B).

Card Set Number	Card Description
	(2) Tailings Pile Preparation. (3) Site Leveling and Grading. (4) Millsite Cleanup. (5) Reclamation and Sprinkling ($/acre). (6) Fencing. (7) Support Services. (8) Miscellaneous Expenses. If IOPT = 1, the card contains the following cost parameters that pertain to the disposal site: (1) Disposal Site Preparation and Fencing Costs. (2) Clearing and Excavation. (3) Tailings Placement Costs. (4) Reclamation and Sprinkling Unit Costs ($/acre). (5) Support Services. (6) Miscellaneous Expenses.
8	Other Remedial Alternative Costs and Factors - This card is needed only if ICF = 1. It contains six cost entries in dollars. (1) Offsite Remedial Action Costs (Section 2, Appendix B). (2) Windblown Tailings Area Remedial Action (Section 3, Appendix B) Costs. (3) Transportation Capital Costs (Section 4, Appendix B). (4) Transportation Haul Costs. (5) Engineering, Design and Construction Management Percentage Fee. (6) Contingency Percentage.

Card Set Number	Card Description
9	Optimization Constraint Card - The following five parameters are input in free format. (1) Thickness Constraint Flag, Integer Format = 0 for no thickness constraints = 1 for minimum specified thickness, D2 above = 2 for minimum specified cover = 12 for both thickness constraints (2) Minimum Thickness above Optimized Layer in cm. (3) Minimum Cover Thickness in cm. (4) First Layer in Optimization, Integer. (5) Second Layer in Optimization, Integer.

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**            R    A    E    C    O                 **
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**                  LEVEL 1.0                       **
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******* CODED DECEMBER 1980 BY V. C. ROGERS AND G.M. SANDQUIST
******* FOR ROGERS AND ASSOCIATES ENGINEERING CORPORATION
*******  P.O. BOX  330, SALT LAKE CITY, UTAH   84110.
      DIMENSION ALP(99),X(99),AIP1MI(99),R(99),A(99),B(99),G(99),BU(99)
     $,AS(99),BS(99),Q(99),D(99),P(99),T(99),W(99),RR(99),DDX(99),
     $RF(99),RC(99),EF(99),DX(99),BC(99),AA(99),RHO(99),
     $C131(99),C522(99),C521(99),RAT(99),C13(99),C52(99),C132(99),C43(99
     $),H(20)
C     *****READ INPUT DATA FOR RADON DIFFUSION CALCULATION
      CHARACTER*8 OPTDT(2)
      CHARACTER*2 STR1,STR2,STR3.STR4,STR5,STR6
  666 READ(5,882,END=555)(H(I),I=1,20)
  882 FORMAT(20A4)
C     ***** READ RADON DIFFUSION DATA
      READ(5,1)N,F01,CN1,ICOST,CRITJ1,ACC
      READ(5,1)(DX(I),D(I),P(I),Q(I),I=1,N)
    1 FORMAT()
      F0=F01/10000.
      CN=CN1/1000.
      CRITJ=CRITJ1/10000.
      WRITE(6,2222)(H(I),I=1,20)
      CALL ADATE(OPTDT(1),OPTDT(2))
      STR1=SUBSTR(OPTDT(1),1,2)
      STR2=SUBSTR(OPTDT(1),3,2)
      STR3=SUBSTR(OPTDT(1),5,2)
      STR4=SUBSTR(OPTDT(2),1,2)
```

```
      STR5=SUBSTR(OPTDT(2),3,2)
      STR6=SUBSTR(OPTDT(2),5,2)
      WRITE(6,781)STR1,STR2,STR3,STR4,STR5,STR6
  781 FORMAT(//,13X,'DATE DF RUN',2X,A2,'/',A2,'/',A2,10X,
     $'TIME',2X,A2,':',A2,':',A2,///)
 2222 FORMAT(1H1,'*****     ',20A4,'     *****')
      WRITE(6,888)N,F01,CN1,ICOST,CRITJ1,ACC
  888 FORMAT(///,'  **********  I N P U T   P A R A M E T E R S
     $**********',//,' NUMBER OF LAYERS =',I2,
     $/,' INITIAL RADON FLUX =',1PE10.3,' PCI/SQM*SEC',/,
     $' SURFACE RADON CONCENTRATION =',1PE10.3,' PCI/LITER',/,
     $' COST FLAG =',I2
     $,/,' FLUX CRITERIA FOR OPTIMIZATION =',1PE10.3,' PCI/SQM*SEC',/,
     $' ACC =',1PE10.3)
      WRITE(6,887)(I,DX(I),D(I),P(I),Q(I),I=1,N)
      WRITE(6,886)
  866 FORMAT(////,' *****  R E S U L T S   O F   R A D O N  D I F F U
     $S I O N   C A L C U L A T I O N *****',///)
  887 FORMAT(' LAYER',7X,'THICKNESS',8X,'DIFF COEFF',8X,
     $'POROSITY',9X,'SOURCE',/,16X,'(CM)',10X,
     $'(SQCM/SEC)',22X,'(PCI/CC*SEC)',/,(2X,I2,2X,4(5X,E12.4)))
      NM1 = N - 1
      NM2 = N - 2
      XL=2.0979E-6
      JTST=0
      DDX(1) = DX(1)
      ALP(1) = SQRT(XL*P(1)/D(1))
      T9T = ALP(1)*DX(1)
      IF(T9T.GT.3.)DX(1) = 3./ALP(1)
   99 CONTINUE
      DO 58, I=2,N
   58 DDX(I) = DX(I)
       SUM = 0.
