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DPST-85-304

AXAIR: A COMPUTER CODE FOR SAR ASSESSMENT OF PLUME-EXPOSURE DOSES FROM POTENTIAL PROCESS-ACCIDENT RELEASES TO ATMOSPHERE

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DPST-85-304

TECHNICAL DIVISION
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INTRODUCTION AND SUMMARY

Safety analysis reports (SAR's) usually require the dose consequences of postulated releases of radioactivity in potential accident scenarios. Standard methods and easily-invoked computational means are being developed to facilitate such dose assessments. This memorandum describes the AXAIR computer code which is available to terminal users for evaluating the doses to man from exposure to the atmospheric plume from postulated stack or building-vent releases at the SRP site. The emphasis herein is on documentation of the methodology; the User's Guide To The AXAIR Code is a separate publication (DPST-85-305).

Given minimal input to characterize the release, the AXAIR code estimates the doses via the inhalation and plume gamma radiation pathways to the onsite population, the offsite population within 80 kilometers (50 miles), and the offsite maximum individuals (adult, teenager, child, and infant). The total-body doses evaluated are those that would be exceeded only 0.5% of the time based on worst-sector, worst-case meteorological probability analysis. The associated doses to other body organs are given in the dose breakdowns by radionuclide, body organ and pathway.

DISCUSSION

A standard methodology has been developed to facilitate SAR assessment of plume-exposure doses from postulated stack or building-vent release of radioactivity at the SRP site. The AXAIR computer code offers several improvements relative to the prototypal NRC145-2 code (DP-1646, Ref. 1), which are listed in Table 1. The high degree of automation enables easy user use of the code as indicated in Section 1, below, following which the methodology is described.

1. Invocation of the AXAIR Code

Table 2 shows the job control language and user input template which is available to terminal users for execution of the AXAIR code. Although the template is reasonably self-explanatory, several major points are clarified below. Further guidance can be found in the User's Guide to the AXAIR Code (Ref. 2), which also shows a sample problem and the typical output from the code.

As indicated on Line 160 of Table 2, the user specifies either a stack release or a building-vent release. However, if the stack height is less than 2 1/2 times adjacent building, the release should be treated as a building-vent release (Ref. 5). The building-vent category also includes ground-level releases.

Table 1. Improvements Relative To The NRC145-2 Computer Code

Automatic Selection And Generation Of Data:

- Dose conversion factors
- Inhalation and gamma exposure parameters
- Offsite population distribution
- Onsite population distribution
- Appropriate meteorological data base
- Minimum distances to SRP boundary by compass sector
- Relative terrain elevations

Relative Air Concentration (X/Q) Modeling:

- Better interpretation of NRC Regulatory Guide 1.145
- Determination of maximum offsite X/Q locations
- Addition of average X/Q models for population doses

Dose Methodology:

- Extended to offsite and onsite populations
- New and more general method for doses via gamma radiation from the nonuniform atmospheric plume
- Consideration of ingrowth of daughter radionuclides from released parent decay during plume transport time

TABLE 2. Job Control Language and User Input Template for AXAIR Code+

```
LINE #  ----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8

     1  //AAAAAAAA JOB (BBBB-BB,CCCCC,DDDD,12,04),'AXAIR CODE',
     2  // MSGLEVEL=(2,0),MSGCLASS=2,NOTIFY=CCCCC
     3  //*
     4  //* USER SHOULD MODIFY JOB CARD, PROCEED TO LINE 000153, FILL IN DATA
     5  //* AND SUBMIT JOB (TO EXIT THIS DSN USE "COMMAND ===> CAN" & "ENTER")
     6  //*
     7  //* --------- INSTREAM-PROCEDURE AXAIR FOLLOWS ----------
     8  //AXAIR PROC OUT='*'
     :
   150  //* ---------- END OF INSTREAM-PROCEDURE AXAIR ------------------
   151  // EXEC AXAIR,XTIME=7
   152  //AXAIN.SYSIN DD *
   153                                           <==(10A4) TITLE LINE 1
   154                                           <==(10A4) TITLE LINE 2
   155
   156   <==(A1) SRP AREA LOCATION OF RELEASE (C,F,H,K OR P) OR, PREFERABLY,
   157        <==(F6.0) SRP-GRID EASTING  OF RELEASE POINT (FT) AND
   158        <==(F6.0) SRP-GRID NORTHING OF RELEASE POINT (FT)?
   159
   160   <==( I1 ) BUILDING VENT (0) OR STACK (1) RELEASE?
   161
   162        <==(F6.0) IF VENT, BLDG MINIMUM VERTICAL X-SECTION (SQ.M)?
   163
   164        <==(F6.0) IF STACK, STACK HEIGHT (M ABOVE GRADE) AND, IF KNOWN,
   165        <==(F6.0) GRADE ELEVATION (FT ABOVE MEAN-SEA-LEVEL)?
   166
   167      <==(I4) CALENDAR YEAR OF POSTULATED RELEASE (1980-2020)?
   168
   169    <==(I2) OPTIONAL SINGLE SECTOR ANALYSIS: 1 FOR S; 2 FOR SSW; ... ;
   170              16 FOR SSE (BLANK FOR ALL SECTORS - NORMALLY BLANK)
   171   <==(I1) OPTIONAL GAMMA-RAY SHINE DOSE METHODOLOGIES (NORMALLY BLANK):
   172             1 FOR NONUNIFORM ATMOSPHERIC PLUME METHOD
   173             2 FOR UNIFORM PLUME APPROXIMATION
   174       (BLANK FOR RECOMMENDED NONUNIFORM PLUME UPPER-BOUND APPROXIMATION)
   175
   176  IN THE FOLLOWING RADIONUCLIDE TABLE, ENTER CURIES RELEASED & ASSOCIATED
   177  RELEASE PERIODS (HOURS) FOR A MAXIMUM OF 100 NUCLIDES (TRUE OR FALSE IN
   178  COLUMNS 9 & 10 INDICATE WHETHER INHALATION & SHINE DOSE FACTORS EXIST):
   179
   180  NUCLIDE    | CURIES  HRS.| CURIES  HRS.| CURIES  HRS.| CURIES  HRS.| CURIES  HRS.
   181  -------      -------- ----  -------- ---- -------- ---- -------- ---- -------- ----
   182  H-3     TF 0.00E-00    2 0.00E-00    0 0.00E-00    0 0.00E-00    0 0.00E-00    0
   183  BE-7    FT 0.00E-00    2 0.00E-00    0 0.00E-00    0 0.00E-00    0 0.00E-00    0
   184  BE-10   TF 0.00E-00    2 0.00E-00    0 0.00E-00    0 0.00E-00    0 0.00E-00    0
   185  C-11    FT 0.00E-00    2 0.00E-00    0 0.00E-00    0 0.00E-00    0 0.00E-00    0
   186  C-14    TF 0.00E-00    2 0.00E-00    0 0.00E-00    0 0.00E-00    0 0.00E-00    0
   187  N-13    TT 0.00E-00    2 0.00E-00    0 0.00E-00    0 0.00E-00    0 0.00E-00    0
     :
   677  FM-256  FF 0.00E-00    2 0.00E-00    0 0.00E-00    0 0.00E-00    0 0.00E-00    0
```

+Available to Terminal Users from DSN=TENVT.TMECA.JCL(AXAIR)

With respect to any released radionuclide (n), the template requires specification of an amount released, q_n, in Curies, and an associated release time period, T_n, in hours of duration. The AXAIR code is well-suited for a release period in the range, 0.25 to 100 hours. However, if the release period is not longer than two hours, the value of T_n is taken to be two hours (user-specified $T_n < 2$ defaults to $T_n = 2$). Further, the use of a longer release period ($T_n > 2$) is appropriate only when the release rate (dq_n/dt) is approximately constant during that period.

In the radionuclide table beginning on Line 182 of Table 2, provisions are made to allow for the possible existence of up to five different-length release periods, T_{np}, for each released nuclide, the corresponding amounts released being q_{np}, p = 1 through 5. Those $q_{np} > 0$ and their T_{np} should appear from left to right in the table; i.e., when the code encounters a $q_{np} = 0$, it is assumed that there are no further entries on the particular radionuclide line.

2. Meteorological Conditions and Probability of Their Occurrence

The basic meteorological data is five years (1975-79) of 15-minute averages of windspeed, wind direction and standard deviations of the fluctuations in wind components at the meteorological towers in A, C, D, F, H, K and P Areas. The preparation of the basic data and the steps required to put these data in proper form have been described in DPST-82-512 (Ref. 3).

With respect to the 62-meter elevation of each tower and based on one-hour averaging as described in Reference 3, data in proper form consists of

- The number, N_{ijk}, of one-hour occurrences of meteorological conditions by windspeed class (i), stability class (j), and compass sector (k); and

- The average windspeeds, $\bar{u}_{ijk}$, during the number of one-hour occurrences (N_{ijk}), in meters per second.

To clarify the meaning of the indices in this report: index i denotes a windspeed range in the list, 0-2, 2-4, 4-6, 6-8, 8-12 and > 12 m/s (6 classes); index j denotes a Pasquill stability class in the list, A, B, C, D, E, F, and G (7 classes); and index k deontes a downwind cardinal compass sector or compass-point direction in the list, S, SSW, SW, . . . , ESE, SE, and SSE (16 sectors).

Based on user's specification of the release-point location, the AXAIR code selects the nearest meteorological tower and the corresponding data in proper form, the N_{ijk} and $\bar{u}_{ijk}$, are read into the code. Following this, the (normalized) meteorological joint frequency distribution, f_{ijk}, is determined; i.e.,

$$f_{ijk} = N_{ijk}/(\sum_{ijk}\sum\sum N_{ijk}). \tag{1}$$

Thus, based on a priori knowledge, there are 42 possible windspeed-stability (ij) conditions in each downwind compass sector (k) and the probabilities of occurrence are the f_{ijk}.

The meteorological joint frequency distribution (Eqn. 1) is assumed to be the same for all release heights. However, the average windspeed at the release height, h, is obtained from the power law in Reference 1; namely,

$$u_{ijk} = \bar{u}_{ijk}(h/62m)^n \tag{2}$$

where

u_{ijk} is the average windspeed at release-height h, m/s;

$\bar{u}_{ijk}$ is the average windspeed at the 62-meter elevation; and

$n = n(j)$ is the appropriate coefficient from Table 5 of Reference 1.

The use of Equation 2 is implicit in the remaining methodology.

In the following sections of this report, the index notation, ijk, will be suppressed except when necessary for clarity. However, by the absence of such notation, we imply a particular probable windspeed-stability (ij) condition in a particular compass sector (k).

3. Downwind Radionuclide Integral Air Concentrations

In the dose methodology, which assumes no evacuation of compass-sector people, we will require the downwind air concentrations of the radionuclides integrated over total exposure time. Appendix B of this report, which utilizes Appendix A, presents a comprehensive description of the constant windspeed model for the (time-dependent) air concentrations, the associated relative air concentration (X/Q) models, and the derived integral air concentrations. In this section, we restate the constant windspeed model assumptions as pertinent to integral concentrations, and recapitulate the integral air concentration formulation.

3.1 Constant Windspeed Model Assumptions

During a release period of time duration, T, radioactivity is released to the atmosphere in nuclide-specific amounts, $q^T{}_n$. The released radioactivity is blown downwind in the x direction at constant windspeed, u, accompanied by diffusion in the crosswind (y) and vertical (z) directions. As the released radioactivity is transported downwind from the release point at (0,0,h), there is decay and ingrowth of radioactivity during the transport time, $\tau = x/u$, with possible appearance of new decay-chain radionuclides. The released radionuclides plus any new radionuclides are called the "exposure" radionuclides. The rate constants for the decay and ingrowth of the exposure radionuclides during the transport are contained in the matrix, A, which has ben described in Appendix A of this report.

3.2 The "Two-Hour" Integral Air Concentrations, $C_n=C_n(x,y,z)$

The so-called "two-hour" model presented in this section is utilized in calculating doses to the offsite maximum individuals in the downwind compass sector. We use the column vector, $\underline{C} = \underline{C}(x,y,z)$, with elements, $C_n = C_n(x,y,z)$, to denote the "two-hour" integral air concentrations of the exposure radionuclides (n) in the downwind region. Then, in accordance with Appendix B:

$$\underline{C}(x,y,z) = \frac{X}{Q}(x,y,z)\ e^{A\tau}\underline{q}^T \qquad (3)$$

where

$C_n(x,y,z)$ the elements of vector $\underline{C}$, are the integral air concentrations of the exposure nuclides, in Ci-sec/m^3;

q_n^T the elements of column-vector $\underline{q}^T$, are the amounts of the exposure radionuclides that were released during the release period (T), in Curies;

$e^{A\tau}$ is the (n-by-n) matrix from Appendix A that operates on vector $\underline{q}^T$ to account for decay and ingrowth during the transport time ($\tau = x/u$), dimensionless; and

$\frac{X}{Q}(x,y,z)$ is the appropriate model for the "two-hour" relative air concentration from Section 5.1 or 5.2 of Appendix B, in sec/m^3.*

3.3 The "Two-Hour" Average Integral Air Concentration, $\bar{C}_n=\bar{C}_n$

The so-called "two-hour" model presented in this section is utilized in calculating doses to onsite and offsite populations in the downwind compass sector. We use the column vector $\underline{\bar{C}} = \underline{\bar{C}}(x,z)$, with the elements, $\bar{C}_n = \bar{C}_n(x,z)$, to denote the exposure-time integrals of the average radionulcide air concentrations with respect to compass-sector arc at downwind distance x. Then, in accordance with Appendix B:

$$\underline{\bar{C}}(x,z) = \frac{\bar{X}}{Q}(x,z)\ e^{A\tau}\underline{q}^T \qquad (4)$$

*The concept of the "two-hour" X/Q is defined in NRC Regulatory Guide 1.145 (Ref. 5).

where

$\overline{C}_n(x,z)$ The elements of vector $\underline{\overline{C}}$, are the average integral air concentrations of the exposure radionuclides in Ci-sec/m^3;

$\frac{\overline{X}}{Q}(x,z)$ is the appropriate model for the "two-hour" average relative air concentration with respect to compass-sector arc, in sec/m^3; and

$e^{A\tau}$ and $\underline{q}^T$ are as defined under Equation 3, above.*

3.4 The Annual-Average Integral Air Concentrations, $\bar{\bar{C}}_n=\bar{\bar{C}}_n(x,z)$

The annual-average (8760-hour) model presented in this section is required when the release period (T) is longer then two hours, to enable the necessary logarithmic interpolation between the "two-hour" integral air concentration (Section 3.2 or 3.3, above) and the 8760-hour integral air concentration.** In accordance with Appendix B and for an implied compass-sector k:

$$\underline{\bar{\bar{C}}}(x,z) = \sum_{ij}\sum f_{ijk}[\frac{\overline{X}}{Q}(x,z)]_{ijk}\underline{q}^T(\tau_{ijk}) \qquad (5)$$

*In later sections, it will be convenient to represent the result from the operation of $e^{A\tau}$ on $\underline{q}^T$ by

$$\underline{q}^T(\tau) \equiv e^{A\tau} \; \underline{q}^T.$$

The methodology for obtaining $\underline{q}^T(\tau)$ and resolving it into exposure radionuclide components associated with the released radionuclide and the associated release periods has been described in Appendix A.

**The logarithmic interpolation, which is analogous to that used for relative air concentrations in NRC Regulatory Guide 1.145 (Ref. 5), is as described in Section 7 of Appendix B. In later sections of this report, we will use the notation, $C^T{}_n(x,y,z)$ and $\overline{C}^T{}_n(x,z)$, to denote the integral air concentrations as determined for the particular release period, T.

where

$\bar{\bar{C}}_n(x,z)$ the elements of vector $\underline{\bar{\bar{C}}}$, are the annual-average integral air concentrations of the exposure nuclides, in Ci-sec/m^3;

f_{ijk} are the probabilities of occurrence from Section 2, dimensionless;

$[\frac{\overline{X}}{Q}(x,z)]_{ijk}$ are the components of the annual-average relative air concentration from Section 7 of Appendix B, in sec/m^3; and

$\underline{q}^T(\tau_{ijk})=e^{A\tau_{ijk}}\underline{q}^T$ is the column vector containing the inventory of the exposure radionuclides at the transport time, $\tau_{ijk} \equiv x/u_{ijk}$, in curies.

4. Doses From Inhalation

The dose receptors of interest in the downwind compass sector are the offsite maximum individuals and the offsite and onsite populations. In the inhalation dose calculations, we assume constant breathing rates and no evacuation of people. The basic equation used in calculating the dose to an individual from inhalation of a particular radionuclide is

$$\text{Dose} = [\text{Amount Inhaled}] \times [\text{Dose Commitment Factor}] \qquad (6)$$

where

$$[\text{Amount Inhaled}] = [\text{Breathing Rate}] \times [\text{Integral Air Concentration}]$$

4.1 Dose Commitment Factors, $DFA^a{}_{on}$, in mrem/pCi

We utilize the age-specific inhalation dose commitment factors of Hoenes and Soldat* (NUREG-0172, Ref. 8), which are tabulated by age group, body organ and radionuclide and are expressed in units of millirem per picocuri inhaled (mrem/pCi). These 50-year dose commitment factors are represented by the notation, $DFA^a{}_{on}$, where index a denotes an age group in the list, adult, teenager, child, and infant (4 groups); index o denotes a body organ in the list, bone, liver, total body, thyroid, kidney, lung, and GI-LLI (7 organs); and index n denotes the exposure radionuclide.

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*More precisely, the inhalation dose factors of Hoenes and Soldat with such corrections as appeared in the Dose Factor Library Of The NRC's LADTAP II Code (NUREG/CR-1276, Ref. 9).

4.2 Breathing Rates, BR^a, in m^3/yr

We utilize the age-specific breathing rates that have been recommended for accident dose calculations in Table 2 of DPST-83-930 (Ref. 10). These recommended breathing rates are summarized in the following table.

		BR^a, cubic meters per year	
Index a	Age Group	Maximum Individual	Population Individual
1	Adult	12,000	10,500
2	Teenager	12,000	10,500
3	Child	7,800	6,840
4	Infant	2,500	2,190

The rates under Column 3 of the above table are used in determining inhalation doses to the offsite maximum individuals and those under Column 4, in determining doses to the onsite and offsite populations. However, as opposed to the offsite population, the onsite population consists entirely of adult workers. The distributions of the populations are as described in Appendix C to this report.

4.3 Inhalation Doses To Offsite Maximum Individuals

These individuals are assumed to be located on the plume centerline (y=0) at ground level (z=0) and that downwind distance, $x=x_o$, where the ground level relative air concentration, $[X/Q](x,y,0)$, attains its maximum offsite value in the particular downwind compass sector.* Then, in accordance with Equation 6, the inhalation doses are given by:

$$DI_{on}^{a} = (3.17 \times 10^{4}) \bullet DFA_{on}^{a} \bullet BR^{a} \bullet C_{n}^{T}(x_o,0,0) \quad (7)$$

where

DI_{on}^{a} is the dose to body-organ o of age-specific individual a from inhalation of exposure nuclide n, in mrem;

*The determination of $x = x_o$ is described in Section 9 of Appendix B.

