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Radon Attenuation Handbook for Uranium Mill Tailings Cover Design

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2.6 MULTIREGION SYSTEMS

The mathematical solutions for multi-layer covers involving three[13] and four[59] region systems have been presented previously. A general multiregion system must be solved by computer using matrix formulations of the diffusion equations; however, approximate analytical solutions are also available.

2.6.1 The RAECOM Computer Code

RAECOM (acronym for Radon Attenuation Effectiveness and Cover Optimization with Moisture effects) is a FORTRAN computer program which determines the radon fluxes and concentrations in a multilayer uranium tailings and cover system and then optimizes the thickness of a specified cover layer to satisfy given constraints on the maximum radon flux.[48]

A logic flow diagram for the code is shown in Figure 6. First, the D's are calculated from a correlation if they are not input directly. Then the migration of radon is determined for the specified cover characteristics and the radon concentrations (C), and the radon fluxes (J) are calculated. The cover optimization is performed yielding adjusted values (x) for the layer thicknesses. The radon migration calculations are then repeated for each J and C with the adjusted cover layer thicknesses, and the resulting surface flux, J_c, is tested against the specified criterion, J_{crit}. If this criterion is satisfied, the code proceeds to final output. 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 prints out all radon attenuation data. The input data format and code listing are given in Appendix B.

2.6.2 Approximate Expressions

When it is necessary to estimate the radon flux from a multilayer system or to determine a cover layer thickness without resorting to a computer calculation, approximate analytical expressions may be used. The expressions presented in this section can be used for that purpose.

The procedure for multilayer systems utilizes a sequential application of Equations 4 or 8 to each cover layer. The procedure treats the cover layer in question as a single cover system with a modified source layer accounting for the tailings and all cover layers beneath the layer in question. In order to apply Equation 8 to the layer in question, an estimate must be made of the radon flux from the previous layer, J_t, and the diffusion coefficient of the source, D_t. Following are the steps in this procedure utilizing the cover system configuration shown in Figure 7:

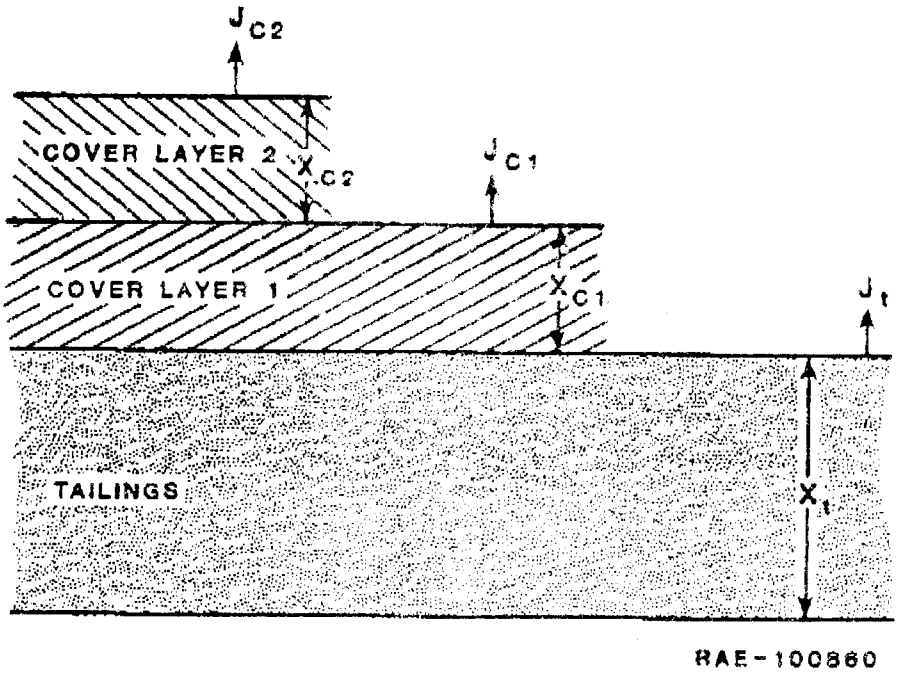

FIGURE 7. PARAMETERS FOR A MULTILAYER COVER SYSTEM.

1. Calculate the radon flux from the first cover layer, J_{c1}, using Equation 4 and the tailings and first cover parameters.

2. Calculate an equivalent source diffusion coefficient, D_{t1}, from Equation 9:

$$D_{t1} = D_t e^{-b_{c1}x_{c1}} + D_{c1}(1 - e^{-b_{c1}x_{c1}}) \tag{9}$$

3. D_{t1} is used in analyzing the second cover layer. If the cover consists of only two layers, use J_{c1} as J_t and D_{t1} as D_t in Equation 8 to calculate the required thickness of layer 2, x_{c2}. The new source term thickness is $x_{c1} + x_t$. The D_{t1} is used to compute a_t and b_t for Equation 8.

