MKE UMTRA DESIGN PROCEDURES

CHAPTER 6

RADON BARRIER

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6A Example Calculation of Growth of Thorium into Radium for Determination of Maximum Radium Content

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CHAPTER 6
RADON BARRIER

6.1 INTRODUCTION

In most cases, the radon barrier thickness will have been determined during the conceptual design phase. The basis for, and adequacy of, this design should be reviewed, as outlined in Chapter 2 of this manual, and the reasons for proceeding with an additional design should be listed as required therein.

As discussed in Chapter 1, the primary purpose of the radon barrier is to limit the average radon exhalation to 20 pCi/m^2/sec. or less, throughout the 200-year to 1000-year design life of the remedial action (Ref. 6-1). This requirement is met by providing a layer or layers of compacted soil of specified thickness. Presently, the minimum acceptable thickness is determined by using the RAECOM model (Ref. 6.2).

Because in most cases the radon barrier provides significant resistance to infiltration of precipitation, this resistance is included in the analysis of infiltration and potential migration of contaminants as described in Chapter 9. If greater infiltration resistance is required, more than one alternative cover design may have to be developed. Modifying the radon barrier soil with the addition of bentonite or inclusion of liner materials (Ref. 6.4, pg. 90) should also be considered, if special site conditions dictate, to control infiltration as outlined in Chapter 9. However, the primary focus of the design will be to utilize natural soil, thus simplifying construction and affording a greater level of confidence in the long-term performance of the cover.

6.2 INPUT DATA AND PARAMETERS

A. Radium Content of Tailings

The radium content changes with time, as the radium present decays into radon and the thorium present decays into radium. The governing equation (Ref. 6.3) is:

$$Ra(t) = \frac{\lambda_2 (Th)_o (e^{-\lambda_1 t} - e^{-\lambda_2 t})}{\lambda_1 - \lambda_2} + (Ra)_o e^{-\lambda_2 t} \qquad \text{(EQUATION 6.1)}$$

where λ_1 = decay constant for Th = 8.63×10^{-6} year^{-1}

λ_2 = decay constant for Ra = 4.32×10^{-4} year^{-1}

$(Th)_o$ = initial content of Thorium-230

$(Ra)_o$ = initial content of Radium-226

e = Napierian base of logarithms

and t = time = design life.

To determine input values, $(Th)_O$ and $(Ra)_O$, it is necessary to obtain average values for the tailings. The concentrations may vary significantly from point to point. It may be necessary to sub-divide the tailings into layers and sub-areas. The concentration in the upper 10 feet is especially important, as this zone has a dominant influence on radon barrier requirements.

The number of sample points needed to develop meaningful average values of $(Th)_O$ and $(Ra)_O$ for a given site will depend on the variability of these parameters at the site. The values determined at each depth in each boring should be shown on soil profiles to aid in deciding whether sufficient data are available.

If sufficient Th and Ra readings are available, the merits of dividing the tailings into layers and sub-areas can be studied. If the average Ra content in a large sub-area or layer of significant thickness differs from that of another area or layer by a factor exceeding 1.5, separate average values should be computed for each sub-area and layer. A similar evaluation should be made with respect to Th content. For sites which exhibit wide spatial variation in radon content, some statistical frequency analyses may be necessary for developing the modeled section and the geometry of the tailing piles.

B. Long-Term (Residual) Moisture Contents of Tailings and Radon Barrier

Soil moisture plays a dominant role in the control of radon diffusion (Ref. 6.4, page 21). The current procedure for estimating the average residual (design life) moisture content for a given soil layer (tail-

ings layer or radon barrier), is to use the following equation (Ref. 6.2, pg. xiv):

$$m_r = (0.124\ P_p^{0.5} - 0.001E_v - 0.04 + 0.156\ f_{cm}) \qquad \text{(EQUATION 6.2)}$$

where m_r = residual fraction of moisture saturation

P_p = annual precipitation (inches)

E_v = annual lake evaporation (inches)

f_{cm} = fraction of soil passing No. 200 sieve

Parameters P_p and E_v are fixed for a given site but, f_{cm} must be known for each layer of tailings and radon barrier.

Recent research (Ref. 6.5, pg. 274) indicates that the wilting point (15-bar moisture content) may be the long-term moisture content of many compacted soils. This parameter is determined by ASTM D2325 (coarse-grained soils) or ASTM 3152 (fine-grained soils). Until this approach is endorsed by NRC, however, Equation 6.2 should be used.

C. Radon Diffusion Coefficients of Tailings and Radon Barrier

Estimated values of the radon diffusion coefficient (D) can be obtained as follows (Ref. 6.2, pg. xiii):

$$D = 0.07\ e^{-4(m_r - m_r p^2 + m_r^5)} \qquad \text{(EQUATION 6.3)}$$

where D = diffusion coefficient in cm^2/sec.

m_r = residual fraction of moisture saturation,

and p = porosity.

This equation can be used for preliminary design but measured values should be used for final design. Measurements should be accomplished at the minimum density required by the specifications and at water contents above and below the expected long-term value so that D versus m_r curves can be constructed for the cover and the tailings. In this way design diffusion coefficients can be determined from the D versus m_r curves for the selected design residual moisture contents (m_r) for the cover and the tailings. If more than one borrow source is considered, or an additive is to be mixed with the radon barrier soil, a D versus m_r curve will be required for each additional material.

D. Radon Emanation Coefficient for Tailings

The emanating power (E) of a soil containing radium is the fraction of the radon generated that is free to diffuse from the soil. E varies from 0.02 to 0.42 depending upon moisture content and other tailings

characteristics (Ref. 6.2, pg. 5-2). E should be determined by laboratory testing of representative tailings samples (Ref. 6-1, p. 13). E values are not needed for layers which do not produce radon.