DFA^{a}_{on} is the dose committment factor from Section 4.1, in mrem/pCi;

BR^{a} is the maximum individual breathing rate from Section 4.2, in m^3/yr;

$C^{T}_{n}(x_o,0,0)$ is the integral air concentration of exposure nuclide n at the receptor location for the particular release period (T), in Ci-sec/m^3*; and

(3.17×10^4) is a conversion factor,

$$(10^{12}\ pCi/Ci)x(3.17x10^{-8}yr/sec).$$

4.4 Inhalation Doses To Compass-Sector Populations

The distributions of the offsite and onsite populations by age group, compass sector and radial increment are as described in Appendix C to this report. Although the inhalation doses to the two compass-sector populations are determined separately, the formulation presented in this section is utilized for either population.

4.4.1 Average Integral Air Concentration In A Compass-Sector Radial Increment

Since the population within a compass-sector radial increment is assumed to be uniformly distributed, the radionuclide amount inhaled will be proportional to the average integral air concentration in that increment. The average integral air concentration of exposure nuclide n in the radial increment r of the particular compass sector is defined by

$$\bar{C}^{r}_{n} = \sum_{T} \int_{x_r}^{x_{r+1}} x\ \bar{C}^{T}_{n}(x,0)dx/(x_{r+1} + x_r) \qquad (8.1)$$

---

*Based on use of Equations 3 and 5, above, in Equation 24 or 26a of Appendix B, depending on the length of the release period, T. If there are multiple release periods (T_p), there is an implied summation over the release periods in Equation 7, above.

where

$\bar{C}_n^T(x,0)$ is the integral of the average air concentration of exposure nuclide n along the ground-level compass-sector arc at downwind distance x which arises from the particular release period, T;*and

x_r and x_{r+1} are the inner and outer radial bounds for the radial increment r as defined in Section 3.1 of Appendix C.

Carrying out the integration on the right-hand side of Equation 8.1 by means of the simple trapezoidal rule, we have the result,

$$\bar{C}_n^r = \sum_T \{x_r \bar{C}^T(x_r,0) + x_{r+1}\bar{C}_n^T(x_{r+1},0)\} / (x_r + x_{r+1}) \quad (8.2)$$

which is the approximation that is used to evaluate the average integral air concentration in the radial-increment r of the particular compass sector (k).

4.4.2 Inhalation Doses

We utilize the notation, $P^a{}_r \equiv P^a{}_{rk}$, to denote the population distribution by age group (a) and radial increment (r) in the implied compass sector (k). Then, based on Equation 6, above, the inhalation doses to the compass-sector population (for the implied meteorological condition, ij) are given by:

$$PDI_{on} = (31.7) \sum_{r=1}^{10} \sum_{a=1}^{4} DFA_{on}^a \bullet BR^a \bullet P_r^a \bullet \bar{C}_n^r \quad (9)$$

where

PDI_{on} is the dose to body-organ o of the compass-sector population from inhalation of exposure nuclide n, in man-rem;

$DFA^a{}_{on}$ are the 50-year dose commitment factors from Section 4.1, in mrem/pCi;

BR^a are the population-individual breathing rates from Section 4.2, in m^3/yr;

*Based on use of Equations 4 and 5, above, in Equation 25 or 27a, depending on the length of the release time period, T.

P^a_r is the number of age-group a individuals in radial increment r of the particular compass sector, in persons;

$\bar{C}^r_n$ is the average integral air concentration of exposure nuclide n in radial increment r from Equation 8.2, in Ci-sec/m^3; and

(31.7) is the conversion of units factor, i.e.,

(10^{-3}rem/mrem)(10^{12}pCi/Ci)(3.17 x 10^{-8}yr/sec).

5. Doses From Plume Gamma Radiation

The basic gamma-ray dose methodology is described in depth in Appendix E to this report. The total-body dose is evaluated at a body-tissue depth of 5 centimeters, assuming body tissue is the same in all individuals; hence, the total-body doses from plume-gamma shine are not age specific. Further, as in the NRC's GASPAR Code (Ref.14), it is assumed that the other body organs (Section 4.1, above) receive the same dose as the total body. Since the doses from plume shine are neither age-group specific nor body-organ specific, they are hereinafter called "shine doses".

The shine dose receptors of interest are the offsite maximum individuals and the offsite and onsite population in the particular downwind compass sector. The offsite maximum individuals are assumed to be fully exposed to the plume shine; for the populations, it is assumed a 50% attenuation of the gamma rays by building structures.

As indicated by Lines 154-157 of Table 2, the AXAIR Code offers a choice of shine dose calculation methods; namely, in decreasing order of realistic dose determination and required computer CPU time:

(1) The nonuniform atmospheric plume method;
(2) The recommended nonuniform plume upper-bound approximation; or
(3) The uniform plume approximation.

The recommended method (Method 2) is a special case of Method 1 in which non-uniform plume method is used to determine the population doses but an upper-bound approach is used to estimate the doses to the offsite maximum individuals. Where necessary, the latter (upper-bound) doses may be reduced several fold in value by subsequent use of Method 1; however, Method 1 is considerably more computationally intensive than Method 2 (about 10 to 20 minutes of additional CPU time). The uniform plume approximation method (Method 3) is an historic method for estimating the individual and population doses; it usually, but not always, overestimates the shine doses.

In Sections 5.1 and 5.2, below, we consider the determination of the shine doses by the uniform plume approximation method and by the nonuniform plume method, respectively. The recommended method is included under the latter section.

5.1 Shine Doses By The Uniform Plume Approximation Method

The integral air concentrtions of the exposure radionuclides in the atmospheric plume have been described in Section 3, above. In the uniform plume approximation, we assume a uniform integral air concentration of the exposure nuclide throughout the infinite hemisphere above ground level, in which the integral air concentration is identical to that at the receptor location. The basic gamma-ray dose methodology associated with this approximation is described in Section 3.2 of Appendix E. Accordingly, the shine dose to an individual from a particular exposure nuclide is directly proportional to the integral air concentration of that nuclide at his location. The shine doses to the offsite maximum individuals and the populations in the particular compass sector are considered separately, below.

5.1.1 Uniform-Plume Shine Doses To Offsite Maximum Individuals

As in Section 4.3, above, these individuals are located on plume centerline (y=0) at ground level (z=0) and downwind distance, $x = x_o$, in the particular compass sector. Then, in accordance with Section 3.2 of Appendix E, the shine dose from exposure nuclide n is given by

$$DS_n = DFB_n \bullet C_n^T(x_o,0,0) \qquad (10)$$

where

DS_n is the shine dose from exposure nuclide n, in mrem;

DFB_n is the uniform-plume shine dose factor for radionuclide n as described in Section 3.2 of Appendix E, in $\frac{mrem}{Ci}$ per $\frac{sec}{m^3}$; and

$C_n^T(x_o,0,0)$ is the integral air concentration of the exposure nuclide n at the receptor location which arises from the particular release period (T), in Ci-sec/m^3.*

5.1.2 Uniform-Plume Shine Doses To Compass-Sector Populations

Although the shine doses to the offsite and onsite populations are determined separately, the methodology is the same for either population. The distribution of the population, P_{rk}, by compass sector (k) and radial increment (r) is as described in Appendix C to this report. Apart from the use of a different and age-independent dose factor, the determination of the shine dose is analogous to the determination of the inhalation dose in Section 4.4, above. Accordingly, the shine dose from exposure nuclide n to the population in the particular downwind compass sector, which is associated with an implied meteorological condition (ijk) is given by:

$$PDS_n = (0.001) \bullet SF \bullet DFB_n \sum_{r=1} P_r \bar{C}_n^r \qquad (11)$$

where

PDS_n is the shine dose from exposure nuclide n to the population in the particular compass sector, in man-rem;

$SF = 0.5$ is the transmission factor for 50% attenuation of the gamma rays by building structures, dimensionless;

DFB_n is the uniform-plume shine dose factor for nuclide n, in $\frac{\text{mrem}}{\text{Ci}}$ per $\frac{\text{sec}}{\text{m}^3}$;

$P_r = P_{rk}$ is the number of people in radial increment r of the sector, persons;

$\bar{C}_n^r$ is the average integral air concentration of nuclide n in radial increment r from Equation 8.2, above, in Ci-sec/m^3; and

---

*Based on use of Equations 3 and 5, above, in Equation 24 or 26a of Appendix B, depending on the length of the release period, T. Further, if there are multiple release periods (T_p) associated with the released radionuclides that yield the exposure nuclide, there is an implied summation over all such release periods in the right-hand side of Equation 10.

is the conversion of units factor, 1 rem per 1000 mrem.

5.2 Shine Doses By The Non-Uniform Plume Method

The basic gamma-ray dose methodology is as described in Appendix E, excluding Section 3.2 thereof. In the non-uniform plume method, we realistically, albeit only to good approximation, account for the Gaussian nature of the atmospheric plume in the hemisphere above ground level. More precisely, the integral air concentration of exposure radionuclide in the yz-plane through the receptor location at downwind distance, $x = x_o$, is as given in Section 3, above, but the integral air concentration in all the other yz-planes is taken to be the same as in the receptor plane.

As described in Appendix E, the gamma rays are accumulated into 23 energy groups which are denoted by the index m. Then, relative to the formulation presented in Section 5.1, above, the shine doses would - in principle but not precisely - be obtained by replacing the uniform-plume dose factor (DFB_n) with energy-group dose factors (DF_{mn}); replacing the integral air concentration (C_n, $\overline{C}_n$ or $\overline{\overline{C}}_n$) with associated energy-group shine integrals (S_{mn}, $\overline{S}_{mn}$ or $\overline{\overline{S}}_{mn}$); and summing over the energy groups (m).

The several types of shine integrals are considered first. Following this we present the formulation for the determintion of the shine doses to the offsite maximum individuals and the offsite and onsite populations in the particular compass sector.

5.2.1 Shine Integrals

For each integral air concentration model in Section 3, there is a corresponding shine integral model; namely, the "two-hour" shine integral (S_{mn}), the "two-hour" average shine integral ($\overline{S}_{mn}$) and the annual-average shine integral ($\overline{\overline{S}}_{mn}$). These three types of shine integrals will be discussed in the following subsections. However, before proceeding with this, we consider a common factor which will appear in the integrands of all the shine integrals.

As indicated in Appendix E, the gamma rays are accumulated into energy groups (m), each group having a characteristic photon energy, E_m. The common factor appearing in the integrands of the shine integrals is defined by

$$F(m,r) = \mu_{am} \frac{B(\mu_m r)\ \exp(-\mu_m r)}{4\pi r^2} \tag{12}$$

where

$r = (x^2 + y^2 + z^2)^{1/2}$, in meters;

μ_{am} is the photon energy absorption coefficient for photons of energy E_m in air, in m^{-1};

μ_m is the photon attenuation coefficient for photons of energy E_m in air, in m^{-1}; and

$B(\mu_m r)$ is the gamma ray buildup function described in Appendix D to this report, dimensionless.

5.2.1.1 The "Two-Hour" Shine Integral, $S_{mn} = S_{mn}(x_o)$

In accordance with Section 4 of Appendix E, the two-hour shine integral, $S_{mn} = S_{mn}(x_o)$, with respect to the receptor on plume centerline at ground level and downwind distance x_o, is given by

$$S_{mn}(x_o) = \int_0^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F(m,r)\ C_n(x_o,y,z)\ dxdydz \tag{13}$$

where

$S_{mn}(x_o)$ is the value of shine integral, in Ci-sec/m^3;

$F(m,r)$ is as given by by Equation 12, in m^{-3}; and

$C_n(x_o,y,z)$ is the "two-hour" integral air concentration in the yz-plane through the receptor location from Equation 3, above, in Ci-sec/m^3.

The methodology for evaluating this integral is described in Appendix E.

Upper-Bound Approximation:

With respect to the integral air concentration, $C_n(x_o,y,z)$, in Equation 13, we note that it attains its maximum value in the y direction at $y = 0$; i.e., $C_n(x_o,0,z) \geq C_n(x_o,y,z)$.

Accordingly, for use in the recommended non-uniform plume upper-bound approximation (Method 2, above), the upper bound to Equation 13 is given by

Upperbound:

$$S_{mn}(x_o) = \int_0^\infty \int_{-\infty}^\infty \int_{-\infty}^\infty F(m,r)\ C_n(x_o,0,z)dxdydz \tag{14}$$

5.2.1.2 The "Two-Hour" Average Shine Integral, $\bar{S}_{mn}=\bar{S}_{mn}(x_o)$

In accordance with Section 4 of Appendix E, the two-hour average shine integral, $\bar{S}_{mn}=\bar{S}_{mn}(x_o)$, with respect to the average ground-level receptor on compass-sector arc at downwind distance x_o, is given by

$$\bar{S}_{mn}(x_o) = \int_0^\infty \int_{-\infty}^\infty \int_{-\infty}^\infty F(m,r)\ \bar{C}_n(x_o,z)\ dxdydz \tag{15}$$

where

$\bar{S}_{mn}(x_o)$ is the value of the shine integral, in Ci-sec/m^3;

$F(m,r)$ is as given by Equation 12, in m^{-3}; and

$\bar{C}_n(x_o,z)$ is the "two-hour" average integral air concentration from Equation 4, avove, in Ci-sec/m^3.

The methodology for evaluating this integral has been described in Appendix E.

5.2.1.3 The Annual-Average Shine Integral, $\bar{\bar{S}}_{mn}=\bar{\bar{S}}_{mn}(x_o)$

In accordance with Section 5 of Appendix E and by analogy with Section 3.4, above, the annual-average (8760-hour) shine integral, $\bar{\bar{S}}_{mn}=\bar{\bar{S}}_{mn}(x_o)$, with respect to any recepton on compass-sector arc at downwind distance x_o in the particular compass sector (k), is given by the following formulation:

$$\bar{\bar{S}}_{mn}(x_o) = \int_0^\infty \int_{-\infty}^\infty \int_{-\infty}^\infty F(m,r)\bar{\bar{C}}_n(x_o,z)\ dxdydz \tag{16}$$

where

$\bar{\bar{S}}_{mn}(x_o)$ is the value of the shine integral, in Ci-sec/m^3;

$F(m,r)$ is as given by Equation 12, in m^{-3}; and

$\bar{\bar{C}}_n(x_o,z)$ is the annual-average integral air concentration of exposure nuclide n at downwind distance x_o, which is obtained from Equation 5, above, in Ci-sec/m^3.

The methodology for evaluating the above shine integral is described in Appendix E.

5.2.2 Release-Period Shine Doses To Individual Receptors

The release-period shine doses are the shine doses from the radioactivity that was released to atmosphere during a specific release time period, T. In the following subsections we consider the release-period shine doses to the individual on plume centerline and the average individual on compass-sector arc at downwind distance, x_o. The required shine integrals from Section 5.2.1 are, of course, based on the radioactivity released during the same release time period.

5.2.2.1 Release-Period Shine Doses To The Plume-Centerline Individual, $D^T{}_n(x_o)$

The "two-hour" shine dose, $D_n(x_o)$, and the annual-average shine dose, $\bar{\bar{D}}_n(x_o)$, from exposure nuclide n to this individual are given by

$$D_n(x_o) = \sum_m DF_{mn} S_{mn}(x_o), \text{ in mrem,} \tag{17.1}$$

and

$$\bar{\bar{D}}_n(x_o) = \sum_m DF_{mn} \bar{\bar{S}}_{mn}(x_o), \text{ in mrem,} \tag{17.2}$$

where

DF_{mn} is the shine dose factor for the gamma rays of nuclide n in the m^{th} energy group (Appendix E), in $\frac{\text{mrem}}{\text{Ci}}$ per $\frac{\text{sec}}{m^3}$;

$S_{mn}(x_o)$ is the "two-hour" shine integral given by Equation 13 or 14, in Ci-sec/m^3; and

$\bar{\bar{S}}_{mn}(x_o)$ is the annual-average shine integral given by Equation 16, in Ci-sec/m^3.

Then, utilizing Equation 17.1 and 17.2 in accordance with Section 8 of Appendix B, the release-period shine dose from exposure nuclide n to the plume-centerline individual at downwind distance x_o is given by

$$D_n^T(x_o) = D_n(x_o) \text{ for } T \leq 2 \text{ hours}$$

or (18)

$$D_n^T(x_o) = D_n(x_o)\exp\{-\frac{\ln(T/2)}{\ln(8760/2)} \circ \ln[D_n(x_o)/\bar{\bar{D}}_n(x_o)]\} \text{ for } T > 2 \text{ hours.}$$

5.2.2.2 Release-Period Shine Doses To The Average Individual, $D^T{}_n(x_o)$

The "two-hour" shine dose, $\bar{D}_n(x_o)$, and the annual-average shine dose, $D_n(x_o)$, from exposure nuclide n to the average population-individual on compass-sector are at downwind distance x_o are given by

$$\bar{D}_n(x_o) = SF \bullet \sum_m DF_{mn}\bar{S}_{mn}(x_o), \text{ in mrem,} \qquad (19.1)$$

and

$$\bar{\bar{D}}_n(x_o) = SF \bullet \sum_m DF_{mn}\bar{\bar{S}}_{mn}(x_o), \text{ in mrem,} \qquad (19.2)$$

where

SF = 0.5 is the transmission factor for 50% attenuation of gamma rays by building structures, dimensionless;

DF_{mn} is the shine dose factor for the gamma rays from nuclide n in the mth energy group, in $\frac{mrem}{Ci}$ per $\frac{sec}{m^3}$;

$\bar{S}_{mn}(x_o)$ is the "two-hour" shine integral given by Equation 15 or 14, in Ci-sec/m^3; and

$\bar{\bar{S}}_{mn}(x_o)$ is the annual-average shine integral given by Equation 16, in Ci-sec/m^3.

Then, utilizing Equation 19.1 and 19.2 in accordance with Section 8 of Appendix B, the release-period shine dose from exposure nuclide n to the average population-individual on compass sector arc is given by

$$\bar{D}_n^T(x_o) = \bar{D}_n(x_o) \text{ for } T \leq 2 \text{ hours}$$

or

$$D_n^T(x_o) = \bar{D}_n(x_o)\exp\{-\frac{\ln(T/2)}{\ln(8760/2)} \bullet \ln[\bar{D}_n(x_o)/\bar{\bar{D}}_n(x_o)]\} \text{ for } T > 2 \text{ hours.} \tag{20}$$

5.2.3 Shine Doses To The Offsite Maximum Individuals

As in Section 4.3, above, these individual are located on plume centerline (y=0) at ground level (z=0) and that downwind distance (x_o) where the ground-level relative air concentation attains its maximum value in the particular downwind compass sector. Then, utilizing Section 5.2.2.1 and summing over all of release time periods, the shine dose from exposure nuclide n to any one of these individuals is given by

$$DS_n = \sum_T D_n^T(x_o) \tag{21}$$

where

DS_n is shine dose to the offsite maximum individual in the particular compass sector from exposure radionuclide n due to all of the release time periods, in mrem; and

$D_n^T(x_o)$ is the shine dose arising from a specific release time period which is given by Equation 18, above.

5.2.4 Shine Doses To Compass-Sector Populations

Although the shine doses to the offsite population and the onsite population in the paticular compass sector are evaluated separately, the methodology is the same for either population. The distribution of the (onsite or offsite) population, $P_r \equiv P_{rk}$, by radial increment (index r) and an implied downwind compass sector (k) is as described in Appendix C to this report. First, we consider the shine doses to the average individual in radial-increment r and, then, the shine doses to the compass-sector population.

