Transactions of the Korean Nuclear Society Autumn Meeting
Pyeongchang,Korea, October30-31, 2014

Assessment of Safety Parameters for Radiological Explosion Based on Gaussian Dispersion Model

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1. Introduction

Post terrorist attack of September 11, 2001, security of radioactive materials has been matter of concern worldwide. Radioactive sources are used for peaceful applications in medical, industrial and research institution. Any missing radioactive source may be used for malevolent act for creating socio-economical havoc. These sources if used with explosive (called RDD - radiological dispersion device), can cause dispersion of radioactive material resulting in public exposure and contamination of the environment. Radiological explosion devices are not weapons for the mass destruction like atom bombs, but can cause the death of few persons and contamination of large areas.

The reduction of the threat of radiological weapon attack by terrorist groups causing dispersion of radioactive material is one of the priority tasks of the IAEA Nuclear Safety and Security Program[1].Emergency preparedness is an essential part for reducing and mitigating radiological weapon threat. Preliminary assessment of dispersion study followed by radiological explosion and its quantitative effect will be helpful for the emergency preparedness team for an early response. The effect of the radiological dispersion depends on various factors like radioisotope, its activity, physical form, amount of explosive used and meteorological factors at the time of an explosion.

This study aim to determine the area affected by the radiological explosion as pre assessment to provide feedback to emergency management teams for handling and mitigation the situation after an explosion. Most practical scenarios of radiological explosion are considered with conservative approach for the assessment of the area under a threat for emergency handling and management purpose.

2.Materials and Methods

Numbers of radioactive materials are used worldwide for medical and industrial purpose having different physical and chemical properties of activity range from MBq to PBq. An ideal radioactive source to be used for the radiological explosion will have portable size, high radiotoxicity, non-metallic form, high activity and easily assessable by antisocial persons. Few commercially used isotopes (e.g. Cs-137) have all these properties. Other radioisotopes which have most of these favorable properties to be used for the radiological explosion are Co-60, Sr-90, Am-241, Cf-252, Ir-192 etc.

Hyeongki Shin et.al conducted study on dispersion of Cs-137 and Am-241 and concluded that Am-241 is more risky on the viewpoint of total effective dose and consequences are more widespread than Cs-137[2]. Co-60 (although in metallic form) is considered as most commonly used sealed radioisotope, for the medical (teletherapy, brachytherapy, blood irradiator, etc) and industrial applications (radiography, gauging devices, food irradiation) which has replaced Cs-137 due to the advantage of its high specific activity and physical form.

Gregory J. Van Tuyleet. al study concluded that Co-60 source used in teletherapy and disused or/and orphaned radioisotope thermoelectric generators (RTGs) sources are the highest risky sources which can be used for the radiological explosion[3]. Co-60 source used in radiotherapy is of considerably high activity and comparably smaller source size, which may be under threat during transportation, use or storage, since not being provided with the security like nuclear material, is considered in scenario S-1 and S-2.

Another source considered for the scenario development is Sr-90, which is 546 keV beta emitter, having high radiotoxicity, used in non-metallic (chloride, fluoride or titanate) physical form. Sr-90 is used for wide applications in industrial and medical purposes. This study considers Sr-90 as realistic scenario because of its use in RTGs. More than 1000 RTGs were manufactured in the former USSR mainly for the purposes of the power provision for the sea navigation and meteorological facilities[4]. National Nuclear Security Administration in the U.S. in partnership with the Russian Federation, claims to remove 14 such RTGS containing Sr-90 sources, in the year 2013, which could have been used in dirty bombs[5]. Most of these RTGs were manufactured during 1980s.

A typical single pellet RTGS contains Sr-90 source of 1.3 PBq [4]. Physical form of Sr-90 source, vulnerability of RTGs, single pallet source, high activity and high toxicity of Sr-90 make this an ideal source to be used for the radiological explosion. Considering a RTGs manufactured in mid 80s with original activity of 1.3 PBq of Sr-90 has been used for the S-3 and S-4 scenario development.

