ATTACHMENT B

Radon Barrier Cover Thickness Design
Calculation 83088.4.4- ALB10CA001

TAILING CELL CLOSURE DESIGN REPORT
ENERGY FUELS RESOURCE CORPORATION
PIÑON RIDGE PROJECT

KLEINFELDER
Bright People. Right Solutions.

CALCULATION COVER SHEET

Date: 9/14/2010 **Page** 1 **of** 23

Project No.: 83088 **Project Title:** Energy Fuels Uranium Mill Licensing Support

Calculation No.: 83088.4.4- ALB10CA001

Calculation Title: Radon Barrier Cover Thickness Design

Design Verification Required: ☒ Yes ☐ No

Calculation Type: ☐ Scoping ☐ Preliminary ☒ Final ☐ Voided
☐ Superseded by Calculation No.: ______

ORIGINAL AND REVISED CALCULATIONS/ANALYSIS APPROVAL

	Rev. 0 Printed Name/Signature/Date	**Rev. 0** Printed Name/Signature/Date	**Rev. ____** Printed Name/Signature/Date
Originator:	John B. Case	John B. Case 9/14/10	
Checked By:	Courtney Vallejo	Courtney Vallejo by AL Kuhn 9/14/10	
Approved By:	Alan Kuhn	Alan Kuhn 9/14/10	
Other:			

AFFECTED DOCUMENTS

Document Number	Document Title	Rev. No.	Responsible Project Manager Initials

RECORD OF REVISION

Rev.	Reason for Revision
A	Original Issue

ATTACHMENTS

Attachment No.	Title	Total Pages
A	RADON Visual Basic Program Listing	11
B	Radon Program Verification	8
C	Radon Scenario 1 Analysis	12
D	Radon Scenario 2 Analysis	7
E	Analysis of Moisture Content for Radon Barrier Analysis	17
F	Review of Soil and Vegetation Parameters	11
G	Estimation of ~~Pond~~ Geosynthetic Liner Porosity and Dry Density	2
H	Verification of Cell Formulas for Diffusion Coefficient Calculation	2

Geosynthetic JBC 9/16/10

This Page is Intentionally Left Blank

KLEINFELDER
Bright People. Right Solutions.

CALCULATION AND ANALYSIS SHEET

CV 9/17/10

Project No.: 83088		**Page** 3	**of** 23
Calculation No.: 83088 - ALB08CA001		**Rev.:** 0	
Calculation Title: Radon Barrier Cover Thickness Design			
Originator: John B. Case (Print Name)	[signature] (Signature)	9/14/2010 (Date)	
Checker: Courtney Vallejo (Print Name)	Courtney Vallejo by [signature] (Signature)	9/14/10 (Date)	

TABLE OF CONTENTS

1.0 INTRODUCTION **Page 6 of 23**

1.1 Objective Page 6 of 23

1.2 Scope Page 6 of 23

2.0 BASIS **Page 6 of 23**

2.1 Design Inputs Page 6 of 23

2.2 Criteria Page 7 of 23

2.3 Assumptions Page 7 of 23

3.0 REFERENCES **Page 10 of 23**

4.0 METHODS **Page 12 of 23**

4.1 General Parameters **Page 12 of 23**

4.1.1 Number of Layers Page 12 of 23

4.1.2 Radon Flux Limit Page 12 of 23

4.1.3 Optimized Layer Page 12 of 23

4.1.4 Radon Concentration Above Top Layer Page 12 of 23

4.1.5 Lower Boundary Radon Flux Page 13 of 23

4.1.6 Surface Flux Precision Page 13 of 23

4.1.7 Increase Moisture Content in the Vegetative Cover Page 13 of 23

4.2 Layer Parameters **Page 14 of 23**

4.2.1 Layer Thickness Page 14 of 23

4.2.2	Specific Gravity	Page 14 of 23
4.2.3	Porosity	Page 14 of 23
4.2.4	Dry Density	Page 15 of 23
4.2.5	Tailings Long-Term Gravimetric Moisture Content	Page 15 of 23
4.2.6	Long-Term Gravimetric Moisture Content of Interim Layer Radon Barrier and Erosion Layer	Page 15 of 23
4.2.7	Total Density	Page 16 of 23
4.2.8	Moisture Saturation Fraction	Page 16 of 23
4.2.9	Radon Diffusion Coefficient	Page 16 of 23
4.2.10	Radon Emanation Coefficient	Page 16 of 23
4.2.11	Radium Activity	Page 17 of 23
5.0	**RESULTS AND CONCLUSIONS**	**Page 18 of 23**
5.1	Radium Barrier Thickness Results	Page 18 of 23
6.0	**CALCULATIONS AND ANALYSIS**	**Page 21 of 23**
6.1	**General Parameters**	**Page 21 of 23**
6.1.1	Number of Layers	Page 21 of 23
6.1.2	Radon Flux Limit	Page 21 of 23
6.1.3	Optimized Layer	Page 21 of 23
6.1.4	Radon Concentration Above Top Layer	Page 21 of 23
6.1.5	Lower Boundary Radon Flux	Page 21 of 23
6.1.6	Surface Flux Precision	Page 21 of 23

Project No.: 83088		**Page** 5	**of** 23
Calculation No.: 83088 - ALB08CA001		**Rev.:** 0	
Calculation Title: Radon Barrier Cover Thickness Design			
Originator: John B. Case (Print Name)	(Signature)	3/14/2010 (Date)	
Checker: Courtney Vallejo (Print Name)	Courtney Vallejo by [signature] (Signature)	9/14/10 (Date)	

6.2 Layer Parameters **Page 22 of 23**

6.2.1 Radon Diffusion Coefficient Page 22 of 23

6.2.2 Radon Emanation Coefficient Page 22 of 23

6.2.3 Radium Activity Source Term for Uranium Tailings Page 22 of 23

6.2.4 Radium Activity Page 23 of 23

6.2.5 Optimized Radium Barrier Thickness Page 23 of 23

6.3 Optimized Radon Barrier Thickness **Page 23 of 23**

1.0 Introduction

1.1 Objective

The purpose of this calculation is to determine the radon barrier cover design parameters for the three proposed tailings cells for Energy Fuels Resource Corporation at its Piñion Ridge Uranium Mill site in Montrose County, Colorado. The radon barrier cover will be part of a closure plan for the tailings cells. The material properties and required minimum thickness for the radon barrier required for closure were calculated for various tailings thicknesses based on anticipated soil properties and EPA and NRC radon flux criteria.

1.2 Scope

The scope of this calculation included the revised radon barrier cover thickness design to reduce radon releases from the tailings produced at the Piñion Ridge Uranium Mill. The minimum cover thickness was designed to meet the requirements to adequately reduce radon emanation based on Environmental Protection Agency (EPA) and U.S. Nuclear Regulatory Commission (NRC) regulations (Reference 8). The cover thickness was designed utilizing the RADON computer software developed by the NRC (Reference 7). The RADON software code utilized for calculations was taken from the NRC Regulatory guide (Reference 8) and was unaltered . The RADON code utilized for calculations is documented in Attachment A of this calculation.

2.0 Basis

2.1 Design Inputs

Design inputs included the following design parameters:

- Tailings material properties were obtained from Golder Associates, Inc. project design criteria (Reference 5), and regional mine data provided by Energy Fuels Resource Corporation (Reference 1). Tailings material properties were also estimated based on Reference 10, a geotechnical investigation from a closed tailings cell at the Crescent Junction, Utah, Disposal Site. The material properties were modified based on anticipated site conditions, construction practices and engineering judgment.

- Radon cover material properties were obtained from Golder Associates, Inc. laboratory test data from the Phase II geotechnical exploration (Reference 3), and laboratory test results of native soils provided by Energy Fuels Resource Corporation (Reference 2). Cover material properties were modified based on anticipated site conditions, construction practices and engineering judgment.

- The cover layer thicknesses, specific gravity of solids, and dry densities for the layers used in the analysis are obtained from Table 5-1 of Reference 9.

2.2 Criteria

The radon barrier minimum cover thickness was designed to meet the EPA and NRC requirements. The following requirements for radon flux criteria established by the EPA and the NRC were used for the radon barrier thickness design:

- EPA requirements state that the radon cover must 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 reasonable achievable and in any case for at least 200 years when averaged over the disposal area over at least a one-year period" (Reference 8, page 3.64-1).

- NRC requirements state that the radon cover must be designed so that "the radon-222 release rate must not exceed 20 pCi m^{-2} s^{-1} for active (UMTRCA Title II) sites" (Reference 8, page 3.64-1).

In addition, engineering judgment, along with data identified in section 2.1 above, were used to estimate the engineering properties and design parameters.

2.3 Assumptions

This calculation assumes the following:

- The tailings will be placed in the tailings cells based on the cross sections provided by Golder Associates, Inc. in their design drawings (Reference 4). The tailings thickness will vary based on the tailings cell basin depth and dike slopes.

- The moisture content and thickness of the tailings material will affect the required radon barrier thickness (Reference 12). The thickness of the tailings which requires the largest radon barrier thickness in order to adequately reduce radon flux will be representative of an "infinitely thick" radon source, as any additional tailings material will effectively reduce radon flux.

  Two values ("Scenarios") for the tailings thickness were selected for the calculations to determine the required radon barrier thickness(Reference 12):

  Scenario 1- 5 feet Tailings (sands) with Source Term 302.5 pCi/g Over 10 feet Tailings (Slimes) with Source Term 1210 pCi/g (Reference 12,15 and 16)

  Scenario 2- 1 foot of Tailings (sands) with Source Term 302.5 pCi/g

  The NRC regulatory guide states that a tailings thickness of 500 cm (approximately 16.4 feet) is representative of an "infinitely thick" radon source. A sensitivity analysis was performed in Reference 15 in order to determine the tailings thickness that represents an "infinitely thick" radon source. It was determined that a 15 foot tailings section represented an infinitely thick radon source. In this regard, 10 feet of tailings slimes and 5 feet of sands was selected to represent the infinitely thick radon source.

Assumptions Continued:

- The radon concentration above the top layer represents the radon concentration of the soil/ air interface (Reference 8). A conservative default value of zero (Reference 8) was used for the radon concentration above the top layer since measured values were not available.

- The tailings are expected to densify over time due to the static loads of the overlying tailings/ cover soils and downward seepage pressures which will result in an overall volume reduction.

- The surface of the tailings will be graded by dozer/ grader to a uniform horizontal surface before the placement of the closure cover.

- The tailings closure cover will consist of a seven layer system as presented in the Kleinfelder Calculation "Hydrological and Geotechnical Properties" (Reference 9, Table 5-1) as summarized below:
  All layers are included in the Radon Barrier Analysis.
  1) An interim cover of native soil approximately 2.0 feet thick. The interim cover will be placed in 12-inch lifts across the tailings surface and compacted by dozer to an assumed 85% of maximum dry density per ASTM D 698 by tracking with a CAT D6 dozer.
  2) A Geosynthetic Liner (1 cm) k=10 e-9 cm/sec.
     Use CH properties of high-plasticity clay (CH) for geosynthetic liner in RADON program.
  3) A radon barrier of native soil compacted to 95% of maximum dry density per ASTM D-698 overlying the interim cover.
  4) A Biointrusion Layer with cobbles to 6 in. diameter, spread to achieve uniform cover without gaps, with interstices filled with capillary break material.
  5) A capillary break layer overlying the radon barrier consisting of 0.5 feet of granular material based on recycled base course (No. 2 and No. 6) from reclaimed pads and roads on site (additional material may also be imported). The capillary break will be placed in a 6-inch lift and compacted with at least two passes of a smooth drum roller. The capillary break layer was included in the radon barrier analysis.
  6) A Vegetative Cover (3.5 ft) consisting of Native soil compacted to 85% Standard Proctor, moisture +/- 2% OMC. Assume Optimum Moisture Content for long-term moisture.
  7) A rock mulch layer (0.5 ft) consisting of of native soil with native seed mix approximately 2.0 feet

- In summary, the radon barrier calculation included the following seven layers: the tailings, interim layer, the ~~pond~~ geosynthetic CV liner, radon barrier, the biointrusion layer, the capillary break layer and the erosion/ vegetative cover.

Calculation No.: 83088.4.4- ALB10CA001 Rev. No.: ~~A~~ 0 Originator: ABC Date: 9/14/10
Calculation Title: Radon Barrier Cover Thickness Design Checker: KWF Date: 9/14/10

Assumptions Continued:

- Volumetric moisture contents of the interim layer and radon barrier was based on the estimated wilting point of the material. The wilting point is estimated at approximately 15 bars when moisture content at which soil can no longer supply sufficient water at a rate to maintain plant life (Reference 8).
  The NUREG 3.64 Regulatory Guide (Reference 8) states that the wilting point is an acceptable estimate for lon moisture content of a soil. The wilting point of the radon barrier and interim layer was estimated as approximat 15 bars. The long-term vegetation trends and soil moisture retention characteristics of the native soils is discuss the Kleinfelder Memo (Reference 11) located in Attachment F.

- The anticipated radium-226 activity of the interim cover and radon barrier soils was obtained from laboratory test results of native soils provided by Energy Fuels Resource Corporation (Reference 1).

- The long-term tailings gravimetric moisture content was estimated as 13% for the slimes, and and 8% for the sands (Reference 12).

3.0 References

The following references have been peer reviewed. The exact page number, table, or figure will be specified in calculations as they are utilized.

1) Energy Fuels Resource Corporation, "ACZ Laboratories, Inc. Analytical Report", Project ID L68386, April 11, 2008.
2) Energy Fuels Resource Corporation, "Energy Laboratories, Inc. Laboratory Analytical Report", March 13 2007, and March 13, 2008.
3) Golder Associates, Inc., "Phase 2 Geotechnical Field and Laboratory Program, Piñon Ridge Project, Montrose County, Colorado", Project No. 073-81694, March 2008.
4) Golder Associates, Inc., Preliminary Design Drawings:
   - File Number 07381694A039, "Tailings Cell A Excavation Grading Plan and Isopach", Drawing 3, Rev. A, dated 03/12/08.
   - File Number 07381694A040, "Tailings Cell B Excavation Grading Plan and Isopach", Drawing 4, Rev. A, dated 03/12/08.
   - File Number 07381694A042, "Tailings Cell C Excavation Grading Plan and Isopach", Drawing 5, Rev. A, dated 03/12/08.
   - File Number 07381694A043, "Tailings Cell Typical Sections", Drawing 6, Rev. A, dated 03/12/08.
5) Golder Associates, Inc., "Project Design Criteria", Revision B, Piñon Ridge Geotechnical Services, Project No. 073-81694, January 15, 2008.
6) Kleinfelder Calculation No. 89241.7 - ALB08CA002, "Volumetrics for Tailings Cell Closure Cover" Rev. 0, Energy Fuels Resource Corporation Piñion Ridge Uranium Mill Project.
7) U.S. Nuclear Regulatory Commission Office of Research, RADON, Version 1.2, May 22, 1989.
8) U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "Regulatory Guide 3.64, calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers", June 1989.
9) Kleinfelder Calculation No. 83088.4.4 - ALB10CA002, "Piñon Ridge Closure Cover Geotechnical and Hydrologic Properties" Rev. 0, Energy Fuels Resource Corporation Piñion Ridge Uranium Mill Project.

References Continued:

10) U.S. Department of Energy, "Final Remedial Action Plan and Site Design for Stabilization of Moab Title I Uranium Mill Tailings at the Crescent Junction, Utah, Disposal Site – Attachment 5: Field and Laboratory Results, Volume I – Appendix A through Appendix K", Office of Environmental Management, MOAB UMTRA Project, February 2008.

11) Kleinfelder Memorandum, "Review of Soil and Vegetation Parameters for Pinon Ridge Closure Cap", Energy Fuels Resource Corporation Piñion Ridge Uranium Mill Project, September 24, 2008.

12) Filas, F., August 3, 2010, "RE:Tailing Cover Design Revisions," Email from Frank Filas to Alan Kuhn Energy Fuels Corporation, Denver Colorado

13) Morrison, Kimberly, August 3, 2010, RE: Tailings Cover Design Revisions, Email from Kimberly Morrison to Frank Filas, Golder Associates, Denver Colorado.

14) Lindeburg, M., 1986, Civil Engineering Reference Manual, Professional Publications, San Carlos, CA.

15) Kleinfelder Calculation No. 89241.7 - ALB08CA001, "Radon Barrier Cover Thickness Design Geotechnical and Hydrologic Properties" Rev. 0, Energy Fuels Resource Corporation Piñion Ridge Uranium Mill Project, Denver Colorado

16) Filas, F., July 15, 2010, "RE: Layering of Tailings", Email from Frank Filas to Alan Kuhn, Energy Fuels Resource Corporation Pinion Ridge Uranium Mill Project, July 15, 2010. Denver, Colorado.

17) Filas, F., August 9, 2010,"RE: Tailing Cover Design Revsions, Energy Fuels Resource Corporation Pinion Ridge Uranium Mill Project, August 9, 2010. Denver, Colorado.

4.0 Methods

The methods utilized to obtain the applicable design properties are presented in the following subsections.

4.1 General Parameters

The general parameters utilized in the RADON program (Reference 7) for the calculation of the optimized radon barrier thickness are provided in the following sections.

4.1.1 Number of Layers

A total of either 8 layers for Scenario 1 or 7 layers for Scenario 2 were utilized for this calculation as outlined in Section 2.3.

4.1.2 Radon Flux Limit, J_c

The radon flux limit is the radon-222 release rate at the surface of the radon barrier, which is regulated by the EPA and the NRC and is averaged over the entire disposal area over a period of at least one year (Reference 8). Based on EPA and NRC regulations, the radon flux should not exceed 20 pCi m^{-2} s^{-1}.

4.1.3 Optimized Layer

The thickness of the radon barrier (Layer 5 for Scenario 1 or Layer 4 for Scenario 2) was optimized to achieve the required radon flux limit.

4.1.4 Radon Concentration Above Top Layer

The radon concentration at the soil/ air interface above the radon barrier was obtained using the RADON program conservative default value of zero (Reference 8) since measured values were not available.

4.1.5 Lower Boundary Radon Flux

The lower boundary radon flux is the downward radon flux of the soil beneath the tailings material. This value is usually zero for most tailings but the downward flux could reduce the amount of radon available for upward diffusion in a thin tailings layer (Reference 8). The RADON program was utilized to calculate the lower boundary radon flux (assuming and infinitely thick subsoil with no radon source) and adjust the available radon for upward diffusion.

4.1.6 Surface Flux Precision

The surface flux precision is the acceptable level of computation error (determined by the RADON program user) for the radon surface flux calculations. A precision value of 0.001 was utilized for calculations.

4.1.7 Increased Moisture Content in the Vegetative Cover

To assess the influence of an increased moisture content in reducing the radon flux through diffusion, the Scenario 1 analysis was run with an increased moisture content to reflect the long term water balance. of the vegetative cover. The moisture content of the vegetative cover was increased to 16.8% (Reference 9).

The radon flux reduction was evaluated by running the RADON program in non-optimization mode, which leaves the layer thicknees constant and does not try to optimize the radon barrier thickness.

4.2 Layer Parameters

The layer parameters utilized in the RADON program (Reference 7) for the calculation of the optimized radon barrier thickness are provided in the following sections. Parameters were calculated for the tailings, interim cover, pond liner, radon barrier, bio intrusion layer, capillary break and erosion barrier/ vegetative cover layers.

4.2.1 Layer Thickness, T

$T_{Tailings}$ = Tailings thickness — Obtained from Reference 12. Two scenarios are evaluated as presented in Section 2.3

$T_{Interim}$ = Interim cover thickness — Assumed thickness of approximately 2 feet.

$T_{Geosynthetic\ Liner}$ = Geosynthetic liner thickness and is 1 cm or 0.03ft.

T_{Radon} = Radon barrier thickness — Calculated with the RADON program (Reference 7) to meet EPA and NRC radon flux criteria (Reference 8, page 3.64-1).

T_{Bio} = Bio Intrusion Layer thickness and is 0.5 ft

$T_{Capillary\ Break}$ = Capillary break layer thickness and is 0.5 ft.

$T_{Vegetative\ Cover}$ = Vegetative cover thickness and is 3.5 ft.

$T_{Rock\ Mulch}$ = Rock mulch thickness and is 0.5 ft.

4.2.2 Specific Gravity, SG

The specific gravity of solids used in the analysis are obtained from Table 5-1 of Reference 9.

4.2.3 Porosity, n

The porosities for the four layers used in the analysis are obtained from Table 5-1 of Reference 9.

