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**A MODELING STUDY OF THE EFFECT OF DEPTH OF BURIAL
OF DEPLETED URANIUM AND THORIUM ON RADON GAS FLUX
AT A DRY DESERT ALLUVIAL SOIL RADIOACTIVE
WASTE MANAGEMENT SITE (RWMS)**

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ABSTRACT

An integral part of designing low-level waste (LLW) disposal pits and their associated closure covers in very dry desert alluvium is the use of a radon gas transport and fate model. Radon-222 has the potential to be a real health hazard. The production of radon-222 results from the radioactive decay (α particle emission) of radium-226 in the uranium-235 and 238 Bateman chains. It is also produced in the thorium-230 series. Both long lived radionuclides have been proposed for disposal in the shallow land burial pits in Area 5 RWMS compound of Nevada Test Site (NTS). The constructed physics based model includes diffusion and barometric pressure-induced advection of an M-chain of radionuclides. The usual Bateman decay mechanics are included for each radionuclide. Both linear reversible and linear irreversible first order sorption kinetics are assumed for each radionuclide.

This report presents the details of using the noble gas transport model, CASCADR9, in an engineering design study mode. Given data on the low-level waste stream, which constitutes the ultimate source of radon-222 in the RWMS, CASCADR9 is used to generate the surface flux ($\text{pCi}/\text{cm}^2\text{-sec}$) of radon-222 under the realistic atmospheric and alluvial soil conditions found in the RWMS at Area 5, of the NTS. Specifically, this study examines the surface flux of radon-222 as a function of the depth of burial below the land surface.

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1.0 INTRODUCTION

"Radioactive Waste Management," DOE Order 5820.2A (1988) requires performance assessment on all new and existing low-level radioactive waste disposal sites. An integral part of the performance assessment is estimating the fluxes of radioactive gases such as radon-220 and radon-222. Mathematical models, which in themselves point out data needs and therefore drive site characterization, provide a logical means of performing the required flux estimations. Mathematical models assist in the engineering design of burial trenches and their associated closure caps to meet or exceed the safety (exposure) standards such as the National Emissions Standards for Hazardous Air Pollutants (NESHAP).

Nazaroff (1992) provides an excellent review of the literature on radon gas transport from soils to the atmosphere. His report also reviews the few existing diffusion models. The noble gas transport model described in this present report was developed largely from his review of the existing mathematical models simulating radon gas transport in soils. His work points out the need for a highly site specific model for radon gas transport in very dry high desert alluvial soils. Thus, the motivation was provided to begin constructing a series of noble gas transport models, beginning the series with a simple one-dimensional isothermal structure. If required by the performance assessment, a two-dimensional non-isothermal model will be developed.

Lindstrom et al. (1992a) built the first one-dimensional isothermal structure, based upon diffusion and induced advection, as a result of barometric pressure disturbances at the soil-air interface. The soil column required homogeneous conditions. This restriction precluded the use of an engineered layered closure cap. The structure did however provide for an M-chain of radionuclides by incorporating the classical Bateman (1910) decay mechanics into the overall transport and fate structure. It also included linear equilibrium sorption kinetics. The associated users manual (Cawfield et al., 1993a) details the use of this structure, called CASCADR8, on IBM and SUN SPARC desk top computers. Included in the users manual for CASCADR8 are several shallow burial scenarios using depleted uranium as the low-level waste, together with an investigation

of the effect of the various Fourier barometric pressure wave components on the surface flux of radon-222.

Additional burial scenarios were considered with CASCADR8 (Lindstrom et al., 1992b) to study the surface flux of radon-220. The radon-220 was derived from the shallow land burial of thorium-232 low-level waste employed in the usual manner (Becker, 1992). No closure cap was used in this simulation since CASCADR8 was designed for a homogeneous alluvial soil. Because the usual emplacement method provides for a native soil cover at least eight feet thick, the worst case scenario for the radon-220 surface flux from the thorium-232 waste fell below the NESHAP standard by five to seven orders of magnitude.

Because engineered barriers, such as landfill closure caps, are highly heterogeneous by design and CASCADR8 is useful only for a homogeneous soil column, it was necessary to extend the concept so as to model the transport and fate of noble gases in highly heterogeneous porous media. The concepts and details of the extension of CASCADR8, to include heterogeneity, are included in the model called CASCADR9 (Lindstrom et al., 1992c). Care was taken to include the appropriate air and radionuclide flux balances at the sharp textural contrasts, which can appear in a layered heterogeneous alluvial soil. A design closure cap with four layers ("four-layered cake") was used as an illustrative example of an engineered closure cap. Depleted uranium was used as the example source radionuclide. A number of different sets of simulations were run, where the effect of varying five factors on radon-222 surface flux was examined. The factors studied were: 1) barometric wave frequency effect, 2) textural contrast effects, 3) a first attempt at depth of burial effects, 4) the magnitude of the diffusion coefficient, and 5) the effect of varying the eddy diffusivity at the soil-atmosphere interface. The model was shown to be sensitive to all five factors. However, from an engineering design point of view, the engineered barrier textural contrasts and the depth of burial are the most important factors. Only depth of burial results will be presented in this paper. The other effects have been considered in detail in the above mentioned CASCADER references.

The users manual for CASCADR9 (Cawfield et al., 1993b) details the use of CASCADR9 in further depth of burial closure cap scenarios. In fact, the concept of burying several layers of thorium-232 waste below a 17 foot thick region of depleted uranium was explored in some detail.

The 17 foot thick waste region is standard operating procedure for current LLW operations in Area 5 RWMS. At this point, it needs to be mentioned that the thorium-232 waste stream is not homogeneous. The waste stream contains roughly 99 grams of thorium-230 per 1,000,000 grams of thorium waste. Therefore, since thorium-230 decays via α emission to radium-226, the parent for radon-222, it must be included in the model scenarios as well. An individual paper (Lindstrom et al. 1993c) detailing the results of 40-day simulations of radon-222 derived from the thorium-230 "impurity," was prepared. In this paper, alternative depth of burial designs, using no engineered closure cap other than a ten foot thick region of native soil above grade over the waste were studied.

It was discovered that the depth of burial effect on the reduction of the surface radon-222 flux appeared to follow an exponential function (Lindstrom et al., 1993a). That is, the surface flux appears to decrease exponentially as the depth of burial increases.

A partial mathematical verification study (Appendix F, Cawfield et al. 1993a) directly supports this concept. This makes the depth of burial effect even more important than previously realized. The depth of burial factor, when both thorium-232 (including the small but significant thorium-230 impurity) and DU are in the same trench, appears now to be the fundamental issue. In Lindstrom et al. (1993c), the Bateman decay chain mechanics indicate clearly that the radium-226 ingrowth from thorium-230 (via one α -decay) reaches a very flat broad peak at about 6,000 years, while the radium-226 ingrowth from uranium-238 does not peak within the first million years of operation. Radium-226 ingrowth from uranium-238 is only 12.5 percent of its peak value after 100,000 years of operation. Because of the vast differences in ingrowth rates in the radium-226 (the parent radionuclide of radon-222), it was decided to stack the thorium

waste on the bottom thereby making it have a much further travel path (attenuation would be greater, Lindstrom et al., 1993b). The thickness of the source layers as well as the initial loading (concentration) effects were investigated in Lindstrom et al. (1993a). Therefore, the remainder of this paper is concerned with describing additional simulations designed to study the effect of different depth of burial and waste emplacement ("stacking") scenarios on surface radon flux. The results of these simulations are intended to provide preliminary guidance to waste operations personnel for the design of disposal pits and waste stacking procedures.

