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Preliminary Evaluation of Doses Following Hypothetical Explosions of Radiological Dispersion Devices

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Abstract

The objective of this research was to perform preliminary evaluation of doses following hypothetical explosions of radiological dispersion devices (RDDs) at the studied areas (Victory Monument and Pattaya city). Calculations were based on the plume dispersion computer code, Hotspot Health Physics Codes program, which implemented the Gaussian plume dispersion model. Parameters used in this study were radionuclide species (Co-60, Cs-137 and Ir-192), material at risk (100 Ci), high explosive (10 and 25 pounds) and meteorological data (wind direction and wind speed period for the past 20 years). For the Victory Monument, results revealed that the maximum distance to receive the dose of 250 mSv for the material at risk of 100 Ci for the three radionuclides were 1.01, 1.42 and 1.30 km, respectively. For Pattaya site, the maximum distance to receive the dose of 250 mSv for the material at risk of 100 Ci for the three radionuclides were 1.28, 1.84 and 1.53 km, respectively. Areas receiving the total effective dose equivalent (TEDE) of more than 250 mSv should be considered immediate evacuation areas.

Keywords: Radiological dispersion device, Radionuclide, Total effective dose equivalent

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Introduction

In current era, international concerns over chemical, biological, radiological and nuclear (CBRN) weapons present special challenges to nuclear security. These four categories of weapons are often grouped together as "weapons of mass destruction" (WMD). However, all three categories except nuclear weapons could also be used in more limited ways. In addition to their physically destructive effects, CBRN weapons have great potential to cause psychological fear and panic. International efforts to control and eventually eliminate CBRN weapons are ongoing, but these control regimes have many limitations and gaps.

For this research work, the interest is only on radiological weapons. There are many kinds of radionuclides that can be used in several fields in Thailand such as industry, hospitalization, agriculture, environmental, education, research, etc. Some of them are the potential isotopes used in radiological dispersion devices (RDDs) such as Americium-241, Californium-252, Cesium-137, Cobalt-60, Iridium-192, Plutonium-238, Polonium-210, Radium-226 and Strontium-90). Via RDDs detonations, they could release alpha, beta, or gamma radiation that can affect the body, risking both external and internal contamination, and could cause wide-area contamination. Theft and sabotage for radiological terrorism act by taking advantage of vulnerabilities in usage securities, import and export control systems.

A radiological terrorism is the use of radioactive materials to cause physical injury and psychological damage, destruction to property and the environment. Terrorists will use the radioactive material to make radiological dispersion devices (e.g., dirty bomb and other dispersal methods) [1] by mixing radioactive materials (potential isotopes used in RDDs) in powder or pellet forms with a conventional explosive, such as dynamite, and attacking the public. It can be made into a small device or a car bomb.

The purpose of this research work is to study the spread of radioactive materials in the air from the start to finish from hypothetical act of explosions of radiological dispersion devices in order to evaluate doses to the unshielded public. Emergency response plans will be offered in order to mitigate and control the studied hypothetical situations.

Objective

The objective of this research work is to perform preliminary evaluation of doses following hypothetical explosions of radiological dispersion devices.

Scope

The scope of this research work is as follows:

1. Study at least 2 potential sites for explosions of radiological dispersion devices.
2. Gather parameters for the above potential sites.
3. Calculate doses for unshielded people in the affected areas using an appropriate computer code.

Research Methodology

The methodologies of this research work are as follows:

1. Study the regulations and practices relating to the calculation of restricted zone and the amount of radiation that has been receive around event areas.

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This research evaluates doses following hypothetical explosions of RDDs, which affect populations in studied areas (Victory Monument and Pattaya city). Evaluated doses are compared with the reference dose rate of The International Commission on Radiological Protection (ICRP).

This research adapted a suitable TEDE levels that may be received by the population as a result of acute radiation exposure from hypothetical explosions of RDDs, which require urgent responses in order to mitigate and control the studied hypothetical situations.

The ICRP has compiled effects of 1-day acute radiation exposure to human (radiation symptom benchmarks) [2], as shown in Table 1.

Table 1 Effects from radiation (symptom benchmarks) from acute radiation exposure

Dose (mSv)	Effects
2.2	Normal radiation level in nature each person receives
5	The maximum threshold allowed for the public
50	The maximum allowed for radiation workers
250	Does not show any symptoms both short and long terms
500	White blood cells will decrease
1,000	Fatigue, nausea and white blood cells will decrease
3,000	Vomiting, fatigue, white blood cells will decrease, hair loss, loss of appetite, dry throat, fever, short life and may die within 3-6 weeks
6,000	Vomiting, diarrhea, fatigue, white blood cells will decrease within 1-2 hours, rapid hair loss, fever and inflammation in the mouth and throat, severe bleeding and may die up to 50% within 2-6 weeks
10,000	Similar to the above symptoms, skin blistering, swelling, hair loss, death within 2-3 weeks

As can be seen in Table 1, as well as the limits in 10 Part 50 of CFR Section 50.67, the acute radiation exposure dose for the unshielded public of 250 mSv (25 Rem) TEDE [3] was chosen as a reference value for the evaluation of the boundaries of the evacuation areas, as people in areas receiving acute radiation dose more than 250 mSv will exhibit radiation sickness symptoms.

