The Study of Atmospheric Dispersion Model on Accident Scenario of Research Reactor G. A. Siwabessy using HotSpot Codes as A Nuclear Emergency Decision Support System

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ARTICLE INFO

A B S T R A C T

G.A. Siwabessy Multipurpose Reactor (RSG-GAS) is a research reactor with thermal power of 30 MW located in the Serpong Nuclear Area (KNS), South Tangerang, Banten, Indonesia. Nuclear emergency preparedness of RSG-GAS needs to be improved by developing a decision support system for emergency response. This system covers three important aspects: accident source terms estimation, radioactive materials dispersion model into the atmosphere and radiological impact visualization. In this paper, radioactive materials dispersion during design basis accident (DBA) is modeled using HotSpot, by utilizing site-specific meteorological data. Based on the modelling, maximum effective dose and thyroid equivalent dose of 1.030 mSv and 26 mSv for the first 7 days of exposure are reached at distance of 1 km from the release point. These values are below IAEA generic criteria related to risk reduction of stochastic effects. The results of radioactive dispersion modeling and radiation dose calculations are integrated with Google Earth Pro to visualize radiological impact caused by a nuclear accident. Digital maps of demographic and land use data are overlayed on Google Earth Pro for more accurate impact estimation to take optimal emergency responses.

1. INTRODUCTION

G. A. Siwabessy Multipurpose Reactor (RSG-GAS) is a research reactor managed by National Nuclear Energy Agency (BATAN) to perform research activities in nuclear field. The reactor was built in 1983 and located in Serpong Nuclear Area (KNS), South Tangerang, Banten, Indonesia. RSG-GAS reached its first criticality in July 1987, and operation at full-power of 30 MW was achieved in March 1992. The initial design of RSG-GAS used U_3O_8-Al oxide fuel with 19.75% enrichment. In July 1999, the fuel is gradually replaced into U_3Si_2-Al. Operation with full silicide fuel at power of 30 MW started in September 2003 [1].

Safety aspects are taken into account in design, construction and operation of RSG-GAS. However, the reactor still possess accident risk that must be anticipated. Emergency preparedness is an important aspect in the operation of a nuclear reactor, both a research reactor and a power reactor. Emergency preparedness aims to ensure the adequacy of resources in emergency response. These resources include authorities and responsibilities, organization, coordination, plans and procedures, equipment and facilities, training, and management systems [2].

Early warning systems for nuclear facilities at KNS, including RSG-GAS, have been implemented based on continuous monitoring of ambient radiation radiation and meteorology [3, 4]. This

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system detects operation abnormalities that cause radiological impact on workers and public members around the area. Continuous monitoring of ambient radiation and meteorology in KNS can be developed into a decision support system for nuclear emergency response.

Atmospheric dispersion model of radioactive materials into the environment plays important roles in supporting the decision makers of nuclear emergency responses [5–9]. There are a number of commonly used software for radioactive dispersion modeling. One of the simplest software is HotSpot Health Physics Codes developed by National Atmospheric Release Advisory Center (NARAC). This software applies a conservative and low range Gaussian plume model (less than 10 km) [10–16].

This paper discusses the application of HotSpot to support the decision making of RSG-GAS nuclear emergency response in KNS. The scope of this paper includes dispersion model of radioactive materials into the environment and radiological impact estimation based on spatial visualization. Radiological impact assessment is focused on International Atomic Energy Agency (IAEA) generic criteria for the first 7 days of exposure related to the risk of stochastic effects. The calculation results are then integrated with Google Earth Pro. Digital maps of site-specific demographic and land use are also exported to Google Earth Pro to provide a comprehensive visualization for decision makers of emergency response organization. The previous study related to radiological assessment of RSG-GAS accident has been performed using PC-COSYMA code. It discussed radiological impact for long term (a year) of exposure, includes contribution of ingestion pathway [17].

2. THEORY

In the emergency preparedness phase, it is necessary to assess potential hazard of a nuclear installation with a graded approach. In addition, the potential impact of nuclear installation accidents needs to be assessed to develop emergency preparedness and response programs. Based on GSR part 7, hazard studies are classified into five categories of emergency preparedness [2].