       DO 74 I=1,N
       SUM = SUM + DX(I)
   74  X(I) = SUM
C     ***** CALCULATE PARAMETERS FOR MATRIX
      DO 10 I=1,NM1
      ALP(I)=SQRT(XL*P(I)/D(I))
      RDUM=SQRT(P(I+1)*D(I+1)/(P(I)*D(I)))
      R(I)=-.5*(1.-RDUM)
      RR(I)=-.5*(1.+RDUM)
      QP=(Q(I+1)/P(I+1)-Q(I)/P(I))/XL
      T(I)=QP*EXP(-ALP(I)*X(I))
      U(I)=QP*.5*EXP(ALP(I)*X(I))
   10 AIP1MI(I)=SQRT(XL)*(SQRT(P(I+1)/D(I+1))-SQRT(P(I)/D(I)))
      ALP(N)=SQRT(XL*P(N)/D(N))
C     ***** SPECIFY MATRIX ELEMENTS AND SOLVE
      DO 20 I=1,NM1
      J=5*I-4
      K=2*I-1
```

```
      A(J)=EXP(-2.*ALP(I)*X(I))
      A(J+1)=-EXP(AIP1MI(I)*X(I))
      A(J+2)=-EXP(-(ALP(I+1)+ALP(I))*X(I))
      A(J+3)=R(I)*EXP((ALP(I+1)+ALP(I))*X(I))
      A(J+4)=RR(I)*EXP(-AIP1MI(I)*X(I))
      B(K)=T(I)
   20 B(K+1)=U(I)
      N5M4=5*N-4
      A(N5M4)=EXP(-2.*ALP(N)*X(N))
      N2M1=2*N-1
      B(N2M1)=(CN-Q(N)/(P(N)*XL))*EXP(-ALP(N)*X(N))
      G(1)=A(1)+1
      G(2)=A(2)/G(1)
      G(3)=A(3)/G(1)
      BU(1)=(B(1)+F0/(D(1)*ALP(1)))/G(1)
      DO 30 I=1,NM2
      J=5*I-1
      K=2*I
      G(J)=A(J)-G(J-2)
      G(J+1)=(A(J+1)-G(J-1))/G(J)
      BU(K)=(B(K)-BU(K-1))/G(J)
      G(J+2)=A(J+2)-G(J+1)
      G(J+3)=A(J+3)/G(J+2)
      G(J+4)=A(J+4)/G(J+2)
   30 BU(K+1)=(B(K+1)-BU(K))/G(J+2)
      N5M6=5*N-6
      G(N5M6)=A(N5M6)-G(N5M6-2)
      G(N5M6+1)=(A(N5M6+1)-G(N5M6-1))/G(N5M6)
      N2M2=2*N-2
      BU(N2M2)=(B(N2M2)-BU(N2M2-1))/G(N5M6)
      G(N5M6+2)=A(N5M6+2)-G(N5M6+1)
      BS(N)=(B(N2M1)-BU(N2M1-1))/G(N5M6+2)
      AS(N)=BU(N2M1-1)-G(N5M6+1)*BS(N)
      DO 40 I=1,NM2
      J=5*(N-I)-3
      K=2*(N-I)-1
      L=N-I
      BS(L)=BU(K)-G(J)*AS(L+1)-G(J+1)*BS(L+1)
   40 AS(L)=BU(K-1)-G(J-2)*BS(L)
      BS(1)=BU(1)-G(2)*AS(2)-G(3)*BS(2)
      AS(1)=BS(1) - F0/(ALP(1)*D(1))
C     ***** MATRIX SOLUTION COMPLETE
      DO 147 I=1,N
      ALPI=ALP(I)*X(I)
      ASI=AS(I)*EXP(ALPI)
      BSI=BS(I)*EXP(-ALPI)
      RC(I)=ASI+BSI+Q(I)/(P(I)*XL)
  147 RF(I)=-D(I)*ALP(I)*(ASI-BSI)
      RC(N)=CN
      IF(ICOST.EQ.0) GO TO 45
      FOP=F0
```

```
      IF(FO.LT.1)FOP=1.
      AA(1)=(ALOG(FOP)-ALOG(RF(1)))/DX(1)
      DO 160 I=1,NM1
      IF(RF(I).GT.0.0.OR.RF(I+1).GT.0.)GO TO 161
      IF(JTST.EQ.0)AA(I+1)=ALP(I+1)
      GO TO 160
  161 AA(I+1)=(ALOG(RF(I))-ALOG(RF(I+1)))/DX(I+1)
  160 CONTINUE
C     ***** BEGIN COST OPTIMIZATION
      IF(JTST.EQ.0)GO TO 44
      IF(CRITJ.GT.99.) GO TO 45
      IF(CRITJ.LE.0.) GOTO 45
      T7 = (RF(N)-CRITJ)/CRITJ
      ABT7 = ABS(T7)
      IF(ABT7.LE.ACC) GO TO 45
      IF(JTST.EQ.1.AND.T7.GT.0.)NTST = NO2
      IF(JTST.EQ.1.AND.T7.GT.0.)IIJ = NO3
      IF(JTST.EQ.1.AND.T7.LT.0.)NTST = NO3
      IF(JTST.EQ.1.AND.T7.LT.0.)IIJ = NO2
      IF(JTST.EQ.2.AND.T7.GT.0.)NTST = NO3
      IF(JTST.EQ.2.AND.T7.GT.0.)IIJ = NO2
      IF(JTST.EQ.2.AND.T7.LT.0.)NTST = NO2
      IF(JTST.EQ.2.AND.T7.LT.0.)IIJ = NO3
      IF(ITHK.EQ.0.AND.T7.LT.0.)NTST=IIJ
      DX(NTST) = DX(NTST)*(1.+T7)
      IF(ITHK.EQ.0)GO TO 99
      T2T = 0.
