World Applied Sciences Journal 34 (7): 979-984, 2016
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2016.34.7.150

Gamma Dose Rate Due to Dispersion of Radionuclides in Stable Conditions

[1]Fawzia Mubarak, [2]Khaled S.M. Essa and [3]Ahlaam Shabaan

[1]Rad. Protection Dept., NRC, AEA, Cairo, Egypt
[2]Mathematics and Theoretical Physics Dept., NRC, AEA, Cairo, Egypt
[3]Ben-Suef University, Faculty of Science, Undergraduate, Egypt

Abstract: Radiological impacts due to γ radiation on the ground at some of the user – defined output points are estimated in stable conditions. Contributions from airborne & deposited material are calculated. In the current study, Gaussian Plume Model is used to examine the time-evolution of the turbulent dispersion of radioactive gases in the atmospheric boundary layer and it is coupled to a gamma dose rate model. In this way, the variability of radiological dose rate from cloud shine due to instantaneous turbulent mixing processes can be evaluated. The maximum exposure from these selected radionclides released during the normal operation of the reactor was 2.63E-03 m Sv/y at distance 100 m downwind from the source. It has only about 0.13% of the recommended limits for occupational persons (20 mSv/y). It can be concluded that the estimated effective doses are below (and often far below) the dose levels regarded by the International Community on Radiological Protection (ICRP 2011).

Key words: Absorbed dose · Gaussian plume model · Infinite cloud and semi-infinite cloud

INTRODUCTION

External exposure generally results in a radiation dose to the entire body usually considered uniformly distributed over the body, particularly when it received from a widespread cloud. Absorbed dose is basically a measure of how much of the energy in the radiation field that is retained in a small volume. Models for calculating dose rates due to a radionuclide release into the atmosphere from a nuclear facilities under accident or normal operation conditions are of great importance, both due to the regulatory requirements, risk assessment and to know the environmental impact of such releases [1]. Dose rate is affected by many factors as stability conditions, photon energy, Eγ, mass energy absorption coefficient for air, μ_{en}/ρ, dry deposition velocity, turbulence, occurrence and intensity of rain, wind, etc. It is proportional to the product of the photon energy and the mass energy absorption coefficient for air [2, 3]. The dose rate arising from external irradiation due to radioactive plume is directly proportional to plume shape, the instantaneous radionuclides distribution in the air, half-life of the radionuclide and its environmental behavior [4].

For calculating the dose rates, also, the plume shape and the radionuclide concentration distribution are very important parameters. In eddy turbulent, the largest variability in local, instantaneous gamma dose rate is found at the distance of ten times the release height in stream-wise direction, regardless of the energy of the gammas. It is also demonstrated that the effective dose can be underestimated by up to a factor of four when long – term measurements are used to estimate the dose from short-term exposures and the variability in the wind field is neglected [5]. While, the importance of dispersion modeling in low wind conditions lies in the fact that such conditions occur frequently and are crucial for air pollution episodes. In such conditions, the pollutants are not able to travel far and thus the near-source areas are affected the most. The classical approach based on conventional models, such as the Gaussian puff/plume or the K-theory with suitable assumptions, are known to work reasonably well during most meteorological regimes, except for weak and variable wind conditions [6, 7]. As stability becomes more stable, thereby causing the mixing layer to decrease, a part of the cloud will remain above the mixing layer and will not be affected by deposition. When weather becomes less stable,

Corresponding Author: Fawzia Mubarak, Rad. Protection Dept., NRC, AEA, Cairo, Egypt.

radioactive material spreads vertically to fill the increased mixing layer. This mean that, during unstable condition the dose increases, due to the fact that radioactive material above the neutral mixing layer can reach the ground and thereby increasing concentrations close to the ground and deposition [8, 9, 10].