The porosity of a layer is given by the following equation:

$$n = 1 - \frac{\gamma_d}{SG\gamma_w}$$

Equation 1 (Reference 8, Page 3.64-7)

where:

SG = specific gravity
γ_d = Dry Density

This relationship was subsequently used to obtain the dry density from the specific gravity of solids and the porosity.

4.2.4 Dry Density, γ_d

Equation 2 was used to calculate the dry density of the tailings:

$\gamma_{d\ Tailings} = SG\ (1\text{-}n)\ \gamma_w$ **Equation 2 (Reference 8, Page 3.64-7)**

where:

$\gamma_{d\ Tailings}$ = Dry density of tailings
SG = specific gravity of tailings (described in Section 4.2)
n = Porosity of tailings (described in Section 4.3)
γ_w = Density of water

$\gamma_{d\ Interim}$ = Dry density of interim cover — 85% of maximum dry density based on Table 5-1 of Reference 9.

$\gamma_{d\ Radon}$ = Dry density of radon barrier — 95% of maximum dry density based on Table 5-1 of Reference 9.

4.2.5 Tailings Long-Term Gravimetric Moisture Content, m_g

$m_{g\ Tailings}$ = Estimated long-term gravimetric moisture content of tailings — Estimated from average moisture content results from the Crescent Junction, Utah disposal site (Reference 10) and reduced for conservative radon barrier design as stated in Section 2.3.

4.2.6 Long-Term Gravimetric Moisture Content of Interim Layer, Radon Barrier and Erosion Barrier

Calculated from the layer long-term volumetric moisture content and dry density with the following equation:

$$m_{g\ Layer} = \frac{m_{v\ Layer}\ \gamma_w}{\gamma_{d\ Layer}}$$ **Equation 3 (Reference 8, Page 3.64-9)**

where:

$m_{g\ Layer}$ = Long-term gravimetric moisture content of layer
$m_{v\ Layers}$ = Long-term volumetric moisture content of layer
γ_w = Density of water

The following table presents estimates of gravimetric moisture content for the various layers.

Layer	Symbol	Notes
Interim Cover	$m_{g\ Interim}$	Based on Equation 3 and a wilting point a gravimetrix moisture content of 6.3% as discussed in Section 2.3.
Geosynthetic Liner	$m_{g\ Pond\ Liner}$	Based on Equation 3 , the wilting point gravimetrix moisture content is estimated as 23.0%
Radon Barrier	$m_{g\ Radon}$	Based on Equation 3 and a wilting point volumetric moisture content of 5.7% as discussed in Section 2.3.
Bio Intrusion Layer.	$m_{g\ BioIntrusion}$	Based on Equation 3 and a wilting point volumetric moisture content of 6.3% as discussed in Section 2.3.
Capillary Break Layer.	$m_{g\ Capillary\ Break}$	Based on Equation 3 and a wilting point volumetric moisture content of 1.0% as discussed in Section 2.3.
Vegetative Cover	$m_{g\ Vegetative\ Cover}$	Based upon Equation 3, the wilting point gravimetric moisture content is 6.3%

4.2.7 Total Density, γ_t

Calculated by the RADON program (Reference 7) from dry density and the gravimetric moisture content:

$$\gamma_t = \gamma_d (1 + m_g)$$ **Equation 4**

where:
γ_t = Total (or moist) density
$m_{g\ Layer}$ = Long-term gravimetric moisture content of layer

4.2.8 Moisture Saturation Fraction, m_f

The volumetric fraction of saturation used in the diffusion coefficient calculations presented for the tailings or cover soils is expressed by the moisture saturation fraction:

$$m_f = \frac{\gamma_d m_g}{n \gamma_w}$$ **Equation 5 (Reference 8, Page 3.64-11)**

where:
m_f = Moisture saturation fraction
m_g = Gravimetric moisture content
γ_d = Dry density
γ_w = Density of water

4.2.9 Radon Diffusion Coefficient, D

The radon diffusion coefficient of the tailings and cover soils was calculated using the moisture saturation fraction and porosity (Reference 8) and calculated with the following equation:

$$D = 0.07 \exp [-4 * (m_f - m_f * n^2 + m^5)]$$ **Equation 6 (Reference 8, Page 3.64-10)**

where:
D = Radon diffusion coefficient (in cm^2/sec)
m_f = Moisture saturation fraction
n = Porosity

4.2.10 Radon Emanation Coefficient, E

The portion of radon that is released from the tailings or cover soil matrix into the pore space is expressed by the radon emanation coefficient (Reference 8). The reference value of 0.35 given in the NRC regulatory guide (Reference 8) was utilized for all materials.

4.2.11 Radium Activity

The uranium tailings activity source term was calculated based on average uranium activities as discussed in Section 2.3.

The anticipated radium-226 activity of the interim cover, radon barrier and erosion barrier/ vegetative cover soils was obtained from laboratory test results of native soils provided by Energy Fuels Resource Corporation (Reference 1).

5.0 Results and Conclusions

5.1 Radon Barrier Thickness Results

The following sections provide a summary of the calculation results. Detailed calculation inputs and results for each material property scenario are presented in Section 6 and Attachments C through E and Attachments G through H.

The optimized radon barrier thickness results for the minimum tailings thickness and an "infinitely thick" radon source (as described in Section 2.3) are presented in Table 5-1 below. Detailed results are presented in Table 5.2 on the following page.

Analysis was performed for Scenario 1 in which the gravimetric moisture content of the vegetative cover, and and rock mulch was increased to 16.8%. The calculation was run in the nonoptimization mode. The calculated radon flux was reduced to 1.45 piCi/m2/s.

Table 5.1 - Optimized Radon Barrier Thickness Results

Scenario	Tailings Thickness	Optimized Radon Barrier Thickness
Scenario 1	5 ft sands over 10 ft slimes.	**5.7 feet**
Scenario 2	1 ft of sands	**0.9 feet**

KLEINFELDER

Calculation No.: 83088.4.4-ALBI0CA001
Calculation Title: Radon Barrier Cover thickness design
Rev. No: 0

Calculation and Analysis Sheet

Orignated By: JBC Date: 9/16/10
Checked By: TON Date: 9/17/10

Table 5.2 - Detailed Input Parameters and Results *

Radon Barrier Scenarios									
Scenario No.	Number of Layers	Source Terms and Thickness	Radon Flux Limit [1], $pCi\ m^{-2}s^{-1}$	Optimized Layer	Radon Concentration Above Top Layer [2]	Lower Boundary Radon Flux	Surface Flux Precision	Radon Barrier Thickness (ft)	Radon Barrier Thickness (cm)
1	8	5 feet Tailings (sands) with Source Term 302.5 pCi/g Over 10 feet Tailings (Slimes) with Source Term 1210 pCi/g	20	5 (Radon Barier)	0	default (calculated)	0.001	5.7	173.2
2	7	1 foot of Tailings (sands) with Source Term 302.5 pCi/g	20	4 (Radon Barrier)	0	default (calculated)	0.001	0.9	27.4

Layer Input Parameters																			
Layer #	Material Type	Thickness, ft	Thickness, cm	Porosity		Dry Density, pcf		Dry Density, g/cc	Radium Activity, R, pCi/ g	Specific Gravity, SG		Volumetric Moisture Content, m_v		Gravimetric Moisture Content, m_g [10]		Total Density [11], g/cc	Moisture Saturation Fraction, m_r [12]	Radon Diffusion Coeff. (cm/sec^2), D [13]	Emanation Coefficient, E [14]
1	Tailings (slimes)	0 - 10	15.2 - 304.8	0.42	(3)	98.0	(18)	1.57	1210 (18)	2.69	(7)	20.4%	(13)	13.0%	(18)	1.77	0.49	0.013	
2	Tailings (sands)	1 - 5	15.2 - 152.4	0.40	(3)	103.0	(5)	1.65	302.5 (18)	2.69	(7)	13.2%	(13)	8.0%	(18)	1.78	0.33	0.023	
3	Interim Layer	2	61.0	0.39	(4)	100.3	(6)	1.61	0.98 (8)	2.65	(8)	10.2%	(6)	6.3%		1.71	0.26	0.029	
4	Geosynthetic Liner	0.033	1.0	0.47	-17	90.0	(16)	1.44	0.98 (8)	2.72	(D)	33.0%	(6)	23.0%	(E)	1.77	0.70	0.004	
5	Radon Barrier	optimized	optimized	0.32	(4)	112.1	(6)	1.80	0.98 (8)	2.65	(8)	10.2%	(11)	5.7%		1.90	0.32	0.022	default, 0.35
6	Bio-intrusion	0.5	30.4	0.39	(6)	100.3	(6)	1.61	0.98 (8)	2.65	(6)	10.2%	(6)	6.30%	(6)	1.71	0.26	0.028	
7	Capillary Break	0.5	15.2	0.33	(6)	112.9	(6)	1.81	0.98 (8)	2.70	(6)	0.0%	(6)	0%	(6)	1.81	0.00	0.070	
8	Vegetative Cover & Rock Mulch combined	4	121.9	0.39	(6)	100.3	(15)	1.61	0.98 (8)	2.65	(8)	10.2%	(9)	6.3%		1.71	0.26	0.029	

KLEINFELDER References provided on the following page

[shaded box] = Values input into RADON program
[unshaded box] = Values calculated internally by RADON program during radon surface flux calculations.

Calculation No.: 83088.4.4-ALB10CA001
Calculation Title: Radon Barrier Cover Thickness Design
Rev. No: 0

Orignated By: ARC Date: 9/16/10
Checked By: CN Date: 9/17/10

Project No.:

Table 5.2 References

Ref. #	Explanation	Source
(1)	Radon flux limit	U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "Regulatory Guide 3.64, calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers", June 1989
(2)	Radon Concentration above top layer: A conservative default value of zero was used since measured values were not available.	U.S. Nuclear Regulatory Commission Office of Research, RADON, Version 1.2, May 22, 1989 (Reference 7).
(3)	Tailings porosity based on Golder Design Criteria.	Golder design criteria (Reference 5).
(4)	Interim layer, radon barrier, and biointrusion r porosity calculated from in-place dry density and a specific gravity of 2.65 as discussed in hydrologic properties calculation.	Kleinfelder Calculation 89088.4.4 - ALB08CA002 Pinon Closure Cover Geotechnical and Hydrologic Properties (Table 5-1 Reference 9).
(5)	Tailings dry density based on anticipated densification of soils (as discussed in Section 2.3) and site-specific data from Crescent Junction, Utah Disposal Site.	US. DOE. 2008. Final Remedial Action Plan and Site Design for Stabilization of Moab Title 1 Uranium Mill Tailings at the Cresent Junction, Utah, Disposal Site (Reference 10).
(6)	Interim layer, radon barrier, and biointrusion barrier dry density calculated from in-place dry density and percent compaction as discussed in hydrologic properties calculation.	Kleinfelder Calculation 89088.4.4 - ALB08CA002 Pinon Closure Cover Geotechnical and Hydrologic Properties (Table 5-1 Reference 9).
(7)	Tailings Specific Gravity based on Golder Design Criteria.	Golder design criteria (Reference 5).
(8)	Interim layer, radon barrier, and vegetative cover specific gravity based typical values for sand as discussed in Reference 9.	Kleinfelder Calculation 89088.4.4 - ALB08CA002 Pinon Closure Cover Geotechnical and Hydrologic Properties (Table 5-1 Reference 9).
(9)	Volumetric moisture content of the vegetative cover are based on the average 15-bar moisture content as an estimate for the wilting point of the soil. The wilting point is acceptable estimate for long-term moisture content in NUREG 3.64)	SWCC report
(10)	Gravimetric moisture content of interim layer and radon barrier calculated from volumetric moisture content and dry density.	Section 4.2.6 Equation 3
(11)	Total density calculated from dry density and gravimetric moisture content.	Section 4.2.7 Equation 4
(12)	Moisture saturation fraction calculated from total density, gravimetric moisture content and porosity.	U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "Regulatory Guide 3.64, calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers", June 1989 (Reference 8).
(13)	Radon diffusion coefficient calculated from moisture saturation fraction and porosity.	U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "Regulatory Guide 3.64, calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers", June 1989 (Reference 8).
(14)	The reference value of given in the NRC regulatory guide was utuilized for the emanation coefficient.	U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "Regulatory Guide 3.64, calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers", June 1989 (Reference 8).
(15)	Porosity and dry density of vegetative cover may be analyzed for both 80% and 85% compaction in the future.	SWCC report
(16)	Dry density and specific gravity of Geosynthetic Liner estimated for high-plasticity clay.	Civil Engineering Reference Manual, Table 9.7, p. 9-11, Reference (14)
(17)	Porosity and gravimetric moisture content of Geosynthetic Liner calculated from dry density and specific gravity assuming a 70% saturation.	See Attachment G
(18)	Radium Activity Source Term, Tailings Thicknesses, and Moisture Contents	Email from Frank Filas to Alan Kuhn, August 3, 2010, Reference(12)
(19)	Dry density of tailings slimes was calculated from porosity and specific gravity values assuming fully saturated conditions.	Email from Kimberly Morrison to Frank Filas August 3, 2010, Reference (13)

6.0 Calculations and Analysis

The calculations for moisture contents used in the Radon program are presented in Attachment E.
The calculations for the diffusion coefficient are presented in Attachment I.

6.1 General Parameters

6.1.1 Number of Layers

Four layers were utilized for this calculation: the tailings layer, interim cover, radon barrier and erosion barrier/ vegetative cover. Note that the erosion barrier/vegetative cover has the same properties as the interim cover.

6.1.2 Radon Flux Limit, J_c

$Jc = 20$ pCi m^{-2} s^{-1} Based on EPA and NRC regulations (Reference 8).

6.1.3 Optimized Layer

Optimized layer = Radon barrier (Layer 5) for Scenario 1
Optimized layer = Radon barrier (Layer 4) for Scenario 2

6.1.4 Radon Concentration Above Top Layer

Radon concentration above top layer = 0 Based on EPA and NRC default values (Reference 8) as discussed in section 4.1.4.

6.1.5 Lower Boundary Radon Flux

The lower boundary radon flux was calculated by the RADON program and adjusted the available radon for upward diffusion during radon flux computations.

6.1.6 Surface Flux Precision

Surface flux precision = 0.001 Acceptable level of computation error as discussed in Section 4.1.6.

6.2 Layer Parameters

The calculations for the dry density, the gravimetric moisture content used in the RADON Program, and the moistu fraction for each of the layers are presented in Attachment E: "Analysis of Moisture Contents for Radon Barrier Analysis".

6.2.1 Radon Diffusion Coefficient

The radon diffusion coefficient, D, for each of the layers based upon the porosity and moisture fraction for each layer is presented in Attachment I: "Verification of Cell Formulas for Diffusion Coefficient Calculation".

6.2.2 Radon Emanation Coefficient, E

The reference value given in the NRC regulatory guide (Reference 8) utilized for all materials is 0.35.

6.2.3 Radium Activity Source Term for Uranium Tailings

The radium source term is obtained from Section 2.3 for Scenarios 1 and 2.
The radium source terms for Scenario 1 were 5 feet Tailings (Sands) with Source Term of 302.5 pCi/g over 10 feet tailings (slimes) with Source Term 1210 pCi/g.

The radium source term for Scenario 2 was 1 foot of tailings with source term of 302.5 pCi/g.

6.2.4 Radium Activity

Obtained from laboratory test results of native soils provided by Energy Fuels Resource Corporation (Reference 2):

$RA_{Interim}$ & RA_{Radon} = 0.98 pCi/g

6.3 Optimized Radon Barrier Thickness, T_{Radon}

The radon barrier thickness optimized to meet EPA and NRC radon flux criteria (Reference 8, page 3.64-1) was calculated with the RADON program with the input values given in Section 6. The radon barrier thickness optimized to meet EPA and NRC radon flux criteria (Reference 8, page 3.64-1) was:

Scenario 1 T_{Radon} = 173.7 cm = 5.7 ft

Scenario 2 T_{Radon} = 27.4 cm = 0.9 ft

File: Edit1 8/26/2010, 8:17:19 AM

```
Sub Radon()

10 Rem KEY OFF: Color 15, 1, 0: CLS
20 Rem Print "                       -----*****! RADON !*****-----": Print
30 Rem Print ""
40 Rem Print "U.S. Nuclear Regulatory Commission Office of Research": Print
50 Rem Print "          RADON FLUX, CONCENTRATION AND TAILINGS COVER
THICKNESS",
60 Rem Print "                      ARE CALCULATED FOR MULTIPLE LAYERS": Print
70 Rem On Error GoTo 90
80 Rem GoTo 120
90  Rem Print "CHECK THE PRINTER & PRESS ANY KEY TO CONTINUE"
100  Rem V$=INPUT$(1)
110  Rem Resume Next
Dim Msg1 As String
Msg1 = "-----*****! RADON !*****-----"
Msg1 = Msg1 + "Version 1 - April 1, 1986 - G.F. Birchard -  tel.# (301)
492-7000 "
Msg1 = Msg1 + "U.S. Nuclear Regulatory Commission Office of Research "
Msg1 = Msg1 + "RADON FLUX, CONCENTRATION AND TAILINGS COVER THICKNESS "
Msg1 = Msg1 + "ARE CALCULATED FOR MULTIPLE LAYERS "
MsgBox (Msg1)
180 TitleAnalysis$ = InputBox("TITLE OF THIS ANALYSIS")
     Rem INPUT "TITLE OF THIS DATA SET";TITLE$ : LPRINT :LPRINT TITLE$ :LPRINT
190 Rem DefDbl A-H, O-Z: DefInt I-N
    Dim ICOST As Integer, I As Integer, N As Integer, NO1 As Integer, NO2 As
    Integer, NO3 As Integer, NO4 As Integer
    Dim NM1 As Integer, NM2 As Integer, JTST As Integer, N5M4 As Integer, N2M1
    As Integer, J As Integer, K As Integer, L As Integer
    Dim NTST As Integer, IIJ As Integer, NSAVE As Integer, ITHK As Integer, IJ
    As Integer
    Rem Input Variables
200 Dim D(50) As Double, DX(50) As Double, P(50) As Double, Q(50) As Double,
XM(99) As Double
    Rem Computation Variables
    Dim ACC As Double
210 Dim AB(50) As Double, AIP1MI(50) As Double, ALP(50) As Double, RHO(50) As
Double, X(50) As Double, XMS(99) As Double
    Rem Output Variables
220 Dim A4(50) As Double, DDX(50) As Double, RC(50) As Double, RF(50) As Double
    Rem Matrix Variables
230 Dim A(245) As Double, ASS(50) As Double, B(99) As Double, BS(50) As Double,
BU(99) As Double, G(245) As Double
    Rem Note that the AS Array Label is Changed to ASS
235 Dim R(50) As Double, RR(50) As Double, T(50) As Double, U(50) As Double
    Rem Constants
240 XL = 0.0000021: PC = 0.26: SG = 2.65
250 Rem Print "TYPE Y TO INPUT INTERACTIVELY OR N TO READ INPUT FROM DRIVE A:"
260 Rem W$=INPUT$(1)
270 Rem If W$ = "y" Or W$ = "Y" Then GoTo 290
280 Rem If W$ = "N" Or W$ = "n" Then GoTo 1750 Else GoTo 250
290 Rem LPRINT: LPRINT " ", "CONSTANTS": LPRINT
    Sheets("Output").Select
    Cells.Select
    Selection.ClearContents
300 Rem Print: Print " ", "CONSTANTS": Print
```

