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HARAD: A Computer Code for Calculating Daughter Concentrations in Air Following the Atmospheric Release of a Parent Radionuclide

R. E. Moore

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HARAD: A COMPUTER CODE FOR CALCULATING DAUGHTER CONCENTRATIONS IN AIR FOLLOWING THE ATMOSPHERIC RELEASE OF A PARENT RADIONUCLIDE

R. E. Moore

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CONTENTS

	Page
ACKNOWLEDGEMENTS	v
ABSTRACT	vii
INTRODUCTION	1
DESCRIPTION OF IN-PLUME PROCESSES	1
SOLUTION OF THE EQUATIONS	3
EVALUATION OF δ	4
DETERMINATION OF TIME INTERVALS	6
COMPUTER IMPLEMENTATION	8
REFERENCES	13
APPENDIX A. Listing of the HARAD Code	15
APPENDIX B. Output of an Example Case Run with the HARAD Code	25

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ABSTRACT

The HARAD computer code, written in FORTRAN IV, calculates concentrations of radioactive daughters in air following the atmospheric release of a parent radionuclide under a variety of meteorological conditions. It can be applied most profitably to the assessment of doses to man from the noble gases such as ^{222}Rn, ^{220}Rn, and Xe and Kr isotopes. These gases can produce significant quantities of short-lived particulate daughters in an airborne plume, which are the major contributors to dose from these chains with gaseous parent radionuclides.

The simultaneous processes of radioactive decay, buildup, and environmental losses through wet and dry deposition on ground surfaces are calculated for a daughter chain in an airborne plume as it is dispersed downwind from a point of release of a parent. The code employs exact solutions of the differential equations describing the above processes over successive discrete segments of downwind distance. Average values for the dry deposition coefficients of the chain members over each of these distance segments were treated as constants in the equations. The methods used for selecting the distance segments and for calculating the appropriate dry deposition coefficients are described. The advantage of HARAD is its short computing time with typical ^{222}Rn calculations requiring only 0.12 s on the IBM 370 3033 computer.

INTRODUCTION

The assessment of the radiation dose to man resulting from the atmospheric release of a radionuclide from a nuclear facility must take into account any significant buildup of radioactive daughters as the airborne plume is dispersed downwind. Calculation of the concentrations of daughters in air as a function of time or downwind distance is complicated by the fact that surface deposition may continuously remove daughters from the air during plume travel. The noble gases ^{220}Rn, ^{222}Rn and Kr and Xe isotopes may serve as examples. These gases do not deposit on ground surfaces, but their radioactive daughters as particulates will deposit through both wet and dry processes. The HARAD code calculates daughter-to-parent activity ratios in an airborne plume as a function of downwind distance for a parent radionuclide released to the atmosphere under a variety of meteorological conditions and release heights. The code can be used as a subroutine in computer codes such as AIRDOS-EPA (Moore et al., 1979) designed to estimate the radiological impact of atmospheric releases of radionuclides.

DESCRIPTION OF IN-PLUME PROCESSES

The release of ^{222}Rn from a nuclear facility or an ore tailings pile may serve as an example case. The nuclear reactions in an airborne plume are

^{222}Rn (gas)	→	^{218}Po (solid)	→	^{214}Pb (solid) →
$T_{1/2}$ = 3.8229 d		$T_{1/2}$ = 3.05 m		$T_{1/2}$ = 26.8 m
^{214}Bi (solid)	→	^{214}Po (solid)	→	^{210}Pb (solid)
$T_{1/2}$ = 19.9 m		$T_{1/2}$ = 1.64×10^{-4} s		$T_{1/2}$ = 20.4 y

The daughters of ^{222}Rn are produced as individual ions that can attach immediately to dust particles and can therefore be subject to deposition onto ground surfaces through both washout by rainfall (scavenging) and dry processes.

The differential equations describing radioactive decay, buildup, and deposition processes occurring in an airborne plume following release of a parent radionuclide are as follows:

$$\frac{dN_1}{dt} = -\psi_1 N_1 \tag{1}$$

$$\frac{dN_2}{dt} = \lambda_1 B_1 N_1 - \psi_2 N_2 \tag{2}$$

$$\frac{dN_3}{dt} = \lambda_2 B_2 N_2 - \psi_3 N_3 \tag{3}$$

$$\frac{dN_4}{dt} = \lambda_3 B_3 N_3 - \psi_4 N_4 \tag{4}$$

$$\frac{dN_n}{dt} = \lambda_{n-1} B_{n-1} N_{n-1} - \psi_n N_n \tag{5}$$

in which the subscript 1 refers to the parent radionuclide and subscripts 2, 3, and 4 refer to daughter radionuclides. Symbols are defined as follows:

N = number of atoms existing within a small unspecified time increment of the airborne plume,
B = branching fraction for production of daughter,
λ = radiological decay constant (s^{-1}),
ϕ = scavenging (or washout) coefficient (s^{-1}),
δ = dry deposition coefficient (s^{-1}), and
ψ = $\lambda + \phi + \delta$ (s^{-1}) .

