〈論　文〉

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Radiological Methodology for Calculating Radiation Dose from Airborne Radioactivity Released to the Environment

大氣環境에 排出된 放射能에 依한 放射線 被曝 線量 計算을 爲한 放射線學的 方法論의 考察

Sun-Tae Hwang, Eui-Hwan Hwang
黃 善 泰*, 黃 義 煥*

國 文 抄 錄

오늘날, 原子力 發電은 전기 에너지의 供給에 主要한 役割을 하고 있다. 그러나 모든 原子力發電所에서는 그 正常 稼動中에 主로 核分裂에 의해서 發生되는 放射性 氣體로 因한 放射能을 적은 量이지만 大氣中에 排出시키는데 事故 發生時에는 상당히 많은 量의 放射能을 放出시킬 수 있다. 正常 稼動되고 있는 原子力發電所의 환경영향을 評價하여 放射線許容標準 內에서 확실히 하며 원자로 事故에 의한 放射線學的 結果를 確認하기 위하여 放出된 放射能으로부터의 住民에게 被曝된 放射線 線量을 計算하는 것은 매우 필요한 過程이다. 그러한 被曝線量計算은 原子力 發展의 受容性을 決定하는데 또한 重要한 役割을 한다. 放射線 被曝線量 計算이 遂行되기 前에 앞서서 放射能 噴出物이 大氣중에 排出된 후 그 濃度가 어떻게 周圍에 分布되는 가를 決定하는 것이 必要하다. 本 論文에서는 이러한 문제를 고려하면서 放射線 被曝線量 計算에 關하여 結論에서 言及된다.

INTRODUCTION

The nuclear power offers an important solution to our national problem of supplying the continuing and expanding demand for electrical energy, and it is an advanced step in reducing the contamination of our environment. The possible and potential risks to individuals of the public due to radioactivity released from nuclear power plants have been analyzed by nuclear and environmental health physicists.

One facet of the complete environmental safety examination of a nuclear power plant is the analysis of the behavior of airborne radioactive effluents both from normal operations and accidents, and the estimation of the resulting exposure to radiations. Such safety analyses are performed to provide operating limits for normal release of effluents and to predict potential exposures from abnormal releases due to the nuclear reactor accident.

With the increase in nuclear power production, there is the possibility of population exposure to fission product gases which are released

* 韓國標準硏究所・放射線硏究室 (Korea Standards Research Institute, Taedok Science Town, Korea)

to the atmosphere. Atmospheric dispersion is a primary pathway for the transportation of radioactivity emissions to man. Members of the general population may be exposed to radiation from radioactivity deposited from the atmosphere to the ground as well as from airborne radionuclides directly.

Total radiation committment consists of an initial and latent dose phase. The initial phase includes the external radiation from the gaseous effluents passage, from the radioactive materials deposited on the ground, and the radiations from inhaled radioactive material during the effluents passage. The dose received in the latent phase consists of external radiation from radioactive material deposited on the ground or other surfaces, and internal radiation from ingestion of foods or liquids contaminated by the effluents passages. Fig. 1 shows the three significant pathways of radiation exposure to man.

