DEVELOPMENT OF A RAPID PREDICTION TECHNOLOGY FOR EMERGENCY PROTECTION AREA AT NUCLEAR ACCIDENTS

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Abstract: The authors have developed a rapid prediction model R-cubic that can predict both a release amount of radioactive materials and a probable protective action area against radiological disasters when nuclear accident occurs. R-Cubic predicts conservative release amounts to MAAP4 analysis. Dose predicted by R-cubic is compatible to SPEEDI within a factor of two. R-cubic has a capability to predict conservative radiation protection area by inputting probable range of meteorological conditions.

Key words: *nuclear emergency preparedness, radioactivity release rate, dose prediction, complex terrain, PIC model.*

INTRODUCTION

When a nuclear accident occurs, it is necessary to perform protective action against the radiation disasters. Under normal situation, the emergency planning must be prepared within the Urgent Protective Action Planning Zone (UPZ) or the Emergency Planning Zone (EPZ). When a real accident occurs at a nuclear power plant, the protective action may be performed within the Precautionary Action Zone (PAZ) described in GS-R-2 (2002).

In Japan, the nuclear emergency protective action area is determined based on the predictive individual dose without protective action. The combined system of ERSS (Emergency Response Supporting System) and SPEEDI (System for Prediction of Emergency Environmental Dose) is the Japanese official system for this purpose. According to the experiences of the official emergency drills performed in Japan, a few hours seem to be required to determine the protective action area in the current situation. Since the ERSS simulates an accident consequence in the nuclear power plant, it requires detailed input data and a relatively long running time for the calculation.

The authors have developed R-cubic (Radioactive release, Radiation dose and Radiological protection area prediction system) as a simplified alternative candidate to predict a radiation protective action area. R-cubic can be applied in advance of the release of a large amount of radioactive materials and can complete one day dose estimation within 10 minutes by using a Pentium 4 (3GHz) PC from accident information input. R-cubic consists of two sub models. The first FPRA (Fission Product Release Amount) model predicts a release amount of radioactive materials into the atmospheric environment. The second AREDES (Atmospheric Release Emergency Dose Estimation System) model predicts a dose distribution. AREDES is composed of a diagnostic wind field model, a particle-in-cell (PIC) diffusion model and an external/internal dose model. This paper reports the model evaluation results of FPRA and AREDES.

Generally predicted dose distribution depends on the predicted wind fields. It is popular to predict wind fields around the accident site by an atmospheric dynamic model such as MM5 with the forecasted meteorological data such as ECMWF or GPV (Grid Point Value). However, there are some cases that the predicted wind fields are not correct. Even if the predicted wind field is correct, a diffusion calculation may not cover the crosswind width of diffused matter. R-cubic has another dose calculation sub model, so-called G-dose. G-dose has the capability to predict the possible maximum width of a protective action area based on the simple Gaussian plume formula and numerically integrated external dose by inputting any presumed range of wind direction, wind speed and atmospheric stability.

METHODOLOGY

Procedure of R-cubic calculation is shown in Figure 1. FPRA calculates the first four processes shown in Figure 1: (1) inventory of accumulated radioactive materials due to reactor operation, (2) emission of radioactive materials from damaged core to the containment vessel (CV), (3) removal of emitted material in CV, and (4) leakage of radioactive materials into the atmosphere. AREDES and G-dose calculate the next two processes: (5) atmospheric advection and diffusion of released materials, and (6) radiation doses of public and employees. Based on the predicted dose distribution, the protective action area is determined according to the Japanese guideline of the protective action criteria for nuclear accidents.

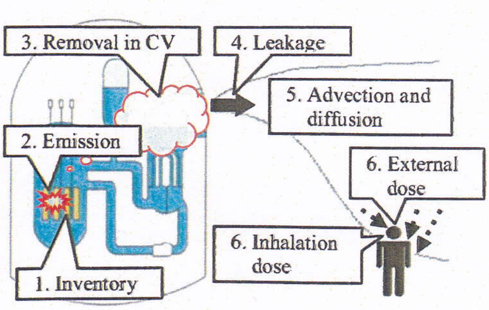


Figure 1. Procedure to predict release amount and dose

The Prediction Method of FPRA model

FPRA sub model is a simplified homogeneous mixture model of radioactive materials. The detailed analysis of accident consequences by the severe accident analysis code of MAAP4, that is implemented in ERSS, showed that the release amount of a radioactive material strongly depends on: (a) radioactive decay, (b) confined time of the radioactive material in CV, (c) action status of the removal system such as a spray for particular materials and (d) a leakage area of CV. Based on this analysis, FPRA calculates the release amount of radioactive material to the atmosphere as a multiplication of an amount of radioactive material in the homogeneous mixture system (HMS), a total removal effect both in HMS and in the leakage process, and a leak rate from HMS. The amount of the radioactive material in HMS is calculated as a difference of a multiplication of inventory and the supply rate to HMS, and a multiplication of the amount and the leak rate from HMS.