      IF(NO4.GT.N) GOTO 55
      DO 46, IJ = NO4,N
   46 T2T = T2T+DX(IJ)
   55 IF(NO1.LT.2) GOTO 47
      DO 56, IJ = 2,NO1
   56 T2T = T2T+DX(IJ)
   47 CONTINUE
      T23=DX(NTST)
      T2T=T2T+DX(NTST)
      IF(NMIN.EQ.NTST)T2T=T2T+DX(IIJ)-DX(NTST)
      DX(NMIN)=X(N)-X(1)-T2T
      IF(DX(NTST).NE.T23)CRITJ=-1.
      GO TO 99
   43 CONTINUE
   44 CONTINUE
C     COST INFORMATION INPUT
C     ICF = FLAG FOR TOTAL REMEDIAL ACTION COSTS
C     ITRAN = 0 COVER HAUL COSTS INCLUDED IN COVER COSTS
C     ICF = 0 FOR COVER COSTS ONLY, 1 FOR TOTAL COSTS
C     IOPT = 1 FOR MOVING OPTION
C     ITRAN = 1 COVER HAUL COSTS GIVEN SEPARATELY
C     IOPT = 0 FOR NON-MOVING OPTION
C     (RHO(I) IS DENSITY OF ITH LAYER G/CM3)
C     0.841 CONVERTS TO TON/YD3
```

```
      READ(5,1)ICF,IOPT,TAREA,DAREA,ITRAN
      T1 = 52.858*TAREA
      IF(IOPT.EQ.1) GO TO 51
C     ***** READ LAYER COST DATA
      READ(5,1)(C131(I),I=2,N)
99999 READ(5,1)(C132(I),I=2,N)
      IF(ITRAN.EQ.1)READ(5,1)(C43(I),I=2,N)
      IF(ITRAN.EQ.1)READ(5,1)(RHO(I),I=2,N)
      DO 3, I=2,N
      BC(I) = T1*(C131(I)+C132(I))
      IF(ITRAN.EQ.1)BC(I) = BC(I)+T1*C43(I)*RHO(I)*0.841
    3 CONTINUE
      READ(5,1)C11,C121,C122,C123,C133,C134,C14,C15
      BC(1) = C11+C122+TAREA*C133+C134+C14+C15
      C5 = 0
      GO TO 4
   51 READ(5,1)(C521(I),I=2,N)
      READ(5,1)(C522(I),I=2,N)
      IF(ITRAN.EQ.1.)READ(5,1)(C43(I),I=2,N)
      IF(ITRAN.EQ.1)READ(5,1)(RHO(I),I=2,N)
      T1=52.858*DAREA
      DO 5, I=2,N
      BC(I) = T1*(C521(I)+C522(I))
      IF(ITRAN.EQ.1)BC(I) = BC(I)+T1*C43(I)*.841*RHO(I)
    5 CONTINUE
      READ(5,1)C51,C520,C52A,C523,C53,C54,C1
      BC(1) = C51+DAREA*C523+C53+C54
    4 CONTINUE
      IF(ICF.EQ.1)READ(5,1)C2,C3,C41,C42,EDF,CONTF
C     COST OPTIMIZATION
C     READ IN THICKNESS RESTRICTIONS
C     ITHK = FLAG FOR THICKNESS RESTRICTIONS
C     ITHK = 0 - NO RESTRICTIONS
C     ITHK = 1 - COVER ABOVE NO2 GT D2
C     ITHK = 2 - TOTAL COVER THICKNESS GT D3
C     ITHK = 12 - BOTH RESTRICTIONS APPLY
C     NO2 = LAYER NO. OF 1ST OPTIMIZATION
C     NO3 = LAYER NO. OF 2ND OPTIMIZATION
C     CRITJ = FLUX CRITERIA
      READ(5,1)ITHK,D2,D3,NO2,NO3
      NO1 =NO2-1
      NO4 = NO3+1
      DO 6, I=NO2,N
    6 RAT(I) = BC(I)/AA(I)
      JTST = 1
      IF(RAT(NO3).LE.RAT(NO2)) JTST = 2
      IF(ITHK.GE.1) GOTO 8
      DO 9, II = NO2,N
    9 DX(II) = 0.01
      NOP = NO2
      IF(JTST.EQ.2)NOP = NO3
```

```
      DX(NOP) = ALOG(RF(NO1)/RF(N))/AA(NOP)
      GO TO 99
    8 IF(ITHK.EQ.2) GOTO 15
      NOP = NO2
      IF(JTST.EQ.2)NOP = NO3
      NOP1 = NOP+1
      T5T=BC(NOP1)
      T4T=0.
       DO 57 IJ=NOP1,N
      T4T=T4T+DX(IJ)
      T5T=AMIN1(T5T,BC(IJ))
   57 IF(T5T.EQ.BC(IJ))NMIN=IJ
      IF(T4T.LT.D2)DX(NMIN)=DX(NMIN)+D2-T4T
      IF(ITHK.EQ.1) GO TO 99
   15 CONTINUE
      T1 = DX(2)
      DO 12, LI=3,N
   12 T1 = T1+DX(LI)
      IF(T1.GE. D3) GO TO 99
      T2 = BC(2)
      NMIN = 2
      DO 14, MI=3,N
      T2 = AMIN1(T2,BC(MI))
   14 IF(T2.EQ.BC(MI)) NMIN = MI
      DX(NMIN) = D3-T1+DX(NMIN)
      GO TO 99
C     TOTAL COST SUMMARY
   45 CONTINUE
C     ***** OUTPUT COST OPTIMIZATION RESULTS
      WRITE(6,881)
  881 FORMAT(6X,' LAYER',3X,'THICKNESS',7X,'EXIT FLUX',10X,
     $'EXIT CONC.',8X,'EFF',/,18X,'(CM)',6X,'(PCI/SQM*SEC)'
     $,10X,'(PCI/L)',/)
      DO 884 I=1,N
      RXYZ=RF(I)*10000.
