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ESTIMATION OF RADIATION DOSES FOLLOWING A REACTOR ACCIDENT

F. T. Binford
J. Barish
F. B. K. Kam

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ESTIMATION OF RADIATION DOSES FOLLOWING A REACTOR ACCIDENT

F. T. Binford
Operations Division

J. Barish
Computing Technology Center
Oak Ridge Gaseous Diffusion Plant

F. B. K. Kam
Operations Division

FEBRUARY 1968

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ESTIMATION OF RADIATION DOSES FOLLOWING A REACTOR ACCIDENT

F. T. Binford, J. Barish, F. B. K. Kam

ABSTRACT

Based upon the "Gaussian Plume" formula, a model has been developed which permits calculation of the downwind radiation doses to be expected following a reactor accident. Although the calculation presented here is concerned only with the thyroid dose due to iodines and the whole body dose due to iodines and noble gases, it can easily be adapted to handle other radioisotopes. The basic assumptions include instantaneous release of a given quantity of radioactive material into a reactor building followed by emission at a constant (volume) rate from a point source. Radioactive decay both within the building and during passage downwind are accounted for as are the growth and decay of daughter products and the effects of physical separation such as filtration. A Fortran IV computer program "PLUME" has been written for the purpose of solving the equations developed.

PART I - CALCULATION OF CONCENTRATIONS

1. Introduction

The situation treated in this analysis is that in which a quantity of volatile fission products is released into a reactor containment volume as a result of a core meltdown or other similar accident. The fission products are assumed to instantly mix with the air in the containment building and to form a homogeneous mixture. It is further assumed that this mixture is emitted to the atmosphere through a stack at a constant rate. The air lost from the building in this fashion is replaced by clean air from the surrounding atmosphere.

Although any isotope may be treated in the same fashion, this study is aimed primarily at obtaining an estimate of the radiation doses delivered downwind due to the release of the iodines and the noble gases. For convenience, all of the calculations are made on a "per kilowatt" basis: that is, the quantity of radioactive material initially present is that which corresponds to a reactor power of one kilowatt for a specific period of time.* Provision is made for the removal of iodine by filtration and for the emission of daughter products from the filter. Variation of the fraction of the material available which is actually released into the building can easily be taken care of by the use of appropriate numerical factors applied to the results. Extrapolation to power levels other than

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*With the exception of 8 day ^{131}I, all of the volatile products of interest are so short lived that saturation may be assumed.

1 kw can also be handled in this way. For example, to obtain the radiation dose from a 500-Mw reactor which suffers a 50% meltdown and releases 25% of the iodine present in the melted region, it is only necessary to multiply the "per kilowatt" result by $5 \times 10^5 \times 0.5 \times 0.25 = 6.25 \times 10^4$ to obtain the correct value.

2. Basic Equation for Concentration

The concentration of a given radioisotope at a point with space coordinates (x,y,z) related to a point emitter located at the origin may be estimated by employing the Gaussian Plume Formula[1]

$$X(x,y,z,u) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-y^2/2\sigma_y^2 - z^2/2\sigma_z^2\right) \qquad (1)$$

where

$X(x,y,z,u)$ = concentration (curies/m^3 or $\mu c/cm^3$),

Q = source strength (curies/min)

u = wind speed (m/min),

x,y,z = space coordinates (m), and

$\sigma_y(x)$, $\sigma_z(x)$ are the horizontal and vertical dispersion parameters respectively (m).

The wind velocity, u, is always taken to be in the direction of the positive x-axis. Transport downwind is assumed to be due to wind speed only with diffusion in the ±x directions neglected.

The source term Q in equation (1) is constant. Consider, however, the case where a quantity q_p° (curies) of a radioisotope having decay constant

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[1]F. A. Gifford, The Problem of Forecasting Dispersion in the Lower Atmosphere (booklet), DTIE, USAEC, Oak Ridge, Tennessee, 1961.

$\lambda_p(\text{min}^{-1})$ is released into a building of volume $V(m^3)$. Let $\alpha(\text{min}^{-1})$ be the constant fraction of the building volume which is passed up the stack each minute, and assume that this loss of the building contents is being constantly replaced by the inleakage of clean air. Then, if mixing within the building is assumed to be uniform and instantaneous, the initial concentration $\xi_p^\circ(\text{curies}/m^3)$ of the radioisotope within the building will be $\xi_p^\circ = q_p^\circ/V$. The rate of change of concentration with time becomes

$$\dot{\xi}_p^\circ(t) = -(\lambda_p + \alpha)\,\xi_p(t)$$

whence, at time t (min) after the initial release, the concentration in the building will be

$$\xi_p(t) = \frac{q_p^\circ}{V}\, e^{-(\lambda_p + \alpha)t}$$

Since a volume αV of this mixture is being emitted from the stack each minute, the emission rate, denoted by $\varepsilon(t)$ (curies/min), will, at time t, be

$$\varepsilon(t) = \alpha V \xi_p(t) = \alpha q_p^\circ e^{-(\lambda_p + \alpha)t}. \tag{2}$$

If decay during passage downwind is neglected, this becomes the source term for equation (1). To include the effect of decay during the time required for the activity to travel a distance x with speed u, it is necessary to multiply the emission rate by $e^{-\lambda_p x/u}$. Thus the effective source term associated with the concentration at a point (x,y,z) due to emission which took place at a time t after the initial release is

$$Q = Q_p(x,t) = \alpha q_p^\circ \exp\,[-\lambda_p(t + x/u) - \alpha t]. \tag{3}$$

Note that the decay occurs over a time $t = x/u$ where t is the time from initial release to emission and x/u is the transport time required for the emitted gas to reach the point x. On the other hand, reduction of the source term due to dilution in the building occurs only during the time t. It is convenient to define a time τ(min) such that

$$\tau \equiv t + x/u. \tag{4}$$

Then

$$Q_p(x,\tau) = \alpha q_p^\circ \exp\left[\alpha x/u - (\lambda_p + \alpha)\tau\right]. \tag{5}$$

The quantity $Q_p(x,\tau)$ is the effective source term associated with all points in a plane normal to the x-axis and located a distance x down wind. Because for values of τ less than x/u the emitted activity has not yet arrived at a distance x downwind, it is clear that equation (5) holds only for values of $\tau \geq x/u$ and for $x \geq 0$. Thus, whenever $\tau < x/u$ $Q_p(x,\tau) = 0$. Consequently, the concentration at the point (x,y,z) at a time τ following initial release becomes

$$X(x,y,z,\tau,u) = \frac{\alpha q_p^\circ e^{-(\lambda_p + \alpha)\tau}}{2\pi u \sigma_y \sigma_z} \exp\left[\alpha x/u - y^2/2\sigma_y^2 - z^2/2\sigma_z^2\right], \ \tau \geq x/u \tag{6}$$

$$= 0, \ \tau < x/u,$$

For brevity, the concentration equations will frequently be written in the form

$$X(x,y,z,\tau,u) = Q_p(x,\tau)S(x,y,z) \tag{7}$$

where $S(x,y,z)$, called the "basic stack factor", contains the information on atmospheric dispersion, and $Q_p(x,\tau)$, the "source term", contains the

information on rate of emission, decay, and on dilution within the building. The basic stack factor is defined to be

$$S(x,y,z) = \frac{\exp\left[-y^2/2\sigma_y^2 - z^2/2\sigma_z^2\right]}{2\pi u\sigma_y\sigma_z} \tag{8}$$

The basic stack factor has been derived under the assumption of an "infinite atmosphere" that is under the assumption that diffusion can continue indefinitely in the y and z directions. In a later section certain modifications will be applied to S(x,y,z) in order to account for ground reflection and for reflection from a temperature inversion.

3. Source Terms for Radioactive Daughters

Equation (5) was derived using the tacit assumption that the radioisotope under consideration decays to a product of no interest and, therefore, only the concentration of the parent was obtained. The foregoing is not, however, always true.

Let q_p° be the number of curies of a parent radioisotope originally released in the building. Then if λp is the decay constant of the parent, the total number of curies of the parent which remain in existance after time τ is

$$q_p(\tau) = q_p^\circ e^{-\lambda_p \tau}$$

and the total number of curies, $q_d(\tau)$, of the daughter present at this time is

$$q_d(\tau) = \frac{\lambda_d q_p^\circ}{\lambda_d - \lambda_p}\left(e^{-\lambda_p \tau} - e^{-\lambda_d \tau}\right)$$

where λ_d is the decay constant of the daughter.