The validation of FPRA model

Yoshida (2007) reported the results of comparison of the predicted release amount of radioactivity by FPRA with the release amount calculated by MAAP4 for the total of 216 cases. The analysed targets were 24 accidents scenarios for a dry CV three loop PWR and an ice condenser CV four loop PWR. For each scenario, three assumed sizes of a leakage area and three starting timings of the prediction were applied. Results are shown in Figure 2 and Figure 3.

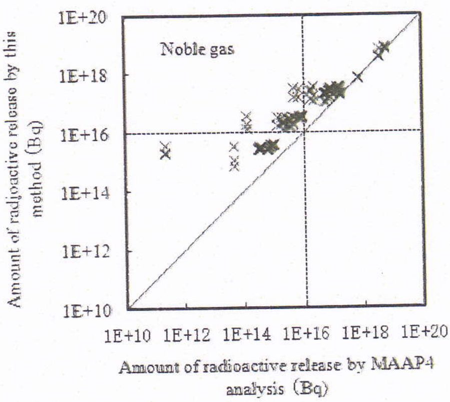


Figure 2. Comparison of noble gas 0.5MeV equivalent release release amounts between MAAP4 and this model

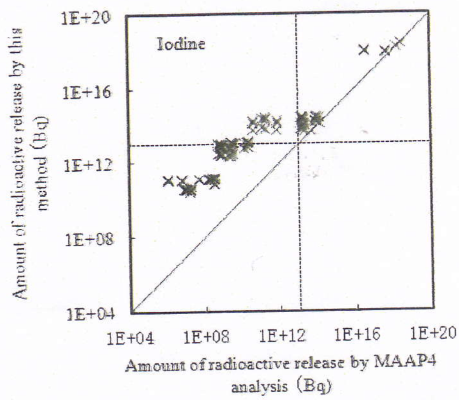


Figure 3. Comparison of iodine-131 equivalent amounts between MAAP4 and this model

Figure 2 and Figure 3 show that FPRA estimates larger amounts of the released activity than MAAP4 for both noble gas and iodine. And difference becomes smaller as the release amount increases. When the release amount of noble gas exceeds about 10^{16} Bq, the external dose around site boundary may exceed the threshold value of 10mSv for the public protective action for target sites. When the release amount of the radioactive iodine exceeds 10^{13} Bq, the thyroid dose may exceed the threshold value of 100mSv. In these regions, difference becomes smaller. Thus it is reasonable to use FPRA as the alternative of MAAP4 to predict release amounts of radioactivity for determining the public protective action area.

The Prediction Method of a Dose Protective Action Area

(1) AREDES model

AREDES model was originally developed in 1983 under the auspices of Japanese ten electric companies for the use in an emergency response system. An example of the on-line real-time emergency response system composed of AREDES with a prognostic wind field model is described in Suzuki, et al. (2000).

(a) Diagnostic wind field model

Observed wind speed data and wind direction data are interpolated and extrapolated in the calculation domain to get an initial conditions of wind field $\mathbf{U_0}$ (U_0,V_0,W_0). Then minimal modification is conducted by a variation method to get mass-consistent wind field $\mathbf{U}$ (U, V, W) according to equations (1) and (2).

$$U = U_0 + \frac{1}{2\alpha_1^2}\frac{\partial\lambda}{\partial x} \quad V = V_0 + \frac{1}{2\alpha_1^2}\frac{\partial\lambda}{\partial y} \quad W = W_0 + \frac{1}{2\alpha_2^2}\frac{\partial\lambda}{\partial z} \tag{1}$$

$$\frac{\partial^2\lambda}{\partial x^2} + \frac{\partial^2\lambda}{\partial y^2} + \left(\frac{\alpha_1^2}{\alpha_2^2}\right)\frac{\partial^2\lambda}{\partial z^2} = -2\alpha_1^2\left(\frac{\partial U_0}{\partial x} + \frac{\partial V_0}{\partial y} + \frac{\partial W_0}{\partial z}\right) \tag{2}$$

λ in Equation (1) is solved by ILUCR method with the boundary conditions of " λ =0" at the free boundary surfaces, and $n_x \cdot \frac{\partial^2\lambda}{\partial x^2} + n_y \cdot \frac{\partial^2\lambda}{\partial y^2} + \left(\frac{\alpha_1^2}{\alpha_2^2}\right) \cdot n_z \cdot \frac{\partial^2\lambda}{\partial z^2} = -2\alpha_1^2 n \cdot U_0$ at the terrain surface.