      CXYZ=RC(I)*1000.
  884 WRITE(6,883)I,DDX(I),RXYZ,CXYZ,AA(I)
  883 FORMAT(8X,I2,5X,F6.0,2X,2(5X,E12.4),4X,E12.4)
      TOTDDX=0.
      IF(ICOST.EQ.0) GO TO 666
      DO 797 JJK=2,N
  797 TOTDDX=DDX(JJK)+TOTDDX
      WRITE(6,880)
  880 FORMAT(/////,21X,' *****  C O S T   R E S U L T S  *****',///,
     $20X,'LAYER NO.',6X,'THICKNESS',8X,'COST',/,38X,'(CM)',
     $11X,'($)',/,20X,'========================================',
     $//)
  798 FORMAT(23X,I2,10X,F6.0,8X,1PE10.3,/)
      IF(IOPT.EQ.1) GO TO 52
      T3 = 0.
      DO 21, III=2,N
```

```
      C13(III) = DX(III)*BC(III)
   21 T3 = T3+C13(III)
      C1 = T3+BC(1)
  799 FORMAT(/,20X,'========================================',//,
     $20X,'TOTAL',10X,F8.2,6X,1PE10.3,//,20X,'SUPPORT COSTS',16X,
     $1PE10.3,//,20X,'========================================',/,
     $20X,'TOTAL COVER COSTS',12X,1PE10.3,/,20X,
     $'========================================')
      DO 777 I=2,N
  777 WRITE(6,798)I,DDX(I),C13(I)
      WRITE(6,799)TOTDDX,T3,BC(1),C1
   33 FORMAT(10X,'TOTAL ',E10.3,///,10X,'SUPPORT COSTS ($) ',E10.3,///
     1,10X,'TOTAL COVER COSTS ($) ',E10.3,//)
      GO TO 25
   52 T4 = 0
      DO 24, KI=2,N
      C52(KI) = DX(KI)*BC(KI)
   24 T4 = T4+C52(KI)
      C5 = T4+BC(1)
      DO 763 I=2,N
  763 WRITE(6,798)I,DDX(I),C52(I)
      WRITE(6,799)TOTDDX,T4,BC(1),C5
   25 IF(ICF.EQ.0) GO TO 999
      C6 = C1+C2+C3+C41+C42+C5+C520+C52A
      C7 = EDF*(C6-C42)/100.
      C8 = C6+C7
      C9 = CONTF*C8/100.
      CTOT = C8+C9
      IEDF=EDF
      ICONTF=CONTF
      C5C520=C5+C520+C52A
      WRITE(6,796)C1,C2,C3,C41,C42,C5C520,C6,IEDF,C7,C8,ICONTF,
     $C9,CTOT
  796 FORMAT(//////,22X,'SUMMARY OF REMEDIAL ACTION COSTS ($)',/,22X,
     $'====================================',///,16X,
     $'TAILINGS SITE COSTS',20X,1PE10.3,//,16X,'REMOTE OFF-SITE',
     $24X,1PE10.3,//,16X,'WINDBLOWN AREA',25X,1PE10.3,//,16X,
     $'TRANSPORTATION',/,21X,'A.  CAPITAL COSTS',17X,1PE10.3,/,
     $21X,'B.  HAUL COSTS',20X,1PE10.3,//,16X,'DISPOSAL SITE',26X,
     $1PE10.3,//,16X,'TOTAL CLEANUP',26X,1PE10.3,//,16X,
     $'ENG. DESIGN, CONST. MGMNT AT ',I2,'%',7X,1PE10.3,/,
     $16X,'==================================================',//,16X,
     $'TOTAL',34X,1PE10.3,//,16X,'CONTINGENCY AT ',I2,'%',
     $21X,1PE10.3.///,16X,
     $'==================================================',/,16X,
     $'GRAND TOTAL',28X,1PE10.3,/,16X,
     $'==================================================',////)
  999 GO TO 666
  555 STOP
      END
```

APPENDIX B

TABLES OF REQUIRED DEPTHS FOR RADON ATTENUATION

TABLES OF REQUIRED DEPTHS FOR RADON ATTENUATION (METERS)

ORE GRADE IS .05

TABLE B. 1

COVER MOISTURE (%)/DIFFUSION COEFFICIENT (CM**2 PER SEC)

TAILINGS MOISTURE (%)	DIFFUSION COEFFICIENT (CM**2/SEC)	(%)	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
		D/P	.0287	.0221	.0171	.0131	.0101	.0078	.0060	.0046	.0036	.0027	.0021