4. If x_{c2} is specified and the thickness of a third cover layer is to be adjusted to satisfy the flux criterion, then use Equation 4 to calculate a new J_{c2} with J_{c1} as J_t, D_{t1} as D_t, and x_{c1} plus x_t as the source thickness. The D_{t1} is used to compute a_t and b_t in Equation 14.

5. Obtain a new source term diffusion coefficient for analyzing layer 3 from Equation 10:

$$D_{t2} = D_t\, e^{-b_{c1}x_{c1} - b_{c2}x_{c2}} + D_{c1}\,(1 - e^{-b_{c1}x_{c1}})e^{-b_{c2}x_{c2}} + D_{c2}\,(1 - e^{-b_{c2}x_{c2}}) \tag{10}$$

6. If the cover consists of three layers use J_{c2} as J_t, D_{t2} as D_t to compute a_t and b_t, and the sum of x_{c1}, x_{c2}, and x_t for the source term thickness in Equation 8 to calculate the required thickness of cover layer 3.

7. For more than three cover layers repeat the above process as often as necessary, using Equation 11 to obtain the diffusion coefficient for the modified source term to layer n + 1:

$$D_{t_n} = D_t \exp\left[-\sum_{i=1}^{n} b_{c_i}x_{c_i}\right] + D_{c_n}(1 - e^{-b_{cn}x_{cn}}) + \sum_{i=1}^{n-1} D_{c_i}(1 - e^{-b_{ci}x_i}) \exp\left[-\sum_{j=i+1}^{n} b_{c_j}x_{c_j}\right] \tag{11}$$

2.6.3 Examples of Multiregion Calculations

The tailings pile described in the first example is to be covered with 0.5 meter of a good quality clay and sufficient overburden to achieve a

surface flux of 20 pCi/m^2s. What thickness of overburden should be used? The basic material parameters are:

	D	P	M	m
tailings	0.013 cm^2/s	0.44	11.7	0.4
clay	0.0078 cm^2/s	0.30	6.3	0.4
overburden	0.022 cm^2/s	0.37	5.4	0.25

First, the bare tailings flux is the same as before:

$$J_t = 198 \ pCi/m^2s$$

Then, calculate the attenuation through the clay component using Equation 4.

$$J_{c1} = \frac{2(198)(0.440)}{2.893 - (0.173)}$$

$$J_{c1} = 64.1 \ pCi \ m^{-2}s^{-1}$$

Now, determine the diffusion coefficient for the source term to the overburden (the source is now the tailings and clay) using Equation 9.

$$D_{t1} = D_t \exp(-b_1x_1) + D_1\left[1 - \exp(-b_1x_1)\right]$$

$$D_{t1} = (0.013)(0.440) + (0.0078)(1 - 0.44)$$

$$D_{t1} = 0.0101 \ cm^2/s$$

The value of D_{t1} is then substituted for D_t and J_{c1} = 64.1 is substituted for J_t in Equation 8, giving

$$x_2 = 102 \ \ln\left[\frac{6.41}{1.475 + 0.051}\right]$$

$$x_2 = 146 \text{ cm} = \text{overburden thickness}$$

The total cover thickness is therefore 146 cm + 50 cm = 196 cm. In this calculation the effective source thickness is assumed to be large enough so that tanh a_tx_t is unity.

The parameters specified in the above example were also used to construct the input to the RAECOM program as specified in Appendix B. The RAECOM calculations, shown in Table 2, yield an overburden thickness of 149 cm. Thus, the approximate procedure gives a result that is 3 cm less than the exact calculation, well within acceptable uncertainty limits.

2.7 COVER SOURCE CONSIDERATIONS

The example calculations of the previous sections 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 radon, the effect of the radon from the covers is very small and 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.

The radon flux from the bulk soil material is related to the radon concentration in its pore space by Fick's Law:

$$J = -10^4 \, Dp \frac{dC}{dx} , \qquad (2)$$

where

J = bulk radon flux (pCi m^{-2} s^{-1})

10^4 = factor to convert units from pCi $cm^{-2}s^{-1}$ to pCi $m^{-2}s^{-1}$

Appendix A contains the mathematical basis for Equation 1 as well as for the solutions used in this handbook. The solutions of interest are for bare tailings, tailings covered with homogeneous material, and a generalized multiregion problem with many tailings and cover layers.