Observed data of wind velocity and atmospheric stability available at the accident site is adequate for this model. In addition, the running time for the calculation of this model is short. Typically running time is within one second.

(b) Diffusion model
Basic equation (3) is derived from diffusion equation and continuity equation for incompressible atmosphere.

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x}\left[C\left(U-\frac{K_x}{C}\right)\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[C\left(V-\frac{K_y}{C}\right)\frac{\partial C}{\partial y}\right]+\frac{\partial}{\partial z}\left[C\left(W-\frac{K_z}{C}\right)\frac{\partial C}{\partial z}\right]=0 \tag{3}$$

Diffusion coefficient is derived by Taylor's relation from the empirical diffusion parameters. This equation is solved by a PIC methodology with the boundary conditions of a steady concentration flux at free boundaries, and a zero concentration flux at the terrain surface. The effects of radioactive decay, dry deposition, wet deposition, and gravitational fall of particular matters can be considered.

(c) Dose model
An external dose model is the cell dose model. The air absorbed dose rate at the terrain surface is calculated by equation (4) as the sum of contributions from spatial cells indexed by (i, j, k).

$$D(x,y,0)=\sum_{i,j,k}\chi(i,j,k)\cdot D(i,j,k),\quad D(i,j,k)=K_1\cdot E\cdot\mu_a\cdot\iiint_{i,j,k}\frac{e^{-\mu r}}{4\pi r^2}B(\mu r)\chi(x',y',z')dx'dy'dz' \tag{4}$$

The thyroid dose from inhalation of radioactive iodine is calculated by equation (5). Conversion factor K_i and inhalation rate M are referred to ICRP pub.71.

$$H=\Sigma_i(K_i\cdot\chi_i\cdot M\cdot T) \tag{5}$$

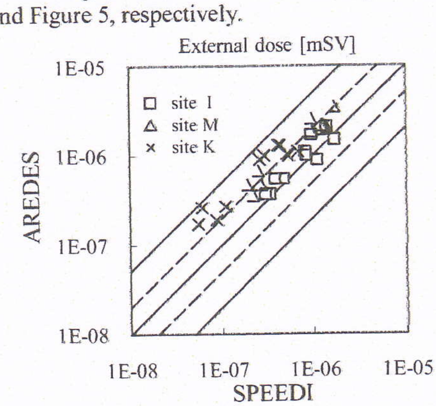
(2) G-dose model
G-dose model calculates the air concentration by the Gaussian concentration formula (6). The external dose at the terrain surface is a numerically integrated value of equation (7). The thyroid dose is calculated by the equation (5).

$$\chi(x,y,z)=\frac{Q}{2\pi\sigma_y\sigma_z U}\cdot\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\cdot\left[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right] \tag{6}$$

$$D(x,y,0)=K_1\cdot E\cdot\mu_a\cdot\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{\infty}\frac{e^{-\mu r}}{4\pi r^2}B(\mu r)\chi(x',y',z')dx'dy'dz' \tag{7}$$

R-cubic accepts any ranges of the input meteorological conditions on wind speed, wind direction and atmospheric stability. G-dose calculates dose at every surface mesh point using all the inputted conditions and presents the dose distribution and the protective action area based on the calculated maximum dose at every mesh point.

The evaluation of AREDES model
AREDES has been evaluated by the comparison with the field tracer experiments and wind tunnel experiments so far. Suzuki, et al. (2000) reported the results for field experiments at Hanford site and San Onofre Nuclear Generating Station that most of the agreements between calculated concentrations and observed concentrations were within factor of 2 for the downwind distance of 0.4km through 7.6km. This report focuses on the comparison of AREDES with SPEEDI. The outline of the results are presented in NUSTEC (2005 & 2006). In this study three sites were selected as the target site.Calculated ratios of the maximum values of external dose and tyroid dose are shown in Figure 4 and Figure 5, respectively.



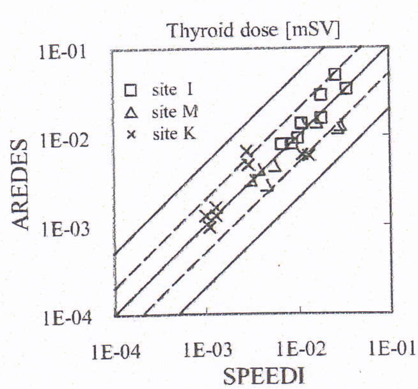


Figure 4. Comparison of maximum effective doses   Figure 5. Comparison of maximum thyroid doses
Solid line, dashed line and dotted line represent factor 1, 2 and 5, respectively.