3.0	.0484		4.9	4.3	3.7	3.2	2.7	2.3	2.0	1.7	1.4	1.2	1.0
5.0	.0287		4.8	4.1	3.6	3.1	2.6	2.3	1.9	1.7	1.4	1.2	1.0
6.0	.0221		4.7	4.1	3.5	3.0	2.6	2.2	1.9	1.6	1.4	1.2	1.0
7.0	.0171		4.6	4.0	3.5	3.0	2.6	2.2	1.9	1.6	1.4	1.2	1.0
8.0	.0131		4.5	3.9	3.4	2.9	2.5	2.2	1.9	1.6	1.4	1.2	1.0
9.0	.0101		4.4	3.8	3.3	2.9	2.5	2.1	1.8	1.6	1.4	1.2	1.0
10.0	.0078		4.3	3.8	3.3	2.8	2.4	2.1	1.8	1.6	1.3	1.1	1.0
11.0	.0060		4.2	3.7	3.2	2.8	2.4	2.1	1.8	1.5	1.3	1.1	1.0
12.0	.0046		4.1	3.6	3.1	2.7	2.3	2.0	1.7	1.5	1.3	1.1	.9
13.0	.0036		4.0	3.5	3.0	2.6	2.3	2.0	1.7	1.5	1.3	1.1	.9
14.0	.0027		3.9	3.4	2.9	2.6	2.2	1.9	1.7	1.4	1.2	1.1	.9
15.0	.0021		3.8	3.3	2.9	2.5	2.2	1.9	1.6	1.4	1.2	1.0	.9

ORE GRADE IS .06

TABLE B. 2

COVER MOISTURE (%)/DIFFUSION COEFFICIENT (CM**2 PER SEC)

TAILINGS MOISTURE (%)	DIFFUSION COEFFICIENT (CM**2/SEC)	(%)	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
		D/P	.0287	.0221	.0171	.0131	.0101	.0078	.0060	.0046	.0036	.0027	.0021
3.0	.0484		5.2	4.4	3.8	3.3	2.8	2.4	2.1	1.8	1.5	1.3	1.1
5.0	.0287		5.0	4.3	3.7	3.2	2.8	2.4	2.0	1.8	1.5	1.3	1.1
6.0	.0221		4.9	4.3	3.7	3.2	2.7	2.4	2.0	1.7	1.5	1.3	1.1
7.0	.0171		4.8	4.2	3.6	3.1	2.7	2.3	2.0	1.7	1.5	1.3	1.1
8.0	.0131		4.8	4.1	3.6	3.1	2.7	2.3	2.0	1.7	1.4	1.2	1.1
9.0	.0101		4.7	4.0	3.5	3.0	2.6	2.3	1.9	1.7	1.4	1.2	1.0
10.0	.0078		4.6	4.0	3.4	3.0	2.6	2.2	1.9	1.6	1.4	1.2	1.0
11.0	.0060		4.5	3.9	3.4	2.9	2.5	2.2	1.9	1.6	1.4	1.2	1.0
12.0	.0046		4.3	3.8	3.3	2.8	2.5	2.1	1.8	1.6	1.4	1.2	1.0
13.0	.0036		4.2	3.7	3.2	2.8	2.4	2.1	1.8	1.5	1.3	1.1	1.0
14.0	.0027		4.1	3.6	3.1	2.7	2.3	2.0	1.8	1.5	1.3	1.1	1.0
15.0	.0021		4.0	3.5	3.0	2.6	2.3	2.0	1.7	1.5	1.3	1.1	.9

TABLES OF REQUIRED DEPTHS FOR RADON ATTENUATION (METERS)

ORE GRADE IS .08

TABLE B. 3

COVER MOISTURE (%)/DIFFUSION COEFFICIENT (CM**2 PER SEC)

TAILINGS MOISTURE (%)	DIFFUSION COEFFICIENT (CM**2/SEC)	(%)	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
		D/P	.0287	.0221	.0171	.0131	.0101	.0078	.0060	.0046	.0036	.0027	.0021
3.0	.0484		5.5	4.7	4.1	3.5	3.0	2.6	2.2	1.9	1.6	1.4	1.2
5.0	.0287		5.4	4.6	4.0	3.5	3.0	2.6	2.2	1.9	1.6	1.4	1.2
6.0	.0221		5.3	4.6	3.9	3.4	2.9	2.5	2.2	1.9	1.6	1.4	1.2
7.0	.0171		5.2	4.5	3.9	3.4	2.9	2.5	2.2	1.8	1.6	1.4	1.2
8.0	.0131		5.1	4.4	3.8	3.3	2.9	2.5	2.1	1.8	1.6	1.3	1.2
9.0	.0101		5.0	4.3	3.8	3.3	2.8	2.4	2.1	1.8	1.5	1.3	1.1
10.0	.0078		4.9	4.3	3.7	3.2	2.8	2.4	2.1	1.8	1.5	1.3	1.1
11.0	.0060		4.8	4.2	3.6	3.1	2.7	2.3	2.0	1.7	1.5	1.3	1.1
12.0	.0046		4.7	4.1	3.5	3.1	2.7	2.3	2.0	1.7	1.5	1.3	1.1
13.0	.0036		4.6	4.0	3.5	3.0	2.6	2.3	2.0	1.7	1.5	1.3	1.1
14.0	.0027		4.5	3.9	3.4	2.9	2.5	2.2	1.9	1.7	1.4	1.2	1.1
15.0	.0021		4.3	3.8	3.3	2.9	2.5	2.2	1.9	1.6	1.4	1.2	1.0

ORE GRADE IS .10

TABLE B. 4

COVER MOISTURE (%)/DIFFUSION COEFFICIENT (CM**2 PER SEC)

TAILINGS MOISTURE (%)	DIFFUSION COEFFICIENT (CM**2/SEC)	(%)	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
		D/P	.0287	.0221	.0171	.0131	.0101	.0078	.0060	.0046	.0036	.0027	.0021
3.0	.0484		5.8	5.0	4.3	3.7	3.2	2.7	2.4	2.0	1.7	1.5	1.3