SOLUTION OF THE EQUATIONS

The simultaneous differential equations (1) through (4) are solvable only if the ψ values are constant over time. Since $\psi = \lambda + \phi + \delta$, λ, ϕ, and δ would have to be constant to satisfy this condition. The λ values are always constant, and the scavenging coefficient ϕ may be regarded as a constant for annual-average meteorological conditions, but the dry deposition coefficient δ is a complex time function. To overcome this difficulty, average values of δ are calculated for each radionuclide over each of a series of time intervals selected so as to minimize the variation of δ. The resulting ψ values are then treated as constants in the successive employment of exact solutions of Eqs. (1) through (4) over these time intervals.

The solution of Eq. (1) for constant ψ_1 is

$$N_1 = N_1^{o} e^{-\psi_1 t} \tag{6}$$

in which N_1^{o} is the initial number of atoms of the parent radionuclide existing within a small unspecified period of time.

Substitution of the expression for N_1 given by Eq. (6) in Eq. (2) results in a linear first order differential equation solvable for N_2. Successive substitutions in the series of equations results in the determination of a general solution for the nth radionuclide in a chain:

$$N_n = K_{n,1} e^{-\psi_1 t} + K_{n,2} e^{-\psi_2 t} + \ldots K_{n,n} e^{-\psi_n t} \tag{7}$$

in which

N_n = number of atoms of nth radionuclide,

$K_{n,a} = k_{a,a}\, k_{a,a+1} \cdots k_{a,n}$, where a = 1 to a = n,

$$k_{a,b}(b > a) = - \frac{\lambda_{b-1}\, B_{b-1}}{\psi_a - \psi_b} ,$$

$$k_{a,b}\,(b = a > 1) = N_a^{\,o} - \sum_{\ell=1}^{\ell = a-1} k_{\ell,\ell} k_{\ell,\ell+1} \cdots k_{\ell,a},$$

$k_{1,1} = N_1^{\,o}$, and

$N_n^{\,o}$ = initial number of atoms of nth radionuclide (t = 0).

EVALUATION OF δ

The dry deposition coefficient to be used to evaluate ψ values in Eq. (7) is

$$\delta = - \frac{dF/F}{dt} \tag{8}$$

in which F is the depletion fraction for dry deposition processes, which is defined as the fraction of a particulate or reactive gas remaining in an airborne plume at a specified downwind distance from a release point. The depletion fraction is calculated to take into account only those losses of material which occur through dry deposition processes, which take place at the bottom of a plume at the ground surface.

The depletion fraction as derived (Van der Hoven, 1968) from the Gaussian atmospheric dispersion equation for pollutant concentrations in air at ground level (Pasquill, 1961; Gifford, 1961) is

$$F = \exp\left\{ - \frac{2}{\pi}^{1/2} \frac{V_d}{\mu} \int_0^x \frac{\exp(-H^2/2\sigma_z^2)}{\sigma_z} dx \right\} \tag{9}$$

in which

V_d = deposition velocity (m/s),
μ = wind speed (m/s),
H = effective release height (m),
σ_z = vertical dispersion coefficient (m), and
x = downwind distance (m) .

Differentiation of Eq. (9) with respect to x, substitution in Eq. (8), and conversion to a time function by use of the relationship $t = x/\mu$ results in

$$\delta = \left(\frac{2}{\pi}\right)^{1/2} V_d \frac{\exp(-H^2/2\sigma_z^2)}{\sigma_z} \tag{10}$$

Equation (10), which can be used to calculate δ values over each time interval, is valid only for distances at which the airborne plume is not affected by the atmospheric lid overlying the system. A recommended "rule of thumb" (Turner, 1969) is to consider the plume to be significantly affected by the lid when $x = 2x_L$ in which x_L is the distance downwind for which $\sigma_z = 0.47$ times the lid height L. It is assumed that pollutant concentrations become uniform from the ground to the lid in the vertical direction at x values greater than $2x_L$. An expression for F for that part of the plume beyond $2x_L$ can be derived (Moore, 1977):

$$F(x = 2x_L, x) = \exp\left[- \frac{V_d (x - 2x_L)}{L\mu} \right] . \tag{11}$$

The value of δ for distances beyond $2x_L$ is

$$\delta = - \frac{dF/F}{dt} = \frac{V_d}{L} \quad . \tag{12}$$

DETERMINATION OF TIME INTERVALS

The time intervals used for successive application of Eq. (7) were selected by examination of plots of F versus x calculated by use of Eq. (9). Distance segments (Δx), which are related to time intervals by the equation $\Delta t = \Delta x/\mu$, were chosen to minimize variation of δ in accordance with the slopes of the F-x plots. Short distance segments were selected close to the source where dF/dx changes most rapidly for low-elevation releases. Increasingly larger segments were selected for increasingly greater downwind distances. Distance segments between the following downwind distances in meters are used in HARAD: 0; 35; 65; 100; 150; 200; 300; 400; 500; 650; 800; 1000; 1500; 2000; 4000; 7000; 10,000; 25,000; 60,000; and 90,000.

The σ_z values used to calculate F were those recommended by G. A. Briggs (Gifford, 1976) of the Air Resources Atmospheric Turbulence and Diffusion Laboratory at Oak Ridge, Tennessee. Briggs' values, which are for open-country conditions, are given in Table 1 as different functions of x for each Pasquill atmospheric stability category ranging from A (extremely unstable) through F (moderately stable). The σ_z values for G category (extremely stable) were calculated to be the σ_z values for the F category minus half of the difference between the σ_z values for the E and F categories.

