H13-26
AN EXAMINATION OF PLUME DOSE IN CROSSWIND DIRECTION BY USING GAUSSIAN PLUME MODEL FOR ROUGH TERRAIN


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Abstract: This paper demonstrates a model designed to estimate plume dose due to elevated releases in a rough terrain. The model uses meteorological parameters and release rate as its input, and predicts the dose rates due to dispersion of radioactive plume. The predictions using Gaussian plume dispersion model at different crosswind distances of a selected downwind distance was studied by comparing acquired dose rate data due to continuous releases of Ar\(^{41}\) from Nuclear Research Facilities (Cirus and Dhruva) of BARC, Trombay. The dose rate data was collected from five different receptors which were placed laterally with respect to direction of radioactive plume (Ar\(^{41}\)). Gammatracers were used during ambient radiation monitoring, which provides the dose and dose rates over the monitoring period, along with specific time, duration, and magnitude of fluctuations in the dose rates. A better agreement (factor of 1.8 to 4.0) was observed between estimated values and experimental data for integrated dose of the selected period, than dose rate at specific hour (t). Comparison under certain meteorological condition. The estimated values predict the trend for the dose and dose rate distribution around the centerline and the experimental measurement validates the trend predicted by the theoretical estimation.

Keywords: Rough terrain, Model evaluation, Ar\(^{41}\) release, Gammatracer

INTRODUCTION
Atmospheric releases of radioactivity from nuclear facilities can be during normal operating conditions or any incident/accident within the facilities. The radiological impact on the environment will depend on several factors such as the nature and magnitude of releases, height of release, meteorological conditions, topography of the site etc (Barratt, R., 2001). The radiological impact analysis is a regulatory requirement in case of atmospheric releases in the environment during normal operation or accident condition. Atmospheric dispersion modeling is an important tool to predict the transport and dispersion of radionuclides in the environment released from nuclear facilities. For estimation of concentration and dose rate distribution in time and space, the plume shape and concentration distribution within the plume is an important parameter. In this paper plume dose has been estimated for elevated releases from nuclear research facilities (Cirus and Dhruva) using Gaussian plume dispersion model. Considering the complex topography of the study area the model has been incorporated with dispersion functions from Briggs-Smith sigma scheme (σ, and σz), plume rise and the power law of wind profile for rough terrain, effective plume stabilization height and effect of Thermal Internal Boundary Layer (TIBL). In course of routine operation of nuclear reactors (Cirus and Dhruva), Ar\(^{41}\) is released in the atmosphere within the authorized limit. Ar\(^{41}\) (T1/2=110 min) is produced due to neutron activation of Ar\(^{40}\) present in the air used to cool the reactor structures and the control rods. Dispersion of this short lived radioisotope within the complex topography of Bhabha Atomic Research Centre (BARC) has been studied by using offline dose logging system (Gammatracer). Dose rate data were collected from different crosswinds of a selected downwind distance and validated with the predicted values generated from atmospheric dispersion model considering meteorological parameters and different release conditions.

METHODOLOGY
The study was carried out at BARC, which is situated at the bank of the Arabian Sea. Because of land and sea interface and due to presence of small hills the topography of the BARC site is complex in nature. Nuclear research facility Cirus and Dhruva have been operating within this complex since 1960 and 1985 respectively. Two tall stacks of Cirus and Dhruva are situated very close to each other and discharging effluents in the atmospheric routes, the details of stacks and their release rates are given in Table 1. Ar\(^{41}\) is the major radioisotope released through the gaseous route within the authorized discharge limit.

The dispersion of Ar\(^{41}\) plume within the site is being studied using different kinds of dose logging equipments/system (TLDs and Environmental Dose Logging Systems). Here, Gammatracers were used (Receptors, R1 to R5) to study the extent of plume dispersion in the crosswind direction of a selected downwind distance (700m) as shown in Figure 1. The collected dose rate data from Gammatracers were validated with the estimated values using the Gaussian plume model modified with the following expressions suitable for rough terrain.