5.0	.0287		5.6	4.9	4.2	3.6	3.1	2.7	2.3	2.0	1.7	1.5	1.3
6.0	.0221		5.5	4.8	4.2	3.6	3.1	2.7	2.3	2.0	1.7	1.5	1.2
7.0	.0171		5.5	4.7	4.1	3.5	3.1	2.6	2.3	2.0	1.7	1.4	1.2
8.0	.0131		5.4	4.7	4.0	3.5	3.0	2.6	2.2	1.9	1.7	1.4	1.2
9.0	.0101		5.3	4.6	4.0	3.4	3.0	2.6	2.2	1.9	1.6	1.4	1.2
10.0	.0078		5.2	4.5	3.9	3.4	2.9	2.5	2.2	1.9	1.6	1.4	1.2
11.0	.0060		5.1	4.4	3.8	3.3	2.9	2.5	2.2	1.9	1.6	1.4	1.2
12.0	.0046		5.0	4.3	3.7	3.3	2.8	2.4	2.1	1.8	1.6	1.4	1.2
13.0	.0036		4.8	4.2	3.7	3.2	2.8	2.4	2.1	1.8	1.5	1.3	1.1
14.0	.0027		4.7	4.1	3.6	3.1	2.7	2.3	2.0	1.8	1.5	1.3	1.1
15.0	.0021		4.6	4.0	3.5	3.0	2.6	2.3	2.0	1.7	1.5	1.3	1.1

TABLES OF REQUIRED DEPTHS FOR RADON ATTENUATION (METERS)

ORE GRADE IS .12

TABLE B. 5

COVER MOISTURE (%)/DIFFUSION COEFFICIENT (CM**2 PER SEC)

TAILINGS MOISTURE (%)	DIFFUSION COEFFICIENT (CM**2/SEC) / (%)	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
	D/P	.0287	.0221	.0171	.0131	.0101	.0078	.0060	.0046	.0036	.0027	.0021
3.0	.0484	6.0	5.2	4.5	3.9	3.3	2.9	2.5	2.1	1.8	1.6	1.3
5.0	.0287	5.8	5.1	4.4	3.8	3.3	2.8	2.4	2.1	1.8	1.5	1.3
6.0	.0221	5.8	5.0	4.3	3.7	3.2	2.8	2.4	2.1	1.8	1.5	1.3
7.0	.0171	5.7	4.9	4.3	3.7	3.2	2.8	2.4	2.0	1.8	1.5	1.3
8.0	.0131	5.6	4.8	4.2	3.6	3.1	2.7	2.3	2.0	1.7	1.5	1.3
9.0	.0101	5.5	4.8	4.1	3.6	3.1	2.7	2.3	2.0	1.7	1.5	1.3
10.0	.0078	5.4	4.7	4.1	3.5	3.1	2.6	2.3	2.0	1.7	1.5	1.3
11.0	.0060	5.3	4.6	4.0	3.5	3.0	2.6	2.2	1.9	1.7	1.4	1.2
12.0	.0046	5.2	4.5	3.9	3.4	3.0	2.6	2.2	1.9	1.7	1.4	1.2
13.0	.0036	5.1	4.4	3.8	3.3	2.9	2.5	2.2	1.9	1.6	1.4	1.2
14.0	.0027	4.9	4.3	3.8	3.3	2.8	2.5	2.1	1.8	1.6	1.4	1.2
15.0	.0021	4.8	4.2	3.7	3.2	2.8	2.4	2.1	1.8	1.6	1.4	1.2

ORE GRADE IS .14

TABLE B. 6

COVER MOISTURE (%)/DIFFUSION COEFFICIENT (CM**2 PER SEC)

TAILINGS MOISTURE (%)	DIFFUSION COEFFICIENT (CM**2/SEC) / (%)	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
	D/P	.0287	.0221	.0171	.0131	.0101	.0078	.0060	.0046	.0036	.0027	.0021
3.0	.0484	6.2	5.3	4.6	4.0	3.4	3.0	2.5	2.2	1.9	1.6	1.4
5.0	.0287	6.0	5.2	4.5	3.9	3.4	2.9	2.5	2.2	1.9	1.6	1.4
6.0	.0221	5.9	5.1	4.5	3.9	3.3	2.9	2.5	2.1	1.8	1.6	1.4
7.0	.0171	5.9	5.1	4.4	3.8	3.3	2.8	2.5	2.1	1.8	1.6	1.3
8.0	.0131	5.8	5.0	4.3	3.8	3.3	2.8	2.4	2.1	1.8	1.6	1.3
9.0	.0101	5.7	4.9	4.3	3.7	3.2	2.8	2.4	2.1	1.8	1.5	1.3
10.0	.0078	5.6	4.8	4.2	3.6	3.2	2.7	2.4	2.0	1.8	1.5	1.3
11.0	.0060	5.5	4.8	4.1	3.6	3.1	2.7	2.3	2.0	1.7	1.5	1.3
12.0	.0046	5.4	4.7	4.1	3.5	3.1	2.7	2.3	2.0	1.7	1.5	1.3
13.0	.0036	5.2	4.6	4.0	3.5	3.0	2.6	2.3	2.0	1.7	1.5	1.3
14.0	.0027	5.1	4.5	3.9	3.4	2.9	2.6	2.2	1.9	1.7	1.4	1.2
15.0	.0021	5.0	4.4	3.8	3.3	2.9	2.5	2.2	1.9	1.6	1.4	1.2

TABLES OF REQUIRED DEPTHS FOR RADON ATTENUATION (METERS)

ORE GRADE IS .16

TABLE B. 7

COVER MOISTURE (%)/DIFFUSION COEFFICIENT (CM**2 PER SEC)

TAILINGS MOISTURE (%)	DIFFUSION COEFFICIENT (CM**2/SEC)	(%) D/P	5.0 .0287	6.0 .0221	7.0 .0171	8.0 .0131	9.0 .0101	10.0 .0078	11.0 .0060	12.0 .0046	13.0 .0036	14.0 .0027	15.0 .0021
3.0	.0484		6.3	5.5	4.7	4.1	3.5	3.0	2.6	2.3	1.9	1.7	1.4
