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A Comparative Study of Assessing the Release of Radioactive Materials in a Nuclear Emergency Using Different Atmospheric Dispersion Models

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1. Introduction

Atmospheric dispersion study is very important in Level 3 PSA. This is because it has so many uncertainties and is affected by different parameters. Therefore, it is important to study the dispersion models in order to estimate accurately the off-site radiological consequences [1]. There are a lot of software used to simulate off-site consequences of radioactive material released during the nuclear emergency. Level 3 Probabilistic Safety Assessment (PSA) was prepared to consider the off-site consequences of nuclear power plant accident. Prediction of the dispersion of radioactive materials into environment is very important because it can assist in planning for emergency preparedness and response [2]. When the radioactive materials are release from the nuclear power plant they can contaminate the environment and public through different pathways. A dispersion model is a set of mathematical equation that represents the discharge and dispersion of air contaminants in the atmosphere. It indicates the physics and chemistry that lead the dispersion and transformation of pollutants in the atmosphere. Computer programs are used to solve these mathematical equations, and using the algorithms embedded in it they simulate the dispersion of the released contaminants [3].

The objective of this study is to compare the results of air concentration and ground deposition for ^{137}Cs, ^{133}Xe and ^{131}I from different atmospheric dispersion models. The accident scenario is Long Term Station Blackout (LTSBO) in APR1400. This scenario was simulated by RASCAL code to estimate the amount of radioactive material released of ^{137}Cs, ^{133}Xe and ^{131}I.

2. Analysis and Methods

In this study, we used three software with different dispersion models; the first software is Radiological Consequence Analysis Program (RCAP). It is a new software developed by Korea Atomic Energy Research Institute (KAERI) and the basic physical model for RCAP to evaluate the diffusion and transport of radioactive materials in the atmosphere and deposition on the surface is the Gaussian plume segment model. The second software is Radiological Assessment System for Consequence Analysis (RASCAL). It developed by the U.S Nuclear Regulatory Commission (NRC) to be used by emergency responders. The atmospheric transport and dispersion model for RASCAL is Gaussian puff model. The last software was used HOTSPOT. It is developed by Lawrence Livermore National Laboratory's National Atmospheric Release Advisory Center (NARAC) and its model is Gaussian plume model (time independent).

2.1. Meteorological data

The meteorological data includes wind direction, wind speed (m/s), stability class (A ~ G), precipitation (mm/hr.), and mixing height (m) was collected from the Korean Meteorological Agency (KMA) from 1-Jan-2010 to 1-Jan -2021 (11 years). We used the median values over 11 years of 2010 and 2021; it is more statistically significant than the average. Figure 1 shows the medians values of wind speed, temperature and atmospheric pressure.

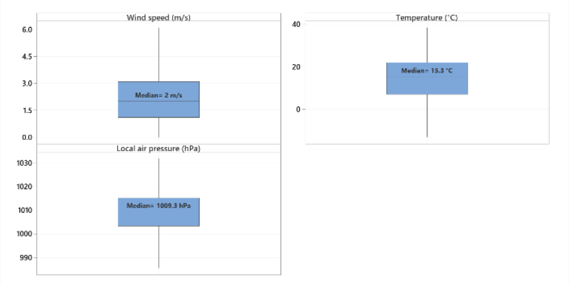

Figure 1. Boxplot of wind speed, temperature and atmospheric pressure from 2010 to 2021

Wind direction determined by wind rose. Figure 2 shows predominate wind direction in Ulsan city. The North-northwest is predominate wind direction which is used in this study. The stability class used in this study is B. Stability class B is the most frequently one from 2010 to 2021. The release height is 60 m for APR 1400 [4]. The deposition velocity for particles regarding to NUREG-1940 is 0.0064 m/s. this value was estimated regarding to stability class (B) and wind speed (2 m/s).

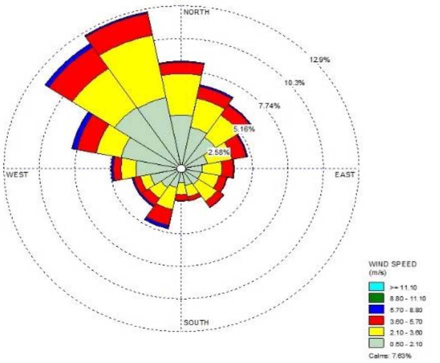

Figure 2. Wind rose diagram from 2010 to 2021

2.2 Source term

The selected scenario for this study is Core damage scenario. An offsite event occurred, lead to loss of offsite power (LOOP) and reactor trip at 1:00, 1-Jan-2020. The emergency core cooling system not activated. Even though, Reactor cooling was continued by natural convection for a period of 8 hours after shutdown. The release started at 9:00, 1-Jan-2020 and continue for 24 hours.