The determination of the average shine dose from exposure nuclide n in radial-increment r is analogous to the determination of the average integral air concentration in Section 4.4.1, above. Accordingly, the shine dose of interest is given by

$$\overline{DS}_n^r = \sum_T [x_r \overline{D}_n^T(x_r) + x_{r+1}\overline{D}_n^T(x_{r+1})]/(x_r + x_{r+1}) \tag{22}$$

where

$\overline{DS}^r{}_n$ is the shine dose from exposure nuclide n to the average individual in radial-increment r from all of the release time periods, in mrem;

x_r and x_{r+1} are the inner and outer radial bounds for radial-increment r as defined in Section 3.1 of Appendix C, in meters; and

$\overline{D}_n^T(x_r)$ and $\overline{D}_n^T(x_{r+1})$ are the release-period-specific shine doses to the average individuals on the compass-sector arcs at the radial bounds, which are given by Equation 20, above, in mrem.

Then, utilizing the known population distribution by radial increment, the shine dose from exposure radionuclide n to the compass-sector population from all of the release time periods is given by

$$PDS_n = (0.001)\sum_r P_r \overline{DS}_n^r \tag{23}$$

where

PDS_n is the shine dose from exposure nuclide n to the compass-sector population, in man-rem;

P_r is the compass sector population distribution by radial increment, in persons;

$\overline{DS}^r{}_n$ is the shine dose to the average individual given by Equation 22, in mrem; and

(0.001) is the conversion of units factor, 1 rem/1000mrem.

6.0 Plume-Exposure Doses For Probable Meteorological Conditions

The plume-exposure dose to a particular body organ is the sum of the shine dose (Section 5) and the organ-specific inhalation dose (Section 4). For each of the probable meteorological (ijk) conditions considered in Section 2, there will be associated plume-exposure doses as described below.

6.1 Doses To The Offsite Maximum Individuals In Compass-Sector k

The plume-exposure dose from nuclide n to organ o of individual a due to windspeed-stability condition ij in downwind compass-sector k is denoted and given by

$$[D^a_{on}]_{ijk} = [DI^a_{on}]_{ijk} + [DS_n]_{ijk}, \text{ in mrem,} \qquad (24)$$

where

$[DI^a{}_{on}]_{ijk}$ is the inhalation organ-dose contribution from Equation 7; and

$[DS_n]_{ijk}$ is the shine-dose contribution from Equation 10 or 21.

In addition, the associated plume-exposure dose from all of the exposure nuclides to organ o is denoted and given by

$$[D^a_o]_{ijk} = \sum_n [D^a_{on}]_{ijk}, \text{ in mrem,} \qquad (25)$$

where

$[D^a{}_{on}]_{ijk}$ is the nuclide-specific contribution from Equation 24.

6.2 Doses To The Offsite Or Onsite Population In Compass-Sector k

The plume-exposure dose from nuclide n to organ o of the (offsite or onsite) population in compass-sector k due to windspeed-stability condition ij is denoted and given by

$$[D_{on}]_{ijk} = [PDI_{on}]_{ijk} + [PDS_n]_{ijk}, \text{ in man-rem,} \tag{26}$$

where

$[PDI_{on}]_{ijk}$ is the inhalation organ-dose contribution from Equation 9; and

$[PDS_n]_{ijk}$ is the shine-dose contribution from Equation 11 or 23.

In addition, the associated plume-exposure dose from all of the exposure nuclides to body-organ o is denoted and given by

$$[D_o]_{ijk} = \sum_n [D_{on}]_{ijk}, \text{ in man-rem,} \tag{27}$$

where

$[D_{on}]_{ijk}$ is the nuclide-specific contribuiton from Equation 26.

7.0 Probability Analysis And Output Doses

The probability ananlysis of the above plume-exposure doses is implemented separately for the onsite population, the offsite population and the four offsite maximum individuals. Since there will be fully analogous analysis and output doses in each instance, we will only consider the case of a population.

The relevant plume-exposure doses to the body organs are given by Equation 27. The frequency of occurrence for such an organ dose of a component thereof (Eqn. 26) is the same as that for the meteorological condition from which it arises (Section 2). Because the total body is by far the most important organ for dose consequence purposes, the probability analysis is carried out with respect to the possible total-body doses and their frequencies of occurrence.*

The total-body dose determined by the AXAIR code is that which would only be exceeded 0.5% of the time based on worst-sector, worst-case meteorological probability analysis. This total-body dose and associated doses to the other body organs, with breakdowns by radionuclide and pathway, are found in the output stream from the AXAIR code. The probability analysis is described in the following two subsections.

7.1 Worst-Case Probability Analysis for Sector k

As described in Section 2, there are 42 possible windspeed-stability (ij) conditions in compass-sector k and their frequencies of occurrence, f_{ijk}, are given by Equation 1; the probable ij conditions are those for which $f_{ijk} > 0$. We assume that the organ doses (Eqn. 27) and their components (Eqn. 26) have been evaluated for the probable conditions. The worst-case analysis is with respect to the probable total-body (o=3) doses, i.e., the $[D_3]_{ijk}$. The objective is to determine the highest total-body dose, $[D_3]_k$, that would be exceeded only during 0.5% of the total meteorological time, and the associated doses to the other body organs.

To enable this, we list the values of $[D_3]_{ijk}$ in descending order, together with their frequencies of occurrence and the doses to the other body organs. Utilizing index d for the order of appearance, let $[D_3]_{dk}$ and f_{dk} denote the total-body doses and their frequencies in the ordered list. Next, we determine the cumulative frequencies, F_{dk}, down the ordered list, i.e., the

$$F_{dk} = \sum_{d=1}^{d} f_{dk}.$$

*Ideally, the probability analysis would be with respect to possible "effective whole-body doses," the effective dose being a relative-importance-weighted sum of the organ doses for the possible meteorological condition. However, in the current dose methodology based on NCR Regulatory Guide 1.109 (Ref. 11), the best measure of the effective whole-body dose is the total-body dose. Accordingly, in effect, we take weight factor for the total body to be unity and those for the other organs as zero.

The required total-body dose, $[D_3]_K$, is that which would occur at the 0.5% cumulative-frequency level, i.e., at F=0.005; this and the associated doses to the other body organs are obtained by linear interpolation between the two d levels nearest to F=0.005.* The associated doses are denoted by $[D_o]_K$, o = 3.

7.2 Worst-Sector Analysis And Output Doses

The worst-case probability analysis (Section 7.1) is carried out for each of the 16 compass sectors. The worst sector is that sector, k=K, with the highest total-body dose. Accordingly, $[D_3]_K$ is the total-body dose that would be exceeded only 0.5% of the time based on worst-sector, worst-case meteorological probability analysis. The worst-sector doses which are provided in the output stream from the AXAIR code are as follows:

$[D_3]_K$, the total-body dose from all of the exposure nuclides;

$[D_{on}]_K$, the breakdown of the doses by body organ and exposure nuclide;

$[PDI_{on}]_K$, the breakdown of the inhalation doses by body organ and exposure nuclide; and

$[PDS_n]_K$, the breakdown of the shine doses by exposure radionuclide.

8.0 Organization Of The AXAIR Code

As indicated in Table 2, the AXAIR code consists of the instream procedure that is found between Lines 7 and 150 in the data set, DSN = TENVT.TMECA.JCL(AXAIR). This instream procedure is invoked by Line 151 of Table 2 for the user input data following Line 152. The insteam procedure contains the following six sequential job steps:

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*However, if all the F_{dk} are less than 0.005, $[D_3]_k$ and the other doses are taken to be zero. In addition, if F_{1k} is greater than 0.005, the values are taken to be the same as those for the first d level (d=1).

Stepname	Primary Function
AXAIN	Reads in and writes out user input data; generates temporary data sets to drive subsequent job steps.
AXATER	For a stack release, generates the relative terrain elevations with respect to the stack location.
AXAPOP	Generates the distributions of the offsite and onsite populations about the release point.
AXAMET	Generates the meteorological parameters and the ground-level relative air concentrations.
PRIMUS	Executes the PRIMUS Code to generate the matrix A and bookkeeping information as described in Appendix A.
AXADOS	Determines and writes out the plume-exposure doses.

8.1 Load Modules For Job Steps

A separate load module is required by each job step in the above instream procedure; namely, DSN=TENVT.TMECA.LOAD(stepname). Each of these load modules has been created by execution of the job steam in the corresponding DSN=TENVT.TMECA.JCL(stepname).

8.2 FORTRAN Source Programs

The FORTRAN programs and subprogrmas, which are utilized in creating the load modules, are stored as members of the partitioned dat set, PDS=TENVT.TMECA.FORT. The names of the members required in creating a specific load module are listed in the corresponding DSN=TENVT.TMECA.JCL(stepname).

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APPENDIX A

DECAY AND INGROWTH OF RADIOACTIVITY

Elsewhere in this report, we utilize the matrix, A, which contains the rate constants for the decay and ingrowth of radioactivity in an inventory of radionuclides. This appendix describes that matrix and the computational means for its preparation and use in determining the time-dependent inventory which have been developed at the Oak Ridge National Laboratory. Further, we describe the utilization of this methodology in the AXAIR code for evaluating the decay and ingrowth of radioactivity during plume transport time.

1. Rate Equations and Matrix A

The rate equations for the decay and ingrowth of radioactivity in an inventory of exposure radionuclides, n = 1, 2, . . ., N, are:

$$\frac{dq_n}{dt} = \sum_p \lambda_n b_{np} q_p(t) - \lambda_n q_n(t), \text{ in Ci/sec,} \tag{1}$$

where

$q_n(t)$ = the activity of nuclide n at time t, in Ci;

λ_n = the decay constant for nuclide n, in sec^{-1};

$q_p(t)$ = the activity of nuclide p, a parent of nuclide n, at time t, in Ci; and

b_{np} = the branching fraction of nuclide p to nuclide n, dimensionless.

The above N rate equations can be rewritten in matrix notation as

$$\dot{\underline{q}}(t) = A\underline{q}(t) \tag{2}$$

where

$\underline{q}(t)$ = the column vector of elements, $q_n(t)$,

$$\dot{\underline{q}}(t) \underline{=} \frac{d}{dt} \underline{q}(t)$$

and

A = the square (N by N) matrix of coefficients to $q_n(t)$ and $q_p(t)$ in Equation 1, i.e., the diagonal elements of the matrix are $A_{nn} = -\lambda_n$ and the off-diagonal elements are $A_{np} = \lambda_n b_{np}$.

2. The Time-Dependent Radioactive Inventory

Assuming that the initial inventory, $\underline{q}(0)$, is known, the analytical solution of Equation 2 (by the calculus of Volterra) for the inventory, $\underline{q}(t)$, at a later time, t, is

$$\underline{q}(t) = e^{At}\underline{q}(0) \tag{3}$$

where the matrix, e^{At}, is defined by the series expansion of the expotential function,

$$e^{At} = I + \sum_{k=1}^{\infty} (At)^k/k!,$$

in which I is the identity matrix.

In addition, the definite time integral of a time-dependent inventory may be of separate interest in developing source terms (Curie amounts released) for user input to the AXAIR code. The definite time integral, which is obtained by integrating Equation 3, is given by

$$\int_0^t \underline{q}(t)dt = A^{-1}[e^{At} - I]\underline{q}(0) \equiv D(At)\underline{q}(0)t \tag{4}$$

where

the matrix, A^{-1}, is the inverse of matrix A, and

$D(At) \equiv (At)^{-1}[e^{At}-I]$ is the "matrix operator" that is employed in Reference 4 in lieu of direct evaluation of e^{At}.*

3. Computational Means

The methodology and computational means for generating the matrix, A, and determining the time-dependent inventory or its definite time integral are described in ORNL-5912 (Ref. 4). The PRIMUS Code, which is the principal topic of ORNL-5912, is invoked to generate a binary "PRIMUS Data Set" containing the matrix, A, and other necessary information. The PRIMUS Data Set is subsequently utilized by a "Package of Decay Subroutines" (Appendix D of ORNL-5912) to evaluate the components of Equation 3 or 4, above, at user-specified times, t. The Package of Decay Subroutines must, of course, have been incorporated into and invoked from an User's program.

The FORTRAN source for the PRIMUS Code is stored within the SRP Central Computer Facility in DSN = TENVT.TMECA.FORT(PRIMUS); the required alphanumeric "Decay Library" is stored in DSN = TENVT. PRIMUS.DECAYLIB.** The FORTRAN source for the Package of Decay Subroutines is stored in DSN = TENVT.TMECA.FORT(DCYPKG). The PRIMUS Code and the Decay Subroutines have been tested within the SRP Central Computer Facility environment and found suitable for the applications described in this appendix provided that the desirable but inoperable matrix truncation option (KTRUNC = 1) is avoided.

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*An example of possible use of Equation 4 in developing source terms would be for a postulated nuclear criticality accident in which the initial inventory, $\underline{q}(0)$, is known and it is assumed that $\underline{q}(t)$ is uniformly released to atmosphere during the time period, $0 \leq t \leq T$. Accordingly, the release rates would be

$$\underline{Q}(t) = \underline{q}(t)/T$$

and the amounts released to atmosphere during the time period, T, would be

$$\underline{q}_T = \int_0^T \underline{Q}(t)dt = \frac{1}{T}\int_0^T \underline{q}(t)dt.$$

**The current Decay Library contains 496 radionuclides. Additional radionuclides may be incorporated later by means of the augmentation procedure described in ORNL-5912.

Prior to use of the PRIMUS Code, we know only the names and amounts of those radionuclides that are initially present (at t=0); these radionuclides are called "released radionuclides" in the PRIMUS and AXAIR codes. When properly invoked with this initial information, the PRIMUS code furnishes the names (i.e., ZAS numbers) of the released nuclides; the names of the exposure radionuclides (all the ingrowth and decay radionuclides in Equation 1); the matrix, A; the initial inventory, $\underline{q}(0)$; and the necessary bookkeeping information. With respect to bookkeeping, we use the index, n_R, to denote a particular released radionuclide in the released radionuclide list, [1, 2, ..., NREL], and the index, n_E, to denote a particular exposure radionuclide in the exposure radionuclide list, [1, 2, ..., NEXP].

When invoked as indicated in Appendix D of ORNL-5912, the Decay Subroutines return the components of Equation 3 or 4, above, at the specified time t in the FORTRAN array, CONC(NEXP,NREL), and, if desired, also in the packed vector form, CPAK(NPACK).* The contents of the CONC array are considered below for the case of the time-dependent inventory (Equation 3); the contents for the other case (Equation 4) are obvious by analogy.

Assuming the initial inventory of the released radionuclides was in curie units (PRIMUS code input), the CONC array will contain the curie amounts of the exposure radionuclides at time t that arise from the decay of each released radionuclide. Using the previously described index notation, n_R and n_E, the meaning of a particular element in the CONC array is as follows:

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*Several errors exist in Appendix D of ORNL-5912, namely:

CONC(NEXP)	should read	CONC(NEXP,NREL);
IC(NEXP)	should read	IC(NPACK);
JC(NEXP)	should read	JC(NPACK);
CPAK(NEXP)	should read	CPAK(NPACK).

The relationship between the elements of CONC and CPAK is given by

CPAK(N) = CONC(IC(N),JC(N)) for N=1, 2, ..., NPACK.

Let n_R denote the index number of the particular released radionuclide (n_R) in the exposure radionuclide list, [1, 2, ..., n_R, ..., NEXP];

Then, with respect to Equation 3, above,

$$CONC(n_E, n_R) = [e^{At}]_{n_E n_R} \, q_{n_R}(0)$$

where (5)

$[e^{At}]_{n_E n_R}$ is the element that is in the n_E-th row n_R-th and column of the matrix, e^{At},

and

$q_{n_R}(0)$ is the n_R-th component of the vector, $\underline{q}(0)$.

In general, the array, CONC(NEXP,NREL), will be a very sparse array, ie.e, a large number of the elements will be identically zero, because only a few of the total number (NEXP) of exposure radionuclides arise from the decay of the particular released radionuclide. The elements that are identically zero are eliminated in the vector form of the array, CPAK(NPACK), which has been characterized in the previous footnote.

4. Decay and Ingrowth During Plume Transport Time

As described in Section 3.1 of the main text in this report, the plume transport time (τ) from the release point to the downwind distance of interest, x (in meters), is given by $\tau = x/u$ where u is the average windspeed (in meters per second). In this application, we specify the initial amounts of the released radionuclides as unity in the input to the PRIMUS code. Then, based on Equation 5, above, with the $q_{n_R}(0) = 1$, the Decay Subroutines are invoked to return to the CONC array for $t=\tau$ and the array elements are given by:

$$CONC(n_E, n_R) = [e^{A\tau}]_{n_E n_R}, \text{ dimensionless,} \quad (6.1)$$

or, in packed vector form, by

$$CPAK(n_p) = [e^{A\tau}]_{n_E n_R} \quad (6.2)$$

where

n_p is the index number in the list, $[1, 2, \ldots, n_p, \ldots, NPACK]$, that corresponds to the pair of indices, (n_E, n_R), for an exposure radionuclide (n_E) that arises from the released radionuclide (n_R).*

Further, as indicated in Section 2 of the main text, there are 42 possible meteorological conditions ($ij = 1, 2, \ldots, 42$) in the particular compass sector, and, hence, 42 possible average windspeeds, u_{ij}. In the dose methodology, we may simultaneously require the CPAK vectors for the 42 possible τ_{ij} at downwind distance x. To allow for this, the results from usage of the Decay Subroutines for each probable τ_{ij} are stored in the augmented array, CPAK(NPACK,42); accordingly, the elements of the augmented array are given by:

$$CPAK(n_p, ij) = [e^{A\tau_{ij}}]_{n_E n_R}. \qquad (6.3)$$

The above formulation is appropriate because the AXAIR code allows for multiple release time periods, T, with different $q^T{}_{n_R}(0)$ as indicated in Section 1 of the main text. Utilizing this and Equation 6.3 in Equation 3, above, the Curie amount of exposure nuclide n_E that arises from the initial amount of released radionuclide n_R associated with release period T is given by

$$q_{n_E}^{Tn_R}(\tau_{ij}) = CPAK(n_p, ij) q_{n_R}^T(0), \text{ in Ci} \qquad (6.4)$$

where

$CPAK(n_p, ij)$ is as given by Equations 6.2 and 6.3,

$q_{n_R}^T(0)$ is the initial amount of released radionuclide n_R from release period T, in Ci, and

$n_E = IC(n_p)$ and $n_R = JC(n_p)$.

The total amount of the exposure radionuclide for time period T is given by

$$q_{n_E}^T(\tau_{ij}) = \sum_{n_R} q_{n_E}^{Tn_R}(\tau_{ij}). \qquad (6.5)$$

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*$n_E = IC(n_p)$ and $n_R = JC(n_p)$.

APPENDIX B

CONSTANT WINDSPEED MODEL FOR DOWNWIND RADIONUCLIDE AIR CONCENTRATIONS

1. Assumptions

Beginning at time $t = 0$ and ending at $t = T$, radioactivity is released to atmosphere from a point source at the nuclide-specific release rates, $Q_n = Q_n(t)$. The released radioactivity is blown downwind in the x direction at constant windspeed, u, accompanied by Fickian apparent-eddy diffusion in the crosswind (y) and vertical (z) directions. As the radionuclides are transported downwind from the release point at (0,0,h), there will be decay and ingrowth of radioactivity during the transport time, $\tau = x/u$, with possible appearance of new decay-chain radionuclides. The released radionuclides plus any new radionuclides are collectively referred to as "exposure" radionuclides. The rate constants for the decay and ingrowth of radioactivity are contained within the matrix, A, which has been described in Appendix A.