5.0	.0287		6.2	5.4	4.6	4.0	3.5	3.0	2.6	2.2	1.9	1.6	1.4
6.0	.0221		6.1	5.3	4.6	4.0	3.4	3.0	2.6	2.2	1.9	1.6	1.4
7.0	.0171		6.0	5.2	4.5	3.9	3.4	2.9	2.5	2.2	1.9	1.6	1.4
8.0	.0131		5.9	5.1	4.5	3.9	3.3	2.9	2.5	2.2	1.9	1.6	1.4
9.0	.0101		5.8	5.1	4.4	3.8	3.3	2.9	2.5	2.1	1.8	1.6	1.4
10.0	.0078		5.7	5.0	4.3	3.8	3.3	2.8	2.4	2.1	1.8	1.6	1.4
11.0	.0060		5.6	4.9	4.3	3.7	3.2	2.8	2.4	2.1	1.8	1.6	1.3
12.0	.0046		5.5	4.8	4.2	3.6	3.2	2.7	2.4	2.1	1.8	1.5	1.3
13.0	.0036		5.4	4.7	4.1	3.6	3.1	2.7	2.3	2.0	1.7	1.5	1.3
14.0	.0027		5.3	4.6	4.0	3.5	3.0	2.6	2.3	2.0	1.7	1.5	1.3
15.0	.0021		5.2	4.5	3.9	3.4	3.0	2.6	2.2	1.9	1.7	1.5	1.3

ORE GRADE IS .18

TABLE B. 8

COVER MOISTURE (%)/DIFFUSION COEFFICIENT (CM**2 PER SEC)

TAILINGS MOISTURE (%)	DIFFUSION COEFFICIENT (CM**2/SEC)	(%) D/P	5.0 .0287	6.0 .0221	7.0 .0171	8.0 .0131	9.0 .0101	10.0 .0078	11.0 .0060	12.0 .0046	13.0 .0036	14.0 .0027	15.0 .0021
3.0	.0484		6.5	5.6	4.8	4.2	3.6	3.1	2.7	2.3	2.0	1.7	1.5
5.0	.0287		6.3	5.5	4.7	4.1	3.5	3.1	2.6	2.3	2.0	1.7	1.4
6.0	.0221		6.2	5.4	4.7	4.1	3.5	3.0	2.6	2.3	1.9	1.7	1.4
7.0	.0171		6.2	5.3	4.6	4.0	3.5	3.0	2.6	2.2	1.9	1.7	1.4
8.0	.0131		6.1	5.3	4.6	4.0	3.4	3.0	2.6	2.2	1.9	1.6	1.4
9.0	.0101		6.0	5.2	4.5	3.9	3.4	2.9	2.5	2.2	1.9	1.6	1.4
10.0	.0078		5.9	5.1	4.4	3.9	3.3	2.9	2.5	2.2	1.9	1.6	1.4
11.0	.0060		5.8	5.0	4.4	3.8	3.3	2.9	2.5	2.1	1.8	1.6	1.4
12.0	.0046		5.7	4.9	4.3	3.7	3.2	2.8	2.4	2.1	1.8	1.6	1.4
13.0	.0036		5.5	4.8	4.2	3.7	3.2	2.8	2.4	2.1	1.8	1.6	1.3
14.0	.0027		5.4	4.7	4.1	3.6	3.1	2.7	2.4	2.0	1.8	1.5	1.3
15.0	.0021		5.3	4.6	4.0	3.5	3.1	2.7	2.3	2.0	1.7	1.5	1.3

TABLES OF REQUIRED DEPTHS FOR RADON ATTENUATION (METERS)

ORE GRADE IS .20

TABLE B. 9

COVER MOISTURE (%)/DIFFUSION COEFFICIENT (CM**2 PER SEC)

TAILINGS MOISTURE (%)	DIFFUSION COEFFICIENT (CM**2/SEC)	(%)	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
		D/P	.0287	.0221	.0171	.0131	.0101	.0078	.0060	.0046	.0036	.0027	.0021
3.0	.0484		6.6	5.7	4.9	4.3	3.7	3.2	2.7	2.4	2.0	1.7	1.5
5.0	.0287		6.4	5.6	4.8	4.2	3.6	3.1	2.7	2.3	2.0	1.7	1.5
6.0	.0221		6.4	5.5	4.8	4.1	3.6	3.1	2.7	2.3	2.0	1.7	1.5
7.0	.0171		6.3	5.5	4.7	4.1	3.5	3.1	2.7	2.3	2.0	1.7	1.5
8.0	.0131		6.2	5.4	4.7	4.0	3.5	3.0	2.6	2.3	2.0	1.7	1.4
9.0	.0101		6.1	5.3	4.6	4.0	3.5	3.0	2.6	2.2	1.9	1.7	1.4
10.0	.0078		6.0	5.2	4.5	3.9	3.4	3.0	2.6	2.2	1.9	1.7	1.4
11.0	.0060		5.9	5.1	4.5	3.9	3.4	2.9	2.5	2.2	1.9	1.6	1.4
12.0	.0046		5.8	5.0	4.4	3.8	3.3	2.9	2.5	2.2	1.9	1.6	1.4
13.0	.0036		5.7	4.9	4.3	3.7	3.3	2.8	2.5	2.1	1.8	1.6	1.4
14.0	.0027		5.6	4.8	4.2	3.7	3.2	2.8	2.4	2.1	1.8	1.6	1.4
15.0	.0021		5.4	4.7	4.1	3.6	3.1	2.7	2.4	2.1	1.8	1.5	1.3

ORE GRADE IS .25

TABLE B.10

COVER MOISTURE (%)/DIFFUSION COEFFICIENT (CM**2 PER SEC)

TAILINGS MOISTURE (%)	DIFFUSION COEFFICIENT (CM**2/SEC)	(%)	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
		D/P	.0287	.0221	.0171	.0131	.0101	.0078	.0060	.0046	.0036	.0027	.0021
3.0	.0484		6.9	5.9	5.1	4.4	3.8	3.3	2.9	2.5	2.1	1.8	1.6