E. Summary of Parameters t. ailings and Radon Barrier

The parameters required for the various sub-areas and layers, and the site and soil characteristics needed to develop these parameters, should be summarized in tables similar to Table 6-1 for each sub-area. The sources of all the basic and computed data also should be clearly identified.

6.3 METHODOLOGY

A. Calculation of Maximum Radium Content

As discussed in Section 6.2.A, the total radium concentration in the tailings at any time (t) will be given by Equation 6.1. The radium concentration may reach a maximum during or at the end of the design life. Lawrence Livermore Laboratory has a computer code for Equation 6.1. The code prints out radium concentrations at equal time periods within each logarithmic interval, along with a plot of radium concentration vs. time. (An example calculation is shown in Appendix 6-A.) This code was used for design calculations for Burrell site. A similar computer code is being developed and introduced into the in-house (MKE) system.

The average values of $(Th)_0$ and $(Ra)_0$ are entered into the computer code, along with λ_1 and λ_2 (see Sec. 6.2 for definitions), and the print-out covering 1000 years is obtained. The maximum value of Ra-226 concentration is selected from the output and used for radon barrier thickness calculations.

B. Calculation of Long-Term Degree of Saturation Values

Annual precipitation, P, annual lake evaporation, E_v, and fraction of soil passing the No. 200 sieve, f_{cm}, are used with Equation 6.2 to calculate the long-term degree of saturation for each layer of tailings and the radon barrier (hand calculation).

C. Determination of Diffusion Coefficients

The long-term degree of saturation (m_r) and the expected average porosity (p) for each material are used with Equation 6.3 to calculate the corresponding diffusion coefficient (D).

The predicted long-term degree of saturation of cover (m_r) and average porosity, p, for each material are used with the corresponding respective best fit curve established from the experimentally-determined plots of D vs. m_r for that material.

D. Determination of Radon Barrier Thickness

As stated in the introduction, the minimum acceptable thickness for a given tailings sub-area is determined using the RAECOM model (Ref. 6.4). The flow chart, showing the major components of the model, is presented in Figure 6-1. The required input parameters are listed in Table 6-2, and the modeled soil profile is shown in Figure 6-2. The Radon Attenuation Handbook (Ref. 6.2) should be reviewed before using this model.

The model code automatically computes the minimum barrier thickness corresponding to the allowable flux of 20 pCi/m^2/sec. An example input and output record from the RAECOM code is included as Appendix 6-B. The computed minimum thickness should be increased by at least 0.2 feet to allow for construction accuracy, and to the next whole inch for construction control simplicity. To accommodate degradation and various other uncertainties associated with the cover design, which is in the process of evolution, the need for multiplying the computed cover thickness by a factor (>1) to arrive at the design thickness is being debated and discussed. If this change is approved, an addendum will be issued.

6.4 DESIGN SUMMARY

The Site Design Engineer shall prepare a cover thickness design summary for different sub-areas, using a format similar to that shown in Table 6-3 and Figure 6-2. The minimum computed thickness and the design thickness should be clearly indicated. It also must be clearly indicated that the design thicknesses shown in Table 6-3 do not include the thickness of the cover protection materials. The prospective borrow source(s) considered for cover design also should be identified. The modeled section developed should be based on either a single layer or multilayer cover system, as appropriate. An example of a multilayer system is shown in Figure 6-2; a single-layer system is shown in Figure 6-3.

6.5 REFERENCES

6.1 U.S. Department of Energy, "Plan for Implementing EP. Standards for UMTRA Sites", UMTRA-DOE/AL-163, January, 1984.

6.2 Rogers, V. C., Nielson, K. K. and ' lkwarf, D. R., Radon Attenuation Handbook for Uranium Mi l Tailings Cover Design, U.S. Nuclear Regulatory Commission, NUREG/CR-3533, 1984.

6.3 Lapp, R. E., and Andrews, H. L., Nuclear Radiation Physics, Second Edition, 1954.

6.4 U.S. Department of Energy, Technical Summary of the UMTRA Project Technology Development Program, (1980-1984), UMTRA-DOE/AL 200125.0000, January, 1985.

6.5 Gee, G. W., Nielson, K. K. and Rogers, V. C., "Predicting Long-Term Moisture in Earthen Covers", Proceedings, Sixth Symposium on Management of Uranium Mill Tailings, Low-Level Waste, and Hazardous Waste, Fort Collins, Colorado, pages 267-276, 1984.

TABLE 6-1. PARAMETERS FOR RADON BARRIER DESIGN

Sub-Area No.	Material Layer & No.	Layer Thickness cm	ft.	Avg. Conc. (pCi/gm) Ra-226	Th-230	Fines Content (-No.200 Frac.), f_{cm}	Moisture Fraction, m_r g/cm^3	Dry Density, γ_d (pcf)	g/cm^3	Sp. Gr. G	Porosity P	Source Term, pCi/cm^3/sec.	Diffusion Coeff., D cm^2/sec.	Moisture Content, M %	Std Proctor Compaction %
1	Tailings-1														
	Tailings-2														
	Tailings-3														
	Tailings-4														
	Tailings-5														
	Tailings-6														
	Tailings-7														
	Radon Barrier														

Average Precipitation, P_p = ________ inches/yr.

Lake Evaporation, E_v = ________ inches/yr.