2. Radionuclide Transport and Diffusion Equation

Let the column vector, $\underline{\chi} = \underline{\chi}(x,y,z,t)$ with elements $\chi_n(x,y,z,t)$, denote the downwind air concentrations of the exposure radionuclides and let $\underline{\underline{F}} = \underline{\underline{F}}(x,y,z,t)$ denote the radioactive flux matrix. By hypothesis, the radioactive flux matrix has the following advection and diffusion components in the x, y, and z directions:

$$\underline{F_x} = u\,\underline{\chi}; \quad \underline{F_y} = -K_y \frac{\partial \underline{\chi}}{\partial y}; \text{ and } \underline{F_z} = -K_z \frac{\partial \underline{\chi}}{\partial z}, \tag{1}$$

where

K_y and K_z are the Fickian diffusivities.

The Fickian diffusivities are treated as "apparent eddy diffusivities"; hence, the relationship between them and the meteorological dispersion coefficients, $\sigma_y = \sigma_y(x)$ and $\sigma_z = \sigma_z(x)$, is given by:

$$K_y = \frac{1}{2}\frac{d}{d\tau}\sigma_y^2 = u\,\sigma_y\sigma_y' \text{ with } \sigma_y' \equiv \frac{d\sigma_y}{dx}$$

and (2)

$$K_z = \frac{1}{2}\frac{d}{d\tau}\sigma_z^2 = u\,\sigma_z\sigma_z' \text{ with } \sigma_z' \equiv \frac{d\sigma_z}{dx}.*$$

* For example, see Section 3.8 of Csanady, G.T., Turbulent Diffusion in the Environment, D. Reidel Publishing Co. (1973). $\tau = x/u$ is the transport or diffusion time.

Conservation of radioactive material with respect to any volume element in the downwind region (x > 0) requires that

$$\frac{\partial \underline{\chi}}{\partial \tau} + \text{div}\ \underline{F} + A\underline{\chi} = 0 \quad \text{for } x > 0. \tag{3}$$

Combining Equations 1, 2 and 3 yields the radionuclide transport and diffusion equation,

$$\frac{\partial \underline{\chi}}{\partial t} + u\frac{\partial \underline{\chi}}{\partial x} - u\sigma_y\sigma_y'\frac{\partial^2 \underline{\chi}}{\partial y^2} - u\sigma_z o_z'\frac{\partial^2 \underline{\chi}}{\partial z^2} + A\underline{\chi} = 0 \quad \text{for } x>0. \tag{4}$$

3. Boundary Conditions

The atmospheric plume is confined to the downwind region above ground level; hence, there will be no radioactive flux through the ground-level xy plane at z = 0, i.e., $F_z\ (x,y,0,t) = 0$. Utilizing Equations 1 and 2, this requires

$$\frac{\partial \underline{\chi}}{\partial z}\Big|_{z=0} = 0. \tag{5}$$

In addition, as the distance x approahces the release point $(x \to 0)$, the total flow rate of radioactivity through the yz plane must approach the release rate from the point source at (0,0,h). Since the radioactive flux in the x direction is $\underline{F_x} = u\ \underline{\chi}$ and the release rate is column-vector $\underline{Q}(t)$ with elements $Q_n(t)$, this requires:

$$\lim_{x \to 0} \int_0^\infty \int_{-\infty}^\infty u\ \underline{\chi}(x,y,z,t)\ dy\ dz = \underline{Q}(t). \tag{6}$$

4. Radionuclide Air Concentrations, $\underline{\chi} = \underline{\chi}(x,y,z,t)$

The air concentrations of the exposure radionuclides in the downwind region (x>0) are obtained by solving the radionuclide transport and diffusion equation (Equation 4) subject to the boundary conditions (Equations 5 and 6). The result, which may be verififed by substitution into those equations, is as follows:

$$\underline{\chi}(x,y,z,t) = \phi(x,y,z)\ e^{A\frac{x}{u}}\ \underline{Q}\left(t - \frac{x}{u}\right) \tag{7}$$

provided that $\phi = \phi(x,y,z)$ is a solution of the partial differential equation,

$$\frac{\partial \phi}{\partial x} - \sigma_y \sigma_y' \frac{\partial^2 \phi}{\partial y^2} - \sigma_z \sigma_z' \frac{\partial^2 \phi}{\partial z^2} = 0, \quad (8a)$$

which satisfies the boundary conditions,

$$\frac{\partial \phi}{\partial z} \Big|_{z=0} = 0 \quad (8b)$$

and

$$\lim_{x \to 0} \int_0^\infty \int_{-\infty}^\infty u\, \phi(x,y,z)\, dydz = 1. \quad (8c)$$

In the above formulation, $\phi = \phi(x,y,z)$ is the (steady-state) relative air concentration, $\chi/Q = \chi/Q\ (x,y,z)$, that would arise from the release of a nonradioactive material at the constant release rate, Q. Generically, the χ/Q models that satisfy Equation(s) 8 are the meteorological Gaussian plume models; e.g., the basic Gaussian plume equation for stack releases,

$$\frac{\chi}{Q}(x,y,z) = \frac{\exp[-y^2/2\sigma_y^2]}{2\pi\sigma_y\ \sigma_z\ u} \left\{ \exp[-\frac{(z-h)^2}{2\sigma_z^2}] + \exp[-\frac{(z+h)^2}{2\sigma_z^2}] \right\}. \quad (9)$$

5. Relative Air Concentration Models, $\phi = \chi/Q(x,y,z)$

The χ/Q models utilized in the AXAIR code satisfy Equation(s) 8, except at ground level (z=0) for building-vent releases when building-wake dilution effects are included. On plume centerline (y=0) at ground level, the models are in accordance with NRC Regulatory Guide 1.145 (Ref. 5), which only considers cases with y = z = 0.

A release at the SRP may be either 1) from a stack or 2) through a building vent or other building penetration. However, if the release is from a stack height, h_s, that is less than 2-1/2 times adjacent building height, the user of the AXAIR code should specify a building-vent release. The constant windspeed, u, which is defined under the following models, is also utilized in determining the transport time, $\tau = x/u$, in Equation 7, above.

5.1 Stack Releases

The stack height, h_s, is assumed to be lower than the inversion-layer (or lid) height, L = 200 meters, which is used in the AXAIR code. The cases of nonfumigation and fumigation conditions are considered separately in Sections 5.1.1 and 5.1.2, below; the method of combining these cases for SRP stack releases is presented in Section 5.1.3..

5.1.1 Stack Release Under Nonfumigation Conditions

For a stack release in the absence of fumigation conditions, we utilize equation 9, above, as follows:

$$\frac{\chi}{Q}(x,y,z) = \frac{\exp[-y^2/2\sigma_y^2]}{2\pi\ \sigma_y\ \sigma_z\ u}\ \{\exp[-\frac{(z-h_e)^2}{2\sigma_z^2}] + \exp[-\frac{(z+h_e)^2}{2\sigma_z^2}]\}. \quad (10)$$

u is the windspeed at the stack height, h_s;

$h_e = h_s - h_t$ is the effective stack height ($h_e > 0$); and

$h_t = h_t(x)$ is the highest terrain elevation above stack grade elevation in the particular downwind compass sector out to radial distance x ($h_t > 0$).*

In the AXAIR code, $\sigma_y(x)$ and $\sigma_z(x)$ are evaluated by means of Subroutine POLYN from the NCR's PAVAN Code (Ref. 6) with minor exception; namely, we utilize the nondesert sigma curves without limitation on the value of σ_y, but limit the value of σ_z by $\sigma_z(x) < 0.8L$ where L is the lid height (200 m).

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* The evaluation of h_t (x) is enabled by the availability of a data base of terrain elevations within 15" by 15" cells of latitude and longitude which has been furnished by ORNL under purchase-order contract (AX-593175).

5.1.2 Stack Release Under Fumigation conditions

Fumigation consists of confinement of the downwind atmosphere plume between ground level and an effective lid height, $L_e = L_e(x)$, with uniform mixing in the vertical (z) direction. At the SRP site, we assume that fumigation can only occur 1) during stable atmospheric conditions (Pasquill Stability Class E, F, or G), 2) when the windspeed at the stack height is not greater than 4 meters per second, and 3) when only out to such a downwind distance x that the value of the "fumigation" χ/Q would not exceed the value given by Equation 10 with $z=h_e=0$.* If these 3 criteria are satisfied, "fumigation" χ/Q is given by:

$$\frac{\chi}{Q}(x,y,z) = \frac{\exp[-y^2/2\sigma_y^2]}{\sqrt{2\pi}\ u\ \sigma_y\ L_e}\ ,\ 0 \leq z \leq L_e, \qquad (11)$$

where

u is the windspeed ($u \leq 4$ m/s) at the stack height, h_s;

$L_e = L - h_t(x) \geq (L_e)\text{min}$; and

$$(L_e)\text{min} \equiv \frac{\pi\sigma_y\sigma_z\ u}{\sqrt{2\pi}\ u\ \sigma_y} = \sqrt{\pi/2}\ \sigma_z.\text{**}$$

5.1.3 Stack Release at SRP

We adopt the recommendations given in Section 2.1.2(a) of Reference 5 concerning determination of "two-hour" χ/Q's from a stack release at an inland site.*** Accordingly, if the criteria of Section 5.1.2

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* These 3 criteria are based on our interpretation of Section 1.3.2 (b) in Reference 5, as applicable to the SRP region.

** The formulation for (L_e) min is derived from the third criterion; namely, out to such distance x that [Eqn. 11] $\leq$ [Eqn. 10 with $z=h_e=0$].

***The χ/Q models presented in Section 5 of this appendix are "two-hour" χ/Q models which are suitable for direct application when the release time period, T, is in the range, 20 min $\leq$ T $\leq$ 2 hours. The usage of the "two-hour" χ/Q models is considered in Section 8, below.

(above) are met, a fumigation condition is assumed to exist during the first half hour of the "two-hour" period. Then, if the fumigation χ/Q (Eqn. 11) exceeds the nonfumigation X/Q at ground level (Eqn. 10 with z=0), we utilize the fumigation $X/Q(x,y,z)$ for the first half hour and the nonfumigation χ/Q (x,y,z) for the remainder of the "two-hour" period; otherwise, we use the nonfumigation $\chi/Q(x,y,z)$ for the entire "two-hour" period.

Summarizing the above in mathematical notation, wherein we utilize square brackets subscripted by 10 and 11 to denote results from Equations 10 and 11, respectively, we have:

If

$$\left[\frac{\chi}{Q}(x,y,0)\right]_{11} > \left[\frac{\chi}{Q}(x,y,0) \text{ with } h_e = 0\right]_{10},$$

Then

$$\frac{\chi}{Q}(x,y,z) = \frac{1}{4}\left[\frac{\chi}{Q}(x,y,z)\right]_{11} + \frac{3}{4}\left[\frac{\chi}{Q}(x,y,z)\right]_{10};$$

Otherwise,

$$\frac{\chi}{Q}(x,y,z) = \left[\frac{\chi}{Q}(x,y,z)\right]_{10}.$$

5.2 Building-Vent Releases

In the section, the χ/Q models are given separately for the relative air concentrattion within the atmospheric plume ($0 < z < \infty$) and for the relative air concentration at ground level (z=0) where building-wake dilution effects are considered. The former is utilized in determining plume gamma radiation doses to ground-level receptors; the latter, in determining inhalation doses from inhalation ground level.

5.2.1 Relative Air Concentration Within the Atmospheric Plume

For the relative air concentration within the atmospheric plume from a building-vent release, we utilize Equation 9, above, with h taken to be zero and the windspeed taken to be that at the ten-meter elevation above building grade level. According, the model is:

$$\frac{\chi}{Q}(x,y,z) = \frac{\exp[-y^2/2\sigma_y{}^2]}{\pi\sigma_y\ \sigma_z\ u} \quad \exp\left[-\frac{z^2}{2\sigma_z{}^2}\right] \tag{12}$$

where

U_{10} is the windspeed at the 10-meter elevation.

5.2.2 Relative Air Concentration at Ground Level

For the relative air concentration on plume centerline ($y=0$) at ground level ($z=0$), we adopt the models that are presented under Section 1.3.1 of Reference 5. In addition, for use in a later section, we include the Gaussian distribution term, $\exp\left[-y^2/2\sigma_y{}^2\right]$, for the y direction off plume centerline which has been omitted in Reference 5 because, therein, y is taken as zero.

Accordingly, the models are as follows:

$$\frac{\chi}{Q}(x,y,0) = \frac{\exp\left[-y^2/2\sigma_y{}^2\right]}{u_{10}\ (\pi\sigma_y\sigma_z + A/2)}\ ; \tag{13}$$

$$\frac{\chi}{Q}(x,y,0) = \frac{\exp\left[-y^2/2\sigma_y{}^2\right]}{u_{10}\ (3\pi\sigma_y\sigma_z)}\ ; \text{ and} \tag{14}$$

$$\frac{\chi}{Q}(x,y,0) = \frac{\exp\left[-y^2/2\sigma_y{}^2\right]}{u_{10}\ \pi\ \Sigma_y\ \sigma_z}\ , \tag{15}$$

where u_{10} is the windspeed at the 10-meter elevation

A is the minimum vertical cross-sectional area of the building; and

Σ_y is the lateral plume spread with meander and building wake effects as defined in Reference 5.

The usage of these models to obtain the proper relative air concentration is similar to that in Reference 5; namely,

During neutral (Pasquill Stability Class D) or stable (Class E, F, or G) atmospheric stability conditions and when the windspeed $u_{10} < 6$ m/s,

$$\frac{\chi}{Q}\ (x,y,0) = \text{minimum of } \left\{\left(\frac{\chi}{Q}\right)_{15},\ \text{maximum of } \left[\left(\frac{\chi}{Q}\right)_{13},\ \left(\frac{\chi}{Q}\right)_{14}\right]\right\} \tag{16}$$

where the subscripts denote Eqns. 13, 14 and 15, above,

and

During all other meteorological conditions,

$$\frac{\chi}{Q}\ (x,y,0) = \text{maximum of } \left[\left(\frac{\chi}{Q}\right)_{13},\ \left(\frac{\chi}{Q}\right)_{14}\right].$$

6. Average Radionuclide Air Concentrations on Compass-Sector Arc, $\underline{\bar{\chi}} = \underline{\bar{\chi}}(x,z,t)$

In determining doses to compass-sector populations, we will use the concept of the average individual at ground level along the 22.5-degree compass-sector arc at downwind distance x. Therefore, we require the average air concentrations with respect to compass-sector arc. These are derived from Equation 7, above, and the observation that all of the relative air concentration models in Section 5 were of the functional form,

$$\frac{\chi}{Q}(x,y,z) = \exp\left[-y^2/2\sigma_y^{\,2}\right] \frac{\chi}{Q}(x,0,z). \tag{17}$$

Since the arc angle is $\theta = \pi/8$, which is centered on the x direction, and the arc length is $x\theta$, the average radionuclide air concentrations are conservatively defined and given by:

$$\underline{\bar{\chi}}(x,z,t) = \frac{1}{x\theta} \int_{-\infty}^{\infty} \underline{\chi}(x,y,z,t)\, dy = \frac{\bar{\chi}}{Q}(x,z) e^{\frac{x}{\bar{A}u}} \underline{Q}(t-\frac{x}{u}) \tag{18a}$$

where

$$\frac{\bar{\chi}}{Q}(x,z) = \overline{\exp\left[-y^2/2\sigma_y^{\,2}\right]} \frac{\chi}{Q}(x,0,z),\ * \text{ with} \tag{18b}$$

$$\overline{\exp\left[-y^2/2\sigma_y^{\,2}\right]} = \frac{1}{x\theta} \int_{-\infty}^{\infty} \exp\left[-y^2/2\sigma_y^{\,2}\right] dy = \frac{\sqrt{2\pi}\,\sigma_y}{x\,(\pi/8)},$$

subject to the proviso, $\overline{\exp\left[-y^2/2\sigma_y^{\,2}\right]} \leqslant -1.$**

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* $\chi/Q\,(x,0,z)$ is obtained from the appropriate χ/Q model in Section 5, above.

**If $\overline{\exp\left[-y^2/2\sigma_y^{\,2}\right]} > 1$, we take $\bar{\chi}/Q\,(x,z) = \chi/Q\,(x,0,z)$ because the average relative air concentration cannot exceed the plume centerline value.

7. Annual Average Radionuclide Air Concentrations, $\bar{\bar{\chi}} = \underline{\bar{\bar{\chi}}}(x,z,t)$

Consistent with Sections 1.4 and 2.2.1 in Reference 5, when the release time period (T) is longer than 2 hours, we also require the annual average radionuclide air concentrations for each downwind compass sector. As indicated in Section 2 of the main text in this report, there are 42 possible windspeed-stability (ij) conditions in each compass sector (k), with (annual) probability of occurrence, f_{ijk}, and windspeed, u_{ijk}. For each ij condition in compass sector k, there will be a component of average relative air concentration; in the following discussion, the index (ijk) notation will be supressed until needed for clarity.

The model for the component of (sector-arc) average relative air concentration is obtained by combining Equations 10, 12, and 18b; namely,

$$\frac{\bar{\chi}}{Q}(x,z) = \overline{\exp\left[-y^2/2\sigma_y^{\ 2}\right]}\ \frac{\chi}{Q}(x,0,z) \tag{19}$$

with

$$\frac{\chi}{Q}(x,0,z) = \frac{1}{2\pi\sigma_y\sigma_z u}\left\{\exp\left[-\frac{(z-h_e)^2}{2\sigma_z^{\ 2}}\right] + \exp\left[-\frac{(z+h_e)^2}{2\sigma_z^{\ 2}}\right]\right\}$$

where, for a stack release, we utilize u at h_e where h_e is as defined under Equation 10, above; otherwise, $h_e = 0$ and $u = u_{10}$, the windspeed at the 10-meter elevation.*

Then, utilizing the index ijk notation and Equations 18a and 19, above, the annual average air concentrations of the radionuclides in the particular compass sector (k) are given by

$$\underline{\bar{\bar{\chi}}}(x,z,t) = \sum_i \sum_j f_{ijk}\left[\frac{\bar{\chi}}{Q}(x,z)\right]_{ijk} e^{A\tau_{ijk}}\ \underline{Q}(t-\tau_{ijk}) \tag{20}$$

where

f_{ijk} is the (annual) probability of occurrence,

$\tau_{ijk} = x/u_{ijk}$ is the transport time, and

$\left[\frac{\bar{\chi}}{Q}(x,z)\right]_{ijk}$ is the ijk-th component of sector-arc-average relative air concentration from Equation 19.

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* When $\overline{\exp\left[-y^2/2\sigma_y^{\ 2}\right]} = \frac{\sqrt{2\pi}\ \sigma_y}{x\ (\pi/8)} \leq 1$ and z=0, Equation 19 reduces

to $\frac{\bar{\chi}}{Q}(x,0) = \frac{2.032}{u\sigma_z x}\left\{\exp\left[-h_e^2/2\sigma_z^{\ 2}\right]\right.$,

which is a component of the annual average relative air concentration in Equation 3 of NRC Regulatory Guide 1.111 (Ref.7).