File: Edit1 8/26/2010, 8:17:19 AM

```
310 Rem LPRINT "RADON DECAY CONSTANT", " ", XL, "1/s"
320 Rem PRINT "RADON DECAY CONSTANT",       " ",XL,"1/s"
330 Rem LPRINT "RADON WATER/AIR PARTITION COEFFICIENT", PC
340 Rem Print "RADON WATER/AIR PARTITION COEFFICIENT", PC
350 Rem LPRINT "SPECIFIC GRAVITY OF COVER & TAILINGS", SG, "g/cm^3": LPRINT
360 Rem Print "SPECIFIC GRAVITY OF COVER & TAILINGS", SG, "g/cm^3": Print
    Cells(1, 1) = TitleAnalysis$
    Cells(2, 2) = "CONSTANTS"
    Cells(3, 1) = "DESCRIPTION": Cells(3, 2) = "VALUE": Cells(3, 3) = "UNITS"
    Cells(4, 1) = "RADON DECAY CONSTANT": Cells(4, 2) = XL: Cells(4, 3) = "1/s"
    Cells(5, 1) = "RADON WATER/AIR PARTITION COEFFICIENT": Cells(5, 2) = PC
    Cells(6, 1) = "SPECIFIC GRAVITY OF COVER & TAILINGS": Cells(6, 2) = SG:
    Cells(6, 3) = "gm/cm^3"
370 Rem Print " ", "GENERAL INPUT PARAMETERS": Print
380 Rem LPRINT:  LPRINT " ", "GENERAL INPUT PARAMETERS": LPRINT
    Cells(8, 2) = "GENERAL INPUT PARAMETERS"
390 Rem Print "ENTER -1 TO USE DEFAULT VALUES WHICH ARE SPECIFIED IF THEY
EXIST."
MsgBox ("ENTER -1 TO USE DEFAULT VALUES WHICH ARE SPECIFIED IF THEY EXIST.")
400 Rem INPUT "NUMBER OF LAYERS COVER AND TAILINGS";N
 N = InputBox("NUMBER OF LAYERS COVER AND TAILINGS")
410 If N < 2 Then GoTo 420 Else If N > 99 Then GoTo 430 Else GoTo 440
420 Rem Print "TWO LAYERS MINIMUM PLEASE": GoTo 400
MsgBox ("TWO LAYERS MINIMUM PLEASE"): GoTo 400
430 Rem Print "NINETY-NINE LAYERS MAXIMUM PLEASE": GoTo 400
MsgBox ("NINTY-NINE LAYERS MAXIMUM PLEASE"): GoTo 400
440 Rem LPRINT "LAYERS OF COVER AND TAILINGS", N: GoTo 460
    Cells(9, 1) = "LAYERS OF COVER AND TAILINGS": Cells(9, 2) = N
450 Rem Print "THE LAYER THICKNESS CANNOT BE OPTIMIZED WITHOUT A FLUX LIMIT"
    MsgBox ("THE LAYER THICKNESS CANNOT BE OPTIMIZED WITHOUT A FLUX LIMIT")
460 Rem INPUT "RADON FLUX LIMIT (pCi*m^-2/s) default=20, enter 0 for no
limit";CRITJ
    CRITJ = InputBox("RADON FLUX LIMIT (pCi*m^-2/s) default=20, enter 0 for no
    limit ", CRITJ)
470 Rem If CRITJ < 0# Then CRITJ = 20#: Print "DEFAULT FLUX LIMIT ASSIGNED"
    If CRITJ < 0# Then CRITJ = 20#: MsgBox ("DEFAULT FLUX LIMIT ASSIGNED")
480 Rem If critj = 0 Then LPRINT "NO LIMIT ON RADON FLUX": GoTo 510
    If CRITJ = 0 Then MsgBox ("NO LIMIT ON RADON FLUX"): GoTo 510
490 Rem LPRINT "DESIRED RADON FLUX LIMIT", " ", critj, "pCi*m^-2/s": GoTo 510
    Cells(10, 1) = "DESIRED RADON FLUX LIMIT": Cells(10, 2) = CRITJ: Cells(10,
    3) = "pCi*m^-2/s": GoTo 510
500 Rem Print "THE LAYER NUMBER CANNOT EXCEED THE NUMBER OF LAYERS."
    MsgBox ("THE LAYER NUMBER CANNOT EXCEED THE NUMBER OF LAYERS.")
510 Rem INPUT "THE LAYER NUMBER FOR THICKNESS OPIMIZATION 0=no
optimization";ICOST
    ICOST = InputBox("THE LAYER NUMBER FOR THICKNESS OPIMIZATION 0=no
    optimization")
520 If CRITJ = 0 And ICOST > 0 Then GoTo 450
530 Rem If ICOST = 0 Then LPRINT "LAYER THICKNESS NOT OPTIMIZED": GoTo 570
    If ICOST = 0 Then MsgBox ("LAYER THICKNESS NOT OPTIMIZED"): GoTo 570
540 Rem If icost <= 1 Then Print "THE LOWEST LAYER CANNOT BE OPTIMIZED": GoTo
510
    If ICOST <= 1 Then MsgBox ("THE LOWEST LAYER CANNOT BE OPTIMIZED"): GoTo
    510
550 If ICOST > N Then GoTo 500
560 Rem LPRINT "NO. OF THE LAYER TO BE OPTIMIZED", icost
```

File: Edit1 8/26/2010, 8:17:19 AM

```
    Cells(11, 1) = "NO. OF THE LAYER TO BE OPTIMIZED": Cells(11, 2) = ICOST
570 Rem INPUT "RADON CONCENTRATION ABOVE TOP LAYER (pCi/l) default=0";CN1
    CN1 = InputBox("RADON CONCENTRATION ABOVE TOP LAYER (pCi/l) default=")
580 If CN1 < 0 Then CN1 = 0
590 Rem If cn1 = 0 Then LPRINT "DEFAULT SURFACE RADON CONCENTRATION", cn1,
"pCi/l"
    If CN1 = 0 Then Cells(12, 1) = "DEFAULT SURFACE RADON CONCENTRATION":
    Cells(12, 2) = CN1: Cells(12, 3) = "pCi/l"
600 Rem If cn1 > 0 Then LPRINT "MEASURED SURFACE RADON CONCENTRATION", cn1,
"pCi/l"
    If CN > 0 Then Cells(11, 1) = "MEASURED SURFACE RADON CONCENTRATION":
    Cells(12, 2) = CN1: Cells(12, 3) = "pCi/l"
610 Rem INPUT "LOWER BOUNDARY RADON FLUX (pCi*m^-2/s) default=calculation";F01
    F01 = InputBox("LOWER BOUNDARY RADON FLUX (pCi*m^-2/s)
    default=calculation")
620 If F01 = -1 Then GoTo 630 Else GoTo 650
630 Rem Print "LOWER BOUNDARY FLUX TO BE CALCULATED ASSUMING AN INFINITE
SUBSOIL"
    Cells(13, 1) = "LOWER BOUNDARY FLUX TO BE CALCULATED ASSUMING AN INFINITE
    SUBSOIL"
640 GoTo 660
650 Rem LPRINT "RADON FLUX INTO LAYER 1", " ", F01, "pCi*m^-2/s"
    Cells(14, 1) = "RADON FLUX INTO LAYER 1": Cells(14, 2) = F01: Cells(14, 3)
    = "pCi*m^-2/s"
660 Rem INPUT "SURFACE FLUX PRECISION (pCi*m^-2/s)  This number is the
acceptable level of computation error.";ACC
    ACC = InputBox("SURFACE FLUX PRECISION (pCi*m^-2/s)  This number is the
    acceptable level of computation error.")
670 If 1 < ACC Or ACC < 0 Then GoTo 680 Else GoTo 700
680 Rem Print "THE SURFACE FLUX PRECISION SHOULD BE BETWEEN 0 AND 1"
    MsgBox ("THE SURFACE FLUX PRECISION SHOULD BE BETWEEN 0 AND 1")
690 GoTo 660
700 Rem LPRINT "SURFACE FLUX PRECISION", " ", ACC, "pCi*m^-2/s"
    Cells(15, 1) = "SURFACE FLUX PRECISION": Cells(15, 2) = ACC: Cells(15, 3) =
    "pCi*m^-2/s"
710 Rem Print: Print " ", "LAYER INPUT PARAMETERS": Print
720 Rem LPRINT:  LPRINT: LPRINT " ", "LAYER INPUT PARAMETERS": LPRINT
    Cells(16, 2) = "LAYER INPUT PARAMETERS"
730 For I = 1 To N
740  Rem Print USING; "LAYER #"; I: Print: Print
    Cells(16 + (I - 1) * 15 + 1, 1) = "LAYER #": Cells(16 + (I - 1) * 15 + 1,
    2) = I
    isin$ = I
    MsgBox ("Inputs for Layer No. " + isin$)
750 Rem LPRINT USING "LAYER #";I : LPRINT :LPRINT
760  Rem INPUT LAYER HICKNESS (cm)";DX(I)
    DX(I) = InputBox("LAYER THICKNESS ")
770  Rem If DX(i) < 0 Then Print "THE THICKNESS CANNOT BE NEGATIVE": GoTo 760
     If DX(I) < 0 Then MsgBox ("THE THICKNESS CANNOT BE NEGATIVE"): GoTo 760
780  Rem LPRINT "LAYER THICKNESS", " ", DX(i), "cm"
     Cells(16 + (I - 1) * 15 + 2, 1) = "LAYER THICKNESS": Cells(16 + (I - 1) *
     15 + 2, 2) = DX(I): Cells(16 + (I - 1) * 15 + 2, 3) = "cm"
790  Rem INPUT "LAYER POROSITY  default =.40. Enter a value >1 to calculate
porosity     ";P(I)
     P(I) = InputBox(" LAYER POROSITY  default =.40. Enter a value >1 to
     calculate porosity")
```

File: Edit1 8/26/2010, 8:17:19 AM

```
800  If P(I) > 1 Then GoTo 820 Else If P(I) = -1 Then GoTo 880 Else If P(I) < 0
Then GoTo 890
810  GoTo 910
820  Rem INPUT "LAYER DENSITY";RHO(I)
     RHO(I) = InputBox("LAYER DENSITY")
830  If RHO(I) < 1 Or RHO(I) > 3 Then GoTo 840 Else GoTo 860
840  Rem Print "ACCEPTABLE DENSITY VALUES ARE BETWEEN 1 AND 3. PLEASE REENTER"
     MsgBox ("ACCEPTABLE DENSITY VALUES ARE BETWEEN 1 AND 3. PLEASE REENTER")
850  GoTo 820
860  P(I) = 1 - RHO(I) / SG
870  Rem LPRINT "CALCULATED LAYER POROSITY ", " ", P(i): GoTo 980
     Cells(16 + (I - 1) * 15 + 3, 1) = "CALCULATED LAYER POROSITY": Cells(16 +
     (I - 1) * 15 + 3, 2) = P(I): GoTo 980
880  Rem P(i) = 0.4: LPRINT "DEFAULT LAYER POROSITY", " ", P(i): GoTo 920
     P(I) = 0.4:   Cells(16 + (I - 1) * 15 + 3, 1) = "CALCULATED LAYER
     POROSITY": Cells(16 + (I - 1) * 15 + 3, 2) = P(I): GoTo 920
890  Rem Print "THE POROSITY VALUE CANNOT BE NEGATIVE. PLEASE REENTER."
     MsgBox ("THE POROSITY VALUE CANNOT BE NEGATIVE. PLEASE REENTER.")
900  GoTo 800
910  Rem LPRINT "LAYER POROSITY ", " ", P(i)
      Cells(16 + (I - 1) * 15 + 3, 1) = "CALCULATED LAYER POROSITY": Cells(16 +
      (I - 1) * 15 + 3, 2) = P(I)
920  Rem INPUT "LAYER DENSITY default=calculated";RHO(I)
     RHO(I) = InputBox(" LAYER DENSITY default=calculated ")
930  If RHO(I) = -1 Then GoTo 940 Else If RHO(I) < 1 Or RHO(I) > 3 Then GoTo
960 Else GoTo 980
940  RHO(I) = SG * (1 - P(I))
950  Rem LPRINT "CALCULATED LAYER DENSITY", " ", RHO(i), "g/cm^3": GoTo 990
     Cells(16 + (I - 1) * 15 + 4, 1) = "CALCULATED LAYER DENSITY": Cells(16 +
     (I - 1) * 15 + 4, 2) = RHO(I): Cells(16 + (I - 1) * 15 + 4, 3) = "g/cm^3":
     GoTo 990
960  Rem Print "ACCEPTABLE DENSITY VALUES ARE BETWEEN 1 AND 3. PLEASE REENTER"
     MsgBox ("ACCEPTABLE DENSITY VALUES ARE BETWEEN 1 AND 3. PLEASE REENTER")
970  GoTo 920
980  Rem LPRINT "MEASURED LAYER DENSITY", " ", RHO(i), "g/cm^3"
     Cells(16 + (I - 1) * 15 + 5, 1) = "MEASURED LAYER DENSITY": Cells(16 + (I
     - 1) * 15 + 5, 2) = RHO(I): Cells(16 + (I - 1) * 15 + 5, 3) = "g/cm^3"
990  Rem Print "CHOOSE TO ENTER EITHER THE RADON SOURCE TERM CONCENTRATION ,THE
ORE GRADE % OR RADIUM ACTIVITY"
1000 Rem Print "TYPE S FOR SOURCE TERM G FOR ORE GRADE OR R FOR RADIUM
ACTIVITY"
     Msg2 = "CHOOSE TO ENTER EITHER THE RADON SOURCE TERM CONCENTRATION ,THE
     ORE GRADE % OR RADIUM ACTIVITY"
     Msg2 = Msg2 + "CHOOSE TO ENTER EITHER THE RADON SOURCE TERM CONCENTRATION
     ,THE ORE GRADE % OR RADIUM ACTIVITY"
     Msg2 = Msg2 + "TYPE S FOR SOURCE TERM G FOR ORE GRADE OR R FOR RADIUM
     ACTIVITY"
     MsgBox (Msg2)
1010  Rem QQ$=INPUT$(1)
      QQ$ = InputBox("TYPE S FOR SOURCE TERM G FOR ORE GRADE OR R FOR RADIUM
      ACTIVITY", QQ$)
1020  If QQ$ = "S" Then GoTo 1230 Else If QQ$ = "s" Then GoTo 1230
1030  If QQ$ = "G" Then GoTo 1060 Else If QQ$ = "g" Then GoTo 1060
1040  If QQ$ = "R" Then GoTo 1100 Else If QQ$ = "r" Then GoTo 1100 Else GoTo
1000
1050  Rem Print "THE ORE GRADE % MUST BE BETWEEN 0 AND 100. PLEASE REENTER"
```

File: Edit1 8/26/2010, 8:17:19 AM

```
        MsgBox ("THE ORE GRADE % MUST BE BETWEEN 0 AND 100. PLEASE REENTER")
1060    Rem INPUT "ORE GRADE PERCENTAGE";OG :IF OG<0 OR OG>100 GOTO 1050
        OG = InputBox("ORE GRADE PERCENTAGE"): If OG < 0 Or OG > 100 Then GoTo
        1050
1070    Rem LPRINT "ORE GRADE PERCENTAGE", " ", OG, "%"
        Cells(16 + (I - 1) * 15 + 6, 1) = "": Cells(16 + (I - 1) * 15 + 6, 2) =
        OG: Cells(16 + (I - 1) * 15 + 6, 3) = "%"
1080    RA = OG * 2812#
1090    Rem LPRINT "CALCULATED RADIUM ACTIVITY", " ", RA, "pCi/g": GoTo 1130
        Cells(16 + (I - 1) * 15 + 7, 1) = "CALCULATED RADIUM ACTIVITY": Cells(16
        + (I - 1) * 15 + 7, 2) = RA: Cells(16 + (I - 1) * 15 + 7, 3) = "PcI/G":
        GoTo 1130
1100    Rem INPUT "RADIUM ACTIVITY (pCi/g)";RA
        RA = InputBox("RADIUM ACTIVITY(pCi/g")
1110    Rem If RA < 0 Then Print "THE RADIUM ACTIVITY CANNOT BE NEGATIVE": GoTo
1100
        If RA < 0 Then MsgBox ("THE RADIUM ACTIVITY CANNOT BE NEGATIVE"): GoTo
        1100
1120    Rem LPRINT "MEASURED RADIUM ACTIVITY", " ", RA, "pCi/g"
        Cells(16 + (I - 1) * 15 + 8, 1) = "MEASURED RADIUM ACTIVITY": Cells(16 +
        (I - 1) * 15 + 8, 2) = RA: Cells(16 + (I - 1) * 15 + 8, 3) = "pCi/g"
1130    Rem INPUT "LAYER EMANATION COEFFICIENT default=.35";E
        E = InputBox("LAYER EMANATION COEFFICIENT default=.35")
1140    If E = -1 Then GoTo 1150 Else If E < 0 Or E > 1 Then GoTo 1160 Else GoTo
1180
1150    Rem E = 0.35: LPRINT "DEFAULT LAYER EMANATION COEFFICIENT", E: GoTo 1190
        E = 0.35: Cells(16 + (I - 1) * 15 + 9, 1) = "DEFAULT LAYER EMANATION
        COEFFICIENT": Cells(16 + (I - 1) * 15 + 9, 2) = E: GoTo 1190
1160    Rem Print "THE EMANATION COEFFICIENT MUST BE BETWEEN 0 AND 1."
        MsgBox ("THE EMANATION COEFFICIENT MUST BE BETWEEN 0 AND 1.")
1170    GoTo 1130
1180    Rem LPRINT "MEASURED LAYER EMANATION COEFFICIENT", E
    E = 0.35: Cells(16 + (I - 1) * 15 + 10, 1) = "MEASURED EMANATION
    COEFFICIENT": Cells(16 + (I - 1) * 15 + 10, 2) = E
1190    Q(I) = XL * RA * E * RHO(I) / P(I)
1200    Rem Print "CALCULATED LAYER SOURCE TERM", Q(i)
1210    Rem LPRINT "CALCULATED LAYER SOURCE TERM",
1220    Rem LPRINT USING "##.###^^^^    ";Q(I), :LPRINT "pCi*cm^-3/s" :GOTO 1270
        Cells(16 + (I - 1) * 15 + 10, 1) = "CALCULATED LAYER SOURCE TERM":
        Cells(16 + (I - 1) * 15 + 10, 2) = Q(I): Cells(16 + (I - 1) * 15 + 10, 3)
        = "pCi*cm^-3/s": GoTo 1270
1230    Rem INPUT "SOURCE TERM (pCi*cm^-3/s)";Q(I)
        Q(I) = InputBox("SOURCE TERM (pCi*cm^-3/s)")
1240    If Q(I) < 0 Then GoTo 1250 Else GoTo 1260
1250    Rem Print "THE SOURCE TERM CANNOT BE NEGATIVE.": GoTo 1230
        MsgBox ("THE SOURCE TERM CANNOT BE NEGATIVE."): GoTo 1230
1260    Rem LPRINT "MEASURED LAYER SOURCE TERM", " ", Q(i), "pCi*cm^-3/s"
        Cells(16 + (I - 1) * 15 + 11, 1) = "MEASURED LAYER SOURCE TERM": Cells(16
        + (I - 1) * 15 + 11, 2) = Q(I): Cells(16 + (I - 1) * 15 + 11, 3) =
        "pCi*cm^-3/s"
1270    Rem INPUT "LAYER WEIGHT % MOISTURE";XM(I)
        XM(I) = InputBox("LAYER WEIGHT % MOISTURE")
1280    If XM(I) < 0 Or XM(I) > 100 Then GoTo 1290 Else GoTo 1310
1290    Rem Print "THE WEIGHT % MOISTURE MUST BE BETWEEN 0 AND 100. "
        MsgBox ("THE WEIGHT % MOISTURE MUST BE BETWEEN 0 AND 100.")
1300    GoTo 1270
```