Emanating Power, E_p = 0.2 for all layers

Thorium decay constant, λ_1 = ________

Radium decay constant, λ_2 = ________

Background Radon Concentration = ________ pCi/1

TABLE 6-2. INPUT DATA FOR RAECOM

(USER INFORMATION FOR RAECOM [1])

		MODELED SECTION	LAYER NOS.
HEADING FOR THE RAECOM RUN			
NUMBER OF LAYERS, TAILINGS AND COVER			1
*INITIAL FLUX INTO LAYER 1 (pCi/m^2-s)	0.		2
*AMBIENT AIR RADON CONCENTRATION (pCi/l)	Background		3
LAYER TO BE OPTIMIZED	(Layer No. or 0.) [2]		
*FLUX LIMIT AT SURFACE (pCi/m^2-s)	20. or 0. [2]		
*ACCURACY NEEDED (.1 TO .0001)	0.001		

Layer No. N	Lowest Layer 1	2	3	4	5	6	7
*THICKNESS OF LAYER N (cm)							
*DIFFUSION COEFF. OF LAYER N (cm^2/s)							
*POROSITY OF LAYER N (FRACTION)							
*PROJECTED RA-226 CONC. OF LAYER N (pCi/g)							
*EMANATING FRACTION OF LAYER N (FRACTION)							
*BULK DENSITY OF LAYER N (g/cm^3)							
*MOISTURE CONTENT OF LAYER N (% DRY WT)							

Notes:

[1] On MKE Harris system RAECOM will read and input file (see User's Manual). File is created by input of all data above in order presented. (All data for each layer is input first.)

[2] First value will cause minimum required thickness of optimized layer to be calculated. Second value will cause flux to be calculated for all layers.

* [illegible]

TABLE 6-3

RADON BARRIER THICKNESS DESIGN SUMMARY

1. Sub Area Number	1	2	3	4
2. Projected Ra-226 (pCi/gm)				
3. Diffusion Coefficient (cm^2/sec.)				
4. Minimum Computed Thickness of Barrier without protective cover				
5. Design Thickness of Barrier without protective cover				
6. Single or Multilayer Cover System				
7. Prospective Cover Material Source				

8. Comments:

1. See Modeled Section in Figure 6-2.

2.

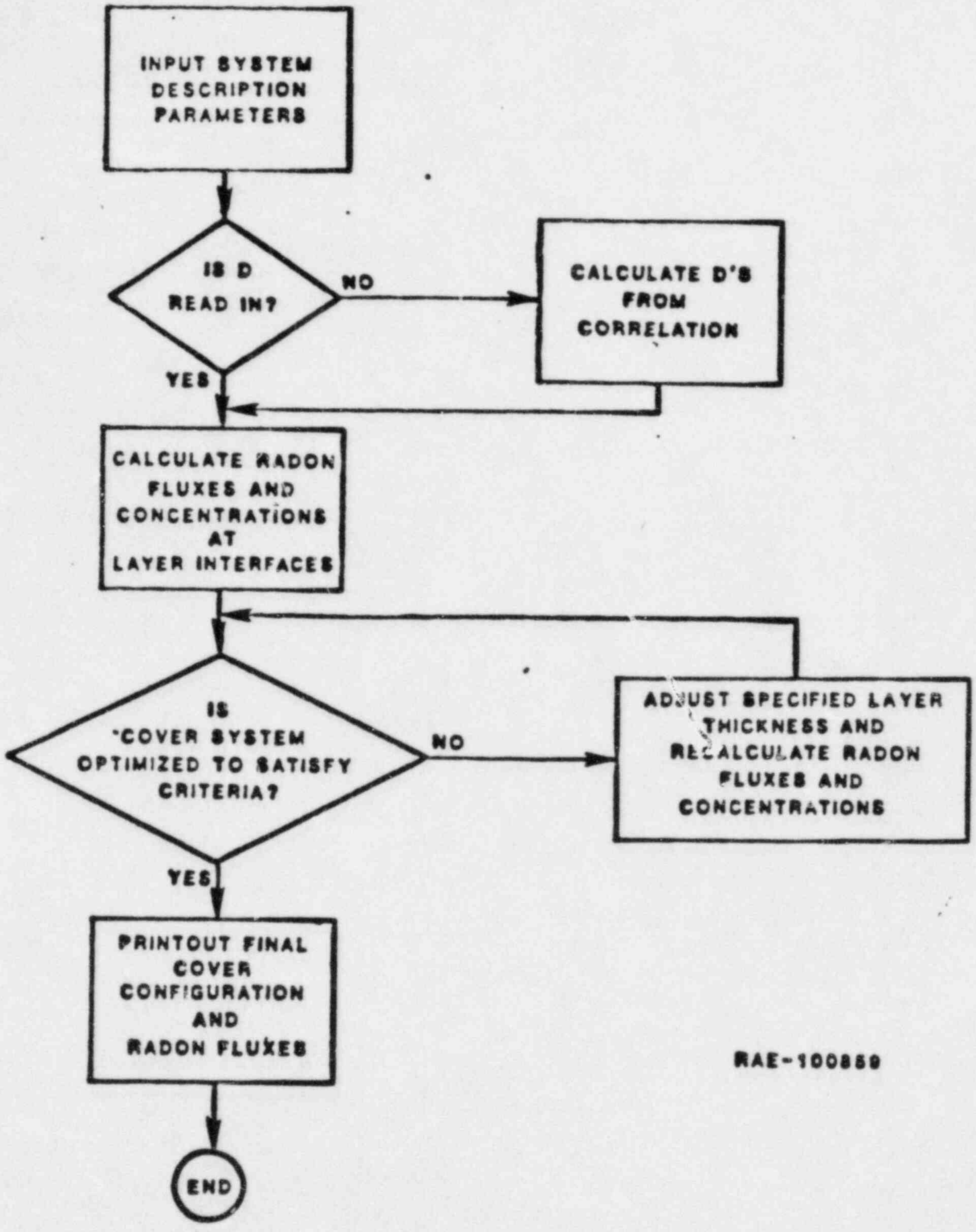


FIGURE 6-1. FLOW CHART SHOWING COMPONENTS OF RAECOM MODEL. (REF. 6-2)