Table 1. Formulas recommended by Briggs[a] for σ_y and σ_z for open-country conditions[b]

Pasquill type	σ_y (meters)	σ_z (meters)
A	$0.22x(1 + 0.0001x)^{-0.5}$	$0.20x$
B	$0.16x(1 + 0.0001x)^{-0.5}$	$0.12x$
C	$0.11x(1 + 0.0001x)^{-0.5}$	$0.08x(1 + 0.0002x)^{-0.5}$
D	$0.08x(1 + 0.0001x)^{-0.5}$	$0.06x(1 + 0.0015x)^{-0.5}$
E	$0.06x(1 + 0.0001x)^{-0.5}$	$0.03x(1 + 0.0003x)^{-1}$
F	$0.04x(1 + 0.0001x)^{-0.5}$	$0.016x(1 + 0.0003x)^{-1}$

[a]G. A. Briggs, Air Resources Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, Oak Ridge, Tennessee.

[b]Values of x are downwind distances in meters.

COMPUTER IMPLEMENTATION

The HARAD code, written in the FORTRAN IV computer language, is organized as follows:

MAIN program

1. SUBROUTINE DIST

    1.1 SUBROUTINE ASIG

    1.2 SUBROUTINE CHAR

MAIN reads the input data, calls subroutine DIST to make the calculations, and then prints tables listing the input data and the calculated ratio of the activity of the parent and each daughter radionuclide to the initial activity of the parent. The input data includes the number of radionuclides in the chain (MEND), and the name (NAME), radiological decay constant λ (LR), the scavenging coefficient ϕ (SC), the dry deposition velocity V_d (VD), and the branching fraction (B) of each radionuclide. Activity ratios can be calculated for as many as 10 radionuclides. The maximum value of MEND is 10. Atmospheric and release data are also read in MAIN. These data are the wind speed μ (U), the release height h (H), the Pasquill atmospheric stability category (IC), the mean mixing depth (or lid height) L (LID1), and the downwind distance beyond which complete mixing is assumed between ground and lid, $2x_L$ (XLIDO). The calculations can be made for as many as 24 downwind distances (XVAL) that are supplied as input. Table 2 defines the input parameters, and Table 3 lists their data card formats.

Subroutine DIST is called from MAIN for each specified downwind distance (XVAL) for which calculations are to be made. This subroutine calculates the dry deposition coefficients (δ values) for the parent and each daughter in the chain for each of the distance intervals listed in the preceding section out to the distance XVAL or out to the distance XLIDO, whichever is smaller. For distances less than XLIDO, this is accomplished by calling subroutine ASIG to obtain σ_z values and then using Eq. (10) to calculate δ values. The average δ value used

Table 2. Definitions of input parameters

Name	Definition	Data type
MEND	Number of nuclides including the parent in the chain (maximum = 10)	Integer
NAME	Name of nuclide	Alphameric
LR	Radiological decay constant (s^{-1})	Floating point
SC	Scavenging coefficient (s^{-1})	Floating point
VD	Dry deposition velocity (m/s)	Floating point
B	Branching fraction	Floating point
IC	Pasquill stability category (1 through 7 for A through G)	Integer
U	Wind speed (m/s)	Floating point
H	Release height (m)	Floating point
LID1	Lid height (m)	Integer
XLIDO	Downwind distance beyond which complete vertical mixing from ground to lid is assumed (m)	Floating point
NX	Number of downwind distances for which chain calculations are to be made (maximum = 24)	Integer
XVAL	Downwind distance for chain calculation (as many as 24 values)	Floating point

Table 3. Data deck preparation for HARAD

Parameters	Number of values	Number of cards	Format
MEND	1	1	I10
NAME, LR, SC, VD, B	1 for each parameter × MEND	MEND	A8, T11, 4E10.3
IC, U, H, LID1, XLIDO	1 for each parameter	1	I10, 2E10.3, I10, E10.3
NX	1	1	I10
XVAL	24	3	8E10.3

for each distance segment is the average value of the two ends and the midpoint of the segment. Equation (12) is used to calcuate δ for all distances greater than XLIDO. The ψ values for each distance segment are calculated by adding λ, ϕ, and δ.

Subroutine CHAR is successively called from DIST to calculate the number of atoms N for the parent and each daughter for each succeeding distance segment by use of Eq. (7). The final values of N calculated at distance x (XVAL) are used to calculate the ratio of the activity of each radionuclide to the initial activity of the parent as follows:

$$r_n = \frac{\lambda_n N_n}{\lambda_1 N_1^{\,o}} \tag{13}$$

in which

r_n = activity ratio for the *nth* radionuclide,

λ_n = radiological decay constant of the *nth* radionuclide (s^{-1}),

λ_1 = radiological decay constant of the parent (s^{-1}),

N_n = number of atoms of the *nth* radionuclide, and

$N_1^{\,o}$ = initial number of atoms of the parent.