File: Edit1 8/26/2010, 8:17:19 AM

```
1310  Rem LPRINT "LAYER WEIGHT % MOISTURE", " ", XM(i), "%"
Cells(16 + (I - 1) * 15 + 12, 1) = "LAYER WEIGHT % MOISTURE": Cells(16 + (I -
1) * 15 + 12, 2) = XM(I): Cells(16 + (I - 1) * 15 + 12, 3) = "%"
1320  XMS(I) = 0.01 * XM(I) * RHO(I) / P(I)

1330  Rem LPRINT "MOISTURE SATURATION FRACTION", :LPRINT USING " .###";XMS(I)
      Cells(16 + (I - 1) * 15 + 13, 1) = "MOISTURE SATURATION FRACTION":
      Cells(16 + (I - 1) * 15 + 13, 2) = XMS(I)
1340  If XMS(I) > 1! Then GoTo 1350 Else GoTo 1370
1350  Rem Print "THE MOISTURE CONTENT IS >100% SATURATION. PLEASE REENTER."
      MsgBox ("THE MOISTURE CONTENT IS >100% SATURATION. PLEASE REENTER.")
1360  Rem LPRINT "MOISTURE SATURATION >100%. NEW VALUE REQUESTED.": GoTo 1270
1370  Rem INPUT "LAYER DIFFUSION COEFFICIENT default=calculated ";D(I)
      D(I) = InputBox("LAYER DIFFUSION COEFFICIENT default=calculated ")
1380  If D(I) = -1 Then GoTo 1410 Else If D(I) < 0 Or D(I) > 1 Then GoTo 1390
Else GoTo 1440
1390  Rem Print "REENTER DIFFUSION COEFFICIENT VALUES BETWEEN 0 AND 1."
      MsgBox ("REENTER DIFFUSION COEFFICIENT VALUES BETWEEN 0 AND 1")
1400  GoTo 1370
1410  D(I) = 0.07 * Exp(-4 * (XMS(I) - XMS(I) * P(I) * P(I) + XMS(I) ^ 5))
1420  Rem LPRINT "CALCULATED LAYER DIFFUSION COEFFICIENT",
1430  Rem LPRINT USING "##.###^^^^    ";D(I), :LPRINT "cm^2/s" :GOTO 1450
1440  Rem LPRINT "MEASURED LAYER DIFFUSION COEFFICIENT", D(i), "cm^2/s"
      Cells(16 + (I - 1) * 15 + 14, 1) = "MEASURED LAYER DIFFUSION
      COEFFICIENT": Cells(16 + (I - 1) * 15 + 14, 2) = D(I): Cells(16 + (I - 1)
      * 15 + 14, 3) = "cm^2/s"
1450  Rem Print: Print: LPRINT: LPRINT
1460  Rem If i = 2 Or i = 5 And N = 5 Or i = 6 Or i > 8 Then LPRINT Chr$(12)
1470 Next I
1480 Rem On Error GoTo 1500
1490 Rem GoTo 1510
1500 Rem If Err = 53 Then GoTo 1540
1510 Rem Print "THE BACKUP FILE RNDATA.BAK WILL BE REPLACED IF IT EXISTS UNLESS
N IS          TYPED. TYPE ANY OTHER KEY TO CONTINUE. IF N IS TYPED THE INPUT
DATA           WILL NOT BE SAVED."
1520 Rem V$=INPUT$(1)
1530 Rem If V$ = "N" Or V$ = "n" Then GoTo 1980 Else GoTo 1550
1540 Rem Resume Next
1550 Rem Kill "A:RNDATA.BAK"
1560 Rem On Error GoTo 1580
1570 Rem GoTo 1600
1580 Rem If Err = 53 Then Print "BACKING UP RNDATA"
1590 Rem Resume Next
1600 Rem Name "A:RNDATA" As "A:RNDATA.BAK"
1610 Rem On Error GoTo 0
1620 Rem Open "A:RNDATA" For Output As #2
1630 Rem Print #2, USING; " ##.# "; N;
1640 Rem Print #2, USING; " ##.###^^^^"; F01; CN1;
1650 Rem Print #2, USING; " ##.# "; ICOST;
1660 Rem Print #2, USING; " ##.###^^^^"; CRITJ; ACC
1670 Rem For I = 1 To N
1680 Rem  Print #2, USING; " ##.###^^^^"; DX(I); D(I); P(I); Q(I); XMS(I);
RHO(I)
1690 Rem Next I
1700 Rem Close #2
1710 Rem LPRINT: LPRINT: LPRINT
```

File: Edit1 8/26/2010, 8:17:19 AM

```
1720 Rem LPRINT " ", "DATA SENT TO THE FILE `RNDATA' ON DRIVE A:": LPRINT
1730 Rem GoSub 1850
1740 Rem GoTo 1980
1750 Rem Open "A:RNDATA" For Input As #3
Sheets("RNDATA").Select
    Cells.Select
    Selection.ClearContents
1760 Rem Input #3, N, F01, CN1, ICOST, CRITJ, ACC
1770 Rem For I = 1 To N
1780 Rem Input #3, DX(I), D(I), P(I), Q(I), XMS(I), RHO(I)
1790 Rem Next I
1800 Rem Close #3
1810 Rem LPRINT: LPRINT: LPRINT
1820 Rem LPRINT " ", "DATA INPUT TO DIFFUSION CALCULATIONS": LPRINT
1830 Rem GoSub 1850
1840 Rem GoTo 1980
1850 Rem  ' PRINT SUBROUTINE
1860  Rem LPRINT "  N        F01          CN1         ICOST       CRITJ         ACC"
Cells(1, 1) = "DATA SENT TO THE FILE RNDATA THAT WAS THE TRUE 5.25 FLOPPY DISK
BEFORE THERE WAS 3.5 DISK AND THE MODERN DAY FLASH DRIVE."
Cells(2, 1) = "N": Cells(2, 2) = "F01": Cells(2, 3) = "CN1": Cells(2, 4) =
"ICOST": Cells(2, 5) = "CRITJ": Cells(2, 6) = "ACC"
Cells(3, 1) = N: Cells(3, 2) = F01: Cells(3, 3) = CN1: Cells(3, 4) = ICOST:
Cells(3, 5) = CRITJ: Cells(3, 6) = ACC
Cells(4, 1) = "LAYER": Cells(4, 2) = "DX": Cells(4, 3) = "D": Cells(4, 4) =
"P": Cells(4, 5) = "Q": Cells(4, 6) = "XMS": Cells(4, 7) = "RHO"
For I = 1 To N
Cells(4 + I, 1) = I: Cells(4 + I, 2) = DX(I): Cells(4 + I, 3) = D(I): Cells(4 +
I, 4) = P(I): Cells(4 + I, 5) = Q(I): Cells(4 + I, 6) = XMS(I): Cells(4 + I, 7)
= RHO(I)
Next I

1870  Rem LPRINT USING "###  ";N; :  LPRINT USING " ##.###^^^^";F01;CN1;
1880  Rem LPRINT USING "    ###    ";ICOST;
1890  Rem LPRINT USING " ##.###^^^^";CRITJ;ACC : LPRINT
1900  Rem LPRINT "LAYER      DX         D          P          Q          XMS
RHO      "
1910  Rem For I = 1 To N
1920  Rem  LPRINT USING "###  ";I;
1930  Rem  LPRINT USING " ##.###^^^^";DX(I);D(I);P(I);Q(I);XMS(I);
1940  Rem LPRINT USING "###.###";RHO(I)
1950  Rem Next I
1960 Rem LPRINT:   If N = 4 Or N = 8 Or N > 11 Then LPRINT Chr$(12)
1970 Rem 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# - 0.74 * XMS(I)
2090 Next I
```

File: Edit1 8/26/2010, 8:17:19 AM

```
2100 ABV = Sqr(XL / D(1))
2110 V = ABV * DX(1)
2120 Rem GoSub 4000
2130 RF(1) = (Q(1) * P(1) / ABV) * FNTANH(V)
2140 If F01 = -1 Then GoTo 2150 Else GoTo 2170
2150 RF(1) = RF(1) / (1 + (0.5 * FNTANH(V)) / 0.5 / (Exp(V) + Exp(-V)))
2160 F0 = -0.5 * RF(1) * FNTANH(V)
2170 DDX(1) = DX(1)
2180 RC(1) = CN / A4(1)
2190 J0# = RF(1) * 10000
    Sheets("Results").Select
    Range("a6:d20").Select
    Selection.ClearContents
2200 Rem Print: LPRINT
2210 Rem Print USING; "BARE SOURCE FLUX FROM LAYER 1:   ##.###^^^^
pCi*cm^-3/s"; J0#
2220 Rem LPRINT USING "BARE SOURCE FLUX FROM LAYER 1:   ##.###^^^^
pCi*cm^-3/s";J0#
2230 Rem Print "calculation in progress"
Cells(2, 1) = "BARE SOURCE FLUX FROM LAYER 1": Cells(2, 2) = J0#: Cells(2, 3) =
"pCi*cm^-3/s"

2240 For I = 1 To N
2250  Q(I) = Q(I) * P(I)
2260  P(I) = P(I) * A4(I)
2270  D(I) = D(I) * P(I)
2280 Next I
2290 DDX(1) = DX(1)
2300 ALP(1) = Sqr(XL * P(1) / D(1))
2310 For I = 2 To N 'THICKNESS OPTIMIZATION FEEDS BACK HERE
2320  DDX(I) = DX(I)
2330 Next I
2340 ' MODIFY PARAMETERS FOR PROGRAM LIMITS
2350 SUMX = 0: SUMA = 0: SUMAX = 0: XRED = 0: XCHG = 0: X(1) = 0: X0 = 0
2360 SUMMAX = ALP(1) * DX(1)
2370 If SUMMAX > 4.61 Then XRED = 4.61 / ALP(1) Else GoTo 2400
2380 F0 = F0 * Exp(4.61 - SUMMAX)
2390 SUMMAX = ALP(1) * (DX(1) - XRED)
2400 If XRED > 0 Then XCHG = DX(1) - XRED
2410 For I = 1 To N
2420  ALPI = Sqr(XL * P(I) / D(I))
2430  SUMX = SUMX + DX(I)
2440  X(I + 1) = SUMX - XCHG
2450  SUMA = SUMA + ALPI
2460  ALSUM = ALPI * X(I + 1)
2470  If ALSUM > SUMMAX Then SUMMAX = ALSUM
2480  SUMAX = SUMAX + ALSUM
2490  ALP(I) = ALPI
2500 Next I
2510 If SUMMAX > 174 Then GoTo 2520 Else GoTo 2540
2520 Rem LPRINT "THE LAYER THICKNESS OR DIFFUSION COEFFICIENT EXCEEDS LIMITS"
2530 Rem LPRINT
     MsgBox ("THE LAYER THICKNESS OR DIFFUSION COEFFICIENT EXCEEDS LIMITS")
2540 If SUMMAX > 87 Then X0 = SUMAX / SUMA Else GoTo 2580
2550 For I = 0 To N
2560  X(I + 1) = X(I + 1) - X0
```

File: Edit1 8/26/2010, 8:17:19 AM

```
2570 Next I
2580 ' CALCULATE PARAMETERS FOR MATRIX
2590 For I = 1 To NM1
2600  RDUM = Sqr(P(I + 1) * D(I + 1) / (P(I) * D(I)))
2610  R(I) = -0.5 * (1 - RDUM)
2620  RR(I) = -0.5 * (1 + RDUM)
2630  QP = (Q(I + 1) / P(I + 1) - Q(I) / P(I)) / XL
2640  T(I) = QP * Exp(-ALP(I) * X(I + 1))
2650  U(I) = QP * 0.5 * Exp(ALP(I) * X(I + 1))
2660  AIP1MI(I) = Sqr(XL) * (Sqr(P(I + 1) / D(I + 1)) - Sqr(P(I) / D(I)))
2670 Next I
2680 ALP(N) = Sqr(XL * P(N) / D(N))
2690 'SPECIFY MATRIX ELEMENTS AND SOLVE
2700 For I = 1 To NM1
2710  J = 5 * I - 4
2720  K = 2 * I - 1
2730  A(J) = Exp(-2 * ALP(I) * X(I + 1))
2740  A(J + 1) = -Exp(AIP1MI(I) * X(I + 1))
2750  A(J + 2) = -Exp(-(ALP(I + 1) + ALP(I)) * X(I + 1))
2760  A(J + 3) = R(I) * Exp((ALP(I + 1) + ALP(I)) * X(I + 1))
2770  A(J + 4) = RR(I) * Exp(-AIP1MI(I) * X(I + 1))
2780  B(K) = T(I)
2790  B(K + 1) = U(I)
2800 Next I
2810 N5M4 = 5 * N - 4
2820 A(N5M4) = Exp(-2 * ALP(N) * X(N + 1))
2830 N2M1 = 2 * N - 1
2840 B(N2M1) = (CN - Q(N) / (P(N) * XL)) * Exp(-ALP(N) * X(N + 1))
2850 'UPPER TRIANGULARIZE MATRIX
2860 G(1) = A(1) + Exp(-2 * ALP(1) * X(1))
2870 G(2) = A(2) / G(1)
2880 G(3) = A(3) / G(1)
2890 BU(1) = (B(1) + F0 * Exp(-ALP(1) * X(1)) / (D(1) * ALP(1))) / G(1)
2900 For I = 1 To NM2
2910  J = 5 * I - 1
2920  K = 2 * I
2930  G(J) = A(J) - G(J - 2)
2940  G(J + 1) = (A(J + 1) - G(J - 1)) / G(J)
2950  BU(K) = (B(K) - BU(K - 1)) / G(J)
2960  G(J + 2) = A(J + 2) - G(J + 1)
2970  G(J + 3) = A(J + 3) / G(J + 2)
2980  G(J + 4) = A(J + 4) / G(J + 2)
2990  BU(K + 1) = (B(K + 1) - BU(K)) / G(J + 2)
3000 Next I
3010 N5M6 = 5 * N - 6
3020 G(N5M6) = A(N5M6) - G(N5M6 - 2)
3030 G(N5M6 + 1) = (A(N5M6 + 1) - G(N5M6 - 1)) / G(N5M6)
3040 N2M2 = 2 * N - 2
3050 BU(N2M2) = (B(N2M2) - BU(N2M2 - 1)) / G(N5M6)
3060 G(N5M6 + 2) = A(N5M6 + 2) - G(N5M6 + 1)
3070 BS(N) = (B(N2M1) - BU(N2M1 - 1)) / G(N5M6 + 2)
3080 ASS(N) = BU(N2M1 - 1) - G(N5M6 + 1) * BS(N)
3090 For I = 1 To NM2
3100  J = 5 * (N - I) - 3
3110  K = 2 * (N - I) - 1
3120  L = N - I
```

File: Edit1 8/26/2010, 8:17:19 AM

```
3130  BS(L) = BU(K) - G(J) * ASS(L + 1) - G(J + 1) * BS(L + 1)
3140  ASS(L) = BU(K - 1) - G(J - 2) * BS(L)
3150 Next I
3160 BS(1) = BU(1) - G(2) * ASS(2) - G(3) * BS(2)
3170 ASS(1) = (BS(1) * Exp(-ALP(1) * X(1)) - F0 / (ALP(1) * D(1))) *
Exp(-ALP(1) * X(1))
3180 'COMPLETE MATRIX SOLUTION
3190 For I = 1 To N
3200  ALPI = ALP(I) * X(I + 1)
3210  ASI = ASS(I) * Exp(ALPI)
3220  BSI = BS(I) * Exp(-ALPI)
3230  RC(I) = ASI + BSI + Q(I) / (P(I) * XL)
3240  RF(I) = -D(I) * ALP(I) * (ASI - BSI)
3250 Next I
3260 RC(N) = CN
3270 If ICOST = 0 Then GoTo 3650
3280 F0P = F0
3290 If F0 < 1 Then F0P = 1
3300 If RF(1) < 0 Or RF(1) = 0 Then RF(1) = 1
3310  'BEGIN COVER THICKNESS OPTIMIZATION
3320 If JTST = 0 Or CRITJ > 99 Or Not CRITJ > 0 Then GoTo 3650
3330 T7 = (RF(N) - CRITJ) / CRITJ
3340 ABT7 = Abs(T7)
3350 If ABT7 < ACC Then GoTo 3650
3360 NTST = NO3
3370 IIJ = NO2
3380 If NTST = NSAVE Then GoTo 3410
3390 DXMAX = 0: DXMIN = 0: RFMAX = 0: RFMIN = 0
3400 NSAVE = NTST
3410 'SET LIMITS AND SEARCH FOR DX
3420 If T7 = 0 Then GoTo 3650
3430 If T7 < 0 Then DXMAX = DX(NTST) Else GoTo 3450
3440 RFMIN = RF(N): GoTo 3460
3450 DXMIN = DX(NTST): RFMAX = RF(N)
3460 If DXMAX = 0 Then GoTo 3470 Else GoTo 3480
3470 DX(NTST) = DX(NTST) * (1 + 0.5 * T7): GoTo 3490
3480 DX(NTST) = DXMIN + (DXMAX - DXMIN) * (RFMAX - CRITJ) / (RFMAX - RFMIN)
3490 If RFMAX = 0 Then DX(NTST) = 0.5 * DXMAX
3500 If Not DX(NTST) > 1 Then DX(NTST) = 0 And JTST = 0
3510 If ITHK = 0 Then GoTo 2310
3520 T2T = 0
3530 If NO4 > N Then GoTo 3570
3540 For IJ = NO4 To N
3550  T2T = T2T + DX(IJ)
3560 Next IJ
3570 If NO1 < 2 Then GoTo 3610
3580 For IJ = 2 To NO1
3590 T2T = T2T + DX(IJ)
3600 Next IJ
3610 T23 = DX(NTST)
3620 T2T = T2T + DX(NTST)
3630 If Not DX(NTST) = T23 Then CRITJ = -1
3640 GoTo 2310
3650 'PRINT RESULTS
3660 Rem Print: Print "    RESULTS OF RADON DIFFUSION CALCULATIONS": Print
3670 Rem Print "  LAYER    THICKNESS    EXIT FLUX    EXIT CONC.",
```

File: Edit1 8/26/2010, 8:17:19 AM

```
3680 Rem Print "                (cm)      (pCi/m^2/s)     (pCi/l) ": LPRINT
Cells(3, 1) = "RESULTS OF RADON DIFFUSION CALCULATIONS"
Cells(5, 1) = "LAYER": Cells(5, 2) = "THICKNESS": Cells(5, 3) = "EXIT FLUX":
Cells(5, 4) = "EXIT CONC."
Cells(6, 1) = "(-)": Cells(6, 2) = "(CM)": Cells(6, 3) = "(pCi/m^2/s)":
Cells(6, 4) = "(pCi/l)"
3690 For I = 1 To N
3700 RXYZ = RF(I) * 10000
3710 CXYZ = RC(I) * 1000 * A4(I)
3720  Rem Print USING; "  ###  "; I;
3730  Rem Print USING; "   ##.###^^^^"; DDX(I); RXYZ; CXYZ
Cells(6 + I, 1) = I: Cells(6 + I, 2) = DDX(I): Cells(6 + I, 3) = RXYZ: Cells(6
+ I, 4) = CXYZ
3740 Next I
3750 Rem LPRINT: LPRINT
3760 Rem LPRINT " ", "RESULTS OF THE RADON DIFFUSION CALCULATIONS"
3770 Rem LPRINT: LPRINT
3780 Rem LPRINT " ", "LAYER    THICKNESS    EXIT FLUX    EXIT CONC."
3790 Rem LPRINT " ", "             (cm)      (pCi/m^2/s)    (pCi/l) "
3800 Rem LPRINT
3810 Rem For I = 1 To N
3820 Rem RXYZ = RF(I) * 10000
3830 Rem CXYZ = RC(I) * 1000 * A4(I)
3840 Rem LPRINT " ", : LPRINT USING "###  ";I;
3850 Rem  LPRINT USING "   ##.###^^^^";DDX(I);RXYZ;CXYZ
3860 Rem Next I
3870 Rem LPRINT Chr$(12)
3880 End

End Sub

Function FNTANH(V)
4000 If V < -9.01 Then GoTo 4120 'THIS FUNCTION CALCULATES TANH
4010 If V < -0.7 Then GoTo 4100
4020 If Abs(V) <= 2 ^ -12 Then GoTo 4060
4030 If Abs(V) <= 0.7 Then GoTo 4070
4040 If V <= 9.01 Then GoTo 4080
4050 If V > 9.01 Then GoTo 4090
4060 FNTANH = V: GoTo 4200
4070 FNTANH = V * (1 - V ^ 2 * (0.0037828 + 0.8145651 / (V ^ 2 + 2.471749))):
GoTo 4200
4080 FNTANH = 1 - 2 / (Exp(V) * Exp(V) + 1): GoTo 4200
4090 FNTANH = 1: GoTo 4200
4100 V = -V
4110 FNTANH = -(1 - 2 / (Exp(V) * Exp(V) + 1)): GoTo 4200
4120 V = -V
4130 FNTANH = -1
4200 'END OF FUNCTION TANH
End Function
```

Radon Visual Basic for Applications

1. The input is entered to the program interactively with the use of input boxes.
2. Message boxes provide information for input using default values.
3. The inputs are output to the EXCEL Workbook Output.
4. The results of the analysis are presented on the EXCEL Workbook Results
5. The analysis is started with the EXCEL command /Tools/Macros/Radon.

The example inputs are obtained from Reference 7.