Explosive quantity consider for the two different scenario are 10 lbs of TNT equivalent, which may be used for small sized explosion device and 100 lbs of TNT equivalent, which can be used in a medium sized explosion device. These four scenarios are described in Table1. Meteorological data and other parameters used for modeling were same for all scenarios, are shown with the results.

The explosion is considered in metropolitan city of Daejeon in the evening time. The wind is assumed to be from the east direction.

Table 1. Scenario development using combination of radioactive sources and explosive

Scenario No.	Radioactive source and application	Source Activity (TBq)	TNT Quantity (lbs)
S-1	Co-60; Radiotherapy	5.6×10^2	100
S-2	Co-60; Radiotherapy	5.6×10^2	10
S-3	Sr-90; RTGS	6.5×10^2	100
S-4	Sr-90; RTGS	6.5×10^2	10

3.Dispersion Modeling

For the dispersion assessment of these scenarios, Hotspot 3.0.1 code was used. Hotspot results are conservative which use the Gaussian model for the dispersion study. Dose coefficients are calculated using the ICRP 60/70 methodology.

Gaussian model is widely used for the dispersion study and their result are in good consensus with experimental results for the simple meteorological and terrain conditions [6]. The complete equation for Gaussian Dispersion modeling of continuous, Byouant air plume is as follows [7]

$$C=\frac{Q}{u}.\frac{f}{\sigma_y\sqrt{2\pi}}.\frac{g_1+g_2+g_3}{\sigma_z\sqrt{2\pi}}. \quad (1)$$

Where

f crosswind dispersion parameter,
$g=g_1+g_2+g_3$ vertical dispersion parameter,
g_1 vertical dispersion with no reflections,
g_2 vertical dispersion for reflection from the ground,
g_3 vertical dispersion for reflection from an inversion aloft,
C concentration of emissions, in g/m³, at any receptor located ,
x downwind from the emission source point, in m,
y crosswind from the emission plume centerline, in m,
z above ground level, in m,
Q source pollutant emission rate, in g/s,
u horizontal wind velocity along the plume centerline, in m/s,
H height of emission plume centerline above ground level, in m,
L height from ground level to bottom of the inversion aloft, in m,
σ_z vertical standard deviation of the emission distribution, in m and
σ_y horizontal standard deviation of the emission distribution, in m

The total effective dose (TED) calculated from modeling is

Total effective dose
=Committed effective dose (inhalation)
+ Effective dose (submersion)
+ Effective dose (ground shine)

This code calculates the 95th percentile of the dose distribution for up to 20 radialcenterline distances in each of 16 wind blow direction sectors (direction dependent), and all 16sectors (direction independent).

4.Results

Dispersion modeling is performed in the four practical scenarios to calculate the geographical areas affected by the radiological explosion on the basis of total effective dose of 50 mSv and 10 mSv which are the generic intervention levels for the emergency management. Results of the entire four scenarios are given in Table 2. Among the assumed scenariosCo-60 results mainly in an external exposure whereas Sr-90 which is strong beta emitter also causes an internal exposure due to its non-metallic form. Resultant total effective dose includes ground shine radiation. Exposure duration is four days from an explosion time.

Table 2. Affected area under different scenarios

Scenario	Area within TED range of 50 mSv (km^2)	Area within TED range of 10 mSv (km^2)

S-1	0.51	1.5
S-2	0.94	3.0
S-3	0.093	0.33
S-4	0.094	0.45

Figure 1 and 2 shows the affected area of Daejeon city followed by radiological explosion under scenario S-2 and S-4 respectively of the Table1, near Daejeon station in the evening time. Red and yellow lines on the map show area affected by radiological explosion, which receives total effective dose of 50 mSv and 10 mSv respectively.