2.0 BRIEF REVIEW OF CASCADR9

2.1 Transport and Fate Equations

Figure 2.1.1 is a sketch of the conceptualized transport and fate processes operating in the representative elementary volume (REV) between x and $x+\Delta x$ on the right-hand side of the half-space ($x \geq 0$) region. The REV is assumed to lie between two textural contrasts (Figure 2.1.2). This figure illustrates a four-chain of radionuclides. The mathematical symbols are defined in Appendix A. Application of the mass balance principle in the REV leads to the following equations:

$$\frac{\partial C^1}{\partial t} + \frac{1}{\varepsilon(1+R^1)} \frac{\partial (q_{air} C^1)}{\partial x} + \left(\lambda_1 + \frac{\lambda_{irr}^1 f_{irr1} (1-\varepsilon)}{\varepsilon(1+R^1)} \right) C^1 =$$

$$\frac{D^1}{1+R^1} \frac{\partial^2 C^1}{\partial x^2} + \frac{(1-\varepsilon) \rho_p S_o(x) + (1-\varepsilon) S_{SP}(x) \left(\frac{M_1}{M_0} \right)}{\varepsilon(1+R^1)} \quad \left(\frac{gm}{cm^3 air} \right) \quad (2.1.1)$$

for the first daughter radionuclide and

$$\frac{\partial C^j}{\partial t} + \frac{1}{\varepsilon(1+R^j)} \frac{\partial (q_{air} C^j)}{\partial x} + \left[\lambda_j + \lambda_{irr}^j f_{irrj} \frac{(1-\varepsilon)}{\varepsilon(1+R^j)} \right] C^j =$$

$$\frac{D^j}{1+R^j} \frac{\partial^2 C^j}{\partial x^2} + \lambda_{j-1} \left(\frac{1+R^{j-1}}{1+R^j} \right) \left(\frac{M_j}{M_{j-1}} \right) C^{j-1} \quad , \quad \left(\frac{gm}{cm^3 air} \right) \quad (2.1.2)$$

for the j th daughter radionuclide, $j = 2, 3, \dots, M$.

The detailed development of these transport and fate equations together with their associated sorption rules are given in Lindstrom et al. (1992a). In equations 2.1.1 and 2.1.2 the reversibly sorbed daughters affect the transport and fate via the use of linear equilibrium distribution coefficients and ultimately through retention coefficients such as

$$R^j = \frac{1-\varepsilon}{\varepsilon} f_{revj} \rho_p K_{eqj} \quad (2.1.3)$$

Figure 2.1.1 Transport and fate region REV showing transport, decay, and sorption paths.

Figure 2.1.2 Schematic diagram of the homogeneous soil layers making up the heterogeneous vadose zone.

The irreversibly bound daughters' sorption rules are given in Lindstrom et al. (1992a). In equations 2.1.1 and 2.1.2 the effect of barometric pressure induced advection is included via the spatially and temporally varying function $q_{air}(x,t)$. Lacking values of the reversible and irreversible sorption coefficients for radon-222 on NTS soils, an err on the conservative side was selected and set all for all parameters to zero. The other data required to run the model, e.g., porosities, diffusivities, etc., can be found in Lindstrom et al. (1992c and 1993b).

2.2 Barometric Induced Air Pumping

The details of barometric induced air pumping in CASCADER are given in Lindstrom et al. (1992a). Briefly, the one-dimensional Darcy air flow on the homogeneous interior of each soil layer is defined as

$$q_{air} = -\frac{K_{air}}{\eta_{air}} \left(\frac{\partial P_{air}}{\partial x} - \rho_{air} g \right) \quad (2.2.1)$$

(Lindstrom et al., 1992a). The assumptions are made that 1) the air can be treated as an ideal gas so that

$$\rho_{air} = \frac{M_{air}}{R_g T} P_{air} \quad , \quad (2.2.2)$$

and 2) isothermal conditions are obtained. Combining these two definitions (constitutive equations) with the continuity equation (mass balance) in the REV

$$\frac{\partial(\epsilon \rho_{air})}{\partial t} + \frac{\partial(\rho_{air} q_{air})}{\partial x} = 0 \quad (2.2.3)$$

provides us a way of estimating the advective velocity $V_{air}(x,t)$ since

$$q_{air} = \epsilon V_{air} \quad . \quad (2.2.4)$$

CASCADR9 makes use of all of these relationships together with initial and boundary data to estimate the advective velocity of the radionuclides.

2.3 Interfacial or Contrast Coupling

Figure 2.3.1 shows a sketch of the following Gaussian "pill box" concept at an arbitrary interface I_j , $j = 1, 2 \dots N_I$, between two soil layers with properties I_j^L and I_j^U , respectively.

Figure 2.3.1 Gaussian pill box of arbitrary cross sectional area γ (cm^2) and thickness T (cm).

Let the thickness of the "pill box" be T cm with half the pill box residing in each soil layer as shown in the sketch. Let $\hat{n}$ be the unit outward normal to the arbitrary cross sectional surface area γ . Let $\hat{r}$ be the unit outward normal to the circumferential surface whose "height" is T . The box is centered on nodal point X_{I_j} . Let $\underline{q}_{cj}$ be the flux vector of radionuclide j . Thus,

$$\underline{q}_{ck} = q_{ck}^x \hat{n} + q_{ck}^r \hat{r} \quad (2.3.1)$$

where in our current one-dimensional model

$$q_{ck}^x = \varepsilon \left(-D^k \frac{\partial C^k}{\partial x} + V_{air} C^k \right) \quad (2.3.2)$$

and

$$q_{ck}^r = 0 \quad (2.3.3)$$

In the most general case q_{ck}^r is not necessarily zero. The time rate of change of the mass in the pill box is equal to the negative of the total flux through the surface of the pill box. This is simply a statement of the conservation of mass condition in classical physics. Thus,

$$\begin{aligned} \frac{\partial (\pi r^2 T C^k)}{\partial t} &= -\pi r^2 \left(q_{ck}^x|_{x_{ij}^-} \hat{n} \cdot (-\hat{n}) + q_{ck}^x|_{x_{ij}^+} \hat{n} \cdot \hat{n} \right) \\ &\quad - 2\pi r \frac{T}{2} \left(q_{ck}^r|_{x_{ij}^-} \hat{r} \cdot \hat{r} + q_{ck}^r|_{x_{ij}^+} \hat{r} \cdot \hat{r} \right) \end{aligned} \quad (2.3.4)$$

where X_{ij}^- is some point on the lower side of I_j and X_{ij}^+ is some point on the upper side of I_j . Letting $T \rightarrow 0^+$ causes the volume to shrink to zero, $\pi r^2 T$ to vanish and in turn causes $\frac{\partial}{\partial t} (\pi r^2 T C^k)$ to vanish as well. Furthermore, assuming that q_{cj}^r is bounded and measurable (integrable) over the small cylindrical surface, the contribution from this surface also vanishes as $T \rightarrow 0^+$. Since r is arbitrary, the interface or coupling condition is

$$q_{ck}^x|_{x_{ij}^-} = q_{ck}^x|_{x_{ij}^+} \quad (2.3.5)$$

or upon substitution for q_{cj}^x then,

$$\varepsilon_{ij-} \left(-D_-^k \frac{\partial C^k}{\partial x} \Big|_{x_{ij}^-} + (V_{air} C^k) \Big|_{x_{ij}^-} \right) = \varepsilon_{ij+} \left(-D_+^k \frac{\partial C^k}{\partial x} \Big|_{x_{ij}^+} + (V_{air} C^k) \Big|_{x_{ij}^+} \right) \quad (2.3.6)$$

A similar argument on the barometric air pumping concept at arbitrary interface l_j leads to

$$q_{air}|_{x_{lj}^-} = q_{air}|_{x_{lj}^+} \quad (2.3.7)$$

Since by assumption there are no sources or sinks of mass, either radionuclide or air, at the interfacial nodes, we must require continuity in the radionuclide concentration at the interfacial node. That is,

$$C^K(x_{lj}^-, t) = C^K(x_{lj}^+, t) = C^K(x_{lj}, t) \quad (2.3.8)$$

Similar reasoning on the barometric pressure field leads to

$$P_{air}(x_{lj}^-, t) = P_{air}(x_{lj}^+, t) = P_{air}(x_{lj}, t) \quad (2.3.9)$$

Using equations 2.3.7 and 2.3.8 in equation 2.3.6 reduces 2.3.6 to the simplified form

$$-\epsilon_{lj}^- \left(D_-^K \frac{\partial C^K}{\partial x} \right) \Big|_{x_{lj}^-} = -\epsilon_{lj}^+ \left(D_+^K \frac{\partial C^K}{\partial x} \right) \Big|_{x_{lj}^+} \quad (2.3.10)$$

CASCADR9 uses the same split operator Euler-Lagrange finite difference numerical method, detailed by Lindstrom et al. (1992a), in solving for the radionuclide concentration distribution over space and time for prescribed initial and boundary conditions. Thus, in the air pumping submodel the interfacial coupling conditions of 2.3.7 and 2.3.9 are present. Using the same one-sided first difference approximation for $\frac{\partial P_{air}}{\partial x}$ as appears in CASCADR8 (Lindstrom et al., 1992a),

$$\begin{aligned} -K_{air|j}^- \left(\frac{P_{air|j} - P_{air|j-1}}{\Delta x_{lj-1}} - \frac{M_{air} g}{R_g T_{air}} P_{air|j} \right) = \\ -K_{air|j}^+ \left(\frac{P_{air|j+1} - P_{air|j}}{\Delta x_{lj}} - \frac{M_{air} g}{R_g T_{air}} P_{air|j} \right) \end{aligned} \quad (2.3.11)$$

as the interfacial coupling condition on the barometric pressure field and similarly for radionuclide k condition 2.3.10 becomes

$$-\epsilon_{ij}^- D_-^K \left(\frac{C_{ij}^K - C_{ij-1}^K}{\Delta x_{ij-1}} \right) = -\epsilon_{ij}^+ D_+^K \left(\frac{C_{ij+1}^K - C_{ij}^K}{\Delta x_{ij}} \right) . \quad (2.3.12)$$

At all other interior points of each soil layer the split operator Euler-Lagrange method is used. The smooth cubic Lagrange spline method of interpolating the advected radionuclide chemical concentration as per detailed in Lindstrom et al. (1992a) is retained in CASCADR9. The thickness of each soil layer as well as the nodal point spacing (either uniform or nonuniform spacing) is the same in CASCADR9 as in CASCADR8.

2.4 Initial and Boundary Conditions

Figures 2.4.1 and 2.4.2 show the conceptual structure used at the two boundaries. Either the same boundary conditions as described in detail in CASCADR8 (Lindstrom et al., 1992a) or direct users supplied barometric pressure wave boundary conditions are used in CASCADR9. The initial pressure distribution in the barometric pumping submodel is

$$P_{air}(x, 0^+) = P_A e^{\frac{M_{air} g x}{R_g T}} . \quad (2.4.1)$$

At the soil-atmospheric boundary layer interface the boundary condition on the pressure field is either

$$P_{air}(0, t) = P_A + \sum_{i=1}^{15} \left(\Delta P_{ci} \cos \left(\frac{2\pi t}{L_i} \right) + \Delta P_{si} \sin \left(\frac{2\pi t}{L_i} \right) \right) , \quad (2.4.2)$$

or a user defined (subsequently smooth cubic splined interpolated) data table for barometric pressure $P_{air}(0, t)$.

Figure 2.4.1 Illustration of the soil-atmosphere boundary layer geometry.

Figure 2.4.2 Illustration of the soil-water interface.

At the water table the boundary condition is

$$q_{\text{air}}|_{x=L_x} = 0 \quad (2.4.3)$$

or

$$\left(\frac{\partial P_{\text{air}}}{\partial x} - \frac{M_{\text{air}} g}{R_g T} P_{\text{air}} \right)_{x=L_x} = 0 \quad (2.4.4)$$

Like CASCADR8, we approximate $\frac{\partial P_{\text{air}}}{\partial x} \Big|_{x=L_x}$ via the one-sided two point difference approximation

$$\frac{\partial P_{\text{air}}}{\partial x} \Big|_{x=L_x} \doteq \frac{P_{\text{air}}(X_{N_x}) - P_{\text{air}}(X_{N_x-1})}{\Delta x_{N_x}} \quad (2.4.5)$$

Substitution into equation 2.4.4 with subsequent rearrangement leads to the simple form

$$-P_{\text{air}N_x-1} + \left(1 - \frac{M_{\text{air}} g}{R_g T} \Delta x_{N_x} \right) P_{\text{air}N_x} = 0 \quad (2.4.6)$$

In the case of the initial conditions for the j th radionuclide chemical concentration, $C^j(x, 0^+)$ is obtained from the secular equilibrium conditions in Bateman chain so that

$$C^j(x, 0^+) = \frac{\lambda_{j-1} \left(\frac{1+R^{j-1}}{1+R^j} \right) \left(\frac{M_j}{M_{j-1}} \right) C^{j-1}(x, 0^+)}{\lambda_j + \lambda_{\text{irr}}^j f_{\text{irr}j} \left(\frac{1-\epsilon}{\epsilon(1+R^j)} \right)} \quad (2.4.7)$$

for $j = 2, 3, 4, \dots M$. $C^1(x, 0^+)$ is prescribed by the user of CASCADR9.

The constant in time background source function $S_0(x)$ is defined from $C_0(x)$ as

$$S_0(x) = \frac{\left(\lambda_1 + \frac{\lambda_{irr}^1 f_{irr1} (1-\epsilon)}{\epsilon (1+R^1)} \right) C_0(x) \epsilon (1+R^1)}{(1-\epsilon) \rho_p} \quad (2.4.8)$$

Figures 2.4.1 and 2.4.2 illustrate the boundary layer concepts used at the soil-atmosphere interface and the soil-water table interface respectively. The water table and the soil are coupled together at the plane $x=L_x$. At this interface we approximate the partial derivative in the boundary condition

$$-\epsilon D^j \frac{\partial C^j}{\partial x} \Big|_{x=L_x} = -\epsilon_{in} D_{in}^j \left(\frac{C_{in}^j - C^j(L_x, t)}{\Delta x_{in}} \right) \quad (2.4.9)$$

via the one sided difference approximation

$$\frac{\partial C^j}{\partial x} \Big|_{x=L_x} \doteq \frac{C^j(x_{Nx}, t) - C^j(x_{Nx} - \Delta x_{Nx}, t)}{\Delta x_{Nx}} \quad (2.4.10)$$

to obtain

$$-\epsilon D^j \left(\frac{C^j(x_{Nx}, t) - C^j(x_{Nx-1}, t)}{\Delta x_{Nx}} \right) = -\epsilon_{in} D_{in}^j \left(\frac{C_{in}^j - C^j(L_x, t)}{\Delta x_{in}} \right) \quad (2.4.11)$$

Boundary condition (2.4.11) is used since it retains the important physical concept of flux balance at the water table. A choice of erring on the conservative side was made in setting $C_{in}^j = 0$ and using $D_{in}^j = 10D^j$, for each j , in view of the lack of knowledge of these parameters values at the water table.

