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CALCULATION OF RADON FLUX ATTENUATION BY EARTHEN URANIUM MILL TAILINGS COVERS

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A. INTRODUCTION

The Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978 (Public Law 95-604) gives the NRC responsibility to ensure, through the licensing process, that final disposal of uranium byproduct material (tailings) is conducted in a way that will protect the public health and safety and the environment. Public Law 95-604 also requires that uranium tailings disposal conform to standards promulgated by the Environmental Protection Agency (EPA). The NRC staff is required to analyze the adequacy of uranium tailings covers proposed in license applications to meet the EPA rules. The EPA rules in 40 CFR Part 192 require that a cover be designed to produce reasonable assurance that the radon-222 release rate would not exceed 20 pCi $m^{-2}s^{-1}$ for a period of 1000 years to the extent reasonably achievable and in any case for at least 200 years when averaged over the disposal area over at least a one-year period. NRC regulations in 10 CFR Part 40 also require that the radon-222 release rate not exceed 20 pCi $m^{-2}s^{-1}$ for active (UMTRCA Title II) sites. Alternatively, for inactive (UMTRCA Title I) sites, the EPA rules permit the Department of Energy (DOE) to choose to meet an optional standard for radon concentration of less than 0.5 pCi per liter over background.

This regulatory guide describes methods acceptable to the NRC staff for calculating radon fluxes through earthen covers and for calculating the resulting minimum cover thickness needed to meet NRC and EPA standards. The guide also suggests methods for obtaining the various parameters used in calculating the radon fluxes and earthen cover thicknesses and suggests default values for certain parameters.

This regulatory guide is applicable to active uranium tailings sites. The NRC staff is using the methods stated in this guide as a basis for review and concurrence of DOE remedial action plans for inactive sites. The guidance is intended to be used for calculating radon flux attenuation by earthen uranium mill tailings covers. The parameter values and examples presented are limited to earthen cover materials, but the diffusion theory and the methods presented are also applicable to man-made materials. Detailed supporting information for calculating minimum cover thickness is published separately in the "Radon Attenuation Handbook For Uranium Mill Tailings Cover Design," NUREG/CR-3533 (Ref. 1).

Any information collection activities mentioned in this regulatory guide are contained as requirements in 10 CFR Part 40, which provides the regulatory basis for this guide. The information collection requirements in 10 CFR Part 40 have been cleared under OMB Clearance No. 3150-0020.

B. DISCUSSION

The design of a cover to reduce radon releases from uranium tailings depends on the values of a variety of fundamental parameters that characterize the tailings and cover materials. Once determined, the values of these parameters may be used to calculate the thickness of cover that is required to reduce the flux of radon from the tailings to any prescribed limit. This guide presents guidance on (1) determining appropriate values of the parameters and (2) exact and approximate methods for calculating radon fluxes for most cover configurations and conditions. The approximate calculation methods give results similar to those from the exact methods and thus provide for flexibility in performing the cover design calculations. For multilayer covers, an exact hand-calculated solution is not available. Either an approximate method or a computer solution must be used for systems with more than two layers.

1. DETERMINATION OF PARAMETERS

Because the radon flux limit in the EPA standard is given as an average over the entire disposal area over a period of at least one year (40 CFR Part 192), anomalies in position and time may be ignored and estimates of the long-term spatial average for all parameters should be used. Because the EPA limit on radon flux is to apply for a period of at least 200 and up to 1000 years, parameter values should be selected conservatively taking into account potential degradation of the cover over time. Parameters needed to characterize the tailings and cover materials include thickness, density, specific gravity, porosity, moisture, radium activity, radon diffusion coefficient, and radon emanation coefficient (Refs. 1 and 2).

Values of some of the parameters such as tailings pile thickness and average radium activity can be reasonably estimated for initial license applications from mill plans, anticipated average ore grades, and tailings dam design. The most significant parameter affecting the thickness of earthen cover needed to meet the EPA radon flux criterion is the radon diffusion coefficient of the cover. The value of the radon diffusion coefficient is very sensitive to the availability of interconnected air-filled pores and therefore, at moderate to high moisture contents, to the cover moisture content and porosity. The parameter that introduces the greatest uncertainty into the calculation of earthen cover thickness for radon attenuation is the cover moisture content. The values for the cover and tailings moisture contents, densities, and radon diffusion coefficients are difficult to estimate or measure because long-term moisture changes and settling may occur after the installation of a cover system. Therefore, conservative values of these parameters measured under similar long-term conditions or conservative predictive correlations of these parameters with the significant variables may be needed. Specific guidance with respect to measuring each parameter is detailed in the regulatory position of this guide. For each parameter, the applicant will provide information describing the test method, its precision and accuracy, and its applicability for representing a long-term, large-area conservative average.

Although accurate site-specific measurements of all parameters would be ideal, the uncertainties, costs, and reliability of such measurements may make the use of default values or conservative correlation predictions a reasonable and satisfactory alternative. However, the applicant should recognize that careful measurement of parameter values may be justified by savings in the cost of covering the tailings. The NRC staff has selected default values with the intent that minimum cover thicknesses calculated using default parameters will be equal to or greater than thicknesses calculated using measured parameters. If reasonable evidence indicates that default values or correlation predictions may not be conservative or realistic for a site, the applicant should measure the parameter values for which default values could be nonconservative.

An important factor in the long-term performance of a tailings cover system is its ability to remain free of defects over long time periods. Centimeter-scale defects caused by soil shrinkage, erosion cracks, erosion piping, animal burrows, and former root channels that are deeply penetrating and relatively frequent could cause a significant loss in cover performance (Ref. 3). To cause a factor of two increase in radon flux, cracks must be at least 2 cm wide, must be spaced less than 1 m apart, and must penetrate at least 75% of the cover thickness (Ref.3). Such defects would be easily detected by visual inspection except when covered by riprap (Ref. 3). To promote long-term effectiveness, the staff recommends that smectite clays or other swelling clays, if used, should be well compacted and protected from excessive wetting and drying by additional soil layers. The staff further recommends that well-compacted soils generally be utilized to minimize biointrusion as well as to minimize shrinkage and formation of other defects. Proper surface covering and contouring are also important to reduce erosion. Cover layers such as riprap or topsoil that are used solely for erosion control should not be included in radon flux calculations. Likewise, cover material subject to erosion should not be included. However, the effects of riprap or topsoil on the long-term moisture content of the earthen cover need to be considered.

2. COVER THICKNESS CALCULATIONS

The basis for the radon flux and minimum cover thickness calculations presented here is one-dimensional steady-state gas diffusion theory (Ref. 1). Only vertical diffusion is considered because the horizontal dimensions of tailings piles are large compared to the typical mean radon diffusion length of at most 1 to 2 meters. Short-term variations are ignored because the regulation addresses the long-term average radon flux. Advective transport, the externally forced movement of radon, also affects radon fluxes, but primarily over short time periods. For tailings covers, advective effects usually have negligible impacts in comparison to diffusion when averaged over the natural long-term cycles in thermal, barometric, and other advective driving forces (Ref. 4). Advective transport may thus be ignored unless local anomalies are known to cause sustained directional transport of soil gases.

The thickness of earthen cover required to reduce radon fluxes to acceptable levels depends on the radon source strength of the tailings and on the efficiency of the cover material in reducing the flux. Radioactive decay of radium-226 in tailings and soil produces radon-222, which is an inert, short-lived, radioactive gas. Radon diffuses through the soil pore space over average distances defined by its 3.8-day half-life and by its diffusion coefficient. The flux of radon reaching the atmosphere is reduced by delaying its release because a greater fraction decays in the cover. The delay may be accomplished by increasing the cover thickness, employing a cover material with a lower diffusion coefficient, increasing the cover compaction, or increasing the long-term moisture content of the cover. Thus the diffusion coefficient for radon in the cover material is a key parameter determining its efficiency.

The one-dimensional steady-state diffusion equation appropriate for radon flux determinations (Ref. 1) is:

$$D\frac{d^2C}{dx^2} - \lambda C + R\rho E\lambda/n = 0 \qquad (1)$$

where

D = diffusion coefficient for radon in the total pore space ($cm^2 s^{-1}$)

C = radon concentration in the total pore space ($pCi\ cm^{-3}$)

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

R = specific activity of radium-226 ($pCi\ g^{-1}$)

ρ = dry bulk mass density of soil or tailings ($g\ cm^{-3}$)

E = radon emanation coefficient (dimensionless)

n = soil or tailings porosity (dimensionless)

Radon flux is related to the radon concentration gradient by:

$$J = -10^4 Dn \frac{dC}{dx} \tag{2}$$

where

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

10^4 = units conversion (cm^2/m^2)

Solutions to Equation 1 are obtained by applying boundary conditions for the system being analyzed and solving for the surface radon flux. For a thick bare tailings source, boundary conditions are typically (1) a specified or zero radon concentration at the air surface and (2) zero or negative radon flux at the base of the tailings. For tailings with covers or other systems consisting of layers of different materials, additional boundary conditions for each interface between layers are (3) continuity in radon concentration and (4) continuity in radon flux. Individual layers should be defined by the occurrence of distinct changes in radium content, soil texture, compaction, or moisture.

The exact solutions to Equations 1 and 2 can be arranged to calculate directly the radon flux for a given set of tailings and cover parameters. The thickness of cover needed to achieve a specified radon flux can also be determined directly. Specific guidance on the cover thickness calculations is given in the regulatory position.

C. REGULATORY POSITION

The parameter values and equations by which the NRC staff will estimate radon flux and minimum thicknesses for uranium tailings covers are presented below. These equations are appropriate for the design criteria that the staff routinely considers in its evaluations.