2.2 FLUX FROM BARE TAILINGS

The solution of Equations 1 and 2 for the flux from a bare, homogeneous tailings pile is:

$$J_t = 10^4 \, R\rho E\sqrt{\lambda D_t} \tanh\sqrt{\frac{\lambda}{D_t}} \, x_t , \qquad (3)$$

where

J_t = radon flux from the tailings surface (pCi $m^{-2}s^{-1}$)

x_t = thickness of tailings (cm)

The subscript "t" refers to the tailings region. A graph of $J_t/R\,E$ is given in Figure 2 as a function of x_t, illustrating the limitation on the radon flux imposed by radon decay, particularly for low diffusion coefficients. As illustrated, most of the radon comes from the surface layers of tailings; hence there is an advantage in consolidating tailings into smaller, thicker piles.

2.3 FLUX FROM COVERED TAILINGS

The exact solution from diffusion theory to the two-region, tailings-cover problem is:

$$J_c = \frac{2J_t \, e^{-b_c x_c}}{\left[1 + \sqrt{a_t/a_c} \tanh(b_t x_t)\right] + \left[1 - \sqrt{a_t/a_c} \tanh(b_t x_t)\right] e^{-2b_c x_c}} \qquad (4)$$

where

$b_i = \sqrt{\lambda/D_i}$ (i = c or t) (cm^{-1})

$a_i = p_i^2 D_i \left[1 - (1-k)\, m_i\right]^2$ ($cm^2 s^{-1}$)

$m = 10^{-2}\, \rho M/p$ = fractional moisture saturation (dimensionless)

M = moisture content (dry weight percent)

k = 0.26 pCi/cm^3 in water per pCi/cm^3 in air

The subscript "c" pertains to the cover region, and J_t is given in Equation 3. A more detailed description of the parameter a_i and its moisture dependence is given in Appendix A.

It is of interest to examine the behavior of J under various conditions. For a_t equal to a_c, and for sufficiently thick tailings such that $\tanh(b_t x_t)$ is approximately unity, then Equation 4 becomes:

$$J_c = J_t \exp(-b_c x_c) \tag{5}$$

which is the simple exponential attenuation shown by Curve A in Figure 3. However, if $a_t \ll a_c$, Equation 4 becomes

$$J_c = \frac{2J_t \exp(-b_c x_c)}{1 + \exp(-2b_c x_c)} \tag{6}$$

For small x_c, the value of J_c is approximately equal to J_t as shown by Curve B in Figure 3, before the cover flux begins to decrease. This effect has been observed in laboratory measurements of radon fluxes from covered tailings.[22] For large x_c, Equation 6 becomes:

$$J_c(x_c \text{ large}) = 2J_t \exp(-b_c x_c)\ , \tag{7}$$

so that J_c decreases exponentially in the same manner as in Equation 5 but retains twice the magnitude which is shown by Curve B in Figure 3. This is also observable[22] in laboratory measurements.

2.4 COVER THICKNESS FROM FLUX CRITERION

The value of x_c required to achieve a specified flux can be obtained by rearranging Equation 4, assuming the tailings are more than 100 cm thick, and approximating $\exp(-2b_c x_c)$ by $(J_c/J_t)^2$. The result is:

$$x_c = \sqrt{\frac{D_c}{\lambda}} \ \ln \left[\frac{2J_t/J_c}{(1 + \sqrt{a_t/a_c} \tanh b_t x_t) + (1 - \sqrt{a_t/a_c} \tanh b_t x_t)(J_c/J_t)^2} \right] \tag{8}$$

Most practical applications require a significant degree of attenuation so that the last term in the denominator of Equation 8 can be neglected. The resulting simplified equation can be expressed in graphic form and is presented as a nomograph in Figure 4.[39]

The required cover thickness, x_c, is found by first determining the ratios J_c/J_t and a_c/a_t and then referring to the nomograph in Figure 4. The value of the ratio J_c/J_t is found on Column A and the value of a_c/a_t on Column B. These two values should be connected with a straight line, and a value read from Column C at the intersection with the line. That same value is located on the modified scale C' and a second line is drawn from that value on C' to the value of D_c on Column D. The intersection of the resulting line with Column E gives the cover thickness, in units of either meters or feet.

2.5 EXAMPLES OF SURFACE FLUX AND COVER THICKNESS DETERMINATIONS

Several examples are given in this section to illustrate the use of the equations and graphs. The first general examples are calculations of the surface flux from covered tailings. Figure 5 contains the results of cover calculations for a bare tailings flux of J_t = 280 pCi/m^{2}s. Various diffusion coefficients for the cover soils are used in Equation 4 to obtain the curves in the figure.[46] As shown in the next chapter, the cover moisture is the dominant parameter affecting the D, and hence, the radon attenuation.

As an example of the calculations used to generate the curves in Figure 5, it is assumed that a tailings pile has the following typical values:

R = 400 pCi/g

ρ = 1.5 g/cm^3

E = 0.2

D_t = 1.3x10^{-2} cm^2/s

p_t = 0.44

M_t = 11.7%

x_t = 300 cm

The radon flux from the surface of the uncovered tailings is calculated from Equation 3: