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RPOUT

A Computer Code for Calculating the Steady State Vertical Distribution of Radon Progeny Outdoors

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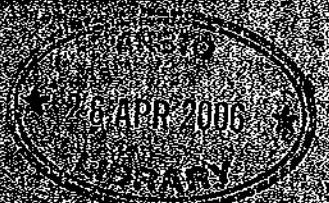

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ABSTRACT

RPOUT is a computer code for calculating the steady-state vertical distribution of radon progeny from ground level to one kilometre above the earth's surface. Given turbulent diffusivity, radon concentration, and attachment rate to aerosols, it provides prediction of both attached and unattached progeny. An option exists for including the effect of the earth's electric field. In addition to basic atmospheric science applications, in combination with radon progeny data, the code should be useful for studying dry deposition, a process important to removal of a number of atmospheric pollutants. The code can facilitate health physics estimates of radiation exposure to radon progeny at ground level as a function of meteorological conditions.

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1. INTRODUCTION

This code grew out of a need to analyze data on radon and its progeny at outdoor sites such as the Cape Grim Observatory, Mauna Loa Observatory, the meteorological tower at the Australian Nuclear Science and Technology Organisation, and the campus at New Mexico Institute of Mining and Technology. It became clear that the classic paper in this area, that of Jacobi and Andre (1963), was inadequate to deal with the observations, particularly in the first hundred metres or so above the earth's surface. Jacobi and Andre did not make a distinction between progeny attached to aerosols and progeny unattached to aerosols. Furthermore, since much of their focus was on higher levels in the troposphere, they did not put into their model much detail for dry deposition at the lower boundary of the earth's surface.

The present code is a first step at rectifying some of their omissions. It provides separate treatment of attached and unattached progeny, and makes use of the concept of a small skin layer of stagnant air just above the ground to model more effectively dry deposition. The code should be useful for analyzing outdoor data on radon and its progeny, and understanding those factors important for controlling disequilibrium of radon progeny and the fraction of potential alpha particle energy concentration (PAEC) due to unattached progeny. In addition to the basic atmospheric science studies for which it was originally intended, in conjunction with appropriate data on radon and radon progeny, the code should be useful for investigating dry deposition, a subject of special importance to air pollution. The code should also enable more accurate prediction of lung dose from radon progeny at breathing heights as a function of meteorological conditions, a subject of increasing interest in health physics.

2. GETTING STARTED

RPOUT is a basic language program for calculating the disequilibrium of radon progeny outdoors. It has been tested with Quick Basic and GwBasic using DOS 3.2. A CGA graphics monitor (640 x 200 lines) is required. It can be run directly by starting the executable file RPOUT.EXE or with a BASIC compiler using the source code RPOUT.BAS. The program uses three ASCII input files of 597 entries each. Entries 1 to 201 correspond to a height above the skin layer of 0 to 10 metres in steps of 0.05 m. Entries 202 to 597 correspond to a height of 12.5 to 1000 m in steps of 2.5 m. RADON is the vertical radon distribution in atoms m^{-3}. COTUR is the turbulent diffusion coefficient in units of $m^2 s^{-1}$. MOBIL is the positive small ion drift velocity in units of m/s. Entries are negative for the down direction. MOBIL may be a null set if electric field effects are neglected.

The output files are PO218F, PO218A, PB214F, PB214A, BI214F and BI214A in units of atoms m^{-3}. Each has 597 entries using the same convention as the input files.

The program requests information from the operator. Entries should be in units of metres and seconds. When multiple entries are requested, the number of values entered should be exactly that requested, on one line separated by commas. Many entries have default options that can be obtained by entering a negative number for each entry. Look at the prompting information for the number of entries required on each line and default options. The skin layer depth is the depth of dead air between the ground and turbulent air where molecular diffusion dominates. Molecular diffusion coefficients must be supplied for attached-to-aerosol and unattached-to-aerosol progeny in this zone. Mobility drift velocity fractions refer to the fraction of unattached particles that are charged and subject to the effect of an electric field. They and the zero-gradient boundary condition parameter are trial features that should only be used by the experienced operator. They will normally be set to zero. The attachment rate is the rate at which unattached particles attach to aerosol. It is the product of the aerosol concentration and the attachment coefficient.

The progeny are calculated sequentially with a subprogram using the shooting method (Conte and de Boor, 1972). The essence of the shooting method as used here can be described as follows. We start with a second order differential equation for the concentration C(x) of a radon progeny as a function of height where the lower value for C(0) is known as well as the boundary condition at the highest position x = L. We evaluate the status of the upper boundary condition by a function ER(L), chosen such that when the boundary condition is satisfied ER(L) = 0. Using C(0) and a guess for C'(0), C1'(0), we can integrate the

differential equation using finite differences to obtain an initial value for ER(L), ER1(L). The procedure is to do this twice with two guesses Cl'(0) and C2'(0) and generate an improved value C3'(0) from interpolation:

$$C3'(0) = C1'(0) - ER2(L)*(C2'(0) - C1'(0))/(ER1(L) - ER2(L)).$$

The procedure is repeated using C3'(0) and C2'(0) and so on until a value for ER(L) satisfactorily close to zero is obtained.

The specific upper boundary condition used requires a balance between sink and source terms. When this balance exists the activity concentration of radon will equal that of the total (attached plus unattached) concentration of each progeny. The lower boundary condition (at the bottom of the skin layer) is C(0) = 0 which assumes complete sticking and hence zero concentration of all progeny. The parameter B0 is used for the gradient C'(0) in the skin layer and is varied in the program. After the first two iterations for B0 the program projects an improved value. Often this projection is quite accurate, but the operator must be alert for unreasonable results and be prepared to carry out some trial and error testing. The operator must monitor the reported error after each iteration, the numerical value for the topmost progeny C(597), and the displayed graph to decide when, and if, convergence is satisfactory. Except for zero concentrations at the upper boundary, the reported error is the fractional error for (source terms - sink terms)/(source terms). A typical indication of convergence is a fractional error less than one and a smoothly varying graphical display with no unlikely excursions at the upper heights.

The shooting method is quite sensitive to the parameter B0. Even with the double-precision math used in the program there may not be enough precision to narrow in on convergence. However, the accuracy of the calculation is good up to mid-height, 215 m by default, and iterations on B0 give good values of both B0 and the progeny up to mid-height. The parameter TWEAK is employed as a fine tune parameter to change slightly the mid-height gradient. It is used if convergence is not satisfactory with B0 alone. If TWEAK is 1, the gradient is increased by one part in 10^6. The calculation proceeds by taking the mid-height value as the starting point and iterating on the mid-height gradient until the upper boundary condition is satisfied. In test problems the changes required in the mid-height gradient from the value calculated using B0 have been very small, less than 0.02%. This confirms that TWEAK serves simply as a device to overcome the inadequacy of the precision of the calculation and does not distort the resulting progeny distribution. TWEAK can take positive or negative values, unlike B0 which must be positive or zero to have physical significance. If selected, TWEAK requires several iterations and is varied in the same fashion as B0 with the computer providing prompting and suggestions.

After all progeny are calculated the result can be observed using the display option. This shows steady-state activity concentration versus height on a linear scale that changes range at 10 m (the portion left of the displayed vertical line is 0 to 10 m; the portion right of the vertical line is 10 to 1000 m). Since the final display breaks the convention used elsewhere and shows concentrations in Bq m^{-3} at the top boundary (right side of the display) the sum of the concentrations for the attached and unattached of each progeny should equal the radon concentration. This equality provides another important indication that the calculations have converged properly.

This manual contains a sample output using the default parameters and representative arrays for RADON, COTUR, and MOBIL (stored on backup files as RADONNT, COTURBNT, and MOBIL1). Replication of this output provides practice and an introduction to the program.

Several utility programs are available as samples of how to generate input arrays. GENRAD.BAS, GENTUR.BAS, and GENMOB.BAS generate arrays for radon, turbulent diffusion, and mobility drift velocity respectively. By simply changing the function defined in line 15 of these programs new arrays can be generated. The program FVALUE.BAS calculates "F value" (progeny disequilibrium parameter) and the fraction of total Potential Alpha Energy Concentration coming from unattached progeny. This utility should be particularly useful for health physics applications where it is desired to estimate exposure to progeny in PAEC from measured radon concentrations.

3. THE MODEL

The model assumes that the outdoor vertical radon and turbulent diffusion distributions are known and calculates the steady-state vertical concentration of the three major radon progeny in both the attached-to-aerosol and unattached-to-aerosol states. The model assumes two layers of air, a thick layer dominated by turbulent diffusion over a thin "skin" layer where only molecular diffusion (strictly speaking, single-particle kinetic diffusion) is important. In the turbulent layer the program assumes transport governed by the following equations:

$$\lambda_0 C_0 + \frac{\partial}{\partial z}\left(K(z)\frac{\partial C_{1f}}{\partial z}\right) - \lambda_1 C_{1f} - \frac{\partial}{\partial z}(v(z)C_{1f}) - XC_{1f} = 0 \quad (1)$$

$$XC_{1f} + \frac{\partial}{\partial z}\left(K(z)\frac{\partial C_{1a}}{\partial z}\right) - \lambda_1 C_{1a} = 0 \quad (2)$$

$$\lambda_1 C_{1f} + \frac{\partial}{\partial z}\left(K(z)\frac{\partial C_{2f}}{\partial z}\right) - \lambda_2 C_{2f} + R\lambda_1 C_{1a} - \frac{\partial}{\partial z}(v(z)C_{2f}) - XC_{2f} = 0 \quad (3)$$

$$(1-R)\lambda_1 C_{1a} + XC_{2f} + \frac{\partial}{\partial z}\left(K(z)\frac{\partial C_{2a}}{\partial z}\right) - \lambda_2 C_{2a} = 0 \quad (4)$$

$$\lambda_2 C_{2f} + \frac{\partial}{\partial z}\left(K(z)\frac{\partial C_{3f}}{\partial z}\right) - \lambda_3 C_{3f} - \frac{\partial}{\partial z}(v(z)C_{3f}) - XC_{3f} = 0 \quad (5)$$

$$\lambda_2 C_{2a} + XC_{3f} + \frac{\partial}{\partial z}\left(K(z)\frac{\partial C_{3a}}{\partial z}\right) - \lambda_3 C_{3a} = 0 \quad (6)$$

where

C_0 is the atomic radon concentration,

C_{1f}, C_{2f}, C_{3f} are the free (unattached) atomic concentrations of ^{218}Po, ^{214}Pb and ^{214}Bi,

C_{1a}, C_{2a}, C_{3a} are the free attached atomic concentrations of ^{218}Po, ^{214}Pb and ^{214}Bi,

λ_0, λ_1, λ_2, λ_3 are the decay constants for ^{222}Rn, ^{218}Po, ^{214}Pb and ^{214}Bi,

K(z) is the turbulent diffusion coefficient,

X = const. is the attachment rate,

v(z) is the drift velocity for positive unattached ions in the earth's electric field, and

R = const. is the recoil detachment probability, the fraction of alpha particle decays of attached ^{218}Po resulting in unattached ^{214}Pb.

Background on this classification of radon progeny as attached and unattached particles, or modelling the influence of aerosols, can be found in Porstendorfer *et al.* (1978). The above equations result from inserting attachment, decay, and recoil as appropriate sink or source terms in the basic equation of the "K diffusion model" (Nieuwstadt and van Dop, 1982, page 295) for each progeny. For example, in equation (1) decay of the parent radon is the source term while decay of free Polonium and attachment of it to aerosol are the sinks.

Normally only a small fraction of the unattached particles is charged. To allow for this and other contingencies, before final calculation the program multiplies the drift velocity V(I) (as stored in the file MOBIL) by a constant called the "mobility fraction coefficient". If used to correct for partial charging, this constant is set to the fraction of the unattached progeny that is charged (a value between zero and one). This is a quite approximate procedure to compensate for partial charging and should only be used with caution. Alternatively, the constant can be used to multiply the drift velocity array by a constant value without need to rewrite the file MOBIL. Before striking and sticking to the ground, the progeny are assumed to pass through a thin "skin" layer of dead air of thickness Z0. Decay and attachment in this layer are neglected since the passage time should be short. Thus the concentration in this layer for each progeny will be described by $C_i(z) = B0_i * z$ where $B0_i$ is the gradient that is

determined from the boundary conditions. Molecular diffusion is assumed present in this layer with potentially different values for the unattached particles (KSF) and attached particles (KSA). The boundary conditions relating this skin layer to the turbulent layer above are continuity of concentration and diffusive atomic flux at z=Z0. It is possible to change this boundary condition with the parameter FF (normally 0) but this is an advanced feature that only should be used in special situations. The remaining boundary condition is the one at the top of the turbulent layer where balance between sink and source terms is assumed for each progeny. This forces the total (attached plus unattached) activity concentration of each progeny to be the same, and equal to that of radon.

4. A SAMPLE CALCULATION

Figure 1 shows the result of a sample calculation. The electric field effects were assumed negligible so the file MOBIL can be a null set. The radon distribution was:

$$C_0(z) = \frac{3.5x10^9}{1000 + 2z} \quad atoms*m^{-3} \qquad (7)$$

The turbulent diffusion coefficient was generated from:

$$K(z) = 0.01 + 0.01z \quad m^2 s^{-1} \qquad (8)$$

The files RADONNT and COTURBNT contain these arrays ready to copy to RADON and COTUR, or they can be generated using equations (7) and (8). Entries 1 to 201 are in steps of 0.05m while entries 202 to 597 are in steps of 2.5m. Hence, entry 1 is at 0m, entry 2 is at 0.05, entry 201 is at 10m, entry 202 is at 12.5m, and entry 597 is at 1000m.

The following values are the default options in the program which were used for the remaining parameters:

skin depth, Z0	$1x10^{-3}$ m
free particle diffusion coefficient, KSF	$1x10^{-5}$ m^2 s^{-1}
attached particle diffusion coefficient, KSA	$1x10^{-7}$ m^2 s^{-1}
aerosol attachment rate, X1	$2x10^{-3}$ s^{-1}
mobility drift velocity fractions, VA,VB,VC	0,0,0, and
zero-gradient boundary parameter, FF	0

The attachment rate corresponds to an aerosol concentration of 10^9 m^{-3} assuming an attachment coefficient of $2x10^{-12}$ m^3 s^{-1}. The program must iterate the calculation twice for a given parameter before it can suggest a meaningful improved value. Particularly for the first progeny ^{218}Po it is necessary to use the fine tune parameter TWEAK. Typical parameter results after iteration for PO218F are B0 = 614085.7595409638 and TWEAK = -0.4006824087112281, resulting in a fractional error of $-3.65x10^{-6}$. Although at the numeric level of the file entries there can be small differences in results due to operator judgments of conversion, at the visual level of Figure 1 results should agree.

5. VERIFICATION OF PROGRAM ACCURACY

The present code is a preliminary version that has not been subjected to outside review and testing. The following steps have been taken to test the accuracy of the code.

The output has been checked on a qualitative basis to see if calculations are reasonable and follow expected trends. Thus it has been verified that decreasing the attachment rate results in lower concentrations of attached progeny, and a smaller value for the thickness of the skin layer results in lower concentrations of progeny at the bottom of the turbulent layer. The presence of a downward drift velocity results in the expected increase in concentrations of unattached progeny at the lower boundary of the turbulent layer. Increasing the molecular diffusion coefficient in the skin layer has been verified to decrease the progeny concentration at the lower boundary of the turbulent layer. The requirement that the total (attached plus unattached) activity concentration of each progeny at the top of the turbulent layer match the activity concentration of radon has been verified for a number of calculations.

In addition, the following quantitative comparison has been carried out. Progeny concentrations were calculated for the following conditions:

radon concentration: $C_0(z) = \text{const.} = 2\text{x}10^6$ atoms* m^{-3},

turbulent diffusion coefficient: $K(z) = \text{const.} = 10\ m^2\ s^{-1}$,

skin layer thickness: $Z0 = 1\text{x}10^{-3}$ m,

molecular diffusion coefficients: $KSF=KSA=1\text{x}10^{-5}\ m^2\ s^{-1}$,

attachment rate: $X1 = 0\ s^{-1}$,

mobility drift velocity parameters: VA=VB=VC=FF=0.

For this situation there exists an analytical solution in the turbulent layer for unattached ^{218}Po given by

$$C_{1f}(z) = -54.23e^{-0.01945z} + 1109.3 \text{ atoms* } m^{-1}. \quad (9)$$

The concentration of all attached progeny should be zero because of the zero attachment rate. Figure 2 shows the output of the code. For comparison, the result $\lambda_1 C_{1f}(z)$ using equation (9) is plotted as a dashed line offset two line widths (pixels) to maintain visibility. Within the tolerance of a graphical plot the numerical results for ^{218}Po and the attached progeny agree. All progeny are calculated with the same subprogram so this calculation checks about 80% of the code.

6. PROGRAMMING NOTES

The program calculates Eqs. (1) through (6) sequentially in a subprogram using a generalized finite difference equation:

```
C(I) = -{(A1*A(I-1)+B1*B(I-1))*DX^2+(KIMH(I-1)+.5*V1*V(I-2)*DX)
      *C(I-2)-C(I-1)*(KIMH(I-1)+KIMH(I)+C1*DX^2)}
      /{KIMH(I)-.5*V1*V(I)*DX}                                    (10)
```

where C(I) is the progeny concentration,
K(I) is the array for the turbulent diffusion coefficient,
V(I) is the array for the drift velocity,
A(I) and B(I) are arrays for parent progeny,
A1 and B1 are source term coefficients,
C1 is the sink coefficient,
V1 is the mobility fraction coefficient, and
DX is the step size for the zone of calculation.

Equation (10) requires mid-point values for K which are calculated by quadratic interpolation using

$$KIMH(I) \equiv K(I-\tfrac{1}{2}) = 3*K(I-1)/8 + 3*K(I)/4 - K(I+1)/8 \quad (11)$$

or

$$KIMH(I) = 3*K(I-1)/4 + 3*K(I)/8 - K(I-2)/8 \quad (12)$$

The lower two values of the array C(I) are used to generate the next value then the process is iterated. For non-zero sources the fractional error reported is calculated from:

$$ER1 = 1 - C1*C(597)/\{A1*A(597) + B1*B(597)\} \quad (13)$$

It is difficult to provide a single, simple code that is capable of providing convergent solutions for all contingencies. Therefore it is quite possible that the code may not converge for certain valid entries. However, the operator should first check that mistakes have not been made in the entered parameters. The calculational algorithm is quite sensitive to the arrays, particularly the array K(I) for turbulent diffusion. A single incorrect entry, such as a negative number or moved decimal, can be sufficient to cause failure of the program. Hence the arrays should be carefully checked for valid smoothly-varying entries. Normally the array K(I) should be generated from a well-behaved function; otherwise, smoothing will certainly be required before entry of a set of isolated data values. If it is suspected that there are no entry errors and the parameters are just out of range of the capabilities of the program,

this possibility can be checked by starting with a working set of parameters and systematically changing them towards the desired values. Often the initial choice of parameter may be so extreme that a slightly different value for it may be more physically reasonable in any case.

If the source code is available it is possible to make programming changes to help with valid calculations that do not converge. None of these changes are routine and they ultimately require intimate knowledge of the program and model. It is often easier to accept estimates for your calculation using better behaved parameters. The simplest modification is to terminate the calculation at a height lower than one kilometre. This is done by lowering the value of IMAX in line 64. The value of ILTWEAK, line 68, must always be kept below IMAX. One danger in this approach is that it may not be physically realistic to assume equilibrium between radon and its progeny at this lower elevation. A more drastic modification is to change the step sizes in the calculation. Modification of line 350 is the starting point with compatible modification of input and output statements. Of course, such a major change also necessitates reformatting the input arrays.

7. APPLICATION NOTES

Many models for dry deposition and atmospheric pollution avoid the physical details of the deposition process at the earth's surface by using an empirical deposition velocity referenced to some height such as 2 or 10 m. This technique is not used in the present code since one of the goals was to provide better details of disequilibrium in this very zone. However, the following approximate procedure can be used to extract an equivalent deposition velocity from the code. Suppose a deposition velocity is desired referenced to two metres. Let KAVE be the average of the turbulent diffusion coefficient from the top of the skin layer to 2 m. Let z0 be the thickness of the skin layer and z1 = 2-z0 the thickness of the turbulent layer to 2 m. Then,

$$\frac{1}{u} = \frac{z0}{KS} + \frac{z1}{KAVE} \qquad (14)$$

relates a deposition velocity u at 2 m to the molecular diffusion coefficient KS in the skin layer and the average turbulent diffusion coefficient KAVE.

It is not difficult to use results from the standard literature on atmospheric science and air pollution to provide predictions with the present model as a function of meteorological conditions. The following is a sample procedure. Suppose a prediction for progeny profiles is desired for conditions of neutral stability, moderate wind (say 4 m/s), and a terrain that is an open woodland. Draxler *et al.* (1979) suggest parameters for turbulent diffusion as a function of stability for heights from 2 to 200 m. For simplicity we will reference their results for neutral stability (class D) to the top of the skin layer rather than to two metres and use

$$K(z) = 0.217*(z+2)^{0.920} \quad m^2\ s^{-1} \qquad (15)$$

to generate the array K(I) for all heights. (Lacking specific information for all heights it is necessary to make this type of small adjustment to avoid singularities in the K(I) array.) Table 2 in Sheih *et al.* (1979) suggests grazed open woodland has a roughness parameter of 0.20 m. From Figure 5 of Wesely and Hicks (1977), using this roughness parameter we estimate a deposition velocity of about 0.065 m/s referenced to a height of 2 m. The diffusion coefficient for unattached progeny is fairly constant at about KSF = $1x10^{-5}$ m^2 s^{-1}. Using a value of KAVE of about 0.60 m^2 s^{-1} for 1m from Eq. (15) then gives a skin depth z0 of about $1.2x10^{-4}$ for use in the program. The value of KSA for attached progeny depends on the aerosol size distribution which is often not well known. The work of Porstendorfer *et al.* (1978) on deposition rates implies, in the present context, a value of about KSA = $1x10^{-8}$ m^2 s^{-1} as representative. Aerosol concentration is quite variable so this would normally require local knowledge, measurement of the actual condensation nuclei concentration, or that it be left as a variable. Hoppel *et al.* (1986) recommend an attachment coefficient $2x10^{-12}$ m^3 s^{-1} to convert aerosol concentration to attachment rate. If the object of the calculation is just disequilibrium of radon progeny in the first 100 m above the earth's

surface, results will be fairly insensitive to typical radon profiles and an assumption of constant concentration with height may be sufficient. Otherwise, measurements or local knowledge is required, or results from Liu *et al.* (1984) can be used to provide estimates. Figure 3 shows the result of a calculation with these parameters assuming an attachment rate of 0.02 (aerosol concentration of about 10^{10} m^{-3}) and a constant radon concentration of $2x10^6$ atoms* m^{-3}. The utility program FVALUE gave a value for f (actual PAEC divided by PAEC assuming 100% equilibrium with radon) of 0.96 at 1 m and the fraction of total PAEC due to unattached progeny of 0.017 for the same height.

It may be of interest to calculate the effect of an outdoor electric field on the deposition of radon progeny. The reference by Hoppel *et al.* (1986) is useful for providing background data. Unfortunately, this is a very complicated problem that has not been fully resolved in the research literature, much less in a code for routine calculations. A rigorous treatment requires dividing the unattached progeny into groups of charged and uncharged particles and then adding an additional series of neutralization coefficients, etc. Even less clear is how to treat the boundary condition at the earth's surface. Pure diffusion and 100% sticking require a zero concentration boundary condition while drift dominated deposition (think about raindrops!) might require a zero gradient boundary condition. One figure of merit for the extent to which conditions are diffusion or drift dominated is

$$\beta = \frac{v_{drift}}{\sqrt{(\lambda * KAVE)}} \quad . \tag{16}$$

A value for β much less (much greater) than one is an indication of diffusion (drift) dominated transport.

In light of the above it should be clear that there is considerable uncertainty at present in using the code to estimate the effects of the electric field. Only a few suggestions can be made. Suppose it is known that the effects of the electric field are weak and constitute only a small perturbation on the diffusion solution. Suppose that all unattached progeny are singly charged (an unlikely scenario) with a drift velocity given in the array V(I). Then setting the mobility fractions to one (VA=VB=VC=1) and the zero gradient condition to zero (FF=0) should reasonably model the situation, particularly away from the top and bottom boundaries. For the more likely situation of only partial-charged unattached progeny and stronger drift conditions, the mobility fractions can be decreased (to a minimum of zero) and the zero-gradient parameter increased (to a maximum of one) in an increasingly more approximate attempt to model the situation. For strong drift conditions one line of reasoning suggests putting the zero-gradient parameter at the average of the mobility fractions.

8. BIBLIOGRAPHY AND REFERENCES

This code was developed independently and there exists no single reference that adequately describes the model. The following references should provide additional background useful for better understanding the model.

Cohen, L.D., S. Barr, R. Krablin and H. Newstwin, 1972, Steady-State Vertical Turbulent Diffusion of Radon, J. of Geophys. Res. 77, 2654-2668.

Gives some ideas for the turbulent diffusion coefficient for radon near the earth's surface.

Conte, S.D. and C. de Boor, 1972, *Elementary Numerical Analysis*, McGraw-Hill Kogakusha Ltd., Tokyo.

The numerical methods and programming used in this code were home spun by a person with training in physics. Nevertheless, this reference should provide some rationale for some of the techniques employed such as the shooting method.

Chang, J.S., R.A. Brost, I.S.A. Isaksen, S. Madronich, P. Middleton, W.R. Stockwell and C.J. Walcek, 1987. A three-Dimensional Eulerian Acid Deposition Model: Physical Concepts and Formulation, J. of Geophys. Res. 92, 14681-14700.

A "state of the art" powerful atmospheric model much wider ranging than the present code. Because of its breadth it may not concentrate sufficiently on specific physical issues important for radon progeny, but is very useful for inspiration. Uses only deposition velocities at the lower boundary.

Draxler, R.R., 1979, Estimating Vertical Diffusion from Routine Meteorological Tower Measurements, Atmos. Environ. 13, 1559-1564.

Provides a formula and parameters useful for generating the turbulent diffusion coefficient as a function of stability.

Hoppel, W.A., R.V. Anderson and J.C. Willett, 1986, Atmospheric Electricity in the Planetary Boundary Layer, in *The Earth's Electrical Environment*, Chapt. 11, National Academy Press, Washington, D.C.

Indispensible information on ions, attachment rates, and the earth's electric field used in developing the code.

Jacobi, J. and K. Andre, 1963, The Vertical Distribution of Radon 222, Radon 220 and their Decay Products in the Atmosphere, J. of Geophys. Res. 68, 3799-3813

Highlights the physical problem addressed by this code and early efforts to model it.

Liu, S.C., J.R. McAfee and R.J. Cicerone, 1984, Radon 222 and Tropospheric Vertical Transport, J. of Geophy. Res. 89, 7291-7297.

Synthesizes much of the data on vertical profiles of radon over the continents. Concentrates on greater heights than is the object of the present code.

McMurry, P.H. and D.J. Rader, 1985, Aerosol Wall Losses in Electrically Charged Chambers, Aerosol. Sci. Tech. 4249-4268.

Should provide an entré into the theory of particle deposition in the aerosol journals.

Nieuwstadt, F.T.M. and H. van Dop, eds, 1982, *Atmospheric Turbulence and Air Pollution Modelling* D. Reidel Pub., Holland.

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Porstendorfer, J., A. Wicke and A. Schraub, 1978, The Influence of Exhalation, Ventilation and Deposition Processes upon the Concentration of Radon (^{222}Ra), Thoron (^{220}Tn) and their Decay Products in Room Air, Health Phys. 34, 465-473.

Provides insight into modelling attached and unattached progeny but in the context of the indoor atmosphere.

Sheih, C.M., M.L. Wesely and B.B. Hicks, 1979, Estimated Dry Deposition Velocities of Sulfur over the Eastern United States and Surrounding Regions, Atmospheric Environment 13, 1361-1368.

The table on roughness parameters could be useful.

Wesely, M.L. and B.B. Hicks, 1977, Some Factors that Affect the Deposition Rates of Sulfur Dioxide and Similar Gases on Vegetation, J. of the Air Pollution Control Association 27, 1110-1116.

Provides valuable information for modelling dry deposition as a function of wind, roughness and stability at the earth's surface.

9. ACKNOWLEDGEMENTS

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APPENDIX

Source code for RPOUT

and

Utility Programs

GENMOB
GENRAD
GENTUR
FVALUE

```
10 REM DRY AND ELECTRIC DEPOSITION SKIN/SURFACE VER 30.07.90A
20 REM UNITS METERS,SECONDS                    9
30 REM IN ARRAYS I=1,2,201,202,597 ARE 0M,.05M,10M,12.5M,1000M
40 DEFDBL A-Z
50 DEFINT I-J
60 DIM C(597),A(597),B(597),V(597),K(597),KIMH(597)
62 REM 350< IMAX <=597 MAXIMUM ARRAY INDEX (HEIGHT) IN CALCULATION
[RECO. 597]
64 IMAX=597
66 REM 202 < ILTWEAK < IMAX  ARRACY POSITION OF TWEAK [ RECO. 300]
68 ILTWEAK = 300
70 CLS
80 PRINT "                  'RPOUT'"
90 PRINT "     PROGRAM TO CALCULATE RADON PROGENY PROFILES OUTDOORS "
100 PRINT "               VERSION 30.07.90A "
110 PRINT "INPUT 0 FOR MORE INFORMATION,  NEGATIVE TO CONTINUE,"
115 PRINT "1 FOR DISPLAY SUBPROGRAM"
120 INPUT IQ
130 IF IQ<0 GOTO 320
135 IF IQ=1 GOTO 5000
140 CLS
150 PRINT "THIS PROGRAM REQUIRES THREE INPUT FILES"
160 PRINT " 'RADON' IS THE VERTICAL RADON DISTRIBUTION IN ATOMS/M^3"
170 PRINT "'COTUR' IS THE TURBULENT DIFFUSION COEF. DISTRIBUTION IN M^2/S"
180 PRINT "'MOBIL' IS THE POSITIVE ION VELOCITY DIST. IN M/S, MINUS FOR DOWN"
190 PRINT "EACH FILE IS ASCII WITH 597 ENTRIES. ENTRIES 1 TO 201 CORRESPOND"
200 PRINT "TO A HEIGHT FROM ZERO TO 10 METERS ABOVE THE SKIN LAYER IN"
210 PRINT "STEPS OF .05M.  ENTRIES 202 TO 597 CORRESPOND TO 12.5 TO 1000M "
220 PRINT "IN STEPS OF 2.5M.  NATURE AND THIS PROGRAM LIKE SMOOTHLY
VARYING"
230 PRINT "FUNCTIONS. 'MOBIL' CAN BE A NULL SET IF CHARGE-EFFECTS
NEGLECTED"
240 PRINT "HEIGHTS ARE REFERENCED FROM THE TOP OF THE SKIN LAYER"
250 PRINT " THERE ARE SIX OUTPUT FILES OF 597 ENTRIES: PO218F,PO218A,PB214F"
260 PRINT "PB214A,BI214F,BI214A IN UNITS ATOMS/M^3(FINAL DISPLAY IN BQ/M^3)"
262 PRINT
264 PRINT"ATTACHMENT RATE IS (ATTACHMENT COEFFICIENT) * (AEROSOL
CONCEN.)"
266 PRINT "FOR EXAMPLE  2E-12 M^3/S  * 1E9 M^-3 = 2E-3 S^-1"
268 PRINT "DEPOSITION VELOCITY = (SKIN LAYER DIFF. COEF.)/(SKIN DEPTH) IF"
269 PRINT "  YOU WISH TO RELATE PRESENT PARAMETERS TO DEPOSITION
VELOCITY"
273 PRINT "THE ZER0-GRADIENT BOUNDARY CONDITION IS NORMALLY ZERO "
274 PRINT
275 PRINT " CARRIAGE RETURN TO CONTINUE"
280 INPUT IQ
290 REM
300 REM
310 REM
320 REM READ DEFAULT DECAY CONSTANTS, ATTACHMENT, DRIFT
COEFFS.,BOUNDARY COND.
330 READ LL0,LL1,LL2,LL3,X1,VA,VB,VC,FF
340 DATA 2.1E-6,3.786E-3,4.310E-4,5.863E-4, 2E-3,0.,0.,0.,0.
345 REM STEP SIZE1, STEP SIZE2, RECOIL COEFF.
```

```
350 READ DX,  DX2,  RC
360 DATA  .05,  2.5,  0.5
370 REM B0 IS GRADIENT PARAMETER IN SKIN ZONE IN ATOMS/M^4
380 REM READ DEFAULT SKIN DEPTH, DIFF. COEF. FREE.,DIFF. COEF. ATTACH., B0
390 READ Z0,KSF,KSA,B0
400 DATA 1.E-3,1E-5,1E-7,100000.
410 PRINT "UNLESS OTHERWISE INDICATED A SEPARATE MINUS ENTRY FOR EACH
DEFAULT"
420 PRINT
430 PRINT "SKIN LAYER DEPTH (DEFAULT [1E-3] METER)"
440 PRINT "Z0 "
450 INPUT Z0T
460 IF Z0T >= 0 THEN Z0=Z0T
470 PRINT
480 PRINT "DIFF. COEF. FREE,  DIFF. COEF. ATTACH.  (DEFAULT [1E-5,1E-7] M^2/S)"
490 PRINT "KSF, KSA     ( TWO ENTRIES PLEASE!)"
500 INPUT KSFT,KSAT
510 IF KSFT >= 0 THEN KSF=KSFT
520 IF KSAT >= 0 THEN KSA=KSAT
530 PRINT
540 PRINT "MOBILITY FRACTIONS FOR FREE PO218,PB214,BI214 (DEFAULT [0,0,0])"
550 PRINT " VA, VB, VC  "
560 INPUT VAT,VBT,VCT
570 IF VAT >= 0 THEN VA=VAT
580 IF VBT >= 0 THEN VB=VBT
590 IF VCT >= 0 THEN VC=VCT
600 PRINT
610 PRINT "FRACTION OF ZERO-GRADIENT BOUNDARY CONDITION FOR"
620 PRINT "UNATTACHED PARTICLES,  0<=FF<=1,  (DEFAULT [0])"
630 PRINT "FF"
640 INPUT FFT
650 IF FFT>=0 THEN FF=FFT
660 PRINT
670 PRINT "ATTACHMENT RATE  ( (ATTACH COEF.)*CN , DEFAULT [2E-3] S^-1)"
680 PRINT "X1"
690 INPUT X1T
700 IF X1T >= 0 THEN X1=X1T
702 PRINT
703 PRINT "INPUT 3 FOR AUTOMATIC FIRST THREE ITERATIONS (DEFAULT [0])"
704 PRINT "IIT"
706 INPUT IITT
707 IF IITT <>3 THEN IITT=4
708 IF IITT=3 THEN IITT=0
710 REM INIALIZE PO218F CALCULATION
720 OPEN "RADON" FOR INPUT AS #1
730 OPEN "MOBIL" FOR INPUT AS #3
740 OPEN "COTUR" FOR INPUT AS #4
750 FOR I=1 TO 597
760 INPUT #1,A(I)
770 B(I)=0
780 INPUT #3,V(I)
790 INPUT #4,K(I)
800 NEXT I
810 CLOSE #1
```

```
820 CLOSE #3
830 CLOSE #4
835 GOSUB 9000
840 KS=KSF
850 FS=FF
860 REM SOURCE COEFFICIENTS
870 A1=LL0
880 B1 =0
890 REM SINK COEFFICIENTS
900 C1=LL1+X1
910 REM OUTPUT FILE
920 OUTPUT$="PO218F"
930 V1=VA
940 CLS
950 PRINT "START PO218F CALCULATION"
951 PRINT "KS,    V1,    FF,    X1"
952 PRINT USING "##.##^^^^";KS,V1,FS,X1
954 IIT=IITT
960 GOSUB 1960
970 REM INITIALIZE PO218A CALCULATION
980 OPEN "PO218F" FOR INPUT AS #1
990 FOR I =1 TO 597
1000 INPUT #1,A(I)
1010 NEXT I
1020 CLOSE #1
1030 KS=KSA
1040 FS=0
1050 A1=X1
1060 B1=0
1070 C1=LL1
1080 OUTPUT$="PO218A"
1090 V1=0
1100 CLS
1110 PRINT "START PO218A CALCULATION"
1111 PRINT "KS,    V1,    FF,    X1"
1112 PRINT USING "##.##^^^^";KS,V1,FS,X1
1114 IIT=IITT
1120 GOSUB 1960
1130 REM INITIALIZE PB214F CALCULATION
1140 OPEN "PO218F" FOR INPUT AS #1
1150 OPEN "PO218A" FOR INPUT AS #2
1160 FOR I = 1 TO 597
1170 INPUT #1,A(I)
1180 INPUT #2,B(I)
1190 NEXT I
1200 CLOSE #1
1210 CLOSE #2
1220 KS=KSF
1230 FS=FF
1240 A1=LL1
1250 B1=LL1*RC
1260 C1=LL2+X1
1270 OUTPUT$="PB214F"
1280 V1=VB
```

```
1290 CLS
1300 PRINT "START PB214F CALCULATION"
1301 PRINT "KS,    V1,    FF,    X1,    RC"
1302 PRINT USING "##.##^^^^";KS,V1,FS,X1,RC
1304 IIT = IITT
1310 GOSUB 1960
1320 REM INITIALIZE PB214A CALCULATION
1330 OPEN "PO218A" FOR INPUT AS #1
1340 OPEN "PB214F" FOR INPUT AS #2
1350 FOR I= 1 TO 597
1360 INPUT #1,A(I)
1370 INPUT #2,B(I)
1380 NEXT I
1390 CLOSE #1
1400 CLOSE #2
1410 KS=KSA
1420 FS=0
1430 A1=LL1*RC
1440 B1=X1
1450 C1=LL2
1460 OUTPUT$="PB214A"
1470 V1=0
1480 CLS
1490 PRINT "START PB214A CALCULATION"
1491 PRINT "KS,    V1,    FF,    X1,    RC"
1492 PRINT USING "##.##^^^^";KS,V1,FS,X1,RC
1494 IIT=IITT
1500 GOSUB 1960
1510 REM INITIALIZE BI214F CALCULATION
1520 OPEN "PB214F" FOR INPUT AS #1
1530 FOR I = 1 TO 597
1540 INPUT #1, A(I)
1550 NEXT I
1560 CLOSE #1
1570 KS=KSF
1580 FS=FF
1590 A1=LL2
1600 B1=0
1610 C1=LL3+X1
1620 OUTPUT$="BI214F"
1630 V1=VC
1640 CLS
1650 PRINT "START BI214F CALCULATION"
1651 PRINT "KS,    V1,    FF,    X1"
1652 PRINT USING "##.##^^^^";KS,V1,FS,X1
1654 IIT=IITT
1660 GOSUB 1960
1670 REM INITIALIZE BI214A CALCULATION
1680 OPEN "PB214A" FOR INPUT AS #1
1690 OPEN "BI214F" FOR INPUT AS #2
1700 FOR I = 1 TO 597
1710 INPUT #1, A(I)
1720 INPUT #2, B(I)
1730 NEXT I
```

```
1740 CLOSE #1
1750 CLOSE #2
1760 KS =KSA
1770 FS=0
1780 A1=LL2
1790 B1 = X1
1800 C1 = LL3
1810 OUTPUT$ = "BI214A"
1820 V1 = 0
1830 CLS
1840 PRINT "START BI214A CALCULATION"
1841 PRINT "KS,    V1,    FF,    X1"
1842 PRINT USING "##.##^^^^";KS,V1,FS,X1
1844 IIT=IITT
1850 GOSUB 1960
1855 CLS
1860 PRINT
1870 PRINT "INPUT -1 TO DISPLAY RESULTS (NEEDS CGA 640x200 LINES),"
1880 PRINT "0 TO STOP, 1 TO START OVER, 2 TO HARDCOPY PARAMETERS"
1890 PRINT "ICOUNT"
1900 INPUT  ICOUNT
1905 IF ICOUNT = 2 THEN GOSUB 8000
1910 IF ICOUNT = 0 THEN STOP
1915 RESTORE
1920 IF ICOUNT = 1 GOTO 10
1930 IF ICOUNT < 0 THEN GOSUB 5000
1940 GOTO 1855
1950 END
1955 REM************************************************************************
1956 REM
1960 REM SUBPROGRAM FOR SHOOTING SOLUTION
1965 TB=10000!
1970 B0=100000!
1980 ER0=0
1990 TWEAK=0
2000 TTWEAK=.01
2002 B0=-1
2004 IF IIT=0 THEN GOTO 2050
2010 PRINT
2020 PRINT " GUESS FOR INITIAL GRADIENT PARAMETER B0 (DEFAULT [100000]) "
2030 PRINT " B0 "
2040 INPUT B0
2050 IF B0 < 0 THEN B0=100000!
2052 ID=0
2060 CZ1=B0*Z0
2070 X=0
2080 CP=KS*B0/K(1)
2090 CZ2=CP*DX+CZ1
2100 REM EXPERIMENTAL BOUNDARY CONDITION FOR MOBILITY USING FS
2110 CZ2=CZ2*(1-FS)+FS*CZ1
2120 C(1)=CZ1
2130 C(2)=CZ2
2140 FOR I=3 TO 201
2150 REM X VALUE FOR CURRENT C(I)
```

```
2160 X=(I-1)*DX
2170 C(I)=(A1*A(I-1)+B1*B(I-1))*DX^2+(KIMH(I-1)+.5*V1*V(I-2)*DX)*CZ1
2175 C(I)=C(I)-CZ2*(KIMH(I)+KIMH(I-1)+C1*DX^2)
2180 C(I)=-C(I)/(KIMH(I)-.5*V1*V(I)*DX)
2185 IF ABS(C(I))>1E37 THEN GOSUB 7000
2190 CZ1=CZ2
2200 CZ2=C(I)
2210 NEXT I
2220 CZ1=C(201)
2230 CZ2=C(201)+(C(201)-C(200))*DX2/DX
2240 CZ2=CZ2
2250 C(202)=CZ2
2260 FOR I=203 TO IMAX
2270 X=200*DX +(I-201)*DX2
2280 C(I)=(A1*A(I-1)+B1*B(I-1))*DX2^2+(KIMH(I-1)+.5*V1*V(I-2)*DX2)*CZ1
2285 C(I)=C(I)-CZ2*(KIMH(I)+KIMH(I-1)+C1*DX2^2)
2290 C(I)=-C(I)/(KIMH(I)-.5*V1*V(I)*DX2)
2295 IF ABS(C(I))>1E37 THEN GOSUB 7000
2300 CZ1=CZ2
2310 CZ2=C(I)
2320 REM MAKE SMALL PERTURBATION ON SOLUTION MID STREAM TO
COMPENSATE
2330 REM FOR LACK OF NUMERICAL PRECISION  THIS IS TWEAK PARAMETER
2340 IF I=ILTWEAK GOTO 2920
2350 REM CONTINUE
2360 NEXT I
2370 CMA=Z0*B0
2400 ER1=(A1*A(IMAX)+B1*B(IMAX))-C1*C(IMAX)
2405 DENOM=A1*A(IMAX)+B1*B(IMAX)
2407 IF DENOM = 0 THEN DENOM = 1.
2410 ER1=ER1/DENOM
2420 IF (ER0-ER1)= 0! THEN GOTO 2460
2430 BSUG=  B0-ER1*(TB-B0)/(ER0-ER1)
2440 TSUG=  TWEAK-ER1*(TTWEAK-TWEAK)/(ER0-ER1)
2460 ER0=ER1
2470 CMA=Z0*B0
2480 CLS
2490 SCREEN 2
2495 IF C(300)=0 THEN C(300)=.001
2500 YY=CMAX/C(300)*400
2510 PRINT OUTPUT$, "          C(1) ",CMA
2515 PRINT "IMAX",IMAX,"C(IMAX)",C(IMAX)
2520 PSET (11,YY)
2530 PSET (12,YY)
2540 FOR I= 1 TO 200
2550 PSET (201+12,I)
2560 NEXT I
2570 FOR I = 1 TO IMAX
2580 Y=C(I)/C(300)*100
2590 IF Y <0 GOTO 2620
2600 IF Y >200 GOTO 2620
2610 PSET (I+12,Y)
2620 NEXT I
2630 PRINT "B0",B0
```

```
2640 PRINT "FRACTIONAL ERROR",ER1
2650 IF TB=B0 GOTO 2670
2655 IF BSUG <0 THEN BSUG = 0
2670 TB=B0
2671 REM IIT=0 FOR AUTOMATIC  THREE ITERATIONS
2672 IIT =IIT +1
2673 IF IIT<3 THEN PRINT "ITERATING AUTOMATICALLY "
2674 IF IIT<3 GOTO 2695
2675 PRINT "SUGGESTED B0",BSUG
2680 PRINT "IMPROVED B0  (NEGATIVE TO ACCEPT SUGGESTION, POSITIVE YOUR
VALUE,"
2690 PRINT "            ZERO  NEXT PROGENY OR TWEAK FOR FINE TUNING)"
2695 IF IIT < 3 THEN B0T =-1
2697 IF IIT < 3 THEN GOTO 2710
2700 INPUT "            ", B0T
2710 IF B0T > 0! THEN B0=B0T
2720 IF B0T < 0! THEN B0=BSUG
2730 IF B0T = 0! GOTO 2750
2740 GOTO 2050
2750 PRINT
2755 PRINT "TWEAK FINE TUNES CALCUALTION"
2760 PRINT "PRESENT VALUE TWEAK = ",TWEAK
2765 IF ID=0 THEN TSUG=1.
2770 PRINT "SUGGESTED VALUE TWEAK =",TSUG
2775 PRINT
2780 PRINT "ENTER 0 TO SAVE THIS RESULT AND START NEXT PROGENY"
2795 PRINT "ENTER <0 TO USE SUGGESTED TWEAK (REQUIRES ITERATION)"
2800 PRINT "ENTER >0 TO ENTER YOUR OWN TWEAK VAUE"
2810 TTWEAK = TWEAK
2820 PRINT "YOUR DECISION?"
2830 INPUT TTT
2832 IF TTT<0 THEN TWEAK=TSUG
2834 IF TTT=0 GOTO 2860
2836 IF TTT<0 GOTO 2845
2838 PRINT "YOUR TWEAK? (-200 <TWEAK< 200)"
2840 INPUT TWEAK
2845 ID=1
2850 GOTO 2060
2860 OPEN OUTPUT$ FOR OUTPUT AS #4
2870 FOR I=1 TO 597
2880 WRITE #4,C(I)
2890 NEXT I
2900 CLOSE #4
2910 RETURN
2920 CZ2=CZ2*(1!+.000001*TWEAK)
2930 GOTO 2350
5000 REM  ************************************************************
5005 REM DISPLAY SUBPROGRAM
5006 PRINT "USE [PRINT SCREEN], IF AVAILABLE, TO PRINT DISPLAY GRAPH"
5007 PRINT "USE [SPACEBAR] TO TERMINATE DISPLAY GRAPH"
5009 REM DISPLAY DELAY
5010 FOR I = 1 TO 1000
5011 ABCD=COS(2)
```

```
5012 NEXT I
5015 OPEN "RADON" FOR INPUT AS #1
5020 INPUT #1, SCALE
5030 CLOSE #1
5040 SCALE = SCALE*.0000021/170
5050 OPEN "RADON" FOR INPUT AS #1
5060 OPEN "PO218F" FOR INPUT AS #2
5070 OPEN "PO218A" FOR INPUT AS #3
5080 OPEN "PB214F" FOR INPUT AS #4
5090 OPEN "PB214A" FOR INPUT AS #5
5100 OPEN "BI214F" FOR INPUT AS #6
5110 OPEN "BI214A" FOR INPUT AS #7
5120 CLS
5130 SCREEN 2
5140 FOR I=1 TO IMAX
5150 X=I
5160 INPUT #1,R
5170 R=R*.0000021
5180 REM print r
5190 RS=R/SCALE
5200 INPUT #2,A
5210 A=A*.00378
5220 AX=A/SCALE
5230 INPUT #3,B
5240 B=B*.00378
5250 BS=B/SCALE
5260 INPUT #4,C
5270 C=C*.000431
5280 CS=C/SCALE
5290 INPUT #5,F
5300 F=F*.000431
5310 FS=F/SCALE
5320 INPUT #6,G
5330 G=G*.000586
5340 GS=G/SCALE
5350 INPUT #7,H
5360 H=H*.000586
5370 HS=H/SCALE
5380 IF ( I/10! -INT(I/10)) = 0 GOTO 5460
5390 IF ((I-1)/10! -INT((I-1)/10)) = 0 GOTO 5460
5400 IF ((I-2)/10! -INT((I-2)/10)) = 0 GOTO 5460
5410 IF ((I-3)/10!-INT((I-3)/10))  =0  GOTO  5460
5420 IF ((I-4)/10!-INT((I-4)/10)) = 0 GOTO 5460
5430 PSET (X,BS)
5440 PSET (X,FS)
5450 PSET (X,HS)
5460 PSET (X,RS)
5470 PSET (X,RS+1)
5480 PSET (X,AX)
5490 PSET (X,CS)
5500 PSET (X,GS)
5510 IF I = 100 GOTO 5530
5520 GOTO 5600
5530 MRN=RS*25/200
```

```
5540 MPOF=AX*25/200
5550 MPOA=BS*25/200
5560 MPBF=CS*25/200
5570 MPBA=FS*25/200
5580 MBIF=GS*25/200
5590 MBIA=HS*25/200
5600 REM PRINT X,RS,AX,BS
5610 NEXT I
5620 CLOSE #1
5630 CLOSE #2
5640 CLOSE #3
5650 CLOSE #4
5660 CLOSE #5
5670 CLOSE #6
5680 CLOSE #7
5690 FOR I = 1 TO 640
5700 PSET (I,0)
5710 NEXT I
5720 FOR I= 1 TO 200
5730 PSET (0,I)
5740 NEXT I
5745 IF MRN <1 THEN MRN = 1
5750 LOCATE MRN,10
5760 PRINT "RN"
5765 IF MPOF <1 THEN MPOF = 1
5770 LOCATE MPOF,10
5780 PRINT "PO218F"
5785 IF MPOA <1 THEN MPOA =1
5790 LOCATE MPOA,10
5800 PRINT "PO218A"
5805 IF MPBF <1 THEN MPBF =1
5810 LOCATE MPBF,10
5820 PRINT "PB214F"
5825 IF MPBA <1 THEN MPBA =1
5830 LOCATE MPBA,10
5840 PRINT "PB214A"
5845 IF MBIF < 1 THEN MBIF =1
5850 LOCATE MBIF,10
5860 PRINT "BI214F "
5865 IF MBIA <1 THEN MBIA = 1
5870 LOCATE MBIA,10
5880 PRINT "BI214A"
5890 LOCATE 24.1,17
5900 PRINT "0 TO 10M   10 TO 1000M";
5910 TIC= SCALE*170
5920 LOCATE MRN,69
5930 PRINT "(BQ/M^3)___"
5940 MT=MRN-1
5950 LOCATE MT,68
5960 PRINT USING "##.##^^^^";TIC;
5970 FOR I = 1 TO 199
5980 PSET (201,I)
5990 NEXT I
6000 REM HOLDING LOOP EXIT WITH [SPACEBAR] OR STOP WITH [CTRL BREAK]
```

```
6002 A$=INKEY$
6004 IF A$=" " GOTO 1855
6010 GOTO 6000
6020 STOP
7000 REM SUBPROGRAM ERROR STATEMENT ******************************
7010 IF C(I)<-1E37 THEN C(I)=-1E37
7020 IF C(I)>1E37 THEN C(I)=1E37
7030 FOR II=1 TO 3
7040 PRINT "CAUTION C(I) OUT OF RANGE FOR I="; I;"CHECK INPUT PARAMETERS"
7050 NEXT II
7060 RETURN
8000 REM SUBPROGRAM HARDCOPY INPUT PARAMETERS ********************
8010 LPRINT "SKIN LAYER DEPTH, Z0              ",Z0
8020 LPRINT "DIFFUSION COEFFICIENT FREE, KSF    ",KSF
8030 LPRINT "DIFFUSION COEFFICIENT ATTACHED,KSA  ", KSA
8040 LPRINT "AEROSOL ATTACHMENT RATE, X1        ",X1
8050 LPRINT "MOBILITY DRIFT FRACTIONS; VA,VB,VC  ", VA,VB,VC
8060 LPRINT "FRACTION ZERO GRADIENT, FF         ",FF
8070 LPRINT "TURBULENT COEFFCIENT 0 METER, K(1)  ",K(1)
8080 LPRINT "DRIFT VELOCITY 0 METER, V(1)       ",V(1)
8100 RETURN
9000 REM  SUBPROGRAM QUADRADIC INTERPOLATION FOR KVALUES**********
9005 REM KIMH(I) IS ESTIMATE OF K(I-.5)
9010 FOR I = 2 TO 200
9020 KIMH(I)= 3.*K(I-1)/8. +3.*K(I)/4. -K(I+1)/8.
9030 NEXT I
9040 KIMH(201) = 3.*K(200)/4. +3.*K(201)/8. -K(199)/8.
9050 FOR I=202 TO 596
9060 KIMH(I)= 3.*K(I-1)/8.+3.*K(I)/4. -K(I+1)/8.
9070 NEXT I
9080 KIMH(597)=3.*K(596)/4.+3.*K(597)/8.-K(595)/8.
9090 RETURN
```

UTILITY PROGRAMS

FVALUE.BAS

```
2 DEFINT I
20 OPEN "RADON" FOR INPUT AS #1
30 OPEN "PO218F" FOR INPUT AS #2
40 OPEN "PO218A" FOR INPUT AS #3
50 OPEN "PB214F" FOR INPUT AS #4
60 OPEN "PB214A" FOR INPUT AS #5
62 OPEN "BI214F" FOR INPUT AS #6
64 OPEN "BI214A" FOR INPUT AS #7
70 FOR I=1 TO 597
100 INPUT #1,R
110 R=R*2.1E-6
115 rem print r
130 INPUT #2,A
140 A=A*3.78E-3
160 INPUT #3,B
170 B=B*3.78E-3
185 INPUT #4,C
```

```
187 C=C*4.31E-4
192 INPUT #5,F
194 F=F*4.31E-4
200 INPUT #6,G
204 G=G*5.86E-4
210 INPUT #7,H
214 H=H*5.86E-4
220 FVF=.579*A+2.86*C+2.10*G
225 FVA=.579*B+2.86*F+2.10*H
230 FVALUE= (FVF+FVA)*.178/R
240 UNF=FVF/(FVA+FVF)
242 XA=(I-1)*.05
244 XB=10+(I-201)*2.5
246 X=XA
248 IF I>201 THEN X=XB
250 PRINT X, FVALUE,UNF
280 NEXT I
289 FOR I = 1 TO 597
290 CLOSE #1
300 CLOSE #2
310 CLOSE #3
320 CLOSE #4
330 CLOSE #5
332 CLOSE #6
334 CLOSE #7
586 NEXT I
700 STOP
```

GENMOB.BAS

```
10 OPEN "MOBIL" FOR OUTPUT AS #1
13 REM FNE IS A SAMPLE UNNORMALIZED E-FIELD
15 DEF FNE(Z)=.5*(1+EXP(-Z/30))
20 FOR I = 1 TO 201
30 Z=(I-1)*.05
40 EFIELD= -100*FNE(Z)
45 REM MOB IS THE MOBILITY ((M/S)/(V/M))
46 MOB=.0001
47 REM V IS DRIFT VELOCITY DUE TO E-FIELD
48 V=EFIELD*MOB
50 WRITE #1,V
55 PRINT V
60 NEXT I
70 FOR I = 202 TO 597
80 Z = 10. +(I-201)*2.5
90 EFIELD = -100*FNE(Z)
92 V=EFIELD*MOB
93 WRITE #1,V
95 PRINT V
100 NEXT I
110 CLOSE #1
```

GENRAD.BAS

```
10 OPEN "RADON" FOR OUTPUT AS #1
15 DEF FNR(Z) = 1000*3.5E6/(1000+2*Z)
20 FOR I = 1 TO 201
30 Z=(I-1)*.05
40 R=FNR(Z)
50 WRITE #1,R
55 PRINT R
60 NEXT I
70 FOR I = 202 TO 597
80 Z = 10. +(I-201)*2.5
90 R=FNR(Z)
93 WRITE #1,R
95 PRINT R
100 NEXT I
110 CLOSE #1
```

GENTUR.BAS

```
10 OPEN "COTURE" FOR OUTPUT AS #1
15 DEF FNK(Z)=.204*(2.+Z)^0.695
20 FOR I =1 TO 201
30 Z=(I-1)*.05
40 K=FNK(Z)
50 WRITE #1,K
55 PRINT K
60 NEXT I
70 FOR I = 202 TO 597
80 Z = 10. +(I-201)*2.5
90 K=FNK(Z)
92 REM IF Z >=200 THEN K=FNK(200)
93 WRITE #1,K
95 PRINT K
100 NEXT I
110 CLOSE #1
```

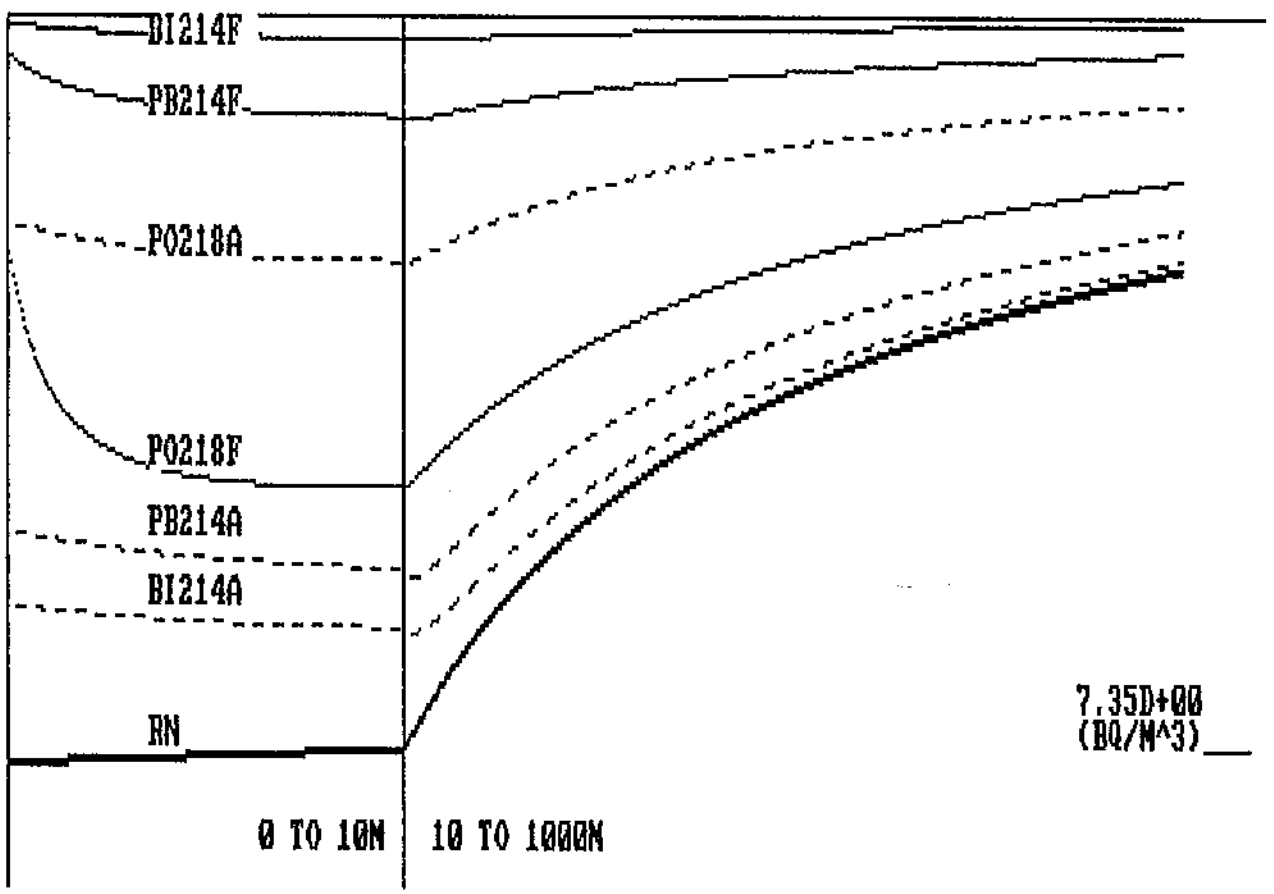

Figure 1: A sample calculation using the default parameters, RADONNT, COTURNT and a null array for MOBIL.

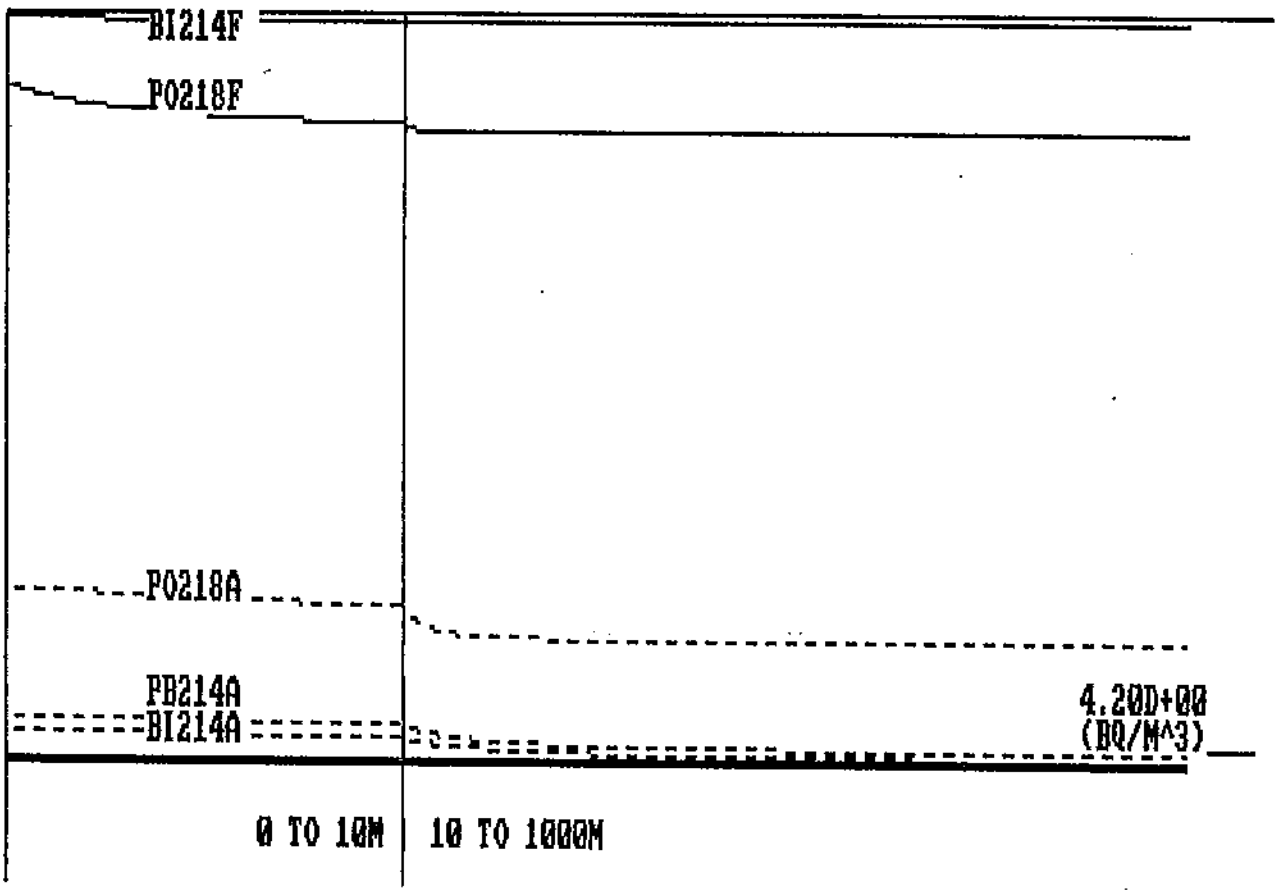

Figure 2: Calculation using parameters giving an analytic solution for unattached ^{218}Po (dashed line displaced 2 pixels for visibility).

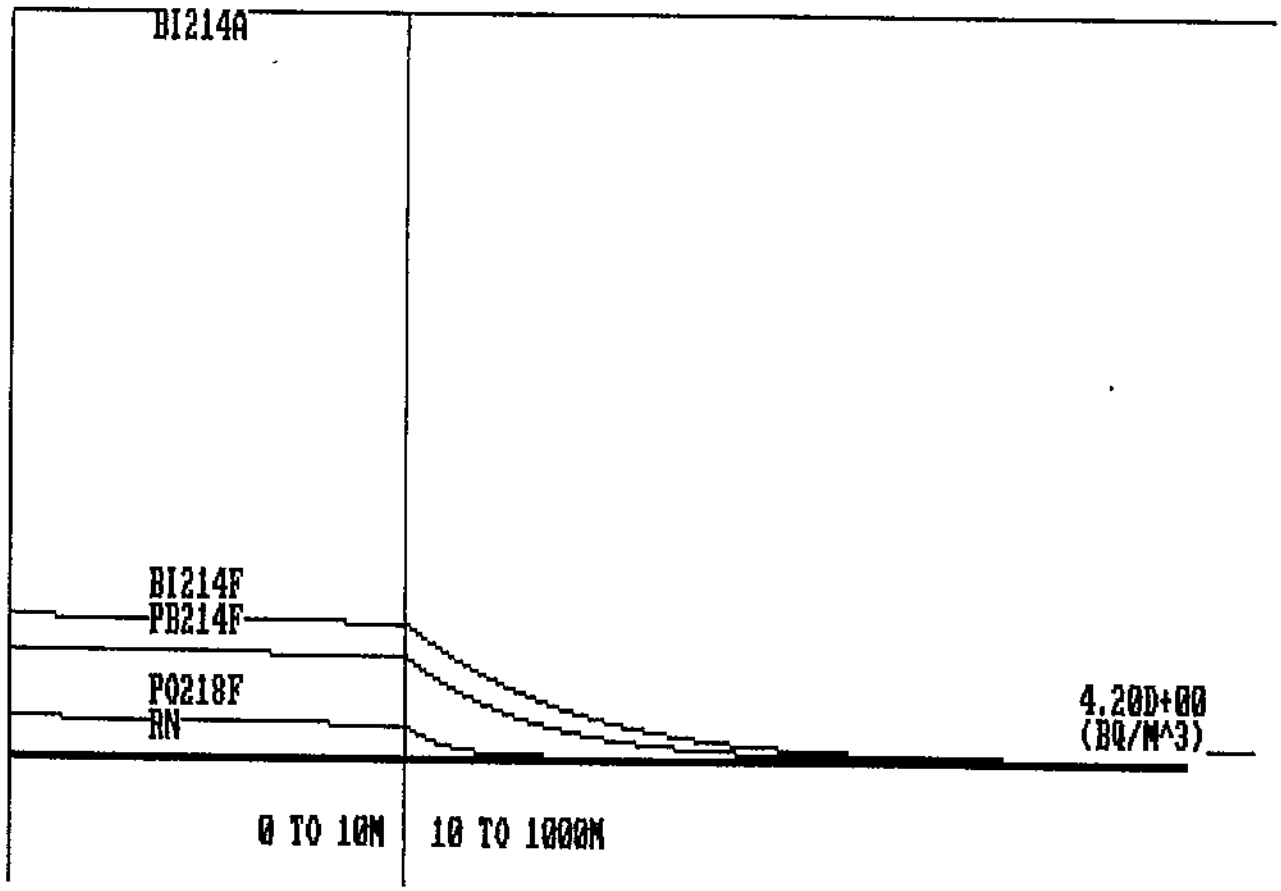

Figure 3: Calculation simulating open woodland and neutral stability.