Double precision is used for the calculations in subroutine CHAR because evaluation of the constants $K_{n,1}$, $K_{n,2}$ etc. of Eq. (7) should be done as precisely as possible. If the differences in any of the ψ values in the chain are small, imprecision in the calculation of k values and consequent imprecision in the K values in Eq. (7) will ensue. This can be seen by reference to the definition of k,

$$k_{a,b}\ (b > a) = -\frac{\lambda_{b-1}\ B_{b-1}}{\psi_a - \psi_b} \quad . \tag{14}$$

Also, if the differences between ψ values are small, exponential overflow of K, which is a product of k values, may occur. These problems are avoided by use of a test of the absolute value of $\psi_a - \psi_b$ for applicable a and b integers. For any test in which $|\psi_a - \psi_b|$ is found to be less than 10^{-7}, the increment 10^{-7} is added to ψ_a. This procedure may be viewed as increasing the scavenging coefficient ϕ by 10^{-7}. It has no effect on the λ values which determine the buildup of succeeding chain members. Since scavenging coefficients generally range from about 5×10^{-6} to 3×10^{-5} the addition of 10^{-7} will have a minimal effect on the final calculated activity ratios.

Code calculations were verified by using two different procedures: (1) comparison of calculated activity ratios for the case in which ground deposition does not occur with ratios calculated using exact solutions of the decay chain equations, and (2) comparison of calculated activity ratios with those calculated through use of an inefficient computer technique which simulates decay and ground deposition processes over consecutive one-second time intervals.

Identical activity ratios were obtained for ^{222}Rn and daughters at all distances from 300 to 80,000 m by the two methods used in procedure 1. Procedure 2 revealed differences of less than 0.5% for distances up to 40,000 m. At 80,000 m. however, the HARAD value for ^{222}Rn was higher than the computer simulation value by 0.8%, and the daughter ratios were higher by about 1.5%. Since the HARAD ratio calculated for ^{222}Rn was exactly equal to the value calculated using the exact solution (procedure 1), it appears likely that the lower values for both ^{222}Rn and daughters obtained through computer simulation were a result of the propagation of small errors in this technique.

The calculational procedure used in HARAD avoids the use of computer-time consuming numerical integration or simulation techniques. A typical HARAD calculation of the activity ratios of ^{222}Rn and its first five daughters at 80,000 m downwind, for example, requires only 0.12 s on the IBM 370 3033 computer. The short running time of HARAD makes it advantageous for adaptation for use as a subroutine in computer codes designed to assess the radiological impact of atmospheric releases of nuclear power plants and fuel-cycle facilities.