1. DETERMINATION OF PARAMETERS

The design of an adequate tailings cover system depends on the values of several fundamental parameters of the tailings and cover materials. These include the thicknesses, densities, specific gravities, moistures, radium activities, radon diffusion coefficients, and radon emanation coefficients of the materials. In addition, several secondary parameters are calculated from the fundamental parameters for simplicity in performing the necessary calculations. Examples of secondary parameters are the fractions of moisture saturation and the radon flux from the uncovered (bare) tailings source. Table 1 lists all of the cover design parameters, their symbols, and reference values or sources of data. Table 1 and other sections of this guide provide default values that are, by their very nature, conservative. If the applicant does not elect to use actual measured values, the default values may be used. The applicant may use other values if it can be demonstrated that the use of such values is appropriate. On the other hand, default values should not be used if the applicant has information or indications that their use would lead to underestimation of the resultant radon flux. An example in point would be to use the default value for E, the radon emanation coefficient, for the case of windblown tailings that may have higher radon emanation rates.

1.1 Fundamental Parameters

Because of the difficulty and possible ambiguity in determining representative values for the fundamental parameters, sections 1.1.1 through 1.1.7 provide guidance on methods acceptable to the NRC staff for determining their values.

1.1.1 Layer Thicknesses

The thickness of the tailings source, x_t, will be determined from the applicant's estimates of total tailings production and areal extent of the pile. Because a tailings thickness greater than about 100-200 cm is effectively equivalent to an infinitely thick radon source (Ref. 1), a value of x_t = 500 cm represents an equivalent infinitely thick tailings source of radon that may be used in the absence of more specific smaller values. Cover layer thicknesses,

TABLE 1 Cover Design Parameters, Symbols, and Reference Values

	Symbol	Parameter and Units	Reference Value
Fundamental Parameters	x_t, x_c	Thickness of tailings (t) and cover (c) layers (cm)	$x_t = 500$
	ρ_t, ρ_c	Dry bulk mass densities of tailings and cover (g cm^{-3})	$\rho_t = 1.6$ ρ_c - measured
	ρ_w	Mass density of water (g cm^{-3})	$\rho_w = 1$
	G_t, G_c	Specific gravities of tailings and cover (dimensionless)	$G_t = G_c = 2.65$
	w_t, w_c	Long-term average moisture content of tailings and cover (dry wt. percent)	$w_t = 6$ w_c - measured or estimated
	R_t, R_c	Specific activities of radium-226 in the tailings and cover (pCi g^{-1})	$R_t = 2812 \cdot U_3O_8$ percentage
	D_t, D_c	Diffusion coefficients for radon in the total pore space of the tailings and cover (cm^{2}s^{-1})	Equation 7
	E	Radon emanation coefficient for the tailings and cover (dimensionless)	$E = 0.35$
	λ	Radon-222 decay constant (s^{-1})	$\lambda = 2.1\text{x}10^{-6}$
	k	Equilibrium distribution coefficient for radon in water and air (pCi cm^{-3} water per pCi cm^{-3} air)	$k = 0.26$
	J_c	Radon flux criterion from the cover into the atmosphere (pCi m^{-2}s^{-1})	$J_c = 20$
Calculated Parameters	n_t, n_c	Porosities of the tailings and cover (dimensionless)	measured or Equation 4
	m_t, m_c	Moisture saturation fractions in tailings and cover (dimensionless)	Equation 8
	J_t	Radon flux from the bare tailings source (pCi m^{-2}s^{-1})	Equation 9
	b_t, b_c	Inverse relaxation lengths for tailings and cover (cm^{-1})	Equation 10
	a_t, a_c	Interface constants for tailings and cover (cm^{2}s^{-1})	Equation 11

x_c, must be calculated to satisfy the radon flux criterion but must be sufficiently thick for the intended application and compaction techniques and for maintaining physical integrity.

1.1.2 Layer Densities, Specific Gravities, and Porosities

Bulk dry mass densities for the tailings, ρ_t, and cover, ρ_c, are related to the specific gravities for the tailings, G_t, and cover, G_c, the mass density of water, ρ_w, and the porosities for the tailings, n_t, and cover, n_c, by the equations

$$\rho_t = G_t \rho_w (1 - n_t) \qquad \rho_c = G_c \rho_w (1 - n_c) \tag{3}$$

Likewise, the porosities may be calculated by the equations

$$n_t = 1 - \frac{\rho_t}{G_t \rho_w} \qquad n_c = 1 - \frac{\rho_c}{G_c \rho_w} \tag{4}$$

Thus only two of the three variables need be determined because the third can be calculated. However, for greater confidence and reliability, the NRC staff suggests measuring all three variables and cross checking for consistency. The density of water, ρ_w, is equal to unity and is generally ignored in calculations but is required to make the equations dimensionally consistent. The staff will use a default tailings density of $\rho_t = 1.6 \text{ g cm}^{-3}$ unless acceptable documented alternative values are provided by the applicant. This dry bulk mass density is equivalent to a porosity of 40% at a specific gravity of 2.65, which is the density of quartz. The value of 2.65 for specific gravity is conservative because other common tailings and cover minerals have densities less than or equal to the density of quartz. The use of reference values for tailings parameters is acceptable because radon flux and cover thickness calculations are more sensitive to cover parameters than to tailings parameters. The staff recommends that cover materials be compacted to approximately 95% of the maximum dry density as determined by the standard Proctor density test. The staff will accept cover densities properly determined by the standard Proctor test (ASTM-D-698, Ref. 5) for the candidate soils. The staff will use a reference specific gravity of 2.65 for all quartzose tailings and cover materials.

If materials with specific gravities significantly different from quartz are used, acceptable documented alternative values should be provided by the applicant.

Porosities may be measured by mercury porosimetry or other reliable method or determined by Equation 4, which, if reference values for bulk density and specific gravity are used, is equivalent to using a default porosity of 40%.

1.1.3 Long-Term Average Moistures

The NRC staff considers several methods for predicting the long-term soil moisture content to be acceptable. An appropriate method is to measure the actual long-term moisture content at the cover material borrow site and to make adjustments, if needed, for differences between the borrow site and the disposal site. The staff recommends that soil moistures for the candidate cover materials, w_c, be measured from samples obtained from depths of 120 to 500 cm. The term w is the long-term average dry weight percent moisture content of the material. It is calculated by dividing the weight of free water by the weight of a dried sample. Shallow samples of the soil should be excluded because of the high seasonal variability in their moisture content. Samples close to a water table should also be excluded to avoid biasing the moisture estimate for the tailings cover.

Moisture contents may be calculated by computer models of unsaturated flow provided that the models are fully documented and are validated for the range of possible site conditions. Parameter values used in modelling must be either accurate measured values or reasonable conservative estimates. Measured and conservative values must be applicable to periods of drought.

Baver (Ref. 6) has indicated that soil moisture reduced by drainage and evapo-transpiration will eventually approach and may even go beyond the permanent wilting point. The wilting point is the soil moisture content at which soil can no longer supply water at a rate sufficient to maintain plant life. The tension of the soil water when permanent wilting occurs is about 15 atmospheres (Ref. 6). The NRC staff will accept the moisture content at which permanent wilting occurs as a reasonable value of the long-term moisture content. This value may be determined from actual laboratory testing or from estimated empirical relationships such as those determined by Rawls and Brakensiek (Ref. 7). Rawls and Brakensiek conducted a study on 1323 soils with approximately 5350 horizons and from 32 states. From their data, relationships were derived for predicting soil water retention volumes at matric potentials ranging from 0.04 to 15 bars based on percent sand, silt, and clay, on percent organic matter, on bulk density, and on the 0.33-bar and 15-bar soil water retention values. The accuracy of these equations increases as a greater number of these soil properties are identified.

The empirical relationship established in Reference 7 that predicts volumetric moisture content of the soil corresponding to 15 bars is

$$\theta = 0.026 + 0.005z + 0.0158y \tag{5}$$

where

z = % of clay in the soil

y = % of organic matter in the soil.

Because the 15-bar water retention value, θ, is the permanent wilting point of the soil, the NRC staff considers that this value is a reasonable lower bound for the soil moisture content over the long term.

The long-term average dry weight percent moisture of the candidate cover material, W_c, is related to θ by the following equation

$$W_c = \frac{100\theta\rho_w}{\rho_c} \tag{6}$$

where ρ_w is generally unity.

The applicant may use a reference value for w_t because the calculation of cover thickness is not nearly as sensitive to the value of the moisture content of the tailings as it is to the moisture content of the cover. If acceptable documented alternative information is not furnished by the applicant, the staff will use a reference value of w_t = 6% for the tailings moisture content because 6% is a lower bound for moisture in western soils (Ref. 8).

1.1.4 Radium Activities

For well-mixed tailings, the average specific radium activity of the tailings can be determined from the average uranium ore grade of the parent material, assuming secular equilibrium between uranium and radium. In this case, the radium activity should be estimated by multiplying the ore grade by 2812 pCi g^{-1} radium per percent U_3O_8. The basis for estimating the average uranium ore grade in units of percent U_3O_8 should be documented. Many tailings piles are layered, so the average radium activity of the tailings may not be adequate for determining the radon flux from the uncovered tailings. Layered tailings that have slimes on top will generally have higher radon fluxes than equivalent well-mixed tailings because tailings slimes generally have much higher radium contents than tailings sands. Therefore, the NRC staff advises in situ measurement of radium activity for nonuniform tailings. Because the criteria of 40 CFR Part 192 deal only with radon generated by the tailings, the radium activity in the cover soils may be neglected ($R_c = 0$) for cover design purposes provided the cover soils are obtained from background materials that are not associated with ore formations or other radium-enriched materials.