The TEDE dose in rem is calculated by the sum of the equivalent dose received from outside the body (Effective Dose Equivalent; D_{EDE}) due to the effects of the radioactive cloud and the equivalent dose received from a radioactive substance into the body by inhalation and collection at various organs within the body for 50 years (Committed Effective Dose Equivalent; D_{CEDE}), as shown in Equation (1) [4].

$$TEDE = D_{EDE} + D_{CEDE} \tag{1}$$

One can calculate the amount of radiation received from outside the body (Effective Dose Equivalent; D_{EDE}) as the result of radioactive cloud from Equation (2) [4].

$$D_{EDE} = \Sigma_i DCF_i \Sigma_j R_{ij} (\chi/Q)_j \tag{2}$$

where D_{EDE} = Effective Dose Equivalent or Dose from radioactive cloud (Rem)
DCF_i = EDE dose conversion factor of radioactive element i (Rem- m^3/Ci-s)
R_{ij} = Amount of radioactive element i released during period j (Ci)
$(\chi/Q)_j$ = Factor of the spread in the atmosphere (Atmospheric dispersion factor) during period j (s/m^3)

The amount of radiation that is absorbed into the body (Inhalation Dose or D_{CEDE} dose) can be calculated from Equation (3) [4].

$$D_{CEDE} = \Sigma_i DCF_i \Sigma_j R_{ij} (BR)_j (\chi/Q)_j \tag{3}$$

where D_{CEDE} = Committed Effective Dose Equivalent (Rem)

DCF_i	= CEDE dose conversion factor of radioactive element i (Rem- m^3/Ci-s)
R_{ij}	= Amount of radioactive element i released during period j (Ci)
$(BR)_j$	= Respiratory rate during period j (m^3/s)
$(\chi/Q)_j$	= Factor of the spread in the atmosphere (Atmospheric dispersion factor) during period j (s/m^3)

2. Study the spread of radioactive substance in the atmosphere.

The spreading behavior of radioactive particles in the atmosphere in the case of accident or terrorism depends on the χ/Q factor (atmospheric dispersion factor) [4], which is required to calculate the quantity and the danger from the spread of radioactive particles from the beginning to the end for effective control and mitigation of the situation.

Calculation is based on the assumption that the spread of radioactive material particles in the air behaves like a smoke plume, which is distributed vertically and horizontally in the form of Gaussian distribution [5]. There is a maximum concentration at the center of the plume (plume centerline), and the distribution of the plume depends on many factors such as wind speed, wind direction, temperature, atmospheric stability and etc.

Gaussian distribution is a mathematical model to predict the concentration of pollutants in the direction of the wind (x-axis) from the point of origin, having the highest concentration at the center of the plume. The concentration also depends on the distribution of the wind direction in the transverse (y-axis) and vertical (z-axis) directions. Normally, when the plume is discharged from the release point, it will initially be floating up high in the air due to heat and exit velocity and subsequently move in the direction of the x-axis by the result of convection. It will then spread out in the directions of the y-axis and z-axis due to diffusion. The result of diffusion process is shown in Figure 1 below.

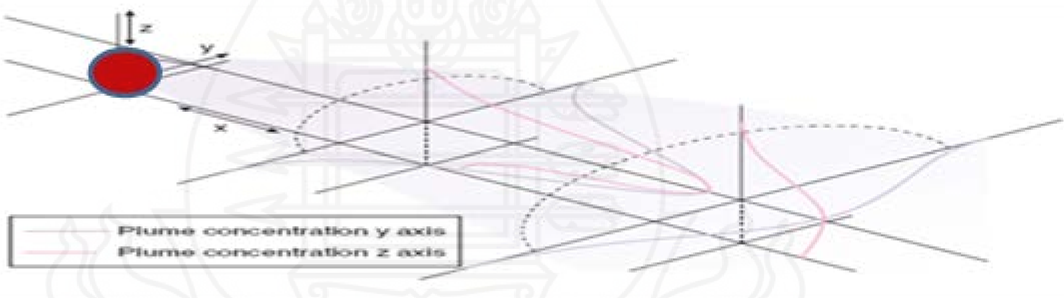


Figure 1 Distribution of particles from the source according to the Gaussian distribution

For this research, the Hotspot health physics computer program (HotSpot program) was applied for the simulation of the Gaussian distribution of the plume as well as the spreading behavior of radioactive particles in the atmosphere in the case of explosions of radiological dispersion devices.

Hotspot was developed by the National Atmospheric Release Advisory Center (NARAC) which is a part of the United States Department of Energy (DOE) that used dose conversion factors from FGR No.11 and 12. Equation (4) shows the governing formula that Hotspot uses to calculate the dose.

$$\chi(x,y,z,H)=\frac{Q}{2\pi u\sigma_y\sigma_z}\left\{\exp\left[-\left(\frac{y^2}{2\sigma_y^2}+\frac{(z+H)^2}{2\sigma_z^2}\right)\right]+\exp\left[-\left(\frac{y^2}{2\sigma_y^2}+\frac{(z-H)^2}{2\sigma_z^2}\right)\right]\right\}\exp\left[-\frac{\lambda x}{u}\right]DF(x) \quad (4)$$

where	(x,y,z)	= Coordinate to calculate concentration (m)
	χ	= Concentration of radioactive materials (Ci/m^3)
	Q	= Release rate (Ci/s)
	H	= Release height (h) + Plume rise (Δh)

u = Wind speed at the release point (m/s)
σ_y = Horizontal diffusion coefficient or y-axis
σ_z = Vertical diffusion coefficient or z-axis
λ = Radioactive decay constant
DF(x) = Plume depletion factor