8. Exposure-Time Integral Air Concentrations

In the dose methodology we will assume no evacuation of potential downwind receptors. Hence, instead of the air concentration (Ci/m^3), we will require the air concentrations integrated over total time t at downwind distance x, in units of $Ci\text{-}sec/m^3$.

To enable determination of the appropriate integral air concentrations for a specific release time period (T), we first integrate Equations 7, 18, and 20, above. The respective results are:

$$\underline{C}\,(x,y,z) \equiv \int_0^\infty \underline{X}\,(x,y,z,t)\,dt = \frac{X}{Q}\,(x,y,z)\,\underline{q}^T(\tau); \qquad (21)$$

$$\underline{\bar{C}}\,(x,y,z) \equiv \int_0^\infty \underline{\bar{X}}\,(x,y,z,t)\,dt = \frac{\bar{X}}{Q}\,(x,y,z)\,\underline{q}^T(\tau); \qquad (22)$$

and

$$\underline{\bar{\bar{C}}}\,(x,y,z) \equiv \int_0^\infty \underline{\bar{\bar{X}}}\,(x,y,z,t)\,dt = \sum_i \sum_j f_{ijk} \left[\frac{\bar{X}}{Q}\,(x,z) \right]_{ijk} \cdot$$

$$\underline{q}^T\,(\tau_{ijk}), \qquad (23)$$

where

$$\underline{q}^T\,(\tau) = e^{A\tau}\,\underline{q}^T(0), \quad \tau = x/u, \text{ and}$$

$$\underline{q}^T\,(0) = \int_0^\infty \underline{Q}\,(t-\tau)\,dt = \int_\tau^{\tau+T} \underline{Q}(t-\tau)\,dt = \int_0^T \underline{Q}\,(t)\,dt,$$

in which the $\underline{q}^T$ (0) are the curie amounts of the radionuclides that are released from the release point during the release time period, T.*

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*Some of the indices (ijk) have been suppressed in the above equations, namely: Equations 21 and 22, which incorporate "two-hour" relative air concentration models, are for a particular ij condition in sector k; and Equation 23 is an annual average formulation for sector k.

In the following discussion, we use the notation, $\underline{C}^T (x,y,z)$ and $\underline{\bar{C}}^T (x,z)$, to represent the appropriate integral air concentrations and integral average air concentrations on compass-sector arc, respectively, for a specific release time period, T. Then utilizing Equations 21 through 23, above, the appropriate formulations for the cases of release time periods shorter and longer than two hours are taken to be as follows.

<u>Case of 20 minutes $\leq$ T $\leq$ 2 hours</u>

$$\underline{C}^T (x,y,z) = \underline{C} (x,y,z) \tag{24}$$

and

$$\underline{\bar{C}}^T (x,z) = \underline{\bar{C}} (x,z). \tag{25}$$

<u>Case of T > 2 hours</u>

Analogous to the treatment of χ/Q's in Sections 1.4 and 2.2.1 of Reference 5, we utilize, in principle, logarithmic interpolation between the "two-hour" model, $\underline{C} = \underline{C} (x,y,z)$ or $\underline{\bar{C}} = \underline{\bar{C}} (x,z)$, and the annual average (8760-hour) model, $\underline{\bar{\bar{C}}} = \underline{\bar{\bar{C}}} (x,z)$; namely,

$$\underline{C}^T (x,y,z) = \underline{C} \exp \left\{ -\ln \left(\underline{C} / \underline{\bar{\bar{C}}} \right) \frac{\ln (T/2)}{\ln (8760/2)} \right\} \tag{26a}$$

and

$$\underline{\bar{C}}^T (x,z) = \underline{\bar{C}} \exp \left\{ -\ln \left(\underline{\bar{C}} / \underline{\bar{\bar{C}}} \right) \frac{\ln (T/2)}{\ln (8760/2)} \right\} \tag{27a}$$

where it is understood that these equations are applied separately for each radionuclide (n) component of the column vectors, $\underline{C}^T$, $\underline{\bar{C}}^T$, $\underline{C}$, $\underline{\bar{C}}$ and $\underline{\bar{\bar{C}}}$. By "utilize, in principle," we mean that where necessary in the dose methodology, the logarithmic interpolation is between the "two-hour" dose model, $\underline{D} = \underline{D} (x,0,0)$ or $\underline{\bar{D}} = \underline{\bar{D}} (x,0)$, and the annual average (8760-hour) dose model, $\underline{\bar{\bar{D}}} = \underline{\bar{\bar{D}}} (x,0)$; i.e.,

$$\underline{D}^T (x,0,0) = \underline{D} \exp \left\{ -\ln \left(\underline{D} / \underline{\bar{\bar{D}}} \right) \frac{\ln (T/2)}{\ln (8760/2)} \right\} \tag{26b}$$

and

$$\underline{\bar{D}}^T (x,0) = \underline{\bar{D}} \exp \left\{ -\ln \left(\underline{\bar{D}} / \underline{\bar{\bar{D}}} \right) \frac{\ln (T/2)}{\ln (8760/2)} \right\} \tag{27b}$$

where, in Equation 26b, the dose is to a ground-level receptor on plume centerline, and, in Equation 27b, the dose is to the average ground-level receptor on compass-sector arc.

9. Downwind Location of Offsite Maximum Individuals

Consistent with Section 1.2 of NRC Regulatory Guide 1.145 (Ref. 5), these ground-level (z=0) individuals are located on plume centerline (y=0) at that downwind distance, $x=x_o$, where the ground-level relative air concentration, X/Q (x,y,0), will attain its maximum value, X/Q (x_o,0,0,), in the offsite downwind region. The relative air concentration models for the cases of stack and building-vent releases have been presented in Sections 5.1 and 5.2, above. On the basis of these models, it is readily apparent that the offsite maximum of X/Q (x,y,0) will occur along plume centerline (y=0), but at an as yet undetermined downwind distance (x_o). The determination of the value of x_o for the two cases is described below, after consideration of the nearest possible location.

9.1 Nearest Possible Offsite Location ($x=x_b$)

The following determination of the minimum downwind distance (x_b) to the exclusion area boundary is in accordance with Section 1.2 of Reference 5. Given the SRP map coordinates of the release point, the AXAIR code determines the minimum distance, d, between the release point and the SRP boundary points within a 45-degree sctor centered on the downwind direction. The minimum downwind distance is then taken to be x_b = d; i.e., the nearest possible offsite location is (x_b,0,0).

9.2 Downwind Distance for a Building-Vent Release ($x=x_o$)

The X/Q models for a building-vent release have been given in Section 5.2, above. On the basis of these models and the observation that $\sigma_y(x)$ and $\sigma_z(x)$ increase in value with increasing x (Figures 1 and 2 of Reference 5), it is apparent that X/Q (x,0,0) decreases in value with increasing x. Hence, its maximum value in the offsite region occurs at the minimum downwind distance (x_b); i.e., at $x = x_o = x_b$.

9.3 Downwind Distance for a Stack Release ($x=x_o$)

The χ/Q models for a SRP stack release have been given in Section 5.1, above. On the basis of these models and their parameters, we can only conclude that the offsite χ/Q (x,0,0) will be maximum in value at or beyond the minimum downwind distance (x_b), but probably not far beyond x_b. In the AXAIR code, we search for the approximate maximum value location by evaluating the χ/Q (x,0,0) at 0.5-kilometer increments out to 20 kilometers beyond x_b, i.e., at the points $x=x_n$, where $x_n=x_b$ + (0.5 km) (n-1) with n=1, 2, 3, ..., 21. The search is as follows:

- For each $x=x_n$, we evaluate all of the meteorologically probable $[\chi/Q(x_n,0,0)]_{ijk}$ in the particular downwind sector (k) and, using these values and the meteorological joint frequency distribution (f_{ijk}), determine the worst-case value at the 0.5% cumulative frequency level, $[\chi/Q(x_n,0,0)]_k$;

- Let n=N denote the value of n for which the highest value of $[\chi/Q\ (x_n,0,0)]_k$ was obtained. Then, the downwind distance for the maximum value location is taken to be $x=x_o=x_N$.

APPENDIX C

OFFSITE AND ONSITE POPULATION DISTRIBUTIONS

The distributions of the offsite and onsite populations about the release point are required in the population dose calculations. This appendix describes the determinations of these distributions. To facilitate the description, we first define the two distributions associated with any population in the dose methodology.

1. Definition of Distribution

1.1 Distribution by Compass Sector and Radial Increment, P_{rk}

In calculating the doses from plume gamma radiation, we utilize the distribution of the population, P_{rk}, in persons, by compass sector (k) and radial increment (r). The index k denotes a downwind cardinal compass sector in the list, S, SSW, SW, ..., SE and SSE (16 sectors). The index r denote an increment of radial distance in the list, 0-1, 1-2, 2-3, 3-4, 4-5, 5-10, 10-20, 20-30, 30-40 and 40-50 miles (10 increments).

1.2 Distribution by Age Group, Compass Sector and Radial Increments, P^a_{rk}

In the inhalation dose calculations, we utilize the population distribution, P^a_{rk}, by age group (2), compass sector (k) and radial increment (r). The index a denotes an age group in the list, adult, teenager, child and infant. The indices k and r are as defined under Section 1.1, above. The relationship between the two distributions is, of course, given by $P_{rk} = \sum P^a_{rk}$.

1.3 Assumption of Uniform Distribution within Compass-Sector Radial Increments

Let x_d, d = 1 through 11, denote the radial distances, 0.5, 1, 2, 3, 4, 5, 10, 20, 20, 40 and 50 miles, respectively. In the dose methodology, we assume that each particular incremental population, P_{rk} or P^a_{rk} is uniformly distributed between the radial bounds, x_r and x_{r+1}, in compass-sector k.

2. Offsite Population With 50 Miles

The estimated distributions of the residential populations within 50 miles may be generated for any release point within the SRP site and any calendar year (Y) in the range, 1980 through 2020.

2.1 Distribution by Compass Sector and Radial Increment, P_{rk}

Based on user's specification of the release location, the AXAIR code first obtains the CY-1980 distributions, P_{rk} (1980). Then, this distribution is projected in time to the user-specified year, Y.

2.1.1 CY-1980 Distribution, P_{rk} (1980)

The basic data is a data base of population densities by 15-second cells of latitude and longitude which has been derived from the U.S. 1980 Census information. This data base, together with the necessary software to aggregate the population by compass sector and radial increment, has been furnished by the Computer Data Systems group at ORNL under a SRP purchase-order contract (AX-598175).

Table C-1 shows the offsite population distribution about the approximate center of the SRP that was obtained using the ORN data base and software. The AXAIR code generates a similar table for the user-specified release location and calendar year.

2.1.2 Time-Projected Distribution, $P_{rk}(Y)$

The CY-1980 distribution, P_{rk} (1980), is projected to a later calendar-year distribution, P_{rk} (Y), based on the assumption that the growth rate will be similar to the growth rate of the total population in the WNW Sector about S Area as shown in Tables 2.2.1-4 through 2.2.1-8 of DPST-80-249 (Ref. 8). Accordingly, the growth by decennial years is given in the following table:

Y	P_{rk} (Y)/P_{rk} (1980)
1980	1.000
1990	1.137
2000	1.301
2010	1.484
2020	1.699

For an intermediate year (Y), we utilize linear interpolation between the values for the two nearest decennial years in the above table.

2.2 Distribution by Age Group, Compass Sector and Radial Increment

2.2.1 Fractional Distribution by Age Groups, $FP^a(Y)$

We use the notation $FP^a(Y)$, for the fractional distribution of the total 50-mile population by age group (a) in the particular calendar year (Y). The index a denotes an age group in the list, adults, teenagers, children and infants (4 groups), with the age ranges being 17 years and older, 11 to 17 years, 1 to 11 years and 0 to 1 year, respectively.

In the current version of the AXAIR code, we include the infants in the "children" category and assume the fractional distributions by age groups will be similar to the distributions about S Area in Table 2.2.1-10 of DPST-80-249 (Ref. 8). Accordingly, the values for the decennial years are as given in the following table:

Y	FP^1 (Y)	FP^2 (Y)	FP^3 (Y)	FP^4 (Y)
1980	.703	.111	.186	0
1990	.683	.090	.227	0
2000	.674	.118	.208	0
2010	.686	.105	.209	0
2020	.672	.109	.219	0

For an intermediate year (Y), we utilize linear interpolation between the values for the two nearest decennial years.

2.2.2 Time-Projected Distribution, $P^a_{rk}(Y)$

Utilizing the results of Sections 2.1.2 and 2.2.1, above, the offsite population distribution by age group, compass sector and radial increment in the specified year is given by:

$$P^a_{rk}(Y) = FP^a (Y) \cdot P_{rk} (Y).$$

2.3 Future Age-Specific Data Bases and Projected Distributions

Near the end of CY-1985 and in fulfillment of the purchase-order contract, ORNL will be furnishing data bases of the population densities by age group (a = 1 through 4) within 15-second cells of latitude and longitude for the 100-mile vicinity of the SRP. Besides the age-specific data base for CY-1980, which is based on the U. S. 1980 Census, there will be "state of the art" time-projected data bases at five-year increments out to and including CY-2020.

Thus, utilizing the aggregation software and linear interpolation between the five-year data bases, it will be possible to directly generate a high-quality offsite population distribution, $P^a_{rk}(Y)$, with respect to the release point. It is anticipated that this new methodology will soon be incorporated into the AXAIR code.

3. Onsite Population

Since we do not know how to model the migratory and growth characteristics of the onsite population, we adopt a benchmark population. The SRP onsite population is assumed to consist of the adult workers at their assigned locations during the day shift of a week day in midsummer 1984. All construction workers were assumed to be present at their paymaster locations. The telephone directory file was utilized for the location of other personnel; for multishift operating areas, it was assumed that 65 to 70 percent of their personnel would be present during the daytime. On this basis, we obtained a total onsite population of 10,791 adults and created a data base of onsite population densities by 15-second cells of latitude and longitude.*

3.1 Onsite Population Distribution, $P_{rk} \equiv P_{rk}$

Utilizing the onsite data base and the ORNL aggregation software, the AXAIR code generates the distribution of the onsite population, P_{rk}, by compass sector and radial increment with respect to the user-specified release location. Since the population consists entirely of adults, $P_{rk} = \sum_a P^a_{rk} = P^1_{rk}$.

Table C-2 shows the estimated distribution of the onsite population with respect to the approximate center of the SRP.

* The development of the onsite population data base was described, in detail, in an inter-office memorandum from L. M. Smolarek to O. M. Morris, "Onsite SRP Population Data Base," DPSP-85-1093, July 23, 1985.

TABLE C-1

Projected CY-1980 Offsite Population Distribution Within 50 Miles of Release Point (SRP Grid Coordinated of Release Point: Easting 58000.; Northing 62000.)

Incremental Population Data

Distance, Miles	0- 1	1- 2	2- 3	3- 4	4- 5	5- 10	10- 20	20- 30	30- 40	40- 50
S	0	0	0	0	0	6	494	1341	6692	3377
SSW	0	0	0	0	0	0	1064	2145	6139	2917
SW	0	0	0	0	0	0	928	1851	2037	2734
WSW	0	0	0	0	0	0	868	7284	1480	7775
W	0	0	0	0	0	60	643	7720	2539	7116
WHW	0	0	0	0	0	280	2201	103455	34470	9114
NW	0	0	0	0	0	105	5596	88119	14765	1578
NNW	0	0	0	0	0	301	9583	26905	6324	6643
N	0	0	0	0	0	2	3710	8271	4849	12618
NNE	0	0	0	0	0	1	690	1516	3811	9080
NE	0	0	0	0	0	0	4372	2792	4795	9303
ENE	0	0	0	0	0	2	1135	5779	5108	40092
E	0	0	0	0	0	1	7547	6346	7832	4802
ESE	0	0	0	0	0	34	1666	1946	2368	2455
SE	0	0	0	0	0	43	649	5705	5737	7555
SSE	0	0	0	0	0	42	413	1069	1069	3294
TOTAL	0	0	0	0	0	877	41559	272244	110015	130453

Age-Group Distribution: 70.3% Adults: 11.1% Teenagers; 18.6% Children.

TABLE C-2

Projected CY-1980 Offsite Population Distribution Within 50 Miles of Release Point (SRP Grid Coordinated of Release Point: Easting 58000.; Northing 62000.)

Incremental Population Data

Distance, Miles	0- 1	1- 2	2- 3	3- 4	4- 5	5- 10	10- 20	20- 30	30- 40	40- 50
S	0	0	0	124	0	0	0	0	0	0
SSW	11	11	0	335	0	0	0	0	0	0
SW	123	370	0	0	0	0	0	0	0	0
WSW	11	530	183	0	0	656	0	0	0	0
W	0	31	337	0	0	0	0	0	0	0
WHW	0	0	39	33	0	318	0	0	0	0
NW	0	0	202	1240	0	3864	0	0	0	0
NNW	0	131	920	0	0	45	0	0	0	0
N	0	98	453	0	0	0	0	0	0	0
NNE	0	0	0	0	0	0	0	0	0	0
NE	0	0	0	0	0	0	0	0	0	0
ENE	0	0	0	0	0	0	0	0	0	0
E	0	0	0	0	0	0	0	0	0	0
ESE	0	0	0	218	82	42	0	0	0	0
SE	0	0	0	92	0	0	0	0	0	0
SSE	0	0	23	171	0	0	0	0	0	0
TOTAL	145	1171	2157	2231	82	4925	0	0	0	0

APPENDIX D

GAMMA RAY BUILDUP IN AIR AND BUILDUP FUNCTION

1. Theoretical Considerations

For a point source of $\dot{s}$ photons per second with photon energy, E_α, the photon flux in air at a radial distance of r meters is given by

$$\phi(r) = \frac{Be^{-\mu r}}{4\pi r^2}\dot{s} \text{ , in photons/m}^2\text{/sec,} \tag{1}$$

where

$B=B(\mu_a,\mu,r)$ is an emperical buildup function which accounts for photon scattering in air, dimensionless;

$\mu a = \mu_a(E\gamma)$ is the photon energy absorption coefficient for air, m^{-1};

and

$\mu = \mu\ (E\gamma)$ is the photon attenuation coefficent for air, m^{-1}.

The total flow rate through the spherical surface with radius r is

$$\Phi(r) = 4\pi r^2\phi(r) = Be^{-\pi r}\ \dot{s}, \text{ in photons/sec.}$$

Since the total flow rate must approach the source rate, $\dot{s}$, as the radius, r, approaches zero, it is necessary that

$$\lim_{r \to o} B = 1. \tag{2}$$

In addition, the buildup function should be chosen such that the (emitted) photon energy would be conserved (by adoption) in an infinite volume of air. On a per photon basis, the emitted energy basis, the emitted energy is $E\alpha$ and the absorbed energy is given by

$$\int_o^\infty \mu_a E\gamma\ [\Phi(r)/\dot{s}]dr = \mu_a E\gamma \int_o^\infty Be^{-\mu r}\ dr;$$

hence, conservation of photon energy requires that

$$\int_o^\infty Be^{-\mu r}\ dr = 1/\mu_a. \tag{3}$$

Prior to the availability of good experimental buildup data for air, a simple buildup function,

$$B = 1 + \left(\frac{\mu-\mu_a}{\mu_a}\right)\mu r,$$

was utilized because it satisfied the necessary conditions imposed by Equations 2 and 3 above. Although it was known that the values generated by this function were in very poor agreement with the available experimental buildup values, this simple function has been utilized in NRC Regulatory Guide 1.109 (Ref.10) for determining plume gamma radiation doses from tall stack releases of the nobles gases. In the AXAIR code, we use an improved emperical buildup function that is in reasonable agreement with the existing experimental buildup data, which is described in the next section.