1.1.5 Radon Diffusion Coefficients

If measurements are not available, the staff estimates the radon diffusion coefficients of the tailings, D_t, and cover materials, D_c, from their moisture saturations, m, and porosities, n, using the correlation function

$$D = 0.07\exp[-4(m - mn^2 + m^5)] \tag{7}$$

The moisture saturation fraction, m, is defined in Table 1 and in section 1.2. This correlation is based on numerous radon diffusion measurements in clays, silts, sands, gravels, and mixed earthen materials with compactions generally in the range of 80-105% of standard Proctor maximum dry density (Ref. 2). The effects of long-term fluctuations of the values of the diffusion coefficients should be factored into the values ultimately used. The staff will accept properly measured radon diffusion coefficients for candidate cover soils if adequate documentation of experimental procedures, including documentation of precision and accuracy, is provided.

1.1.6 Radon Emanation Coefficients

The radon emanation coefficient, E, is the fraction of radon that is released from the tailings or soil matrix into the pore space. The reference value of the radon emanation coefficient used by the NRC staff is 0.35 for all materials. The staff will accept measured or other substantiated values of E provided the applicant uses proper experimental procedure or provides clear documentation. Nielson et al. (Ref. 9) describe methods of measuring E that, if properly implemented and documented, would be acceptable.

1.1.7 Other Fundamental Parameters

The accepted value for the radon decay constant is 2.1×10^{-6} s^{-1}. The value of the equilibrium distribution coefficient for radon between air and water that should be used is k = 0.26 pCi cm^{-3} water per pCi cm^{-3} air. This is the value of the distribution coefficient at a temperature of 20°C (Ref. 10).

1.2 Calculated Parameters

Values of several parameters that occur frequently in cover design and radon flux calculations are generally calculated separately for use in subsequent design calculations. These include the moisture saturation fraction, m, and the bare source flux, J_t.

The moisture saturation fraction, m, is the volumetric fraction of saturation of pore space for the tailings or cover soil. It is calculated by converting weight percent moisture, w, to the percent of water-filled porosity with the equations

$$m_t = \frac{10^{-2}\, \rho_t w_t}{n_t \rho_w}, \qquad m_c = \frac{10^{-2}\, \rho_c w_c}{n_c \rho_w} \tag{8}$$

where ρ_c, ρ_t, ρ_w, n, and w are defined in Table 1. A reference value of 1 for the density of water, ρ_w, is generally used, but for saline pore fluids, higher values would be appropriate.

The radon flux from the bare tailings source and the other calculated parameters are also defined here for use in calculating radon flux, J_c, and cover thickness, x_c. The radon flux from the bare (homogeneous) tailings source is calculated as

$$J_t = 10^4 \ R_t \rho_t E_t \sqrt{\lambda D_t} \tanh(x_t \sqrt{\lambda / D_t}) \qquad (9)$$

where R_t, ρ_t, E_t, D_t, x_t, and λ are defined in Table 1 and 10^4 changes the radon flux units from pCi $cm^{-2}s^{-1}$ to pCi $m^{-2}s^{-1}$. The inverse relaxation lengths for the tailings, b_t, and cover soils, b_c, are calculated as

$$b_t = \sqrt{\lambda / D_t}, \qquad b_c = \sqrt{\lambda / D_c} \qquad (10)$$

where λ and D are defined in Table 1. The respective interface constants a_t and a_c for the tailings and cover soils are calculated as (Ref. 1)

$$a_t = n_t^2 D_t [1 - (1 - k)m_t]^2, \quad \text{or} \quad a_c = n_c^2 D_c [1 - (1 - k)m_c]^2 \qquad (11)$$

where n, D, and k are defined in Table 1, and m is defined by Equation 8.

2. CALCULATIONS OF COVER THICKNESS

The applicant should determine the minimum necessary cover thickness by utilizing appropriate estimates of all parameters in one of several equivalent calculation methods. For simple single-layer covers, the radon flux penetrating the cover can be calculated as

$$J_c = \frac{2 J_t \exp(-b_c x_c)}{1 + \sqrt{a_t / a_c} \tanh(b_t x_t) + [1 - \sqrt{a_t / a_c} \tanh(b_t x_t)] \exp(-2 b_c x_c)} \qquad (12)$$

where J_t is defined by Equation 9, b_t and b_c are defined by Equation 10, a_t and a_c are defined by Equation 11, and x_t and x_c are defined in Table 1 and tanh is the hyperbolic tangent. For thick tailings sources, the hyperbolic tangent term, $\tanh(b_t x_t)$, is equal to unity and may be ignored. However, if the tailings are less than 200 cm thick, Equation 12 should be used.

For practical applications for which the tailings are more than 200 cm thick and the cover achieves a flux reduction greater than a factor of ten, the following simplified equation is acceptable.

$$J_c = \frac{2J_t \exp(-b_c x_c)}{1 + \sqrt{a_t/a_c}} \tag{13}$$

Equation 12 can be solved for x_c

$$x_c = \frac{1}{b_c} \ln \frac{J_c/J_t(1 - \sqrt{a_t/a_c}\tanh(b_t x_t))}{1 - [1 - (J_c/J_t)^2(1 + \sqrt{a_t/a_c}\tanh(b_t x_t))(1 - \sqrt{a_t/a_c}\tanh(b_t x_t))]^{1/2}} \tag{14}$$

The term $\tanh(b_t x_t)$ is approximately equal to 1 for uranium tailings thicknesses of 200 cm or more. Also, for almost all uranium tailings applications, the desired reduction of radon flux from the cover is significant, so that J_c is much less than the bare tailings flux J_t. In these cases, Equation 14 may be adequately approximated by solving Equation 13 for x_c.

$$x_c = \sqrt{D_c/\lambda}\ \ln\left[\frac{2\ J_t/J_c}{1 + \sqrt{a_t/a_c}}\right] \tag{15}$$

Further, Equation 15 can be expressed by a nomograph presented in Reference 1. Cover thicknesses determined accurately from the nomograph in Reference 1 are acceptable to the staff if the applicant shows that the tailings are more than 2 meters thick and the required flux attenuation ratio, J_c/J_t, is less than 0.1. Examples of the cover thickness calculations for a single-layer cover are presented in Appendix A.

Although flux and thickness calculations may be performed for multilayer covers using computer programs, the following approximate method will be accepted as an alternative provided the results agree with staff calculations. This method utilizes successive applications of Equation 13 to individual cover layers with modifications in the source parameters to account for any underlying cover layers. Because Equation 13 does not allow for radon sources (radium) in the cover layer, this approximate method may be applied to multilayer covers, but not to multilayer tailings sources. For multilayer covers, the subscripts $_{c1}$ and $_{c2}$ are used to denote cover layers 1 and 2. For example, J_{c1} denotes the radon flux out of layer 1 and J_{c2} the flux out of layer 2. If the tailings are less than 2 meters thick, Equation 12 should be used instead of Equation 13. The specific steps in the approximate multilayer cover calculation are:

1. Calculate the radon flux through the first cover layer, J_{c1}, using Equation 13 as if there were no other cover layers.

2. Calculate an equivalent source diffusion coefficient, D_{t1}, for use in analyzing the second cover layer by the following equation:

$$D_{t1} = D_t \exp(-b_{c1}x_{c1}) + D_{c1}\,[1 - \exp(-b_{c1}x_{c1})] \qquad (16)$$

3. For two-layer covers, calculate the required thickness of the second layer, x_{c2}, using J_{c1} as J_t in Equation 15. Use D_{t1} as D_t, n_{c1} as n_t, and m_{c1} as m_t in Equation 11 to define a_t for Equation 15. The new source term thickness is $x_{c1} + x_t$.

Examples of the cover thickness calculations for a three-layer system with two cover layers are presented in Appendix A. Should the user wish to use this iterative method for more than three layers, Reference 1 provides the general formulae. If the user wishes to calculate radon flux and cover thickness for multiple tailings layers for more than three layers total, the NRC staff advises using a computer program. The NRC staff has developed an interactive version of the RAECOM computer program, which has been named the RADON program. The RADON program is documented in Appendix B.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this regulatory guide.

Except in those cases in which an applicant proposes an acceptable alternative method for complying with specified portions of the Commission's and EPA's regulations, the methods described in this guide will be used in the evaluation of the adequacy of uranium tailings covers proposed in license applications.

APPENDIX A

EXAMPLES OF URANIUM TAILINGS COVER THICKNESS CALCULATIONS

Two examples are presented to illustrate the use of the equations and other guidance in this regulatory guide. The first example is for a single-layer cover system, and the second example is for a three-layer cover system. The uses of Equations 13 and 15 are illustrated by the first example. Applications of the approximate multilayer method defined by Equations 12 through 16 are illustrated by the second example.

EXAMPLE 1. SINGLE-LAYER COVER THICKNESS CALCULATION

For the first example, the tailings pile has the following typical values:

R_t = 400 pCi g^{-1}
ρ_t = 1.5 g cm^{-3}
E = 0.2
D_t = 1.3×10^{-2} $cm^2 s^{-1}$
n_t = 0.44
w_t = 11.7%
x_t = 300 cm

First, the radon flux from the surface of the uncovered tailings is calculated from Equation 9:

$$J_t = (10^4\ cm^2 m^{-2})(400)(1.5)(0.2)[(2.1 \times 10^{-6})(0.013)]^{\frac{1}{2}} \tanh(3.8)$$
$$= 198\ pCi\ m^{-2} s^{-1}$$

Cover material that can be compacted to have the following properties is available:

$$D_c = 7.8\text{x}10^{-3}\ \text{cm}^2\text{s}^{-1}$$
$$n_c = 0.3$$
$$w_c = 6.3\%$$

Furthermore, it is assumed that $m_c = m_t$.