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APPENDIX A

LISTING OF THE HARAD CODE

```
C
C              HARAD CODE
C
C        R. E. MOORE  HEALTH AND SAFETY RESEARCH DIV.  ORNL  11-7-79
C
C        A COMPUTER CODE TO CALCULATE DAUGHTER-TO-PARENT ACTIVITY
C        RATIOS IN AN AIRBORNE PLUME FOLLOWING ATMOSPHERIC RELEASE OF
C        A PARENT RADIONUCLIDE.
C
      COMMON /JCHA/ W(10),LR(10),LT(10),SC(10),B(10)
      COMMON /KCHA/ VD(10)
      REAL*8 LR,LT
      REAL*8 NAME(10)
      DIMENSION XVAL(24)
      REAL*8 W
C        READ INPUT DATA FOR NUCLIDE CHAIN.
C          NEND=NUMBER OF NUCLIDES IN CHAIN INCLUDING THE PARENT
C          NAME=NAME OF NUCLIDE(8 CHARACTERS)
C          LR=RADIOLOGICAL DECAY CONSTANT(PER SEC)
C          SC=SCAVENGING COEFFICIENT(PER SEC)
C          VD=DRY DEPOSITION VELOCITY(METERS/SEC)
C          B=BRANCHING FRACTION
      READ(50,100)NEND
      READ(50,101)((NAME(I),LR(I),SC(I),VD(I),B(I)),I=1,NEND)
C        READ ATMOSPHERIC PARAMETERS.
C          IC=PASQUILL ATMOSPHERIC STABILITY CATEGORY
C             (1 TO 7 FOR CATEGORIES A TO G)
C          U=WIND SPEED(METERS/SEC)
C          H=RELEASE HEIGHT(METERS)
C          LID1=LID HEIGHT(METERS)
C          XLIDO=DOWNWIND DISTANCE FOR ASSUMED COMPLETE VERTICAL
C          MIXING FROM THE GROUND TO THE LID(METERS)
      READ(50,102)IC,U,H,LID1,XLIDO
C        READ NUMBER OF DOWNWIND DISTANCES FOR CALCULATIONS.
      READ(50,100)NX
C        READ DOWNWIND DISTANCES.
      READ(50,103)(XVAL(I),I=1,24)
C        PRINT INPUT DATA.
      WRITE(51,104)
      WRITE(51,109)
      WRITE(51,105)
      WRITE(51,106)
      WRITE(51,107)
      WRITE(51,108)
      WRITE(51,109)
      DO 1 I=1,NEND
      WRITE(51,110)NAME(I),LR(I),SC(I),VD(I),B(I)
    1 CONTINUE
      WRITE(51,109)
      WRITE(51,111)
      WRITE(51,109)
      WRITE(51,112)H
      WRITE(51,113)IC
      WRITE(51,114)U
      WRITE(51,115)LID1
      WRITE(51,116)XLIDO
```

```
      WRITE(51,117)
      WRITE(51,109)
C        CALL SUBROUTINE DIST TO CALCULATE ACTIVITY RATIOS.
      DO 2 I=1,NI
      CALL DIST(XVAL(I),U,IC,H,LID1,XLIDO,MEND)
C        PRINT OUTPUT TABLES OF ACTIVITY RATIOS.
      WRITE(51,118)XVAL(I)
      WRITE(51,119)NAME(1)
      WRITE(51,109)
      WRITE(51,120)
      WRITE(51,109)
      DO 3 J=1,MEND
      WRITE(51,121)NAME(J),W(J)
 3    CONTINUE
 2    CONTINUE
      STOP
 100  FORMAT(I10)
 101  FORMAT(A8,I11,8E10.3)
 102  FORMAT(I10,2E10.3,I10,E10.3)
 103  FORMAT(8E10.3)
 104  FORMAT('1',T57,'OUTPUT OF HARAD CODE')
 105  FORMAT('0',T58,'NUCLIDE CHAIN DATA')
 106  FORMAT('0',T31,'NUCLIDE',T42,'DECAY CONSTANT',T60,'SCAVENGING',
     >T75,'DEPOSITION',T91,'BRANCHING')
 107  FORMAT(' ',T60,'COEFFICIENT',T76,'VELOCITY',T91,'FRACTION')
 108  FORMAT(' ',T44,'(PER SEC)',T61,'(PER SEC)',T74,'(METERS/SEC)')
 109  FORMAT(' ')
 110  FORMAT('0',T31,A8,T44,E10.3,T60,F10.3,T75,F10.5,T88,F10.3)
 111  FORMAT('0',T25,'ATMOSPHERIC PARAMETERS---')
 112  FORMAT('0',T30,'RELEASE HEIGHT(METERS)',T80,F10.2)
 113  FORMAT('0',T30,'PASQUILL CATEGORY',T80,I10)
 114  FORMAT('0',T30,'WIND SPEED(METERS/SEC)',T80,F10.2)
 115  FORMAT('0',T30,'LID HEIGHT(METERS)',T80,I10)
 116  FORMAT('0',T30,'DOWNWIND DISTANCE FOR BELOW-LID MIXING(METERS)',
     >T80,F10.1)
 117  FORMAT('1',T38,'RATIO OF ACTIVITY OF NUCLIDE TO INITIAL ACTIVITY O
     >F PARENT')
 118  FORMAT('0',T30,'DISTANCE (METERS)=',E10.3)
 119  FORMAT('0',T30,'PARENT',T38,A8)
 120  FORMAT('0',T56,'NUCLIDE',T71,'ACTIVITY RATIO')
 121  FORMAT(' ',T58,A8,T73,F10.4)
      END
```

```
      SUBROUTINE DIST(X,U,XC,H,XIDI,XLIDO,NEND)                         DIST   5
C                                                                       DIST  10
C        R. E. MOORE  HEALTH AND SAFETY RESEARCH DIV.  ORNL  11-7-79    DIST  15
C                                                                       DIST  20
C                                                                       DIST  25
C        A SUBROUTINE OF HARAD TO CALCULATE DRY DEPOSITION AND TOTAL    DIST  30
C        LOSS COEFFICIENTS FOR EACH DISTANCE INTERVAL OUT TO            DIST  35
C        THE SPECIFIED DOWNWIND DISTANCE.                               DIST  40
C                                                                       DIST  45
      COMMON /HCHA/ HFLAG                                               DIST  50
      COMMON /JCHA/ W(10),LR(10),LT(10),SC(10),B(10)                    DIST  55
      COMMON /KCHA/ VD(10)                                              DIST  60
      DIMENSION XIDI(20)                                                DIST  65
      REAL*8 LR,LT                                                      DIST  70
      REAL*8 W                                                          DIST  75
      DATA XIDI/35.,65.,100.,150.,300.,400.,500.,650.,800.,1000.,       DIST  80
     > 1500.,2000.,4000.,7000.,10000.,25000.,60000.,90000.,200000./     DIST  85
      HFLAG=1                                                           DIST  90
      XT1=XLIDO                                                         DIST  95
      IF(X.LE.XLIDO)XT1=X                                               DIST 100
      IF(X.GT.XIDI(1))GO TO 1                                           DIST 105
      XC=X                                                              DIST 110
      GO TO 2                                                           DIST 115
 1    XC=XIDI(1)                                                        DIST 120
C        CALCULATION FOR THE FIRST DISTANCE INTERVAL.                   DIST 125
 2    TC=XC/U                                                           DIST 130
      XL=XC/2.                                                          DIST 135
C        ASIG IS CALLED TO CALCULATE SIGMA Z TO CALCULATE THE DRY       DIST 140
C        DEPOSITION COEFFICIENT OVER THE DISTANCE INTERVAL.             DIST 145
      CALL ASIG(XC,XL,SIGZ)                                             DIST 150
      DO 3 IB=1,NEND                                                    DIST 155
 3    LT(IB)=LR(IB)+SC(IB)+.797885*VD(IB)*(EXP(-H**2/(2.*SIGZ**2))/SIGZ) DIST 160
C        CHAR IS CALLED TO CALCULATE NUMBER OF ATOMS OF EACH NUCLIDE    DIST 165