RSG-GAS, a 30 MW research reactor, is included in category II. It has potential hazard of releasing radioactive materials that give radiation doses above the permissible value, but could not give severe deterministic effects off the site.

Hotspot applies a Gaussian equation, as expressed in Eq. (1), to calculate time-integrated atmospheric concentration of radioactive discharges (gas or aerosol) at distances from release point [10].

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

where C is time-integrated atmospheric concentration (Ci-s/m^3), Q is source term (Ci), 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 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 (m/s), L is inversion layer height (m), and DF(x) is Plume Depletion factor.

HotSpot applies several parameters related to dose calculation. Total effective dose is sum of cloud submersion effective dose and inhalation committed effective dose. Optionally, groundshine effective dose and resuspension effective dose can be taken into account for total effective dose calculation. Effective dose is obtained by multiplying time-integrated atmospheric concentration and dose conversion factors (DCF) for each radiation pathway. Total effective dose is the sum of effective dose caused by all pathways, as expressed in Eq. (2).

$$
\begin{aligned}
&\text{total effective dose} \\
&= \text{committed effective dose of inhalation} \\
&+ \text{effective dose of cloud submersion} \\
&+ \text{effective dose of groundshine} \\
&+ \text{effective dose of resuspension}
\end{aligned}
\tag{2}
$$

3. METHODOLOGY

Several radionuclides were selected as atmospheric source terms of postulated design basis accident (DBA) (i.e. cooling channel blockage) for HotSpot inputs to represent several groups, i.e. noble gases, halogens, alkali metals, Strontium and Tellurium, as listed in **T**able **1**.

Table 1. Source terms for HotSpot inputs [17]

Radionuclide	Activity (Bq)
Kr-85	1.21×10^{12}
Kr-85m	1.05×10^{14}
Kr-87	2.12×10^{14}
Kr-88	2.99×10^{12}
Xe-133	5.60×10^{14}
Xe-135	5.73×10^{13}
I-131	2.37×10^{13}
Cs-134	2.61×10^{10}
Cs-137	9.94×10^{10}
Rb-88	3.01×10^{12}
Sr-90	9.59×10^{10}
Te-132	3.56×10^{12}

Meteorological data used for radioactive dispersion modeling were taken from meteorological monitoring station of KNS. The meteorological data were available from January 2010 to December 2017 [18, 19]. Meteorological parameters considered as input data include wind direction, wind speed, atmospheric stability and mixing layer height. Wind direction and wind speed were taken from monitoring data at 60 m of height and processed into monthly averages data, as listed in **Table 2**.

Table 2. Monthly averages of wind data in KNS between 2010 and 2017

Month	Wind direction* (degree)	Wind speed (m/s)
January	231	6.07
February	207	5.16
March	208	5.85
April	193	5.43
May	167	4.49
June	171	3.98
July	156	4.83
August	161	5.96
September	151	3.91
October	181	4.46
November	164	3.66
December	220	6.05

Note: * blowing from

The dominant Pasquill stability class in KNS is D (neutral), with 38.52% of occurrence [18]. Observation of mixing layer height (MLH) in KNS was performed by releasing radiosonde. The results show that MLH vary in the range of 100 – 200 m (morning), 1400 – 1500 m (day) and 150 – 250 m (night). A conservative approach assumed that the mixing occurs at a height of 100 m [19].

In this study, dose calculation was performed using HotSpot version 3.0.2. Prior to running the software, it is necessary to set up several parameters. The International System of Units (SI) were applied for radiologic units, i.e. Sv, Gy, Bq. The metric system was applied for distance unit (m, km). Meanwhile, dose conversion factors used in this study referred to Federal Guidance Report No. 13 [20]. This report applies new lung model of International Commission on Radiological Protection (ICRP) Publication 66, tissue weighting factors of ICRP Publication 60 and absorption rate types of particulate materials into blood "F" (fast), "M" (moderate), "S" (slow). Groundshine and resuspension effective dose were taken into account for total effective dose calculation. Resuspension factor for calculating resuspension effective dose referred to equation modified by Maxwell and Anspaugh-2010 [21]. Source terms release time was set for 10 minutes. The duration of exposure time period was set from initial release plus 7 days to

assess the projected dose related to generic criteria for protective actions to reduce the risk of stochastic effects. Standard surface roughness was selected for conservative option. Light-activity breathing rate for common adult inhalation rate (4.17×10^{-4} m^3/s) in ICRP Publication 66 was adopted for the calculation [22].