Next, the flux attenuation with 2 meters of cover material is calculated from Equation 13:

$$J_c = \frac{2(198)\exp[-(2.1 \times 10^{-6}/7.8 \times 10^{-3})^{\frac{1}{2}}(200)]}{1 + [((0.44)^2(0.013))/((0.3)^2(0.0078))]^{\frac{1}{2}}}$$

$$J_c = \frac{2(198)(3.76\text{x}10^{-2})}{2.893}$$

$$J_c = 5.1\ \text{pCi m}^{-2}\text{s}^{-1}$$

If a greater flux is acceptable, the same calculation can be repeated with smaller cover thicknesses, or the required thickness can be directly calculated from Equation 15. For example, what cover thickness would yield a radon flux of 20 pCi $m^{-2}s^{-1}$? This is determined from Equation 15 as:

$$x_c = 61 \ln \frac{19.8}{2.893 - 0.009}$$

$$x_c = 118\ \text{cm}$$

EXAMPLE 2. THREE-LAYER COVER THICKNESS CALCULATION

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 radon flux of 20 pCi $m^{-2}s^{-1}$. What thickness of overburden should be used? The basic material parameters are:

	D	n	w	m
Tailings	0.013 cm^2s^{-2}	0.44	11.7	0.4
Clay	0.0078 cm^2s^{-2}	0.30	6.3	0.4
Overburden	0.022 cm^2s^{-2}	0.37	5.4	0.25

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

$$J_t = 198 \text{ pCi m}^{-2}\text{s}^{-1}$$

Then, calculate the attenuation through the clay component using Equation 13 in the same way as in Example 1. The equation is simplified to:

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

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

Now, determine the diffusion coefficient for the source term to the overburden (the source is now the tailings and clay) using Equation 16:

$$D_{t1} = D_t\exp(-b_{c1}x_{c1}) + D_{c1}[1 - \exp(-b_{c1}x_{c1})]$$

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

$$D_{t1} = 0.0101 \text{ cm}^2\text{s}^{-1}$$

The value of D_{t1} is then substituted for D_t, and $J_{c1} = 64.1$ is substituted for J_t in Equation 15, giving:

$$x_{c2} = 102 \ln \frac{6.41}{1.475 + 0.051}$$

$$x_{c2} = 146 \text{ cm} = \text{overburden thickness}$$

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 that $\tanh(a_tx_t)$ is unity.

The parameters specified in the above example were also used as example input to the RADON program. The RADON calculations, shown in Appendix B, yield an overburden thickness of 149 cm. Thus the approximate solution of 146 cm is 3 cm less than the exact calculation. This typical example demonstrates that the approximate procedure yields acceptable results.

EXAMPLE 3. COMPUTATION OF SOIL MOISTURES AND DIFFUSION COEFFICIENTS AT THE PERMANENT WILTING POINT

As was mentioned previously, the 15-bar soil moisture retention value is estimated using Equation 5, which is taken from Reference 7:

$$\theta = 0.026 + 0.005z + 0.0158y$$

where

z = % of clay in soil

y = % of organic matter in soil

A candidate soil being considered for a cover material contains approximately 16% clay and 0.5% organics. Using the above equation:

$$\theta = 0.114$$

The associated moisture saturation fraction is computed to be:

$$m = \frac{0.114}{0.40} \cong 0.29$$

where we use the reference value of $n = 0.40$.

The radon diffusion coefficient could then be estimated using Equation 7:

$$D = 0.07\exp[-4(m - mn^2 + m^5)]$$

$$D = 0.026 \text{ cm}^2\text{s}^{-1}$$

The user then proceeds in the manner shown in the previous examples.

APPENDIX B

THE RADON PROGRAM

1. INTRODUCTION

The RADON computer program, shown in Table 1B, is an interactive BASIC version of the FORTRAN computer program RAECOM listed in Reference 1. Reference 1 describes the procedures for implementing the RAECOM program and provides examples of its input and output for those who wish to use a FORTRAN program. The RADON program was designed specifically for interactive use on personal computers. The program is written for the IBM PC and compatibles. Minor modifications in input/output parameters may be required for use on other personal computers. The RADON program calculates the radon concentration and flux at the boundaries of defined layers and calculates the thickness of a cover layer needed to meet a defined flux limit. This appendix is structured to follow the order of operations that is followed in using the RADON program.

1.1 Hardware Requirements

The RADON program assumes that the user has, as a minimum, a monochrome or color graphics monitor, a printer, and one disk drive. Input may be entered interactively or from a diskette file named RNDATA on disk drive A. The interactive input sets up an input file that is recorded as RNDATA on drive A so that, following an initial interactive run, the line editor may be used to vary input parameters without going through the interactive program.

2. CONSTANTS USED

The RADON program uses a radon decay constant of 2.1×10^{-6} s^{-1}, a water/ ir partition coefficient for radon of 0.26, and a specific gravity for tail- s and cover materials of 2.65. If the materials have specific gravities ntially different from 2.65, both porosity and dry bulk mass density should be entered into the program as measured values, in which case the specific gravity value is not used.

3. INTERACTIVE INPUT PARAMETERS

3.1 Title of Data Set

When prompted, enter the title of the data set, not to exceed 254 characters, exactly as you want it to appear in the printed output.

3.2 Interactive or Direct Input

When prompted, type Y to input interactively or type N to read input from drive A. Do not hit the return key. Either upper or lower case letters may be used. The user is given a choice of using the interactive input program, which gives a detailed printed record of input, or proceeding directly to the calculational part of the program with input that is taken from a diskette file. The interactive program will not accept erroneous input data that violate parameters defined in the program. For example, the program will not allow less than two layers total of cover plus tailings or more than ninety-nine total layers, and it will prompt the user to input again if unacceptable values are entered. However, if erroneous data are entered on the diskette file, they will not be screened again by the program, and the program will either "crash" or produce meaningless results.

3.3 Input Total Number of Layers

Following the prompt, enter the total number of layers of cover plus tailings.

3.4 Input Desired Radon Flux Limit

Following the prompt, enter the value of radon flux i
top boundary. The default value for the radon flux limits
which is the EPA flux limit for uranium mill tailings. The

substa
ing
a

be selected by entering -1. For problems for which no flux limit is desired, enter Ø (zero). Note that entering zero is <u>not</u> entering a flux of zero. It is entering a flag to the program that there is no flux limit and that the thickness of a cover layer will <u>not</u> be optimized to meet a flux limit.

3.5 Input the Number of the Layer To Undergo Thickness Optimization

Enter the number of the layer for which the layer thickness is to be optimized in order to achieve a desired flux value. The layers are numbered starting from the bottom, with the tailings as layer number 1. Therefore, layer 1 cannot be optimized, and optimization cannot be done if a flux limit has not been entered. Enter Ø (zero) if optimization is <u>not</u> desired.

3.6 Input Radon Concentration Above Top Layer

When prompted, enter the radon concentration above the top layer (in picocuries per liter). This concentration is generally the value of the soil/air interface, and a default value of Ø (zero) is assigned by entering any value less than or equal to Ø. If a value for the radon concentration at the soil/air interface were measured, it could be entered, but for tailings covers, a value of Ø is conservative and is recommended.

3.7 Input Lower Boundary Radon Flux

When prompted, enter the value for radon flux (in picocuries per square meter per second) into the soil layer beneath the tailings. For most tailings situations, this value can be considered to be zero, but for the case of a thin tailings layer, this downward flux would reduce the amount of radon available for upward diffusion. Enter -1 to calculate the radon flux out of the tailings into an infinitely thick subsoil with no radon source and to adjust the source of radon available for upward diffusion accordingly.

3.8 Input Surface Flux Precision

When prompted, enter the value for the acceptable level of numerical precision in the radon surface flux computations (in picocuries per meter squared per second). The number that should be entered is the level of computation error that is acceptable to the user between Ø (zero) and 1. The program assumes that values greater than 1 are unacceptably high. The user is cautioned that computation time increases as the value approaches zero.

4. LAYER INPUT PARAMETERS

The RADON program will enter a loop that will prompt for input parameter values that define each layer in the tailings and cover system starting from the bottom layer of the system.

4.0 Input Material Type

Name the layer.

4.1 Input Thickness

Enter the thickness of the layer in centimeters.

4.2 Input Porosity

Enter the measured porosity (unitless). The measured porosity must be between Ø (zero) and 1. Enter -1 to choose a default value of 0.40 or enter a value greater than one to calculate porosity based on a specific gravity of 2.65 and a measured value of bulk density.

4.3 Input Mass Density

If the dry bulk mass density was measured, enter a density value between 0.5 and 3 g cm^{-3}. Otherwise enter -1 to calculate the mass density of the layer based on the porosity and a specific gravity of 2.65. If the dry bulk density was measured in engineering units in terms of pounds (weight) per cubic foot, the bulk density value should be divided by 62.43, which is the weight in pounds of 1 cubic foot of water.

4.4 Type S for Source Term, G For Ore Grade, or R for Radium Activity

The user is given a choice of ways to enter the radon source term for the layer. Type S, G, or R to choose to enter the source term, to calculate it from the uranium ore grade, or to calculate it from the radium activity, respectively.