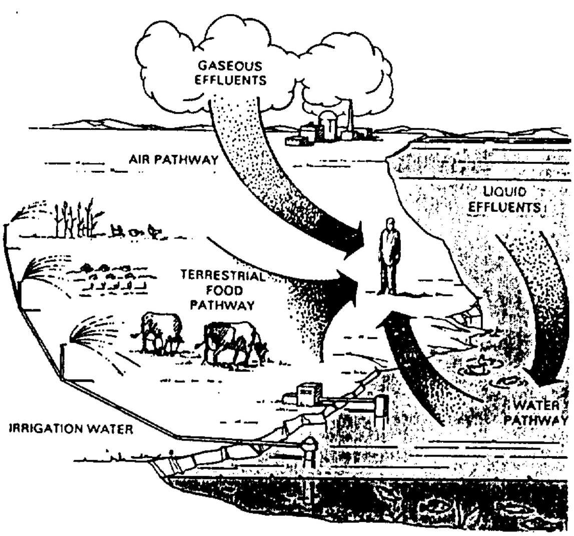

Fig. 1 Three significant pathways of radiation exposure to man

The radiation dose calculations are based on a complex function of the actual atmospheric distribution of the radioactive materials in time and space. This distribution depends on the physical properties of the radioactive material emitted and the method of gaseous effluents release as well as on the meteorological situation following and during the release. The methodology for calculating doses and ground depositions from gaseous effluents are discussed in detail on the basis of atmospheric dispersion modeling.

ATMOSPHERIC DISPERSION MODEL

Plume Behavior and Model

The radioactive gaseous effluents are carried about in complex ways once they enter the moving atmosphere. Among the several ways to analyze this transport process, the one most often taken as a starting point is an examination of the gaseous effluents plume issuing from a single stack. In the customary view of this continuous point source, the instantaneous and time-averaged behaviors of a plume are illustrated in Fig. 2 by the coordinate system. In the system considered here, the origin is at ground level beneath the point of emission with the X-axis extending horizontally in the direction of the mean wind. The Y-axis is in the horizontal plane perpendicular to the X-axis and the Z-axis extends vertically. The concentration of effluents has a

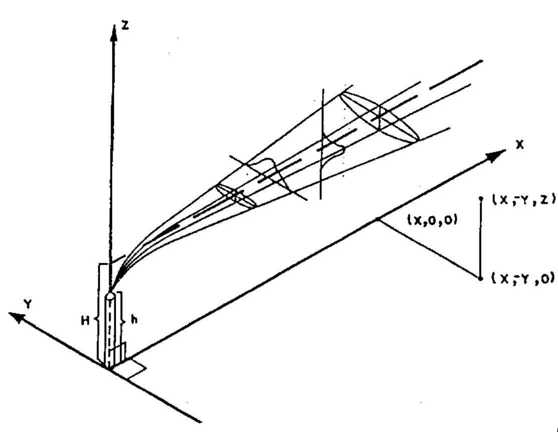

Fig. 2 Coordinate system showing Gaussian distributions in the horizontal and vertical

roughly Gaussian distribution within any vertical cross section. The behavior of a plume is sensitive to the interplay of atmospheric temperature structure and wind.

A number of formulas for dealing with various practical dispersion problems that arise in nuclear reactor risk analysis are based on the widely used dispersion model formulated by Sutton.[1] The usual way of deriving average plume dispersion formulas starts with the assumption of an instantaneous point source of effluents dispersing in three dimensions. In terms of statistical theory, the Gaussian formula for an instantaneous point source is[2]

$$\chi(x,y,z;t) = Q_0(2\pi\sigma_y^2)^{-3/2} \exp(-r^2/2\sigma_y^2) \quad (2.1)$$

where $r^2 = (x-\bar{U}t)^2 + y^2 + z^2$,

$\bar{u}$ =mean wind speed in m/s at stack height,
χ = concentration at a point (x, y, z) at time t in Bq/m^3,
Q_0 =activity released in Bq

It is assumed that $\sigma_y = \sigma_x = \sigma_z$, i.e., that the atmospheric dispersion is isotropic in Eq. (2.1). Strictly speaking, however, it is usually assumed that the dispersion takes place independently in the three coordinate directions. Hence, the concentration of effluents from the stack may be expressed as[3]

$$\chi(x,y,z;t) = \frac{Q_0(2\pi)^{-3/2}}{\sigma_x \cdot \sigma_y \cdot \sigma_z} \exp\{-\frac{1}{2} [(\frac{x-\bar{U}t}{\sigma_x})^2 + (\frac{y}{\sigma_y})^2 + \{[_z(\frac{z_0}{H-Z}) \quad (2.2)$$

where σ^2 represents the variance of the Gaussian distribution.[4] H is the effective stack height which represents the physical stack height(h) plus the plume rise. For large dispersion times, the statistical theory supplies the well-known Gaussian distribution of the radioactive effluents from the stack of nuclear power plant in the atmosphere as a fundamental solution to the socalled Fickian diffusion equation, $d\chi/dt = K\nabla^2\chi$[5] Where K is the diffusivity of stack effluents.

