Applied Radiation and Isotopes 79 (2013) 1–4

Contents lists available at SciVerse ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Radiological risk assessment caused by RDD terrorism in an urban area

Hyojoon Jeong*, Misun Park, Haesun Jeong, Wontae Hwang, Eunhan Kim, Moonhee Han

Nuclear Environment & Safety Research Division, Korea Atomic Energy Research Institute, 989-111, Daedeok-Daero, Yuseong, Daejeon 305-353, South Korea

HIGHLIGHTS

- This study is to assess radiological consequences assuming a radiological terrorism.
- A RDD explosion scenario for the metropolitan area of Seoul is introduced.
- To protect the public in cases of radiological emergencies, the best management practices are discussed in this study.

ARTICLE INFO

Article history:
Received 9 March 2012
Received in revised form
4 April 2013
Accepted 10 April 2013
Available online 25 April 2013

Keywords:
Radiological risk assessment
HYSPLIT
RDD
Monte Carlo simulation

ABSTRACT

This paper specifically discusses a radiological risk assessment due to RDDs (Radiological Dispersion Devices) containing Cs-137 in the metropolitan area of Seoul, South Korea. The comparison of an effective dose caused by airborne plume and deposited Cs-137 is performed with and without consideration of the wind direction. When the dose is computed conservatively, an effective dose is around twice that of a dose computed realistically. Monte Carlo simulations showed that the 95% confidence interval for morbidity was 2.40×10^{-5} to 8.55×10^{-5}, and mortality was 3.53×10^{-5} to 1.25×10^{-4}.

1. Introduction

Most governments around the world and their citizens have become increasingly worried about intentional accidents in urban areas since the 911 terrorist event in the United States. Radiological sources are ubiquitous and invaluable in modern society worldwide. Sealed radiation sources are used for industrial and peaceful purposes such as smoke detectors, radiotherapy, medical devices, meteorology, thermoelectric generators, and mining. The relative ease of access to radiological sources as compared to nuclear materials, such as uranium, plutonium and thorium increases the probability of their use for terrorist activities. Radiological dispersal devices (RDDs) can be used for the dispersions of lost radiological sources and their explosions can be highly effective in causing a high number of casualties and extensive economic damage, including social chaos.

When an RDD explosion occurs in an urban area, air concentration of the radioactive materials in the environment is of great importance for countermeasures and environmental risk assessments. Air quality studies on radionuclides in the environment have been performed many times for Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) such as radon and uranium (Ho, 2008; Voitsekhovitch et al., 2006). Several studies have investigated the consequences of accidental or deliberate releases in terms of the fate and transport of radioactive materials in the atmosphere (Stocki et al., 2008; Thiessen et al., 2009). However, there have been few radioogical consequence assessments due to RDD explosion.

In this study, we made a RDD explosion scenario for the metropolitan area of Seoul, South Korea using Cs-137 of 50 TBq, which is a lost radiological source from Goiania, Brazil. The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model was used for assessing radiological consequences conservatively and realistically. A comparison of modeling approaches was performed, and which will be the best approach is briefly discussed to protect the public in cases of radiological emergencies.

2. Material and methods

2.1. The explosion scenario

In September 1987, an old radiation source was lost from an abandoned hospital in Goiania, the capital of the central Brazilian

---

* Corresponding author. Tel.: +82 42 868 2087; fax: +82 42 868 2368.
E-mail address: jeong1208@kaeri.re.kr (H. Jeong).

0969-8043/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apradiso.2013.04.018

state of Goias (Cruz et al., 2008). The radiation source consisted of 50 TBq of Cs-137 in the form of cesium chloride salt, and was sealed within two nested stainless steel containers. The lost radiation source was subsequently handled by several people and caused serious radioactive contamination, resulting in a number of deaths. Cs-137 is water-soluble and extremely toxic in minute amounts. Once released into the environment, it remains present for many years as its radiological half-life is 30.07 years. It can cause cancer 10, 20 or 30 years from the time of ingestion, inhalation, or absorption provided sufficient material enters the body (www.bt.cdc.gov/radiation/isotopes/cesium.asp). Sohier and Hardeman (2006) and Thiessen et al. (2009) used this source term as an intentional release. We introduced the total activity for the Goias accident as a hypothetical scenario for this study, and assumed that it was exploded using a RDD with 10 lbs of high explosives in the metropolitan area of Seoul, South Korea. Table 1 shows the conditions of air dispersion modeling for the RDD explosion. The duration time of the accident lag is 2 h. Wind speed and wind direction are used for the measurement at the time of explosion for assessing the radiological consequences conservatively, while 10 min averages of the wind speed and wind direction are used for assessing the radiological consequences realistically. The explosion height is calculated using the HotSpot health physics code. Exploded radiation sources are distributed as follows: 20% of the activity above 0.8 of the height of the cloud top, 35% of 0.6 cloud top, 25% of 0.4 cloud top, 16% of 0.2 cloud top, and 4% of ground level in the HotSpot code (Homann, 2009). The effective height was assumed to be 0.5 of the height of the cloud top in this study. The time required for an evacuation of all people who live in the accident area was assumed to be one day.