4.4.1 Input Ore Grade Percentage

If G is selected, a prompt to enter the ore grade percentage of U_3O_8 will follow. The value entered must be between Ø and 100.

4.4.2 Input Radium Activity

If R is selected, a prompt to enter the radium activity of the layer in picocuries per gram of tailings or soil will follow.

4.4.3 Input Source Term

If S is selected, a prompt to enter the radon source term for the layer in picocuries per cubic centimeter per second will follow. This input option would be used when measurements of the radon source term from the layer are available.

4.5 Input Emanation Coefficient

Following the prompt, enter the value of the radon emanation coefficient (unitless). Enter -1 to use the default value, which is 0.35.

4.6 Input Weight Percent Moisture

Following the prompt, enter the value of the weight percent moisture. This value is the weight of "free" water divided by the total weight of a dried sample. Negative values and values greater than 100 will not be accepted because they are meaningless. A calculation will be made to determine the moisture saturation fraction (the fraction of available pore space occupied by water). If the moisture saturation fraction is greater than 100%, which is physically impossible, a prompt will appear to enter an acceptable weight percent moisture value. The weight percent moisture of the layer must be entered whether the diffusion coefficient is measured or calculated.

4.7 Input Diffusion Coefficient

Following the prompt, enter either the measured diffusion coefficient or -1 to use the default calculation of the diffusion coefficient using equation 7 as described in Regulatory Position 1.1.5.

The diffusion coefficient is the final input parameter needed for the layer. The program will prompt for input for layer 2 and so on up to the maximum layer number in the same way as for layer 1.

5. INPUT DATA STORAGE

5.1 Save Data File, Erase Backup Data File

The program has a built-in procedure to save the input data file on disk drive A. This feature allows the program to be rerun without going through the data entry steps. If an error is made in data entry, the data may be easily corrected using the EDLIN program or other editing programs. Likewise, if the user wishes to analyze the effects of varying a parameter, the EDLIN program can be used to modify the input data without going through the data entry procedures. A formatted floppy diskette with available storage space must be placed in disk drive A for the program to proceed. If the user wishes to write to a hard disk, the user will need to change "A:" to "C:" in lines 1550, 1600, 1620, 1720, and 1750. The file saved on the floppy diskette will appear like the data in Table 2B under the heading "DATA SENT TO THE FILE 'RNDATA' ON DRIVE A:" None of the headings are recorded on the saved file nor are the layer numbers under the heading "LAYER." The headings in this portion of Table 2B are explained as follows:

N = number of layers
FO1 = radon flux into layer 1
CN1 = surface radon concentration
ICOST = the number of the layer to be optimized
CRITJ = desired radon flux limit
ACC = surface flux precision
DX = layer thickness
D = layer diffusion coefficient

P = layer porosity

Q = layer source term

XMS = layer moisture saturation fraction

RHO = layer density

If any key other than N is typed, the input data set will be saved. If N is typed, the program will go directly to the calculations without saving the data set on disk drive A. The data set is filed under the name RNDATA. If a second data set is entered, the first data set is renamed RNDATA.BAK, and the second set is named RNDATA. Entering more than two data sets will result in erasing RNDATA.BAK, so the user should rename RNDATA.BAK if it is to be saved. Once the RNDATA file is created, minor changes in input values can be made by using EDLIN or an editing program. A "hard" copy of the contents of the RNDATA file is part of the printed output.

6. METHODS OF COMPUTATION

The RADON program uses the computational procedures of the RAECOM program, which is listed in Reference 1 and documented in Reference 11. The diffusion equation is solved for a system of simultaneous equations for radon flux and concentration by the Gaussian elimination method. A recursion method is used to optimize the cover thickness to meet the desired radon flux.

7. OUTPUT

Table 2B displays the printed output of the RADON program for the three-layer sample problem in Appendix A and Reference 1. The printed output displays the constants used by the program, the general input parameters, the layer input parameters, including the default or calculated layer input parameters, the data saved on the floppy disk file, the calculated bare source term flux from layer 1, and the results from the radon diffusion calculations. The data for many of the output parameters are printed in the exponential format in which D is used to denote the base 10 exponent rather than the usual E because D is the notation in double-precision BASIC. Note that, for the sample problem, the input thickness for layer 3 is 100 cm, but the output thickness is 149 cm because layer 3 was specified to be adjusted so that the output radon flux would be 20 pCi $m^{-2}s^{-1}$.

A very slight difference exists between the sample problem results shown here and those in Reference 1 because the specific gravity in Reference 1 was specified to be 2.7 whereas 2.65 is used in the RADON program. Exact agreement between Reference 1 and the RADON program would result if the same specific gravities were used.

Modifications such as changing the specific gravity may be made very easily by the user because the BASIC interpreter may be used and because items in the interactive part of the program are labeled.