If the atmospheric turbulence were homogeneous, the mean concentration of species emitted from a point source would have a Gaussian distribution [11, 12]. Dose rate is proportional to ground concentration at any crosswind point Y, while the dose rate on the centerline, D_i, is constant at some distance downwind [13]. The accumulated dose rate distribution has a maximum point at the foot of the stack; while dose rate distribution under a single weather condition has a maximum point occurs at a few hundred meters downwind from the stack [14].

However, for simplicity and obtaining conservative results, usually a uniform concentration distribution assumed within a plume extending finitely in all directions. This assumption results in a very simple expression for the dose calculations by assuming equilibrium between the γ energy released and the energy absorbed in air, (The uniform cloud approximation), . A more appropriate assumption is to assume a Gaussian concentration distribution that results in a rather complicated formula containing triple integral over the plume dimensions, (The Gaussian cloud approximation), [11, 15].

In this study, the uniform cloud approximation was used to calculate the dose rate to a receptor at specific downwind distance from the nuclear facility.

Theoritcal Aspects

Calculation of γdose Due to Airborne Material: During the normal operation of nuclear instillations, several fission radionuclides are released to the surrounding atmosphere. The releases during the normal operation of nuclear reactors are of the planned, chronic type [16]. Much of the dose from these radionuclides delivered by the pathway of cloud shine and immersion.

The Uniform Cloud Approximation: A simplified approach to estimate the dose from a passing cloud is based on the assumption that the individual is standing on the ground immersed in a cloud that is infinite in size , through which radioactivity is uniformly dispersed for a period during which the total exposure is given as D. When the radionuclide is uniformly distributed in the atmosphere or the photon energy is sufficiently low that this is a reasonable approximation over the volume of a plume, then the simplest calculation method is the semi-infinite cloud model [17, 18]. Simulation of the atmospheric dispersion of radioactive gases, released from a nuclear installation after an accident and computation of the resulting dose rate, is an essential part of the nuclear emergency planning. It is in particular important in order to be able to take effective countermeasures. Gaussian models perform reasonably well in predicting the spatial distribution of the gas concentration at larger distance from the source, i.e. from a few hundred meters on, they have shown to be unreliable at closer range [15, 19].

The radioactive materials released into the atmosphere are transported according to the wind field over the terrain and dispersed over a wide area in an arbitrary form of distribution. The amount of radioactive material in the atmosphere was changed by radioactive decay and chemical reactions as well as wet and dry deposition, jointly represented in equation (1). The wind field is dependent on both geometrical and meteorological conditions [20].

Most models for estimating γ-absorbed dose rate use a two-step process. First, (1): the average concentration distribution predicted using a dispersion model such as Gaussian plume model. Then (2): the absorbed dose rate is estimated using a dose calculation methodology with this average concentration distribution [21].

- The use of Gaussian air pollution model requires the estimation of horizontal and vertical growth of the plumes for predicting the air pollutant concentration. The horizontal and vertical growth of plumes are generally expressed in terms of standard deviations of concentrations in lateral (y) and vertical (z) directions i.e., σ_y and σ_z respectively and parameterize the dispersion due to atmospheric turbulence [22]. The equation of Gaussian air pollution model can be expressed as:

$$C = \frac{Q}{2\partial u\, \acute{o}_y \acute{o}_z}\left[\exp\left(\frac{-y^2}{2\acute{o}_y^2}\right)\left[\exp\left(\frac{-(z-H)^2}{2\acute{o}_z^2}\right)+\exp\left(\frac{-(z+H)^2}{2\acute{o}_z^2}\right)\right]\right] \quad (1)$$

where the parameters are defined by the following descriptions:

C (Bq m^{-3}) = Concentration of air pollutant;
Q (Bq s^{-1}) = Continuous point source strength;
u (m s^{-1}) = Wind speed at height H;
σ_y (m) = Lateral dispersion parameter;

σ_z (m) = Vertical dispersion parameter;
x (m) = Horizontal distance in the direction of downwind.
y (m) = Lateral distance from plume centerline,
z (m) = Height above ground;

H(m) = effective height of plume above ground; H=h+Δh; where h is the stack height and Δh is the plume rise equals 3(wD/u); D is the internal stack diameter and w is the exit velocity of the pollutants [23].