Two of target sites are PWR sites located beside the sea shore under complex terrain. One is a BWR site located beside the sea shore under flat terrain.The total of 30 cases of simulation calculation, 10 cases of diferent meteorological conditions for each site, were conducted. Simulation conditions were set to be as common as possible for the three sites. In Figure 5, results of 6 cases for atmospheric stability F were omitted, because the thicker concentration sapmling cell height of AREDES at the terrain surface caused an overestimation to SPEEDI when vartical plume width was very narrow and the surface of downwind direction was flat. Omitted values ranged from 1.5 to 10. The ratios of calculated maximum external dose and thyroid dose from AREDES over SPEEDI were from 0.8 to 3.1 and from 0.4 to 1.3, respectively. The mean value and the standard deviation of AREDES/SPEEDI was 2.0 $\pm$0.5. For thyroid dose of AREDES/SPEEDI, it was 1.1$\pm$0.4. It is suggested that the bias of facor 2 for external dose is caused mainly by the difference of dose conversion coeficient from the air absorbed dose to the effective dose. AREDES adopts 1 Sv/Gy. SPEEDI applies a realistic value dependent on the gamma ray energy, that ranges typically from 0.4 Sv/Gy to 0.7 Sv/Gy.

The Comparison of AREDES simulation to Tokai91 field tracer experiment

Comparison of AREDES to one of the Tokai 91 field tracer diffusion experiments was performed. Simulation conditions are listed in Table 1. Vertical wind profiles observed by rawinsonde and Doppler soda were available but neglected, because they may be unavailable at the accident. Results are shown in Figure 7 through Figure 12. Sampling point ID represents downwind direction, such as 3, 11 and 19 represents north, west and south, respectively. Observed and calculated air concentration of the tracer was a day averaged value.

Table 1. Input data for simulations of the Tokai91 field experiment

item	one experiment in Tokai 91 series
Date of Experiment	Oct. 28, 1991 at JAERI Tokai site
Tracer emission	250g of PMCH were emitted from 14:00 to 15:00
Emission Height	41m above terrain
Sampling points	19 points on each of six arcs A, B, C, D, E, F. Samplers were located at every 11.25 degrees apart on each arc. Sampling data were collected at 0:10 once every day.
Downwind Distances of sampling Arcs	arc A: 0.4 km, B: 0.8 km, C: 1.4 km, D: 2.5 km, E: 3.5 km, F: 5.0km
Atmospheric stability	Observed atmospheric stability was D.
Wind Velocity	Wind velocities were observed at heights of 10m and 40m of the tower by ultrasonic anemometer every an hour.
At 10m (dir, ms^{-1})	14:00 (ESE, 1.4) 15:00 (SE, 1.5) 16:00 (SSE, 1.4)
At 40m (dir, ms^{-1})	14:00 (E, 1.9) 15:00 (ESE,1.6) 16:00 (SE, 1.2)
Region of Simulation	12.5km x 12.5km x 500m (mesh size: 250m x 250m x 25m)