At the soil-atmosphere interface the partial derivative in the boundary condition

$$-\epsilon_{out} D_{out}^j \left(\frac{C^j(0,t) - C_{out}^j}{\Delta x_{out}} \right) = -\epsilon D^j \frac{\partial C^j}{\partial x} \Big|_{x=0} \quad (2.4.12)$$

is approximated via the one-sided difference approximation

$$\frac{\partial C^j}{\partial x} \Big|_{x=0} \doteq \frac{C^j(x_1,t) - C^j(0,t)}{\Delta x_0} \quad (2.4.13)$$

to obtain

$$-\epsilon D^j \left(\frac{C^j(x_1,t) - C^j(0,t)}{\Delta x_0} \right) = -\epsilon_{out} D_{out}^j \left(\frac{C^j(0,t) - C_{out}^j}{\Delta x_{out}} \right) \quad (2.4.14)$$

Boundary condition (2.4.12) is used since it also retains the important physical concept of flux balance at the soil-atmosphere interface. Well-known historical data on radon-222 near-surface air concentrations at the RWMS in Area 5 of NTS clearly show that the radon-222 air concentration one to two meters above the land surface is below detection limits. Thus, C_{out}^j was set to zero for all j . Equations 2.4.11 and 2.4.14 therefore define the boundary conditions on the j th radionuclide, $j = 1, 2, \dots M$.

2.5 Numerical Solution Method

The two-time level, time marching algorithm used in CASCADR8 is preserved in CASCADR9. The only difference between the two numerical methods comes in the definitions of the tridiagonal system coefficients at each soil layer interface or contrast nodal point. The interface conditions are used directly to define the linear system coefficients. Both the air pumping submodel and the radionuclide transport and fate portions are treated in this way at the contrasts. Because of the low order of accuracy associated with the two-point one-sided derivatives, the nodal point spacing in the neighborhood of the contrast nodes is kept quite small and gradually expands in spacing size as we go away from the interfaces. Also, the Lagrangian treatment of the advection

terms (particle back tracking) is carried out only on the interior nodal points of each homogeneous region between the contrasts. Nodal spacing close to the leading and lagging edges of the manmade waste package region (i.e., source region where $S_{SP}(x) > 0$), are again kept small, but on an expanding scale as we go away from the edges. This scheme tends to preserve the accuracy of the approximate solution.

The solution procedure outlined in Section 3.4, the mass accounting techniques detailed in Section 3.5, and the specific activity computations discussed in Section 3.6 of Lindstrom et al. (1992a) are retained in CASCADR9.

3.0 DEPLETED URANIUM OVER THORIUM STUDY

3.1 Burial Concepts

Figure 3.1.1 shows the first few 16-fold stacking scenarios in the numerical study of the stacking of depleted uranium over thorium. The thorium of concern here is the impurity thorium-230 in the thorium-232 matrix. The depth of the pit and the thickness of temporary soil cover shown in Figure 3.1.1 were specified by the Waste Operations Department. The 16 stacking scenarios (Figure 3.1.2) were also selected by the Waste Operations Department.

Figure 3.1.1 Vertical profile schematic for several of the 16 different stacking combinations.

The assumption on the stacking of waste is that each 4 ft by 4 ft by 7 ft box contains either 1,000 kg of DU or thorium. The thorium is always on the bottom. Each tier is 4 ft high with no gap between the boxes. The original bottom (old pit design) has been dug out to equate to double its original depth (51 ft total below the land surface).

Number of DU Tiers

Number of Thorium Tiers	# Tiers DU # Tiers Thorium	1	2	3	4
	1	Run 1	Run 5	Run 9	Run 13
	2	Run 2	Run 6	Run 10	Run 14
	3	Run 3	Run 7	Run 11	Run 15
	4	Run 4	Run 8	Run 12	Run 16

Figure 3.1.2 Matrix of 16 combinations for DU-Thorium study.

The 10 foot thick region of native soil between the top tier of the thorium and the bottom tier of the DU is included for conservative geotechnical reasons. The physical properties used in the simulations are summarized in Table 3.1.1, while the radium-226 source concentrations are summarized in Table 3.1.2. The strengths for the sources have been estimated on the conservative side by using the peak ingrowth radium-226 value at time $t = 0$ and holding this source constant in time.

Table 3.1.1 Soil properties used in the 16 simulation runs

PROPERTY	REGION				
	SURFACE-TOP OF DU	DU REGION	GEO. TECH. SLAB	THORIUM REGION	NATIVE SOIL TO WATERTABLE
K_{air}	4.0	200.0	4.0	200.0	4.0
ϵ (cm ³ /cm ³)	0.37	0.67	0.37	0.67	0.37
D_s (cm ² /sec)	0.022	0.055	0.022	0.055	0.022

Table 3.1.2 Source strengths used in the 16 simulation runs

TYPE UNITS	REGION				
	SURFACE-TOP OF DU	DU REGION	GEO. TECH. SLAB	THORIUM REGION	NATIVE SOIL TO WATERTABLE
Man made * (gm/cm ³ -sec)	0.0	1.4×10^{-18}	0.0	5.04×10^{-20}	0.0
Native * (gm/cm ³)	1.3×10^{-18}	1.3×10^{-18}	1.3×10^{-18}	1.3×10^{-18}	1.3×10^{-18}
Initial Conc. ** (gm/cm ³)	1.3×10^{-18}	1.3×10^{-18}	1.3×10^{-18}	1.3×10^{-18}	1.3×10^{-18}

* Obtained from $(0.2 \text{ pCi/cm}^3) / (1.54 \times 10^{17} \text{ pCi/gm})$ where 0.2 pCi/cm^3 is the average experimentally determined radon-222 background soil-air phase concentration and the $1.54 \times 10^{17} \text{ pCi/gm}$ is the specific activity of radon-222.

+ DU region see equation 3.1.1 in Section 3.1 of Lindstrom et al (1992a) and for the thorium region see equation 3.2.1 in Section 3.2 of Lindstrom et al. (1993c).

** Discussion immediately following equation (5.0.1) in Cawfield et al. (1993a).

Figure 3.1.3 shows the real barometric pressure data obtained from the NOAA META 5 weather station (Cawfield et al., 1993b) used in all 16 simulation runs.

Figure 3.1.3 Real barometric pressure data used in the 40-day simulations.

Table 3.1.3 defines the set of hourly D_{out}^1 values used in a modulo 24 hour fashion in CASCADR9. Δx_{out} is held fixed at 100 cm. The effect is to define the quotient $D_{out}^1 / \Delta x_{out}$ (cm/sec) as varying in an hourly stair step fashion from a low value of 1.0×10^{-3} cm/sec under very still (neutral) boundary layer air conditions extending from about 10 p.m. through about 7:00 a.m. to a mid afternoon highly unstable turbulent value of 10.0 cm/sec. Figure 3.1.4 shows a sketch of the assumed D_{out}^1 function over a basal 24 hour period. These values reflect realistic effective eddy diffusivity values for Area 5, NTS, warm dry summertime atmospheric conditions. These values were estimates supplies by Dr. H. Weaver (Spar, Inc. Baker City, OR) our expert consultant in micrometeorology and near-surface boundary layer atmospherics. Dr. Weaver obtained these effective eddy diffusivities using a combination of well-known Prandtl and Monin-Obukov similarity theories.