If the emission and dispersion is assumed to involve no physical separation of the two species, then the ratio $q_d(\tau)/q_p(\tau)$ is everywhere the same; in particular at the point (x,y,z). Since the basic stack factor is the same for both parent and daughter

$$X_d(x,y,z,\tau)/X_p(x,y,z,\tau) = Q_d(x,\tau)/Q_p(x,\tau) = q_d(\tau)/q_p(\tau)$$

where the subscript d refers to the daughter and the other symbols have the same meaning as before. Upon introducing the value of $Q_p(x,\tau)$ from equation (5) and the explicit expression for the ratio $q_d(\tau)/q_p(\tau)$, the appropriate form of the source term for the unseparated daughter is found to be

$$Q_d(x,\tau) = \frac{\alpha q_p^{\circ}\lambda_d}{\lambda_d - \lambda_p} e^{\alpha x/u} \left(e^{-(\lambda_p + \alpha)\tau} - e^{-(\lambda_d + \alpha)\tau}\right), \ \tau \geq x/u \qquad (9)$$

$$= 0, \ \tau < x/u$$

In some cases, notably those involving the noble gases, the parent isotope is volatile, whereas the daughter is solid. Thus if the stack is equipped with a suitable decontamination device such as a filter or charcoal absorber, the parent may be stripped of that portion of the daughter which was formed by decay during the time that the parent isotope was in the building. The rate of emission of the parent at time t is given by equation (2), and for this case it will be assumed that when emitted the parent has no daughter accompanying it. When the parent has reached a point x downwind it will have decayed by an amount $e^{-\lambda_p x/u}$. At this time the ratio of daughter to parent activity will be

$$\lambda_d\left(1 - e^{-(\lambda_d - \lambda_p)x/u}\right)/\left(\lambda_d - \lambda_p\right)$$

Upon multiplying the source term for the parent, equation (5), by this ratio the source term for the daughter, is found to be

$$Q_d(x,\tau) = \frac{\alpha q_p^\circ \lambda_d}{\lambda_d - \lambda_p}\left(1 - e^{-(\lambda_d - \lambda_p)x/u}\right)e^{\alpha x/u} \cdot e^{-(\lambda_p + \alpha)\tau}, \quad \tau \geq x/u \qquad (10)$$

$$= 0, \quad \tau < x/u.$$

In other cases (the Iodines), the parent may be effectively removed by the filter system, but the daughter is volatile and is, therefore, emitted from the filter at some rate which depends upon the amount of parent on the filter, the rate of decay of the parent, and the physical situation under consideration. The downwind concentration from a daughter emitted in this fashion is estimated under the simplifying assumption: (1) that all of the parent which reaches the filter is trapped thereon, and (2) that the daughter is emitted just as fast as it is formed.

The rate at which the parent is being deposited on the filter is numerically equal to the emission rate computed in equation (2). The only loss mechanism is radioactive decay. Hence, the rate equation for the parent activity $q_p(t)$ (curies) on the filter becomes

$$\dot{q}_p(t) = \alpha q_p^\circ e^{-(\lambda_p + \alpha)t} - \lambda_p q_p(t), \qquad q_p(0) = 0$$

so that, at a time t after the initial release the filter contains

$$q_p(t) = q_p^\circ e^{-\lambda_p t}\left(1 - e^{-\alpha t}\right)$$

curies of the parent. Under assumption (2) there are $\lambda_d q_p(t)$ curies of daughter escaping per minute ($\lambda_d = \text{min}^{-1}$). This activity decays by an

amount $e^{-\lambda_d x/u}$ during its passage downwind. Hence, the source term which represents daughter activity emitted by the trapped parent is

$$\lambda_d q_p^\circ e^{-\lambda_p t} (1 - e^{-\alpha t}) e^{-\lambda_d x/u}$$

There is also daughter activity being emitted directly from the building as a result of decay of the parent which has not yet reached the filter. The number of curies of daughter in the building at time t is obtained from

$$\dot{q}_d(t) = \lambda_d q_p^\circ e^{-(\lambda_p + \alpha)t} - (\lambda_d + \alpha) q_d(t), \quad q_d(0) = 0$$

whence

$$q_d(t) = \frac{\lambda_d q_p^\circ}{\lambda_d - \lambda_p} \left[e^{-(\lambda_p + \alpha)t} - e^{-(\lambda_d + \alpha)t} \right].$$

The emission rate is just $\alpha q_d(t)$. Upon correcting for decay during passage downwind, the contribution to the source term due to daughter activities formed in the building becomes

$$\frac{\alpha \lambda_d q_p^\circ}{\lambda_d - \lambda_p} \left[e^{-(\lambda_p + \alpha)t} - e^{-(\lambda_d + \alpha)t} \right] e^{-\lambda_d x/u}.$$

Upon adding the two contributions and introducing the relation $t = \tau - x/u$, the appropriate source term for this case is found to be

$$\begin{aligned} Q_d(x,\tau) = q_\circ \lambda_d \Big\{ & e^{-\lambda_p \tau} \left[1 - e^{-\alpha(\tau - x/u)} \right] e^{-(\lambda_d - \lambda_p)x/u} \\ & + \frac{\alpha}{\lambda_d - \lambda_p} \Big[e^{-(\lambda_p + \alpha)(\tau - x/u)} \\ & - e^{-(\lambda_d + \alpha)(\tau - x/u)} \Big] e^{-\lambda_d x/u} \Big\}, \quad \tau \geq x/u \\ = 0, & \quad \tau < x/u. \end{aligned} \tag{11}$$

Of considerable interest with respect to this case is the limiting value where $\alpha \to \infty$. Physically this represents the situation where all of the parent is instantly conveyed to the filter at time $t = 0$. In this case the second term in braces vanishes and the remaining term of equation (11) reduces to

$$Q_d(x,\tau) = q_p^\circ \lambda_d e^{-(\lambda_d - \lambda_p)x/u} \cdot e^{-\lambda_p \tau}, \quad \tau \geq x/u \tag{12}$$

$$= 0, \quad \tau < x/u.$$

4. Modification of the Basic Stack Factor to Account for Boundaries

The basic stack factor, defined in equation (8) was developed using the assumption that the stack plume is unrestricted in its diffusion in both the vertical (z) and lateral (y) direction. This assumption is valid insofar as the lateral direction is concerned unless the stack is located in a narrow valley. However, for a stack of finite height the plume will eventually intersect the ground and be reflected upward. The simplest method of accounting for ground reflection is to merely multiply the stack factor by 2. This procedure gives correct results everywhere if the source of emission is at ground level. If the source is at some height, h, above ground multiplication of the stack factor by 2 gives the correct result for points in the plane $z = -h$, but overestimates the concentration elsewhere.

A more satisfactory method of handling ground reflection has been described by D. S. Duncan and his coworkers.[2] This involves the use of an imaginary source located on the negative z-axis in such a position that

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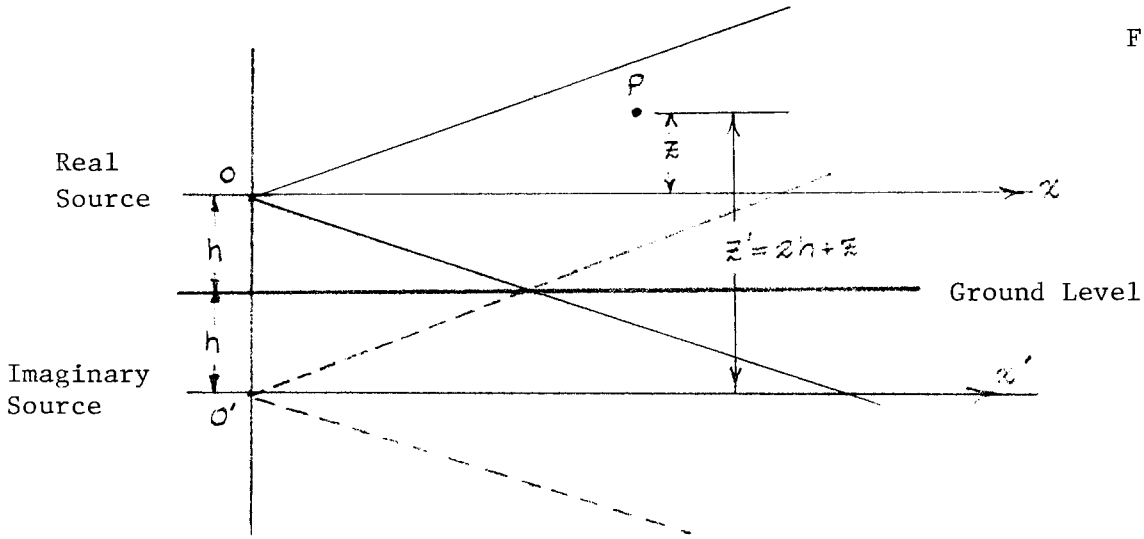
[2]D. S. Duncan et al, Cloud, an IBM Program for Computing Gamma-Ray Dose Rate from a Radioactive Cloud, NAA-SR-Memo 4822.

its plume will emerge from the ground at precisely the position predicted by the concept of perfect reflection. The geometrical situation is illustrated in Fig. 1.

Fig. 1



Since at the point P the x and y coordinates are identical for both the real and imaginary plumes, it is only necessary to correct that factor of equation (8) which contains the z-dependance. Upon making this correction the stack factor becomes

$$S_g(x,y,z,u) = \frac{e^{-y^2/2\sigma_y^2}}{2\pi u\sigma_y\sigma_z}\left[e^{-z^2/2\sigma_z^2} + e^{-(2h + z)^2/2\sigma_z^2}\right] \tag{13}$$

where the subscript g is used to denote the fact that the stack factor has been modified to include ground reflection.*

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*Note that if the origin of coordinates is moved from the elevation h to ground level by means of the transformation z' = z + h, equations (8) and (13) become respectively

$$S(x,y,z',u) = \frac{\exp\left[-y^2/2\sigma_y^2 - (z' - h)2/2\sigma_z^2\right]}{2\pi u\sigma_y\sigma_z}$$

$$Sg(x,y,z',u) = \frac{e^{-y^2/2\sigma_y^2}}{2\pi u\sigma_y\sigma_z}\left\{\exp\left[-(z' - h)^2/2\sigma_z^2\right] + \exp\left[-(z' + h)^2/2\sigma_z^2\right]\right\}$$

It is easy to see that when h = 0, i.e., for ground level emission, equation (13) reduces to $S_g(x,y,z,u) = 2S(x,y,z,u)$. Moreover, if z is set equal to -h, corresponding to ground level concentrations from elevated emission $S_g(x,y,-h,u) = 2S(x,y,-h,u)$ as previously stated.

Under some conditions a temperature inversion may be present. Such a condition often results in a layer of warm air which acts as a barrier to diffusion in the positive z direction. Such a layer, if it is located above the stack oriface will tend to prevent vertical dispersion above this point. Duncan[2] has suggested that inversions can be handled by using the concept of imaginary sources located along the z-axis. However, a procedure recommended by Gifford[1] is simpler to use and appears to give very nearly the same results as Duncan's procedure. This consists of holding the vertical dispersion parameter σ_z constant when it reaches the value $\sigma_z = H/2.15$, where H is the elevation of the inversion lid expressed in meters. This method will be used in computing the inversion cases.

5. Summary of Source and Concentration Relations

For convenience, the various source equations derived in the previous sections are summarized below. The corresponding concentration equations may be obtained from the relation

$$X(x,y,z,\tau,u) = S_g(x,y,z,u)Q(x,\tau) \tag{14}$$

where

$$S_g(x,y,z,u) = \frac{e^{-y^2/2\sigma_y^2}}{2\pi u\sigma_y\sigma_z} \exp\left[e^{-z^2/2\sigma_z^2} + e^{-(2h + z)^2/2\sigma_z^2}\right] \tag{13}$$

Type 1, Pure Parents

$$Q_1(x,\tau) = \alpha q_p^\circ \exp\left[\alpha x/u - (\lambda_p + \alpha)\tau\right], \ \tau \geq x/u \tag{3}$$

$$= 0, \ \tau < x/u$$

Type 2, Unseparated Daughters

$$Q_2(x,\tau) = \frac{\alpha q_p^\circ \lambda_d}{\lambda_d - \lambda_p} e^{\alpha x/u} \left[e^{-(\lambda_p + \alpha)\tau} - e^{-(\lambda_d + \alpha)\tau}\right], \ \tau \geq x/u \tag{9}$$

$$= 0, \ \tau < x/u$$

Type 3, Solid Daughters Removed By Filter

$$Q_3(x,\tau) = \frac{\alpha q_p^\circ \lambda_d}{\lambda_d - \lambda_p}\left(1 - e^{-(\lambda_d - \lambda_p)x/u}\right) \exp\left[\alpha x/u - (\lambda_p + \alpha)\tau\right], \ \tau \geq x/u$$

$$= 0, \ \tau < x/u \tag{10}$$

Type 4, Volatile Daughters of Filtered Parents

(a) General Case

$$Q_4(x,\tau) = \lambda_d q_p^\circ \left\{\left[1 - e^{-\alpha(\tau - x/u)}\right] \exp\left[-\lambda_p(\tau - x/u) - \lambda_d x/u\right]\right.$$

$$+ \frac{\alpha}{\lambda_d - \lambda_p} e^{-\lambda_d x/u} \left[\exp\left\{-(\lambda_p + \alpha)(\tau - x/u)\right\}\right.$$

$$\left.\left. - \exp\left(-(\lambda_d + \alpha)(\tau - x/u)\right)\right]\right\}, \ \tau \geq x/u$$

$$= 0, \ \tau < x/u \tag{11}$$

(b) Limiting Case ($\alpha \to \infty$)

$$Q_4(x,\tau) = q_p^\circ \lambda_d \exp\left[-\lambda_p(\tau - x/u) - \lambda_d x/u\right], \ \tau \geq x/u$$

$$= 0, \ \tau < x/u \tag{12}$$

Nomenclature

$X(x,y,z,\tau,u)$ = Concentration at point (x,y,z,τ) (c/m^3 min or $\mu c/cm^3$ min)*

$Q_m(x,\tau)$ = Effective source term at x and τ (curies/kw min)

$S_g(x,y,z,u)$ = Modified stack factor (min/m^3)

q_p^o = quantity of parent originally released in building (c/kw)

α = fractional exhaust rate (min^{-1})

τ = time since initial release in the building (min)

x,y,z = space coordinates of point at which concentration is computed (m)

u = wind velocity (m/min) (in. + x-direction)

h = effective stack height (m)

σ_y, σ_z = horizontal and vertical dispersion parameters respectively (m)

λ = decay constant (min^{-1})

Subscripts: p = parent, d = daughter, m = type of source term

PART II - THE RADIATION DOSE EQUATIONS

6. Introduction

The primary objective of this analysis is to obtain estimates of the radiation doses delivered to receptors who are exposed to the cloud of radioactive effluent for various periods of time and at various locations relative to the point of emission. As previously pointed out, interest centers mainly on the so-called "volatile" fission products, namely: the iodine, the noble gases, Kr and Xe, and the noble gas daughters. Consequently, the remainder of this work is directed specifically toward the computation of the radiation doses associated with these materials.

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*Note that since 1 cubic meter contains 10^6 cm^3 the units c/m^3 and $\mu c/cm^3$ are numerically equal.

Two types of radiation dose will be considered: (1) The dose which is received due to the inhalation of radioactive material. This is primarily due to the presence of the iodine isotopes and will be called the "internal dose." (2) The whole body γ-radiation dose which results from the submersion of the receptor in an atmosphere containing γ-emitting radionuclides; this will be referred to as the "external dose."

The first of these depends only upon the concentration of radioactive material in the immediate vicinity of the receptor, the length of the exposure period, and the rate at which contamination is being inhaled. The external dose, however, is delivered by the entire inventory of activity in the plume and depends, therefore, upon the concentration at each point in space. It is, therefore, necessary in this case to perform a space integration over the entire plume in order to compute the value of this dose.

7. The Internal Dose

The rate at which radioactive material is being inhaled by a receptor located at the space point (x,y,z) at a time τ after the initial release in the building is just the rate of inhalation of air multiplied by the concentration of radioactive material in the air at that point. The dose rate may be obtained by multiplying this product by the dose delivered per unit activity inhaled.

Let β (cm^3/min) be the constant inhalation rate, $X(x,y,z,\tau,u)$($\mu c/cm^3$) be the activity concentration and δ(rem/μc) be the dose delivered per unit of activity inhaled. Then the dose rate, designated by $R_{int}(x,y,z,\tau,u)$ (rem/min), is given by

$$R_{int}(x,y,z,\tau,u) = \beta\delta X(x,y,z,\tau,u) = \beta\delta S_g(x,y,z,u)Q(x,\tau) \tag{15}$$

where $S_g(x,y,z,u)$ is given by equation (13) and the appropriate value of $Q(x,\tau)$ is chosen from those listed in Sect. 5.

The dose $D_{int}(x,y,z,t,u)$ (rem) delivered to a receptor who remains at the space point (x,y,z) for a time T (min) following the initial release in the building is

$$D_{int}(x,y,z,T,u) = \beta\delta S_g(x,y,z,u) \int_{x/u}^{T} Q(x,\tau)d\tau \tag{16}$$

where $T \geq x/u$ and the integration is performed over the range x/u to T because for values of T less than x/u the activity has not yet arrived a distance x downwind, and consequently the value of D_{int} is zero.

The quantity δ represents the total dose in rem which will eventually be delivered by one inhaled microcurie during its residence time in the body. Hence, D_{int} is not the dose actually delivered during the time T, but the dose which will eventually be received because of activity inhaled during this time period.

8. The External Dose

The external dose delivered to a receptor located at a space point P depends not only upon the concentration of γ-emitting activity in the immediate vicinity of this point, but also upon the flux of γ-radiation which originates at every point within the radioactive cloud. Moreover, if P is located near the building in which the active material is released, there may be a direct contribution due to radiation from the building contents. This latter point will be neglected for the moment, and only the radiation dose from the cloud itself will be considered.

Consider a receptor located at the point (ξ, η, ζ) relative to an origin of Cartesian coordinates located at the point of emission. At each point (x,y,z) relative to the same origin the plume contains, at time τ, a concentration $X(x,y,z,\tau)$ (c/m^3) of the radioisotope under consideration. For simplicity assume that this radioisotope emits a single γ-ray of energy E^γ per disintegration. Let $\mu(m^{-1})$ be the linear absorbtion coefficient in air for this γ-ray and let $B(\mu r)$ be the corresponding point isotropic dose buildup factor in air.* Then the photon flux at the point (ξ, η, ζ) due to activity contained in a volume element dv located at (x,y,z,τ) will be

$$\frac{2.22 \times 10^{12}\ X(x,y,z,\tau)\ B(\mu r) e^{-\mu r} dv}{4\pi r^2} \text{ photons/m}^2 \text{ min}$$

where

$$r^2 \equiv (x - \xi)^2 + (y - \eta)^2 + (z - \zeta)^2 \qquad (\text{meters}^2) \qquad (17)$$

The geometric configuration is shown in Fig. 2.