2. Gamma-ray Buildup Function for AXAIR Code

We have chosen a polynomial form of the buildup function that intrinsically satisfies the necessary conditions (Eqns. 2 and 3) and is amenable to least-squares fitting of the experimental build-up data for air at selected photon energies. Utilizing the subscript m to denote the photon energies, this polynomial function is

$$B_m(\mu r) = 1 + \sum_{k=1}^{K} \alpha_{mk} \cdot (\mu r)_m^k \tag{4}$$

where

$$\alpha_{mk} = \left[\left(\frac{\mu-\mu_a}{\mu_a}\right)_m - \sum_{k=1}^{K-1} k!\ \alpha_{mk}\right]/K!$$

and

K = 4 or 5, whichever yields positive-valued α_{mk} in the fitting process.

The parameters, α_{mk}, have been determined by least-squares fitting of the buildup function (Eqn. 4) to the experimental buildup values at 23 photon energies; the goodness of these fits is shown in Table D-1, which also indicates the source of the experimental buildup data.

The photon attenuation and energy absorption coefficients for air that were also used in fitting process are contained in Table D-2. The values of the parameters, α_{mk}, that were determined are shown in Table D-3. In the AXAIR code, we utilize Equation 4 either directly on analytical integration or indirectly in numerical integration; in the latter case, we use the FORTRAN function sub-program shown in Table D-4 to generate the required buildup values.

TABLE D-1

Comparison of Buildup-Function Generated Values to Experimental Values*

Index m	Photon Energy (Mev)	μr -->	1.	2.	4.	7.	10.	15.	20.
1	0.015		9.6	11.9	3.5	-3.8	2.4	-0.47	0.07
2	0.020		12.4	15.2	3.6	-4.2	2.9	-0.64	0.10
3	0.030		13.6	12.5	2.3	-1.7	2.1	-0.62	0.11
4	0.040		11.8	8.5	2.5	0.56	0.77	-0.40	0.09
5	0.050		9.1	6.2	2.8	1.4	0.37	-0.43	0.13
6	0.060		7.0	4.8	2.9	1.5	0.32	-0.57	0.20
7	0.080		4.5	4.0	2.6	1.0	0.27	0.01	-0.09
8	0.10		2.6	2.9	1.6	0.44	0.33	0.27	-0.24
9	0.15		1.6	2.3	0.86	0.23	0.29	0.40	-0.32
10	0.20		0.63	1.1	0.42	-0.14	0.12	0.42	-0.27
11	0.30		1.1	1.5	0.51	0.01	0.09	0.26	-0.16
12	0.40		0.46	0.75	0.54	-0.07	0.40	-0.25	0.06
13	0.50		1.1	1.0	0.20	0.25	0.19	-0.19	0.06
14	0.60		1.0	0.33	0.15	0.26	0.20	-0.30	0.11
15	0.80		0.51	-0.63	-0.41	0.63	0.11	-0.46	0.17
16	1.0		1.4	-0.08	-0.12	0.41	0.37	-0.50	0.16
17	1.5		1.8	0.07	-0.27	0.52	0.31	-0.43	0.01
18	2.0		2.8	1.1	0.25	0.09	0.44	-0.32	0.08
19	3.0		4.1	3.0	0.66	-0.16	0.40	-0.14	0.02
20	4.0		4.6	3.4	0.73	-0.31	0.51	-0.17	0.03
21	6.0		2.1	2.1	0.29	-0.28	0.36	-0.11	0.02
22	8.0		0.28	0.50	0.14	-0.24	0.19	-0.05	0.01
23	10.0		-1.7	-1.4	-0.80	0.19	0.16	-0.18	0.05

*The experimental buildup values from:

(1) Engineering Compendium on Radiation Shielding, Vol. 1, p. 208, Springer-Velag, NY, 1968 for m = 1 through 18; and

(2) Nuclear Appl. 6, 588 (1969) for m = 19 through 23.

TABLE D-2

Reference Values for Photon Attenuation Coefficients (μ) and Energy Absorption Coefficients (μ_a) at Various Photon Energies*

Photon Energy (Mev)	μ/ρ (cm^2/g) Air[a]	μ_a/ρ (cm^2/g) Air[a]	μ_a/ρ (cm^2/g) Tissue[b]
0.010	4.99	4.61	4.87
0.015	1.55	1.27	1.32
0.020	0.752	0.511	0.533
0.030	0.349	0.148	0.154
0.040	0.248	0.0668	0.0701
0.050	0.208	0.0406	0.0431
0.060	0.188	0.0305	0.0328
0.080	0.167	0.0243	0.0264
0.10	0.154	0.0234	0.0256
0.15	0.136	0.0250	0.0275
0.20	0.123	0.0268	0.0294
0.30	0.107	0.0287	0.0317
0.40	0.0954	0.0295	0.0325
0.50	0.0870	0.0296	0.0328
0.60	0.0805	0.0295	0.0325
0.80	0.0707	0.0289	0.0318
1.0	0.0636	0.0278	0.0308
1.5	0.0518	0.0254	0.0282
2.0	0.0445	0.0234	0.0259
3.0	0.0358	0.0205	0.0226
4.0	0.0308	0.0186	0.0203
5.0	0.0275	0.0174	0.0188
6.0	0.0252	0.0164	0.0178
8.0	0.0223	0.0152	0.0163
10.0	0.0204	0.0145	0.0154

* Data taken from D. A. Kocher, "Dose-Rate Conversion Factors for Exposure to Photon and Electron Radiation from Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities." NUREG/CR-0494 or ORNL/NUREG/TM-283, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1979).

[a] The density of dry air at 20°C and 750 mm Hg, ρ_A = 1.189E-3 g/cm^3, is used in converting the coefficients to units of reciprocal meters.

[b] The density of body tissue is taken to be that of water at 20°C, i.e, ρ_T = 0.99823 g/cm^3, for converting the coefficients to units of reciprocal meters.

TABLE D-3

Parameter Values for Buildup Function*

Em (MeV)	αm_1	αm_2	αm_3	αm_4	αm_5
0.015	3.936302E-01	-1.286161E-01	1.773490E-02	-1.037939E-03	2.146134E-05
	4064C4F8[a]	C020ECFC	3F48A468	BE4406BC	3D1680FC
0.020	7.896692E-01	-2.349542E-01	3.201975E-02	-1.870851E-03	3.871250E-05
	40CA27C3	C03C25F6	3F832725	BE7A9BAD	3D2897CF
0.030	1.884768E+00	-3.897569E-01	5.339210E-02	-3.138705E-03	6.524402E-05
	411E2808	C063C71C	3FDAB1AE	BECDB2BD	3D4469CF
0.040	2.818302E+00	-1.223871E-01	2.957190E-02	-1.792018E-03	3.853383E-05
	412D17C4	C01F54C3	3F792062	BE757112	3D2867B6
0.050	3.131006E+00	5.096659E-01	-6.034620E-03	3.759076E-04	0.0
	4132189A	40827977	BF18B7C2	3E18A2AF	00000000
0.060	3.006179E+00	1.082902E+00	-5.644042E-03	1.075619E-03	0.0
	4130194F	41115391	BF171E35	3E467DE6	00000000
0.080	2.410051E+00	1.568236E+00	4.335826E-02	2.789759E-03	0.0
	41268F92	4119177E	3FB1986F	3EB[illegible]	00000000
0.100	2.004208E+00	1.507468E+00	8.001709E-02	3.414487E-03	0.0
	4120113C	41181E97	40147C00	3EDFC594	00000000
0.150	1.551580E+00	1.133058E+00	9.092295E-02	3.198539E-03	0.0
	4118D346	41122101	401746BA	3ED19E98	00000000
0.200	1.337172E+00	8.749806E-01	7.664448E-02	1.773057E-03	0.0
	4115650E	40DFFEBB	40139EF9	3E7482F5	00000000
0.300	1.176989E+00	6.673377E-01	3.575335E-02	8.489664E-05	0.0
	4112D4F2	40AAD6A5	3F92721B	3D590545	00000000
0.400	1.046228E+00	5.522488E-01	1.334766E-02	1.289653E-04	0.0
	4110BD5A	408D5FD9	3F36AC09	3D873ADB	00000000
0.500	1.003901E+00	4.626213E-01	1.248495E-03	1.063950E-04	0.0
	41100FFB	40766E62	3E51D247	3D6F9032	00000000
0.600	9.695208E-01	3.864344E-01	-2.741461E-03	1.197040E-04	0.0
	40F83284	4062ED5D	BEB3AA15	3D7D84CB	00000000
0.800	9.118329E-01	2.859737E-01	-6.874368E-03	1.596693E-04	0.0
	40E96DE1	40493598	BF1C284C	3DA76CE9	00000000
1.000	9.065277E-01	2.084394E-01	-6.490294E-03	1.377140E-04	0.0
	40E81233	40355C48	BF1A9591	3D906755	00000000
1.500	8.557272E-01	1.026900E-01	-3.921155E-03	7.456340E-05	0.0
	40DB10F0	401A49E5	BF100FA1	3D4E2F76	00000000
2.000	8.136679E-01	4.900757E-02	-1.782431E-03	3.003622E-05	0.0
	40D04C8A	3FC8BC29	BE74D03B	3D1F7EC9	00000000
3.000	7.667351E-01	-2.218879E-02	5.227193E-03	-3.439821E-04	7.301522E-06
	40C448C1	BF5AE2A1	3F15691C	BE168B10	3C7A7FCC
4.000	7.112619E-01	-4.565192E-02	7.762395E-03	-4.956159E-04	1.063713E-05
	40B61542	BFBAFD83	3F1FCB76	BE207B0E	3CB27623
6.000	5.807378E-01	-3.345012E-02	4.834585E-03	-2.910707E-04	6.050594E-06
	4094AB3B	BF8902FF	3F13CD6E	BE13135B	3C65831A
8.000	4.866058E-01	-1.428804E-02	1.926105E-03	-1.154733E-04	2.418998E-06
	407C9233	BF3A8618	3E7E3AAE	BD79151F	3C289584
10.000	4.027880E-01	3.021814E-03	-3.628470E-04	1.007919E-05	0.0
	40671D1E	3EC609A1	BE17C790	3CA919CE	00000000

* Least-square-fit parameter values for use in Equation 4.

[a] Hexadecimal equivalent of the REAL*4 value for FORTRAN programs.

TABLE D-4

FORTRAN Function Subprogram for Buildup Values

```
CARD #  ----+----1----+----2----+----3----+----4----+----5----+----6----+----7---
              FUNCTION BFCN(UR,N)
              DIMENSION A1(23),A2(23),A3(23),A4(23),A5(23)
        C        THE GAMMA-RAY BUILDUP FACTOR IN AIR, B(U*R,N), FOR GAMMA RAYS
        C        OF ENERGY E(N).  U(N) IS THE ATTENUATION COEFFICIENT FOR GAMMA
        C        RAYS OF ENERGY E(N) IN AIR AND R IS THE RADIAL DISTANCE IN AIR.
        C         THE E(N) & U(N) ARE TABULATED FOR REFERENCE IN THE FOLLOWING
        C         COMMENT CARDS:
        C REFERENCE GAMMA-RAY ENERGIES, IN MEV --
        C     DATA E/.015,.02,.03,.04,.05,.06,.08,.10,.15,.2,.3,.4,.5,.6,
        C    *       .8,1.0,1.5,2.,3.,4.,6.,8.,10./
        C REFERENCE GAMMA-RAY ATTENUATION COEFFICIENTS FOR AIR, IN CM**2/G --
        C     DATA AMU/1.5500,0.7520,0.3490,0.2480,0.2080,0.1880,0.1670,0.1540,
        C    *         0.1360,0.1230,0.1070,0.0954,0.0870,0.0805,0.0707,0.0636,
        C    *         0.0518,0.0445,0.0358,0.0308,0.0252,0.0223,0.0204/
        C DENSITY OF DRY AIR AT 20 DEGREES C & 750 MM HG, IN G/CM**3 --
        C     DATA ARHO/1.189E-03/
        C
              DATA  A1/Z4064C4F3,Z40CA27C3,Z411E2803,Z412D17C4,Z41132189A,
             *         Z4130194F,Z41268F92,Z4120113C,Z4118D346,Z4115650E,
             *         Z4112D4F2,Z4110BD5A,Z41100FFB,Z40F83284,Z40E96DE1,
             *         Z40E81233,Z40DB10F0,Z40D04C8A,Z40C448C1,Z40B61542,
             *         Z4094AB3B,Z407C9233,Z40671D1E/
              DATA  A2/ZC020ECFC,ZC03C25F6,ZC063C71C,ZC01F54C3,Z40827977,
             *         Z41115391,Z4119177E,Z41181E97,Z41122101,Z40DFFEBB,
             *         Z40AAD65A,Z408D5FD9,Z40766E62,Z4062ED5D,Z40493593,
             *         Z40355C48,Z401A49E5,Z3FC8BC29,ZBF5AE2A1,ZBFBAFD83,
             *         ZBF8902FF,ZBF3A8618,Z3EC609A1/
              DATA  A3/Z3F48A463,Z3F832725,Z3FDAB1AE,Z3F792062,ZBF18B7C2,
             *         ZBF171E35,Z3FB1986F,Z40147C00,Z401746BA,Z40139EF9,
             *         Z3F92721B,Z3F36AC09,Z3E51D247,ZBEB3AA15,ZBF1C284C,
             *         ZBF1A9591,ZBF100FA1,ZBE74D03B,Z3F15691C,Z3F1FCB76,
             *         Z3F13CD6E,Z3E7E3AAE,ZBE17C790/
              DATA  A4/ZBE4405BC,ZBE7A9BAD,ZBECDB2BD,ZBE757112,Z3E18A2AF,
             *         Z3E467DE6,Z3EB38D87,Z3EDFC594,Z3ED19E93,Z3E7432F5,
             *         Z3D590545,Z3D873ADB,Z3D6F9032,Z3D7D84CB,Z3DA76CE9,
             *         Z3D906755,Z3D4E2F76,Z3D1F7EC9,ZBE168B10,ZBE207B0E,
             *         ZBE13135B,ZBD79151F,Z3CA919CE/
              DATA  A5/Z3D1680FC,Z3D2897CF,Z3D4469CF,Z3D2867B6,Z00000000,
             *         Z00000000,Z00000000,Z00000000,Z00000000,Z00000000,
             *         Z00000000,Z00000000,Z00000000,Z00000000,Z00000000,
             *         Z00000000,Z00000000,Z00000000,Z3C7A7FCC,Z3CB27623,
             *         Z3C65831A,Z3C289584,Z00000000/
        C
              BFCN = 1.0 + UR*(A1(N)+UR*(A2(N)+UR*(A3(N)+UR*(A4(N)+UR*A5(N)))))
              RETURN
              END
```

APPENDIX E

GAMMA RAY DOSE METHODOLOGY

1. Dose Concepts

1.1 Gamma Dose to Air from a Point Source

Consider a point source of q_n curies of nuclide n located in air at (x,y,z) which emits gamma rays with photon energies, E_{pn}, and relative intensities, A_{pn}, where index p denotes the photon energy levels. Then, utilizing Appendix D to this report and summing over all the photon energy levels, the gamma dose to air at the point, (x_o,o,o), during an exposure period of Δt seconds is given by:

$$D_n^{Air} = \frac{Kq_n \ \Delta t}{\rho} \sum_p A_{pn} \mu_a(E_{pn}) E_{pn} \frac{B(E_{pn}, r) \exp\left[-\mu(E_{pn})r\right]}{4\pi r^2}, \text{ in mrad,} \quad (1)$$

where

ρ = the density of air, in g/m^3;

A_{pn} = the fractional number of pth photons per disintegration of nuclide n, in dis^{-1};

E_{pn} = the energy of the pth photon of nuclide n, in MeV;

$\mu_a(E_{pn})$ = the photon energy absorption coefficient for air, in m^{-1};

$\mu(E_{pn})$ = the photon attenuation coefficient for air, in m^{-1};

= the radial distance from the point source to the receptor point, i.e., $r = \sqrt{(x-x_o)^2+y^2+z^2}$, in m;

$B(E_{pn},r)$ = the gamma ray buildup factor for air from Appendix D, dimensions;

and

k = the conversion of units factor, 5.927×10^5 g-mrad-dis/Ci-sec-Mev, i.e., (3.7×10^{10}dis/sec/Ci) (1.602×10^{-6}erg/MeV)(1000 mrad/rad)/(100 erg/g-rad).

1.2 Total Body Dose From a Point Source

As in NRC Regulatory Guide 1.109 (Ref. 11), the total body dose is evaluated at a body tissue depth of 5 centimeters, assuming a relative biological effectiveness of unity for absorption of gamma radiation in tissue. Accordingly, the ratio, $R(E_{pn})$, of the total body dose to the gamma dose to air from absorption of a photon of energy, E_{pn}, is given by;

$$R(E_{pn}) = \left[\frac{\mu_a^T (E_{pn})/\rho_T}{\mu_a (E_{pn})/\rho} \right] \exp \{ -\mu_a^T (E_{pn}) d \}, \text{ in } \frac{\text{mrem}}{\text{mrad}}, \qquad (2)$$

where

$\mu_a^T (E_{pn})$ = is the photon energy absorption coefficient for tissue, in m^{-1};

ρ_T = is the density of tissue, in g/m^3;

$d \equiv 0.05m$ (the evaluation depth); and are the other parameters are as defined under Eqn. 1, above.*

Combining Equations 1 and 2, the total body dose from nuclide n is given by:

$$D_n = \frac{K}{\rho} \sum_p R(E_{pn}) A_{pn} E_{pn} s(E_{pn}, r, q_n \Delta t), \text{ in mrem}, \qquad (3)$$

where

$$s(E_{pn}, r, q_n \Delta t) \equiv \mu_a(E_{pn}) \frac{B(E_{pn}, r) \exp [-\mu(E_{pn}) r]}{4 \pi r^2} q_n \Delta t, \text{ in Ci-sec/m}^3.$$

Due to the profusion of radionuclides (the n) and their gamma rays with different photon energies (the E_{pn}) and relative intensities (the A_{pn}), we will accumulate the gamma rays into energy groups (m) with characteristic photon energies, E_m, and nuclide-specific effective relative intensities, A_{mn}. Then, to good approximation, the total body dose from nuclide n will be given by:

$$D_n = \sum_m DF_{mn} \, s(E_m, r, q_n \Delta t), \text{ in mrem}, \qquad (4)$$

where

$$DF_{mn} = \frac{K}{\rho} R(E_m) A_{mn} E_m, \text{ in } \frac{\text{mrem}}{\text{Ci}} \text{ per } \frac{\text{sec}}{m^3},$$

is the dose factor for the gamma rays of nuclide n that fall into the m$\underline{\text{th}}$ energy group;

$R(E_m)$ is as given in Equation 2 except that E_m replaces E_{pn}, in mrem/mrad;

---

* The value of the term within the square brackets is approximately costant over the photon energy range. For example, based on the parameters given in Table D-2 of Appendix D for the range from 0.10 to 10.0 MeV, the average value of the term is 1.08 with extreme of 1.04 and 1.11.

and

> $s(E_m, r, q_n \Delta t)$ is as given under Equation 3 except that E_m replaces E_{pn}, in Ci-sec/m^3.