The values of D_{out}^1 appearing in Table 3.1.3 are considerably larger than those appearing in Table 3.6.1 of Lindstrom et al. (1992c). The reason for this is the values used in Table 3.6.1 of Lindstrom et al. (1992c) were ad hoc feasibility study values. They were designed to study the effect of allowing the eddy diffusivity of radon-222 across the boundary layer to vary diurnally. Real world estimates were lacking at that time. Subsequently, Dr. H. Weaver, of Soil-Plant-Atmosphere-Research (SPAR) Inc., Baker City, OR. provided a set of realistic effective eddy diffusivities. The numbers shown in Table 3.1.3 reflect his latest estimates for dry, high wind, summer time conditions in Area 5 of NTS. As actual estimates of the real time eddy diffusivity across a two meter boundary layer are the goals of the micrometeorological station at RWMS in Area 5, currently being installed, radon-222 surface flux estimates done in the future, using any of the CASCADR9 or later models, will reflect the use of the latest micromet data.

The remaining system parameters are given in the 16 input data files. The data files used for runs 1 and 16 are given in Appendix B for illustrative purposes.

Table 3.1.3 Hourly values of D_{out}^1 - modulo 24 hours

Time	D_{out}^1 (cm ² /sec)	Time	D_{out}^1 (cm ² /sec)	Time	D_{out}^1 (cm ² /sec)
1 AM	0.1	9 AM	200.0	5 PM	750
2	0.1	10	750.0	6	500
3	0.1	11	950.0	7	250
4	0.1	12 Noon	1,000	8	100
5	0.1	1 PM	1,000	9	50
6	0.1	2	1,000	10	2.5
7	1.0	3	1,000	11	0.1
8	60.0	4	1,000	12 midnight	0.1

Figure 3.1.4 Shaped effective boundary layer diffusivity function D_{out}^1 for radon-222. Modulo 24 hours assumed.

3.2 Results of Simulations

Figure 3.2.1 summarizes visually, the average radon-222 surface flux in $\text{pCi}/\text{cm}^2\text{-sec}$ at 40 days as a function of the number of tiers of DU and thorium. The NESHAP standard is plotted as the stippled fishnet surface. The average surface flux of radon-222 is plotted as the solid fishnet surface. Clearly portions of the average surface flux of radon-222 lie below the standard and clearly portions lie well above the standards. Figure 3.2.2 (similar to Figure 3.1.2) shows the summary in a pass/fail fashion.

Figure 3.2.1 Average radon-222 surface flux in $\text{pCi}^2/\text{cm}\text{-sec}$ at 40 days as a function of the number of tiers of DU and thorium.

Number of DU Tiers

Number of Thorium Tiers	# Tiers DU # Tiers Thorium	1	2	3	4
	1	Run 1 PASS	Run 5 PASS	Run 9 PASS	Run 13 FAIL
	2	Run 2 PASS	Run 6 PASS	Run 10 FAIL	Run 14 FAIL
	3	Run 3 PASS	Run 7 FAIL	Run 11 FAIL	Run 15 FAIL
	4	Run 4 PASS	Run 8 FAIL	Run 12 FAIL	Run 16 FAIL

Figure 3.2.2 Summary of 16 simulation runs in pass/fail format.

Figures 3.2.3 - 3.2.18 show the actual plots of the 40-day simulation runs for all 16 experiments. Figure 3.2.3 shows the radon-222 surface flux in pCi/cm²-sec for one tier of DU stacked above one tier of thorium low-level waste. It appears to take about eight to ten days for the effect of the buried waste to begin appearing at the surface. The first eight to ten days is largely a simulation of the native or background radon-222 flux at the surface. Things seem to be close to equilibrium by the end of the 40-day simulation time.

The word equilibrium is used loosely here for in Lindstrom et al. 1992c several 400-day simulation runs were made. In their work the daily average surface radon-222 flux

tracked the annual barometric pressure wave component very well. Using 400 days of consecutive barometric pressure data, with smooth cubic splining being used to fill in the gaps in the META 5 NOAA barometric pressure weather record, several 400-day simulation runs (runs numbered 1, 7, and 14 in Figure 3.2.2) were made (not shown here). The average daily radon-222 surface flux did indeed track the longer wave (low frequency) barometric pressure wave components from about day 40 onward. The near "hit" shown for one tier of DU above four tiers of thorium on about day 38 is probably not worth being concerned with. Recall that erring is always on the conservative side. If daily averages were to reach or exceed the NESHAP standard, then there could be cause for concern over "too high of a surface flux of radon-222." The case of thorium only was reported in detail in Lindstrom et al. (1992b and 1993c).

Figure 3.2.3 Surface flux of radon-222 (pCi/cm²-sec) for one tier of DU over one tier of thorium waste.

Figure 3.2.4 Surface flux of radon-222 (pCi/cm²-sec) for one tier of DU over two tiers of thorium waste.

Figure 3.2.5 Surface flux of radon-222 (pCi/cm²-sec) for one tier of DU over three tiers of thorium waste.

Figure 3.2.6 Surface flux of radon-222 (pCi/cm²-sec) for one tier of DU over four tiers of thorium waste.

Figure 3.2.7 Surface flux of radon-222 (pCi/cm²-sec) for two tiers of DU over one tier of thorium waste.

Figure 3.2.8 Surface flux of radon-222 (pCi/cm²-sec) for two tiers of DU over two tiers of thorium waste.

Figure 3.2.9 Surface flux of radon-222 (pCi/cm²-sec) for two tiers of DU over three tiers of thorium waste.

Figure 3.2.10 Surface flux of radon-222 (pCi/cm²-sec) for two tiers of DU over four tiers of thorium waste.

Figure 3.2.11 Surface flux of radon-222 (pCi/cm²-sec) for three tiers of DU over one tier of thorium waste.

Figure 3.2.12 Surface flux of radon-222 (pCi/cm²-sec) for three tiers of DU over two tiers of thorium waste.

Figure 3.2.13 Surface flux of radon-222 (pCi/cm²-sec) for three tiers of DU over three tiers of thorium waste.

Figure 3.2.14 Surface flux of radon-222 (pCi/cm²-sec) for three tiers of DU over four tiers of thorium waste.

Figure 3.2.15 Surface flux of radon-222 (pCi/cm²-sec) for four tiers of DU over one tier of thorium waste.

Figure 3.2.16 Surface flux of radon-222 (pCi/cm²-sec) for four tiers of DU over two tiers of thorium waste.

Figure 3.2.17 Surface flux of radon-222 (pCi/cm²-sec) for four tiers of DU over three tiers of thorium waste.

Figure 3.2.18 Surface flux of radon-222 (pCi/cm²-sec) for four tiers of DU over four tiers of thorium waste.

4.0 DISCUSSION AND CONCLUSIONS

4.1 Discussion

Recall that the peak ingrowth concentration of radium-226 has been used in every simulation. This causes the flux estimates to be conservative. The effective eddy diffusivity is an estimated quantity and will hopefully be validated in the near future by the eddy correlation data to be obtained from the Area 5 RWMS micromet weather station. Note that it plays a fundamental role in shaping the radon flux peaks and valleys over time. The model remains to be validated in so far as it can be validated by radon gas flux experiments currently under way by Mr. Dudley Emer of the REEC Co SPS. Therefore, the results given in this modeling study should serve as a guide for engineering design of the LLW pit and its associated closure cap.