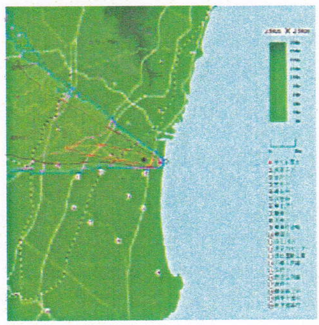


Figure 6. A sample output of AREDES

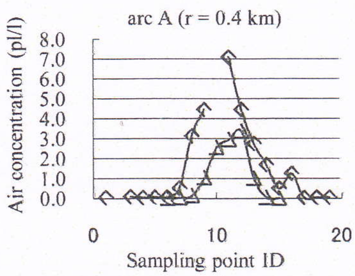


Figure 7. Concentrations on arc A

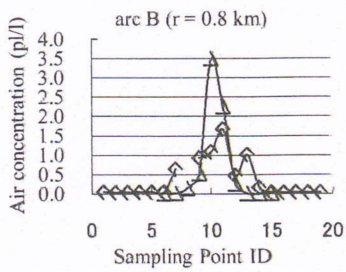


Figure 8. Concentrations on arc B

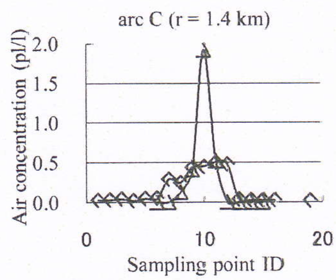


Figure 9. Concentrations on arc C

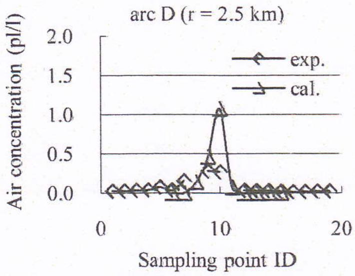


Figure 10. Concentrations on arc D

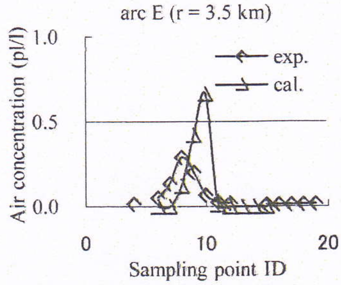


Figure 11. Concentrations on arc E

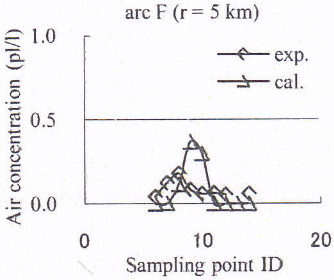


Figure 12. Concentrations on arc F

Except the results on the arc A, calculated maximum concentrations were 2.1 times to 3.9 times as large as observed maximum values. On the arc A, horizontal mesh size of the model (250 m) is too large compared with the distance of contiguous sampling points (79m). The cross wind position of the calculated maximum concentration differed 11.25 degrees or 22.5 degrees from the observed maximum position on all the arcs. Calculated cross wind concentration distributions were narrower than the observed distributions.

G-dose model

According to G-dose, R-cubic has a capability to predict the widest area taking the uncertainty of meteorological conditions into account. A sample output of R-cubic is shown in Figure 13.

In figure 13, a red zone, a yellow zone and a blue zone represents an area for an evacuation or staying in concrete buildings, stable iodine injection, and staying in buildings, rspectively. Input conditions to FPRA were: (1) a total loss of core cooling function occurred after 12 months operation of the reactor, (2) radioactive materials were emitted into CV, (3) mitigation function did not work, (4) leakage paths were design based paths (97% from stack and 3% from ground level) and a leak rate was 100 times larger than a design based rate. The calculated amount of noble gas (0.5MeV equivalent) and iodine (I-131 equivalent) were 2.8E+18 Bq and 1.4E+14 Bq, respectively. Meteorological conditions for G-dose were: (5) wind direction was NNE to NNW, wind speed was over 3 m/s, and atmospheric stability was A to B.

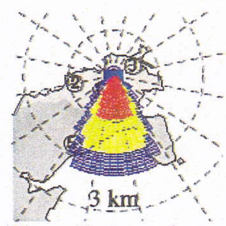


Figure 13. A sample output of R-cubic

RESULTS AND DISCUSSION

The tendency of release amount prediction by FPRA was conservative compared to the detailed MAAP4 analysis. For three nuclear power sites, maximum values of external dose and thyroid dose predicted by AREDES over SPEEDI was 2.0 ± 0.5, and 1.1 ± 0.4, respectively. In comparison with one of the Tokai 91 field tracer experiments, AREDES showed over estimation to observed maximum concentrations and narrower cross wind concentration distribution. One reason is because the calculation assumes that wind direction does not change in an hour. And applied P-G chart diffusion parameters, adequate for diffusions of several minutes long, may be too narrow.

As a simple tool to predict a release amount of radioactivity and a dose impact area, RASCAL (McGuire et al., 2007) is available for US NRC staff. Operation of R-cubic is as simple as RASCAL. When the radiation protective action area is decided, it should be considered that the meteorological forecast may fail to produce a correct prediction and/or that the predicted cross wind distributions of concentration and dose may be too narrow. In order to compensate above situation, one method is the application of PAZ, and the other possibility we think is the dose prediction calculation taken probable range of meteorological conditions into account, as R-cubic does.

SUMMARY

We developed a rapid model, so-called R-cubic, for prediction of the release amount of radioactive materials and the environmental dose to judge the protective action area. R-cubic can work under the condition that the accident information is insufficient before the radioactivity release into atmospheric environment occurs, and completes 24 hours dose prediction calculation within ten minutes. To cover from anxiety of a forecast error of meteorological condition and/or the model error of dose calculation, R-cubic accepts the probable range of meteorological conditions to calculate the possible maximum dose at every mesh point so that the predicted radiation protection area would be conservative.

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