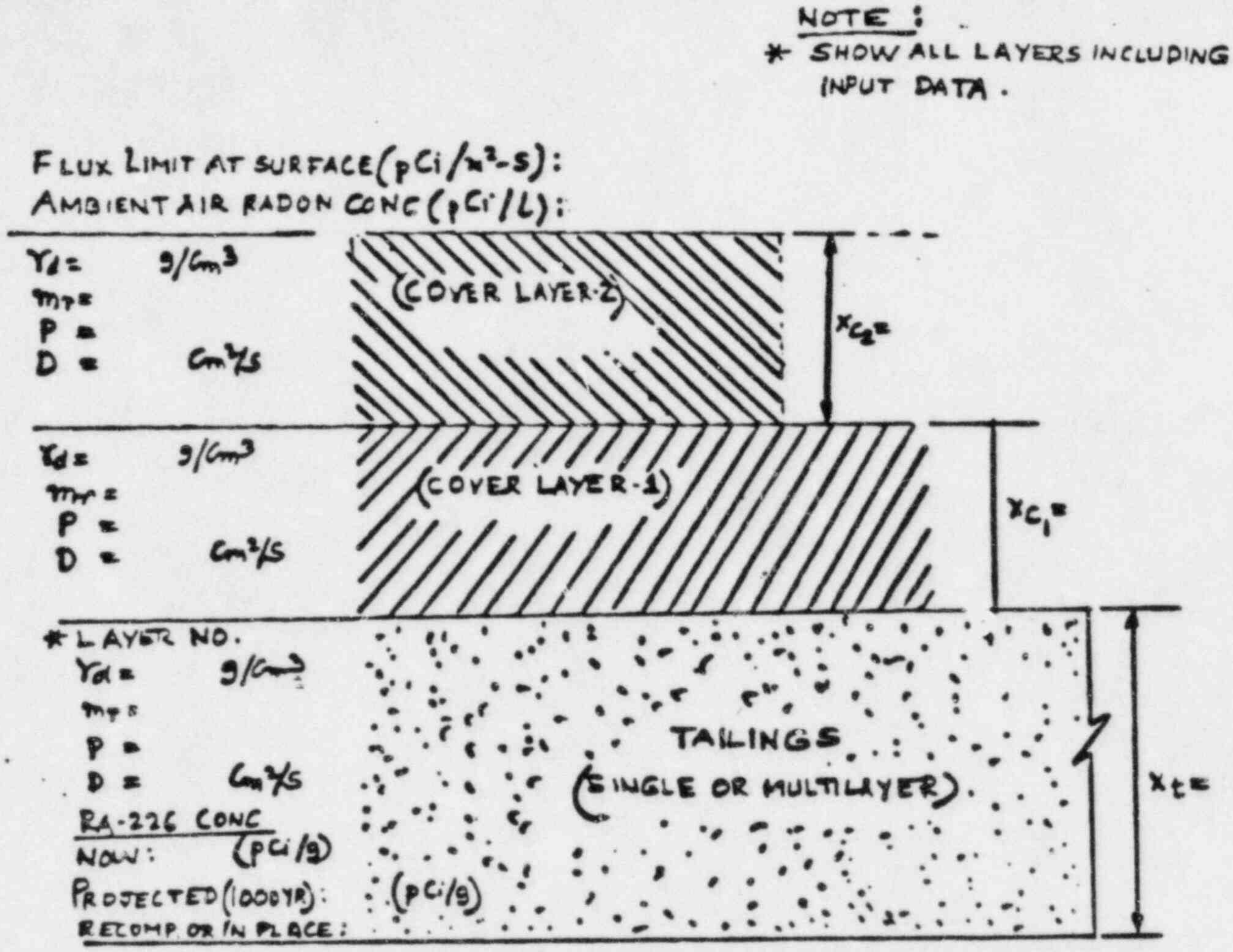


FIGURE 6-2. MODELED SECTION WITH MULTI-LAYER COVER

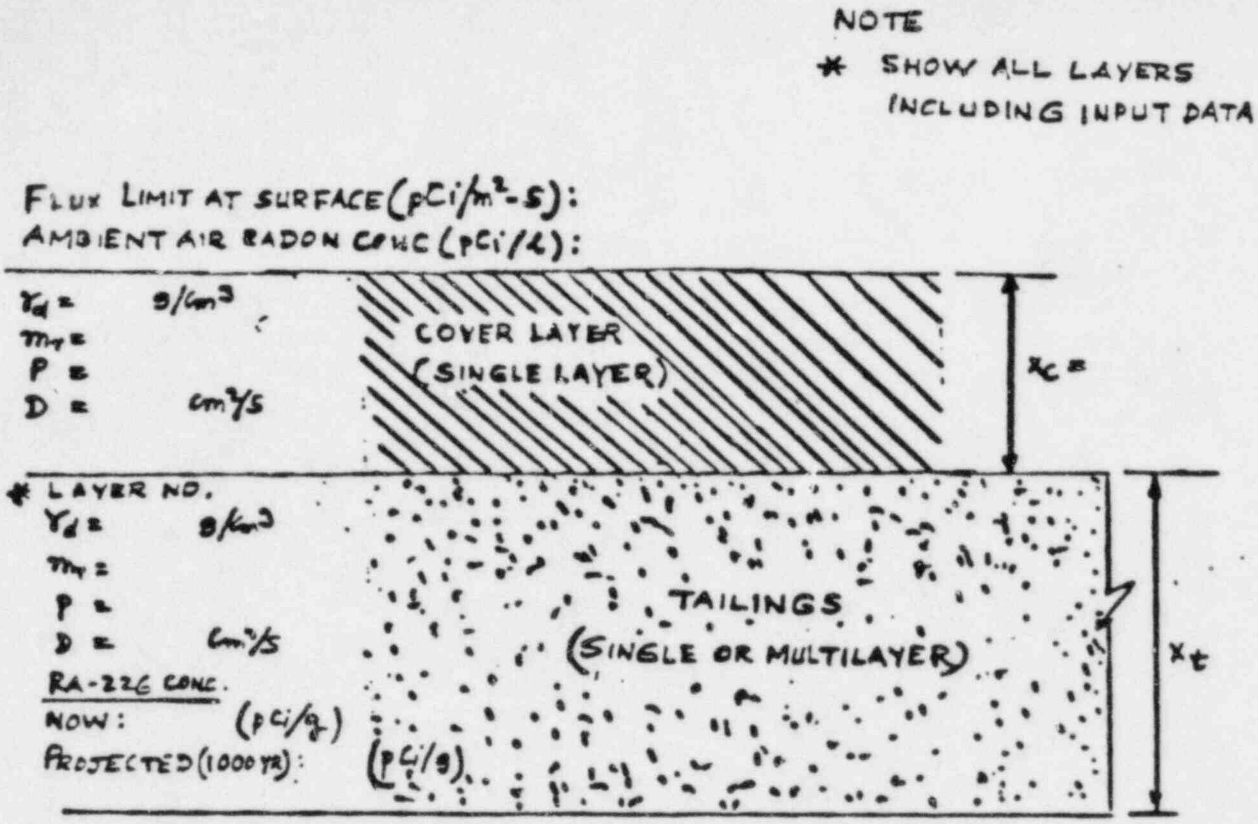


FIGURE 6-3. MODELED SECTION WITH SINGLE LAYER COVER

APPENDIX 6A

EXAMPLE CALCULATION OF DECAY OF THORIUM INTO RADIUM FOR DETERMINATION OF MAXIMUM RADIUM CONTENT

APPENDIX 6A

EXAMPLE CALCULATION OF DECAY OF THORIUM INTO RADIUM FOR DETERMINATION OF MAXIMUM RADIUM CONTENT

The enclosed calculation was produced by substituting the values given for time, t, in the first column, into Equation 6.1, with the values for λ_1 and λ_2 shown on page 6-2, and the following values for the other parameters:

$(Th)_o$ = 3,080 pCi/g,

and $(Ra)_o$ = 640 pCi/g.

The $(Ra)_o$ value is given for Canonsburg in Ref. 6A-1, page F.2-11, and the $(Th)_o$ value was computed from the average Th/Ra ratio given for Canonsburg Area A in Ref. 6A-2, page 464.

The results of the calculations, as shown in Columns 2 and 3, are the values of Th-230 and Ra-226 corresponding to each value of t. Ra-226 increases continually throughout the 1,000-year design period, as shown in the plot at the end of the calculations, so that the maximum value is reached at the end of the design period. From the tabulation of values, $(Ra)_{max} = (Ra)_{1000}$ = 1500 pCi/g. Thus the ratio $(Ra)_{1000}/(Ra)_o$ = 1500/640 = 2.34. This is essentially the same value as that reported for this situation in Ref. 6A-2, page 465.

References for Appendix 6A

6A-1 Baker, K. R., D. E. Mohr, and R. L. Hillman, "Radiological Aspects - Canonsburg, Pennsylvania UMTRA Site," Sixth Symposium on Management of Uranium Mill Tailings, Low-Level Waste, and Hazardous Waste, Fort Collins, Colorado, February 1984, pp 463-472.