5.0	.0287		6.7	5.8	5.0	4.4	3.8	3.3	2.8	2.4	2.1	1.8	1.6
6.0	.0221		6.6	5.8	5.0	4.3	3.7	3.2	2.8	2.4	2.1	1.8	1.5
7.0	.0171		6.5	5.7	4.9	4.3	3.7	3.2	2.8	2.4	2.1	1.8	1.5
8.0	.0131		6.5	5.6	4.9	4.2	3.7	3.2	2.7	2.4	2.0	1.8	1.5
9.0	.0101		6.4	5.5	4.8	4.2	3.6	3.1	2.7	2.3	2.0	1.8	1.5
10.0	.0078		6.3	5.4	4.7	4.1	3.6	3.1	2.7	2.3	2.0	1.7	1.5
11.0	.0060		6.2	5.4	4.7	4.1	3.5	3.1	2.7	2.3	2.0	1.7	1.5
12.0	.0046		6.0	5.3	4.6	4.0	3.5	3.0	2.6	2.3	2.0	1.7	1.5
13.0	.0036		5.9	5.2	4.5	3.9	3.4	3.0	2.6	2.2	1.9	1.7	1.4
14.0	.0027		5.8	5.1	4.4	3.9	3.4	2.9	2.5	2.2	1.9	1.7	1.4
15.0	.0021		5.7	5.0	4.3	3.8	3.3	2.9	2.5	2.2	1.9	1.6	1.4

TABLES OF REQUIRED DEPTHS FOR RADON ATTENUATION (METERS)

ORE GRADE IS .30

TABLE B.11

COVER MOISTURE (%)/DIFFUSION COEFFICIENT (CM**2 PER SEC)

TAILINGS MOISTURE (%)	DIFFUSION COEFFICIENT (CM**2/SEC)	(%)	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0
		D/P	.0287	.0221	.0171	.0131	.0101	.0078	.0060	.0046	.0036	.0027	.0021
3.0	.0484		7.1	6.1	5.3	4.6	4.0	3.4	3.0	2.6	2.2	1.9	1.6
5.0	.0287		6.9	6.0	5.2	4.5	3.9	3.4	2.9	2.5	2.2	1.9	1.6
6.0	.0221		6.8	5.9	5.2	4.5	3.9	3.4	2.9	2.5	2.2	1.9	1.6
7.0	.0171		6.8	5.9	5.1	4.4	3.8	3.3	2.9	2.5	2.1	1.8	1.6
8.0	.0131		6.7	5.8	5.0	4.4	3.8	3.3	2.8	2.5	2.1	1.8	1.6
9.0	.0101		6.6	5.7	5.0	4.3	3.7	3.3	2.8	2.4	2.1	1.8	1.6
10.0	.0078		6.5	5.6	4.9	4.3	3.7	3.2	2.8	2.4	2.1	1.8	1.6
11.0	.0060		6.4	5.6	4.8	4.2	3.7	3.2	2.7	2.4	2.1	1.8	1.5
12.0	.0046		6.3	5.5	4.8	4.1	3.6	3.1	2.7	2.4	2.0	1.8	1.5
13.0	.0036		6.2	5.4	4.7	4.1	3.5	3.1	2.7	2.3	2.0	1.7	1.5
14.0	.0027		6.0	5.3	4.6	4.0	3.5	3.0	2.6	2.3	2.0	1.7	1.5
15.0	.0021		5.9	5.2	4.5	3.9	3.4	3.0	2.6	2.2	2.0	1.7	1.5

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Rogers and Associates
Engineering Corporation
P.O. Box 330
Salt Lake City, UT 84110

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16. ABSTRACT *(200 words or less)*

Radon emissions from bare and covered uranium mill tailings can be estimated by diffusion theory if appropriate diffusion coefficients are known. The mathematical bases for the diffusion theory expressions are herein presented, as is a general survey of previous and present research, as well as technological developments associated with radon transport through tailings cover systems.

Research is presently being conducted to define more clearly the influences of moisture, porosity, pore size distribution and other factors, on the attenuative properties of cover materials. The results of these present investigations will be incorporated in a subsequent addendum to this handbook.

The radon fluxes or cover thicknesses can be calculated by hand or by available computer programs. The equations and procedure for the hand calculations is in direct support of the methodology contained in Appendix P of the Generic Environmental Impact Statement on Uranium Milling. Several examples are given to demonstrate the methodology.

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