HotSpot output can be integrated with Google Earth Pro. HotSpot generates a KML file by setting appropriate location of release point. The KML file along with thematic digital maps related to demographic and land use in SHP file can be overlaid into Google Earth Pro. This feature is helpful for decision makers in estimating the radiological impact caused by postulated DBA of RSG-GAS.

4. RESULTS AND DISCUSSION

Maximum effective doses received by workers and public members standing at ground level around the site are listed in **Table 3**, in accordance with monthly averages of wind data. The effective doses for 7 days of exposure vary in the range of 0.624 – 1.030 mSv at a distance of 1.0 km from the stack of RSG-GAS. The highest maximum effective dose occurs in November, when the wind blows the slowest. This phenomenon is in accordance with Equation (2) [10]. Slow wind speed causes high concentration of radioactive materials at a distance from release point. Furthermore, high concentration of radioactive materials causes high effective dose received by workers and public members.

Table 3. Monthly maximum total effective dose and distance from release point

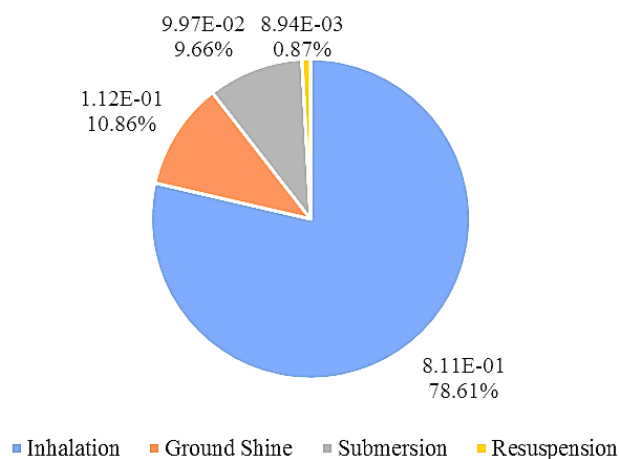| Month	Maximum total effective dose (mSv)	Distance from release point (m)
January	0.624	1.0
February	0.734	1.0
March	0.648	1.0
April	0.698	1.0
May	0.843	1.0
June	0.950	1.0
July	0.784	1.0
August	0.636	1.0
September	0.967	1.0
October	0.849	1.0
November	1.030	1.0
December	0.626	1.0

Profile of effective dose in case of November (highest effective dose) as a function of downwind distance is shown in Fig. 1. The effective dose rises sharply with high gradient at short distance, until 1 km from the release point. Beyond 1 km, the effective dose decreases gradually with increasing distance. Radioactive dispersion with atmospheric

stability class D does not give significant radiological impact to person who stay at short distance from release point.
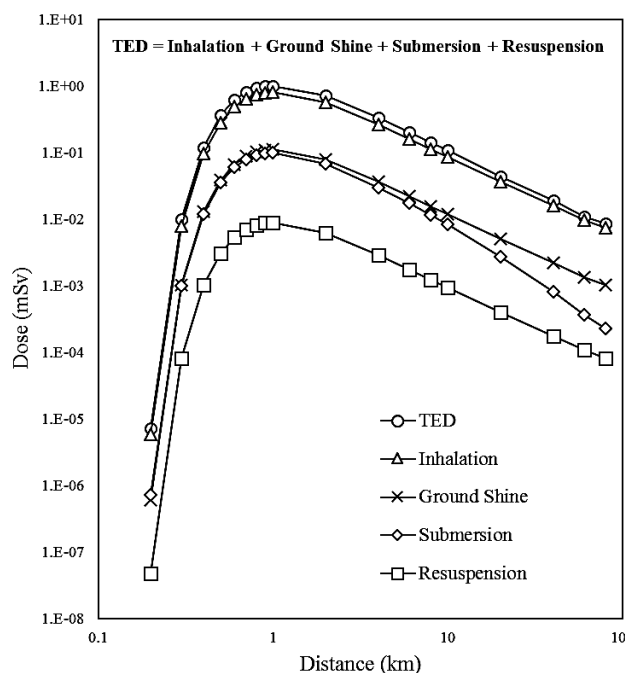
Fig. 1. Total effective dose (TED) and effective dose of each pathway as a function of downwind distance (case: November)