6A-2 U.S. Department of Energy, Remedial Action Plan for Stabilization of the Inactive Uranium Mill Tailings Site at Canonsburg, Pennsylvania, UMTRA-DOE/AL-140, October 1983.

RADIOACTIVE DECAY CHAIN
FROM (T1) = 1.00E+03 TO (T2) = 1.00E+07

INITIAL INPUT

		HALF-LIFE	CURIE
ISOTOPE 1 =	TH230	8.03E+07	1.08E+02
ISOTOPE 2 =	RA226	1.60E+03	6.40E+02
ISOTOPE 3 =	BK101	1.00E+10	0.
ISOTOPE 4 =	BK102	1.10E+10	0.
ISOTOPE 5 =	BK103	1.20E+10	0.
ISOTOPE 6 =	BK104	1.30E+10	0.
ISOTOPE 7 =	BK105	1.40E+10	0.

TIME IS IN HOURS, ACTIVITY IS IN PCI/G

TIME	TH 230	RA 226
1.00E+03	1.08E+01	6.40E+02
1.20E+03	1.08E+01	6.40E+02
1.40E+03	1.08E+01	6.40E+02
1.60E+03	1.08E+01	6.40E+02
1.80E+03	1.08E+01	6.40E+02
2.00E+03	1.08E+01	6.40E+02
2.20E+03	1.08E+01	6.40E+02
2.40E+03	1.08E+01	6.40E+02
2.60E+03	1.08E+01	6.40E+02
2.80E+03	1.08E+01	6.40E+02
3.00E+03	1.08E+01	6.40E+02
3.20E+03	1.08E+01	6.40E+02
3.40E+03	1.08E+01	6.40E+02
3.60E+03	1.08E+01	6.40E+02
3.80E+03	1.08E+01	6.40E+02
4.00E+03	1.08E+01	6.40E+02
4.20E+03	1.08E+01	6.41E+02
4.40E+03	1.08E+01	6.41E+02
4.60E+03	1.08E+01	6.41E+02
4.80E+03	1.08E+01	6.41E+02
5.00E+03	1.08E+01	6.41E+02
5.20E+03	1.08E+01	6.41E+02
5.30E+03	1.08E+01	6.41E+02
5.60E+03	1.08E+01	6.41E+02
5.80E+03	1.08E+01	6.41E+02
6.00E+03	1.08E+01	6.41E+02
6.20E+03	1.08E+01	6.41E+02
6.40E+03	1.08E+01	6.41E+02
6.60E+03	1.08E+01	6.41E+02
6.80E+03	1.08E+01	6.41E+02
7.00E+03	1.08E+01	6.41E+02
7.20E+03	1.08E+01	6.41E+02
7.40E+03	1.08E+01	6.41E+02
7.60E+03	1.08E+01	6.41E+02
7.80E+03	1.08E+01	6.41E+02
8.00E+03	1.08E+01	6.41E+02
8.20E+03	1.08E+01	6.41E+02
8.40E+03	1.08E+01	6.41E+02
8.60E+03	1.08E+01	6.41E+02
8.80E+03	1.08E+01	6.41E+02
9.00E+03	1.08E+01	6.41E+02
9.20E+03	1.08E+01	6.41E+02
9.40E+03	1.08E+01	6.41E+02
9.60E+03	1.08E+01	6.41E+02