C        IN THE PLUME AT END OF THE DISTANCE INTERVAL.                  DIST 170
      CALL CHAR(NEND,TC)                                                DIST 175
      IF(X.LE.XIDI(1))GO TO 8                                           DIST 180
C        CALCULATIONS FOR EACH DISTANCE INTERVAL BEYOND THE FIRST       DIST 185
C        DISTANCE INTERVAL UP TO X OR XLIDO WHICHEVER IS SMALLER.       DIST 190
      KTE=0                                                             DIST 195
      DO 4 I=2,20                                                       DIST 200
      IF(XIDI(I).GT.XT1)GO TO 5                                         DIST 205
      XC=XIDI(I)-XIDI(I-1)                                              DIST 210
      TC=XC/U                                                           DIST 215
      XL=XIDI(I)-(XC/2.)                                                DIST 220
      XLT=XIDI(I)                                                       DIST 225
      XLB=XIDI(I)-XC                                                    DIST 230
      GO TO 6                                                           DIST 235
 5    XC=XT1-XIDI(I-1)                                                  DIST 240
      TC=XC/U                                                           DIST 245
      XL=XT1-(XC/2.)                                                    DIST 250
      XLT=XT1                                                           DIST 255
      XLB=XT1-XC                                                        DIST 260
      KTE=I-1                                                           DIST 265
C        ASIG IS CALLED TO CALCULATE SIGMA Z TO CALCULATE THE DRY       DIST 270
C        DEPOSITION COEFFICIENT OVER THE DISTANCE INTERVAL.             DIST 275
 6    CALL ASIG(XC,XL,SIGZ)                                             DIST 280
```

```
      CALL ASIG(IC,XLT,SIGZT)                                           DIST 285
      CALL ASIG(IC,XLB,SIGZB)                                           DIST 290
      EFAC=(EXP(-H**2/(2.*SIGZ**2))/SIGZ+EXP(-H**2/(2.*SIGZT**2))/      DIST 295
     >SIGZT+EXP(-H**2/(2.*SIGZB**2))/SIGZB)/3.                          DIST 300
      DO 7 IB=1,NEND                                                    DIST 305
 7    LT(IB)=LR(IB)+SC(IB)+.797885*VD(IB)*EFAC                          DIST 310
C        CHAR IS CALLED TO CALCULATE NUMBER OF ATOMS OF EACH NUCLIDE    DIST 315
C        IN THE PLUME AT END OF THE DISTANCE INTERVAL.                  DIST 320
      CALL CHAR(NEND,TC)                                                DIST 325
      IF(RTE.NE.0)GO TO 8                                               DIST 330
 4    CONTINUE                                                          DIST 335
 8    CONTINUE                                                          DIST 340
C        CALCULATION FOR THE DISTANCE BETWEEN XLIDO AND X IF X IS       DIST 345
C        GREATER THAN XLIDO(X=SPECIFIED DOWNWIND DISTANCE OR XVAL).     DIST 350
      IF(X.LE.XLIDO)GO TO 9                                             DIST 355
      T=(X-XLIDO)/U                                                     DIST 360
      DO 10 IB=1,NEND                                                   DIST 365
 10   LT(IB)=LR(IB)+SC(IB)+VD(IB)/LFD1                                  DIST 370
C        CHAR IS CALLED TO CALCULATE NUMBER OF ATOMS OF EACH NUCLIDE    DIST 375
C        IN THE PLUME AT END OF THE DISTANCE INTERVAL.                  DIST 380
      CALL CHAR(NEND,T)                                                 DIST 385
 9    CONTINUE                                                          DIST 390
      RETURN                                                            DIST 395
      END                                                               DIST 400
```

```
      SUBROUTINE CHAR(NEND,TC)                                          CHAR   5
C                                                                       CHAR  10
C        R. E. MOORE  HEALTH AND SAFETY RESEARCH DIV.  ORNL  11-7-79    CHAR  15
C                                                                       CHAR  20
C        A SUBROUTINE OF DIST TO CALCULATE THE NUMBER OF ATOMS OF EACH  CHAR  25
C        NUCLIDE IN THE CHAIN AND THE DAUGHTER-TO-PARENT ACTIVITY RATIOSCHAR  30
C        IN THE PLUME AT THE END OF EACH DISTANCE INTERVAL.             CHAR  35
C                                                                       CHAR  40
      COMMON /HCHA/ NPLAG                                               CHAR  45
      COMMON /JCHA/ W(10),LR(10),LT(10),SC(10),B(10)                    CHAR  50
      REAL*8 Z(10),K(10,10),KE(10,10),LU(10),W,SUM,A                    CHAR  55
      REAL*8 LR,LT                                                      CHAR  60
      IF(NPLAG.EQ.127)GO TO 1                                           CHAR  65
      Z(1)=1.E30                                                        CHAR  70
      DO 2 I=2,NEND                                                     CHAR  75
 2    Z(I)=0.                                                           CHAR  80
      NPLAG=127                                                         CHAR  85
 1    CONTINUE                                                          CHAR  90
      NEND=NEND-1                                                       CHAR  95
      K(1,1)=Z(1)                                                       CHAR 100
      NCON=0                                                            CHAR 105
      LU(NEND)=LT(NEND)                                                 CHAR 110
C        THE ADDITION OF 1.E-7 TO THE TOTAL LOSS CONSTANT OF A NUCLIDE  CHAR 115
C        IF THE DIFFERENCE BETWEEN IT AND THE VALUE FOR THE SUCCEEDING  CHAR 120
C        NUCLIDE IS LESS OR EQUAL TO 1.E-7.  THIS PROCEDURE IS EQUIV-   CHAR 125
C        ALENT TO ADDING THE SMALL INCREMENT 1.E-7 TO THE SCAVENGING    CHAR 130
C        COEFFICIENT.                                                   CHAR 135
      DO 3 NO=1,NEND                                                    CHAR 140
      LU(NO)=LT(NO)                                                     CHAR 145