The method of obtaining a continuous point source dispersion formula from Eq. (2.1) or (2.2) proceeds according to the principle of superposition. The plume is regarded as resulting from the addition of an infinite number of overlapping averaged puffs, carried along the X-axis by the mean wind speed, $\bar{U}$. With the Frenkiel's spreading-disk dispersion model, integration of Eq. (2.2) with respect to time, t, from 0 to ∞ can readily be carried out

$$\chi(x,y,z)/Q' = \frac{1}{2\pi\sigma_y\sigma_z\bar{U}} \exp[-\frac{1}{2}(\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2})] \quad (2.3)$$

where Q' is continous source strength in Bq/s, the left-hand side of Eq (2.3), namely, χ/Q' is called the atmospheric dispersion factor in s/m^3. In the present context, the quantities σ_y and σ_z are functions of x. σ_y and σ_z are called, respectively, the horizontal and vertical dispersion coefficients.

In general, the concentration (χ) distributions along all coordinate axes are different. For the specific case of equal dispersion in all directions, spherical plumes will form, featuring a spherosymmetric normal distribution of the effluents. Assuming that dispersion along X-axis is small compared to transport and total reflection on the ground surface can be neglected, it is possible to calculate the average concentration inside the contaminant plume by means of[6]

$$\bar{\chi} = \frac{Q'}{2\pi\bar{U}\sigma_y\sigma_z} \exp(-y^2/2\sigma_y^2)\{\exp[-(Z-H)^2/2\sigma_z^2] + \exp[-(Z+H)^2/2\sigma_z^2]\} \quad (2.4)$$

It is possible to visualize how this describes the situation by referring to Fig. 3. The ambient concentration predicted by Eq. (2.4) is the same as it would be if effluents were reflected from the ground surface when they hit. Therefore, Eq. (2.4) can be regarded as giving the maximum expected concentration at any point, and its use would provide a conservative estimate. In Fig. 2, however neglecting dispersion along the X-axis implies that the individual spherical plumes form infinitely thin slices instead. The rectangular coordinate system is oriented with the X-axis along the direction of the wind, the Y-axis cross-wind, and the Z-axis vertical with the origin at ground level beneath the stack. The lateral and vertical dispersion coefficients vary with distance X downwind and with the stability. An unstable (turbulent) atmosphere means more mixing hence lower concentration. The lateral dispersion coefficient $\sigma_y(X)$ is plotted in Fig. 4.1, and the vertical dispersion coefficient $\sigma_z(X)$ is plotted in Fig. 4.2. The stable atmospheric con-

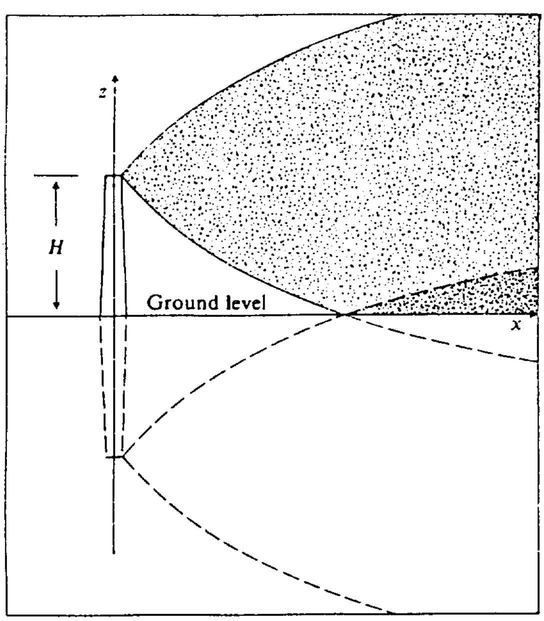

Fig. 3 Real source (above ground) and image source (below ground).