Radon Program Verification Sample Problem Output

DESCRIPTION	CONSTANTS VALUE	UNITS
RADON DECAY CONSTANT	0.0000021	1/s
RADON WATER/AIR PARTITION COEFFICIENT	0.26	
SPECIFIC GRAVITY OF COVER & TAILINGS	2.65	gm/cm^3
	GENERAL INPUT PARAMETERS	
LAYERS OF COVER AND TAILINGS	3	
DESIRED RADON FLUX LIMIT	20	pCi*m^-2/s
NO. OF THE LAYER TO BE OPTIMIZED	3	
DEFAULT SURFACE RADON CONCENTRATION	0	pCi/l
LOWER BOUNDARY FLUX TO BE CALCULATED ASSUMING AN INFINITE SUBSOIL		
SURFACE FLUX PRECISION	0.001	pCi*m^-2/s
	LAYER INPUT PARAMETERS	
LAYER #	1	
LAYER THICKNESS	500	cm
CALCULATED LAYER POROSITY	0.44	
MEASURED LAYER DENSITY	1.484	g/cm^3
MEASURED LAYER SOURCE TERM	0.000573	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	11.7	%
MOISTURE SATURATION FRACTION	0.394609091	
MEASURED LAYER DIFFUSION COEFFICIENT	0.013	cm^2/s
LAYER #	2	
LAYER THICKNESS	50	cm
CALCULATED LAYER POROSITY	0.3	
MEASURED LAYER DENSITY	1.855	g/cm^3
MEASURED LAYER SOURCE TERM	0	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	6.3	%
MOISTURE SATURATION FRACTION	0.38955	
MEASURED LAYER DIFFUSION COEFFICIENT	0.0078	cm^2/s
LAYER #	3	
LAYER THICKNESS	100	cm
CALCULATED LAYER POROSITY	0.37	
MEASURED LAYER DENSITY	1.67	g/cm^3
MEASURED LAYER SOURCE TERM	0	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	5.4	%
MOISTURE SATURATION FRACTION	0.24372973	
MEASURED LAYER DIFFUSION COEFFICIENT	0.022	cm^2/s

N	F01	CN1	ICOST	CRITJ	ACC
3	-1	0	3	20	0.001

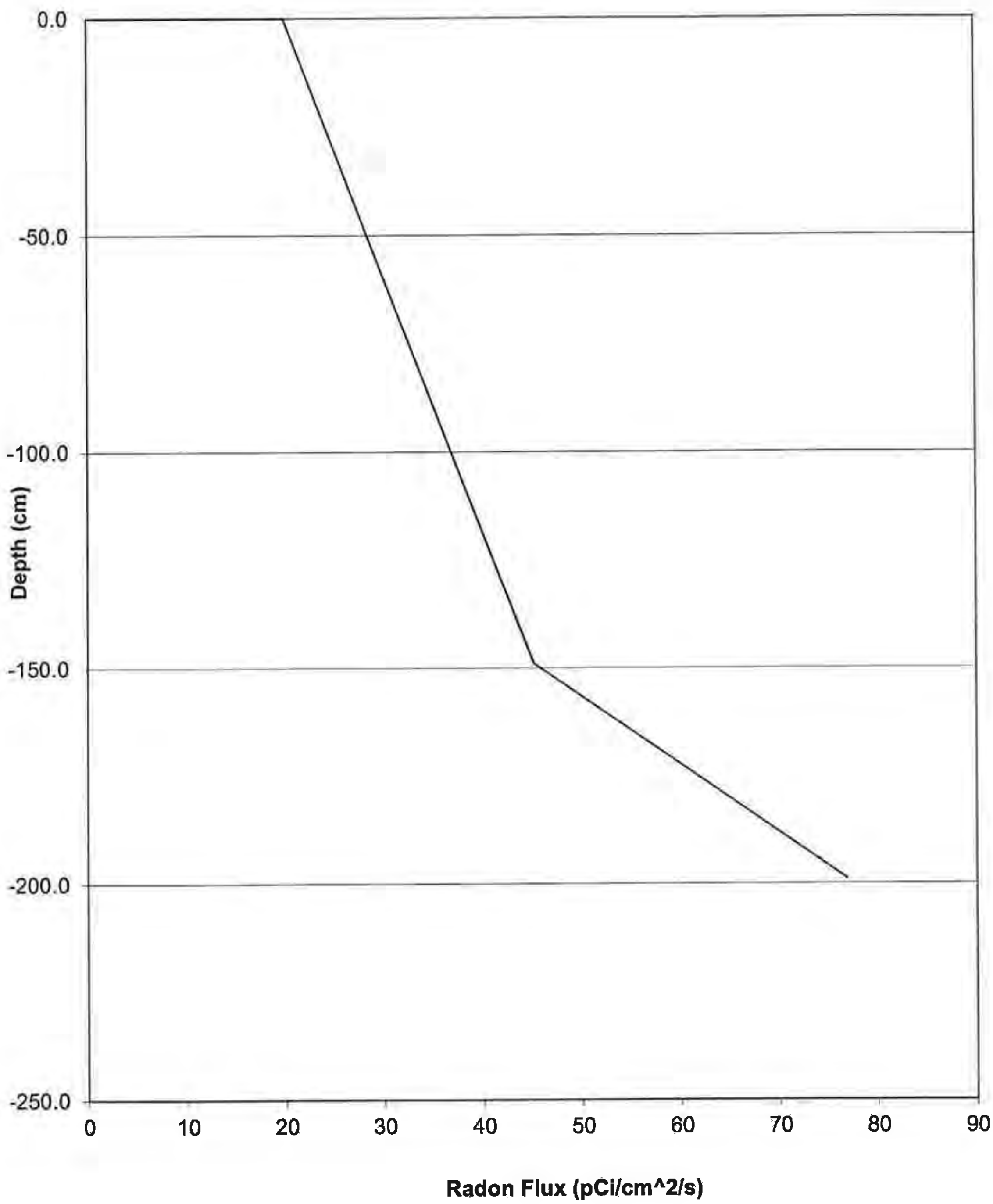
LAYER	DX	D	P	Q	XMS	RHO
1	500	0.013	0.44	0.000573	0.394609	1.484
2	50	0.0078	0.3	0	0.38955	1.855
3	100	0.022	0.37	0	0.24373	1.67

BARE SOURCE FLUX FROM LAYER 1 198.021553 pCi*cm^-3/s
RESULTS OF RADON DIFFUSION CALCULATIONS

LAYER	THICKNESS	EXIT FLUX	EXIT CONC.
(-)	(CM)	(pCi/m^2/s)	(pCi/l)
1	500.0	76.9	167050.2
2	50.0	45.2	44296.9
3	149.0	20.0	0.0

DEPTH	EXIT FLUX	EXIT CONC.
(CM)	(pCi/m^2/s)	(pCi/l)
-699.0		
-199.0	76.9	167050.2
-149.0	45.2	44296.9
0.0	20.0	0.0
0.0	0.0	0.0
0.0	0.0	0.0
0.0	0.0	0.0
0.0	0.0	0.0
0.0	0.0	0.0

Radon Flux Through Tailings and Cover System



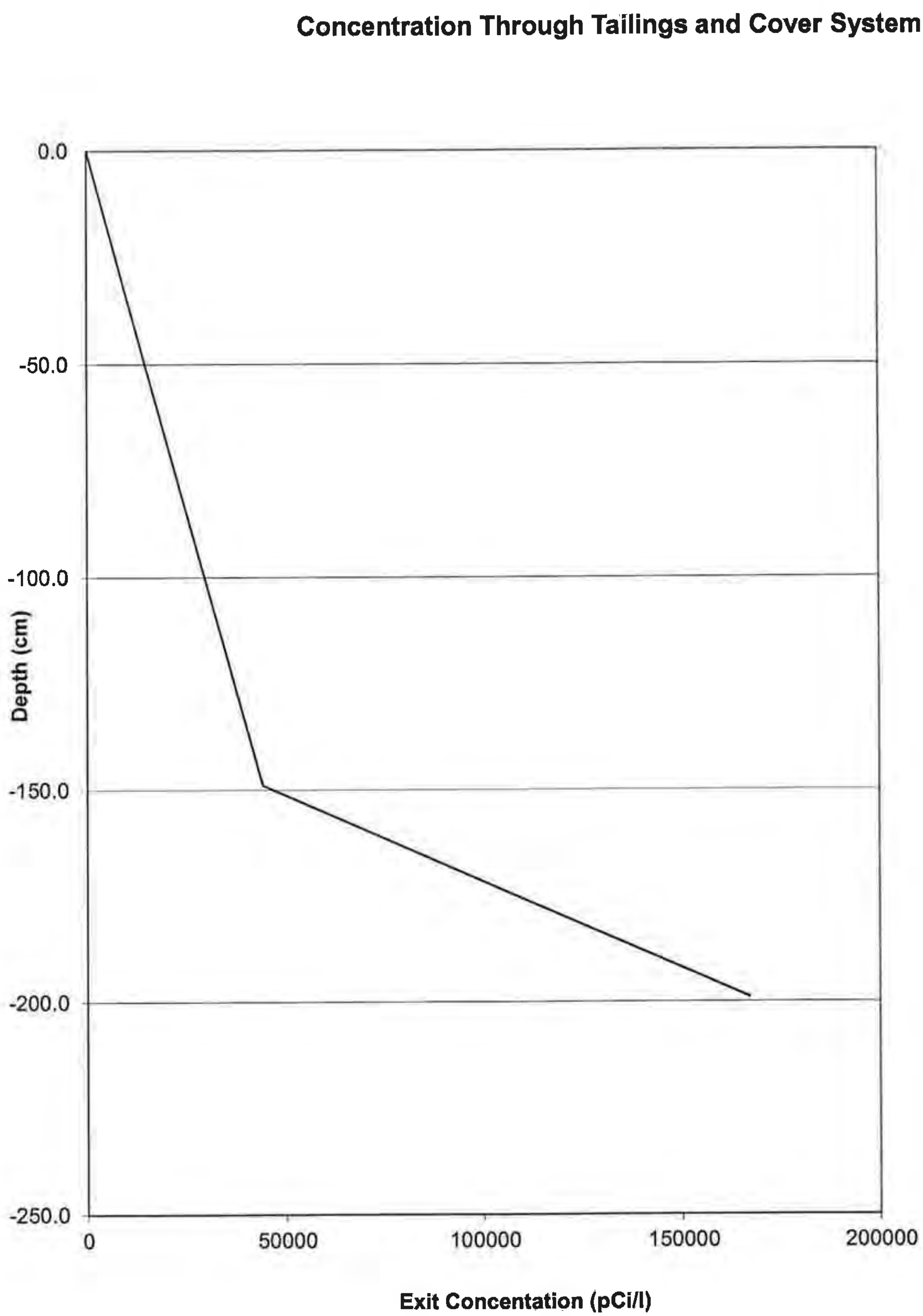

Concentration Through Tailings and Cover System
0.0
-50.0
-100.0
-150.0
-200.0
-250.0
Depth (cm)
0
50000
100000
150000
200000
Exit Concentation (pCi/l)

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

3.64-40

Scenario 1 Two Tailings Layers 10 ft Slimes over 5 ft Coarse

DESCRIPTION	CONSTANTS VALUE	UNITS
RADON DECAY CONSTANT	0.0000021	1/s
RADON WATER/AIR PARTITION COEFFICIENT	0.26	
SPECIFIC GRAVITY OF COVER & TAILINGS	2.65	gm/cm^3
GENERAL INPUT PARAMETERS		
LAYERS OF COVER AND TAILINGS	8	
DESIRED RADON FLUX LIMIT	20	pCi*m^-2/s
NO. OF THE LAYER TO BE OPTIMIZED	5	
DEFAULT SURFACE RADON CONCENTRATION	0	pCi/l
LOWER BOUNDARY FLUX TO BE CALCULATED ASSUMING AN INFINITE SUBSOIL		
SURFACE FLUX PRECISION	0.001	pCi*m^-2/s
LAYER INPUT PARAMETERS		
LAYER #	1	
LAYER THICKNESS	304.8	cm
CALCULATED LAYER POROSITY	0.42	
MEASURED LAYER DENSITY	1.57	g/cm^3
MEASURED RADIUM ACTIVITY	1210	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	0.003324475	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	13	%
MOISTURE SATURATION FRACTION	0.485952381	
MEASURED LAYER DIFFUSION COEFFICIENT	0.012669201	cm^2/s
LAYER #	2	
LAYER THICKNESS	152.4	cm
CALCULATED LAYER POROSITY	0.42	
MEASURED LAYER DENSITY	1.65	g/cm^3
MEASURED RADIUM ACTIVITY	302.5	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	8.73E-04	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	8	%
MOISTURE SATURATION FRACTION	0.314285714	
MEASURED LAYER DIFFUSION COEFFICIENT	0.024553317	cm^2/s
LAYER #	3	
LAYER THICKNESS	61	cm
CALCULATED LAYER POROSITY	0.39	
MEASURED LAYER DENSITY	1.61	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2.97355E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	6.3	%
MOISTURE SATURATION FRACTION	0.260076923	
MEASURED LAYER DIFFUSION COEFFICIENT	0.028836985	cm^2/s
LAYER #	4	
LAYER THICKNESS	1	cm
CALCULATED LAYER POROSITY	0.47	
MEASURED LAYER DENSITY	1.44	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g

DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2.20688E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	23	%
MOISTURE SATURATION FRACTION	0.704680851	
MEASURED LAYER DIFFUSION COEFFICIENT	0.003885951	cm^2/s
LAYER #	5	
LAYER THICKNESS	1	cm
CALCULATED LAYER POROSITY	0.32	
MEASURED LAYER DENSITY	1.8	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	4.05169E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	5.7	%
MOISTURE SATURATION FRACTION	0.320625	
MEASURED LAYER DIFFUSION COEFFICIENT	0.021840584	cm^2/s
LAYER #	6	
LAYER THICKNESS	15.2	cm
CALCULATED LAYER POROSITY	0.39	
MEASURED LAYER DENSITY	1.61	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2.97355E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	6.3	%
MOISTURE SATURATION FRACTION	0.260076923	
MEASURED LAYER DIFFUSION COEFFICIENT	0.028836985	cm^2/s
LAYER #	7	
LAYER THICKNESS	15.2	cm
CALCULATED LAYER POROSITY	0.33	
MEASURED LAYER DENSITY	1.81	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	3.95074E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	0	%
MOISTURE SATURATION FRACTION	0	
MEASURED LAYER DIFFUSION COEFFICIENT	0.07	cm^2/s
LAYER #	8	
LAYER THICKNESS	121.9	cm
CALCULATED LAYER POROSITY	0.39	
MEASURED LAYER DENSITY	1.61	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2 97355E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	6.3	%
MOISTURE SATURATION FRACTION	0.260076923	
MEASURED LAYER DIFFUSION COEFFICIENT	0.028836985	cm^2/s

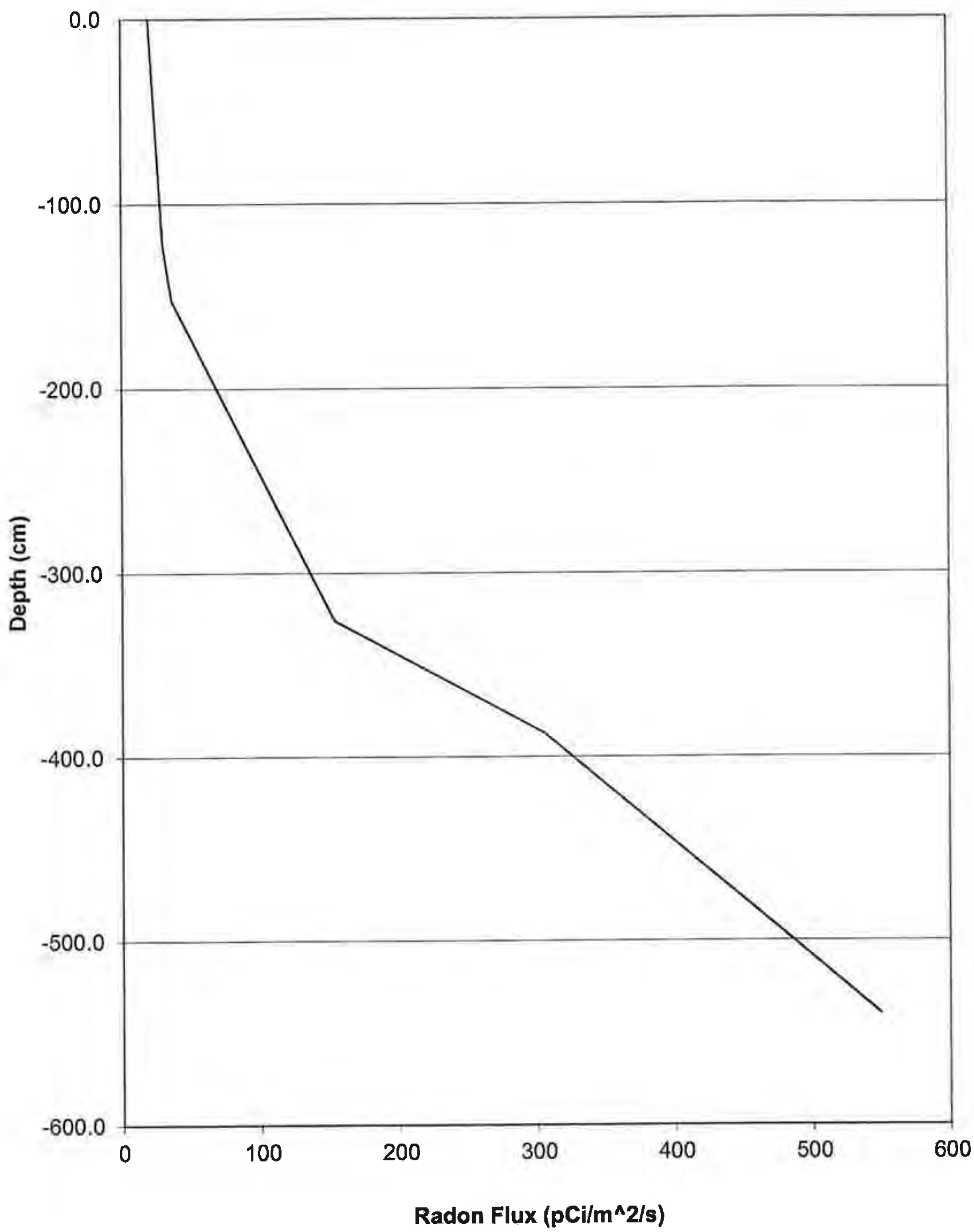
N	F01	CN1	ICOST	CRITJ	ACC	
8	-1	0	5	20	0.001	
LAYER	DX	D	P	Q	XMS	RHO
1	304.8	0.012669	0.42	0.003324	0.485952	1.57
2	152.4	0.024553	0.42	0.000873	0.314286	1.65
3	61	0.028837	0.39	2.97E-06	0.260077	1.61
4	1	0.003886	0.47	2.21E-06	0.704681	1.44
5	1	0.021841	0.32	4.05E-06	0.320625	1.8
6	15.2	0.028837	0.39	2.97E-06	0.260077	1.61
7	15.2	0.07	0.33	3.95E-06	0	1.81
8	121.9	0.028837	0.39	2.97E-06	0.260077	1.61