There are many kinds of radionuclides that can be used in several fields in Thailand. Some of them are the potential isotopes used in RDDs (e.g., Americium-241, Californium-252, Cesium-137, Cobalt-60, Iridium-192, Plutonium-238, Polonium-210, Radium-226 and Strontium-90) [6]. For this research, Cobalt-60, Cesium-137 and Iridium-192 were chosen for evaluation.

The reason for choosing these three high-energy gamma-emitting radioisotopes is because they are used in several fields in Thailand such as industry, hospitalization, agriculture, environment, education and research. Because of their availability in several fields, they could be potential targets for theft. Moreover, the long half lives of Cobalt-60 (5.27 years) and Cesium-137 (30 years) and the medium half-life of Iridium-192 (73.83 days) make them suitable for a dirty bomb because they can contaminate the affected area for a long time.

Table 2 Properties of radionuclides chosen for this research

Isotope	Half-Life (years)	Emitted radiation
Cobalt-60	5.27	β, γ
Cesium-137	30	β, γ
Iridium-192	0.2 (73.83 d)	β, γ

3. Select potential sites for hypothetical explosions of radiological dispersion devices in Thailand using data from related agencies.

For this research, 2 potential sites (Victory Monument and Pattaya city) were chosen as the areas for hypothetical explosions of RDDs because they have high population density and are the centers for tourists, community, business and etc. These areas are very prime for acts of terrorism.

4. Select the appropriate computer code and study how to use it.

The HotSpot program [7] was designed to assist during radiation emergency events because it can evaluate radiation doses rapidly, facilitating quick emergency planning during radiological emergencies. For this research it was adopted for the evaluation of the boundaries of the distance to be affected and safe areas from hypothetical explosions of RDDs.

5. Collect and analyze meteorological data from ground stations in each potential site.

After potential sites were selected, data in each site were collected and analyzed as follows:

5.1 Collect and analyze meteorological data

In the atmosphere, there is a combination of atmospheric stability. Atmospheric stability class is defined according to 5 lapse rates (unstable, neutral, stable, isothermal and inversion) [8] as shown in Figure 2. HotSpot allows users to explicitly select the atmospheric stability class, or the program can evaluate the stability class according to the data observed in studied areas which includes wind speed, sun position and time of the day as shown in Table 3.

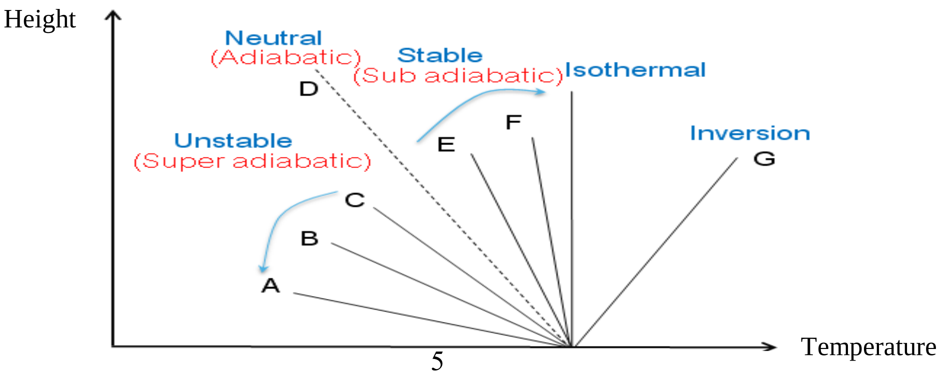


Figure 2 Types of atmospheric stability

Table 3 Atmospheric stability class according to atmospheric condition

Ground wind speed (m/s)	Sun high in sky	Sun low in sky or cloudy	Night time
< 2	A	B	F
2 - 3	A	C	E
3 - 4	B	C	D
4 - 6	C	D	D
> 6	C	D	D

Pasquill stability types:
A: Extremely Unstable
B: Moderately Unstable
C: Slightly Unstable
D: Neutral
E: Slightly Stable
F: Moderately Stable

For this research, the most conservative condition resulting in the largest spead of the radioactive material was assumed. The deposition velocity was set to 0 and the atmospheric stability class was F. The plume travel distances for stability class F was greater than for stability classes A - E.

In categorizing metrological data (wind direction and wind speed), it could be done by collecting metrological data in each month for 1 year, finding the average for the year for the percentage of each range and then presented the meteorological data, the wind rose map of a particular location gives information on the frequency of each wind speed range and direction, as shown in Figure 3.

Pattaya:

Analysis of the meteorological data from 1995-2014 (20 years) into wind rose map at Pattaya Meteorological Station revealed that the wind speed of 4-10 knots (3.0-5.0 m/s) blowing from SSW and NE directions occurred at the highest frequency.