In this study, there are four radiation exposure pathways considered on total effective dose calculation, i.e. inhalation, submersion, groundshine and resuspension. Fig. 2 describes the contribution of each pathway on the maximum total effective dose at 1 km from release point in case of November. According to **Fig. 1** and Fig. 2, inhalation is the most contributing exposure pathway to total effective dose (78.61%). Radioactive plume which contains gas, aerosol and particulate radionuclides has a large possibility to be inhaled by respiratory system and deposited in target organs or tissues, such as lung, liver, thyroid, etc. Each radionuclide has specific target organ or tissue and gives different contribution on committed equivalent dose. Committed effective dose is calculated by combining committed equivalent dose of each organ and tissue with specific weighting factors. The second most contributing exposure pathway to total effective dose comes from groundshine (10.86%), slightly more contributing compared to submersion (9.66%). In this case, most of radionuclides that provide external dose tend to be deposited on soil surfaces instead of dispersed in the air. The least contributing exposure pathway is resuspension (0.87%), due to only a fraction of radionuclides deposited on surface soil are resuspended in the air.

Fig. 2. Pathways contribution on the maximum total effective dose at 1 km from release point (case: November)

Radionuclides contribution of each pathway on the maximum total effective dose is shown in **Fig. 3**. Radionuclide I-131 gives largest contribution to inhalation, resuspension and groundshine pathways. Radioiodine in atmosphere exist both in aerosol and vapor form [23]. Vapor phase of radioiodine deposits faster than its aerosol phase. Meanwhile, aerosol radioiodine give significant contribution to inhalation and resuspension pathways. Vapor radioiodine is potentially deposited on the ground surface and gives contribution to groundshine pathways. Examples of this phenomenon can be observed in case of Fukushima nuclear accident [24, 25]. The previous study also described similar phenomenon, in which I-131 gives dominant contribution to inhalation of radioactive plume and groundshine of deposited radioactive materials [17].

On submersion pathway, Kr-87 and other noble gases provide the majority of dose contribution. In general, noble gases rarely react with other elements due to their stable nature, and neither they deposit on the ground surface. Therefore, noble gases are potentially hazardous through submersion, but gives no contribution to inhalation, resuspension and groundshine pathways.

A safety assessment related to the IAEA generic criteria was performed to evaluate protective actions needed to reduce the risk of stochastic effects [2]. The protective actions include sheltering/evacuation and iodine thyroid blocking. According to Table 3 and Fig. 1, the maximum total effective dose of 1.030 mSv occurs in case of November at a distance of 1 km from release point for the first 7 days of exposure. The effective dose is far below the IAEA generic criteria of 100 mSv for the first 7 days of exposure for sheltering/evacuation. Another important parameter related to generic criteria is thyroid equivalent dose

for the first 7 days of exposure. The calculation result of the maximum thyroid equivalent dose (26 mSv) for the first 7 days of exposure in case of November is shown in **Fig. 4**. The thyroid

