研究論文

245. *External Exposure from the Coning Radioactive Cloud in the Vicinity of Release Point*

放出点近辺における円錐型放射性雲からの外部被曝

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The immersion model based on the meteorological dispersion of the cloud can not be applicable to the estimation of exposure dose near the release point. And it is also important to estimate the exposure of personnel in site of the reactor, and results of the estimation would be useful to know the exposure pattern of ^{41}A which is released in normal operation of the reactor. In this paper the estimation was made of the external dose near the release point, comparing with those in immersion case, and the aspect of external dose from radioactive cloud in whole area of interest was figured out.

The calculation was carried out under the following assumptions:

- (1) The cloud is of the coning shape with a vertex angle 20° which corresponds to category D (stable) in Meade and Pasquill's classification.
- (2) The condition of continuity of radioactivity holds and the distribution of the radioactive concentration is Gaussian in the radial direction of the cross section of the cloud.

The results show that the external dose near the release point from the coning cloud is in the same order as the maximum dose in immersion case and never exceeds it. Figures were given showing the effect of variation of release point height and iso-dose distribution near the release point. The error resulted from some simplifications of the original equation was within 10 %.

I. INTRODUCTION

In the hazard reports, it is usual to analyse the environmental hazards resulted from the accidental release of fission products under the assumption of MCA (Maximum Credible Accident) of the reactor. Therefore, analysis has been mainly on the hazards of the inhabitants in off-site area which would be at least several hundred meters away from the release point (stack) of radioactive cloud. And the external exposure is estimated with the model of immersion in the cloud covering the people on the ground, diffused according to the meteorological conditions.

This model naturally can not be applied to the analysis of the exposure of the people who would be or work very near to the release

point, and if one wants to figure out and gets more detail of the exposure aspect from the radioactive cloud on the whole range of distance from the release point, it is necessary to carry out another calculations though mathematically little more complex. Only one environmental analysis on the NS "Savannah"⁽¹⁾, gives attention about the problem, and takes the same dose as the maximum dose in the immersion case up to the release point without any calculation, by the reason that near the release point the dose should not be less than the maximum dose in the immersion case.

The objectives of this paper are to get the

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external dose near the release point, where "immersion model" can not be applied, under some assumptions and see how it would connect with the one in "immersion model". This result may give the level of exposure dose of personnel in site in accidental release of fission products, and also be applicable to the estimation of dose from—say, ^{41}A cloud which is released in normal operation of a reactor.

II. ASSUMPTIONS TAKEN AND BASIC FORMULA OF CALCULATION

Assumption: (1) The shape of the cloud was taken to be "cone" with a vertex angle 20° which corresponds to the spreading angle of cloud in the category D of Meade and Pasquill's classification⁽²⁾, which meteorological condition has 75 ~ 80 % frequency distribution per year in Tokai Area.

Assumption: (2) About the radioactivity in the cone, the condition of continuity holds; that is, the radioactivity in the cross-sectional volume of cloud with unit length be always equal, having the lateral Gaussian distribution of concentration. This would not reflect the exact meteorological diffusion conditions, but for making the calculation simple we took the assumption above.

Now, in Fig. 1, the external dose from the coning cloud to 1 cm^3 of air (receiver) at A ($x_0, y_0, 0$) would be expressed as

$$D = \frac{k}{4\pi} \sum_i E_i \int_V \frac{1}{l^2} e^{-\mu_i l} B(l) e^{-\lambda_i l} dV \quad (1)$$

where k : a conversion factor to dose (roentgen) from the concentration (c/m^3)

E_i : i -th γ ray energy emitted (MeV)
 λ_i : the radioactive concentration at P

λ_i

in the cloud (c/m^3)

λ_i : a decay constant

$\bar{u}$: mean wind velocity (m/sec)

l : distance between elemental volume in cloud and A (m)

B : build up factor of air

μ_i : absorption coefficient of air

x : distance of the cross-sectional cloud from the release point (m)

Radioactive decay is negligible, because $x/\bar{u}$ is so small for x of interest. Build up factor increases and absorption factor $e^{-\mu l}$ decreases as the distance increases, and so these factors were neglected because both factors cancel each other to some extent, and the error coming from this neglect would be less than several percent. (See Appendix)

Then Eq. (1) can be rewritten in the simple form, in the cylindrical coordinates x, r and φ , x being in the wind direction,

$$D = \frac{k}{4\pi} \sum_i E_i \int_x \int_{\varphi} \int_r \frac{\chi}{l^2} r dr d\varphi dx. \quad (2)$$