Victory Monument:

Analysis of the meteorological data from 1995-2014 (20 years) into wind rose map at Bangkok Meteorological Station (Queen Sirikit National Convention Centre) revealed that the wind speed of 1-6 knots (1.5-3.0 m/s) blowing from S and E directions occurred at the highest frequency.

Site Name: Pattaya
Pasquill Stability Class: F
period of record: January: 1995 - 2014

Wind Direction	The percentage of wind speed (knots)							
	<1	1-3	4-6	7-10	11-16	17-21	22+	Total
N		0.40	1.05	0.67	0.38	0.03	0.00	2.53
NNE		0.48	2.37	2.82	2.12	0.48	0.03	8.30
NE		0.27	2.93	4.14	2.85	0.62	0.27	11.08
ENE		0.32	1.85	1.94	1.13	0.24	0.05	5.53
E		0.67	1.13	0.65	0.05	0.00	0.00	2.50
ESE		0.22	0.78	0.24	0.11	0.00	0.00	1.35
SE		0.05	0.03	0.03	0.00	0.00	0.00	0.11
SSE		0.46	0.59	0.30	0.11	0.00	0.00	1.46
S		0.89	2.26	0.99	0.16	0.03	0.00	4.33
SSW		0.56	2.77	2.10	0.65	0.00	0.00	6.08
SW		0.38	0.89	1.13	0.40	0.08	0.00	2.88
WSW		0.22	2.53	2.31	0.38	0.00	0.00	5.44
W		0.43	2.34	2.23	0.16	0.00	0.05	5.21
WNW		0.30	1.32	1.18	0.27	0.00	0.00	3.07
NW		0.08	0.78	0.65	0.19	0.03	0.00	1.73
NNW		0.08	1.08	1.08	0.32	0.03	0.00	2.59
Total	35.81	5.81	24.70	22.46	9.28	1.54	0.40	64.19

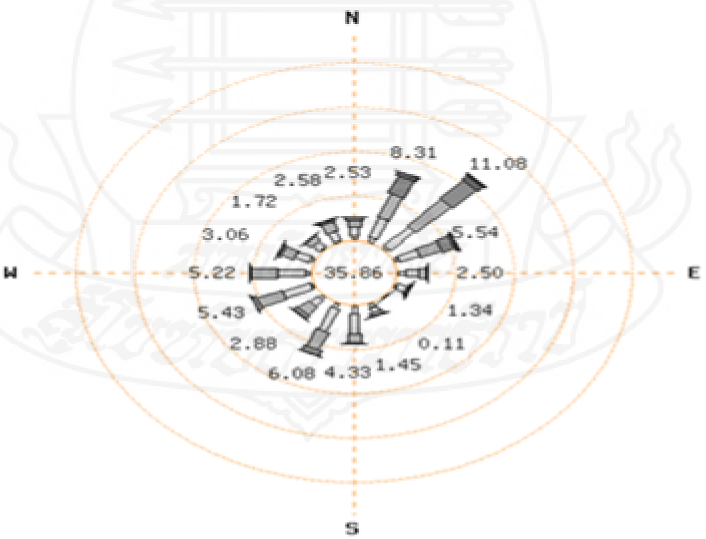


Figure 3 Example of meteorological data and wind rose map

6. Calculate doses for unshielded public in the affected areas using an appropriate computer code.

After potential sites were selected, data in each site were collected and analyzed. Doses for unshielded public in the affected areas were calcuated using HotSpot program. The following illustrates steps for data input:

6.1 Models: Atmospheric dispersion model was choosen with the General Explosion simulation.

6.2 Source Term: The involved radioactive materials data were input into HotSpot program. Co-60, Cs-137 and Ir-192 were considered with the high explosives of 10 and 25 pounds (approximately equal to 4.5 and 11.33 kg, referring to hidden bomb and car bomb, respectively). Materials at risk were 100 Ci and other information were set automatically (e.g., damage ratio, leakpath factor, airborne fraction, respirable fraction and deposition velocity).

6.3 Meteorology: The following meteorological data were input into HotSpot program: wind speed and wind direction from the wind rose map (the highest frequency was chosen), atmospheric stability class F and the wind speed at the 10-meter reference height.

6.4 Receptor: The altitude of 0 m was chosen for the height of the receptor. In this research, it was determined that the receptor height of 0 m will be most affected.

6.5 Setup: details were set as follows:

- Terrain was set as City,
- Respiratory rate was set at 3.5 x 10-4 m3/s in all cases,
- Height reference (Wind Reference Height) was set at 10 meters. This is the height that is used most frequently.
- Estimate the approximate value of the spread of the radioactivity (χ / Q),
- Dose conversion factor (DCF) adopted FGR 11,
- Contour values were set for TEDE of 100, 25 and 0.5 rem, respectively.

6.6 Output:

- The coordinates of locations in the UTM WGS 84 form Pattaya: 47P 1432335N705360E and Victory monument: 47P 1522200N666300E.
- Results of analysis included distance to reveice the highest dose (Maximum Dose Distance), maximum TEDE and the farthest distance of the plume (Exceeds dose out to). The Inner, Middle and Outer TEDE contours were set equal to 100, 25 and 0.5 rem (1,000 mSv, 250 mSv and 5 mSv), respectively.
- Results were saved as TEDE Contour Lines with the .kml extension, which can be directy displayed in Google Earth, as shown in Figure 4.