BARE SOURCE FLUX FROM LAYER 1 1062.700551 pCi*cm^-3/s
RESULTS OF RADON DIFFUSION CALCULATIONS

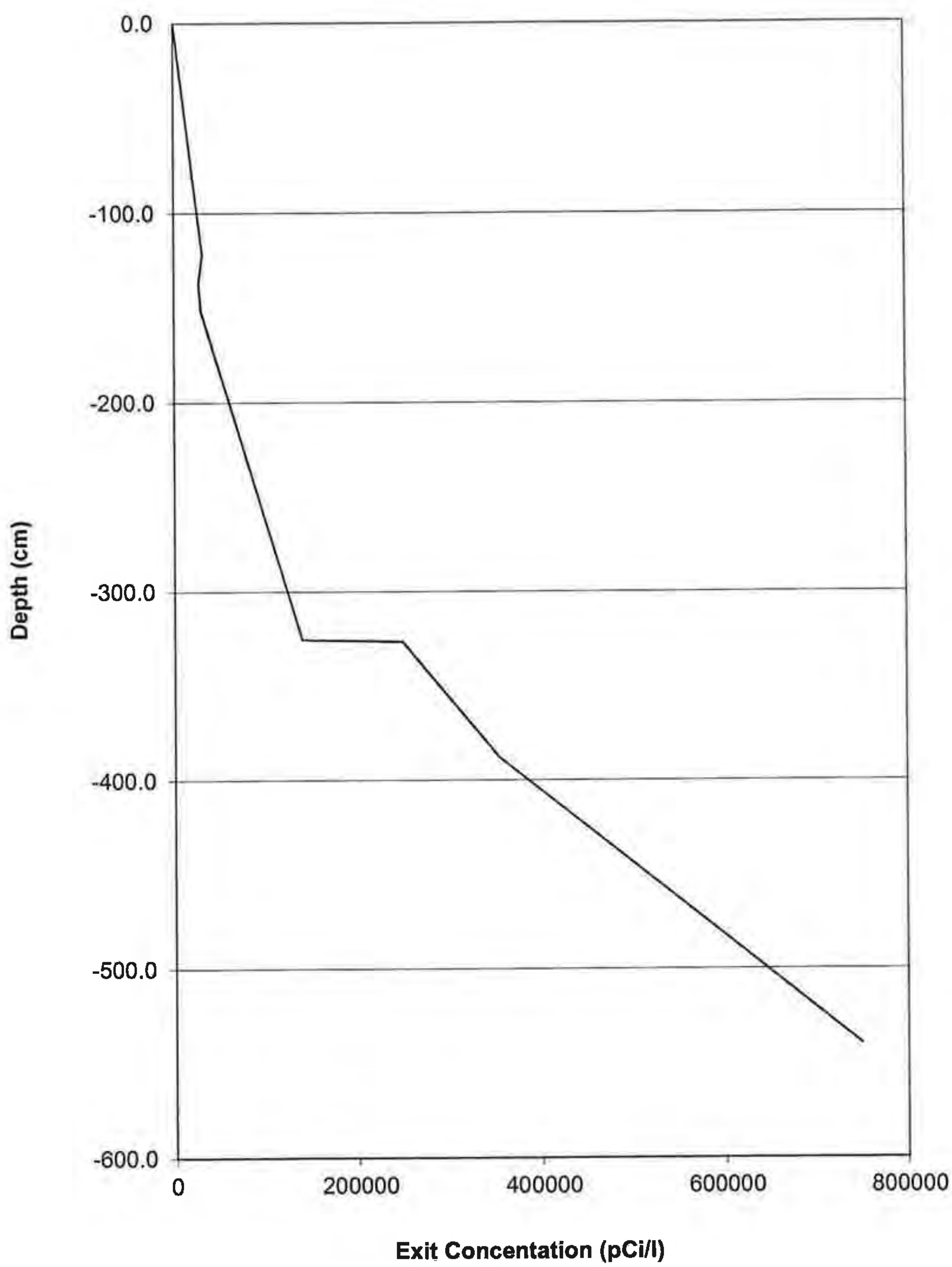
LAYER	THICKNESS	EXIT FLUX	EXIT CONC.
(-)	(CM)	(pCi/m^2/s)	(pCi/l)
1	304.8	549.5	749649.8
2	152.4	306.4	353257.3
3	61.0	155.4	249231.3
4	1.0	154.0008139	139220.1
5	173.2	36.75655722	29646.1
6	15.2	33.32462226	26658.4
7	15.2	30.15723501	30924.4
8	121.9	20.00443134	0.0

DEPTH	EXIT FLUX	EXIT CONC.
(CM)	(pCi/m^2/s)	(pCi/l)
-844.7		
-539.9	549.5	749649.8
-387.5	306.4	353257.3
-326.5	155.4	249231.3
-325.5	154.0	139220.1
-152.3	36.8	29646.1
-137.1	33.3	26658.4
-121.9	30.2	30924.4
0.0	20.0	0.0

Radon Flux Through Tailings and Cover System



Concentration Through Tailings and Cover System



Scenario 1 Two Tailings Layers 10 ft Slimes over 5 feet Sands Increase Moisture Content

DESCRIPTION	CONSTANTS VALUE	UNITS
RADON DECAY CONSTANT	0.0000021	1/s
RADON WATER/AIR PARTITION COEFFICIENT	0.26	
SPECIFIC GRAVITY OF COVER & TAILINGS	2.65	gm/cm^3
GENERAL INPUT PARAMETERS		
LAYERS OF COVER AND TAILINGS	8	
DESIRED RADON FLUX LIMIT	20	pCi*m^-2/s
DEFAULT SURFACE RADON CONCENTRATION	0	pCi/l
LOWER BOUNDARY FLUX TO BE CALCULATED ASSUMING AN INFINITE SUBSOIL		
SURFACE FLUX PRECISION	0.001	pCi*m^-2/s
LAYER INPUT PARAMETERS		
LAYER #	1	
LAYER THICKNESS	304.8	cm
CALCULATED LAYER POROSITY	0.42	
MEASURED LAYER DENSITY	1.57	g/cm^3
MEASURED RADIUM ACTIVITY	1210	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	0.003324475	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	13	%
MOISTURE SATURATION FRACTION	0.485952381	
MEASURED LAYER DIFFUSION COEFFICIENT	0.012669201	cm^2/s
LAYER #	2	
LAYER THICKNESS	152.4	cm
CALCULATED LAYER POROSITY	0.42	
MEASURED LAYER DENSITY	1.65	g/cm^3
MEASURED RADIUM ACTIVITY	302.5	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	8.73E-04	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	8	%
MOISTURE SATURATION FRACTION	0.314285714	
MEASURED LAYER DIFFUSION COEFFICIENT	0.024553317	cm^2/s
LAYER #	3	
LAYER THICKNESS	61	cm
CALCULATED LAYER POROSITY	0.39	
MEASURED LAYER DENSITY	1.61	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2.97355E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	6.3	%
MOISTURE SATURATION FRACTION	0.260076923	
MEASURED LAYER DIFFUSION COEFFICIENT	0.028836985	cm^2/s
LAYER #	4	
LAYER THICKNESS	1	cm
CALCULATED LAYER POROSITY	0.47	
MEASURED LAYER DENSITY	1.44	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g

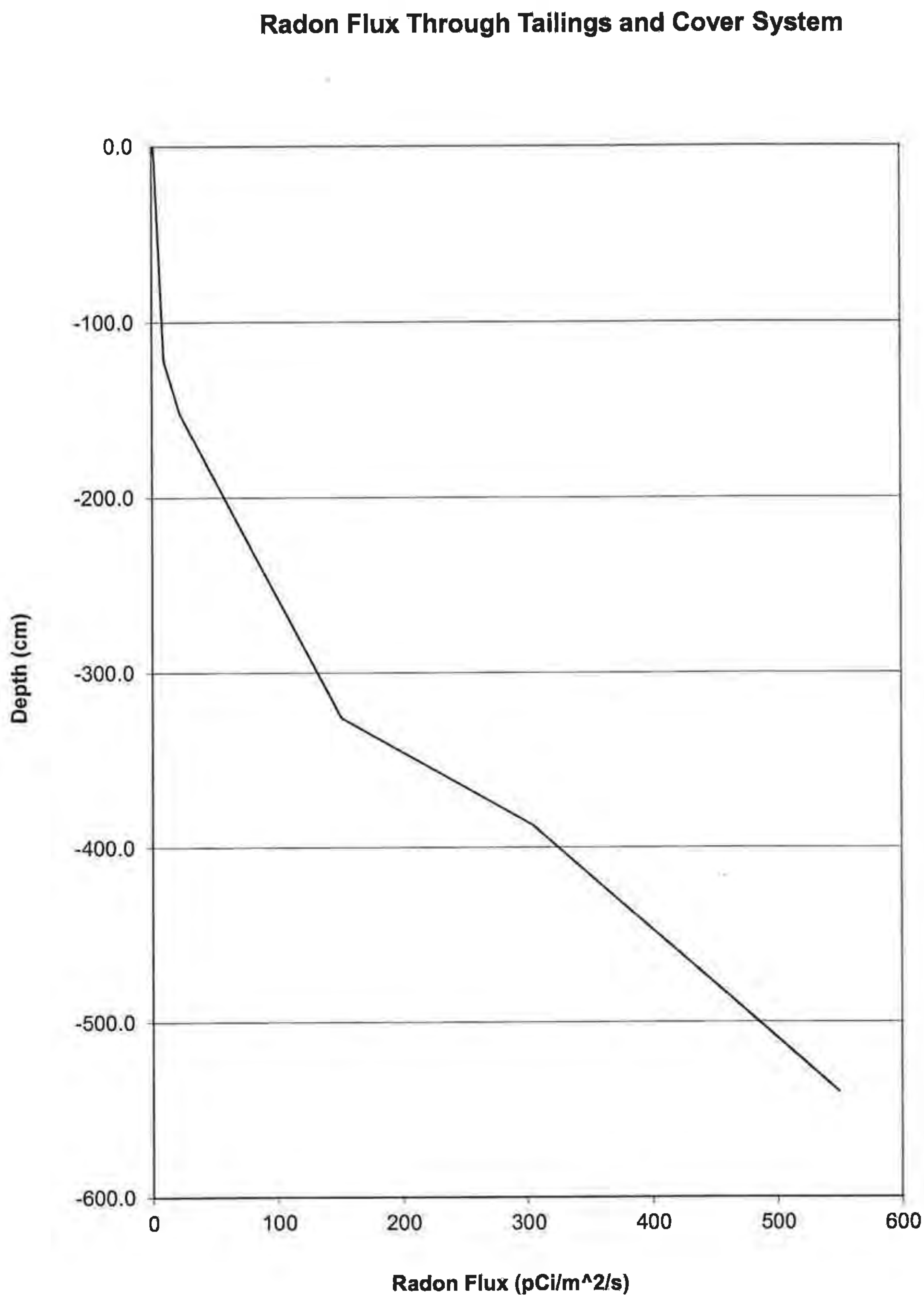
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2.20688E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	23	%
MOISTURE SATURATION FRACTION	0.704680851	
MEASURED LAYER DIFFUSION COEFFICIENT	0.003885951	cm^2/s
LAYER #	5	
LAYER THICKNESS	173.2	cm
CALCULATED LAYER POROSITY	0.32	
MEASURED LAYER DENSITY	1.8	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	4.05169E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	5.7	%
MOISTURE SATURATION FRACTION	0.320625	
MEASURED LAYER DIFFUSION COEFFICIENT	0.021840584	cm^2/s
LAYER #	6	
LAYER THICKNESS	15.2	cm
CALCULATED LAYER POROSITY	0.39	
MEASURED LAYER DENSITY	1.61	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2.97355E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	6.3	%
MOISTURE SATURATION FRACTION	0.260076923	
MEASURED LAYER DIFFUSION COEFFICIENT	0.028836985	cm^2/s
LAYER #	7	
LAYER THICKNESS	15.2	cm
CALCULATED LAYER POROSITY	0.33	
MEASURED LAYER DENSITY	1.81	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	3.95074E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	0	%
MOISTURE SATURATION FRACTION	0	
MEASURED LAYER DIFFUSION COEFFICIENT	0.07	cm^2/s
LAYER #	8	
LAYER THICKNESS	121.9	cm
CALCULATED LAYER POROSITY	0.39	
MEASURED LAYER DENSITY	1.61	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2.97355E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	16.8	%
MOISTURE SATURATION FRACTION	0.693538462	
MEASURED LAYER DIFFUSION COEFFICIENT	0.003505983	cm^2/s

N	F01	CN1	ICOST	CRITJ	ACC	
8	-1	0	0	20	0.001	
LAYER	DX	D	P	Q	XMS	RHO
1	304.8	0.012669	0.42	0.003324	0.485952	1.57
2	152.4	0.024553	0.42	0.000873	0.314286	1.65
3	61	0.028837	0.39	2.97E-06	0.260077	1.61
4	1	0.003886	0.47	2.21E-06	0.704681	1.44
5	173.2	0.021841	0.32	4.05E-06	0.320625	1.8
6	15.2	0.028837	0.39	2.97E-06	0.260077	1.61
7	15.2	0.07	0.33	3.95E-06	0	1.81
8	121.9	0.003506	0.39	2.97E-06	0.693538	1.61

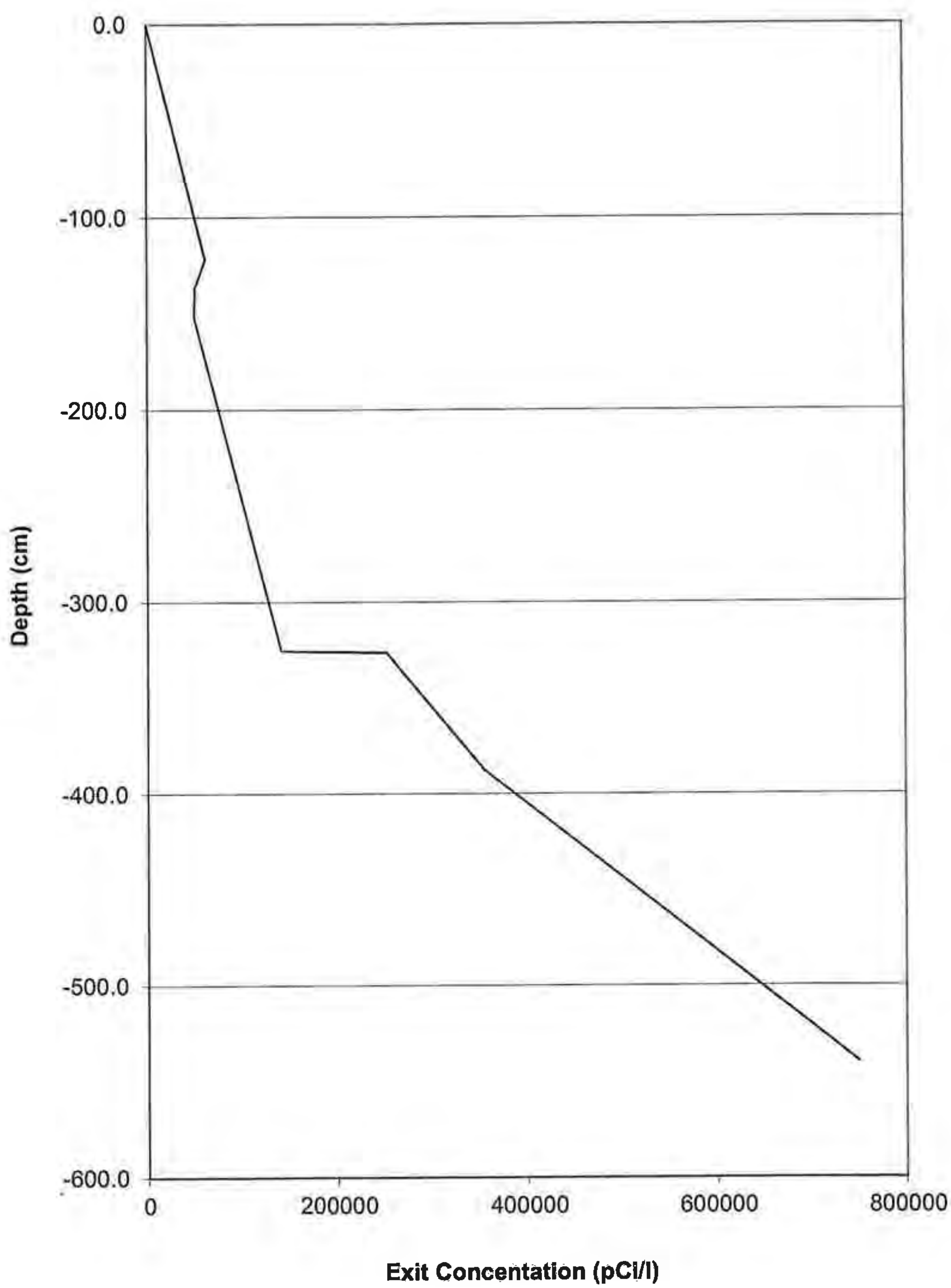
BARE SOURCE FLUX FROM LAYER 1 1062.700551 pCi*cm^-3/s
RESULTS OF RADON DIFFUSION CALCULATIONS

LAYER	THICKNESS	EXIT FLUX	EXIT CONC.
(-)	(CM)	(pCi/m^2/s)	(pCi/l)
1	304.8	549.2	750114.8
2	152.4	304.7	355108.2
3	61.0	152.4	252420.6
4	1.0	151.01322	141273.1
5	173.2	22.40228088	50413.4
6	15.2	16.10460012	50776.3
7	15.2	9.727926514	62028.1
8	121.9	1.453787672	0.0

DEPTH	EXIT FLUX	EXIT CONC.
(CM)	(pCi/m^2/s)	(pCi/l)
-844.7		
-539.9	549.2	750114.8
-387.5	304.7	355108.2
-326.5	152.4	252420.6
-325.5	151.0	141273.1
-152.3	22.4	50413.4
-137.1	16.1	50776.3
-121.9	9.7	62028.1
0.0	1.5	0.0


Radon Flux Through Tailings and Cover System
0.0
-100.0
-200.0
-300.0
-400.0
-500.0
-600.0
Depth (cm)
0
100
200
300
400
500
600
Radon Flux (pCi/m^2/s)

Concentration Through Tailings and Cover System



Radon Visual Basic for Applications

1. The input is entered to the program interactively with the use of input boxes.
2. Message boxes provide information for input using default values.
3. The inputs are output to the EXCEL Workbook Output.
4. The results of the analysis are presented on the EXCEL Workbook Results
5. The analysis is started with the EXCEL command /Tools/Macros/Radon.

Scenario 2 Radon Barrier Thickness for a 1 ft Tailings Layer

DESCRIPTION	CONSTANTS VALUE	UNITS
RADON DECAY CONSTANT	0.0000021	1/s
RADON WATER/AIR PARTITION COEFFICIENT	0.26	
SPECIFIC GRAVITY OF COVER & TAILINGS	2.65	gm/cm^3
	GENERAL INPUT PARAMETERS	
LAYERS OF COVER AND TAILINGS	7	
DESIRED RADON FLUX LIMIT	20	pCi*m^-2/s
NO. OF THE LAYER TO BE OPTIMIZED	4	
DEFAULT SURFACE RADON CONCENTRATION	0	pCi/l
LOWER BOUNDARY FLUX TO BE CALCULATED ASSUMING AN INFINITE SUBSOIL		
SURFACE FLUX PRECISION	0.001	pCi*m^-2/s
	LAYER INPUT PARAMETERS	
LAYER #	1	
LAYER THICKNESS	30.4	cm
CALCULATED LAYER POROSITY	0.4	
MEASURED LAYER DENSITY	1.65	g/cm^3
MEASURED RADIUM ACTIVITY	302.5	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	0.000917142	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	8	%
MOISTURE SATURATION FRACTION	0.33	
MEASURED LAYER DIFFUSION COEFFICIENT	0.022738081	cm^2/s
LAYER #	2	
LAYER THICKNESS	61	cm
CALCULATED LAYER POROSITY	0.39	
MEASURED LAYER DENSITY	1.61	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2.97E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	6.3	%
MOISTURE SATURATION FRACTION	0.260076923	
MEASURED LAYER DIFFUSION COEFFICIENT	0.028836985	cm^2/s
LAYER #	3	
LAYER THICKNESS	1	cm
CALCULATED LAYER POROSITY	0.47	
MEASURED LAYER DENSITY	1.44	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2.20688E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	23	%
MOISTURE SATURATION FRACTION	0.704680851	
MEASURED LAYER DIFFUSION COEFFICIENT	0.003885951	cm^2/s
LAYER #	4	
LAYER THICKNESS	1	cm
CALCULATED LAYER POROSITY	0.32	
MEASURED LAYER DENSITY	1.8	g/cm^3

MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	4.05169E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	5.7	%
MOISTURE SATURATION FRACTION	0.320625	
MEASURED LAYER DIFFUSION COEFFICIENT	0.021840584	cm^2/s
LAYER #	5	
LAYER THICKNESS	15.2	cm
CALCULATED LAYER POROSITY	0.39	
MEASURED LAYER DENSITY	1.61	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2.97355E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	6.3	%
MOISTURE SATURATION FRACTION	0.260076923	
MEASURED LAYER DIFFUSION COEFFICIENT	0.028836985	cm^2/s
LAYER #	6	
LAYER THICKNESS	15.2	cm
CALCULATED LAYER POROSITY	0.33	
MEASURED LAYER DENSITY	1.81	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	3.95074E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	0	%
MOISTURE SATURATION FRACTION	0	
MEASURED LAYER DIFFUSION COEFFICIENT	0.07	cm^2/s
LAYER #	7	
LAYER THICKNESS	121.9	cm
CALCULATED LAYER POROSITY	0.39	
MEASURED LAYER DENSITY	1.61	g/cm^3
MEASURED RADIUM ACTIVITY	0.98	pCi/g
DEFAULT LAYER EMANATION COEFFICIENT	0.35	
CALCULATED LAYER SOURCE TERM	2.97355E-06	pCi*cm^-3/s
LAYER WEIGHT % MOISTURE	6.3	%
MOISTURE SATURATION FRACTION	0.260076923	
MEASURED LAYER DIFFUSION COEFFICIENT	0.028836985	cm^2/s