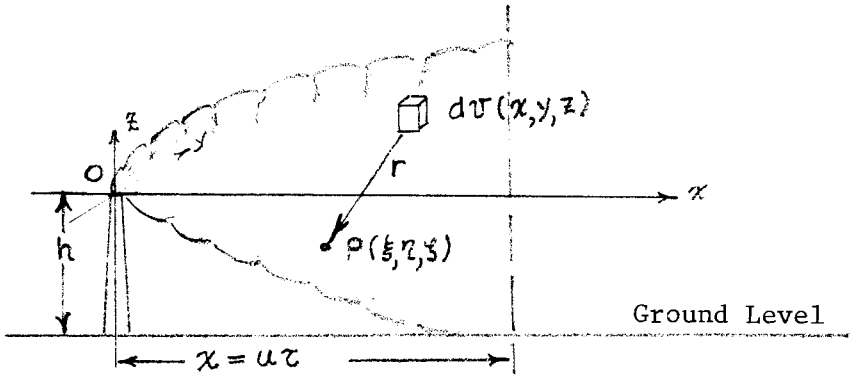

Fig. 2

Note that the plume extends in the x-direction a distance $u\tau$ where τ is the time since initial release in the building. This is because, at a windspeed u, the first increment released from the stack will be transported just that distance.

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*See Sect. 14.

The energy flux in mev/m^2 min is obtained by multiplying the photon flux by the energy per photon - E^γ mev. Then, if σ(cm^2/g) is the energy absorbtion coefficient in photons of energy E^γ, and it is recalled that one Rem is equivalent to the absorbtion of 6.242 x 10^7 mev per gram the dose rate at (ξ,η,ζ) due to photons which originate in the incremental volume dv at (x,y,z) may be written

$$dR^\gamma_{ext} = \frac{3.556\,\sigma E^\gamma X(x,y,z,\tau)B(\mu r)e^{-\mu r}dv}{4\pi r^2} \tag{18}$$

Note that this is the dose rate at the surface of the body and is not the average dose rate within the body. This is because no credit has been taken for attenuation in tissue itself. Thus equation (18) represents the dose rate at the body surface and is, therefore, a conservative upper limit to the whole body dose rate. In developing equation (18) a factor of 10^4 has been included in the denominator to account for the fact that the energy flux is given in mev/m^2 min, whereas the absorbtion coefficient, σ, has been expressed in cm^2/g.

The total dose rate at the point (ξ,η,ζ) at time τ is obtained by integrating equation (17) over the entire volume of the plume.

$$R^\gamma_{ext}(\xi,\eta,\zeta,\tau) = \frac{3.556\sigma E^\gamma}{4\pi}\int_{-h}^{\infty}\int_{-\infty}^{\infty}\int_0^{u\tau}\frac{X(x,y,z,\tau)B(\mu r)e^{-\mu r}}{r^2}\,dxdydz \text{ (Rem/min)} \tag{19}$$

The dose which is delivered to a receptor who remains at the point (ξ,η,ζ) for a time T following the initial release in the building requires integration of equation (18) over time from $\tau = 0$, to $\tau = T$. Hence,

$$D^\gamma_{ext}(\xi,\eta,\zeta,T) = \frac{3.556\sigma E^\gamma}{4\pi}\int_0^T\int_{-h}^{\infty}\int_{-\infty}^{\infty}\int_0^{u\tau}\frac{X(x,y,z,\tau)B(\mu r)e^{-\mu r}}{r^2}\,dxdydzd\tau \text{ (Rem)} \tag{20}$$

Now the concentration $X(x,y,z,\tau) = S_g(x,y,z)Q(x,\tau)$ where $Q(x,\tau)$ is the appropriate source term selected from those listed in Sect. 5. Because the time dependence occurs only in the source term it is possible to interchange the order of the x and τ integration. Thus,*

$$\int_0^T \int_{-h}^{\infty} \int_{-\infty}^{\infty} \int_0^{u\tau} \frac{S_g(x,y,z)Q(x,\tau)B(\mu r)e^{-\mu r}}{r^2} dxdydzd\tau$$

$$= \int_{-h}^{\infty} \int_{-\infty}^{\infty} \int_0^{uT} \frac{S_g(x,y,z)B(\mu r)e^{-\mu r}}{r^2} dxdydz \int_{x/u}^{T} Q(x,\tau)d\tau \qquad (21)$$

Thus the external dose equation may be written

$$D^{\gamma}_{ext}(\xi,\eta,\zeta,T) = \frac{3.556\sigma E^{\gamma}}{4\pi} \int_{-h}^{\infty} \int_{-\infty}^{\infty} \int_0^{uT} \frac{S_g(x,y,z)B(\mu r)e^{-\mu r}}{r^2} dxdydz \int_{x/u}^{T} Q(x,\tau)d\tau \qquad (22)$$

Note that the time integral in this equation is exactly the same as that which appears in equation (16) which gives the internal dose. Since the time integration of $Q(x,\tau)$ can be performed analytically for all of the source terms under consideration, the number of numerical integrations required to evaluate equation (22) is reduced to three.

PART III - APPLICATIONS

9. Introduction

The dose equations derived above are all based upon a single isotope, and in the case of the external γ-dose upon a single isotope which emits one monoenergetic gamma ray with each disintegration. In practice, however,

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*See for example R. Courant, Differential and Integral Calculus, Vol. II, p. 241, 1957.

it is convenient to consider groups of isotopes which have similar chemical and physical properties. Moreover, in most cases each isotope will emit several gamma rays of different energies and with different abundance.

The internal dose will be assumed to be due entirely to the five important iodine isotopes, and these will be considered as a single group. The external γ-dose is due to both iodines and noble gases. Since these two types of isotopes behave differently with regard to filtration, they will be computed separately, one group consisting of the iodine, and the other of the noble gases together with their daughters.

The computation of the internal dose is quite simple because it is dependent only on the time integral of the concentration at the position of the receptor and thus involves only the evaluation of a function. On the other hand, an accurate calculation of the external dose requires a space integration as well as summation over all of the various γ-energies.

The integrals

$$I_m(x,T) \equiv \int_{x/u}^{T} Q_m(x,\tau)d\tau \tag{23}$$

are needed for both types of calcualtion. For convenience, the integrals which correspond to the four types of source terms are given below.

<u>Type 1, Pure Parents</u>

$$I_1(x,T) = \alpha q_p^\circ \, e^{-\lambda_p x/u} \left[\frac{1 - e^{-(\lambda_p + \alpha)(T - x/u)}}{\lambda_p + \alpha} \right] \tag{24}$$

Type 2, Unseparated Daughters

$$I_2(x,T) = \frac{\alpha q_p^\circ \lambda_d}{\lambda_d - \lambda_p} \left\{ \frac{e^{-\lambda_p x/u}\left(1 - e^{-(\lambda_p + \alpha)(T - x/u)}\right)}{(\lambda_p + \alpha)} - \frac{e^{-\lambda_d x/u}\left(1 - e^{-(\lambda_d + \alpha)(T - x/u)}\right)}{(\lambda_d + \alpha)} \right\} \tag{25}$$

Type 3, Solid Daughters Removed by Filter

$$I_3(x,T) = \frac{\alpha q_p^\circ \lambda_d}{\lambda_d - \lambda_p} \left[e^{-\lambda_p x/u} - e^{-\lambda_d x/u} \right] \left[\frac{1 - e^{-(\lambda_p + \alpha)(T - x/u)}}{(\lambda_p + \alpha)} \right] \tag{26}$$

Type 4, Volatile Daughters of Filtered Parents

$$I_4(x,T) = \lambda_d q_p^\circ e^{-\lambda_d x/u} \left[\frac{1 - e^{-\lambda_p (T - x/u)}}{\lambda_p} - \frac{1 - e^{-(\lambda_p + \alpha)(T - x/u)}}{\lambda_p + \alpha} \right] + \frac{\alpha}{\lambda_d - \lambda_p} \left[\frac{1 - e^{-(\lambda_p + \alpha)(T - x/u)}}{\lambda_p + \alpha} - \frac{1 - e^{-(\lambda_d + \alpha)(T - x/u)}}{\lambda_d + \alpha} \right] \tag{27}$$

The limiting case where α becomes very large is

$$I_4(x,T) = \frac{\lambda_d}{\lambda_p} q_p^\circ e^{-\lambda_d x/u} \left[1 - e^{-\lambda_p (T - x/u)} \right] \tag{27^1}$$

10. Calculation of the Internal Dose Due to Iodine Inhalation

The source term associated with each of the five radioiodine species (I^{131} through I^{135}) has the simple form given by equation (3). The time integrals, then, are all of Type 1 as given in equation (24). Consequently, by equation (16) the internal dose delivered to a receptor located at the point (x,y,z) for a time T following the initial release in the

building is

$$D_{int}(x,y,z,T) = \alpha\beta S_g(x,y,z) \sum_{i=1}^{5} \delta_i q^o_{pi} e^{-\lambda_{pi} x/u} \frac{\left[1 - e^{-(\lambda_{p_i} + \alpha)(T - x/u)}\right]}{(\lambda_{p_i} + \alpha)} \quad (28)$$

For the particular case where $\alpha >> \lambda_{p_i}$ and $T \to \infty$, this reduces to

$$D_{int} \simeq \beta S_g(x,y,z) \sum_{i=1}^{5} \delta_i q^o_{pi} \; e^{-\lambda_{pi} x/u} \quad (28^1)$$

The proper parameters to employ in these and in the subsequent dose equations are discussed in Sect. 14.