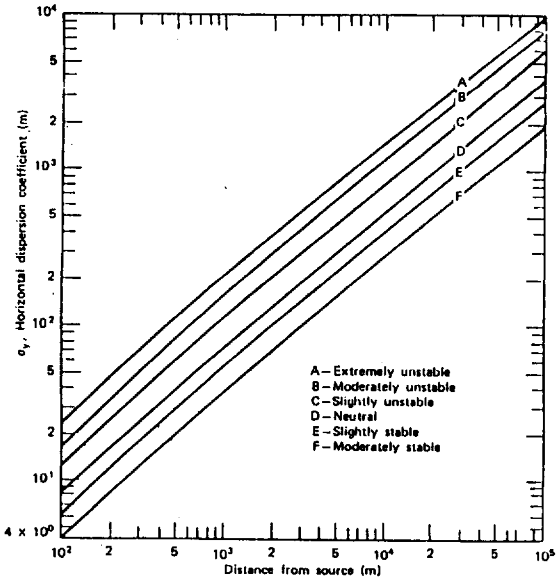

Fig. 4.1 Lateral dispersion coefficient

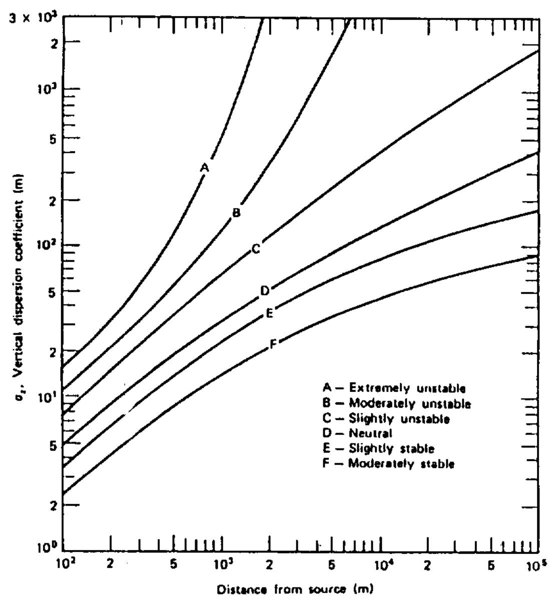

Fig. 4.2 Vertical dispersion coefficient

ditions, hence little vertical mixing, when there is a temperature inversion. The dispersion coefficients are illustrated as a function of distance downwind and Pasquill stability class.[7]
The Pasquill class can be obtained from measurements of the temperature gradient or can be in-

ferred from records of the wind direction as a function of time. The correlations between the standard deviation of the horizontal wind direction and the Pasquill conditions are given in Table 1. In Table 1, a seventh stability condition, type G, may be approximated by the following relations.[8)]

$$\sigma_y(G) = \frac{2}{3}\sigma_y(F)\ ;\ \sigma_z(G) = \frac{3}{5}\sigma_z(F) \qquad (2.5)$$

Table 1. Standard Deviation of Horizontal Wind Direction, σ_θ

σ_θ [(a)]	Pasquill Stability Categories
25°	A, extremely unstable
20°	B, moderately unstable
15°	C, slightly unstable
10°	D, neutral
5°	E, slightly stable
2.5°	F, moderately stable
1.7°	G, extremely stable

(a) θ is σ_θ: the angle of a simple wind vane.

Pasquill's method of estimating dispersion is well suited to field use because a simple wind vane and anemometer erected at a proposed site can furnish climatologically useful estimates of σ_θ. In the absence of such information, an estimate of the stability class can be obtained from the surface wind speed and insolation by incoming solar radiation or night-time radiation conditions by cloud cover as given in Table 2.