- Estimation of absorbed dose in air from a plume emitting photons is most simply achieved by use of a semi-infinite cloud model. Implicit in this approach are the assumptions that the activity concentration in air is uniform over the volume of the plume from which photons can reach the point at which the dose is delivered and that the cloud is in radio-equilibrium. The amount of energy absorbed by a given element of cloud is then equal to that released by the same element [18]. A semi-infinite homogeneous cloud could be assumed for calculating absorbed gamma dose at large distances (up to several kilometers). For smaller distances the dose rate has to be calculated by 3- dimensional integration over the activity concentration in the plume [24, 25]. The general expression for dose calculation is:

$$D_\gamma = K_1 x \sum_{j=1}^{n} I_j E_j \quad (2)$$

where,
D_γ is the absorbed dose rate in air (Gy/y)
X is the atmospheric concentration of the radionuclide calculated using equ. (1) (Bq/m^3)
E_j is the initial energy of the photon (MeV)
I_j is the fraction of photon of initial energy E_j emitted per disintegration
n is the number of photons of particular energies emitted per disintegration
K_1 = 2*10^{-6} (Gy/y MeV m s) [3, 18].

RESULTS AND DISCUSION

Table (1) shows the activity concentration of different radionuclides at different distances (Bq/m^3) as calculated using equation (1). Calculations show that the maximum ground level concentrations appear at distances of 100-120 meter at downwind distances.

Absorbed dose rate (Gy/y) is estimated using a dose calculation methodology with this average concentration distribution as shown in equation (2).

For I-131 the energy of 364.48 keV (with intensity 81.2%) and 529.9 keV (with intensity 87.3%) for I-133 were used in equation (2). While for I-135 the summation of 1131.5 keV (with intensity 22.5%) and 1260.4 keV (with intensity 28.6%), this also made with 462.8 keV, 1009.8 keV and 1435.9 keV for Cs-138 (with intensity 30.7 %, 29.8% and 76.3% respectively), Tables (2 &3).

A coefficient of 0.7 Sv/Gy has been used to convert the annual absorbed dose in air to annual effective dose Equivalent, [26, 27], as shown in Tables (4 & 5).

The summation of external dose rate to the workers from I-133, I-135 and Cs-138 at different distances were also calculated. Therefore, we assume that the worker may be exposed to the total annual release from the selected radionuclides and the annual exposure due to these radionuclides was calculated as shown in Table (6).

Table (1): Concentration of different radionuclides at different distances (Bq/m^3)

Distance (m)	I-131 Bq/m^3	I-133 Bq/m^3	I-135 Bq/m^3 (*10^{-2})	Cs-137 Bq/m^3 (*10^{-6})	Cs-138 Bq/m^3 (*10^{-3})
20	4.1	2.16	0.209	0.16	0.24
40	4.3	2.69	0.292	0.19	0.31
60	4.6	3.33	0.356	0.029	0.39
80	4.7	3.82	0.369	0.036	0.45
100	4.9	4.05	0.374	0.43	0.47
120	6.9	4.03	0.309	0.36	0.48
140	6.2	3.86	0.269	0.29	0.45
160	5.3	3.57	0.231	0.24	0.42
180	4.8	3.29	0.199	0.2	0.39
200	3.1	2.99	0.172	0.18	0.35
300	2.1	1.83	0.091	0.09	0.21
400	1.2	1.18	0.055	0.05	0.14

Table 2: Annual absorbed dose, Dγ, due to different isotopes of Iodine (Gy/y)