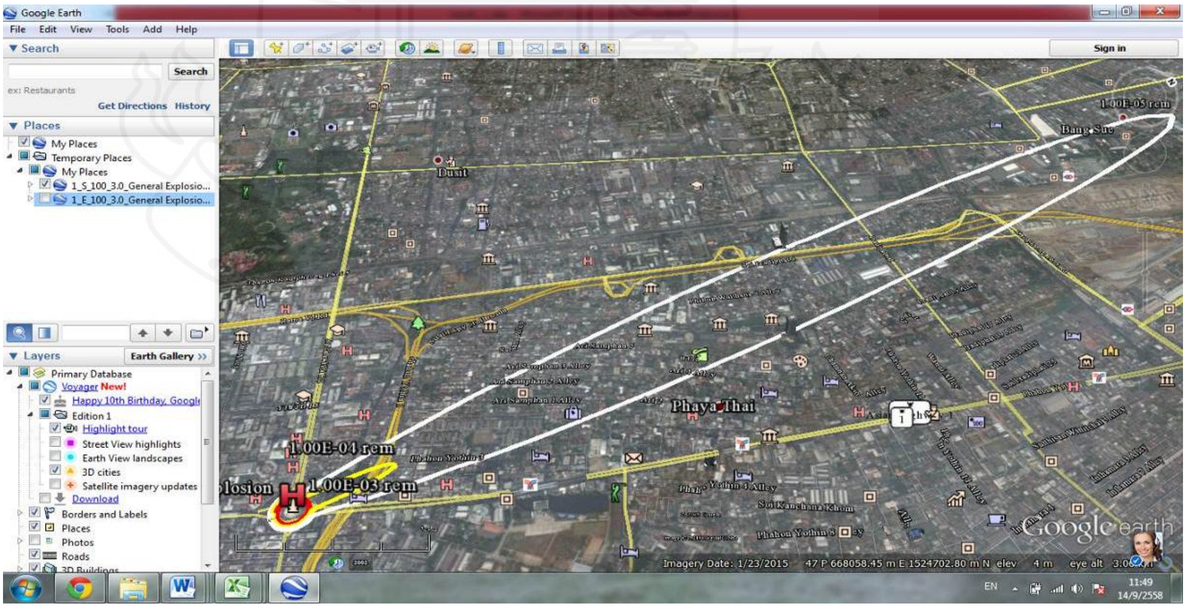
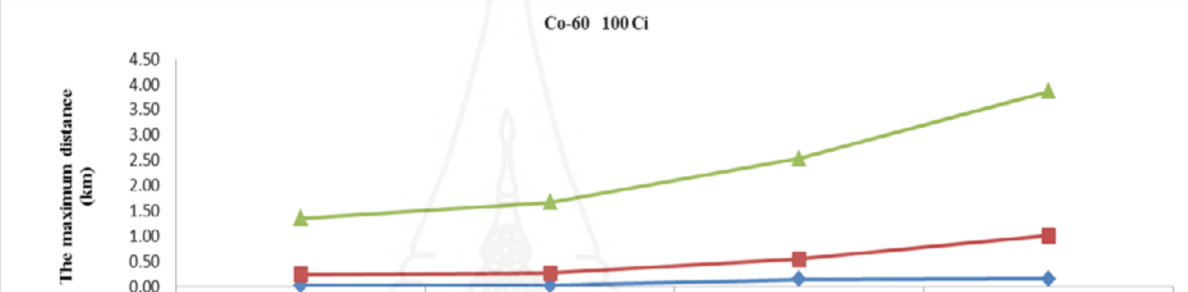


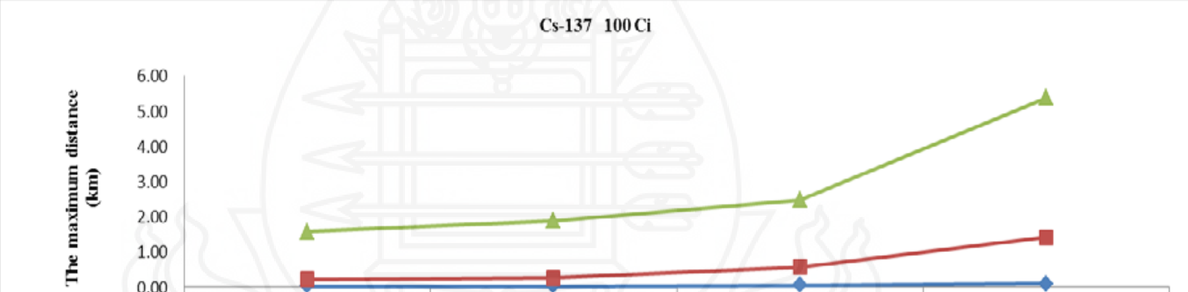
Figure 4 Example of results for TEDE Contour Lines of the effect areas shown in Google Earth program (white line: 5 mSv, yellow line: 250 mSv and red line: 1,000 mSv)