The gamma ray energy group and the evaluation of the dose factors will be described in Sections 2 and 3, below.

1.3 Total Body Dose From a Radioactive Atmospheric Plume

1.3.1 Individual on Plume Centerline

Instead of the single point-source term, $q_n \Delta_t$, that appeared in the previous sections, we now have a continuum of infinitesimal source terms, $C_n(x,y,z)$ dxdydz, where $C_n(x,y,z)$ is the integral air concentration of radionuclide n from Section 8 of Appendix B to this report and dxdydz is the infinitesimal volume. Thus, based on Equation 4, above, and spatial integration over all of the infinitesimal source terms, the total body dose to the receptor at $(x_o,0,0)$ from radionuclide n in the radioactive plume is given by:

$$D_n = \sum_m DF_{mn} S_{mn} \qquad (5.1)$$

where

$$S_{mn} = \int d S_{mn} ;$$

$$dS_{mn} \equiv s(E_m, r, C_n(x,y,z) dxdydz);$$

and

> the integration is over the hemispherical air space above ground level.

The evaluation of the shine integrals, S_{mn}, will be considered in Section 4, below.

1.3.2 Average Individual on Compass-Sector Arc

Instead of the single point-source term, $q_n \Delta_t$, that appeared in Section 1.2, above, we have a continuum of infinitesimal source terms, $\bar{C}_n (x,z)$ dxdydz, where $\bar{C}_n (x,z)$ is the average integral air concentration of radionuclide n with respect to compass-sector arc from Section 8 of Appendix B and dxdydz is the infinitesimal volume. Thus, based on Equation 4, above, and spatial integration over all of the infinitesimal source terms, the total body dose to the average individual on compass-sector arc at downwind distance x_o from radionuclide n is given by:

$$\bar{D}_n = \sum_m DF_{mn} \bar{S}_{mn} \tag{5.2}$$

where

$$\bar{S}_{mn} = \int d\,\bar{S}_{mn};$$

$$d\,\bar{S}_{mn} \equiv s\left(E_m, r, \bar{C}_n(x,z)dxdydz\right);$$

and

the integration is over the hemispherical air space above ground level.

The evaluation of the shine integrals, $\bar{S}_{mn}$, is considered in Section 4, below.

2. Gamma-ray Energy Groups

Similar to the approach in Appendix B of NRC Regulatory Guide 1.109 (Ref. 11), we accumulate the gamma rays into M contiguous energy groups, each group having a "characteristic" photon energy, E_m, and an energy range, R_m, to be specified later in this section. The effective relative intensity, A_{mn}, of the nuclide-n gamma rays that fall into m^{th} energy group is taken to be:

$$A_{mn} = {\sum_p}' A_{pn} R(E_{pn})E_{pn}/R(E_m)E_m, \text{ in dis}^{-1}, \tag{6}$$

where

A_{pn} = the actual relative intensities (Eqn.1), in dis^{-1};
E_{pn} = the actual photon energies (Eqn.1), in MeV;
E_m = the photon energy of the m^{th} energy group, in MeV;
$R(E)$ with $E=E_{pn}$ or $E=E_m$, is given by Eqn.2, in mrem/mrad;

and the prime on the summation symbol, i.e., the symbol, ${\sum_p}'$, indicates that only those gamma rays with photon energies, E_{pn}, in the energy range, R_m, are to be included in the summation.

The characteristic photon energies, E_m, for the M energy groups are taken to be the 23 photon energies for which the buildup function, $B_m(\mu r)$, has been determined in Appendix D; namely,

$\{E_1, E_2, \ldots, E_{M=23}\}$ = {0.015, 0.020, ..., 10.0 MeV}, as listed in Table D-1 of Appendix D to this report.

The energy ranges, R_m, for accumulating the gamma rays into the M energy groups are taken to be as follows:

Group Number (m)	Energy Range, R_m
1	$0 < R_1 \leq \sqrt{E_1 E_2}$
2	$\sqrt{E_1 E_2} < R_2 \leq \sqrt{E_2 E_3}$
.	.
.	.
.	.
m	$\sqrt{E_{m-1} E_m} < R_m \leq \sqrt{E_m E_{m+1}}$
.	
.	
.	
M	$\sqrt{E_{m-1} E_m} < R_m < \infty$

3. Gamma-ray Dose Factors

In view of Equations 4 and 6, above, the total body dose factors, DF_{mn}, are given by:

$$DF_{mn} \equiv \frac{K}{\rho} R(E_m) A_{mn} E_m = \frac{K}{\rho} \sum_p{}' R(E_{pn}) A_{pn} E_{pn}, \tag{9}$$

in $\frac{\text{mrem}}{\text{Ci}}$ per $\frac{\text{sec}}{\text{m}^3}$,

where the summation is as indicated in Section 2, above.

3.1 Evaluation of the DF_{mn}

Based on Equation 9 and the available parameter values, the total body dose factors, DF_{mn} have been evaluated using the FORTRAN Program, DFLIB. The FORTRAN Source and the JCL used for execution of that program are stored within the SRP Central Computer Facility as:

DSN = TENVT.TMECA.FORT(DFLIB) and
DSN = TENVT.TMECA.JCL(DFLIB), respectively,

and the results are contained within the dose factor library,

DSN = TENVT.AXAIR.DFLIB,

which may be viewed by terminal users. Within this library, there are 8 card images (lines) for each named radionuclide (n); the values of the DF_{mn}, m=1 through 23, appear on the last 3 lines in the FORTRAN line format: 1P8E9.2.

Input data and part of the FORTRAN source for the DFLIB program have been obtained from the Radiation Shielding Information Center (RSIC) at the Oak-Ridge National Laboratory (ORNL). The photon energies, E_{pn}, and the relative intensities, A_{pn}, were obtained from the "DRALIST Radioactive Decay Data in Simplified Format (Kocher's Format)" (Ref. 12). Reference data and computational means to evaluate the μ_a (E_{pn}) and the μ_a^T (E_{pn}) taken from were D.C. Kocher's DOSFACTER II Computer Code (Ref. 13); the reference data values are the same as listed in Table D-2 of Appendix D.

3.2 Dose Factors for Special Case of an Uniform Semi-Infinite Plume

When this special case is the selected option in the AXAIR Code, the integral air concentration of nuclide n is taken to be uniform throughout the hemisphere above ground level, having the same values as at the receptor location; e.g., $C_n = C_n\ (x_o,0,0)$, a constant. Then, utilizing spherical polar coordinates for the spatial integration in Equation 5 $(dxdydz \rightarrow r^2 \sin\theta d\theta d\phi dr)$, the total body dose from nuclide n is given, in integral form, by:

$$D_n = \sum_{m=1}^{23} DF_{mn} \frac{C_n \mu_a(E_m)}{4\pi} \int_0^{2\pi} \int_0^{\pi/2} \int_0^{\infty} B_m(\mu r) \exp[-\mu(E_m) r] \cdot dr \sin\theta d\theta d\phi\}$$

Carrying out the simple integration over ϕ and θ, and then using Equation 3 of Appendix D for the integration over r, this reduces to

$$D_n = \sum_{m=1}^{23} DF_{mn} \left\{ \frac{C_n}{2} \right\},$$ which may be rewritten as

$$D_n = DFB_n \cdot C_n\ (x_o,0,0)$$

where

$$DFB_n \equiv 1/2 \sum_{m=1}^{23} DF_{mn}$$ are the special-case dose factors. (10)

The special-case dose factors, DFB_n, are stored in the dose factor library, DSN = TENVT.AXAIR.DFLIB, in Columns 20-28 of the lines that specify the radionuclide (n) names. With respect to the noble gases, the values of the DFB_n are in excellent agreement with those listed in the last column of Table B-1 in NRC Regulatory Guide 1.109 (Ref. 11).

4. Evaluation of the Shine Integrals

The shine integrals, S_{mn} and $\bar{S}_{mn}$, have been defined, in concept in Section 1.3. In this section, we describe the methodology that has been developed to evaluate the shine integrals and the associated relative shine integrals (S_m and $\bar{S}_m$). The FORTRAN subprograms referred to later in this section will be found, within the SRP Central Computer Facility, in DSNAME = TENT.TMECA.FORT(GRAYSUBS).

4.1 Introduction

The gamma-ray buildup function, B_m (μr) with implicit $\mu=\mu(E_m)$, has been described in Appendix D. Based on incorporation of this funcitons into Equation 5.1 and use of μ_{am} and μ_m to denote $\mu_a(E_m)$ and $\mu(E_m)$, the value of the shine integral, S_{mn}, would be obtained by integrating the integrand,

$$d\,S_{mn} \equiv \mu_{am} \left\{\frac{B_m(\mu_r)\exp(-\mu_m r)}{4\pi r^2}\right\} C_n\ (x,y,z)\ dxdydz, \qquad (11)$$

in which $r^2 = (x-x_o)^2 + y^2 + z^2$,

over the infinite hemisphere above ground level. Utilizing Equation 21 of Appendix B, the downwind integral air concentration of nuclide n is given by:

$$C_n\ (x,y,z) = \frac{X}{Q}\ (x,y,z) q_n(\tau) \text{ with } \tau = \frac{x^*}{u.}$$

However, since use of $C_n(x,yz)$ as a function of x in Equation 11 would lead to innumerable formidable numerical integrations in the AXAIR code, we adopt the customary approximation method. Namely, we assume that the downwind distance to the receptor location, $x=x_o$, is sufficiently large enough that $C_n(x,y,z)$ can be replaced by $C_n(x_o,y,z)$ for the purpose of integrating Equation 11.**

---

* More precisely, the concentration of exposure nuclide n_E that arises from released radionuclide n_R and its associated release time period (T). See Section 4 of Appendix A for the more precise definition of q_n (τ).

**The basis for this assumption is the observation that the exponential terms, $\exp(-\mu_m r)$, in Equation 11 would rapidly attenuate the photon flux reaching the receptor from increasing radial distance r, and that, for a large x_o, $C_n(x,y,z)$ would be a monotonic function of x in the important region near the receptor location.

Accordingly, the value of the shine integral, $S_{mn} = S_{mn}(x_o)$, at the receptor location is obtained from the following formulation:

$$S_{mn}(x_o) = S_m(x_o)\ q_n(\tau_o) \quad \text{with } \tau_o \equiv \frac{x_o}{u}, \text{ in Ci-sec/m}^3, \tag{13}$$

where the associated relative shine integral, $S_m = S_m(x_o)$, is given in units of sec/m^3, by:

$$S_m(x_o) \equiv \mu_{am} \int_0^\infty \int_{-\infty}^\infty \int_{-\infty}^\infty \frac{B_m(\mu r)\exp(-\mu_m r)}{4\pi r^2} \frac{X}{Q}(x_o,y,z)\ dxdydz, \tag{14}$$

in which $r^2 = x^2+y^2+z^2$.*

Similarly, by the analogous consideration of Equation 5.2, above, and Equation 22 of Appendix B, the shine integral, $\bar{S}_{mn}=\bar{S}_{mn}(xo)$, with respect to the average receptor along compass-sector arc at downwind distance, $x=x_o$, is obtained from the following formulation:

$$\bar{S}_{mn}(x_o) = \bar{S}_m(x_o)\ q_n(\tau_o) \quad \text{with } \tau_o \equiv \frac{x_o}{u}, \text{ in Ci-sec/m}^3, \tag{15}$$

where the associated average relative shine integral, $\bar{S}_m = \bar{S}_m(x_o)$, is given, in units of sec/m^3, by

$$\bar{S}_m(x_o) \equiv \mu_{am} \int_0^\infty \int_{\infty}^\infty \int_{\infty}^\infty \frac{B_m(\mu r)\exp(-\mu_m r)}{4\mu r^2} \frac{X}{Q}(x_o,z)\ dxdydz, \tag{16}$$

in which $r^2 = x^2+y^2+z^2$.

---

*Note that for integration purposes we have translated the origin of the cartesian coordinate system from (0,0,0) to x_o,0,0) with respect to the original system in Equation 11.

With respect to Equation 13 and 15, the evaluation of $q_n(\tau_o)$ - more precisely, $q_{n_E}^{nR\ TnR}(\tau_o)$ is as described in Appendix A of this report. In the following subsections, we will consider the remaining the remaining evaluation of the relative shine integrals, S_m and $\bar{S}_m$, based on Equations 14 and 16, above, and on the X/Q and $\bar{X}$/Q models that have been presented in Appendix B to report. In the ensuing discussion, we will suppress the index m notation except when it is essential for clarity.

4.2 Evaluation of the Average Relative Shine Integral, $\bar{S}_m(x_o)$

The models for the average relative air concentrations with respectzm to compass-sector arc - the $\bar{X}/Q = \bar{X}/Q(x,z)$ - are as described in Appendix B of this report. In the following subsections, we des describe the evaluation of the relative shine integrals, $\bar{S}_m(x_o)$, for the corresponding cases of stack and building-vent releases.

4.2.1 Stack Release under Fumigation Conditions

The average relative air concentration model for this case is given by Equation 11 and 18b of Appendix B; accordingly,

$$\frac{\bar{X}}{Q}(x_o,z) = \frac{\overline{\exp\,[-y^2/2\sigma_y^2]}}{\sqrt{2\pi}\,u\sigma_y\,Le} \quad \text{for } 0 \leqslant z \leqslant Le \qquad (17)$$

$$= 0 \quad \text{for } z > Le.$$

Utilizing this in Equation 16, above, transforming from cartesian (x,y,z) to cylindrical (ρ,ϕ,z) coordinates and carrying out the simple integration over ϕ, the relative shine integral is then given by:

$$\bar{S} = \frac{\overline{\exp\,[-y^2/2\sigma_y^2]}}{2\sqrt{2}\,u\sigma_y\,L_e}\,\bar{V}_f \qquad (18)$$

$$\text{where } \bar{V}_f = \mu_a \int_0^{L_e}\int_0^{\infty} \frac{B(\mu r)\exp(-\mu r)}{r^2}\,\rho\,d\rho dz \qquad (19.1)$$

in which $r^2 = \rho^2 + z^2$.

Under the variable transformations, $v = \mu(\rho^2+z^2)^{1/2}$ for the integration over ρ and $u = \mu z$ for the integration over z, Equation 19.1 transforms to:

$$\bar{V}_f = \frac{\mu_a}{\mu} \int_o^{\mu L_e} \int_u^{\infty} \frac{B(v)e^{-v}}{v} \, dv \, du. \qquad (19.2)$$

In accordance with Appendix D of this report, the functional form of the buildup function is:

$$B(v) = 1 + \sum_{k=1}^{5} \alpha_k v^k \qquad (19.3)$$

and

the values of the coefficients, α_k, are as given in Table D-3 of Appendix D for the particular energy group (m).

Utilizing Equation 19.3 in Equation 19.2 and carrying out the integration analytically, first over variable v and then over variable u, the required value of $\bar{V}_f$ for use in Equation 18 is given by:

$$\bar{V}_f = \frac{\mu_a}{\mu} \{ x E_1(x) + (1 + \alpha_1 + 2\alpha_2 + 6\alpha_3 + 24\alpha_4 + 120\alpha_5) -$$

$$e^{-x} [(1 + \alpha_1 + 2\alpha_2 + 6\alpha_3 + 24\alpha_4 + 120\alpha_5) +$$

$$(\alpha_2 + 4\alpha_3 + 18\alpha_4 + 96\alpha_5) x +$$

$$(\alpha_3 + 6\alpha_4 + 36\alpha_5) x^2 +$$

$$(\alpha_4 + 8\alpha_5) x^3 + \alpha_5 x^4] \} \qquad (19.4)$$

where

$x = \mu L_e$

and

$E_1(x) = \int_x^{\infty} \frac{e^{-t}}{t} dt$ is the familiar exponential integral.

Within the AXAIR code, the $\bar{V}_f$'s are evaluated, as indicated above, by means of the FORTRAN subprogram, SUBROUTINE VIFBAR. Invocation of the subprogram is as follows:

```
CALL VIFBAR (HLE,LM,VFB)
```

with

HLE = the value of L_e, in meters, and

LM = an input logical vector whose components are either LM(m) =.TRUE. or LM(m) = .FALSE. for m = 1, 2, ..., 23*

returns

VFB = the output vector whose components are either the value of $(\bar{V}_f)_m$ or zero, depending upon whether or not LM(m)=.TRUE., for each of the 23 gamma ray energy groups (m).

4.2.2 Stack Release Under Nonfumigation Conditions

The average relative air concentration model for this case is given by Equations 10 and 18b of Appendix B; accordingly,

$$\frac{X}{Q}\ (x_o,z) = \frac{\exp(-y^2/2\sigma_y^2)}{2\pi\sigma_y\sigma_z\ \bar{u}}\ H(x_o,h,z) \tag{20.1}$$

where

$$\bar{H}\ (x_o,h,z) = \exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right) \tag{20.2}$$

---

* In subsequent FORTRAN subroutines evaluating similar output vectors, we will utilize the same logical input vector, LM, as described above. In addition, one should observe that all of the V functions - here, $\bar{V}_f$ as defined by Equation 19.4 - are formulated such that the values of the associated components will be in the range, $0 \leq V_m \leq 1$.

Using this in Equation 16, above, and transforming from cartesian (x,y,z) to spherical polar (r, ϕ, θ) coordinates, the average relative shine integral is then given by:

$$\bar{S} = \frac{\overline{\exp(-y^2/2\sigma_y^2)}}{2\pi\, \sigma_y\, \sigma_z\, u}\, \bar{V} \tag{21}$$

where

$$\bar{V} = \frac{\mu_a}{4\pi} \int_0^{2\pi} d\phi \int_0^{\infty} \int_0^{\pi/2} B(\mu r) e^{-\mu r}\, \bar{H}\,(x_o, h, r\cos\theta) \cdot \sin\theta d\theta dr.^{*} \tag{22.1}$$

After carrying out the simple integration over ϕ, Equation 22.1 may be reexpressed as:

$$\bar{V} = \frac{\mu_a}{2\pi} \int_0^{\infty} B(\mu r)\; e^{-\mu r}\; F(r)\; dr \tag{22.2}$$

where

$$F\,(r) \equiv \int_0^{\pi/2} \bar{H}\,(x_o, h, r\cos\theta)\; \sin\theta d\theta. \tag{23.1}$$

The integration over θ on the right-hand side of Equation 23.1 may be carried out analytically and the result is:

$$F(r) \equiv F(u, u_o) = \frac{\sqrt{\pi}}{2}\, \frac{\mathrm{erf}\,(u + u_o) + \mathrm{erf}\,(u - u_o)}{u} \tag{23.2}$$

---

* Note that, except for the use of a better buildup function, $B(\mu r)$, $\bar{V} / \sqrt{2}\, \sigma_z \mu_a$ is equivalent to the "I Function" that is described in Appendix F or NRC Regulatory Guide 1.109 (Ref. 11).

where

$$u = \frac{r}{\sqrt{2}\ \sigma_z}, \quad u_o = \frac{h}{\sqrt{2}\ \sigma_z} \quad \text{and}$$

$$\text{erf}\ (x) \equiv \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\, dt \text{ is the well-known error function.}$$

Incorporating Equation 23.2 into Equation 22.2, we have

$$\bar{V} = \frac{\mu_a}{2\pi} \int_0^\infty B(\mu r)\, e^{-\mu r}\, F(u,u_o)\, dr \qquad (22.3)$$

where

$F(u,u_o)$ is the analytical function of r defined by Equation 23.2.*

The remaining integration over r on the right-hand side of Equation 22.3 is carried out by means of a combination of numerical and analytical integration methods which, by design, enable reasonably fast evaluation of the $\bar{V}$ to at least three significant decimal places. The associated evaluation methodology has been incorporated into the FORTRAN subprogram, SUBROUTINE VIBAR. Invocation of this subroutine is as follows:

```
CALL VIBAR (SIGZ,HE,LM,VB)
```

with

SIGZ = the value of $\sigma_z = \sigma_z(x_o)$, in meters, and

HE = the value of the effective stack height (h), in meters,

returns

VB = the output vector whose components are either the value of $(\bar{V})m$ or zero, depending upon whether or not LM(m) =.TRUE., for each of the 23 gamma ray energy groups (m).