An extremely important mathematical and physical concept is used here and should not be overlooked. The concept is that of linearity in the model. Physically, this means that the individual contributions to the surface flux of radon-222 can be estimated separately and then simply added at common points in time. Mathematically this is called superposing solutions. Thus, the contribution to the flux generated from the background (native) distribution of radium-226, by the DU source region and by the thorium-230 impurity, in the thorium region, can all be estimated independently. Cawfield et al. (1993a) demonstrates this very important physical and mathematical principle in Appendix E of their report. Again, because of the linearity, it is possible to change the magnitude of the scale factor for each source region and simply multiply the individual surface fluxes by the same respective scale factor and then add the results to obtain the total flux at the surface due to the new source. In the above work, each scale factor is arbitrarily chosen to be 1.0. For example, instead of using 0.2 pCi/cm^3 (200 pCi/liter) as the initial radon-222 concentration in the alluvium, 1.0 pCi/cm^3 (1000 pCi/liter) was used, then the initial concentration shown in Table 3.1.2 ($1.3 \times 10^{-18} \text{ gm/cm}^3$) would increase five-fold to $6.5 \times 10^{-18} \text{ gm/cm}^3$. A new total radon-222 surface flux can be obtained by separately running each individual component (the initial distribution-native source distribution), then multiply each initial distribution-native source distribution time point flux

by five and add the result to the sum of the other two component fluxes. The DU and thorium source components follow suit in exactly the same way. The figures included in this report were made using the scale factors all equal to 1.0.

Another closely related concept is that of using the maximum value of radionuclide ingrowth (radium-226 in this exercise) in each source region. Appendix B of Lindstrom et al. (1993c) and Appendix D of Cawfield et al. (1993b) give developments on chemical mass based versions at the classical Bateman M-chain of radionuclides differential equations systems. Either program can be used to develop the radium-226 mass as a function of time in the source region given the initial mass of all the radionuclides in the chain. The radium-226 mass in the thorium-230 chain peaks 7,700 years, whereas the radium-226 mass in the DU region peaks at 3.8×10^6 years. Figure 3.1.3 in Lindstrom et al. (1992c), shows that at 100,000 years the ingrowth for radium-226 from the DU (uranium-238 chain) is about ten percent its maximum value. Thus, the scale factor for radium-226 from the DU at 100,000 years is 0.1 (an order of magnitude). Table 4.1.1 details some ingrowth data on the thorium-230-radium-226-radon-222 chain. The half-lives and atomic masses are given in Lindstrom et al. (1993c).

Table 4.1.1 Thorium - Radium - Radon ingrowth data based upon a unit mass of thorium-230 at time $t = 0$ years.

time t (yrs)	$C(t)^*$	Scale factor	time t (yrs)	$C(t)$	Scale factor
0.0	0.0	0.0	100,000	0.407	0.452
5,000	0.841	0.933	200,000	0.165	0.183
10,000	0.901	1.0	300,000	0.067	0.074
20,000	0.841	0.933	500,000	0.011	0.012
50,000	0.638	0.708	1,000,000	$<1.25 \times 10^{-4}$	$<1.4 \times 10^{-4}$

* $c(t) = 0.9826 (e^{-9.0 \times 10^{-4}t})$, time t is in years. The $0.9826 = M_{ra226} / M_{rn230} = 226.0/230.0$

It is clear from the scale factors in Table 4.1.1 that by 500,000 years the radium-226 derived from the thorium-230 impurity has vanished to the point that its contribution to the radon-222 flux at the surface is barely 1.2 percent of its peak value at 7,700 years. Meanwhile the radium-226 derived from the DU has increased at 500,000 years to about two-thirds its peak value. Putting these notions together that both sources contribute their maximum amount of radium-226 instantaneously and constantly at time $t \geq 0$ (years), contributes to an error on the conservative side (perhaps overly conservative). The interesting design questions arise when playing with scale factors and much shorter time frames, say 1,000 or 10,000 years max. In these much shorter time ranges, the scale factors for the DU contributions range from 10^{-3} to 10^{-2} , whereas the scale factors for the thorium are given in Table 4.1.1. The time frame chosen will affect both the design of the trench, its associated closure cap, and the performance assessment.

4.2 Conclusion

The concept of burying thorium-232, with small amounts of thorium-230 as an impurity, underneath depleted uranium appears to be sound. However, as an added safety margin it might be wise to consider using engineered closure cap, which contains a flexible self-sealing type layer (asphalt perhaps), in place of simply a 10 foot thick slab of native alluvium. This would certainly obtain an order of magnitude or two reduction in the radon-222 surface flux rather than using the current burial scheme (Figure 3.1.1). The highly impermeable layer need not be more than a meter thick, judging from the modeling experiments done by Lindstrom et al. (1992c). As it now stands, a single tier of DU over a four tier stack of thorium just meets the NESHAP standard. The addition of an engineered closure cap would increase the safety margin. Two tiers of DU over two tiers of thorium also appears to be an acceptable configuration. Several other alternatives are also acceptable. Roughly half of the alternatives exceed NESHAP and are therefore unacceptable as shown in figures 3.2.1 and 3.2.2.

APPENDIX A

NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
A	total cross-sectional area at source region-soil interface	(cm ²)
V_o	total volume of source region	(cm ³)
ϵ_{in}	porosity of water table region	(cm ³ /cm ³)
V_{in}	average flow velocity in the water table region	(cm/sec)
D_{in}^j	average dispersion coefficient of jth radionuclide in the water table region	(cm ² /sec)
ϵ	porosity of soil region (homogeneous)	(cm ³ /cm ³)
V_{air}	average gas flow velocity (seepage velocity) at (x,t) in the soil region	(cm/sec)
V_{out}	average gas flow velocity in the boundary layer region exterior to the soil-atmosphere boundary $X = X_{Nx}$	(cm/sec)
D_j	jth average dispersion coefficient in soil region	(cm ² /sec)
Δx_{in}	thickness of water table coupling region	(cm)
Δx_{out}	thickness of boundary layer	(cm)
Δx	spacing between nodal points	(cm)
D_{out}^j	average dispersion coefficient of jth radionuclide in the boundary layer region	(cm ² /sec)
C^j	concentration of jth radionuclide in the soil subregion	(gm/cm ³)
R^j	linear equilibrium retardation coefficient of jth radionuclide in the soil subregion	(dimensionless)

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
R_0	mass flow rate from stationary source to the first radionuclide compartment	(gm/sec)
λ_0	decay constant for stationary source	(1/sec)
SA_j	specific activity of the radionuclide j	(pCi/gm)
M_s	initial mass of radionuclide 1 source material in the source region	(gm)
λ_j	decay coefficient for jth radionuclide	(1/sec)
λ_{irr}^j	rate coefficient for irreversible binding of jth radionuclide	(1/sec)
ρ_p	porous medium particle density	(gm/cm ³)
f_{revj}	fraction of porous medium solids available for reversible binding of jth radionuclide	(dimensionless)
f_{irrj}	fraction of porous medium solids available for irreversible binding of jth radionuclide	(dimensionless)
K_{Aj}	adsorption rate coefficient of radionuclide j onto solid particles	($\frac{\text{cm}^3 \text{ air}}{\text{cm}^3 \text{ particles-sec}}$)
K_{Dj}	desorption rate coefficient of radionuclide j onto solid particles	(1/sec)
K_{eqj}	linear equilibrium reversible sorption coefficient for radionuclide j onto the solid particles	($\frac{\text{cm}^3 \text{ air}}{\text{gm particles}}$)
q_{air}	specific discharge of air in the porous medium	(cm ³ /cm ² -sec)
$S_0(x)$	first constant in time, distributed in space source function, for first radionuclide in the transport and fate region	($\frac{\text{gm radionuclide}}{\text{gm soil-sec}}$)