Table 1 shows the activity of ^{137}Cs, ^{133}Xe and ^{131}I that released to the atmosphere. These radionuclides are representative for radionuclides groups that released. This source term was used as input for the three software.

Table 1. Source terms used in this study

Isotopes	Groups	Activity (Bq)
^{131}I	Halogen	7.40E+14
^{133}Xe	Noble gas	1.63E+15
^{137}Cs	Alkali metal	5.92E+13

2.3 Dispersion Models

2.3.1. HOTSPOT

Hotspot program provides a first order approximation of radiation effects due to the atmospheric release of radioactive substances. HOTSPOT uses Gaussian plume model. Equation 1 determine the time-integrated atmospheric concentration of a gas or an aerosol at any point in space.

$$C(x,y,z)=\frac{Q}{2\pi\sigma_y(x)\sigma_z u}\times\Big(exp\Big\{-\frac{1}{2}\Big[\frac{z-H}{\sigma_z}\Big]^2\Big\}+exp\Big\{-\frac{1}{2}\Big[\frac{z\mp H}{\sigma_z}\Big]^2\Big\}\Big)\ (\exp(\frac{\lambda_x}{u}) \qquad (1)$$

Where C is time-integrated atmospheric concentration (Bq-s)/ (m^3), Q is source term (Bq), H is effective release height (m), λ is radioactive decay constant (s^{-1}), x is downwind distance (m), y is crosswind distance (m), z is vertical axis distance (m), σ_y is standard deviation of the integrated concentration distribution in the crosswind direction (m), σ_z is standard deviation of the integrated concentration distribution in the vertical direction (m) and u is average wind speed at the effective release height. This program is designed for short-range (less than 10 km), and short-term (less than a few hours) predictions.

2.3.2. RCAP

RCAP is new software developed by the Korea Atomic Energy Research Institute (KAERI) to perform Level 3 probabilistic safety assessments (PSAs), which estimate the off-site consequences of nuclear power plant accidents. RCAP assesses the impacts of the release of radioactive materials to the environment. The basic physical model of RCAP for evaluating the diffusion and transport of radioactive materials in the atmosphere and their deposition on surfaces is the Gaussian plume segment model. Equation 2 used in RCAP to calculate the plume centerline air concentration and ground level concentration from the time plume segment is released until the vertical distribution segment becomes uniform with inversion layer (mixing height).

$$\begin{aligned}
&C(x,y,z)\\
&=\frac{Q}{2\pi\sigma_y(x)\sigma_z u}\\
&\times\left(exp\left\{-\frac{1}{2}\left[\frac{z-H}{\sigma_z}\right]^2\right\}+exp\left\{-\frac{1}{2}\left[\frac{z+H}{\sigma_z}\right]^2\right\}\right)\\
&+\sum_{n=1}^{n}\left(exp\left\{-\frac{1}{2}\left[\frac{z-H-2nl}{\sigma_z}\right]^2\right\}\right.\\
&\left.+\ exp\left\{-\frac{1}{2}\left[\frac{z+H-2nl}{\sigma_z}\right]^2\right\}\right)\\
&+exp\left\{-\frac{1}{2}\left[\frac{z-H+2nl}{\sigma_z}\right]^2\right\}\\
&+\ exp\left\{-\frac{1}{2}\left[\frac{z+H+2nl}{\sigma_z}\right]^2\right\})
\end{aligned} \qquad (2)$$

Where C is time-integrated atmospheric concentration (Bq-s)/ (m^3), Q is source term (Bq), H is effective release height (m), λ is radioactive decay constant (s^{-1}), x is downwind distance (m), y is crosswind distance (m), z is vertical axis distance (m), σ_y is standard deviation of the integrated concentration distribution in the crosswind direction (m), σ_z is standard deviation of the integrated concentration distribution in the vertical direction (m), u is average wind speed at the effective release height and L is height of inversion layer (m).

2.3.3. RASCAL

RASCAL is a computer software tool developed by the U.S Nuclear Regulatory Commission (NRC) to be used by emergency responders for dose evaluation and consequences projection during radiological emergencies. Several changes of RASCAL versions has been done to account for new features and any shortcomings in previous versions(s). RASCAL version 4.3 account for lessons learned by NRC staff in response to nuclear accident at Fukushima Daiichi nuclear power plant in March 11, 2011. RASCAL uses Gaussian puff model. Using the principle of superposition, the one-dimensional solution of the diffusion equation can be expanded to three dimensions to obtain the basic Gaussian puff model. Equation 3 is a basic version of the puff model in RASCAL.

$$.\quad \frac{X(x,y,z)}{Q}=\frac{1}{(2\pi)^{\frac{3}{2}}\sigma_x\sigma_y\sigma_z}exp\left[-\frac{1}{2}\left(\frac{x-x_0}{\sigma_x}\right)^2\right]\times exp\left[-\frac{1}{2}\left(\frac{y-y_0}{\sigma_y}\right)^2\right]\times exp\left[-\frac{1}{2}\left(\frac{z-z_0}{\sigma_z}\right)^2\right] \qquad (3)$$

Where χ is the concentration (Bq/m^3 or g/m^3), Q is the amount of material unconfined (Bq or g) and σ is the dispersion parameter (m) which is a function of distance from the release point. When joint with a transport mechanism to passage the center of the puff (x_o, y_o, z_o).