Fig. 1 Schematic figure for the calculation

III. CALCULATION OF THE EXTERNAL DOSE

From assumption (2), the radioactive concentration at any point is

$$\chi = f \exp(-ar^2), \quad (3)$$

where r is radius of the cross section of the cloud and f is the concentration at the center of cloud. Suppose, at the boundary of the cloud, the concentration be $1/10$ that on the central⁽²⁾.

$$\chi_R = f \exp(-aR^2) = 0.1f, \therefore a = 2.30/R^2 \quad (4)$$

where R is radius of the section and consequently related geometrically to x as

$$R = x \tan \theta, \quad (\theta = 10^\circ). \quad (5)$$

In the cross-sectional volume, the below relation holds from assumption (2);

$$q = \int_x^{x+1} \int_0^{2\pi} \int_0^\infty f \exp(-ar^2) r dr d\varphi dx = \text{const.} \quad (6)$$

Then we have

$$q = \pi f/a \quad \text{or} \quad f = aq/\pi. \quad (7)$$

In conclusion, the expression of concentration satisfying the assumptions is obtained by substitution of both Eqs. (4) and (7) in (3) as

$$\chi = \frac{2.30 q}{\pi R^2} \exp(-2.3 r^2/R^2), \quad (8)$$

which is function of r and implicitly of x , and is independent of the angular variable φ .

The final equation, substituting the previous results, is

$$D = \frac{kq}{4\pi} \sum_i E_i \int_0^\infty \int_0^{2\pi} \int_0^{\sqrt{2}R} \frac{2.30}{\pi R^2 l^2} \exp\left(-\frac{2.30}{R^2} r^2\right) r dr d\varphi dx, \quad (9)$$

$$l^2 = (x - x_0)^2 + (r \sin \varphi - y_0)^2 + (h + r \cos \varphi)^2.$$

The integration is carried out in turn with respect to each variable; first the exact integration about φ can be obtained as

$$\int_0^{2\pi} d\varphi / l^2 = 2\pi / \sqrt{(l_1^2 + r^2)^2 - 4l_0^2 r^2} \quad (10)$$

where $l_1^2 = (x - x_0)^2 + l_0^2$; $l_0^2 = y_0^2 + h^2$,

being independent of r . As Eq. (9) can not be integrated analytically with respect to r , we tried to expand the denominator in Eq. (10) about $(r/l_1)^2$; fortunately it can be shown that the error caused from expansion of the equation does not exceed 10% in maximum when one would take the range of x_0 not more than 200 m. In integrating with respect to r , the upper limit is chosen $\sqrt{2}R$ instead of infinity, where the concentration is 100th that on the central axis, because, if the upper limit were chosen infinity, the expansion method could not be applied. After integrations, the integrated dose at any receiver due to any total released radioactive quantity is given by

$$D = D_1 + D_2 \quad (11)$$

where

$$\left. \begin{aligned} D_1 &= 7.89 \times 10^{-2} kq \left(\frac{\pi}{2} + \tan^{-1} \frac{x_0}{l_0} \right) \sum_i E_i / l_0 \\ D_2 &= -1.01 \times 10^{-3} kq \sum_i E_i \left[\frac{l_0^2 - x_0^2}{4 l_0^2} \left\{ \frac{1}{l_0} \left(\frac{\pi}{2} + \tan^{-1} \frac{x_0}{l_0} \right) + \frac{x_0}{x_0^2 + l_0^2} \right\} - \frac{x_0^3}{2 (x_0^2 + l_0^2)^2} \right] \end{aligned} \right\} \quad (12)$$

In Eq. (11), the first term represents the dose when the all activity were concentrated on the axis, and the second one is considered to be the correction term to this due to the spreading of the cloud. As seen from the equation, the first term is hundred times of the second in order.

The relation between q , activity in the sectional volume, and Q , total actually released curie, with mean wind velocity $\bar{u}$ (m/sec) is

$$q = Q/\bar{u}. \quad (13)$$

And if the release rate Q c/sec is given in place of the total curie, the dose above will give the exposure dose rate per second.

In order to calculate and compare results with those in immersion case, the following data have been used for estimation.