Regulations governing licensing of nuclear power plants may specify average or pessimistic conditions to be used for a preliminary evaluation, until on-site meterological data are obtained.

Table 2. Key to Stability Catergories

Surface Wind Speed (m/s)	Daytime (Insolation)			Night-time (Cloudiness)	
	Strong	Moderate	Slight	Thin Overcast or > 1/2 Cloudiness	Cloudliness ⩽ 3/8
< 2	A	A to B	B		
2	A to B	B	C	E	F
4	B	B to C	C	D	E
6	C	C to D	D	D	D
> 6	C	D	D	D	D

For example, Pasquill class F and a mean wind speed of 1 m/s are very pessimistic, giving little mixing and transport, hence large concentrations. If the stack releases a puff of activity, Q Bq, instead of a continuous release, Eq. (2.4) may be used to calculate the average exposure, $\overline{\psi}$, in Bq.s recived at a given point during the passage of the puff, by replacing $\overline{\chi}$ by $\overline{\psi}$ and Q' by Q.[9)] Effectivve dispersion of gaseous or finely divided material released into the atomosphere near the ground depends on natural mixing processes on a variety of scales. In the main, this mixing is a direct consequence of turbulent and conventive motions generated in the boundary layer itself. This is the layer containing typically some 10% of the overlaying mass of air, in which the flow properties are determined partially by the aerodynamic friction of the underlying surface but also to an important extent by the density stratification of the air which results from differences in temperature of the surface and the air.[6)]

EQUATIONS FOR CALCULATING CONCENTRATION

From Eq. (2.4) the concentration at ground level, Z =0, is

$$\bar{\chi} = \frac{Q'}{\pi \bar{U} \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{H^2}{\sigma_z^2}\right)\right] \quad (3.1)$$

where the value of $\bar{\chi}$ is largest along the center of the plume, i.e., where y=0. The concentration there is

$$\bar{\chi} = \frac{Q'}{\pi \bar{U} \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \quad (3.2)$$

In many contexts, it is convenient to divide Eq. (3.2) by Q'. Then $\bar{\chi}/Q'$ is called the dilution factor. Incidentally, it is easy to see from Eq. (3.2) and Figs. 4.1 and 4.2 that in the case of ground level emission (H=0), the effluent concentration is greatest everywhere under stable conditions. Fig. 5 shows the quantity $\bar{\chi}\bar{U}/Q'$ for effluent released at a height of 30m (about 100ft) under the various Pasquill conditions as computed from Eq. (3.2). The location of the maximum of the curves in Fig. 5 can be estimated by placing the derivative of Eq. (3.2) with respect to $\bar{\chi}$ equal to zero.

Concentrations due to the fumigation effect can be estimated by integrating Eq. (2.4) with respect to z from o to ∞ and then considering the radioactive effluent in the cloud to be distributed uniformly through a mixing layer of height, h_m. Then the equation for the fumigation concentration, χ_F, is accordingly[2)]

$$\chi_F = \frac{Q'}{\sqrt{2\pi}\, \bar{U}\, h_m \sigma_y} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \quad (3.3)$$

Eq. (3.3) can also be used to describe the trapping condition during which the effluent disperses rapidly below the base of an elevated inversion but is prevented by the stable layer from dispersing to greater heights. By considering both the ground and the inversion base to be reflecting barriers, Hewson derived the following formula for trapping:[10)]

$$\frac{\chi}{Q'} = \frac{1}{\pi \bar{U} \sigma_y \sigma_z} \left\{\exp\left(-\frac{H^2}{2\sigma_z^2}\right) + \exp\left[-\frac{(2h_i - H)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(-2h_i - H)^2}{2\sigma_z^2}\right]\right\} \quad (3.4)$$

where hi is the height of the inversion base and the the result is expressed in terms of σ_y and σ_z