Table 1. Stack parameters of nuclear research facilities

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Cirus</th>
<th>Dhruva</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power/capacity</td>
<td>20(40) MWth</td>
<td>50(100) MWth</td>
</tr>
<tr>
<td>Stack Height (H(_\text{L}))</td>
<td>120 m</td>
<td>100 m</td>
</tr>
<tr>
<td>Stack internal Diameter(D(_\text{L}))</td>
<td>1.2m</td>
<td>1.1m</td>
</tr>
<tr>
<td>Exhaust flow rate (F)</td>
<td>15.8 m(^3) s(^{-1})</td>
<td>27.7 m(^3) s(^{-1})</td>
</tr>
<tr>
<td>Ar(^{41}) release rate (Q(_\text{L}))</td>
<td>4.70E+08 Bq s(^{-1})</td>
<td>2.57E+08 Bq s(^{-1})</td>
</tr>
<tr>
<td>Exit velocity of effluent (w(_\text{L}))</td>
<td>15.4 m s(^{-1})</td>
<td>24.5 m s(^{-1})</td>
</tr>
</tbody>
</table>

*Study period’s data has been considered

Figure 1. Placement of Gammatracers w.r.t. stack during monitoring period
Gaussian plume model (GPM)

In Gaussian plume model, the plume concentration \( C \) (Bq m\(^{-3}\)) and dose rate \( D \) (\( \mu \)Sv h\(^{-1}\)) at any receptors location for a given release is calculated by the following expressions (1-2). (Jones, J.A., NRPB-R157, 1983).

\[
X_{\text{exp}} = \frac{\lambda}{2 \pi} \exp \left( -\frac{x^2 + y^2}{\lambda} \right)
\]

\[
D = \frac{K E \delta}{\mu} \exp \left( -\frac{-x^2 + y^2}{\lambda} \right)
\]

Where \( Q_0 \) is the radioactivity release rate (Bq s\(^{-1}\)), \( H' \) is effective plume height (m), \( U \) is the mean wind velocity (m s\(^{-1}\)) at effective height and \( U_0 \) is the frictional wind speed over land (0.5 m s\(^{-1}\)) (Stunder, M. and S. Sethuraman, 1985), \( \alpha_H \) and \( \alpha_U \) are atmospheric dispersion coefficients (m) for the horizontal and vertical directions. \( A \) is TBL, \( x \) is the downwind distance (m), \( T_l \) and \( T_w \) are temperature over land and water surface, \( \theta \) is the lapse rate at neutral category (- 0.0098 K m\(^{-1}\)) (Barratt, R., 2001). \( K \) is the multiplication factor (5.0E-4), \( E_\gamma \) is average gamma energy of \( \gamma \) (1.29 MeV), \( \mu_\delta \) is the linear energy absorption coefficient (2.7E-3 m\(^{-1}\)) and \( \mu_\rho \) is the linear attenuation coefficient (7.5E-3 m\(^{-1}\)) in the medium (air), \( r \) is the distance between source and the receptors (m). \( B(\gamma, \mu, \rho) \) is the Berger form of dose build-up factor. Parameters \( a \) (0.75) and \( b \) (0.0175) depends on average gamma energy (\( \gamma \)) and the attenuating medium (air) (Faw, R.E. and Shultis, J.K., 1999).

Dispersion coefficient

The two key parameters, vertical and horizontal dispersion coefficients for rough terrain were estimated by using equation 3. Briggs-Smith sigma function has been considered here, which is effective for elevated releases in rough terrain (surface roughness, \( z_0 \), of 100cm) on the basis of tracer experiment simulated in that condition (Miller C.W., 1978).

\[
\sigma = \max(1 + m \cdot \rho \cdot p_0, c \cdot d) \sigma_0
\]

Where, \( x \) is the downwind distance (m). The coefficients \( m \) and \( n \) and the exponent \( p \) for neutral category is given by 0.16, 0.004 and -0.5 respectively. \( c \) and \( d \) for neutral category is 0.22 and 0.78 respectively (Carrascal, M.D., Puigcercer, M. and Puig, P., 1993).