2.2. Air dispersion modeling

The HYSPLIT modeling system is used for estimating the particle trajectory, complex dispersion, and deposition simulations using particle and puff methodologies (Draxler and Hess, 1998). It can estimate forward and backward trajectories from a specified height and location using an advection and diffusion algorithm, which integrates the initial position of an air parcel in time. The HYSPLIT model has been widely used to estimate the dispersions of radioactive materials. Recently, many scientific articles have estimated the radiological consequences after the Fukusima nuclear accident. In the HYSPLIT model, the incremental concentration contribution by each puff of mass (m) to a grid point is computed as follows for a top-hat puff (Draxler et al., 2009).

$$\Delta c = m(\pi r^2 \Delta z)^{-1} \tag{1}$$

where the vertical extent is $\Delta c = 3.08\sigma_z$, and the horizontal radius is $r = 1.54\ \sigma_h$. All grid-nodes within the puff extent receive the same Δc. The incremental concentration contribution for a Gaussian puff is as follows:

$$\Delta c = m(2\pi\sigma_h^2\Delta z)^{-1}\exp(-0.5\times^2/\sigma_h^2) \tag{2}$$

where x is the distance from the puff center to the grid-node, σ_h is a horizontal dispersion coefficient, and σ_z is a vertical dispersion coefficient. Horizontal and vertical dispersion coefficients are dependent on the distance, x. The deposition concentration of interest from both dry and wet removal processes is expressed in terms of time constants as follow:

$$D_{\text{wet+dry}} = m\{1-\exp[-\Delta t(\beta_{\text{dry}} + \beta_{\text{gas}} + \beta_{\text{inc}} + \beta_{\text{bel}})]\} \tag{3}$$

where β_{dry} is for dry deposition, β_{gas} is for the removal process for gas, β_{inc} is for in-cloud wet removal of particles, and β_{bel} is for below-cloud wet removal of particles.

Meteorological data fields used to run HYSPLIT can be obtained from routine analysis archives or forecasting model outputs such as MM5 (Meso-scale Model 5), WRF (Weather Research and Forecasting model), and ECMWF (European Centre for Medium-Range Weather Forecasts) for considering a long-range dispersion of radiological materials. User-defined meteorological data which is measurement data used in this study is also available for short-range dispersion problems. HYSPLIT is used here to calculate a realistic dispersion for short-range Cs-137 transport from the accident point. The model was configured to compute Cs-137 dispersions for 2 h starting at an accident time of 14:00 May 1st, 2011 Korea Standard Time.

3. Results and discussion

The accident point is assumed to be the central area of Seoul, called Gangnam. Fig. 1 shows the wind rose for 2 h after the outbreak of the terror event. A westerly wind direction is dominant during the accident time. The first records of wind direction and wind speed are used for estimating radiological consequences conservatively, while all records of wind direction and wind speed are used for a realistic estimation of radiological consequences due to a Cs-137 explosion.

HYSPLIT outputs are air concentrations and deposition concentrations for Cs-137 in this study. To convert the air concentration and ground deposition values into a number that can be more easily related to health effects, we used the dose conversion factors for Cs-137. Dose conversion factors are 3.34×10^{-10} (mSv/h)/(Bq/m^3) for the airborne plume and 1.08×10^{-11} (mSv/h)/(Bq/m^2) for the deposited material. The accident duration time was assumed as 2 h in this study. Fig. 2(a) shows the effective dose due to a 2-h air submersion, and this dose contour is the result of multiplying 6.68×10^{-10} into a 2-h air concentration on average. The maximum dose was 3.90×10^{-5} mSv, while 1 mSv is equal to 0.1 REM. Fig. 2(b) shows the effective dose due to the deposited material of Cs-137 for 24 h, and this dose contour is the result of multiplying 2.64×10^{-10} into the deposition concentration for Cs-137. The maximum dose due to external dose is 5.6×10^{-4} mSv. Fig. 3(a) shows a conservative dose estimation from air submersion, where the maximum dose is 6.5×10^{-5} mSv, which is around twice that compared to the realistic estimation of radiation dose. Fig. 3(b) shows a conservative estimation from deposited Cs-137,

Table 1
Conditions of air dispersion modeling for RDD explosion.

	Scenario 1 (realistic)	Scenario 2 (conservative)
Computation time	2 h (14:00 May 1, 2011)	2 h (14:00 May 1, 2011)
Total activity (TBq)	50	50
Time of release duration after explosion ($_{\text{min}}$)	10	Evenly distributed
Wind direction (degrees from North)	239, 244, 260, 272, 238, 249,265, 271, 276, 263, 268, 235, and 240 (10 min average)	239 (constant)
Wind speed (m/s)	4.7, 5.2, 5.5, 5.0, 5.8, 6.1, 4.8,7.0, 5.6, 3.9, 4.6, 4.7, and 5.2 (10 min average)	4.7 m/s (constant)
Explosion height (m)	67.5	67.5