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
$S_{SP}(x)$	second constant in time, distributed in space, source function, for first radionuclide in the transport and fate region	$(\frac{\text{gm radionuclide}}{\text{cm}^3\text{-sec}})$
κ_{air}	air permeability	(cm^2)
K_{air}	pneumatic conductivity	(cm/sec)
η_{air}	air viscosity	(dyne-sec/cm^2)
ρ_{air}	air density	(gm/cm^3)
g	gravitational acceleration	(cm/sec^2)
ΔP_A	amplitude of barometric pressure change	(dyne/cm^2)
P_{air}	barometric air pressure	(dyne/cm^2)
P_A	average barometric pressure	(dyne/cm^2)
M_{air}	molecular mass of air	(gm/mole)
M_j	atomic mass of radionuclide j	(gm/mole)
R_g	gas constant	$(\frac{\text{erg}}{\text{mole-}^\circ\text{K}})$
T	kelvin temperature	$(^\circ\text{K})$
D_{air}	pneumatic diffusivity	(cm^2/sec)
S_R^j	reversibly bound concentration of radionuclide j in the transport and fate region $[0, L_x]$	(gm/gm)
S_I^j	irreversibly bound concentration of radionuclide j in the transport and fate region $[0, L_x]$	(gm/gm)
N_x	number of equal length subintervals into which $[0, L_x]$ is subdivided	(dimensionless)

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
Δt	time increment between adjacent time levels	(sec)
$M_{Tfree\ k, n+1}^j$	mobile phase mass of radionuclide j at nodal point x_k in the transport and fate region at time level t_{n+1}	(gm)
$M_{TR\ k, n+1}^j$	reversibly sorbed mass of radionuclide j at nodal point x_k in the transport and fate region at time level t_{n+1}	(gm)
$M_{TI\ k, n+1}^j$	irreversibly sorbed mass of radionuclide j at nodal point x_k in the transport and fate region at time level t_{n+1}	(gm)
$C_{um, n+1}^j$	cumulative mass loss of the jth radionuclide from the surface $x = 0$	(gm or pCi)
$q_{cj, n+1}$	flux of radionuclide j at time t_{n+1} at the atmosphere-soil interface	(gm/cm ² -sec)

APPENDIX B

Data files used for runs 1 and 16 respectively are given below. The remaining 14 data files are being kept on file for future reference.

Run Datafile is (C9310201.DAT) Transport of (Radon gas) chain.

This is a re-hash of the DU/Thorium burial scenario.
The runs each have 1..4 containers of DU, on top of
10' native soil, 1..4 containers of Thorium on the bottom.
As a first approximation, 4'=1.25m, to make the nodes even.

This Run:

Material	Thickness	Cumulative
Native Soil	45' (13.75 m)	45' (13.75 m)
1 tier DU	4 1.25	49 15.00
Native Soil	8 2.50	57 17.50
1 tier Th	4 1.25	61 18.75
Native Soil	720 219.50	781 238.00

Note -- Comment lines now end with "\$" in column 1

\$

SET OF FLAGS: NFLAG(I): 01 02 03 04 05 06 07 08 09 10
0, 0, 0, 0, 0, 0, 1, 1, 1, 0

NLAYER NODES NUCS NOUT
5 371 1 600

Spacing is 'A' for Absolute, 'R' for Relative
'R'

ZOFF, then NM1 spacings for DZZ
0.0D0

1.0D0	2.0D0	4.0D0	8.0D0
1.0D1	2.0D1	4.0D1	8.0D1
1.0D2	1.0D2	1.0D2	
8.0D1	4.0D1	2.0D1	1.0D1
6.0D0	3.0D0	1.0D0	
1.0D0	2.0D0	4.0D0	8.0D0
1.0D1	2.0D1	4.0D1	
2.0D1	1.0D1	6.0D0	3.0D0 1.0D0
1.0D0	2.0D0	4.0D0	8.0D0
1.0D1	2.0D1	4.0D1	
2.0D1	1.0D1	6.0D0	3.0D0 1.0D0
1.0D0	2.0D0	4.0D0	8.0D0
1.0D1	2.0D1	4.0D1	
2.0D1	1.0D1	6.0D0	3.0D0 1.0D0
1.0D0	2.0D0	4.0D0	8.0D0
1.0D1	2.0D1	4.0D1	
2.0D1	1.0D1	6.0D0	3.0D0 1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	1.0D1	3.0D1	3.5D1	
217*1.0D2				
6.0D1	3.0D1	1.0D1	1.0D1	
8.0D0	4.0D0	2.0D0	1.0D0	

Spacing for layers: 'A' for absolute, 'R' for relative
'A'

BOTTOM DEPTH FOR N-1 LAYERS; LAST ONE IS DEPTH OF WATER TABLE, NOT LISTED

6.25D2
11.25D2
13.75D2
18.75D2

NDEP; then 'N' for nodes or 'Z' for actual depths
14 'Z'

PRINT AT THESE NODAL POSITIONS

0.00D0 1.00D2 6.25D2 7.50D2 8.75D2
1.00D3 1.125D3 1.25D3 1.375D3 1.50D3
1.625D3 1.75D3 1.875D3 2.379D3

INITIAL TIME: T0
0.0D0

FINAL TIME: TIME
3.456D+6

NUMBER OF PRINT TIMES: NPRT
360

DT
60.0D0

PARTDN	EPS	KAPPA	ONE ROW FOR EACH LAYER
2.6D0	0.37D0	4.00D-8	
2.6D0	0.67D0	2.00D-6	
2.6D0	0.37D0	4.00D-8	
2.6D0	0.67D0	2.00D-6	
2.6D0	0.37D0	4.00D-8	

EPSIN, EPSOT
0.37D0, 1.0D0

DSO1 DSO2, DSO3, DSO4
0.10D0

DSP1 DSP2 DSP3 DSPn ONE ROW FOR EACH LAYER
 0.022D0
 0.055D0
 0.022D0
 0.055D0
 0.022D0
 DSOT1, DSOT2, DSOT3, DSOTn
 1.00D0
 FREV1 FREV2 FREV3 FREVn ONE ROW FOR EACH LAYER
 0.10D0
 0.10D0
 0.10D0
 0.10D0
 0.10D0
 FIRR1 FIRR2 FIRR3 FIRRn ONE ROW FOR EACH LAYER
 0.10D0
 0.10D0
 0.10D0
 0.10D0
 0.10D0
 KEQ1 KEQ2 KEQ3 KEQn ONE ROW FOR EACH LAYER
 0.0D0
 0.0D0
 0.0D0
 0.0D0
 0.0D0
 THALF[0..MNUCS]
 4.990D+10, 3.327D+5, 1.800D+2, 1.560D+3, 1.140D+3
 AM[0..MNUCS]
 226.D0, 222.D0, 218.D0, 214.D0, 214.D0
 SA[0..MNUCS]
 0.989D12, 1.5377D17, 2.768D20, 3.28D19, 4.41D19
 LTIRR1 LTIRR2 LTIRR3 LTIRRn; ONE ROW FOR EACH LAYER
 0.0D0
 0.0D0
 0.0D0
 0.0D0
 0.0D0
 AREA
 1.0D+4
 COT1, COT2, COT3, COTn
 0.0D0
 CIN1, CIN2, CIN3, CINn
 1.30D-18
 DXIN
 100.0D0
 DXOUT
 100.0D0
 TAIR, RG, MASSA, GRAV, RHOWAT
 2.93D+2, 8.3143D+7, 29.0D0, 9.8D+2, 1.0D0
 PAIRO AND NPRES
 917.0D0, 1
 POC'S FROM 1 TO 15
 +0.0000D0, +0.0491D0, +0.0285D0, -0.0349D0, +0.0316D0
 +0.0122D0, -0.0465D0, +0.0456D0, -0.1103D0, 0.0000D0
 0.0000D0, 0.0000D0, 0.0000D0, 0.0000D0, 0.0000D0