3. Results and Discussion

In this study, we are concerned about comparing the amount of ^{137}Cs and ^{131}I deposit on the ground with distance from the three codes. In addition, comparing the concentration of ^{131}I and ^{133}Xe on the air with distance from the three codes.

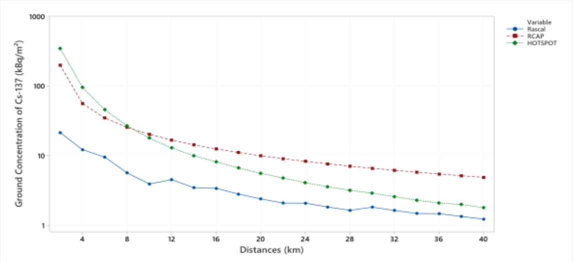

Figure 3. Ground deposition of ^{137}Cs with downwind distance

Figure 3 and figure 4 show the ground deposition for ^{137}Cs and ^{131}I respectively against downwind distance calculated using the three computer codes namely HOTSPOT, RASCAL and RCAP. Among the three codes HOTSPOT is the highest curve in the short distance but in long distances RCAP is the highest curve. The lowest curve represent RASCAL. RASCAL assumes the Gaussian Puff. The Gaussian Puff consider the varying wind speed hence the puff model result in relatively real estimates than plume model.

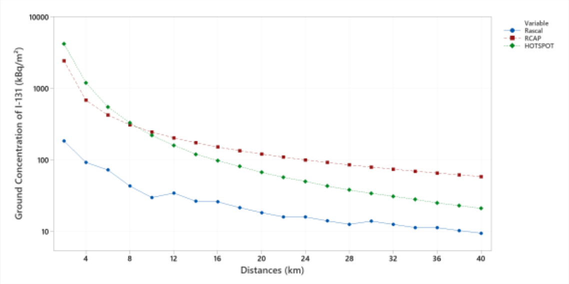

Figure 4. Ground deposition of ^{131}I with downwind distance

Figure 5 and figure 6 show the airborne concentrations for ^{133}Xe and ^{131}I respectively against downwind distance calculated using the three computer codes namely HOTSPOT, RASCAL and RCAP. Among the three codes, HOTSPOT is the highest curve in the short again. While in long distances, the HOTSPOT curve is degraded quickly and the highest curve is RCAP. In the long distances, the values of three codes are close.

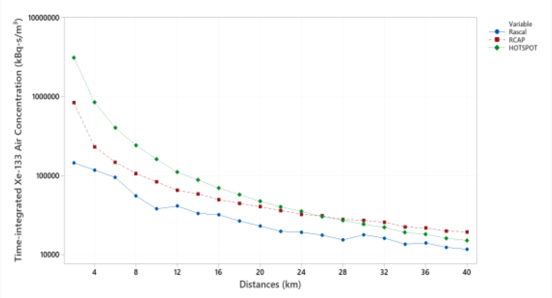

Figure 5. Air concentration of ^{133}Xe with downwind distance

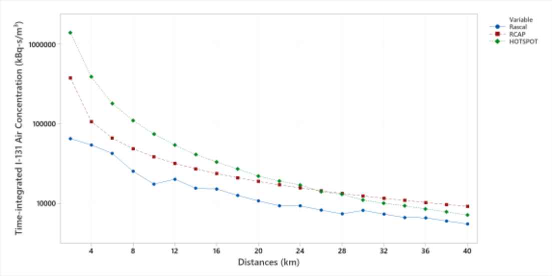

Figure 6. Air concentration of ^{131}I with downwind distance

4. Conclusion

The airborne concentration for ^{133}Xe and ^{131}I in addition to ground deposition for ^{137}Cs and ^{131}I were calculated by three different computer code with different dispersion model to verify the result of calculation. It was also found that, generally the HOTSPOT computer code estimated the higher values compared to the rest of the codes followed by RASCAL, RCAP in the mentioned order. HOTSPOT codes are a conservative (estimated radiation dose is usually greater) estimation of the radiation effects associated with the atmospheric release of radioactive materials.

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