Results

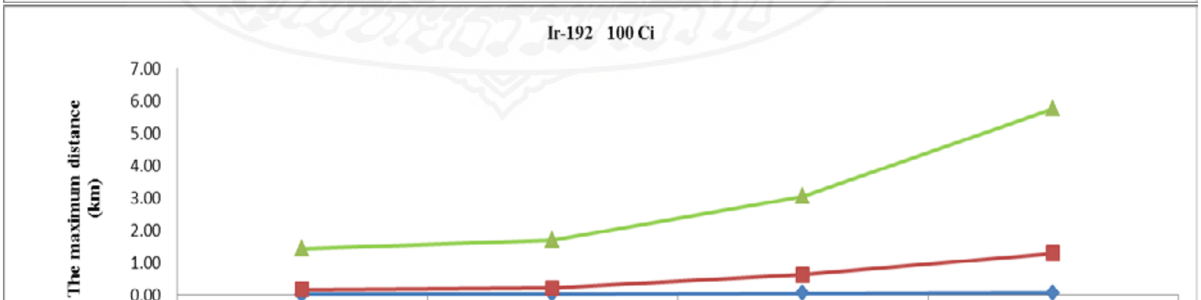
Results show the maximum boundaries of the affected areas following hypothetical explosions of RDDs at the 2 potential sites (Victory Monument and Pattaya city). The results for Victory Monument site and Pattaya city site are summarized in Figures 5 and 6, respectively.



	10lb_1.5m/s	10lb_3.0m/s	25lb_1.5m/s	25lb_3.0m/s
1,000 mSv	0.03	0.03	0.15	0.16
250 mSv	0.24	0.27	0.55	1.01
5 mSv	1.36	1.67	2.54	3.87



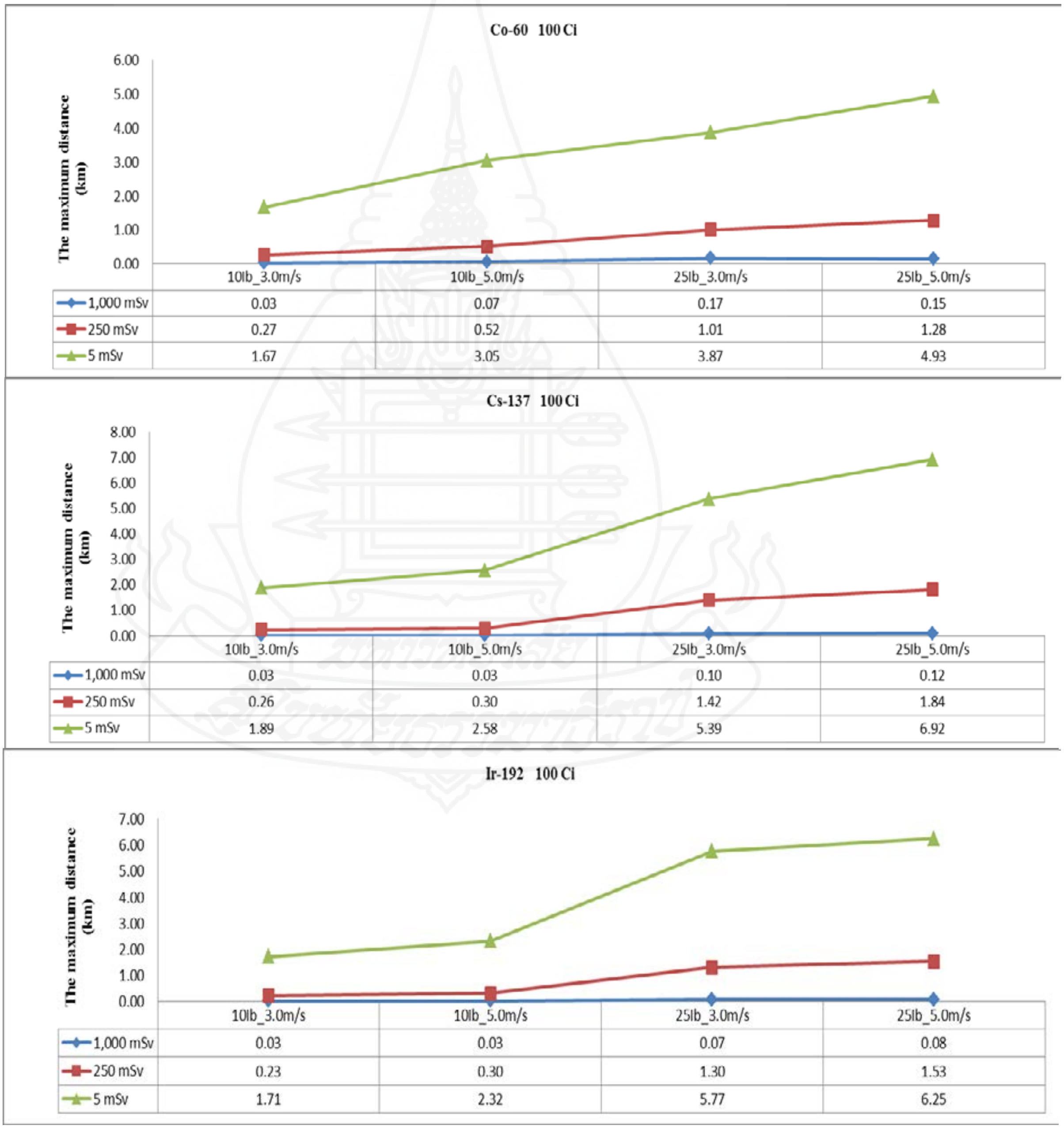
	10lb_1.5m/s	10lb_3.0m/s	25lb_1.5m/s	25lb_3.0m/s
1,000 mSv	0.03	0.03	0.06	0.10
250 mSv	0.22	0.26	0.57	1.42
5 mSv	1.58	1.89	2.48	5.39