TABLE 1B RADON Program Listing

```
10 KEY OFF : COLOR 15,1,0 : CLS
20 PRINT "                    -----*****! RADON !*****-----" :PRINT
30 PRINT "Version 1.2 - May 22, 1989 - G.F. Birchard -  tel.# (301)492-7000"
40 PRINT "U.S. Nuclear Regulatory Commission Office of Research" : PRINT
50 PRINT "          RADON FLUX, CONCENTRATION AND TAILINGS COVER THICKNESS",
60 PRINT "                    ARE CALCULATED FOR MULTIPLE LAYERS"  : PRINT
70 ON ERROR GOTO 90
80 GOTO 120
90  PRINT "CHECK THE PRINTER & PRESS ANY KEY TO CONTINUE"
100  V$=INPUT$(1)
110  RESUME NEXT
120 LPRINT "                  -----*****! RADON !*****-----" : LPRINT
130 LPRINT "Version 1.2 - May 22, 1989 - G.F. Birchard tel.# (301)492-7000"
140 LPRINT "U.S. Nuclear Regulatory Commission Office of Research" : LPRINT
150 ON ERROR GOTO 0
160 LPRINT "        RADON FLUX, CONCENTRATION AND TAILINGS COVER THICKNESS",
170 LPRINT "                  ARE CALCULATED FOR MULTIPLE LAYERS" : LPRINT
180 INPUT "TITLE OF THIS DATA SET";TITLE$ : LPRINT :LPRINT TITLE$ :LPRINT
190 DEFDBL A-H,O-Z : DEFINT I-N
200 DIM D(50),DX(50),P(50),Q(50),XM(99) 'INPUT VARIABLES
210 DIM AB(50),AIP1MI(50),ALP(50),RHO(50),X(50),XMS(99) 'COMPUTATION VARIABLES
220 DIM A4(50),DDX(50),RC(50),RF(50) 'OUTPUT VARIABLES
230 DIM A(245),AT(50),B(99),BS(50),BU(99),G(245),R(50),RR(50),T(50),U(50)
        'MATRIX VARIABLES
240 XL=.0000021# : PC=.26# : GCT=2.65#    'CONSTANTS
250 PRINT "TYPE Y TO INPUT INTERACTIVELY OR N TO READ INPUT FROM DRIVE A:"
260 W$=INPUT$(1)
270 IF W$="y" OR W$="Y" GOTO 290
280 IF W$="N" OR W$="n" GOTO 1750 ELSE 250
290 LPRINT :LPRINT " ","CONSTANTS" :LPRINT
300 PRINT :PRINT " ","CONSTANTS" :PRINT
310 LPRINT "RADON DECAY CONSTANT"," ",XL,"s^-1"
320 PRINT "RADON DECAY CONSTANT",      " ",XL,"s^-1"
330 LPRINT "RADON WATER/AIR PARTITION COEFFICIENT",PC
```

```
340 PRINT "RADON WATER/AIR PARTITION COEFFICIENT",PC
350 LPRINT "SPECIFIC GRAVITY OF COVER & TAILINGS",GCT :LPRINT
360 PRINT "SPECIFIC GRAVITY OF COVER & TAILINGS",GCT :PRINT
370 PRINT " ","GENERAL INPUT PARAMETERS" : PRINT
380 LPRINT : LPRINT " ","GENERAL INPUT PARAMETERS" : LPRINT
390 PRINT "ENTER -1 TO USE DEFAULT VALUES WHICH ARE SPECIFIED IF THEY EXIST."
400 INPUT "NUMBER OF LAYERS OF COVER AND TAILINGS";N
410 IF N<2 GOTO 420 ELSE IF N>99 GOTO 430 ELSE 440
420 PRINT "TWO LAYERS MINIMUM PLEASE" : GOTO 400
430 PRINT "NINETY-NINE LAYERS MAXIMUM PLEASE" : GOTO 400
440 LPRINT "LAYERS OF COVER AND TAILINGS",N : GOTO 460
450 PRINT "THE LAYER THICKNESS CANNOT BE OPTIMIZED WITHOUT A FLUX LIMIT"
460 INPUT "RADON FLUX LIMIT (pCi m^-2 s^-1) default=20, no limit=0";CRITJ
470 IF CRITJ<0# THEN CRITJ=20# : PRINT "DEFAULT FLUX LIMIT ASSIGNED"
480 IF CRITJ=0 THEN LPRINT "NO LIMIT ON RADON FLUX" : GOTO 510
490 LPRINT "DESIRED RADON FLUX LIMIT"," ",CRITJ,"pCi m^-2 s^-1" :GOTO 510
500 PRINT "THE LAYER NUMBER CANNOT EXCEED THE NUMBER OF LAYERS.
510 INPUT "THE LAYER NUMBER FOR THICKNESS OPIMIZATION 0=no optimization";ICOST
520 IF CRITJ=0 AND ICOST>0 GOTO 450
530 IF ICOST=0 THEN LPRINT "LAYER THICKNESS NOT OPTIMIZED" :GOTO 570
540 IF ICOST<=1 THEN PRINT "THE LOWEST LAYER CANNOT BE OPTIMIZED" :GOTO 510
550 IF ICOST>N GOTO 500
560 LPRINT "NO. OF THE LAYER TO BE OPTIMIZED",ICOST
570 INPUT "RADON CONCENTRATION ABOVE TOP LAYER (pCi l^-1) default=0";CN1
580 IF CN1<0 THEN CN1=0
590 IF CN1=0 THEN LPRINT "DEFAULT SURFACE RADON CONCENTRATION",CN1,"pCi l^-1"
600 IF CN1>0 THEN LPRINT "MEASURED SURFACE RADON CONCENTRATION",CN1,"pCi l^-1"
610 INPUT "LOWER BOUNDARY RADON FLUX (pCi m^-2 s^-1) default=calculation";F01
620 IF F01=-1 GOTO 630 ELSE 650
630 PRINT "LOWER BOUNDARY FLUX TO BE CALCULATED ASSUMING AN INFINITE SUBSOIL
640 GOTO 660
650 LPRINT "RADON FLUX INTO LAYER 1"," ",F01,"pCi m^-2 s^-1"
660 INPUT "SURFACE FLUX PRECISION (pCi m^-2 s^-1)  This number is the acceptable
              level of computation error.";ACC
670 IF 1<ACC OR ACC<0 GOTO 680  ELSE 700
```

```
680 PRINT "THE SURFACE FLUX PRECISION SHOULD BE BETWEEN 0 AND 1"
690 GOTO 660
700 LPRINT "SURFACE FLUX PRECISION"," ",ACC,"pCi m^-2 s^-1"
710 PRINT : PRINT " ","LAYER INPUT PARAMETERS" : PRINT
720 LPRINT : LPRINT : LPRINT " ","LAYER INPUT PARAMETERS" :LPRINT
730 FOR I=1 TO N
740  PRINT USING "LAYER #";I : PRINT :PRINT : INPUT "MATERIAL TYPE"; MT$
750  LPRINT USING "LAYER #";I, : LPRINT "    ", MT$ : LPRINT : LPRINT
760  INPUT "THICKNESS (cm)";DX(I)
770  IF DX(I)<0 THEN PRINT "THE THICKNESS CANNOT BE NEGATIVE" : GOTO 760
780  LPRINT "THICKNESS"," ",DX(I),"cm"
790  INPUT "POROSITY  default =.40. Enter a value >1 to calculate porosity
     ";P(I)
800  IF P(I)>1 GOTO 820 ELSE IF P(I)=-1 GOTO 880 ELSE IF P(I)<0 GOTO 890
810  GOTO 910
820  INPUT "MASS DENSITY(G CM^-3)";RHO(I)
830  IF RHO(I)<.5 OR RHO(I)>3 GOTO 840 ELSE 860
840  PRINT "ACCEPTABLE DENSITY VALUES ARE BETWEEN 0.5 AND 3. PLEASE REENTER"
850  GOTO 820
860  P(I)=1-RHO(I)/GCT:  LPRINT "CALCULATED POROSITY "," "," ";
870  LPRINT USING "#.###"; P(I) :GOTO 980
880  P(I)=.4# : LPRINT "DEFAULT POROSITY"," ",P(I) : GOTO 920
890  PRINT "THE POROSITY VALUE CANNOT BE NEGATIVE. PLEASE REENTER."
900  GOTO 790
910  LPRINT "POROSITY "," "," ",P(I)
920  INPUT "MASS DENSITY (G/CM^-3) default=calculated";RHO(I)
930  IF RHO(I)=-1 GOTO 940 ELSE IF RHO(I)<.5 OR RHO(I)>3 GOTO 960 ELSE 980
940  RHO(I)=GCT*(1-P(I))
950  LPRINT "CALCULATED MASS DENSITY"," ",RHO(I),"g cm^-3" : GOTO 990
960  PRINT "ACCEPTABLE DENSITY VALUES ARE BETWEEN 0.5 AND 3. PLEASE REENTER"
970  GOTO 920
980  LPRINT "MEASURED MASS DENSITY"," ",RHO(I),"g cm^-3"
990  PRINT "CHOOSE TO ENTER EITHER THE RADON SOURCE TERM CONCENTRATION ,
                    THE ORE GRADE % OR RADIUM ACTIVITY"
1000  PRINT "TYPE S FOR SOURCE TERM G FOR ORE GRADE OR R FOR RADIUM ACTIVITY"
```

```
1010  QQ$=INPUT$(1)
1020  IF QQ$="S" GOTO 1230 ELSE IF QQ$="s" GOTO 1230
1030  IF QQ$="G" GOTO 1060 ELSE IF QQ$="g" GOTO 1060
1040  IF QQ$="R" GOTO 1100 ELSE IF QQ$="r" GOTO 1100 ELSE 1000
1050  PRINT "THE ORE GRADE % MUST BE BETWEEN 0 AND 100. PLEASE REENTER"
1060  INPUT "ORE GRADE PERCENTAGE";OG :IF OG<0 OR OG>100 GOTO 1050
1070  LPRINT "ORE GRADE PERCENTAGE"," ",OG,"%"
1080  RA=OG*2812#
1090  LPRINT "CALCULATED RADIUM ACTIVITY"," ",RA,"pCi g^-1" :GOTO 1130
1100  INPUT "RADIUM ACTIVITY (pCi g^-1)";RA
1110  IF RA<0 THEN PRINT "THE RADIUM ACTIVITY CANNOT BE NEGATIVE" :GOTO 1100
1120  LPRINT "MEASURED RADIUM ACTIVITY"," ",RA,"pCi/g^-1"
1130  INPUT "EMANATION COEFFICIENT default=.35";E
1140  IF E=-1 GOTO 1150 ELSE IF E<0 OR E>1 GOTO 1160 ELSE 1180
1150  E=.35# : LPRINT "DEFAULT LAYER EMANATION COEFFICIENT",E : GOTO 1190
1160  PRINT "THE EMANATION COEFFICIENT MUST BE BETWEEN 0 AND 1."
1170  GOTO 1130
1180  LPRINT "MEASURED EMANATION COEFFICIENT",E
1190  Q(I)=XL*RA*E*RHO(I)/P(I)
1200  PRINT "CALCULATED SOURCE TERM CONCENTRATION",Q(I)
1210  LPRINT "CALCULATED SOURCE TERM CONCENTRATION",
1220  LPRINT USING "##.###^^^^    ";Q(I), :LPRINT "pCi cm^-3 s^-1" :GOTO 1270
1230  INPUT "SOURCE TERM (pCi cm^-3 s^-1)";Q(I)
1240  IF Q(I)<0 GOTO 1250 ELSE 1260
1250  PRINT "THE SOURCE TERM CANNOT BE NEGATIVE." :GOTO 1230
1260  LPRINT "MEASURED SOURCE TERM CONCENTRATION",Q(I),"pCi cm^-3 s^-1"
1270  INPUT "WEIGHT % MOISTURE";XM(I)
1280  IF XM(I)<0 OR XM(I)>100 GOTO 1290 ELSE 1310
1290  PRINT "THE WEIGHT % MOISTURE MUST BE BETWEEN 0 AND 100. "
1300  GOTO 1270
1310  LPRINT "WEIGHT % MOISTURE"," ", XM(I), "%"
1320  XMS(I)=.01*XM(I)*RHO(I)/P(I)
1330  LPRINT "MOISTURE SATURATION FRACTION", :LPRINT USING " .###";XMS(I)
1340  IF XMS(I)>1! GOTO 1350 ELSE 1370
1350  PRINT "THE MOISTURE CONTENT IS >100% SATURATION. PLEASE REENTER."
```

```
1360  LPRINT "MOISTURE SATURATION >100%. NEW VALUE REQUESTED." :GOTO 1270
1370  INPUT "DIFFUSION COEFFICIENT (cm^-2 s^-1) default=calculated ";D(I)
1380  IF D(I)=-1 GOTO 1410  ELSE IF D(I)<0 OR D(I)>1 GOTO 1390 ELSE 1440
1390  PRINT "REENTER DIFFUSION COEFFICIENT VALUES BETWEEN 0 AND 1.
1400  GOTO 1370
1410  D(I)=.07*EXP(-4*(XMS(I)-XMS(I)*P(I)*P(I)+XMS(I)^5))
1420  LPRINT "CALCULATED DIFFUSION COEFFICIENT",
1430  LPRINT USING "##.###^^^^    ";D(I), :LPRINT "cm^2 s^-1" :GOTO 1450
1440  LPRINT "MEASURED DIFFUSION COEFFICIENT",D(I),"cm^2 s^-1"
1450  PRINT : PRINT : LPRINT : LPRINT