TIME	TH 230	RA 226
0.00E+00	3.08E+03	6.41E+02
1.00E+04	3.08E+03	6.41E+02
1.20E+04	3.08E+03	6.41E+02
1.40E+04	3.08E+03	6.42E+02
1.60E+04	3.08E+03	6.42E+02
1.80E+04	3.08E+03	6.42E+02
2.00E+04	3.08E+03	6.42E+02
2.20E+04	3.08E+03	6.43E+02
2.40E+04	3.08E+03	6.43E+02
2.60E+04	3.08E+03	6.43E+02
2.80E+04	3.08E+03	6.43E+02
3.00E+04	3.08E+03	6.44E+02
3.20E+04	3.08E+03	6.44E+02
3.40E+04	3.08E+03	6.44E+02
3.60E+04	3.08E+03	6.44E+02
3.80E+04	3.08E+03	6.45E+02
4.00E+04	3.08E+03	6.45E+02
4.20E+04	3.08E+03	6.45E+02
4.40E+04	3.08E+03	6.45E+02
4.60E+04	3.08E+03	6.46E+02
4.80E+04	3.08E+03	6.46E+02
5.00E+04	3.08E+03	6.46E+02
5.20E+04	3.08E+03	6.46E+02
5.40E+04	3.08E+03	6.47E+02
5.60E+04	3.08E+03	6.47E+02
5.80E+04	3.08E+03	6.47E+02
6.00E+04	3.08E+03	6.47E+02
6.20E+04	3.08E+03	6.47E+02
6.40E+04	3.08E+03	6.48E+02
6.60E+04	3.08E+03	6.48E+02
6.80E+04	3.08E+03	6.48E+02
7.00E+04	3.08E+03	6.48E+02
7.20E+04	3.08E+03	6.49E+02
7.40E+04	3.08E+03	6.49E+02
7.60E+04	3.08E+03	6.49E+02
7.80E+04	3.08E+03	6.49E+02
8.00E+04	3.08E+03	6.50E+02
8.20E+04	3.08E+03	6.50E+02
8.40E+04	3.08E+03	6.50E+02
8.60E+04	3.08E+03	6.50E+02
8.80E+04	3.08E+03	6.51E+02
9.00E+04	3.08E+03	6.51E+02
9.20E+04	3.08E+03	6.51E+02
9.40E+04	3.08E+03	6.51E+02
9.60E+04	3.08E+03	6.52E+02
9.80E+04	3.08E+03	6.52E+02
1.00E+05	3.08E+03	6.53E+02
1.20E+05	3.08E+03	6.54E+02
1.40E+05	3.08E+03	6.57E+02
1.60E+05	3.08E+03	6.59E+02
1.80E+05	3.08E+03	6.62E+02
2.00E+05	3.08E+03	6.64E+02

TIME	TH 230	RA 226
2.20E+05	2.98E+03	6.66E+02
2.40E+05	3.08E+03	6.69E+02
2.60E+05	3.08E+03	6.71E+02
2.80E+05	3.08E+03	6.74E+02
3.00E+05	3.08E+03	6.76E+02
3.20E+05	3.08E+03	6.78E+02
3.40E+05	3.08E+03	6.81E+02
3.60E+05	3.08E+03	6.83E+02
3.80E+05	3.08E+03	6.85E+02
4.00E+05	3.08E+03	6.88E+02
4.20E+05	3.08E+03	6.90E+02
4.40E+05	3.08E+03	6.93E+02
4.60E+05	3.08E+03	6.95E+02
4.80E+05	3.08E+03	6.97E+02
5.00E+05	3.08E+03	7.00E+02
5.20E+05	3.08E+03	7.02E+02
5.40E+05	3.08E+03	7.04E+02
5.60E+05	3.08E+03	7.07E+02
5.80E+05	3.08E+03	7.09E+02
6.00E+05	3.08E+03	7.11E+02
6.20E+05	3.08E+03	7.14E+02
6.40E+05	3.08E+03	7.16E+02
6.60E+05	3.08E+03	7.18E+02
6.80E+05	3.08E+03	7.21E+02
7.00E+05	3.08E+03	7.23E+02
7.20E+05	3.08E+03	7.25E+02
7.40E+05	3.08E+03	7.28E+02
7.60E+05	3.08E+03	7.30E+02
7.80E+05	3.08E+03	7.32E+02
8.00E+05	3.08E+03	7.35E+02
8.20E+05	3.08E+03	7.37E+02
8.40E+05	3.08E+03	7.39E+02
8.60E+05	3.08E+03	7.42E+02
8.80E+05	3.08E+03	7.44E+02
9.00E+05	3.08E+03	7.46E+02
9.20E+05	3.08E+03	7.48E+02
9.40E+05	3.08E+03	7.51E+02
9.60E+05	3.08E+03	7.53E+02
9.80E+05	3.08E+03	7.55E+02
1.00E+06	3.08E+03	7.58E+02
1.20E+06	3.08E+03	7.80E+02
1.40E+06	3.08E+03	8.03E+02
1.60E+06	3.08E+03	8.25E+02
1.80E+06	3.07E+03	8.48E+02
2.00E+06	3.07E+03	8.69E+02
2.20E+06	3.97E+03	8.91E+02
2.40E+06	3.07E+03	9.13E+02
2.60E+06	3.07E+03	9.34E+02
2.80E+06	3.07E+03	9.55E+02
3.00E+06	3.07E+03	9.76E+02
3.20E+06	3.07E+03	9.96E+02
3.40E+06	3.07E+03	1.02E+03