	10lb_1.5m/s	10lb_3.0m/s	25lb_1.5m/s	25lb_3.0m/s
1,000 mSv	0.02	0.03	0.06	0.07
250 mSv	0.18	0.23	0.63	1.30
5 mSv	1.45	1.71	3.06	5.77

Figure 5 Maximum boundaries of affected areas for materials at risk of 100 Ci for the three radionuclides (Co-60, Cs-137 and Ir-192) at Victory Monument site

Results revealed that the maximum distances to receive the TEDE equal to 1,000 mSv for the Victory Monument site of the three radionuclides (Co-60, Cs-137 and Ir-192) were 0.16, 0.10 and 0.07 km, respectively. The maximum distances to receive the TEDE equal to 250 mSv were 1.01, 1.42 and 1.30 km, respectively. The maximum distances to receive the TEDE equal to 5 mSv were 3.87, 5.39 and 5.77 km, respectively.



Co-60 100 Ci

	10lb_3.0m/s	10lb_5.0m/s	25lb_3.0m/s	25lb_5.0m/s
1,000 mSv	0.03	0.07	0.17	0.15
250 mSv	0.27	0.52	1.01	1.28
5 mSv	1.67	3.05	3.87	4.93

Cs-137 100 Ci

	10lb_3.0m/s	10lb_5.0m/s	25lb_3.0m/s	25lb_5.0m/s
1,000 mSv	0.03	0.03	0.10	0.12
250 mSv	0.26	0.30	1.42	1.84
5 mSv	1.89	2.58	5.39	6.92

Ir-192 100 Ci

	10lb_3.0m/s	10lb_5.0m/s	25lb_3.0m/s	25lb_5.0m/s
1,000 mSv	0.03	0.03	0.07	0.08
250 mSv	0.23	0.30	1.30	1.53
5 mSv	1.71	2.32	5.77	6.25

Figure 6 Maximum boundaries of affected areas for materials at risk of 100 Ci for the three radionuclides (Co-60, Cs-137 and Ir-192) at Pattaya city site

Results revealed that the maximum distances to receive the TEDE equal to 1,000 mSv for Pattaya city of the three radionuclides (Co-60, Cs-137 and Ir-192) were 0.15, 0.12 and 0.08 km, respectively. The maximum distances to receive the TEDE equal to 250 mSv were 1.28, 1.84 and 1.53 km, respectively. The maximum distances to receive the TEDE equal to 5 mSv were 4.93, 6.92 and 6.25 km, respectively.

Discussion

From the results presented in Figures 5 and 6, hight wind resulted in greater affected distances. The same trend was observed for the case of explosives – higher explosives resulted in greater affected distances than lower explosives. These findings correspond with expectations as faster wind will blow radioactive materials to a greater distance and as higher explosives mean more radioactive materials being dispersed at the beginning of the postulated RDD explosion.

Following hypothetical explosions of RDDs, HotSpot program provides contour lines corresponding to specified radiation levels. The KMZ or KML output files can be directly displayed on Google Earth for visual presentation as three affected distances (TEDE of 1,000, 250 and 5 mSv). Subsequently, emergency response plans can be prepared and and offered in order to mitigate and control the hypothetical situations.