Cs-137 E=0.6616 MeV	Cs-138 E=0.4628 MeV	Cs-138 E= 1.0098 MeV	Cs-138 E=1. 4359 MeV
2.12E-13	6.82E-11	6.82E-11	5.26E-10
2.51E-13	8.81E-11	8.81E-11	2.19E-10
3.84E-14	1.11E-10	1.11E-10	2.75E-10
4.76E-14	1.28E-10	1.28E-10	3.18E-10
5.69E-13	1.34E-10	1.34E-10	3.32E-10
4.76E-13	1.36E-10	1.36E-10	3.39E-10
3.84E-13	1.28E-10	1.28E-10	3.18E-10
3.18E-13	1.19E-10	1.19E-10	2.97E-10
2.65E-13	1.11E-10	1.11E-10	2.75E-10
2.38E-13	9.95E-11	9.95E-11	2.47E-10
1.19E-13	5.97E-11	5.97E-11	1.48E-10
6.62E-14	3.98E-11	3.98E-11	9.89E-11

Table 3: Annual absorbed dose, Dγ, due to different isotopes of Cesium (Gy/y)

I-131 E=0.3645 MeV	I-133 E=0.5299 MeV	I-135 E=1.1315 MeV	I-135 E=1.2604 MeV
2.43E-06	2.00E-06	1.06E-09	1.51E-09
2.55E-06	2.49E-06	1.49E-09	2.11E-09
2.72E-06	3.08E-06	1.81E-09	2.57E-09
2.78E-06	3.53E-06	1.88E-09	2.66E-09
2.90E-06	3.75E-06	1.90E-09	2.70E-09
4.08E-06	3.73E-06	1.57E-09	2.23E-09
3.67E-06	3.57E-06	1.37E-09	1.94E-09
3.14E-06	3.30E-06	1.18E-09	1.67E-09
2.84E-06	3.04E-06	1.01E-09	1.43E-09
1.84E-06	2.77E-06	8.76E-10	1.24E-09
1.24E-06	1.69E-06	4.63E-10	6.56E-10
7.10E-07	1.09E-06	2.80E-10	3.97E-10

Table 4: Annual effective dose, Hγ, due to different isotopes of Iodine (mSv/y)

Cs-137 E=0.6616 MeV	Cs-138 E=0.4628 MeV	Cs-138 E= 1.0098 MeV	Cs-138 E=1. 4359 MeV
1.48E-10	4.77E-08	1.01E-07	3.68E-07
1.76E-10	6.17E-08	1.31E-07	1.53E-07
2.69E-11	7.76E-08	1.64E-07	1.93E-07
3.33E-11	8.95E-08	1.90E-07	2.22E-07
3.98E-10	9.35E-08	1.98E-07	2.32E-07
3.33E-10	9.55E-08	2.02E-07	2.37E-07
2.69E-10	8.95E-08	1.90E-07	2.22E-07
2.22E-10	8.35E-08	1.77E-07	2.08E-07
1.85E-10	7.76E-08	1.64E-07	1.93E-07
1.67E-10	6.96E-08	1.47E-07	1.73E-07
8.34E-11	4.18E-08	8.85E-08	1.04E-07
4.63E-11	2.78E-08	1.01E-07	6.92E-08

Table (5): Annual effective dose, Hγ, due to different isotopes of Cesium (mSv/y)

Distance (m)	Total annual effective dose, Hγ (mSv/y)
20	1.40E-03
40	1.75E-03
60	2.16E-03
80	2.48E-03
100	2.63E-03
120	2.61E-03
140	2.50E-03
160	2.31E-03
180	2.13E-03
200	1.94E-03
300	1.19E-03
400	7.65E-04

Table 6: Total annual effective dose, Hγ, due to different radionuclides (mSv/y) at different distances