1460  IF I=2 OR I=5 AND N=5 OR I=6 OR I>8 THEN LPRINT CHR$(12)
1470 NEXT I
1480 ON ERROR GOTO 1500
1490 GOTO 1510
1500  IF ERR=53 GOTO 1540
1510 PRINT "THE BACKUP FILE RNDATA.BAK WILL BE REPLACED IF IT EXISTS UNLESS N
IS            TYPED. TYPE ANY OTHER KEY TO CONTINUE. IF N IS TYPED THE INPUT
DATA             WILL NOT BE SAVED."
1520 V$=INPUT$(1)
1530 IF V$="N" OR V$="n" GOTO 1980 ELSE GOTO 1550
1540 RESUME NEXT
1550 KILL "A:RNDATA.BAK"
1560 ON ERROR GOTO 1580
1570 GOTO 1600
1580  IF ERR=53 THEN PRINT "BACKING UP RNDATA"
1590  RESUME NEXT
1600 NAME "A:RNDATA" AS "A:RNDATA.BAK"
1610 ON ERROR GOTO 0
1620 OPEN "A:RNDATA" FOR OUTPUT AS #2
1630 PRINT #2,USING " ##.# ";N;
1640 PRINT #2,USING " ##.###^^^^";F01;CN1;
1650 PRINT #2,USING " ##.# ";ICOST;
1660 PRINT #2,USING " ##.###^^^^";CRITJ;ACC
1670 FOR I=1 TO N
1680  PRINT #2,USING " ##.###^^^^";DX(I);D(I);P(I);Q(I);XMS(I);RHO(I)
1690 NEXT I
```

```
1700 CLOSE #2
1710 LPRINT :LPRINT :LPRINT
1720 LPRINT " ","DATA SENT TO THE FILE `RNDATA' ON DRIVE A:" :LPRINT
1730 GOSUB 1850
1740 GOTO 1980
1750 OPEN "A:RNDATA" FOR INPUT AS #3
1760 INPUT #3,N,F01,CN1,ICOST,CRITJ,ACC
1770 FOR I=1 TO N
1780  INPUT #3,DX(I),D(I),P(I),Q(I),XMS(I),RHO(I)
1790 NEXT I
1800 CLOSE #3
1810 LPRINT :LPRINT :LPRINT
1820 LPRINT " ","DATA INPUT TO DIFFUSION CALCULATIONS" : LPRINT
1830 GOSUB 1850
1840 GOTO 1980
1850  ' PRINT SUBROUTINE
1860  LPRINT "  N        F01         CN1        ICOST       CRITJ        ACC"
1870  LPRINT USING "###  ";N; :  LPRINT USING " ##.###^^^^";F01;CN1;
1880  LPRINT USING "    ###    ";ICOST;
1890  LPRINT USING " ##.###^^^^";CRITJ;ACC : LPRINT
1900  LPRINT "LAYER      DX          D          P          Q          XMS
      RHO      "
1910  FOR I=1 TO N
1920   LPRINT USING "###  ";I;
1930   LPRINT USING " ##.###^^^^";DX(I);D(I);P(I);Q(I);XMS(I);
1940   LPRINT USING "###.###";RHO(I)
1950  NEXT I
1960  LPRINT : IF N=4 OR N=8 OR N>11 THEN LPRINT CHR$(12)
1970 RETURN  'END PRINT SUBROUTINE
1980   ' END DATA INPUT MODULE BEGIN RAECOM MODULE
1990 NO3=0
2000 IF ICOST>0 THEN NO3=ICOST : ICOST=1
2010 ITHK=0
2020 NO2=NO3-1 : NO1=NO2-1 : NO4=NO3+1
2030 NM1=N-1 : NM2=N-2 : JTST=1
```

```
2040 F0=F01/10000
2050 CN=CN1/1000
2060 CRITJ=CRITJ/10000
2070 FOR I=1 TO N
2080  A4(I)=1-.74*XMS(I)
2090 NEXT I
2100 AB=SQR(XL/D(1))
2110 V=AB*DX(1)
2120 GOSUB 2140
2130 GOTO 2280
2140  IF V<-9.01 GOTO 2260 'THIS SUBROUTINE CALCULATES TANH
2150  IF V<-.7 THEN GOTO 2240
2160  IF ABS(V)<=2^-12 THEN GOTO 2200
2170  IF ABS(V)<=.7 THEN GOTO 2210
2180  IF V<=9.01 THEN GOTO 2220
2190  IF V>9.01 THEN GOTO 2230
2200  TANH=V :RETURN
2210  TANH=V*(1-V^2*(.0037828+.8145651/(V^2+2.471749))) :RETURN
2220  TANH=1-2/(EXP(V)*EXP(V)+1) :RETURN
2230  TANH=1 :RETURN
2240  V=-V
2250  TANH=-(1-2/(EXP(V)*EXP(V)+1)):RETURN
2260  V=-V
2270 TANH=-1 :RETURN  'END OF SUBROUTINE TANH
2280 RF(1)=(Q(1)*P(1)/AB)*TANH
2290 IF F01=-1 GOTO 2300 ELSE 2320
2300 RF(1)=RF(1)/(1+(.5*TANH)/.5/(EXP(V)+EXP(-V)))
2310 F0 =-.5*RF(1)*TANH
2320 DDX(1)=DX(1)
2330 RC(1)=CN/A4(1)
2340 J0#=RF(1)*10000
2350 PRINT : LPRINT
2360 PRINT USING "BARE SOURCE FLUX FROM LAYER 1: ##.###^^^^ pCi m^-2 s^-1";J0#
2370 LPRINT USING "BARE SOURCE FLUX FROM LAYER 1: ##.###^^^^ pCi m^-2 s^-1";J0#
2380 PRINT "calculation in progress"
2390 FOR I=1 TO N
```

```
2400  Q(I)=Q(I)*P(I)
2410  P(I)=P(I)*A4(I)
2420  D(I)=D(I)*P(I)
2430 NEXT I
2440 DDX(1)=DX(1)
2450 ALP(1)=SQR(XL*P(1)/D(1))
2460 FOR I=2 TO N 'THICKNESS OPTIMIZATION FEEDS BACK HERE
2470  DDX(I)=DX(I)
2480 NEXT I
2490 ' MODIFY PARAMETERS FOR PROGRAM LIMITS
2500 SUMX=0 : SUMA=0 : SUMAX=0 : XRED=0 : XCHG=0 : X(1)=0 : X0=0
2510 SUMMAX=ALP(1)*DX(1)
2520 IF SUMMAX>4.61 THEN XRED=4.61/ALP(1) ELSE GOTO 2550
2530 F0=F0*EXP(4.61-SUMMAX)
2540 SUMMAX=ALP(1)*(DX(1)-XRED)
2550 IF XRED>0 THEN XCHG=DX(1)-XRED
2560 FOR I=1 TO N
2570  ALPI=SQR(XL*P(I)/D(I))
2580  SUMX=SUMX+DX(I)
2590  X(I+1)=SUMX-XCHG
2600  SUMA=SUMA+ALPI
2610  ALSUM=ALPI*X(I+1)
2620  IF ALSUM>SUMMAX THEN SUMMAX=ALSUM
2630  SUMAX=SUMAX+ALSUM
2640  ALP(I)=ALPI
2650 NEXT I
2660 IF SUMMAX>174 GOTO 2670 ELSE 2690
2670 LPRINT "THE LAYER THICKNESS OR DIFFUSION COEFFICIENT EXCEEDS LIMITS"
2680 LPRINT
2690 IF SUMMAX>87 THEN X0=SUMAX/SUMA : ELSE GOTO 2730
2700 FOR I=0 TO N
2710  X(I+1)=X(I+1)-X0
2720 NEXT I
2730 ' CALCULATE PARAMETERS FOR MATRIX
2740 FOR I=1 TO NM1
2750  RDUM=SQR(P(I+1)*D(I+1)/(P(I)*D(I)))
```

```
2760  R(I)=-.5*(1-RDUM)
2770  RR(I)=-.5*(1+RDUM)
2780  QP=(Q(I+1)/P(I+1)-Q(I)/P(I))/XL
2790  T(I)=QP*EXP(-ALP(I)*X(I+1))
2800  U(I)=QP*.5*EXP(ALP(I)*X(I+1))
2810  AIP1MI(I)=SQR(XL)*(SQR(P(I+1)/D(I+1))-SQR(P(I)/D(I)))
2820 NEXT I
2830 ALP(N)=SQR(XL*P(N)/D(N))
2840 'SPECIFY MATRIX ELEMENTS AND SOLVE
2850 FOR I=1 TO NM1
2860  J=5*I-4
2870  K=2*I-1
2880  A(J)=EXP(-2*ALP(I)*X(I+1))
2890  A(J+1)=-EXP(AIP1MI(I)*X(I+1))
2900  A(J+2)=-EXP(-(ALP(I+1)+ALP(I))*X(I+1))
2910  A(J+3)=R(I)*EXP((ALP(I+1)+ALP(I))*X(I+1))
2920  A(J+4)=RR(I)*EXP(-AIP1MI(I)*X(I+1))
2930  B(K)=T(I)
2940  B(K+1)=U(I)
2950 NEXT I
2960 N5M4=5*N-4
2970 A(N5M4)=EXP(-2*ALP(N)*X(N+1))
2980 N2M1=2*N-1
2990 B(N2M1)=(CN-Q(N)/(P(N)*XL))*EXP(-ALP(N)*X(N+1))
3000 'UPPER TRIANGULARIZE MATRIX
3010 G(1)=A(1)+EXP(-2*ALP(1)*X(1))
3020 G(2)=A(2)/G(1)
3030 G(3)=A(3)/G(1)
3040 BU(1)=(B(1)+F0*EXP(-ALP(1)*X(1))/(D(1)*ALP(1)))/G(1)
3050 FOR I=1 TO NM2
3060  J=5*I-1
3070  K=2*I
3080  G(J)=A(J)-G(J-2)
3090  G(J+1)=(A(J+1)-G(J-1))/G(J)
3100  BU(K)=(B(K)-BU(K-1))/G(J)
3110  G(J+2)=A(J+2)-G(J+1)
```

```
3120  G(J+3)=A(J+3)/G(J+2)
3130  G(J+4)=A(J+4)/G(J+2)
3140  BU(K+1)=(B(K+1)-BU(K))/G(J+2)
3150 NEXT I
3160 N5M6=5*N-6
3170 G(N5M6)=A(N5M6)-G(N5M6-2)
3180 G(N5M6+1)=(A(N5M6+1)-G(N5M6-1))/G(N5M6)
3190 N2M2=2*N-2
3200 BU(N2M2)=(B(N2M2)-BU(N2M2-1))/G(N5M6)
3210 G(N5M6+2)=A(N5M6+2)-G(N5M6+1)
3220 BS(N)=(B(N2M1)-BU(N2M1-1))/G(N5M6+2)
3230 AT(N)=BU(N2M1-1)-G(N5M6+1)*BS(N)
3240 FOR I=1 TO NM2
3250  J=5*(N-I)-3
3260  K=2*(N-I)-1
3270  L=N-I
3280  BS(L)=BU(K)-G(J)*AT(L+1)-G(J+1)*BS(L+1)
3290  AT(L)=BU(K-1)-G(J-2)*BS(L)
3300 NEXT I
3310 BS(1)=BU(1)-G(2)*AT(2)-G(3)*BS(2)
3320 AT(1)=(BS(1)*EXP(-ALP(1)*X(1))-F0/(ALP(1)*D(1)))*EXP(-ALP(1)*X(1))
3330 'COMPLETE MATRIX SOLUTION
3340 FOR I=1 TO N
3350  ALPI=ALP(I)*X(I+1)
3360  ASI=AT(I)*EXP(ALPI)
3370  BSI=BS(I)*EXP(-ALPI)
3380  RC(I)=ASI+BSI+Q(I)/(P(I)*XL)
3390  RF(I)=-D(I)*ALP(I)*(ASI-BSI)
3400 NEXT I
3410 RC(N)=CN
3420 IF ICOST=0 GOTO 3800
3430 FOP=F0
3440 IF F0<1 THEN FOP=1
3450 IF RF(1)<0 OR RF(1)=0 THEN RF(1)=1
3460  'BEGIN COVER THICKNESS OPTIMIZATION
3470 IF JTST=0 OR CRITJ>99 OR NOT CRITJ>0 GOTO 3800
```

```
3480 T7=(RF(N)-CRITJ)/CRITJ
3490 ABT7=ABS(T7)
3500 IF ABT7<ACC GOTO 3800
3510 NTST=NO3
3520 IIJ=NO2
3530 IF NTST=NSAVE GOTO 3560
3540 DXMAX=0 : DXMIN=0 : RFMAX=0 : RFMIN=0
3550 NSAVE=NTST
3560 'SET LIMITS AND SEARCH FOR DX
3570 IF T7=0 GOTO 3800
3580 IF T7<0 THEN DXMAX=DX(NTST) ELSE 3600
3590 RFMIN=RF(N) : GOTO 3610
3600 DXMIN=DX(NTST) : RFMAX=RF(N)
3610 IF DXMAX=0 GOTO 3620 ELSE 3630
3620 DX(NTST)=DX(NTST)*(1+.5*T7) : GOTO 3640
3630 DX(NTST)=DXMIN+(DXMAX-DXMIN)*(RFMAX-CRITJ)/(RFMAX-RFMIN)
3640 IF RFMAX=0 THEN DX(NTST)=.5*DXMAX
3650 IF NOT DX(NTST)>1 THEN DX(NTST)=0: JTST=0
3660 IF ITHK=0 GOTO 2460
3670 T2T=0
3680 IF NO4>N GOTO 3720
3690 FOR IJ=NO4 TO N
3700  T2T=T2T+DX(IJ)
3710 NEXT IJ
3720 IF NO1<2 GOTO 3760
3730 FOR IJ=2 TO NO1
3740 T2T=T2T+DX(IJ)
3750 NEXT IJ
3760 T23=DX(NTST)
3770 T2T=T2T+DX(NTST)
3780 IF NOT DX(NTST)=T23 THEN CRITJ=-1
3790 GOTO 2460
3800 'PRINT RESULTS
3810 PRINT : PRINT "    RESULTS OF RADON DIFFUSION CALCULATIONS" : PRINT
3820 PRINT "  LAYER    THICKNESS    EXIT FLUX    EXIT CONC.",
3830 PRINT "             (cm)    (pCi m^-2 s^-1) (pCi l^-1) " : LPRINT
```

```
3840 FOR I=1 TO N
3850 RXYZ=RF(I)*10000
3860 CXYZ=RC(I)*1000*A4(I)
3870  PRINT USING "  ###  ";I;
3880  PRINT USING "   ##.###^^^^";DDX(I);RXYZ;CXYZ
3890 NEXT I
3900 LPRINT :LPRINT
3910 LPRINT " ","RESULTS OF THE RADON DIFFUSION CALCULATIONS"
3920 LPRINT :LPRINT
3930 LPRINT " ","LAYER    THICKNESS    EXIT FLUX    EXIT CONC."
3940 LPRINT " ","           (cm)    (pCi m^-2 s^-1) (pCi l^-1) "
3950 LPRINT
3960 FOR I=1 TO N
3970  RXYZ=RF(I)*10000
3980  CXYZ=RC(I)*1000*A4(I)
3990  LPRINT " ", : LPRINT USING "###  ";I;
4000  LPRINT USING "   ##.###^^^^";DDX(I);RXYZ;CXYZ
4010 NEXT I
4020 LPRINT CHR$(12)
4030 END
```