Plume rise function

The gaseous effluent from the tall stack is released with a certain exit velocity, which tends to displace the plume more upward. The effective plume rise can be derived by the following equations (4-5).

\[
H_p = H_s + \Delta h
\]

Where, \( H_s \) is the physical stack height (m), \( \Delta h \) is the plume rise (m) and \( H' \) is the effective stack height (m). Plume rise (\( \Delta h \)) for neutral category is estimated by the given equation.

\[
\Delta h = \frac{2 \sqrt{U_c}}{D_0}
\]

Power law for wind profile


\[
U_z = U_0 \left( \frac{z}{z_0} \right)^n
\]

Where \( U_z \) is the wind speed at height \( z \), \( U_0 \) is the wind speed at height \( z_0 \). Using this formula, wind speed at height of release was calculated by considering the wind speed at 25 m (\( z_0 \)). The power law coefficient \( n \) increases with increasing surface roughness, the value of coefficient (\( n = 0.39 \)) considered for rough terrain (\( z_0 = 100 \)cm) and at neutral stability category (Barratt, R., 2001).

Effective plume stabilization height

\[
H' = H + Z(\alpha, \beta)
\]

\( H' \) = Effective plume height (m), \( H \) = Effective stack height (m), \( Z(\alpha, \beta) \) = elevation of stack base and \( Z(\alpha, \beta) \) = elevation of terrain at the receptor location (m) (McDonald, R., 2003).

The gamma dose rates from the Gaussian plume suitable for rough terrain have been calculated using the above mentioned equations and by employing the numerical integration over a 3D domain based on trapezoidal rule using C++.

Gammatracrader and data collection

Gammatracrader is a hermetically sealed battery operated and portable offline dose logging system. It has two inbuilt GM detector sand covers a dose rate range of 20 nSv h\(^{-1}\) to 10 mSv h\(^{-1}\). The data acquiring time interval of Gammatracrader can be varied and is capable of storing data for many days (Genitron instruments, 1996). These monitoring instruments were calibrated by using standard radioactive sources (\( \text{Cs}^{137} \) and \( \text{Co}^{60} \)) prior to installation. The dose rate data acquisition period of each were kept at 1 minute during study period.
As shown in Figure 1, five Gammatracers were placed laterally with respect to direction of plume at NE and NNE sector. Periodically the dose rate data were collected and analyzed in the laboratory over a period of six months.

RESULTS AND DISCUSSION
In this study the best three crosswind plume dispersion under PG stability category D have been considered to compare with the predicted values and shown in Figure 2. During the passage of radioactive plume, R3 receptor was considered in at centerline of the plume, since in all observations (Figure 3) it was showing higher dose rate compared to other four receptors (R1, R2, R4, and R5) and micro meteorological data confirms that the plume direction was also lying over receptor R3.

Table 2. Typical data set of meteorological parameters used for theoretical estimation

<table>
<thead>
<tr>
<th>Date</th>
<th>Time Period (hrs)</th>
<th>Stability Class</th>
<th>Average Wind Speed (m s(^{-1}))</th>
<th>Wind speed at (t_0) (m s(^{-1}))</th>
<th>(T_L) (K)</th>
<th>(T_W) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17/05/2009</td>
<td>09:00 to 13:00</td>
<td>D</td>
<td>1.64</td>
<td>1.56</td>
<td>305.10</td>
<td>294.83</td>
</tr>
<tr>
<td>18/06/2009</td>
<td>07:00 to 10:00</td>
<td>D</td>
<td>1.13</td>
<td>1.03</td>
<td>300.40</td>
<td>293.60</td>
</tr>
<tr>
<td>11/09/2009</td>
<td>10:00 to 14:00</td>
<td>D</td>
<td>1.28</td>
<td>1.11</td>
<td>301.52</td>
<td>293.50</td>
</tr>
</tbody>
</table>