11. Calculation of the External γ-Dose Due To Iodines

Consider a single iodine isotope which emits photons of η different energies. Let E_j^γ be the energy (Mev) of the j'th gamma ray, and let f_j be the number of such gamma rays emitted per disintegration. Then, upon recalling that all of the source terms are of Type 1, the external γ-ray dose delivered at the point (ξ,η,ζ) in the time T by this isotope will be

$$D^\gamma_{ext}(\xi,\eta,\zeta,T) = \frac{3.556}{4\pi} \sum_{j=1}^{n} E_j^\gamma \sigma_j f_j \int_{-h}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{uT} S_g(x,y,z) I_1(x,T) \frac{B_j(\mu_j r) e^{-\mu_j r}}{r^2} \, dxdydz \quad (29)$$

where $I_1(x,T)$ is given by equation (23), $S_g(x,y,z)$ by equation (13), and r^2 by equation (17). Appropriate forms of the buildup factor, $B(\mu r)$, will be discussed later.

Since there are five iodine isotopes, the total iodine dose is obtained by summing five relations similar to equation (29). Thus the

total external iodine dose due to the iodines is

$$D^{\gamma}_{ext}(\xi,\eta,\zeta,T)$$

$$= \frac{3.556}{4\pi} \sum_{i=1}^{5} \sum_{j=1}^{n_i} E^{\gamma}_{ij}\sigma_{ij}f_{ij} \int_{-h}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{uT} S_g(x,y,z)I_{ij}(x,T)\frac{B_{ij}(\mu_{ij}r)e^{-\mu_{ij}r}}{r^2}\,dxdydz \tag{30}$$

Here the index i refers to the i'th isotope and the double index ij refers to the j'th γ-ray of the i'th isotope. The upper limit of the second summation n_i refers to the total number of different γ-ray energies emitted by the i'th isotope.

12. Calculation of the External γ-Dose Due To Noble Gases

Computation of the noble gas gamma dose is accomplished in exactly the same manner as that for the iodines except that not all of the source terms have the simple form of equation (3). There are ten noble gas nuclides (Kr^{83m}, Kr^{85m}, Kr^{87}, Kr^{88}, Kr^{89}, Xe^{133m}, Xe^{133}, Xe^{135m}, Xe^{135}, Xe^{138}) which behave as pure parents. Three of these have significant solid daughters ($Kr^{88} \rightarrow Rb^{88}$, $Kr^{89} \rightarrow Rb^{89}$, $Xe^{138} \rightarrow Cs^{138}$) and require a source term of the form given in equation (10) with corresponding integral (26). Of the iodines, two decay to noble gases which contribute to the external dose ($I^{133} \rightarrow Xe^{133}$, $I^{135} \rightarrow Xe^{135m}$, Xe^{135}). If no iodine removal system is provided, these will require use of the source term (9); however, if it is assumed that the iodines are effectively removed by some decontamination device such as a charcoal absorber, then the appropriate source term to use is that of equation (11). In this treatment it will be assumed that the iodine is removed. Moreover, for simplicity the limiting case of

Type 4 will be used so that the appropriate integral is given by equation (27^1). Hence, the external γ-dose due to noble gases is given by

$$D^{\gamma}_{ext}(\xi,\eta,\zeta,T)$$

$$= \frac{3.556}{4\pi}\left\{\sum_{i=1}^{10}\sum_{j=1}^{n_i} E^{\gamma}_{ij}\sigma_{ij}f_{ij}\int_{-h}^{\infty}\int_{\infty}^{\infty}\int_{0}^{uT} S_g(x,y,z)I_{1i}(x,T)\frac{B_{ij}(\mu_{ij}r)e^{-\mu_{ij}r}}{r^2}\,dxdydz\right.$$

$$+\sum_{i=1}^{3}\sum_{j=1}^{n_i} E^{\gamma}_{ij}\sigma_{ij}f_{ij}\int_{-h}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{uT} S_g(x,y,z)I_{3i}(x,T)\frac{B_{ij}(\mu_{ij}r)e^{-\mu_{ij}r}}{r^2}\,dxdydz$$

$$\left.+\sum_{i=1}^{3}\sum_{j=1}^{n_i} E^{\gamma}_{ij}\sigma_{ij}f_{ij}\int_{-h}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{uT} S_g(x,y,z)I_{4i}(x,T)\frac{B_{ij}(\mu_{ij}r)e^{-\mu_{ij}r}}{r^2}\,dxdydz\right\} \tag{31}$$

Here the first double sum represents the pure parents, the second the solid daughters, and the third the noble gas daughters of the iodines. In this last case, both Xe^{135m} and Xe^{135} have the same precursor. This is handled by utilizing the branching ratio of I^{135} decay and treating the two species as if they came from different precursors.

13. A Method of Approximating the External γ Dose

Equations (30) and (31) represent, within the limits of the physical model and the accuracy of the values of the parameters, exact solutions to the external dose problem. They are, however, difficult to evaluate because they involve triple integrals which must be performed numerically. In some cases it is convenient to obtain an estimate of the external doses using a somewhat less difficult, although less exact procedure. This may be done by assuming that at distances sufficiently far from the source the gamma energy release from the plume is adiabatic; that is, exactly as

much energy is absorbed in each unit volume of the plume as is produced there.

Let E^{γ} be the total gamma energy (Mev) emitted per disintegration from a given radioisotope. Then, if the concentration of this isotope at the point (x,y,z) and the time τ is $X(x,y,z,\tau)$ $\mu c/cm^3$, the γ-energy emission density at that point will be $3.7 \times 10^4 E_i^{\gamma} X_i(x,y,z,\tau)$ mev/cm^{3}sec. Under the foregoing assumption, this is also the rate at which energy is being absorbed at that point. If the density of air is taken to be 1.25×10^{-3} g/cm^3 and it is recalled that 1 Mev is equivalent to 1.6021×10^{-6} erg, the energy absorbtion rate becomes

$$3.7 \times 10^4 E^{\gamma} X(x,y,z,\tau) \times 1.6021 \times 10^{-6}/1.25 \times 10^{-3} = 47.42\ E^{\gamma} X(x,y,z,\tau) \text{erg/g sec}$$

or, since by definition the absorbtion of 100 ergs/g is equal to one Rad and there are 60 seconds in a minute, the external γ-dose rate becomes

$$R^{\gamma}_{ext}(x,y,z,\tau) = 28.4\ E^{\gamma} X(x,y,z,\tau) = 28.4\ E^{\gamma} S_g(x,y,z) Q(x,\tau) \quad \text{Rad/min}$$

The total dose delivered at the point (x,y,z) in a time T following initial release in the building is obtained by integrating R^{γ}_{ext} over time from $\tau = x/u$ to $\tau = T$. Thus

$$D^{\gamma}_{ext}(x,y,z,T)$$

$$= 28.4\ E^{\gamma} S_g(x,y,z) \int_{x/u}^{T} Q(x,\tau)d\tau = 28.4\ E^{\gamma} S_g(x,y,z) I(x,T) \quad \text{Rad} \qquad (32)$$

The integral I(x,T) is chosen from among those given in Sect. 9 depending upon the behaviour of the isotope under consideration. Thus,

in this approximation the external γ dose due to iodine becomes

$$D^{\gamma}_{ext}(x,y,z,T) = 28.4\ S_g(x,y,z) \sum_{i=1}^{5} E^{\gamma}_i I_{1i}(x,T) \quad \text{Rad} \tag{33}$$

while that due to noble gases is

$$D^{\gamma}_{ext}(x,y,z,T)$$
$$= 28.4\ S_g(x,y,z) \left[\sum_{i=1}^{10} E^{\gamma}_i I_{1i}(x,T) + \sum_{i=1}^{3} E^{\gamma}_i I_{3i}(x,T) + \sum_{i=1}^{3} E^{\gamma}_i I_{4i}(x,T) \right] \text{Rad} \tag{34}$$

Implicit in this procedure are the assumptions that the concentration gradient is small, and that no dose is received until the plume actually reaches the receptor. The first of these will cause the doses on the plume axis to be overestimated; however, for receptors located a considerable distance off the plume axis (i.e., a receptor at ground level relative to an elevated source) the doses computed by this method will be significantly underestimated for receptors located such that $x \leq \sim 10h$. This is because the contribution from the high concentration on the plume axis is neglected. For values of x greater than $\sim 10h$, the approximation is fairly good and in fact gives conservative (high) results. The fact that this approximation assumes that the receptor receives no radiation until the plume has arrived at the location of the receptor also tends to underestimate the dose, particularly if the total exposure time is short compared to the transport time of the plume.

Despite the shortcomings of the adiabatic approximation, it is useful for estimating external doses at points where x, the downwind distance, is greater than about 10h, and where the exposure times are considerably

longer than the transport time of the plume from source to receptor. Moreover, because of its simpler form, the adiabatic approximation is useful in studying the effort of parameter variation on the doses delivered.

14. Selection of Parameters

A computer program has been developed for the purpose of calculating the doses. This program computes both the external γ-ray doses by performing the space and time integrations and also the internal iodine doses by performing the required time integration. The program is discussed in detail in Part III.