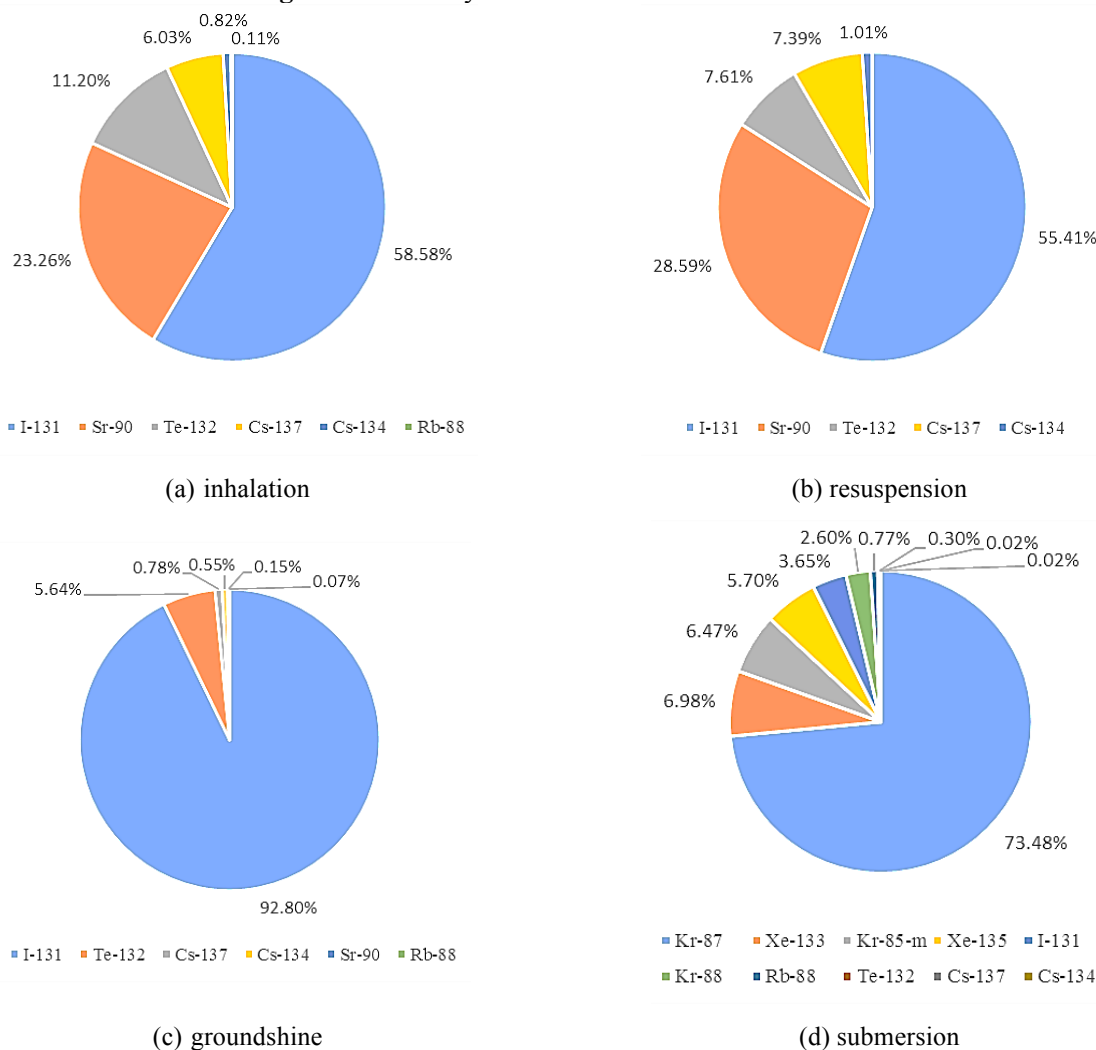equivalent dose is below the IAEA generic criteria of 50 mSv.

(a) inhalation

(b) resuspension

(c) groundshine

(d) submersion

Fig. 3. Radionuclides contribution of each pathway on the maximum total effective dose at 1 km from release point (case: November)