N	F01	CN1	ICOST	CRITJ	ACC
7	-1	0	4	20	0.001

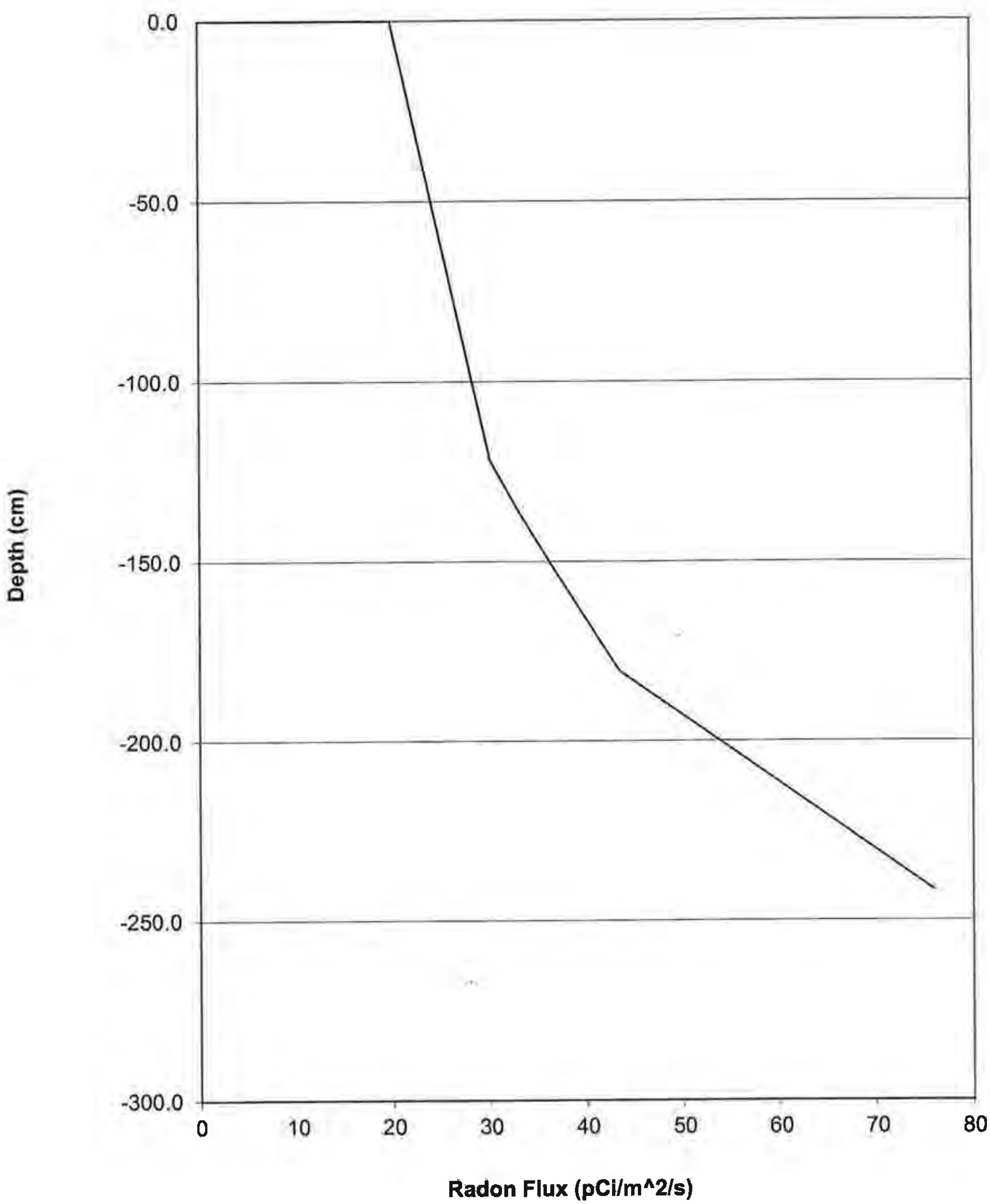
LAYER	DX	D	P	Q	XMS	RHO
1	30.4	0.022738	0.4	0.000917	0.33	1.65
2	61	0.028837	0.39	2.97E-06	0.260077	1.61
3	1	0.003886	0.47	2.21E-06	0.704681	1.44
4	1	0.021841	0.32	4.05E-06	0.320625	1.8
5	15.2	0.028837	0.39	2.97E-06	0.260077	1.61
6	15.2	0.07	0.33	3.95E-06	0	1.81
7	121.9	0.028837	0.39	2.97E-06	0.260077	1.61

BARE SOURCE FLUX FROM LAYER 1 95.45505773 pCi*cm^-3/s
RESULTS OF RADON DIFFUSION CALCULATIONS

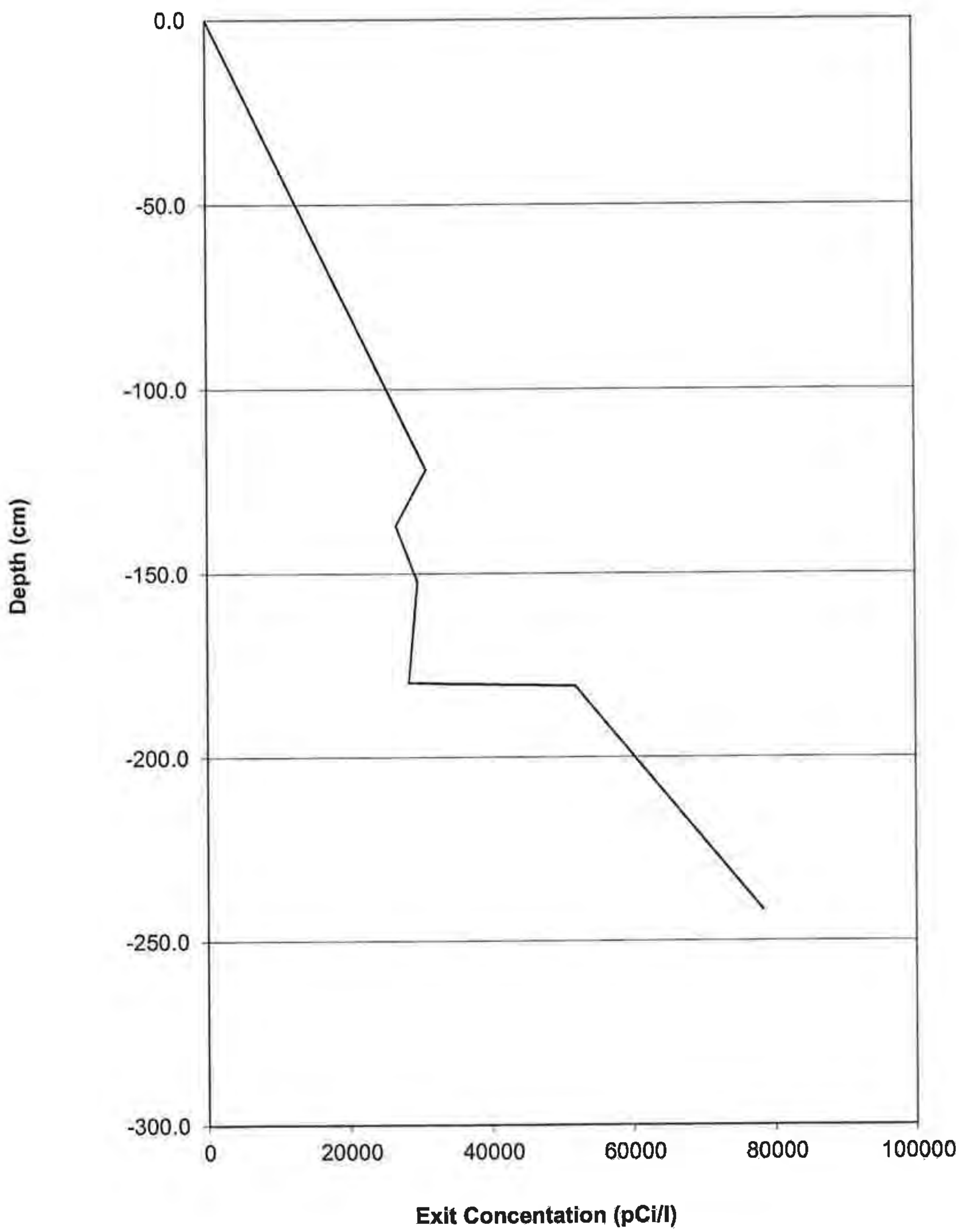
LAYER	THICKNESS	EXIT FLUX	EXIT CONC.
(-)	(CM)	(pCi/m^2/s)	(pCi/l)
1	30.4	76.0	78301.4
2	61.0	43.6	51944.4
3	1.0	43.3	28403.4
4	27.4	36.78644223	29669.7
5	15.2	33.35164426	26679.5
6	15.2	30.18159388	30948.8
7	121.9	20.01973553	0.0

DEPTH	EXIT FLUX	EXIT CONC.
(CM)	(pCi/m^2/s)	(pCi/l)
-272.1		
-241.7	76.0	78301.4
-180.7	43.6	51944.4
-179.7	43.3	28403.4
-152.3	36.8	29669.7
-137.1	33.4	26679.5
-121.9	30.2	30948.8
0.0	20.0	0.0
0.0	0.0	0.0

Radon Flux Through Tailings and Cover System



Concentration Through Tailings and Cover System



PROBLEM STATEMENT:

Develop the properties for use in the radon barrier calculation. The properties include the dry density expressed in gm/cc, the gravimetric moisture content, and the percent saturation of the voids.

DOCUMENTS CITED

Kleinfelder Calculation 89241.7 - ALB08CA003 Piñon Ridge Closure Cover Geotechnical and Hydrologic Properties (Reference 9).

U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "Regulatory Guide 3.64 (Reference 8).

US. DOE. 2008. Final Remedial Action Plan and Site Design for Stabilization of Moab Title 1 Uranium Mill Tailings at the Cresent Junction, Utah, Disposal Site (Reference 10).

URANIUM TAILINGS

From **Kleinfelder 2008 Pinon Ridge Closure Cover Geotechnical and Hydrologic Properties, Table 5-1**:

Tailings (Slimes)

$pcf := \frac{lbf}{ft^3}$ $\gamma_w := 1.0 \cdot \frac{gm}{cm^3}$ 62.4 pcf

Input the porosity and the dry density:

$n := 0.42$ $\gamma_d := 98 \cdot pcf$ $\frac{\gamma_d}{g} = 1.57 \frac{gm}{cm^3}$

From Table 5-1, the volumetric moisture content is:

$m_v := 0.204$

Calculate the gravimetric moisture content from:

$m_g := \frac{m_v}{\frac{\gamma_d}{\frac{gm}{cm^3}}} \cdot g$ $m_g = 0.13$

Equation 3 (Reference 8, Page 3.64-9)

From **Eq. 4 of Section 4.2.7**:

$\gamma_t := \gamma_d \cdot (1 + m_g)$ $\gamma_t = 110.735 \cdot pcf$ $\frac{\gamma_t}{g} = 1.774 \frac{gm}{cm^3}$

Calculate the moisture saturation fraction from Equation 5 of the main calculation:

$m_f := \frac{\frac{\gamma_d}{g} \cdot m_g}{n \cdot \gamma_w}$ $m_f = 0.486$

Eq. 5, Reference 8 Page 3.64-11

Use this moisture saturation and porosity for calculation of the diffusion coefficient presented in Attachments E and summarized in Table 5-2.

Tailings (Coarse)

$pcf := \frac{lbf}{ft^3}$ $\gamma_w := 1.0 \cdot \frac{gm}{cm^3}$ 62.4 pcf

Input the porosity and the dry density:

$n := 0.40$ $\gamma_d := 103 \cdot pcf$ $\frac{\gamma_d}{g} = 1.65 \frac{gm}{cm^3}$

From Table 5-1, the volumetric moisture content is:

$m_v := 0.132$

Calculate the gravimetric moisture content from:

$$m_g := \frac{m_v}{\frac{\gamma_d}{\frac{gm}{cm^3}}} \cdot g \qquad m_g = 0.08$$

Equation 3 (Reference 8, Page 3.64-9)

From **Eq. 4 of Section 4.2.7**:

$\gamma_t := \gamma_d \cdot (1 + m_g)$ $\gamma_t = 111.24 \cdot pcf$ $\frac{\gamma_t}{g} = 1.782 \frac{gm}{cm^3}$

Calculate the moisture saturation fraction from Equation 5 of the main calculation:

$$m_f := \frac{\frac{\gamma_d}{g} \cdot m_g}{n \cdot \gamma_w} \qquad m_f = 0.33$$

Eq. 5, Reference 8 Page 3.64-11

Use this moisture saturation and porosity for calculation of the diffusion coefficient presented in Attachments E and summarized in Table 5-2.

Interim Layer

$pcf := \frac{lbf}{ft^3}$ $\gamma_w := 1.0 \cdot \frac{gm}{cm^3}$ 62.4 pcf

Input the porosity and the dry density:

$n := 0.39$ $\gamma_d := 100.3 \cdot pcf$ $\frac{\gamma_d}{g} = 1.607 \frac{gm}{cm^3}$

From Table 5-1, the volumetric moisture content is:

$m_v := 0.102$

Calculate the gravimetric moisture content from:

$m_g := \frac{m_v}{\frac{\gamma_d}{\frac{gm}{cm^3}}} \cdot g$ $m_g = 0.063$

Equation 3 (Reference 8, Page 3.64-9)

From **Eq. 4 of Section 4.2.7**:

$\gamma_t := \gamma_d \cdot (1 + m_g)$ $\gamma_t = 106.668 \cdot pcf$ $\frac{\gamma_t}{g} = 1.709 \frac{gm}{cm^3}$

Calculate the moisture saturation fraction from Equation 5 of the main calculation:

$m_f := \frac{\frac{\gamma_d}{g} \cdot m_g}{n \cdot \gamma_w}$ $m_f = 0.262$

Eq. 5, Reference 8 Page 3.64-11

Use this moisture saturation and porosity for calculation of the diffusion coefficient presented in Attachments E and summarized in Table 5-2.

Geosynthetic Liner

$pcf := \frac{lbf}{ft^3}$ $\gamma_w := 1.0 \cdot \frac{gm}{cm^3}$ 62.4 pcf

Input the porosity and the dry density:

$n := 0.47$ $\gamma_d := 90.0 \cdot pcf$ $\frac{\gamma_d}{g} = 1.442 \frac{gm}{cm^3}$

From Table 5-1, the volumetric moisture content is:

$m_v := 0.33$

Calculate the gravimetric moisture content from:

$$m_g := \frac{m_v}{\frac{\gamma_d}{\frac{gm}{cm^3}}} \cdot g$$ $m_g = 0.229$

Equation 3 (Reference 8, Page 3.64-9)

From **Eq. 4 of Section 4.2.7**:

$\gamma_t := \gamma_d \cdot (1 + m_g)$ $\gamma_t = 110.601 \cdot pcf$ $\frac{\gamma_t}{g} = 1.772 \frac{gm}{cm^3}$

Calculate the moisture saturation fraction from Equation 5 of the main calculation:

$$m_f := \frac{\frac{\gamma_d}{g} \cdot m_g}{n \cdot \gamma_w}$$ $m_f = 0.702$

Eq. 5, Reference 8 Page 3.64-11

Use this moisture saturation and porosity for calculation of the diffusion coefficient presented in Attachments E and summarized in Table 5-2.

Radon Barrier Layer

$$pcf := \frac{lbf}{ft^3} \qquad \gamma_w := 1.0 \cdot \frac{gm}{cm^3}$$ 62.4 pcf

Input the porosity and the dry density:

$$n := 0.32 \qquad \gamma_d := 112.1 \cdot pcf \qquad \frac{\gamma_d}{g} = 1.796 \frac{gm}{cm^3}$$

From Table 5-1, the volumetric moisture content is:

$$m_v := 0.102$$

Calculate the gravimetric moisture content from:

$$m_g := \frac{m_v}{\frac{\gamma_d}{\frac{gm}{cm^3}}} \cdot g \qquad m_g = 0.057$$

Equation 3 (Reference 8, Page 3.64-9)

From **Eq. 4 of Section 4.2.7**:

$$\gamma_t := \gamma_d \cdot (1 + m_g) \qquad \gamma_t = 118.468 \cdot pcf \qquad \frac{\gamma_t}{g} = 1.898 \frac{gm}{cm^3}$$

Calculate the moisture saturation fraction from Equation 5 of the main calculation:

$$m_f := \frac{\frac{\gamma_d}{g} \cdot m_g}{n \cdot \gamma_w} \qquad m_f = 0.319$$

Eq. 5, Reference 8 Page 3.64-11

Use this moisture saturation and porosity for calculation of the diffusion coefficient presented in Attachments E and summarized in Table 5-2.

Bio Intrusion Barrier Layer

$pcf := \frac{lbf}{ft^3}$ $\gamma_w := 1.0 \cdot \frac{gm}{cm^3}$ 62.4 pcf

Input the porosity and the dry density:

$n := 0.39$ $\gamma_d := 100.3 \cdot pcf$ $\frac{\gamma_d}{g} = 1.607 \frac{gm}{cm^3}$

From Table 5-1, the volumetric moisture content is:

$m_v := 0.102$

Calculate the gravimetric moisture content from:

$$m_g := \frac{m_v}{\frac{\gamma_d}{\frac{gm}{cm^3}}} \cdot g \qquad m_g = 0.063$$

Equation 3 (Reference 8, Page 3.64-9)

From **Eq. 4 of Section 4.2.7**:

$\gamma_t := \gamma_d \cdot (1 + m_g)$ $\gamma_t = 106.668 \cdot pcf$ $\frac{\gamma_t}{g} = 1.709 \frac{gm}{cm^3}$

Calculate the moisture saturation fraction from Equation 5 of the main calculation:

$$m_f := \frac{\frac{\gamma_d}{g} \cdot m_g}{n \cdot \gamma_w} \qquad m_f = 0.262$$

Eq. 5, Reference 8 Page 3.64-11

Use this moisture saturation and porosity for calculation of the diffusion coefficient presented in Attachments E and summarized in Table 5-2.

Capillary Break Barrier Layer

$pcf := \frac{lbf}{ft^3}$ $\gamma_w := 1.0 \cdot \frac{gm}{cm^3}$ 62.4 pcf

Input the porosity and the dry density:

$n := 0.33$ $\gamma_d := 112.9 \cdot pcf$ $\frac{\gamma_d}{g} = 1.808 \frac{gm}{cm^3}$

From Table 5-1, the volumetric moisture content is:

$m_v := 0.00$

Calculate the gravimetric moisture content from:

$$m_g := \frac{m_v}{\frac{\gamma_d}{\frac{gm}{cm^3}}} \cdot g$$

$m_g = 0$

Equation 3 (Reference 8, Page 3.64-9)

From **Eq. 4 of Section 4.2.7**:

$\gamma_t := \gamma_d \cdot (1 + m_g)$ $\gamma_t = 112.9 \cdot pcf$ $\frac{\gamma_t}{g} = 1.808 \frac{gm}{cm^3}$

Calculate the moisture saturation fraction from Equation 5 of the main calculation:

$$m_f := \frac{\frac{\gamma_d}{g} \cdot m_g}{n \cdot \gamma_w}$$

$m_f = 0$

Eq. 5, Reference 8 Page 3.64-11

Use this moisture saturation and porosity for calculation of the diffusion coefficient presented in Attachments E and summarized in Table 5-2.

Vegetative Cover Layer

$pcf := \frac{lbf}{ft^3}$ $\gamma_w := 1.0 \cdot \frac{gm}{cm^3}$ 62.4 pcf

Input the porosity and the dry density:

$n := 0.39$ $\gamma_d := 100.3 \cdot pcf$ $\frac{\gamma_d}{g} = 1.607 \frac{gm}{cm^3}$

From Table 5-1, the volumetric moisture content is:

$m_v := 0.102$

Calculate the gravimetric moisture content from:

$$m_g := \frac{m_v}{\frac{\gamma_d}{\frac{gm}{cm^3}}} \cdot g \qquad m_g = 0.063$$

Equation 3 (Reference 8, Page 3.64-9)

From **Eq. 4 of Section 4.2.7**:

$\gamma_t := \gamma_d \cdot (1 + m_g)$ $\gamma_t = 106.668 \cdot pcf$ $\frac{\gamma_t}{g} = 1.709 \frac{gm}{cm^3}$

Calculate the moisture saturation fraction from Equation 5 of the main calculation:

$$m_f := \frac{\frac{\gamma_d}{g} \cdot m_g}{n \cdot \gamma_w} \qquad m_f = 0.262$$

Eq. 5, Reference 8 Page 3.64-11

Use this moisture saturation and porosity for calculation of the diffusion coefficient presented in Attachments E and summarized in Table 5-2.

CALCULATION AND ANALYSIS SHEET

KLEINFELDER
Bright People. Right Solutions.