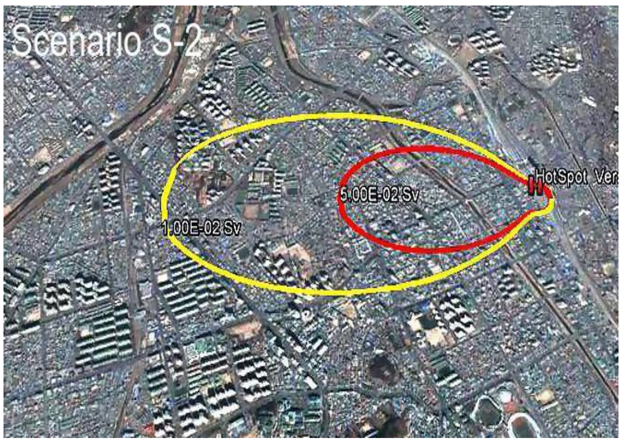

Figure 1. TED contour followed by a radiological explosion in scenario S-2

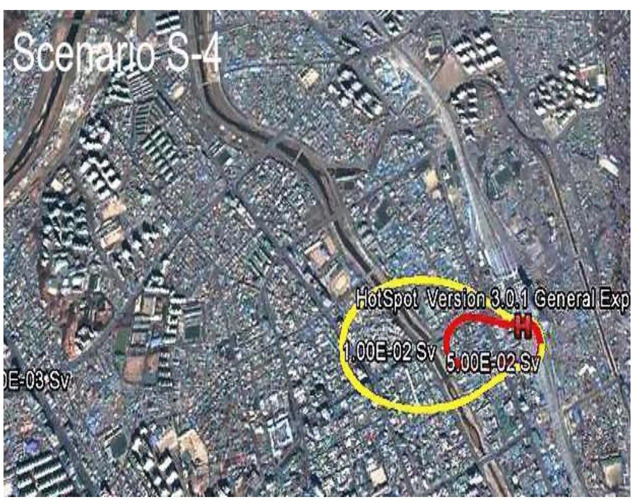

Figure 2. TED contour followed by a radiological explosion in scenario S-4

- Red line 50 mSv; Yellow line:10 mSv;
- Wind speed at reference height of 10 m:1 m/s;
- Receptor Height:1.5 m; Sample time: 10 minute and
- Images from the eye altitude of about 4300 m

Beside source activity and explosive quantity, all other factors considered for the study of entire four scenarios are the same for better inter-comparison. Affected area in case of Co-60 is much more than Sr-90 explosion for comparable radioactivity.

Dispersion study result shows for Sr-90 source affected area is not a strong function of explosive quantity, whereas reverse is true for Co-60 source.

5.Conclusion

Radioisotopes under weak security controls can be used for a radiological explosion to create terror and socioeconomic threat for the public. Prior assessment of radiological threats is helpful for emergency management teams to take prompt decision about evacuation of the affected area and other emergency handling actions.

Comparable activities of Co-60 source used in radiotherapy and Sr-90 source of disused and orphaned RTGs with two different quantities of TNT were used for the scenario development of radiological explosion.

In the Basic Safety Standard (BSS), IAEA recommends the generic intervention level of 10 mSv avertable dose for sheltering and 50 mSv for temporary evacuation[8].In the scenario S-2 an area of about 0.94 $km^2$and in scenario S-3 and S-4 an area of about 94,000 m^2 is required to be evacuated. Sheltering may be initiated in the area of 1.5 km^2 and 0.33 km^2 in the explosion of scenario S-1 and S-3 respectively.

In case of non-metallic source, Sr-90 in this case, the affected area doesn't vary strongly with explosive quantity. Small quantity of explosive material is sufficient for an explosion involving non-metallic source. Dispersion study using Gaussian model demonstrates that in spite of metallic form of Co-60, population in large area is affected by Co-60 explosion as compared to Sr-90 explosion from total effective dose viewpoint for the comparable source activity.

These results provide quantitative estimation of consequences of radiological explosion in the scenarios considered in the study. Further dispersion study is recommended for other radioisotopes which are risky from radiological explosion viewpoint like seed irradiators, orphan well logging sources, industrial radiography sources during transportation etc.

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