Table 3. Comparison of dose and dose rates during study period

<table>
<thead>
<tr>
<th>Date</th>
<th>Time Period (hrs)</th>
<th>Average Dose rate (µSv h(^{-1}))</th>
<th>Total Dose of 4 hrs (µSv)</th>
<th>Dose rate at (t_0) (µSv h(^{-1}))</th>
<th>Average Dose rate (µSv h(^{-1}))</th>
<th>Total Dose of 4 hrs (µSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17/05/2009</td>
<td>0900 – 1300 hrs</td>
<td>0.10±0.05</td>
<td>0.51</td>
<td>0.09</td>
<td>0.13±0.06</td>
<td>0.53</td>
</tr>
<tr>
<td>18/06/2009</td>
<td>0700 – 1100 hrs</td>
<td>0.30±0.14</td>
<td>1.50</td>
<td>0.48</td>
<td>0.31±0.15</td>
<td>1.57</td>
</tr>
<tr>
<td>11/09/2009</td>
<td>1000 – 1400 hrs</td>
<td>0.11±0.09</td>
<td>0.56</td>
<td>0.19</td>
<td>0.20±0.16</td>
<td>0.98</td>
</tr>
</tbody>
</table>

To establish the correlation between measured and the predicted values onsite meteorological data, hourly wind speed (WS), wind direction (WD), heat flux and wind fluctuations were used from meteorological tower located at 25 m height. Average wind speed, stability classes and temperatures of the three different time periods are shown in Table 2.

Dose rate data analysis
A comparison of dose and dose rate data collected by Gammatracer from different receptors is presented in Table 3 which includes average dose rate, dose rate at specific time \(t_0\) and integrated dose of four hours data set at three different time intervals. The dose rate at \(t_0\), shown in Figure 2 and Table 3 (17th May 2009 at 1000 hrs, 18th June 2009 at 0900 hrs and 11th Sept 2009 at 1200 hrs) compared separately with the estimated value. During the monitoring period, the average dose rate varied between 0.10±0.05 µSv h\(^{-1}\) to 0.44±0.25 µSv h\(^{-1}\). Among the entire observation the maximum and minimum dose was 2.20 µSv at R3 (average WS = 1.13 m s\(^{-1}\)) and 0.51 µSv at R1 (average WS = 1.64 m s\(^{-1}\)). The maximum dose was observed at R3 compared to other receptors, in all observations dose and dose rates are normally distributed in both the sides of R3.

Comparison with GPM estimates
A comparison between estimated dose (for 4 hrs) and dose rate (at \(t_0\)) by using GPM suitable for rough terrain and observed values from Gammatracers are shown in Figure 3. The model predicts a dose rate at different crosswind due to release of Ar\(^{40}\), atmospheric stability (D), effective release height, effective wind speed at that height and exact elevation of the receptors with respect to stack. GPM estimates are made conservatively assuming the uniform wind speed and continuous release during monitoring period. Examination of predicted and observed values at different crosswind shows the same decrement characteristics around the centerline of plume. The difference between observed and predicted values increases as...
we go away from the centerline. In case of dose rate comparison, predicted values are 1.2 to 4.5 times more than the observed values. Similarly in case of dose comparison the above mentioned estimate varies at a factor of 1.8 to 4.0. The deviation in case of dose comparison of an integrated period is less compared to dose rate of a specific time and it is due to statistical fluctuation of Gammatracers data and less uniform distribution of meteorological parameters.

Figure 3. Comparison of (——) estimated and (----) observed values at different crosswind distances

CONCLUSIONS
In this study an attempt was made to predict the behavior of radioactive plume in crosswind direction in a complex topography of BARC site using Gammatracers. Since the meteorological conditions and dispersion of radioactive plume is complex due to the topography of BARC site, the experimental values are well below the predicted results. Considering other factors like effect of small hills and building wake effect predicted values can be improved. The estimated values predict the trend of normal distribution of the dose and dose rate profile in the horizontal direction around the centerline of the plume and the experimental measurement validates the trend predicted by the theoretical estimation.

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