The selection of parameters for use in this program requires some judgment. The quantity per kilowatt of each isotope present in the reactor is well known as are the corresponding decay constants, gamma ray energies, and doses delivered per inhaled microcurie. These quantities are listed in Tables I and II for the noble gases and the iodines. On the other hand, the fraction of the total radioisotope inventory which is released depends on the particular situation which is being studied. It is assumed, however, that all the noble gases behave alike, all the iodines behave alike, and all the solid daughters behave alike.

The source height h is usually the effective height of the stack which, in general, is greater than the actual stack height h_o. This is because of the effects of buoyancy and upward velocity of the effluent plume. There is little agreement among meteorologists concerning the best method of estimating the effective stack height; however, Holland[3]

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[3]Meteorology and Atomic Energy, AECU-3066, USAEC Publication, p. 72 (1955).

has proposed a relation which appears to agree with observation in the Oak Ridge area.

$$h = h_o + \frac{1.5\ vd + 3 \times 10^{-4} s}{u}$$

where u, the wind speed, and v, the exit velocity, are expressed in miles per hour, d, the orifice diameter, is in feet, s is the heat input in calories per second; and h, h_o are respectively the effective and actual stack heights in feet. For the present purpose, the heat input is neglected and the effective stack is taken to be

$$h = h_o + \frac{1.5\ vd}{u} = h_o + \frac{\kappa}{u}$$

with h and h_o both expressed in meters if d is given in meters and v and u are expressed in the same units, and κ is a constant equal to 1.5 vd.

The choice of the parameters σ_y and σ_z depends upon the atmospheric stability condition which is assumed to exist during the time of the release. These parameters which are functions of x, the downwind distance x are shown in Fig's. 3 and 4. The categories A, B, C, etc., refer to stability conditions ranging from "unstable" for category A to "stable" for category F. Similarly, the wind speed u for the assumed condition must be chosen. Two cases which usually encompass the various conditions to be expected are C-stability and moderate winds (100-200 m/min) and F-stability with low wind speed ($\sim$50 m/min) coupled with inversion conditions, i.e., σ_z held constant once it reaches the value $\sim h_o/2.15$.

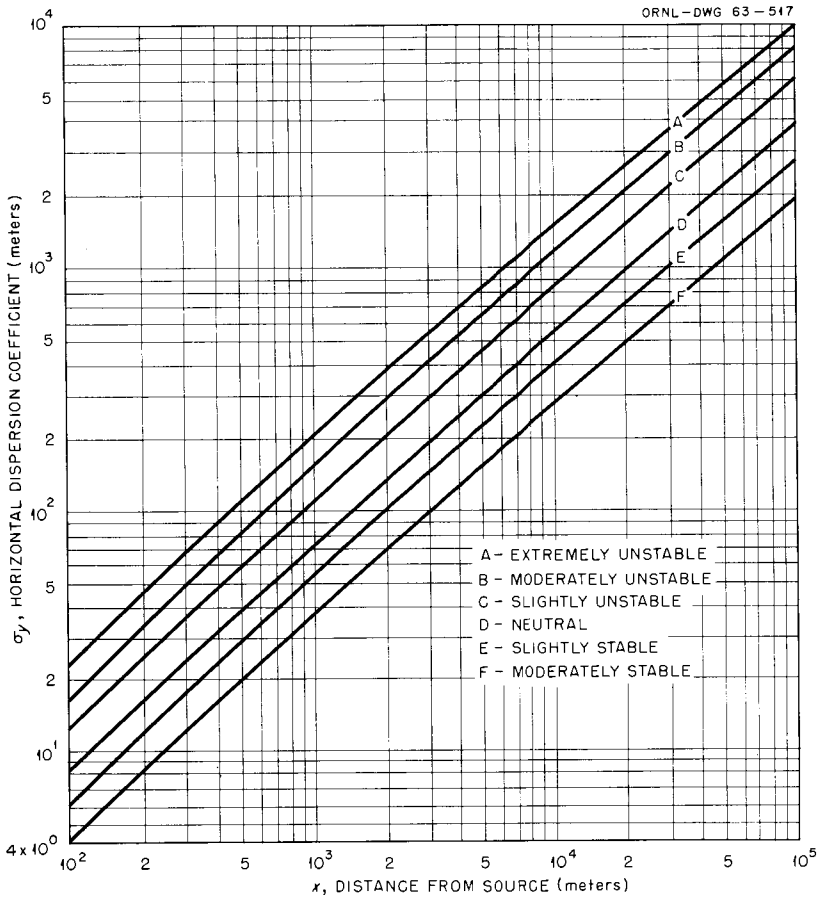

Fig. 3. Horizontal Dispersion Parameter

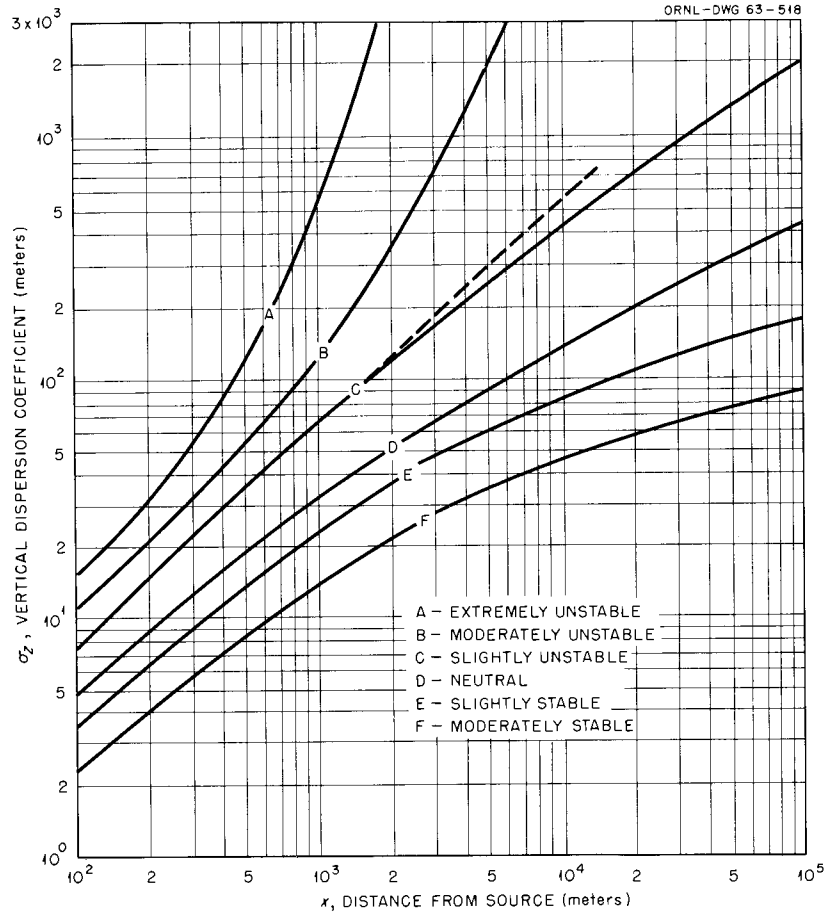

Fig. 4. Vertical Dispersion Parameter

Table I. Iodine Internal and External Dose

Isotope	$\lambda p(min^{-1})$	δi Rem/μc	E^B_{ij} mev/dis	E^γ_{ij} mev/dis	f_{ij}	σ_{ij} cm^2/g	μ_{ij} $Meters^{-1}$	C_{ij}	D_{ij}	q°_p curies/kw
I^{131} (8.06 d)	5.97×10^{-5}	1.484	0.191	0.66	0.12	0.032	9.34×10^{-3}	1.22	0.175	26.15*
				0.34	0.94	0.032	1.23×10^{-2}	1.53	0.240	
			Total γ	0.400 mev						
I^{132} (2.3 h)	5.02×10^{-3}	0.054	0.449	1.87	0.04	0.025	5.64×10^{-3}	0.84	0.046	
				1.04	1.17	0.029	7.54×10^{-3}	1.01	0.100	39.64
				0.66	1.24	0.032	9.34×10^{-3}	1.22	0.175	
			Total γ	2.11 mev						
I^{133} (20.9 hr)	5.53×10^{-4}	0.399	0.401	0.60	1.00**	0.032	9.69×10^{-3}	1.26	0.100	58.20
			Total γ	0.60 mev						
I^{134} (53 m)	1.31×10^{-2}	0.025	0.57	1.64	0.14	0.026	6.00×10^{-3}	0.89	0.057	
				1.08	0.34	0.029	7.43×10^{-3}	1.04	0.096	65.79
				0.86	1.77	0.031	8.26×10^{-3}	1.17	0.050	
				0.52	0.48	0.032	1.03×10^{-2}	1.32	0.205	
			Total γ	2.36 mev						
I^{135} (6.7 h)	1.72×10^{-3}	0.123	0.305	1.73	0.30	0.025	5.76×10^{-3}	0.87	0.056	51.45
				1.24	0.43	0.028	6.79×10^{-3}	0.99	0.082	
				0.42	0.07	0.032	1.13×10^{-2}	1.43	0.224	
			Total γ	1.08 mev						

*Saturation value - to obtain correct value multiply by $(1 - e^{-0.086t})$ where t is the irradiation time in days.