POS'S FROM 1 TO 15
-10.000D0, +0.0513D0, +0.0209D0, +0.0166D0, -0.0067D0
-0.0008D0, +0.0821D0, -0.0194D0, +0.1103D0, 0.0000D0
0.0000D0, 0.0000D0, 0.0000D0, 0.0000D0, 0.0000D0
PERIODS OF EACH COMPONENT IN SECS.
3.4560D+5, 1.5768D+7, 3.9420D+6, 8.6400D+5, 3.4560D+5
2.5920D+5, 8.6400D+4, 4.3200D+4, 7.2000D+3, 1.0000D+0
1.0000D+0, 1.0000D+0, 1.0000D+0, 1.0000D+0, 1.0000D+0
Number of Source Regions; 'N' for nodes, 'Z' for depths.
02 'Z'
INITIAL DISTRIBUTION AND SOURCES
00 0.00D0 2.38D4 1.30D-18, 0.00D+00
01 13.75D2 15.00D2 1.30D-18, 1.40D-18
02 17.50D2 18.75D2 1.30D-18, 5.04D-20

Run Datafile is (C9310216.DAT) Transport of (Radon gas) chain.

This is a re-hash of the DU/Thorium burial scenario.
The runs each have 1..4 containers of DU, on top of
10' native soil, 1..4 containers of Thorium on the bottom.
As a first approximation, 4'=1.25m, to make the nodes even.

This Run:

Material	Thickness	Cumulative
Native Soil	21' (6.25 m)	21' (6.25 m)
4 tier DU	16 5.00	37 11.25
Native Soil	9 2.50	45 13.75
4 tier Th	16 5.00	61 29.75
Native Soil	720 219.50	781 238.00

Note -- Comment lines now end with "\$" in column 1

\$
SET OF FLAGS: NFLAG(I): 01 02 03 04 05 06 07 08 09 10
0, 0, 0, 0, 0, 0, 1, 1, 1, 0

NLAYER NODES NUCL NOUT
5 371 1 600

Spacing is 'A' for Absolute, 'R' for Relative
'R'

ZOFF, then NM1 spacings for DZZ
0.0D0

1.0D0	2.0D0	4.0D0	8.0D0
1.0D1	2.0D1	4.0D1	8.0D1
1.0D2	1.0D2	1.0D2	
8.0D1	4.0D1	2.0D1	1.0D1
6.0D0	3.0D0	1.0D0	

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	2.0D1	4.0D1		
2.0D1	1.0D1	6.0D0	3.0D0	1.0D0

1.0D0	2.0D0	4.0D0	8.0D0	
1.0D1	1.0D1	3.0D1	3.5D1	
217*1.0D2				

6.0D1	3.0D1	1.0D1	1.0D1	
-------	-------	-------	-------	--

8.0D0	4.0D0	2.0D0	1.0D0	
-------	-------	-------	-------	--

Spacing for layers: 'A' for absolute, 'R' for relative
'A'

BOTTOM DEPTH FOR N-1 LAYERS; LAST ONE IS DEPTH OF WATER TABLE, NOT LISTED

6.25D2

11.25D2

13.75D2

18.75D2

NDEP; then 'N' for nodes or 'Z' for actual depths

14 'Z'

PRINT AT THESE NODAL POSITIONS
 0.000D0 1.000D2 6.250D2 7.500D2 8.750D2
 1.000D3 1.125D3 1.250D3 1.375D3 1.500D3
 1.625D3 1.750D3 1.875D3 2.379D3
 INITIAL TIME: TO
 0.0D0
 FINAL TIME: TIME
 3.456D+6
 NUMBER OF PRINT TIMES: NPRT
 360
 DT
 60.0D0
 PARTDN EPS KAPPA ONE ROW FOR EACH LAYER
 2.6D0 0.37D0 4.00D-8
 2.6D0 0.67D0 2.00D-6
 2.6D0 0.37D0 4.00D-8
 2.6D0 0.67D0 2.00D-6
 2.6D0 0.37D0 4.00D-8
 EPSIN, EPSOT
 0.37D0, 1.0D0
 DSO1 DSO2, DSO3, DSO_n
 0.10D0
 DSP1 DSP2 DSP3 DSP_n ONE ROW FOR EACH LAYER
 0.022D0
 0.055D0
 0.022D0
 0.055D0
 0.022D0
 DSOT1, DSOT2, DSOT3, DSOT_n
 1.00D0
 FREV1 FREV2 FREV3 FREV_n ONE ROW FOR EACH LAYER
 0.10D0
 0.10D0
 0.10D0
 0.10D0
 0.10D0
 FIRR1 FIRR2 FIRR3 FIRR_n ONE ROW FOR EACH LAYER
 0.10D0
 0.10D0
 0.10D0
 0.10D0
 0.10D0
 KEQ1 KEQ2 KEQ3 KEQ_n ONE ROW FOR EACH LAYER
 0.0D0
 0.0D0
 0.0D0
 0.0D0
 0.0D0
 THALF[0..MNUCS]
 4.990D+10, 3.327D+5, 1.800D+2, 1.560D+3, 1.140D+3
 AM[0..MNUCS]
 226.D0, 222.D0, 218.D0, 214.D0, 214.D0
 SA[0..MNUCS]
 0.989D12, 1.5377D17, 2.768D20, 3.28D19, 4.41D19


```

LTIRR1 LTIRR2 LTIRR3 LTIRrn; ONE ROW FOR EACH LAYER
0.0D0
0.0D0
0.0D0
0.0D0
0.0D0
0.0D0
AREA
1.0D+4
COT1, COT2, COT3, COTn
0.0D0
CIN1, CIN2, CIN3, CINn
1.30D-18
DXIN
100.0D0
DXOUT
100.0D0
TAIR, RG, MASSA, GRAV, RHOWAT
2.93D+2, 8.3143D+7, 29.0D0, 9.8D+2, 1.0D0
PAIRO AND NPRES
917.0D0, 1
POC'S FROM 1 TO 15
+0.0000D0, +0.0491D0, +0.0285D0, -0.0349D0, +0.0316D0
+0.0122D0, -0.0465D0, +0.0456D0, -0.1103D0, 0.0000D0
0.0000D0, 0.0000D0, 0.0000D0, 0.0000D0, 0.0000D0
POS'S FROM 1 TO 15
-10.000D0, +0.0513D0, +0.0209D0, +0.0166D0, -0.0067D0
-0.0008D0, +0.0821D0, -0.0194D0, +0.1103D0, 0.0000D0
0.0000D0, 0.0000D0, 0.0000D0, 0.0000D0, 0.0000D0
PERIODS OF EACH COMPONENT IN SECS.
3.4560D+5, 1.5768D+7, 3.9420D+6, 8.6400D+5, 3.4560D+5
2.5920D+5, 8.6400D+4, 4.3200D+4, 7.2000D+3, 1.0000D+0
1.0000D+0, 1.0000D+0, 1.0000D+0, 1.0000D+0, 1.0000D+0
Number of Source Regions; 'N' for nodes, 'Z' for depths.
02 'Z'
INITIAL DISTRIBUTION AND SOURCES
00 0.00D0 2.38D4 1.30D-18, 0.00D+00
01 6.25D2 11.25D2 1.30D-18, 1.40D-18
02 13.75D2 18.75D2 1.30D-18, 5.04D-20

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