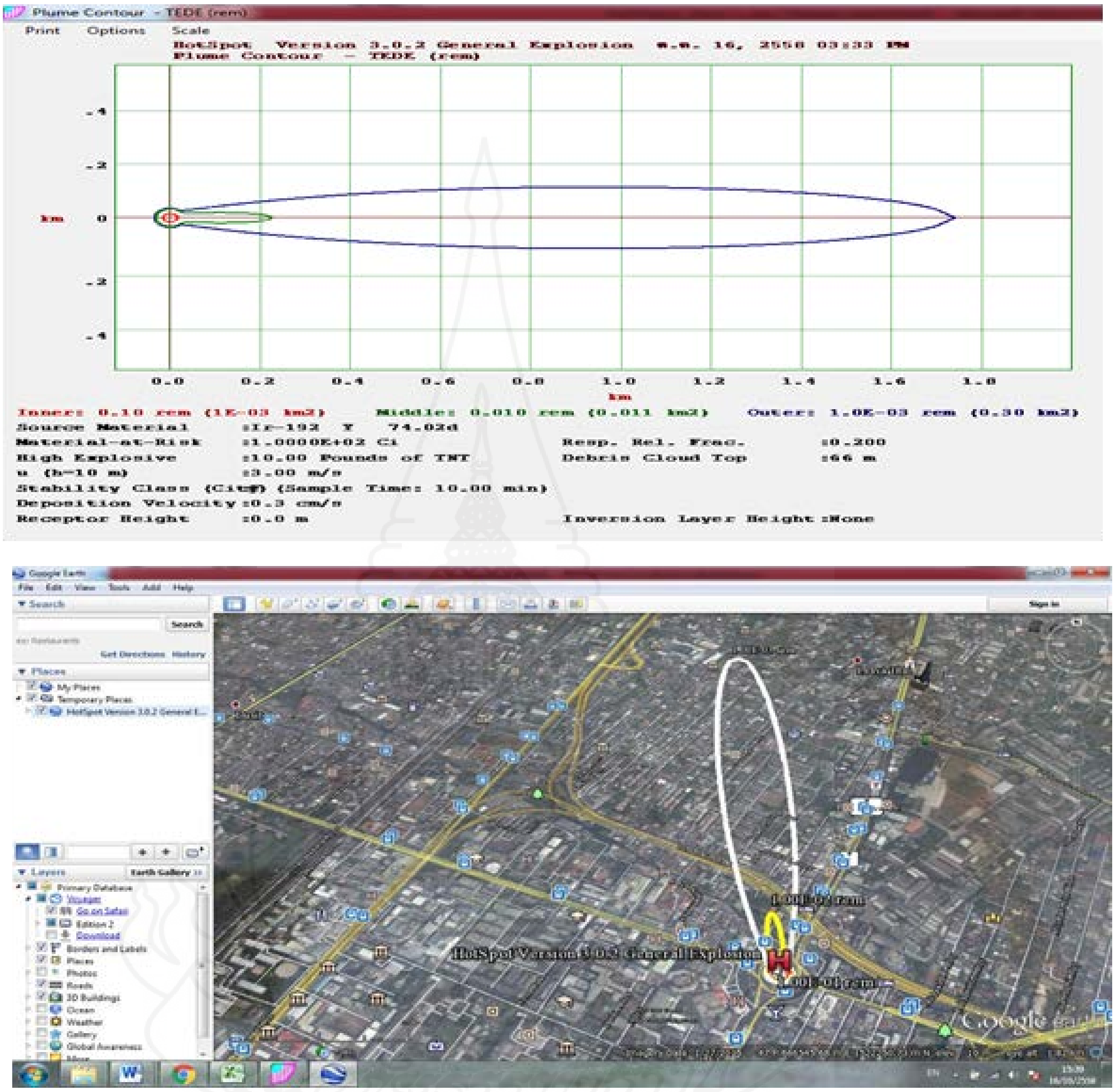


Figure 7 Example of results at Victory Monument with the explosive of 10 pounds (4.5 kg) with 100 Ci Ir-192 with wind speed of 3.0 m/s blowing from the south

For example, for the case of Victory Monument (Figure 5 and 7), if a hypothetical explosion of RDD occurred with the explosive of 10 pounds (4.5 kg) of 100 Ci Ir-192 with the assumed wind speed of 1-6 knots (1.5-3.0 m/s), people who stay at less than 0.03 km from the center of the explosion will receive a TEDE of 1,000 mSv or more. This would result in the decrease in the number of white blood cells and possibly result in deaths. Immediate medical assistance must be provided to victims to heal physical injuries from the explosive and radiation sickness. People who stay at 0.03 - 0.23 km from the center of the exploiton, especially in the S and E wind directions, must be evacuated immediately to avoid receiving a TEDE of 250 mSv or more to avoid radiation sickness. People who stay at more than 0.23 km from the center of the exploiton could still stay in the area because there will be no symptoms in both short and long terms.

Suggestions

A computer program should be developed to analyze the characteristics of more complex plumes, such as those originated in the city ares with numerous buildings, in order to realistically take into account complex city terrains. The program must also be designed in accordance with the ICRP Publication 103.

Although explosions of RDDs cannot cause mass casualties compared to a nuclear explosion, all or most immediate fatalities or injuries to persons will probably be due to the force of explosion. RDDs may affect small, localized areas (e.g., a street, single building, or city block) or large areas up to several square kilometers, depending on the nature of the dispersion and the amount and type of radioactive material. Other hazards may also be present (e.g., fire, smoke, shock, shrapnel from an explosion or chemicals). Furthermore, health and environmental consequences from RDDs will depend on the design of the device, type and quantity of radioactive material and the pattern of dispersion following the release. While large numbers of people in a densely populated area around the explosion of a RDD might become contaminated and require radioactive decontamination of persons and areas affected, few, if any, will be contaminated to a level requiring medical treatment.

After the knowledge on the resulting spread of radioactive materials following hypothetical explosions of RDDs from the beginning to the end of accidents was gained, emergency evacuation plans must be offered by authority in the affected areas. Public health authorities will have to assess the persons who were close to the point of release for the needed medical intervention when receiving an acute radiation dose of more than 250 mSv in order to control and mitigate the situation.

In an RDD event, the radiation will likely be coming from the ground and other horizontal surfaces where the radioactive materials will have been distributed by the blast. One must exercise the 3 golden rules for radiation protection: reduce time, increase distance, and use shielding.

- Time: The less time you spend near the radiation source, the lower your exposure will be.
- Distance: The greater your distance from the source, the less your exposure will be. Radiation exposure decreases with distance according to the inversed square law.
- Shielding: External exposure to radiation can be partially blocked by the use of shielding. Traditionally, shielding is made of lead or concrete. However, staying behind vehicles, buildings, or other objects will also decrease exposure.

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