      NA=NO+1                                                           CHAR 150
      DO 4 NR=NA,NEND                                                   CHAR 155
      IF(DABS(LT(NO)-LT(NR)).GT.1.E-7)GO TO 5                           CHAR 160
      NCON=NCON+1                                                       CHAR 165
      A=1.E-7*NCON                                                      CHAR 170
      LU(NO)=LT(NO)+A                                                   CHAR 175
 5    CONTINUE                                                          CHAR 180
 4    CONTINUE                                                          CHAR 185
 3    CONTINUE                                                          CHAR 190
C        CALCULATION OF SMALL K VALUES.                                 CHAR 195
      DO 6 NO=1,NEND                                                    CHAR 200
      NA=NO+1                                                           CHAR 205
      DO 7 NR=NA,NEND                                                   CHAR 210
 7    K(NO,NR)=-(LR(NP-1)*B(NR-1))/(LU(NO)-LU(NR))                      CHAR 215
 6    CONTINUE                                                          CHAR 220
C        CALCULATION OF LARGE K VALUES.                                 CHAR 225
      KE(1,1)=K(1,1)                                                    CHAR 230
      DO 8 NN=2,NEND                                                    CHAR 235
      NE=NN-1                                                           CHAR 240
      SUM=0.                                                            CHAR 245
      DO 9 NT=1,NE                                                      CHAR 250
      KE(NT,NN)=1.                                                      CHAR 255
      NS=NT                                                             CHAR 260
      DO 10 NP=NS,NN                                                    CHAR 265
 10   KE(NT,NN)=K(NT,NP)*KE(NT,NN)                                      CHAR 270
      SUM=SUM+KE(NT,NN)                                                 CHAR 275
 9    CONTINUE                                                          CHAR 280
```

```
C        CALCULATION OF LARGE K VALUE FOR THE LAST TERM OF EQUATION.     CHAR 285
      K(NN,NN)=Z(NN)-SUM                                                 CHAR 290
      KE(NN,NN)=K(NN,NN)                                                 CHAR 295
 8    CONTINUE                                                           CHAR 300
C        CALCULATION OF NUMBERS OF ATOMS OF EACH NUCLIDE IN CHAIN.       CHAR 305
      DO 11 NN=1,MEND                                                    CHAR 310
      NEN=NN                                                             CHAR 315
      W(NN)=0.                                                           CHAR 320
      DO 12 NT=1,NEN                                                     CHAR 325
      IF((LU(NT)*TC).GT.100.)GO TO 12                                    CHAR 330
      W(NN)=KE(NT,NN)*DEXP(-LU(NT)*TC)+W(NN)                             CHAR 335
 12   CONTINUE                                                           CHAR 340
 11   CONTINUE                                                           CHAR 345
C        CALCULATION OF ACTIVITY RATIOS.                                 CHAR 350
      Z(1)=W(1)                                                          CHAR 355
      W(1)=W(1)/1.E30                                                    CHAR 360
      DO 13 NN=2,MEND                                                    CHAR 365
 13   W(NN)=(W(NN)*LR(NN))/(1.E30*LR(1))                                 CHAR 370
C        CALCULATION OF NUMBER OF ATOMS.                                 CHAR 375
      DO 14 NN=2,MEND                                                    CHAR 380
 14   Z(NN)=(W(NN)*LR(1)*1.E30)/LR(NN)                                   CHAR 385
      RETURN                                                             CHAR 390
      END                                                                CHAR 395
```

```
      SUBROUTINE ASIG(IC,XL,SIGZ)                                       ASIG   5
C                                                                       ASIG  10
C        R. E. MOORE  HEALTH AND SAFETY RESEARCH DIV.  ORNL  11-7-79    ASIG  15
C                                                                       ASIG  20
C        A SUBROUTINE OF DIST TO CALCULATE SIGMA Z VALUES BASED ON      ASIG  25
C        BRIGGS' ATDL RECOMMENDATIONS FOR OPEN-COUNTRY CONDITIONS.      ASIG  30
C                                                                       ASIG  35
      GO TO (1,2,3,4,5,6,7),IC                                          ASIG  40
 1    SIGZ=.2*XL                                                        ASIG  45
      GO TO 8                                                           ASIG  50
 2    SIGZ=.12*XL                                                       ASIG  55
      GO TO 8                                                           ASIG  60
 3    SIGZ=.08*XL/SQRT(1.+.0002*XL)                                     ASIG  65
      GO TO 8                                                           ASIG  70
 4    SIGZ=.06*XL/SQRT(1.+.0015*XL)                                     ASIG  75
      GO TO 8                                                           ASIG  80
 5    SIGZ=.03*XL/(1.+.0003*XL)                                         ASIG  85
      GO TO 8                                                           ASIG  90
 6    SIGZ=.016*XL/(1.+.0003*XL)                                        ASIG  95
      GO TO 8                                                           ASIG 100
 7    SIGZ=(.016*XL/(1.+.0003*XL))-(((.03*XL/(1.+.0003*XL))-            ASIG 105
     >(.016*XL/(1.+.0003*XL)))/2.)                                      ASIG 110
 8    CONTINUE                                                          ASIG 115
      RETURN                                                            ASIG 120
      END                                                               ASIG 125
```