**Estimated.

Table II. Noble Gas External Dose

Subgroup I: Parents

Isotope	Half Life	$\lambda p(min^{-1})$	E_i^B Mev/dis	E_{ij}^γ Mev/dis	f_{ij}	σ_{ij} cm^2/g	μ_{ij} $Meters^{-1}$	C_{ij}	D_{ij}	q_p° curies/kw
Kr^{83m}	1.9 h	6.08×10^{-3}	0.000	0.032	1.00	0.150	3.46×10^{-2}	4.85	0.338	4.05
				0.009	1.00	---	0.55	9.10	0.345	
			Total γ	0.041 mev						
Kr^{85m}	4.4 h	2.63×10^{-3}	0.222	0.305	0.19	0.031	1.29×10^{-2}	1.61	0.249	12.65
			Total γ	0.058 mev						
Kr^{87}	76.4 min	9.07×10^{-3}	1.038	2.500	0.25	0.023	4.87×10^{-3}	0.74	0.019	
				0.660	0.13	0.032	9.34×10^{-3}	1.22	0.175	21.00
				0.150	0.87	0.027	1.64×10^{-2}	2.23	0.285	
			Total γ	0.841 mev						
Kr^{88}	2.8 hr	4.13×10^{-3}	0.331	2.33	0.51	0.024	5.05×10^{-3}	0.76	0.028	
				1.21	0.47	0.029	7.06×10^{-3}	0.99	0.085	30.11
				0.36	0.05	0.032	1.21×10^{-2}	1.51	0.237	
				0.16	0.49	0.028	1.61×10^{-2}	2.16	0.290	
			Total γ	1.85 mev						
Kr^{89}	3.2 m	0.217	3.23	3.84	0.16	0.021	3.79×10^{-3}	0.61	0.0035	
				3.03	0.26	0.022	4.30×10^{-3}	0.68	0.0120	
				2.17	0.31	0.024	5.24×10^{-3}	0.78	0.028	38.72
				1.50	0.52	0.027	6.22×10^{-3}	0.92	0.065	
				0.92	0.57	0.030	8.00×10^{-3}	1.10	0.120	
				0.43	1.15	0.032	1.12×10^{-2}	1.41	0.250	
			Total γ	3.87 mev						

Table II. (Continued)

Subgroup I: Parents (Continued)

Isotope	Half Life	$\lambda p (min^{-1})$	E_i^B Mev/dis	E_{ij}^{γ} Mev/dis	f_{ij}	σ_{ij} cm^2/g	μ_{ij} $Meters^{-1}$	C_{ij}	D_{ij}	q_p^o curies/kw
Xe^{133m}	2.3 d	2.09×10^{-4}	0.000 Total γ	0.233 0.233 mev	1.00	0.030	1.41×10^{-2}	1.81	0.269	1.40
Xe^{133}	5.3 d	9.08×10^{-5}	0.115 Total γ	0.80 0.80 mev	1.0	0.031	8.51×10^{-3}	1.14	0.145	55.84
Xe^{135m}	16 m	4.33×10^{-2}	0.000	0.528	1.00	0.032	1.03×10^{-2}	1.30	0.202	15.44
Xe^{135}	9.1 hr	1.27×10^{-3}	0.300 Total γ	0.604 0.250 0.261 mev	0.03 0.97	0.032 0.030	9.68×10^{-3} 1.38×10^{-2}	1.25 1.77	0.185 0.265	53.14*
Xe^{138}	14 m	4.95×10^{-2}	0.60 Total γ	0.42 0.42 mev	1.00	0.032	1.13×10^{-2}	1.43	0.224	50.61

$$^{*}q_p^o = \frac{2.115 \times 10^{-5}}{2.115 \times 10^{-5} + 2.8 \times 10^{-18}\phi} \quad \therefore \text{ For } \phi = 2 \times 10^{14} \qquad q_p^o = 1.93$$

This accounts for burnup of Xe^{135}.

Table II. (Continued)

Subgroup II: Solid Daughters

Isotope	$\lambda d (min^{-1})$	$\lambda p (min^{-1})$	E^{B}_{ij} Mev/dis	E^{γ}_{ij} Mev/dis	f_{ij}	σ_{ij} cm^2/g	μ_{ij} $Meters^{-1}$	C_{ij}	D_{ij}	q°_{p} curies/kw
Rb^{88} (18 m)	3.85×10^{-3}	4.13×10^{-3}	1.35	3.67	0.013	0.021	3.89×10^{-3}	0.63	0.0050	30.11
				1.90	0.28	0.025	5.58×10^{-3}	0.83	0.430	
				0.90	0.145	0.030	8.09×10^{-3}	1.10	0.120	
			Total γ	0.71 mev						
Rb^{89} (15 m)	4.62×10^{-2}	0.217	0.51	2.49	0.32	0.023	4.88×10^{-3}	0.74	0.044	38.72
				1.15	1.32	0.029	7.23×10^{-3}	1.01	0.089	
				0.66	0.15	0.032	9.34×10^{-3}	1.22	0.175	
			Total γ	2.41 mev						
Cs^{138} (32 m)	2.16×10^{-2}	4.95×10^{-2}	0.86	2.37	0.27	0.024	5.01×10^{-3}	0.75	0.025	50.61
				1.30	1.02	0.029	6.80×10^{-3}	0.97	0.077	
				0.48	0.34	0.032	1.07×10^{-2}	1.35	0.214	
				0.18	0.04	0.029	1.54×10^{-2}	2.05	0.283	
			Total γ	2.14 mev						

Table II. (Continued)

Subgroup III. Iodine Daughters

Isotope	$\lambda d(min^{-1})$	$\lambda p(min^{-1})$	E^{B}_{ij} Mev/dis	E^{γ}_{ij} Mev/dis	f_{ij}	σ_{ij} cm^2/g	μ_{ij} $Meters^{-1}$	C_{ij}	D_{ij}	q°_{p}
Xe^{133} (5.3 d)	9.08×10^{-5}	5.53×10^{-4}	0.115 Total γ	0.80 0.80 mev	1.00	0.031	8.51×10^{-3}	1.14	0.145	58.20
Xe^{135m} (16 m)	4.33×10^{-2}	1.72×10^{-3}	0.000 Total γ	0.528 0.528 mev	1.00	0.032	1.03×10^{-2}	1.30	0.202	15.43*
Xe^{135} (9.1 hr)	1.27×10^{-3}	1.72×10^{-3}	0.300 Total γ	0.604 0.205 0.261 mev	0.03 0.97	0.320 0.300	9.68×10^{-3} 1.38×10^{-3}	1.25 1.77	0.185 0.265	36.02*

*Corrected for branching ratio.

The form of the buildup factor which has been chosen for use with the external dose equations is that recommended by Berger[4]

$$B(E,\mu r) = 1 + C(E)\mu r e^{D(E)\mu r}$$

Values of C(E) and D(E) have been given by Trubey[5] and are listed in Tables I and II. Trubey's values are actually given for water; however, the values for water and air are nearly identical. Supplementary calculations to extend the results below 0.255 mev were made by F. B. K. Kam of Oak Ridge National Laboratory.

PART IV - PROGRAM: PLUME

15. Computer Program: PLUME

PLUME is a FORTRAN IV program which performs the integrations specified by equations 30 (Sect. 11) and 31 (Sect. 12). These equations were rewritten in a more convenient form for computer computation before being evaluated. The program uses a Gauss-Hermite quadrature scheme on the y-integration and a Gauss-Legendre quadrature scheme on the x- and z-integration. The upper limit of the x-integration should not exceed 20,000 meters because of the meteorological data built into the program. This restriction can be easily removed by inserting additional data into the meteorological data table. In addition, the program evaluates equation (16) using the integral (24), and this computes the thyroid dose due to iodine release.

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[4]M. J. Berger, Proceedings of Shielding Symposium held at the Naval Radiological Defense Laboratory, USNRDL Reviews and Lectures, No. 29, p. 47 (1956).

[5]D. K. Trubey, A Survey of Empirical Functions Used to Get Gamma Ray Buildup Factors, ORNL RSIC-10 (1966).

This section describes the format and defines the terms of the input data required by the program. A sample problem with the input data and the corresponding output listing are presented. Finally, a FORTRAN IV listing of the program is given. Note that the results obtained are based upon one kilowatt operation. For extrapolation to other powers, see Part I, Section 1.