The average concentration during plume looping probably corresponds to a Pasquill type A condition and can thus be estimated from Eq. (2.4). Holland suggested that the maximum ground concentration during looping, Xmax, could be estimated from the usual plume equation expressed for the axial concentration, X(x,o,o;o). Thus Holland's equation for the maximum concentration during looping is[11)]

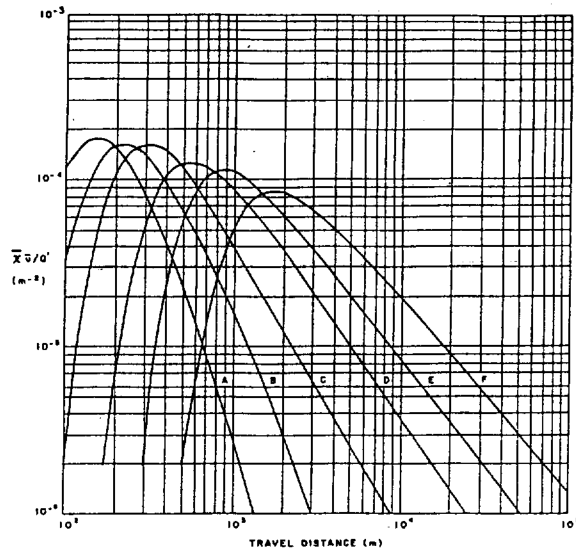

Fig. 5 Quantity $\bar{\chi}\bar{U}/Q'$ at ground level (D.H. Slade)

$$\chi_{max} = \frac{Q'}{\pi \bar{U} \sigma_y(x') \sigma_z(x')} \qquad (3.5)$$

where $x' = \sqrt{(X^2 + H^2)}$, X being the actual distance.

Taking the logarithms of both sides of Eq. (3.2). and determing the location of the maximum, the maximum concentration is [8)]

$$\chi_{max} = \frac{Q'}{\pi e \bar{U} (\sigma_y \sigma_z) max} \qquad (3.6)$$

where $(\sigma_y \ \sigma_z)_{max}$ means that both σ_y and σ_z are to be evaluated at the value of X determined from $H^2 = 2\sigma_z^2$.

The crosswind integrated concentration, χcw, from a continuous source is obtained by integrating Eq. (2.4) with respect to y from $-\infty$ to ∞ The result is

$$\chi cw = \left(\frac{\sqrt{2} Q'}{\sqrt{\pi} \bar{U} \sigma_z} \right) \exp\left(- \frac{H^2}{2\sigma_z^2} \right) \qquad (3.7)$$

Eq. (3.7) is particularly useful as an interpolation formula in connection with field dispersion trials because it contains one dispersion coefficient.

To obtain an estimate of the average concentration over a period that is very long compared with that over which the mean wind speed is computed, the integrated concentration of χcw must be multiplied by the frequency with which the wind flows towarr a gived sector and divided by the width of that sector at distance of interest. The resulting equation is then

$$\bar{\chi} = \frac{\sqrt{2} Q' f}{\sqrt{\pi} \bar{U} \sigma_z (2\pi x/n)} \exp\left(- \frac{H^2}{2\sigma_z^2} \right) \qquad (3.8)$$

where the frequency, f, is the wind fraction, $2\pi x/n$ is the sector width at distance, x, from the source, n is the number of sector. Fig. 6 presents evaluations of Eq. (3.1) with the σ_y and σ_z values of Fig. 4.1 and 4.2 and thus can be used for $\bar{\chi}$max and its distance from the continuous