Project No.: 89241		**Page** F-1 **of** F-11	
Calculation No.: 89241.7 - ALB08CA001		**Rev.:** 0	
Calculation Title: Radon Barrier Cover Thickness Design			
Originator:	Courtney Vallejo Print Name	Signature	Date
Checker:	John B. Case Print Name	Signature	Date

ATTACHMENT F

Kleinfelder Memorandum:
Review of Soil and Vegetation Parameters for the Piñon Ridge Closure Cap

KLEINFELDER
Bright People. Right Solutions.

CALCULATION AND ANALYSIS SHEET

Project No.: 89241		**Page** F-2	**of** F-11
Calculation No.: 89241.7 - ALB08CA001		**Rev.:** 0	
Calculation Title: Radon Barrier Cover Thickness Design			
Originator: Courtney Vallejo Print Name	Signature	Date	
Checker: John B. Case Print Name	Signature	Date	

MEMORANDUM

TO: Alan Kuhn

FROM: Stephen Caruana

DATE: 9/24/08

SUBJECT: Review of Soil and Vegetation Parameters for Piñon Ridge Closure Cap

CC: R. McKinney, C. Vallejo, J. Case, and L. Bridges

This memo is a summation of my findings regarding the long-term vegetation trends and soil moisture retention characteristics of Piñon Ridge Closure Cap. This analysis was conducted utilizing a number of sources. A literature search of AGRICOLA and University of Oregon Library Catalog was performed incorporating the keywords: Colorado native vegetation, arid and semi-arid evapotranspiration, long-term vegetational dynamics, and southwest rangeland trends. Also consulted was the USDA Soil Survey for San Miguel Area, Colorado, Parts of Dolores, Montrose, and San Miguel Counties, 2003; and the literature database of the Jornada Experimental Range.

Site Location: 38° 14' 47" North Latitude, 108° 46' 9" West Longitude

Long-term Vegetation Trends

Predicting the response of a rangeland grass planting over a long time period is dependent upon several factors, notably the success of the initial planting, weed control and competition during the establishment period, inherent soil fertility, use by wild and domesticated herbivores, and climatic flux. Rangelands of the American Southwest have been influenced by both large scale climatic events and human influence through the introduction on non-native herbivores (primarily sheep, cattle, and horses).

In order to understand the possible trends that the grass plantings of the Piñon Ridge Closure may experience over time, the literature was consulted for rangeland areas of the Southwest that were studied over relatively long periods. One such area is the Jornada Experimental Range in New Mexico. Although the Jornada is located approximately 380 miles southeast of Piñon Ridge and is part of the northern Chihuahuan Desert and not the Colorado Plateau; rainfall is similar at approximately 10 inches per year and with similar sandy loam soils. The harsher conditions at the Jornada may better represent possible future conditions under climate change.

Grasslands of the Jornada have been studied since 1858. Various ecological sites of the Jornada have been dominated by black and blue grama, tobosa, burrograss, and poverty threeawn. Basal area of these dominant grasses exhibit sharp decreases during severe drought periods and partial recovery during more favorable periods (Gibbens and Beck, 1988). Over the past 150 years the long term trend has been for the basal area of perennial grasses to decline and for non-native weeds and woody brush to increase. The basal area of the perennial grasses on the Jornada Range is somewhat associated with the antecedent moisture of the previous 3 to 4 years. Drought years had a tremendous impact on perennial grass basal area whereas grazing appears not to have had as significant an impact. Different perennial grasses respond differently and have different recovery rates when subjected to drought stress. Even with a conservative grazing management scheme, unpalatable shrubs have become widespread across the Jornada Range.

Long term observations on the Jornada (Buffington and Herbel, 1965) have recorded a decline since 1858 of over 90% of the range covered in good grass to less than 25% in 1963. The main invasive was mesquite on sandy soils. Grass cover on this range was reduced by grazing pressure and periodic droughts.

There are significant implications for the establishment of the Piñon Ridge Closure Cap from the above research. Initial establishment of a vigorous, healthy stand is essential. If at all possible the seedings should be planted following several years of above normal rainfall. If the sites are irrigated this becomes less critical. The mix of initially planted species is likely to simplify over time, especially shorter lived perennial grasses.

The area of the proposed closure cap is classified as a Semidesert Loam and Semidesert Sandy Loam ecological site. Current dry-weight production on this site is 600 to 850 lbs/ac in a normal year. A normal year's precipitation for these sites is 9 to 12 inches, with a mean annual air temperature of 46 to 48° F, and an average frost-free period of 90 to 120 days. The characteristic vegetation for these sites (under excellent, climax conditions) is:

Semidesert Sandy Loam:

- Galleta 20%
- Wyoming big sagebrush 15%
- Needleandthread 10%
- Indian ricegrass 10%
- Bottlebrush squirreltail 5%
- Blue grama 5%
- Sand dropseed 5%

Semidesert loam:

- Wyoming big sagebrush 15%
- Needleandthread 15%
- Galleta 15%
- Indian ricegrass 5%
- Bottlebrush squirreltail 5%

The following is the proposed seeding mix for the closure cap (percentages as reported):

- Needleandthread 20%
- Indian ricegrass 20%
- Thickspike wheatgrass 20%
- Sandberg bluegrass 10%
- Bottlebrush squirreltail 10%
- Blue grama 10%
- Galleta 10%

Grass Basal Area Coverage

Studies were conducted by Ambos et al. (2000) on Dutchwoman Butte, an isolated, ungrazed butte located in the transition zone between the Colorado Plateau and the Basin and Range province. Elevation at the site is approximately 5,000 feet, and the estimated annual rainfall at is 17 inches, slightly more than the Piñon Ridge site. The vegetation of the site is a semidesert grassland with widely scattered juniper. Grasses consist primarily of grama grasses and plains lovegrass. Soils are gravelly and stony loams. Grass species diversity is high at the site. Grass canopy cover is 35 to 45%, grass basal area is 8% and grass litter is 25%, thus giving an effective vegetative cover of 35%. Bare soil and rock fragments were approximately 65%. This site represents the extreme cool/moist end of the semi-desert grassland gradient and as such would likely represent the best possible conditions that could be expected at the Piñon Ridge site.

Grass basal area on the Jornada range exhibited similar characteristics in basal area trends. Maximum rates of basal area coverage for perennial grasses were 30% on the heavy soils in low lying areas that received supplemental runoff water. Basal area coverage at these rates occurred during the wet cycles over the past century. Perennial grasses located on the sandy loam soils approached 15% basal area coverage during the wet periods.

Cryptobiotic Crusts

Healthy, living soils of the American deserts are characterized by cryptobiotic crusts. These crusts are composed of cyanobacteria, soil lichens, mosses, green algae, microfungi, and bacteria. Cryptobiotic crusts perform important soil ecosystem functions including soil aggregation and binding, nitrogen fixation, water storage, and contributions to organic matter nutrient flow. Cryptobiotic crusts provide essential resistance to wind and water erosion (NPS, 2008).

A stable soil surface with an intact cryptobiotic can make stabilize the area between the perennial grass plants. Once disturbed it may take up to 50 to 100 years for a fully functioning, stable soil crust to form. Further research may be necessary to identify procedures for promoting the growth of a cryptobiotic crust on the Piñon Ridge Closure Cap, however every effort should be made to keep the site free from any disturbance that may limit the establishment of a soil crust.

Soil Moisture Retention Characteristics

Soil Survey: The Piñon Ridge Closure Cap proposes to utilize locally available, native soil material. The area proposed for the tailings cap is mapped as part of the USDA Soil Survey of San Miguel Area, Colorado, Parts of Dolores, Montrose, and San Miguel Counties. 2003. The area of the proposed cap is mapped with two separate soil series – 18 Begay fine sandy loam and 56 Mikim loam. Both soils are deep, with reported depths of 60 inches.

KLEINFELDER
Bright People. Right Solutions.

CALCULATION AND ANALYSIS SHEET

Project No.:	89241	**Page**	F-7	**of**	F-11
Calculation No.:	89241.7 - ALB08CA001	**Rev.:**	0		
Calculation Title:	Radon Barrier Cover Thickness Design				
Originator:	Courtney Vallejo (Print Name)	Signature		Date	
Checker:	John B. Case (Print Name)	Signature		Date	

Begay fine sandy loam soil hydraulic properties:

♦ Moist bulk density (g/cc)	1.40 – 1.50
♦ Saturated Hydraulic Conductivity (micro m/sec)	14.11 – 42.34
♦ Available water capacity (in/in)	0.09 – 0.18
♦ Total Available Water (24 inches of soil)	7.74 inches
♦ Organic Matter	0.0 – 3.0
♦ Water Content, 15 Bar	6.9%
♦ Water Content, 0.33 Bar	16.2%

Mikim Loam

♦ Moist bulk density (g/cc)	1.30 – 1.50
♦ Saturated Hydraulic Conductivity (micro m/sec)	4.23 – 14.11
♦ Available water capacity (in/in)	0.07 – 0.18
♦ Total Available Water (24 inches of soil)	8.30 inches
♦ Organic Matter	0.5 – 3.0
♦ Water Content, 15 Bar	13.4%
♦ Water Content, 0.33 Bar	27.1%

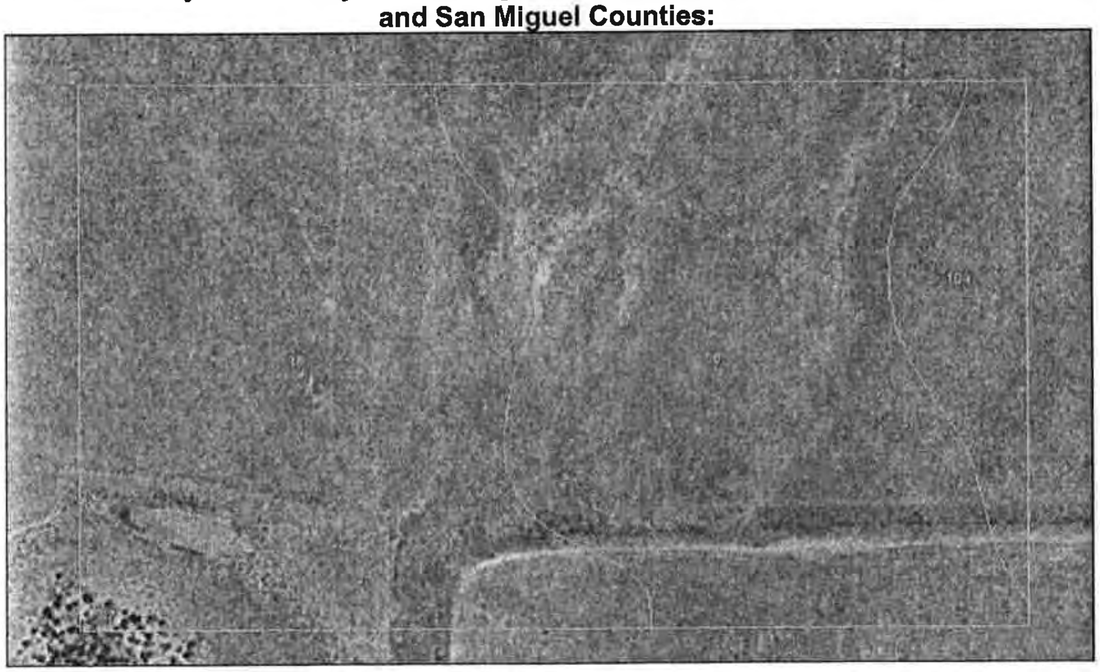
Note: Water content, one-third bar, is the amount of soil water retained at a tension of 1/3 bar, expressed as a percentage of the oven-dry weight of soil material that is less than 2 mm in diameter. Water retained at 1/3 bar is significant in the determination of soil water-retention difference, which is used as the initial estimation of available water capacity for some soils. Water retained at 1/3 bar is the value commonly used to estimate the content of water at field capacity for most soils.

Water content, 15 bar, is the amount of soil water retained at a tension of 15 bars, expressed as a percentage of the oven-dry weight of soil material that is less than 2 mm in diameter. Water retained at 15 bars is significant in the determination of soil water-retention difference, which is used as the initial estimation of available water capacity for some soils. Water retained at 15 bars is an estimation of the wilting point (USDA, 2003).

CALCULATION AND ANALYSIS SHEET

Project No.:	89241	**Page** F-8	**of** F-11
Calculation No.:	89241.7 - ALB08CA001	**Rev.:**	0
Calculation Title:	Radon Barrier Cover Thickness Design		
Originator:	Courtney Vallejo (Print Name)	Signature	Date
Checker:	John B. Case (Print Name)	Signature	Date

USDA Soil Survey Soil Survey for San Miguel Area, Colorado, Parts of Dolores, Montrose, and San Miguel Counties:



Soil Hydraulic Properties:

The attached spreadsheet developed by Saxton and Rawls (2006) will compute a variety of soil moisture percentages. The prediction equations were derived for soil moisture tensions of 0, 33, and 1500 kPa and air-entry based on commonly available variables of soil texture and organic matter.

Evapotranspiration Values

Studies conducted at the Amargosa Desert Research Site in Nye County near Beatty, Nevada (Johnson et al., 2007) report the following evapotranspiration values:

Amargosa Desert Research Site Evapotranspiration Rates		
Year	**Annual Precipitation (mm/yr)**	**Annual Evapotranspiration (mm/yr)**
2001	164.8	-
2002	3.5	48.0
2003	131.8	148.0
2004	173.6	198.0
2005	177.7	233.0
Average	130.3	
Long Term Average (25 yrs)	112.0	-

Various authors have reported the following Penman-Monteith values:

Kc = Dimensionless Crop Coefficient (Burman and Pochop, 1994)				
Dry, with light to moderate winds	**Kc**	**Grass Hay**	**Clover/Grass/Legumes**	**Pasture**
	Mean	0.90	1.05	1.00
	Peak	1.10	1.15	1.10
	Low	0.55	0.55	0.50

Stage 1 and 2 Evaporation Values of Constants U and Cs (Burman and Pochop, 1994)		
Soil Texture	**Cs (mm/day/**	**U (mm)**
Loam	4.50	10.60
Clay loam	6.67	11.38
Sand	3.32	5.70

Leaf Area Index for Growing Season Fractions (Burman and Pochop, 1994)	
Fraction of Growing Season	**Excellent Grass**
0.0	0.00
0.1	1.84
0.2	3.00
0.3	3.00
0.4	3.00
0.5	3.00
0.6	3.00
0.7	2.70
0.8	1.96
0.9	0.96
1.0	0.50

Reporting on maximum evapotranspiration at eight arid sites across the western United States Evans et al. (1981) that evapotranspiration rates ranged 2 mm/d to 10 mm/d as influenced by vegetation, water availability and climate. During extended periods of no precipitation rates of evapotranspiration were less than 1 mm/d.

In studies of Great Basin sagebrush communities (Prater and DeLucia, 2006) evapotranspiration is observed to increase in a linear manner correlated with soil moisture (top 20 cm). However, they did note that the evapotranspiration was very closely tied to the top (<5 cm) soil moisture in the New Mexico arid grass and shrublands. The authors in independent studies found that perennial bunchgrasses had higher morning evapotranspiration rates than sagebrush. They note that in sagebrush ecosystems annual evapotranspiration typically exceeds precipitation, whereas evapotranspiration from grass stands in similar environments may equal annual precipitation.

KLEINFELDER
Bright People. Right Solutions.

CALCULATION AND ANALYSIS SHEET

Project No.: 89241		**Page** F-11	**of** F-11
Calculation No.: 89241.7 - ALB08CA001		**Rev.:** 0	
Calculation Title: Radon Barrier Cover Thickness Design			
Originator: Courtney Vallejo (Print Name)	Signature		Date
Checker: John B. Case (Print Name)	Signature		Date

References

Ambos, N. G. Robertson, and J. Douglas. 2000. Dutchwoman Butte: A relict grassland in central Arizona. Rangelands 22(2):3-8.

Buffington, L.C and C.H. Herbel. 1965. Vegetational changes on a semideseret grassland range. Ecological Monographs. 35(2): 139-164.

Burman, R. and L.O. Pochop. 1994. Evaporation, Evapotranspiration and Climatic Data. Elsevier, New York.

Evans, D.D., T.W. Sammis, and D.R. Cable. 1981. Actual Evapotranspiration under Desert Conditions. In Water in Desert Ecosystems. Ed. D.D. Evans and J.L. Thames (eds.), pp 195-218. Dowden, Hutchinson and Ross, Inc. Stroudsburg, Pennsylvania.

Gibbens, R.P. and R.F. Beck. 1988. Changes in grass basal area and forb densities over a 64-year period on grassland types of the Jornada Experimental Range. Journal of Range Mangement. 41(3): 186-192.

Johnson, M.J., C.J. Mayers, C.A. Garcia, and B.J. Andraski. 2007. Selected micrometerological, soil-moisture, and evapotranspiration data at Amargosa Desert Research Site in Nye County near Beatty, Nevada, 2001-05: U.S. Geological Survey Data Series 284.

Prater, M.R and E.H. DeLucia. 2006. Non-natve grasses alter evapotranspiration and energy in Great Basin sagebrush communities. Agrcultural and Forest Meteorology 139 (2006): 154-163.

National Park Service. Capitol Reef Cryptobiotic Soil. 2008. accessed at: http://www.nps.gov/archive/care/crypto.htm

Saxton, K.E. and W.J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Science Society of America Journal 70: 1569-1578.

USDA. Natural Resources Conservation Service. 2003. Soil Survey for San Miguel Area, Colorado, Parts of Dolores, Montrose, and San Miguel Counties. U.S. Government Printing Office Washington D.C.

Calculate the dry density of the clay. Set the volume of the solids to one.

$$V_s := 1 \cdot m^3$$

From the **Civil Engineering Handbook Table 9.7 Reference 14**, the range of dry density is from 75 to 105 pcf for a CH material. Use a dry density of 90 pcf, and solve for the porosity.

$G_s := 2.72$ $\qquad$ $\gamma_w := 62.4 \cdot pcf$ $\qquad$ $\gamma_d := 90 \cdot pcf$

The dry density is given by:

$$\gamma_d = \frac{G_s \cdot \gamma_w}{1 + E}$$

$$\frac{G_s \cdot \gamma_w}{\gamma_d} - 1$$

Solving for the void ratio

$$e := \frac{G_s \cdot \gamma_w}{\gamma_d} - 1 \qquad e = 0.886$$

$$n := \frac{e}{1 + e} \qquad n = 0.47$$

Estimate the moisture content of the Pond LIner. At 15300 cm, volumetric
moisture
content is 0.33.

$\frac{\gamma_d}{\gamma_w} = 1.442$ $\theta := 0.33$ $w := \frac{.33}{1.442}$ $w = 0.229$

Use 23 percent as the initial moisture content for the Pond Liner.

Problem Statement:

Verify the cell formula calculations for determining the diffusion coefficient as presented in Table 5-2 of the main calculation.

Documents Cited

U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "'93Regulatory Guide 3.64 (Reference 8).

Input the porosity(n), and moisture saturation fraction (m_f) from the four layers in **Attachment D**

$Array :=$

$$Array = \begin{pmatrix} 0.42 & 0.486 \\ 0.4 & 0.33 \\ 0.39 & 0.262 \\ 0.47 & 0.705 \\ 0.32 & 0.319 \\ 0.39 & 0.26 \\ 0.33 & 0 \\ 0.39 & 0.262 \end{pmatrix}$$

CV 9/17/10

From REG Guide 3.64 based upon Equation 6 in the main calculation

$$D(m_f, n) := 0.07 \cdot exp\left[-4 \cdot \left(m_f - m_f \cdot n^2 + m_f^5\right)\right]$$

Equation 6 Reference 8, Page 3.64-10

$n := Array^{\langle 1 \rangle}$ $\quad m_f := Array^{\langle 2 \rangle}$

$$n = \begin{pmatrix} 0.42 \\ 0.4 \\ 0.39 \\ 0.47 \\ 0.32 \\ 0.39 \\ 0.33 \\ 0.39 \end{pmatrix} \qquad m_f = \begin{pmatrix} 0.486 \\ 0.33 \\ 0.262 \\ 0.705 \\ 0.319 \\ 0.26 \\ 0 \\ 0.262 \end{pmatrix}$$

$$\overrightarrow{D(m_f, n)} = \begin{pmatrix} 0.013 \\ 0.023 \\ 0.029 \\ 3.886 \times 10^{-3} \\ 0.022 \\ 0.029 \\ 0.07 \\ 0.029 \end{pmatrix}$$

Note the units are in the cgs system.
cm/sec^2

CONCLUSION: The results are in agreement with the cell formulas for in Column S of the EXCEL workbook (Table 5-2) and the cell formulas are verified.