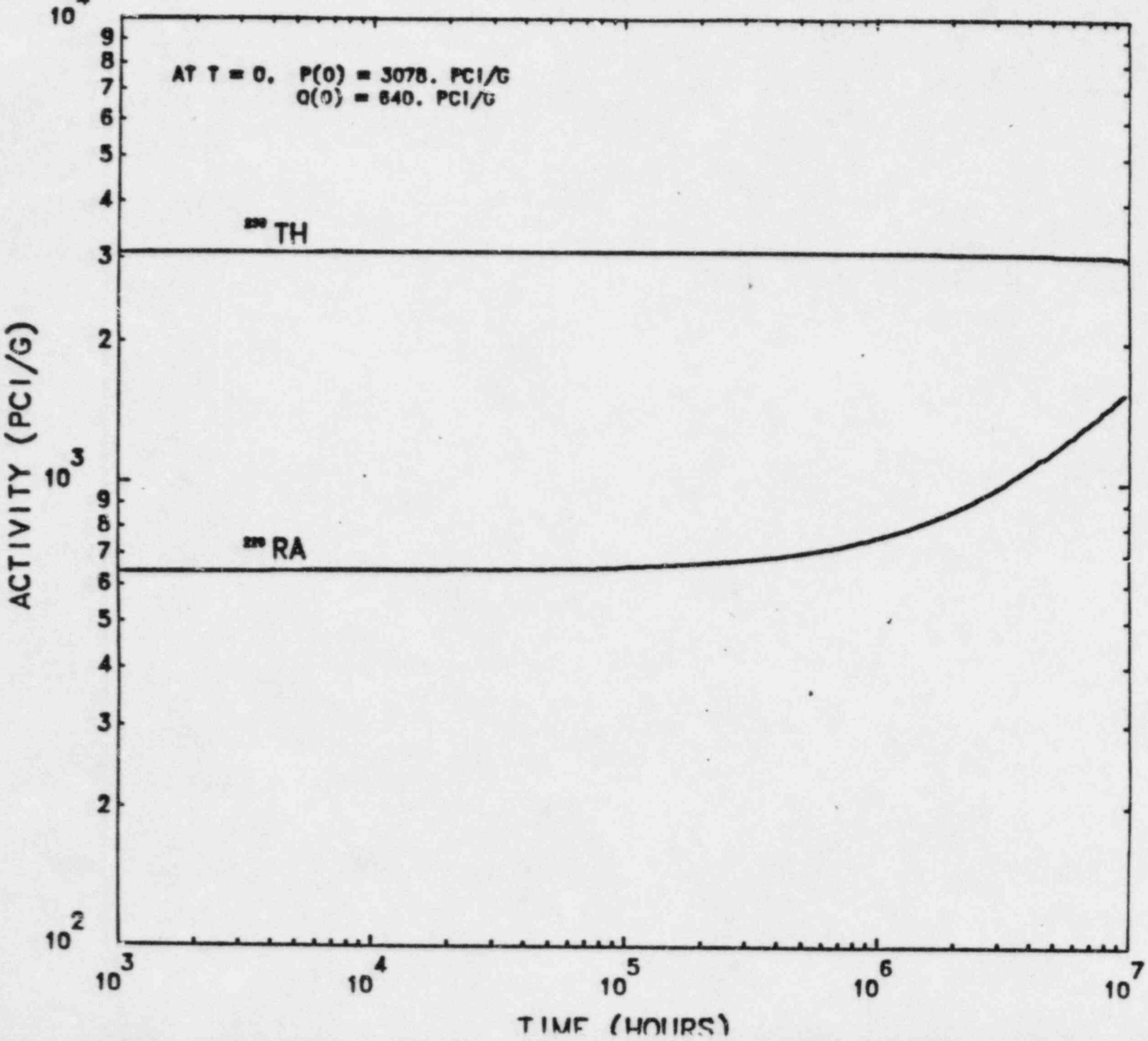
TIME	TH 230	RA 226
3.60E+06	3.07E+03	1.04E+03
3.80E+06	3.07E+03	1.06E+03
4.00E+06	3.07E+03	1.08E+03
4.20E+06	3.07E+03	1.10E+03
4.40E+06	3.07E+03	1.12E+03
4.60E+06	3.07E+03	1.13E+03
4.80E+06	3.07E+03	1.15E+03
5.00E+06	3.06E+03	1.17E+03
5.20E+06	3.06E+03	1.19E+03
5.40E+06	3.06E+03	1.21E+03
5.60E+06	3.06E+03	1.23E+03
5.80E+06	3.06E+03	1.25E+03
6.00E+06	3.06E+03	1.26E+03
6.20E+06	3.06E+03	1.28E+03
6.40E+06	3.06E+03	1.30E+03
6.60E+06	3.06E+03	1.32E+03
6.30E+06	3.06E+03	1.33E+03
7.00E+06	3.06E+03	1.35E+03
7.20E+06	3.06E+03	1.37E+03
7.40E+06	3.06E+03	1.38E+03
7.60E+06	3.06E+03	1.40E+03
7.80E+06	3.06E+03	1.42E+03
8.00E+06	3.06E+03	1.43E+03
8.20E+06	3.06E+03	1.45E+03
8.40E+06	3.05E+03	1.46E+03
8.60E+06	3.05E+03	1.48E+03
8.80E+06	3.05E+03	1.50E+03
9.00E+06	3.05E+03	1.51E+03
9.20E+06	3.05E+03	1.53E+03
9.40E+06	3.05E+03	1.54E+03
9.60E+06	3.05E+03	1.56E+03