- (1) mean wind speed is 2.5 m/sec
- (2) spreading angle is 20° in the range of 1 km (as previously described)
- (3) height of stack is taken to be 20 m and 40 m
- (4) total released radioactive quantity is 1 c

The absorption coefficient μ , that depends on the γ energy, is nearly constant ($3.38 \times 10^{-3}/\text{m}$) in the range of E between 0.7 and 1.5 MeV⁽³⁾, and consequently the conversion factor k is given

$$\begin{aligned} k &= \frac{3.70 \times 10^{10} (\text{dis/c} \cdot \text{sec}) \times 1 (\text{MeV/dis}) \times 3.38 \times 10^{-3} (1/\text{m})}{6.77 \times 10^{10} (\text{MeV/m}^3 \cdot \text{r})} \\ &= 1.85 \times 10^{-3} \text{ m}^2 \text{ r/c} \cdot \text{sec} \end{aligned}$$

Variation of the integrated dose at A along the wind direction is shown in Fig. 2, with parameter y_0 . The upper curve corresponds to height 20 m and the others are with 40 m. As the change of y_0 effects in the similar way for the dose as that of h ,

this figure can be applied for parameter h . x_0 was taken from negative infinity to 200 m, because the receiver is immersed geometrically in the cloud for x_0 greater than 240 m, when the stack height is 40 m. When the stack height is 20 m, x_0 can not be over 100 m in

Fig. 2 Distribution of integrated dose in the wind direction

Fig. 3 Distribution of integrated dose in the cross-wind direction

our equation. Any way it can be seen that dose increases rapidly with h decreasing. In Fig. 3 was shown the variation of dose in cross-wind direction. Fig. 4 gives the iso-dose aspect.

Comparing our results with those obtained in immersion case⁽⁴⁾, it is found to be conne-

height of release-point : 40 m
mean wind speed : 2.5 m/sec
stability : D
released curie : 1 c
spreading angle : 20°
Fig. 4 Iso-dose curve (μr/MeV)

Fig. 5 Exposure dose of non-immersion and immersion case

ected in good sense on the x -axis but to differ gradually with y_0 increasing, as shown in Fig. 5.

IV. CONCLUSION

- (1) The external dose of the coning cloud near the release point was calculated, and compared with the calculation in the immersion case. And Cottrell, *et al.*'s estimation was verified to be reasonable in practical purpose.
- (2) More detail aspects of the external exposure from the radioactive cloud were figured out on the whole distance from the release point.
- (3) The result would be applicable also to the estimation of exposure dose of radio-argon in the site, which is released in normal operation of the reactor.

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(APPENDIX)

The errors from neglecting the following factors were estimated in brief.

(1) Decay factor

Since it is impossible to see the behavior of this factor in the integration, only the order of error was estimated. The mean value of $e^{-\Lambda x}$ is

$$\langle e^{-\Lambda x} \rangle = \frac{1}{L} \int_0^L e^{-\Lambda x} dx$$

where $\Lambda = \lambda/\bar{u}$, λ being a decay constant. Taking ^{41}A , for example; $\lambda = 1.05 \times 10^{-4}/\text{m}$, and if L , length of the cloud, is taken 500 m,

$$\langle e^{-\Lambda x} \rangle \doteq 1$$

Thus, this may not be considered.

(2) Build up factor

The expression of this factor is given empirically as⁽⁵⁾

$$B = 1 + \mu l + (\mu l)^2 / 7 E^{2.4}$$

The third term can be immediately shown to be negligibly small;

$$\int \frac{\mu^2 l^2}{7 E^{2.4}} dD = \frac{\mu^2}{7 E^{2.4}} \int l^2 dD < 1.62 \times 10^{-9}$$

$$\text{for } \begin{cases} E = 1.29 \text{ MeV} \\ \mu = 3.38 \times 10^{-3}/\text{m} \end{cases}$$

For the second term, however, the examination is also difficult, and the same way was used as the decay factor. Let l be distance from the central axis of the cloud to the receiver, through rough calculation, then the mean value of l is

$$\langle l \rangle = \int_0^\alpha h \sec \theta d\theta / \int_0^\alpha d\theta; \tan \alpha = L/h.$$

Again taking $L = 500$ m, then $\alpha = 85.5^\circ$ for the receiver on the origin and 80.9° for one on the middle place (250 m off from the origin).

$\langle l \rangle = 38$ m for the former and 31 m for the latter, and consequently

$$\langle \mu l \rangle = 0.13 \text{ and } 0.10, \text{ respectively.}$$

In conclusion, if this factor is considered, the dose increases about 10 %.

(3) Absorption factor

The possible error in the term $e^{-\mu l}$ will be obtained by substitution of $\langle \mu l \rangle$ above:

$$\langle e^{-\mu l} \rangle = 0.88 \text{ and } 0.90, \text{ respectively.}$$

Therefore the decrease of dose due to this factor is about 10 %, comparable to that from the build up factor.

After all, the whole error coming from the neglect of the terms above does not exceed 10 %, which is mainly contributed from the expansion method.