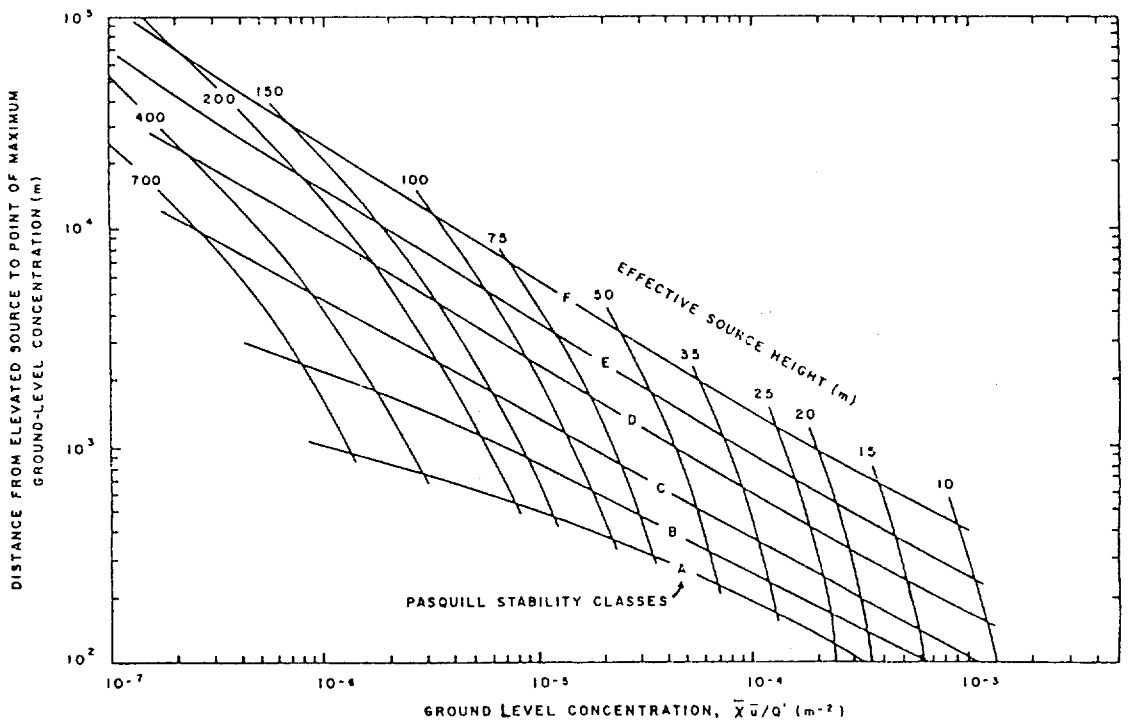

Fig. 6 Maximum ground level concentrations (D.H. Slade)

elevated source.

DISCUSSION

Up to this point, the possibility that the radioactive effluents may decay while being dispersed has not been taken into account. This can be handled by replacing Q' in Eq. (3.2) by Q'_0 exp $(-\lambda t)$, where Q'_0 is the emitted radioactivity in Bq/s, λ is the decay constant of effluent in S^{-1}, and t is the elapsed time from emission to observation. Replacing t by $\frac{X}{\bar{U}}$, Eq. (3.2) then becomes

$$\frac{\bar{\chi}}{Q'_0}=\frac{1}{\pi\bar{U}\sigma_y\sigma_z}\exp\left[-\left(\frac{\lambda x}{\bar{U}}+\frac{H^2}{2\sigma_z^2}\right)\right] \quad (3.9)$$

Likewise, Eq. (3.8) becomes

$$\bar{\chi}(x)=\frac{\sqrt{2}\,Q'_0 f}{\sqrt{\pi}\,\bar{U}\sigma_z(2\pi x/n)}\exp\left[-\left(\frac{\lambda x}{\bar{U}}\right)+\frac{H^2}{2\sigma_z^2}\right)\right] \quad (3.10)$$

In many nuclear reactor safety studies, the decay of the effluent is ignored with an assumption which leads to conservative estimates of effluent concentrations. It is very clear that with a decaying effluent, the locations of the maximum of Fig. 5 move closer to the release point of effluents.