I-131 E=0.3645 MeV	I-133 E=0.5299 MeV	I-135 E=1.1315 MeV	I-135 E=1.2604 MeV
1.70E-03	1.40E-03	7.45E-07	1.05E-06
1.78E-03	1.74E-03	1.04E-06	1.47E-06
1.91E-03	2.16E-03	1.27E-06	1.80E-06
1.95E-03	2.47E-03	1.32E-06	1.86E-06
2.03E-03	2.62E-03	1.33E-06	1.89E-06
2.86E-03	2.61E-03	1.10E-06	1.56E-06
2.57E-03	2.50E-03	9.59E-07	1.36E-06
2.20E-03	2.31E-03	8.23E-07	1.17E-06
1.99E-03	2.13E-03	7.09E-07	1.00E-06
1.28E-03	1.94E-03	6.13E-07	8.68E-07
8.70E-04	1.19E-03	3.24E-07	4.59E-07
4.97E-04	7.64E-04	1.96E-07	2.78E-07

CONCLUSIONS

The maximum exposure from these selected radionclides released during the normal operation of the reactor was 2.63E-03 m Sv/y at distance 100 m downwind from the source. It has only about 0.13% of the recommended limits for occupational persons (20 mSv/y). It can be concluded that the estimated effective doses are below (and often far below) the dose levels regarded by the International Community Radiological Protection [28].

REFERENCES

1. Nielsen, S.P., S.E. Gryning, O. Karlberg, E. Lyck and S. Thykier Nielsen, 1990. Dry Deposition of ^{88}Rb and ^{138}Cs from A boiling Water Reactor Plume. Health Phys., 58(3): 283-289.
2. Hoffman, E.L., T. Loose and L. Mokhber Shahin, 2001. Environmental and effluents monitoring at ANSTO sites, 2000. Australian Nuclear Science and Technology Organization (ANSTO), Lucas Heights NSW (Australia), (Report), ANSTOE745.
3. Mats Isaksson 2011. Environmental Dosimetry Measurements and Calculations. University of Gothenburg, Sweden, Radioisotopes – applications in Physical Sciences, pp: 175-196.
4. Smith, J.G. and J.R. Simmonds, 2009. The Methodology for Assessing the Radiological Consequences of Routine Releases of radionuclides to the Environment used in PC-CREAM 08. Health Protection Agency, Oxford shire.
5. LievenVervecken, Johan Camps and johan Meyers 2015. Dynamic Dose Assessment by Large Eddy Simulation of Near-Range Atmospheric Dispersion, Journal of Radiological Protection, 35: 165-178.
6. Galmarini, S., R. Bianconi, T. Mikkelsen, W. Klug and S. French, 2002. ENSEMBLE: Real Time Multi-Model ensemble Dispersion Forcast for Nuclear Emergencies. Eighth Topical Meeting-Emergency Preparedness and Response, Washington DC, 17-21 November.
7. Davidson M. Moreiraa, Tiziano Tirabassib, Jonas C. Carvalhoa 2005. Plume dispersion simulation in low wind conditions in stable and convective boundary layers. Atmospheric Environment, 39: 3643-3650.
8. Nordland, G., J.P. Partanen, J. Rossi, I. Savolainen, and I. Valkama, 1985. Radiation Doses due to Long-Range Transport of Airborne Radionuclide Released by A reactor Accident-Effects of Changing Dispersion Conditions during Transport. Health Phys., 46(6): 1239-1249.
9. Sherbini, S., D. Tamasanis, J. Sykes III and S.W. Poorter, Jr., 1986. A Monte Carlo Program to Calculate the Exposure Rate from Airborne Radioactive Gases Inside A nuclear Reactor Containment Building. Health Phys., 51(6): 699-713.
10. William H. Hallenbeck, 1994. Radiation Protection. Lewis Publishers, CRC Press, London.
11. Syed Shoaib RAZA, Ruben AVILA and Jaime CERVANTES, 2001. A 3-D Lagrangian (Monte Carlo) Method for Direct Plume Gamma Dose Rate Calculations. Journal of Nuclear Science and Technology, 38(4): 254-260.
12. John M. Stockie, 2011. The Mathematics of Atmospheric Dispersion Modeling. Society for Industrial and Applied Mathematics, 53(2): 349-372.
13., Sabol, J. and P.S. Weng, 1995. Introduction to Radiation Protection Dosimetry. World Scientific, Singapore.