TABLE 2B RADON Program Sample Problem Output

-----*****! RADON !*****-----

Version 1.2 - May 22, 1989 - G.F. Birchard tel. # (301)492-7000
U.S. Nuclear Regulatory Commission Office of Research

RADON FLUX, CONCENTRATION, AND TAILINGS COVER THICKNESS ARE CALCULATED FOR MULTIPLE LAYERS

THREE-LAYER SAMPLE PROBLEM

CONSTANTS

RADON DECAY CONSTANT	.0000021	s^-1
RADON WATER/AIR PARTITION COEFFICIENT	.26	
SPECIFIC GRAVITY OF COVER & TAILINGS	2.65	

GENERAL INPUT PARAMETERS

LAYERS OF COVER AND TAILINGS	3	
DESIRED RADON FLUX LIMIT	20	pCi m^-2 s^-1
NO. OF THE LAYER TO BE OPTIMIZED	3	
DEFAULT SURFACE RADON CONCENTRATION	0	pCi l^-1
RADON FLUX INTO LAYER 1	0	pCi m^-2 s^-1
SURFACE FLUX PRECISION	.001	pCi m^-2 s^-1

LAYER INPUT PARAMETERS

LAYER 1 TAILINGS

THICKNESS	500	cm
POROSITY	.44	
CALCULATED MASS DENSITY	1.484	g cm^-3
MEASURED SOURCE TERM CONCENTRATION	.000573	pCi cm^-3 s^-1
WEIGHT % MOISTURE	11.7	%
MOISTURE SATURATION FRACTION	.395	
MEASURED DIFFUSION COEFFICIENT	.013	cm^-2 s^-1

LAYER 2 CLAY COVER

THICKNESS	50	cm
POROSITY	.3	
CALCULATED MASS DENSITY	1.855	g cm^-3
MEASURED SOURCE TERM CONCENTRATION	0	pCi cm^-3 s^-1
WEIGHT % MOISTURE	6.3	%
MOISTURE SATURATION FRACTION	.390	
MEASURED DIFFUSION COEFFICIENT	.0078	cm^-2 s^-1

LAYER 3 SOIL COVER

THICKNESS	100	cm
POROSITY	.37	
CALCULATED MASS DENSITY	1.6695	g cm^-3
MEASURED SOURCE TERM CONCENTRATION	0	pCi cm^-3 s^-1
WEIGHT % MOISTURE	5.4	%
MOISTURE SATURATION FRACTION	.244	
MEASURED DIFFUSION COEFFICIENT	.022	cm^2 s^-1

DATA SENT TO THE FILE 'RNDATA' ON DRIVE A:

N	F01	CN1	ICOST	CRITJ	ACC
3	0.000D+00	0.000D+00	3	2.000D+01	1.000D-03

LAYER	DX	D	P	Q	XMS	RHO
1	5.000D+02	1.300D-02	4.400D-01	5.730D-04	3.946D-01	1.484
2	5.000D+01	7.800D-03	3.000D-01	0.000D+00	3.895D-01	1.855
3	1.000D+02	2.200D-02	3.700D-01	0.000D+00	2.437D-01	1.670

BARE SOURCE FLUX FROM LAYER 1: 1.984D+02 pCi m^-2 s^-1

RESULTS OF THE RADON DIFFUSION CALCULATIONS

LAYER	THICKNESS (cm)	EXIT FLUX (pCi m^-2 s^-1)	EXIT CONC. (pCi l^-1)
1	5.000D+02	7.691D+01	1.670D+05
2	5.000D+01	4.524D+01	4.430D+04
3	1.490D+02	2.001D+01	0.000D+00

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VALUE/IMPACT STATEMENT

A draft value/impact statement was published with the draft version of this regulatory guide (Task WM 503-4) when the draft guide was published for public comment in May 1987. No changes were necessary, so a separate value/impact statement for the final guide has not been prepared. A copy of the draft value/impact statement is available for inspection and copying for a fee at the Commission's Public Document Room at 2120 L Street NW., Washington, DC, under Task WM 503-4.

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