It is not so easy to determine the location of the maximum concentration with a decaying effluent as may readily be seen by differentiating Eq. (3.9). For times greater than 8 hours, the wind is supposed to vary somewhat in direction so that the plume is dispersed uniformly over a 22.5° sector.[12] From Eq. (3.10), the dilution factor formula is then given by

$$\frac{\bar{\chi}(x)}{Q'_0}=\frac{2.032f}{x\bar{U}\sigma_z}\exp\left[-\left(\frac{\lambda x}{\bar{U}}+\frac{H^2}{2\sigma_z^2}\right)\right] \quad (3.11)$$

However, since reflections are assumed to have only vertical components, the normalized form of Gaussian plume model is given by

$$\frac{\bar{\chi}\bar{U}}{Q'}(x,y,z;H)=\frac{1}{2\pi\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2+\exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} \quad (3.12)$$

Taking into account Eq. (3.12), the concentration on the ground level plane is

$$\frac{\bar{\chi}\bar{U}}{Q'}(x,y,o;H)=\frac{1}{\pi\sigma_y\sigma_z}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

The ground-level concentration beneath the plume centerline is

$$\frac{\bar{\chi}\bar{U}}{Q'}(x,o,o;H)=\frac{1}{\pi\sigma_y\sigma_z}\exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

Since exp (o) = 1, the ground-level concentration of the centerline of a plume from a ground level source is

$$\frac{\bar{\chi}\bar{U}}{Q'}(x,o,o;0)=\frac{1}{\pi\sigma_y\sigma_z}$$

CONCLUSION

With the increase in nuclear power production, there is the possibility of population exposure to radioactive effluents which are released to the ambient atmosphere. Nuclear power plants provide a number of sources of radiation exposure to persons residing in their vicinity. From their radioactive effluents, there are the following cases:

(1) an external dose from radiation emitted from the plume,

(2) an external dose from radiation emitted

by radionuclides deposited on the ground

(3) an external dose from radionuclides deposited on the body and clothing,

(4) an internal dose from the inhalation of radionuclides.

Each of these doses has two components, a dose from γ-rays and a dose from β particles. In addition, radiation doses may also be received from the ingestion of foodstuffs contaminated by gaseous effluents from a nuclear power plant.

In the case of routine releases, the exposure is directly proportional to the time-integral of the activity concentration. An important quantity in practical dose evaluations is the dose equivalent in rem or Sv. Basically, the Gaussian plume model can be applied to the calculation dose over the entire period of exposure when the release duration is broken into individual duration intervals in which the stationary condition is fulfilled.

The dose equivalent (H) is calculated by $H \propto \int_0^t \chi(x,y,o)dt$. In the case of routine releases, the exposure periods of interest are days, weeks, months, or years. In the dose calculations, there are two cases to be considered. First is the calculation of the dose rate from the continued inhalation of radionuclides at a more or less constant average concentration in the atmosphere. This situation applies to individuals living in the vicinity of a normally operating nuclear power plant. Second in the calculation of the total dose commitment arising from inhalation of usually larger and time varying concentrations of radionuclides for a finite period of time. This is the case following a reactor accident. With regard to radiation dose calculation, it is recommended that the illustrative example be reviewed in two references.[3,8)]

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ABSTRACT

Nowadays, nuclear power production plays a principal role in the electrical energy supply. However, a nuclear power plants emit small amounts of radio-activity due to mostly fission product gases to the local environment during their normal operation. They may release considerably more radioactivity when accidents occur. It is quite necessary to be able to calculate the radiation doses to the general public from such radioactivity releases in order to evaluate the environmental impact of the normally operating nuclear power plant, to assure that this is within acceptable radiation standards, and to ascertain the radiological consequences of nuclear reactor accidents. Such computations also play an important role in determining the acceptability of a proposed nuclear reactor site. Before radiation dose calculations can be carried out, therefore, it is necessary to determine how the concentration of the radioactive effluents is distributed in the environment following their emissions into the atmosphere. This matter is considered and radiation dose calculations are mentioned in conclusions,