14. Thomas, J. Overcamp, 1991. Modeling γAbsorbed Dose Due to Meandering Plumes. Healthphys, 61(1): 111 -115.
15. Camps, J., C. Turcanu, D. Braekers, G. Olyslaegers, J.E.A. Paridaens, 2010. The 'NOODPLAN' early phase nuclear emergency models: an evaluation. Helsinki, Finland, 14-18 June 2010 / IRPA.
16. Raymond A. Serway, Robert J. Beichner and John W. Jewett, Jr., 2000. Physics for Scientists and Engineers with Modern Physics. 5th edition, Saunders College Publishing, (a division of Harcourt College Publishers), New York, pp: 592-593
17. Kimiaki Saito; Nina Petoussi-Henss and Maria Zankl, 1998. Calculation of the Effective Dose and its Variation from Environmental Gamma Ray Sources. Health Phys., 74(6): 698-706.
18. UNSCEAR, 2013. Methodology for the Assessment of Dose from External Exposure and Inhalation of Radioactive Material. Attachment C12.
19. Kevin Kenis, Lieven Vervecken and Johan Camps 2013. Gamma Dose Assessment in Near Range Atmospheric Dispersion Simulations. External Report of the Belgian Nuclear Research Center, Belgium.
20. Thykier Nielsen S., S. Deme and A. Lang, 1995. Calculation Method for Gamma Dose Rates from Gaussian Puff. Risk National Laboratory, Roskilde, Denmark.
21. World Health Organization, 2012. Preliminary Dose Estimation from the Nuclear Accident After the 2011 Great East Japan earthquake and Tsunami. Geneva, Switzerland.
22. Ronbanchob Apiratikul 2015. Approximation Formula for The Prediction of Downwind Distance That Found The Maximum Ground Level Concentration Of Air Pollution Based On The Gaussian Model. Proedia- Social and Behavioral Sci., 197: 1257-1262.
23. Mohamed M. Abdel-Wahab, Khaled S.M. Essa, Mokhtar Embaby and Sawsan E.M. Elsaid, 2013. Derivation the Schemes of Lateral and Vertical Dispersion Parameters: Application in Gaussian Plume Model. Open Journal of Air Pollution, 2: 19-24.
24. Andersson, K.G., J. Brown, K. Mortimer, J.A. Jones, T. Charnock, S. Thykier-Nielsen, J.C. Kaiser, G. Proehl and S.P. Nielsen, 2008 a. New developments to support decision-making in contaminated inhabited areas following incidents involving a release of radioactivity to the environment. J. Environmental Radioactivity, 99: 439-454.
25. Andersson, K.G., T. Mikkelsen, P. Astrup, S. Thykier-Nielsen, L.H. Jacobsen, L. Schou-Jensen, S.C. Hoe and S.P. Nielsen, 2008 b. Estimation of health hazards resulting from a radiological terrorist attack in a city. Radiation Protection Dosimetry, 131(3): 297-307.
26. Merril Eisenbud and Thomas Gesell, 1997. Environmental Radioactivity, from Natural, Industrial and Military sources. 4th edition, Academic Press, Inc. (AP), San Diego.
27. UNSCEAR, 2000. Sources and Effects of Ionizing Radiation. (Report to the General Assembly), United Nation, New York.
28. ICRP, 2011. Radiation Protection and Safety of Radiation Sources, International Basic Safety Standards and General Safety Requirements. International Commission on Radiological protection Publication, Part 3, No. GSRPart 3 (Interim), pp: 65-90, Vienna.