---

* In the mathematical sense, the function, $F(u,u_o)$, is a well-behaved analytical function of the real variables, u and u_o, and, hence, of r. Since both $B(\mu r)$ and $e^{-\mu r}$ are also analytical functions of the real variable r, no singularities will occur in the integrand of Equation 22.3. Accordingly, the integrand is readily amenable to integration by numerical and analytical techniques.

4.2.3 Building-Vent Release

The average relative air concentration model for a building-vent release is given by Equations 12 and 18b of Appendix B; accordingly,

$$\frac{\bar{\chi}}{Q}(x_o,z) = \frac{\overline{\exp(-y^2/2\sigma_y^2)}}{2\pi\ \sigma_y\ \sigma_z\ u_{10}}\ \bar{H}(x_o,0,z) \tag{24.1}$$

where

(24.2)

$\bar{H}(X_o,0,z)$ is as given by $\bar{H}(x_o,h,z)$ in Equation 20.2, above, except that h=0.

Then, by analogy with Section 4.2.2, above, the average relative shine integral for this case is given by:

$$\bar{S} = \frac{\overline{\exp(-y^2/2\sigma_y^2)}}{2\pi\ \sigma_y\ \sigma_z\ u_{10}}\ \bar{V} \tag{25.1}$$

where

$$\bar{V} = \frac{\mu_a}{2\pi} \int_0^{\infty} B(\mu r)e^{-ur}\ F(u,0), \tag{25.2}$$

which is identical to Equation 22.3, above, except that $u_o = 0$

In view of fact that Equation 25.2 is a special case of Equation 22.3, the $(\bar{V})$m are obtained by means of the FORTRAN subprogram, SUBROUTINE VIBAR; i.e., CALL VIBAR (SIGZ,0.,LM,VB) will return the vector VB whose components are the required $(\bar{V})$m.

4.3 Evaluation of the Relative Shine Integrals, $S_m(x_o)$

The models for relative air concentrations in the downwind compass sector - the X/Q = X/Q (x,y,z) - are as described in Section 5 of Appendix B to this report. In the following subsections, we describe the evaluation of the relative shine integrals, $S_m = S_m(x_o)$, with respect to the receptor on plume centerline at ground level for the corresponding cases of stack and building-vent releases. In addition, at the end of each subsection, we describe the upper-bound to the value of $S_m(x)$ which is obtained by using X/Q (x,0,z) in lieu of X/Q (x,y,z).

4.3.1 Stack Release Under Fumigation Conditions

The relative air concentration model for this case is given by Equation 11 of Appendix B; accordingly,

$$\frac{X}{Q}(x_o,y,z) = \frac{\overline{\exp[-y^2/2\sigma_y^2]}}{\sqrt{2\pi}\;\mu\sigma_y L_e} \qquad \begin{matrix}\text{for } 0 \leq z \leq L_e \\ \text{for } z > L_e.\end{matrix} \qquad (26)$$

Utilizing Equation 26 in Equation 14, above, and transforming from cartesian (x,y,z) to spherical polar (r,ϕ,θ) coordinates, the relative shine integral is then given by:

$$S(x_o) = \frac{1}{2\sqrt{2\pi}\,u\sigma_y L_e} V_f \qquad (27)$$

where

$$V_f = \frac{\mu_a}{2\pi} \int_0^{\pi/2} \int_0^{L_e/\cos\theta} \int_0^{2\pi} B(\mu r)e^{-\mu r} \exp\left[-\frac{(r\sin\theta\cos\theta)^2}{2\sigma_y^2}\right] \cdot$$

$d\phi dr\sin\theta d\theta$. (28.1)

To enable analytical integration over the azimuthal angle, ϕ, we rewrite Equation 28.1 in the form,

$$S = \mu_a \int_0^{\pi/2} \int_0^{\frac{L_e}{\cos\theta}} B(\mu r)e^{-\mu r} P(t)\; dr\sin\theta d\theta \qquad (28.2)$$

where

$$P(t) \equiv \frac{1}{2\pi} \int_0^{2\pi} \exp\left[-2t\,\sin^2\phi\, d\phi\right] \text{ with } t \equiv \left(\frac{r\sin\theta}{2\sigma_y}\right)^2. \qquad (29.1)$$

Utilizing the trigonometric relationships, $\sin^2 x = \frac{1-\cos 2x}{2}$, $\cos(x-\pi) = -\cos x$ and $\cosh x = (1/2)(e^{x} + e^{-x})$, and the transformation, $\phi' = 2\phi$, Equation 29.,1 reduces to:

$$P(t) = \frac{e^{-t}}{2\pi} \int_0^{2\pi} e^{t\cos 2\phi} d\phi = \frac{e^{-t}}{4\pi} \int_0^{4\pi} e^{t\cos\phi'} d\phi' = \frac{e^{-t}}{2\pi} \int_0^{2\pi} e^{t\cos\phi'} d\phi'$$

$$= \frac{e^{-t}}{2\pi} \left\{ \int_0^{\pi} e^{t\cos\phi'} d\phi' = \int_0^{\pi} e^{-t\cos\phi'} d\phi' \right\}$$

$$= e^{-t} \left\{ \frac{1}{\pi} \int_0^{\pi} \cosh(t \cos\phi') \, d\phi' \right\}.$$

Further because the term within the last pair of curly brackets is the integral representation of the modified Bessel function of zero order, i.e,

$$I_o(x) \equiv \frac{1}{\pi} \int_0^{\pi} \cosh(x \cos\phi) \, d\phi,$$

Equation 29.1 simplifies to the analytical form,

$$P(t) = e^{-t} I_o(t)' \text{ with } t \equiv \left(\frac{r\sin\theta}{2\sigma_y}\right)^2. * \qquad (29.2)$$

---

* $P(t)$ is a monotonically decreasing-value function of increasing x in the range, $0 \leq t < \infty$, with $P(0)=1$ and $\lim_{t\to\infty} P(t) = \lim [0.39894228/\sqrt{t}] = 0$. It is evaluated by means of the FORTRAN subprogram, FUNCTION EIO(T).

Next, we use the variable transformations, $u=\cos\theta$ and $v=\mu r$, in Equations 28.2 and 29.2 and the result is:

$$V_f = \frac{\mu_a}{\mu} \int_0^1 f(u)\, du \qquad (29.3)$$

where

$$f(u) = \int_0^{\mu L_e/u} B(v)e^{-v}\, P(t)dv, \text{ with } t = \frac{v^2(1-u^2)}{4\mu^2\sigma_y^{\,2}} .$$

The remaining integration over the variables v and u in Equation 29.3 is carried out by up to tenfold subdivision of the integration ranges and use of Gaussian numerical integration of order 9. This is accomplished within the FORTRAN subprogram, SUBROUTINE VIFIND. Invocation of this subroutine is as follows:

```
CALL  VIFIND (HLE,SIGY,LM,VF)
```

with

HLE = the value of Le, in meters, and
SIGY = the value of $\sigma_y=\sigma_y(x_o)$, in meters,

returns

VF = the output vector whose components are either $(V_f)_m$ or zero, depending upon whether or not LM(m) = .TRUE., for each of the 23 gamma ray groups (m).

The estimated precision in the returned values is at least three significant decimal places. Use of these $(V_f)_m$ in Equation 27 enables the evaluation of the relative shine integrals, the $S_m(x_o)$.

4.3.1.1 Upper-bound Values of $S_m(x_o)$ for Fumigation Case

With respect to Equation 26, above, we note that $X/Q\ (x_o,0,z) > X/Q\ (x_o,y,z)$ and that the upper-bound to the relative air concentration is given by:

$$\frac{X}{Q}(x_o,0,z) = \frac{1}{\sqrt{2\pi}\, u\sigma_y\, L_e} \qquad \text{for } 0 < z < L_e$$

$$= 0 \qquad \text{for } z > L_e$$

Then, by analogy to Section 4.2.1, above, the upper-bound value of $S_m(x_o)$ is given by:

$$S\ (x_o) = \frac{1}{2\sqrt{2\pi}\ u\sigma_y L_e}\quad \bar{V}_f$$

where

$\bar{V}_f$ is as given by Equation 19.4, above,

and

the $(\bar{V}_f)_m$ are evaluated by means of the FORTRAN subprogram, SUBROUTINE VIFBAR, as has been described in Section 4.2.1.

4.3.2 Stack Release Under Nonfumigation Conditions

The relative air concentration model for this case is as given by Equation 10 of Appendix B; accordingly,

$$\frac{\chi}{Q}\ (x_o, y, z) = \frac{\exp\ (-y^2/2\sigma_y^{\ 2})}{2\pi\ \sigma_y\ \sigma_z\ u}\ \bar{H}(x_o, h, z) \tag{30.1}$$

where

$$\bar{H}\ (x_o, h, z) = \exp\left[-\frac{(z-h)^2}{2\sigma_z^{\ 2}}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^{\ 2}}\right] \tag{30.2}$$

Utilizing Equation 30 in Equation 14, above, and transforming from cartesian (x,y,z) to spherical polar (r, ϕ, θ) coordinates, the relative shine integral, $S_m\ (x_o)$, is given by:

$$S\ (x_o) = \frac{1}{2\pi\ \sigma_y\ \sigma_z\ u}\ V \tag{31}$$

where

$$V = \frac{\mu_a}{2\pi}\int_0^\infty \int_0^{\pi/2} \int_0^{2\pi} B(\mu r)e^{-\mu r} \exp\left(-\frac{(r\sin\theta\sin\ \phi)^2}{2\sigma_y^{\ 2}}\right) \bar{H}(x_o, h, r\cos\theta)$$

$$d\phi\sin\theta d\theta dr. \qquad (32.1)$$

The integration over the azimuthal angle, ϕ, on the right-hand side of Equation 32.1 may be carried out analytically as has been done in Section 4.3.1 and the result is given by:

$$V = \frac{\mu_a}{2}\int_0^\infty B(\mu r)\ e^{-\mu r}\ T(r)\ dr \tag{32.2}$$

where

$$T(r) = \int_{o}^{\pi/2} P(t)\ \bar{H}\ (x_o,h,r\ \cos\theta)\ \sin\theta d\theta$$

and

$$P(t) = e^{-t}\ I_o(t)\quad \text{with } t \equiv \left(\frac{r\sin\theta}{2\sigma_y}\right)^2$$

The remaining double integration over the variables θ and r in Equation 32.2 must be carried out numerically. In this, we use numerous subdivisions of the integral ranges into subintegrals, Gaussian numerical integration of order 8 and Laguerre numerical integration of order 12. Accordingly, the evaluation of the $S_m(x_o)$ based on Equations 31 and 32.2 is computationally intensive.*

The required double integration in Equation 32.2 is accomplished by means of the FORTRAN subprogram, SUBROUTINE VIND. Invocation of this subroutine is as follows:

```
CALL VIND (SIGY,SIGZ,HE,LM,V)
```

with

SIGY = the value of $\sigma_y = \sigma_y(x_o)$, in meters,
SIGZ = the value of $\sigma_z = \sigma_z(x_o)$, in meters, and
HE = the value of the effective stack height (h), in meters

returns

V = the output vector whose components are either $(V)_m$ or zero, depending upon whether or not LM(m) = .TRUE., for each of the 23 energy groups (m).

The estimated precision in the returned values, $(V)_m$, is about three significant decimal places.

4.3.2.1 Upper-bound Values of $Sm(x_o)$ for Nonfumigation Case

With respect to Equation 30, above, we note that $X/Q\ (x_o,0,z) \geq X/Qv\ (x_o,y,z)$ and that the upper bound to the relative air concentration is given by:

$$\frac{X}{Q}\ (x_o,0,z) = \frac{1}{2\pi\ \sigma_y \sigma_z u}\ \bar{H}\ (x_o,h,z)$$

where

$\bar{H}(x_o,h,z)$ is as defined by Equation 30.2 or 20.2.

---

* For this reason, we recommend that the upper-bound values of $S_m(x_o)$, as presented in the next subsection, be utilized resulting in upper-bound shine doses. If the upper-bound are unacceptably high, they can be reduced, perhaps about threefold, by invocation of the full methodology.

Then, by analogy with Section 4.2.2, above, the upper-bound value of $S_m(x_o)$ is given by:

$$S(x_o) = \frac{1}{2\pi \sigma_y \sigma_z u} \bar{V}$$

where

$\bar{V}$ is as given by Equation 22.3, above,

and

the $(V)_m$ are evaluated by means of the FORTRAN subprogram, SUBROUTINE VIBAR, as has been described in Section 4.2.2.

4.3.3 Building-Vent Release

The relative air concentration model for this case is as given by Equation 12 of Appendix B; accordingly,

$$\frac{\chi}{Q}(x_o,y,z) = \frac{\exp(-y^2/2\sigma_y^2)}{2\pi \sigma_y \sigma_z u_{10}} \bar{H}(x_o,0,z) \qquad (33.1)$$

where

$\bar{H}(x_o,0,z)$ is as given by Equation 30.2, above with h=0. (33.2)

Utilizing Equation 33 in Equation 14, above, and transforming from cartesian (x,y,z) to spherical polar (r,ϕ,θ) coordinates, the relative shine integral, $S_m(x_o)$, is given by:

$$S(x_o) = \frac{1}{2\pi \sigma_y \sigma_z u_{10}} V \qquad (34.1)$$

where

$$V = \frac{\mu_a}{2\pi} \int_0^\infty \int_0^{\pi/2} \int_0^{2\pi} B(\mu r)e^{-\mu r} \exp\left(-\frac{(r\sin\theta\sin\phi)^2}{2\sigma_y^2}\right) \bar{H}(x_o,0,r\cos\theta)$$
$$d\phi \sin\theta d\theta dr. \qquad (34.2)$$

Then, by analogy with Section 4.3.2, the values of the $(V)_m$ are obtained by means of the FORTRAN subprogram, SUBROUTINE VIND, as in Section 4.3.2 except that the subroutine is called with HE = 0.

4.3.3.1 Upper-bound Values of $\dot{S}_m(x_o)$ for Building-vent Case

With respect to Equation 33, above, we note that $X/Q\ (x_o,0,z) > X/Q(x_o,y,z)$ and that the upper bound to the relative air concentration is given by:

$$\frac{X}{Q}\ (x_o,0,z) = \frac{1}{2\pi\ \sigma_y\ \sigma_z\ u_{10}}\ \bar{H}\ (x_o,0,z)$$

where

$\bar{H}\ (x_o,0,z)$ is as given by Equation 30.2, above with $h = 0$.

Utilizing this equation in Equation 14, above, and transforming from cartesian (x,y,z) to spherical polar (r,ϕ,θ) coordinates, the upper-bound, $S_m\ (x_o)$, is given by:

$$S = \frac{1}{2\pi\ \sigma_y\ \sigma_z\ u_{10}}\ \bar{V} \tag{31}$$

where

$$\bar{V} = \frac{\mu_a}{4\pi}\ \int_0^{2\pi} d\phi \int_0^{\infty} \int_0^{\pi/2} B(\mu r)e^{-\mu r}\ \bar{H}\ (x_o,0,r\cos\theta)\ \sin\theta d\theta dr.$$

Then, by analogy with Section 4.2.2, the values of the $(\bar{V})_m$ are obtained by means of the FORTRAN subprogram, SUBROUTINE VIBAR, as in Section 4.2.2 except that the subroutine is called with HE = 0.

5. Annual Average Total-Body Dose and Associated Shine Integrals

The annual average dose, $\bar{\bar{D}}_n$, is required only when the release time period (T), which is associated with the released radionuclide that yields exposure radionuclide n, is longer than two hours.* The utilization of $\bar{\bar{D}}_n$, in conjunction with the so-called "two hour" doses (D_n and $\bar{D}_n$, above), has been described in Section 8 of Appendix B.

---

* Here and elsewhere in this appendix, we are considering only the doses (D_n, $\bar{D}_n$, and $\bar{\bar{D}}_n$) from that component, $q \equiv q_{n_E} T^{n_R}\ (\tau)$, of the exposure nuclide (n_E) which arises from a particular released nuclide (n_R) and its particular release time period (T). The component, $q_{n_E} T^{n_R}\ (\tau)$, is as described in Section 4 of Appendix A.

Utilizing the gamma-ray dose factors, DF_{mn}, from Section 3, above, the annual average dose is given by:

$$\bar{\bar{D}}_n = \sum_m DF_{mn} \; \bar{\bar{S}}_{mn} \qquad (31)$$

where the $\bar{\bar{S}}_{mn}$ are the annual average shine integrals.

Analogous to the derivation of the annual average air and integral air concentrations in Sections 7 and 8 of Appendix B, the annual average shine integral, $\bar{\bar{S}}_{mn} = \bar{\bar{S}}_{mn}(x_o)$, is derived for a specific downwind distance (x_o) in the particular compass sector (k) by accumulating the frequency-weighted contributions from the probable meteorological conditions (ij). Therefore, by analogy with Appendix B and Equations 15 and 16, above, the annual average shine integral is given by:

$$\bar{\bar{S}}_{mn}(x_o) = \sum_i \sum_j f_{ijk} \; [\bar{S}_{mn}(x_o)]_{ijk} \qquad (32.1)$$

where

$$[\bar{S}_m(x_o)]_{ijk} = q_n(\tau_{ijk}) \; [\bar{S}_m(x_o)]_{ijk} \quad \text{with } \tau_{ijk} \equiv \frac{x_o}{u_{ijk}} ; \qquad (32.2)$$

$$[\bar{S}_m(x_o)]_{ijk} = \frac{\mu_{am}}{4\pi} \int_0^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} B_m(\mu r) e^{-\mu_m r} \cdot [\bar{\frac{X}{Q}}(x_o, z)]_{ijk} \, dxdydz; \qquad (32.3)$$

and

the average relative air concentration, $[\bar{\frac{X}{Q}}(x_o, z)]_{ijk}$, is obtained from Section 7 of Appendix B.

The evaluation of the average relative shine integral, $[\bar{S}_m(x_o)]_{ijk}$, is as described in Section 4.2.2 or 4.2.3, above, depending upon whether the release is a stack release or a building-vent release.