Format and Glossary of Input Data

Card A. FORMAT (10$\overset{a}{A}$6)

a. Title - 60 columns of alphameric information

Card B. FORMAT ($\overset{a}{E}$10.3, $\overset{b}{E}$10.3, $\overset{c}{E}$10.3, $\overset{d}{E}$10.3, $\overset{e}{E}$10.3)

a. W1 - fraction of the iodines that is thought to escape through the water from the affected portion of the core and reach the building atmosphere

b. W2 - fraction of the noble gases that is thought to escape from the affected portion of the core

c. FF - fraction of the iodines which pass through the factor

d. FLUX - thermal flux at full power ($n/cm^2/sec$)

e. B - breathing rate (cm^3/min)

Card C. FORMAT ($\overset{a}{I}$5, $\overset{b}{I}$5, $\overset{c}{E}$10.5, $\overset{d}{E}$10.5, $\overset{e}{E}$10.5, $\overset{f}{E}$10.5)

a. NTM - number of time periods in problem. Each time period represents time since initial release.

b. NGD = 0 without filtration option
= 1 with filtration option

c. W2D2 - determines the upper and lower limit in the z-integration. A value of 7 is usually sufficient.

d. SZTEST - maximum value of σ_z in inversion condition

e. EPLO - convergence criteria for integration (.04 should be acceptable)

f. EPHI - convergence criteria for integration (.02 should be acceptable)

Card D. FORMAT (I5, I5, E10.5, E10.5, E10.5, E10.5)
(a, b, c, d, e, f)

a. METYPE - meteorological condition

METYPE	= 1	a-condition
	= 2	b-condition
	= 3	c-condition
	= 4	d-condition
	= 5	e-condition
	= 6	f-condition

b. NϕDET - number of detector positions

c. PHGT - physical stack height (meters)

d. STKC - stack constant (meter^2/min)

e. AF - leak rate (min^{-1})

f. U - wind speed (meters/min)

Card E. FORMAT (3E8.5, I8, I8, 5E8.5)
(a, b, c, d)

a. XDET, YDET, ZDET — coordinates of detector position

b. NLO - number of integrations between 0 and XDET

c. NHI - number of integrations between XDET and XMAX

d. T(J), J = 1, NTM
T(J) - value of jth time period in minutes

Sample Problem

The sample problem evaluates the iodine inhalation dose and the whole body gamma dose at several detector points located at ground level along the plume axis. The accident considered assumes a 16.67% release of iodine from the effected portion of the core (W1 = .1667), a 100% release of noble gases (W2 = 1.0), and a factor of 0.01 (FF = 0.01). The results are always based upon a portion of the reactor which is developing 1 kw being effected. Extrapolation to larger effected portions

may be made by multiplying by the product of the ratio of the portion effected to the whole reactor and the total power level expressed in kilowatts.

PLUME OUTPUT LISTING

SAMPLE PROBLEM - HEIR WITH FILTRATION

NO. OF ISOTOPES=21
NO. OF GROUPS= 4 NO. OF ISOTOPES IN GROUP 1=10 IN GROUP 2= 3 IN GROUP 3= 3 IN GROUP 4= 5
W1=0.1667 W2=1.0000 FF=0.0100 FLUX= 2.0000D 14 B= 2.0800D 04
NTM= 1 NGD= 1 W2D2= 7.00 SZTEST= 10000000.00 EPLO= 0.1000 EPHI= 0.0500

TABLE OF ISOTOPE CONSTANTS

ISOTOPE	E MEV/DIS	F	SIG CMSQPERGM	XMU 1/METER	C	D	DELTA	QPO	LAMBDAP 1/MIN	LAMBDAD 1/MIN
KR83M	0.032	1.000	0.150	3.460D-02	4.850	0.338	0.0	4.05	6.080D-03	0.0
	0.009	1.000	4.200	5.500D-01	9.100	0.345				
KR85M	0.305	0.190	0.031	1.290D-02	1.610	0.249	0.0	12.65	2.630D-03	0.0
KR87	2.500	0.250	0.023	4.870D-03	0.740	0.019	0.0	21.00	9.070D-03	0.0
	0.660	0.130	0.032	9.340D-03	1.220	0.175				
	0.150	0.870	0.027	1.640D-02	2.230	0.285				
KR88	2.330	0.510	0.024	5.050D-03	0.760	0.028	0.0	30.11	4.130D-03	0.0
	1.210	0.470	0.029	7.060D-03	0.990	0.085				
	0.360	0.050	0.032	1.210D-02	1.510	0.237				
	0.160	0.490	0.028	1.610D-02	2.160	0.290				
KR89	3.840	0.160	0.021	3.790D-03	0.610	0.003	0.0	38.72	2.170D-01	0.0
	3.030	0.260	0.022	4.300D-03	0.680	0.012				
	2.170	0.310	0.024	5.240D-03	0.780	0.028				
	1.500	0.520	0.027	6.220D-03	0.920	0.065				
	0.920	0.570	0.030	8.000D-03	1.100	0.120				
	0.430	1.150	0.032	1.120D-02	1.410	0.250				
XE133M	0.233	1.000	0.030	1.410D-02	1.810	0.269	0.0	1.40	2.090D-04	0.0
XE133	0.800	1.000	0.031	8.510D-03	1.140	0.145	0.0	55.84	9.080D-05	0.0
XE135M	0.528	1.000	0.032	1.030D-02	1.300	0.202	0.0	15.44	4.330D-02	0.0
XE135	0.604	0.030	0.032	9.680D-03	1.250	0.185	0.0	1.94	1.270D-03	0.0
	0.250	0.970	0.030	1.380D-02	1.770	0.265				
XE138	0.420	1.000	0.032	1.130D-02	1.430	0.224	0.0	50.61	4.950D-02	0.0
RB88	3.670	0.013	0.021	3.890D-03	0.630	0.005	0.0	30.11	4.130D-03	3.850D-03
	1.900	0.280	0.025	5.580D-03	0.830	0.043				
	0.900	0.145	0.030	8.090D-03	1.100	0.120				
RB89	2.490	0.320	0.023	4.880D-03	0.740	0.044	0.0	38.72	2.170D-01	4.620D-02
	1.150	1.320	0.029	7.230D-03	1.010	0.089				
	0.660	0.150	0.032	9.340D-03	1.220	0.175				
CS138	2.370	0.270	0.024	5.010D-03	0.750	0.025	0.0	50.61	4.950D-02	2.160D-02
	1.300	1.020	0.029	6.800D-03	0.970	0.077				
	0.480	0.340	0.032	1.070D-02	1.350	0.214				
	0.180	0.040	0.029	1.540D-02	2.050	0.283				
XE133	0.800	1.000	0.031	8.510D-03	1.140	0.145	0.0	58.20	5.530D-04	9.080D-05
XE135M	0.528	1.000	0.032	1.030D-02	1.300	0.202	0.0	15.43	1.720D-03	4.330D-02
XE135	0.604	0.030	0.032	9.680D-03	1.250	0.185	0.0	36.02	1.720D-03	1.270D-03
	0.250	0.970	0.030	1.380D-02	1.770	0.265				
I131	0.660	0.120	0.032	9.340D-03	1.220	0.175	1.484	26.15	5.970D-05	0.0
	0.340	0.940	0.032	1.230D-02	1.530	0.240				
I132	1.870	0.040	0.025	5.640D-03	0.840	0.046	0.054	39.64	5.020D-03	0.0
	1.040	1.170	0.029	7.540D-03	1.010	0.100				
	0.660	1.240	0.032	9.340D-03	1.220	0.175				
I133	0.600	1.000	0.032	9.690D-03	1.260	0.100	0.399	58.20	5.530D-04	0.0
I134	1.640	0.140	0.026	6.000D-03	0.890	0.057	0.025	65.79	1.310D-02	0.0
	1.080	0.340	0.029	7.430D-03	1.040	0.096				
	0.860	1.770	0.031	8.260D-03	1.170	0.050				
	0.520	0.480	0.032	1.030D-02	1.320	0.205				
I135	1.730	0.300	0.025	5.760D-03	0.870	0.056	0.123	51.45	1.720D-03	0.0
	1.240	0.430	0.028	6.970D-03	0.990	0.082				
	0.420	0.070	0.032	1.130D-02	1.430	0.224				

METEOROLOGICAL CONDITION=C
PEAK RATE= 0.146D 00 T/MIN
WIND SPEED= 100.00 METERS/MIN
EFFECTIVE STACK HEIGHT= 86.83 METERS

XDET METERS	YDET METERS	ZDET METERS	XLOW METERS	XHIGH METERS	TIME SINCE INITIAL RELEASE MINUTES	IODINE PARENTS REM/KW	NOBLE GAS PARENTS REM/KW	SOLID DAUGHTERS REM/KW	DAUGHTERS OF FILTERED PARENTS REM/KW	UNSEPARATED DAUGHTERS REM/KW	WHOLE BODY DOSE TOTAL REM/KW	THYROID DOSE REM/KW
100.0	0.0	-86.8	0.0	500.0	1.440D 03	9.323D-07	3.050D-04	6.319D-06	6.246D-05		3.748D-04	6.464D-31
200.0	0.0	-86.8	0.0	600.0	1.440D 03	1.035D-06	3.266D-04	1.091D-05	6.740D-05		4.060D-04	1.112D-10
500.0	0.0	-86.8	0.0	900.0	1.440D 03	1.057D-06	3.023D-04	2.242D-05	6.214D-05		3.879D-04	1.619D-04
1000.0	0.0	-86.8	600.0	1400.0	1.440D 03	7.888D-07	2.058D-04	2.624D-05	3.920D-05		2.720D-04	4.713D-04
2000.0	0.0	-86.8	1200.0	2400.0	1.440D 03	3.637D-07	9.160D-05	1.668D-05	1.298D-05		1.216D-04	2.522D-04
5000.0	0.0	-86.8	3000.0	5600.0	1.440D 03	6.715D-08	1.854D-05	3.673D-06	9.623D-07		2.325D-05	6.221D-05
10000.0	0.0	-86.8	6000.0	10600.0	1.440D 03	8.943D-09	3.071D-06	4.598D-07	5.280D-08		3.593D-06	1.886D-05

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