The result shows that postulated DBA of RSG-GAS do not need further protective action (sheltering/evacuation and iodine thyroid blocking) to reduce the risk of stochastic effects. In comparison, a study of thyroid equivalent dose assessment for severe accident of Tehran Research Reactor gives 27 mSv for first 4 days of exposure [26]. Several other studies related to Fukushima accident show that maximum thyroid equivalent dose vary in the range of 4 – 33 mSv for first 30 days of exposure [27, 28].
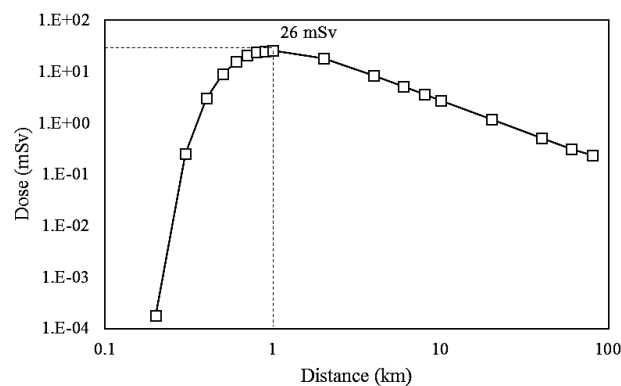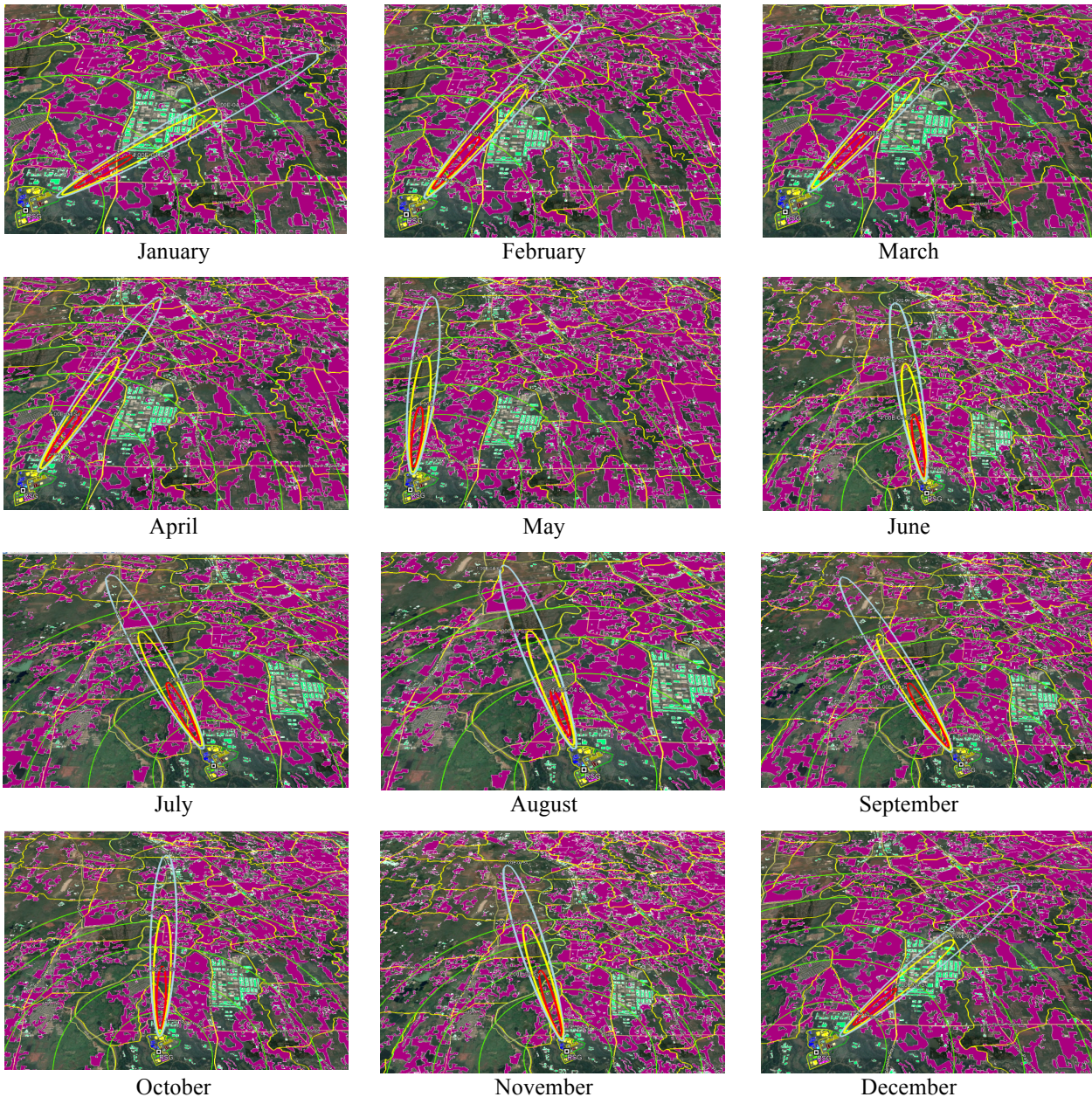