APPENDIX B

OUTPUT OF AN EXAMPLE CASE RUN WITH THE HARAD CODE

APPENDIX B

OUTPUT OF AN EXAMPLE CASE RUN WITH THE HARAD CODE

The example case consists of the release of ^{222}Rn gas from a point source with a 1-m elevation. The wind speed is 1 m/s, and Pasquill atmospheric stability category B (unstable) is assumed. The mean mixing depth (lid height) is 2000 m, and complete mixing between ground and lid is assumed to occur beyond a distance of 15,667 m. The following daughters of ^{222}Rn were assumed to build up in the airborne plume: ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, and ^{210}Pb.

OUTPUT OF HARAD CODE

NUCLIDE CHAIN DATA

NUCLIDE	DECAY CONSTANT (PER SEC)	SCAVENGING COEFFICIENT (PER SEC)	DEPOSITION VELOCITY (METERS/SEC)	BRANCHING FRACTION
RN-222	0.210D-05	0.0	0.0	1.000
PO-218	0.379D-02	0.200E-04	0.01000	1.000
PB-214	0.431D-03	0.200E-04	0.01000	1.000
BI-214	0.586D-03	0.200E-04	0.01000	1.000
PO-214	0.423D 04	0.200E-04	0.01000	1.000
PB-210	0.108D-08	0.200E-04	0.01000	1.000

ATMOSPHERIC PARAMETERS---

RELEASE HEIGHT(METERS)	1.00
PASQUILL CATEGORY	2
WIND SPEED(METERS/SEC)	1.00
LID HEIGHT(METERS)	2000
DOWNWIND DISTANCE FOR BELOW-LID MIXING(METERS)	15667.0

RATIO OF ACTIVITY OF NUCLIDE TO INITIAL ACTIVITY OF PARENT

DISTANCE (METERS) = 0.300E 03

PARENT RN-222

NUCLIDE	ACTIVITY RATIO
RN-222	0.9994D 00
PO-218	0.6436D 00
PB-214	0.4516D-01
BI-214	0.2716D-02
PO-214	0.2716D-02
PB-210	0.2305D-09

DISTANCE (METERS) = 0.500E 03

PARENT RN-222

NUCLIDE	ACTIVITY RATIO
RN-222	0.9990D 00
PO-218	0.8129D 00
PB-214	0.9995D-01
BI-214	0.1021D-01
PO-214	0.1021D-01
PB-210	0.1500D-08

DISTANCE (METERS) = 0.100E 04

PARENT RN-222

NUCLIDE	ACTIVITY RATIO
RN-222	0.9979D 00
PO-218	0.9489D 00
PB-214	0.2469D 00
BI-214	0.5143D-01
PO-214	0.5143D-01
PB-210	0.1640D-07

DISTANCE (METERS) = 0.200E 04

PARENT RN-222

NUCLIDE	ACTIVITY RATIO
RN-222	0.9958D 00
PO-218	0.9800D 00
PB-214	0.4811D 00
BI-214	0.1927D 00
PO-214	0.1927D 00
PB-210	0.1395D-06

DISTANCE (METERS) = 0.400E 04

PARENT RN-222

NUCLIDE	ACTIVITY RATIO
RN-222	0.9916D 00
PO-218	0.9808D 00
PB-214	0.7325D 00
BI-214	0.4888D 00
PO-214	0.4888D 00
PB-210	0.8496D-06

DISTANCE (METERS) = 0.800E 04

PARENT RN-222

NUCLIDE	ACTIVITY RATIO
RN-222	0.9834D 00
PO-218	0.9764D 00
PB-214	0.8845D 00
BI-214	0.7853D 00
PO-214	0.7853D 00
PB-210	0.3466D-05

DISTANCE (METERS) = 0.120E 05

PARENT RN-222

NUCLIDE	ACTIVITY RATIO
RN-222	0.9751D 00
PO-218	0.9690D 00
PB-214	0.9104D 00
BI-214	0.8597D 00
PO-214	0.8597D 00
PB-210	0.6517D-05

DISTANCE (METERS) = 0.200E 05

PARENT RN-222

NUCLIDE	ACTIVITY RATIO
RN-222	0.9589D 00
PO-218	0.9531D 00
PB-214	0.9047D 00
BI-214	0.8700D 00
PO-214	0.8700D 00
PB-210	0.1213D-04

DISTANCE (METERS) = 0.400E 05

PARENT RN-222

NUCLIDE	ACTIVITY RATIO
RN-222	0.9195D 00
PO-218	0.9140D 00
PB-214	0.8679D 00
BI-214	0.8352D 00
PO-214	0.8352D 00
PB-210	0.2179D-04

DISTANCE (METERS) = 0.800E 05

PARENT RN-222

NUCLIDE	ACTIVITY RATIO
RN-222	0.8455D 00
PO-218	0.8404D 00
PB-214	0.7980D 00
BI-214	0.7680D 00
PO-214	0.7680D 00
PB-210	0.2968D-04