4.210

← 1,000 Yrs. = 8.8 X10^6 Hrs

$$\frac{Ra_{1000\ Yrs}}{Ra_0} = \frac{1500\ pCi/gm}{640\ pCi/gm} = 2.34$$

TH-230, RA-226 IN MILL TAILINGS



APPENDIX 6B

EXAMPLE CALCULATION OF RADON BARRIER THICKNESS

APPENDIX 6B

EXAMPLE CALCULATION OF RADON BARRIER THICKNESS

This calculation uses the computer code RAECOM as explained in Ref. 6-2. The use of RAECOM at MKE starts with an intermediate program INRAEC, which takes the input information, computes the source term,

$$Q = D \times p,$$

and enters the data into RAECOM. RAECOM can be used to compute 1) the minimum thickness of radon barrier (or of one layer of a multi-layered cover) required to limit radon exhalation to 20 pCi/cm^2/sec; or 2) the radon exhalation corresponding to a specific cover system or for uncovered tailings.

The example is arranged as follows:

Sheet 1: Input to INRAEC to compute Q.

Sheet 2: Input to RAECOM.

Sheet 3: Output from RAECOM. Repeats input for quality assurance check. Presents required thickness for Layer 3, the layer being adjusted.

The following is an example of input for INRAEC.

HEADING FOR THE RAECO2 RUN--> TEST RUN

NUMBER OF LAYERS, TAILINGS & COVER--> 2

INITIAL FLUX INTO LAYER 1 (pCi/m^2-s)--> 0. *

AMBIENT AIR RADON CONCENTRATION (pCi/1)--> 0.18 *

LAYER TO BE OPTIMIZED--> 2 0--> optimization
2--> optimization of second layer

FLUX LIMIT AT SURFACE (pCi/m^2-s)--> 20. *

ACCURACY NEEDED (.1 TO .0001)--> .001 *

THICKNESS OF LAYER 1 (cm)--> 548.6 *

DIFFUSION COEFF. OF LAYER 1 (cm^2/s)--> .000326 *

POROSITY OF LAYER 1 (FRACTION)--> .466 *

RA-226 CONC. OF LAYER 1 (pCi/g)--> 2200. *

EMANATING FRACTION OF LAYER 1 (FRACTION)--> .2 *

BULK DENSITY OF LAYER 1 (g/cm^3)--> 1.44 *

MOISTURE CONTENT OF LAYER 1 (% DRY WT)--> 29.1 *

THICKNESS OF LAYER 2 (cm)--> 91.4 initial thickness *

DIFFUSION COEFF. OF LAYER 2 (cm^2/s)--> .00193 *

POROSITY OF LAYER 2 (FRACTION)--> .326 *

RA-226 CONC. OF LAYER 2 (pCi/g)--> 0. *

EMANATING FRACTION OF LAYER 2 (FRACTION)--> 0. *

BULK DENSITY OF LAYER 2 (g/cm3)--> 1.82 *

MOISTURE CONTENT OF LAYER 2 (% DRY WT)--> 15. *

* Note that a decimal point is required for these entries.

SUMMARY OF RAECOM INPUT

[illegible]DING: TEST RUN 8-7-84
LAYERS: 3
INITIAL FLUX: 0.000
AMBIENT RN: 0.000
OPTIMIZED LAYER: 3
SURFACE FLUX LIMIT: 20.000
PRECISION: .0010

LAYER NO.	X_0 THICKNESS CM	D_t, D_c DIFFUSION CM2-SEC	P_t, P_c POROSITY FRACTION	RA-226 PCI/G	EMANATING FRACTION	BULK DENSITY G/CM3	Q_t, Q_c SOURCE TERM PCI/CM3-SEC	MOISTURE % DRY WT
1	500.0	.01300	.440	400.4	.20	1.50	.0005733	11.7000
2	50.0	.00780	.300	0.0	0.00	1.60	0.0000000	6.3000
3	100.0	.02200	.370	0.0	0.00	1.60	0.0000000	5.4000

TEST RUN 8-7-84

********** INPUT PARAMETERS **********

NUMBER OF LAYERS : 3
RADON FLUX INTO LAYER 1 : 0.00 pCi/m2/sec
SURFACE RADON CONCENTRATION : 0.00 pCi/liter

LAYER 3 ADJUSTED TO MEET Jcrit : 20.0 +/- .100E-02 pCi/m2/sec

RF(1) = (Q(1)*P(1)/AB)*TANH(AB*DI(1))

RF(1)	0.00000000
Q(1)	.573299958E-03
P(1)	.440000000
AB	.127097782E-01
DI(1)	500.000000

BARE SOURCE FLUX (Jo) FROM LAYER 1 : 0.000 pCi/m2/sec

LAYER	THICKNESS (cm)	DIFF COEFF (cm2/sec)	POROSITY	SOURCE (pCi/cm3/sec)	MOISTURE (dry wt. percent)
1	500.	1.3000E-02	.4400	5.7330E-04	11.70
2	50.	7.8000E-03	.3000	0.0000E+00	6.30
3	100.	2.2000E-02	.3700	0.0000E+00	5.40

***** RESULTS OF RADON DIFFUSION CALCULATION *****

LAYER	THICKNESS (cm)	EXIT FLUX (pCi/m2/sec)	EXIT CONC. (pCi/liter)	WIC
1	500.	7.6977E+01	1.6710E+05	.7025
2	50.	4.5307E+01	4.4224E+04	.7063
3	149.	2.0011E+01	0.0000E+00	.8163