Fig. 4. Thyroid equivalent dose as a function of downwind distance (case: November)

Total Effective Dose

	0.1 mSv (outer)		0.2 mSv (middle)		4 mSv (inner)

Fig. 5. Simulation of effective dose contour in the first 7 days from RSG-GAS DBA postulation

The calculation result of total effective dose (KML file) generated by HotSpot was integrated to Google Earth Pro. The contour of total effective dose on Google Earth Pro is shown in **Fig. 5**. The color scheme of the contour legends in diagrams are the same. The contour magnitude of each month in diagram describes the total dose effective listed in Table 3, affected by wind speed. The contour direction should be in the same direction with the blowing wind. In general, the wind blows to Northern region (North West – North East) of the reactor site.

Thematic digital map of residential areas (SHP file) was also imported to Google Earth Pro. The

areas marked in purple and blue represent residential areas and office areas. The contour of total effective dose shown in Fig. 5 gives radiological impact to workers and public members who stay in offices and residential area. However, the magnitude of the total effective dose is insignificant.

Maps on Google Earth Pro is customizable with necessary information to support decision making in an event of nuclear emergency, as shown in Fig. 6. Identification area (name of area, population, etc), land use (residential area, office, etc), and optional evacuation route and place (if necessary) can be added into the map. Quickly-

obtained information will help the decision makers to quickly impose protective actions in order to reduce the radiological impact on workers and public members.
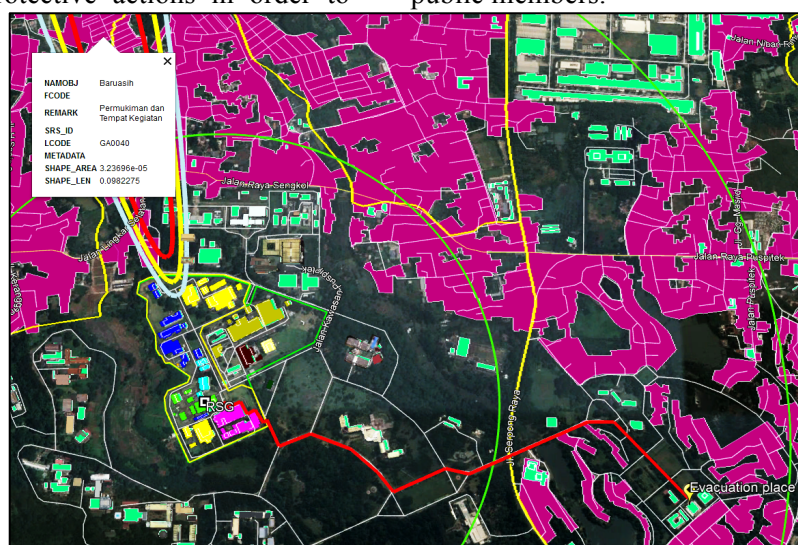

Fig. 6. Google Earth Pro costumization for supporting a decision making in a nuclear emergency

5.　CONCLUSION

Study on DBA scenario of RSG-GAS research reactor has been performed by postulating cooling channel blockage accident. The accident caused the release of a number of radioactive materials into the atmosphere. Site-specific meteorological data were used to estimate the radioactive materials dispersion using HotSpot. The calculation results show that the maximum effective total dose and the maximum thyroid equivalent dose for the first 7 days exposure duration are below the IAEA generic criteria.

Output data of HotSpot was visualized on Google Earth Pro by generating KML file. The costumization of Google Earth Pro is performed by adding thematic digital maps (SHP file) of demographic and land use data. Comprehensive visualization is potentially useful as important information for decision makers to determine protective actions quickly, in order to reduce the risk of radiological impact on workers and public members.

ACKNOWLEDGMENT

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