Technical Note

Radiological Environmental Consequence Analysis of Hypothetical Severe Accidents at Nuclear Power Plants

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Abstract : Analysis of radiological environmental consequences for hypothetical severe accidents at Korean nuclear power plants (NPPs) was performed using radiological assessment system for consequence analysis (RASCAL) and hybrid single particle Lagrangian integrated trajectory (HYSPLIT) code. Through the benchmarking study of radiological source terms released to the atmosphere in case of Fukushima Daiichi NPP (FDNPP) accident, it was proved that the results of this study would fall within a reasonable range of the same order of magnitude compared with existing research results. Assuming a long-term station blackout (LTSBO) similar to FDNPP accident, we also analyzed the potential consequences of Shin Kori units 3 and unit 4 following postulated reactor core meltdown accidents which would lead to large releases of radioactive materials to the atmospheric environment and total source terms were estimated to be 4.1×10^{16} Bq. Korean regulatory standards of emergency management recommended immediate protective actions of sheltering-in-place and evacuation if the projected radiation doses to the population exceeded 10 mSv and 50 mSv in the first 2 days and 1 week after the accident, respectively. It was found that total effective dose equivalent (TEDE) ranged from 11 mSv at 4.83 km to 50 mSv at 1.61 km around Shin Kori NPPs and therefore urgent public protective actions should be implemented in case of an emergency.

Key Words : Nuclear Accident, Radiological Consequence, Source Term, Public Evacuation

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단 보

원자력발전소 가상 중대사고시 방사선 환경영향 분석

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요약: 본 연구에서는 국내 원자력발전소의 가상 중대사고시 RASCAL 및 HYSPLIT 코드를 사용해 방사선 환경영향분석을 수행하였다. 후쿠시마 사고와 벤치마킹 분석을 통해 대기로 유출된 방사선원항이 기존의 연구결과와 동일한 크기 자릿수로 합리적인 범위 내에 있음을 입증하였다. 또한 후쿠시마 사고와 유사한 장기전원상실사고를 가정하여 신고리 3, 4호기의 노심용융에 따른 영향평가를 수행한 결과, 사고로 인해 대기환경으로 유출된 방사성 물질의 양은 상당하였으며 총 방사선원항은 4.1×10^{16} Bq로 평가되었다. 국내 방사능방재 규제기준은 사고후 예상 주민피폭선량이 2일에 10 mSv를 초과하면 옥내대피를, 1주일에 50 mSv를 초과하면 주민소개를 권고한다. 총유효 선량당량은 신고리 원자력발전소로부터 반경 4.83 km에서 11 mSv, 1.61 km에서 50 mSv로 평가되었으며 비상시 주민보호조치가 신속히 이행되어야 하는 것으로 확인되었다.

주제어: 원자력 사고, 방사선 영향, 방사선원항, 주민 대피

1. INTRODUCTION

A nuclear accident has been defined by the International Atomic Energy Agency (IAEA) as a radiation release event that leads to significant consequences for the public, the environment or the nuclear facility where it occurs.¹⁾ Nuclear power plants must operate in the most secure manner respecting all safety measures. There have been three major nuclear power plant accidents with serious negative consequences and they include the Fukushima Daiichi Nuclear Power Plant (FDNPP) disaster in 2011, Chernobyl disaster in 1986 and the Three Mile Island accident in 1979.²⁾ When safety measures are not properly operated, a nuclear accident could occur with serious consequences for the environment and human health. Several factors such as wind speed, wind direction, temperature and humidity can influence the dispersion behaviors of radioactive materials and the mixing processes.³⁾ In order to set countermeasures for nuclear accidents, forecasting the dispersion of radioactive materials based on various emission conditions need to be identified and addressed.

In this study, radioactive materials released to the environment in the event of a severe accident were analyzed using radiological assessment system for consequence analysis (RASCAL) of the Nuclear Regulatory Commission (NRC) and

hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) of the National Oceanic and Atmospheric Administration (NOAA). Total effective dose equivalent (TEDE) was estimated as a combination of inhalation committed effective dose equivalent (CEDE), cloud-shine and 4-day ground-shine using RASCAL and airborne concentrations and ground depositions were predicted using HYSPLIT.

This study aimed at analyzing the radiological environmental consequence of severe accident of advance power reactor (APR1400) of Shin Kori unit 3 and unit 4 using a similar scenario as FDNPP accident which involved reactor core meltdown following a long-term station blackout (LTSBO). APR1400 is a pressurized water reactor (PWR) developed by Korea Hydro & Nuclear Power Co. (KHNP). Emergency planning zone (EPZ) has been established around NPPs in order to implement prompt and effective protective actions to protect the general public in nuclear emergency situations at NPPs.⁴⁾ Nuclear Safety and Security Commission (NSSC), a regulatory organization in Korea, classified the emergency planning zone (EPZ) around NPPs into precautionary action zone (PAZ) and urgent protective action planning zone (UPZ) according to safety requirements and guidelines of IAEA. PAZ has a radius of 3~5 km while UPZ has a radius of 20~30 km around NPPs. Within PAZ, protective actions should be implemented before

or shortly after releases of radioactive materials on the basis of plant conditions at nuclear facilities in order to prevent or minimize any kinds of deterministic effects, while protective actions of UPZ are to be taken on the basis of results from environmental monitoring in order to prevent or minimize stochastic effects. The Korean standard protective actions have been classified into five categories which are; sheltering-in-place (10 mSv within 2 days), public evacuation (50 mSv within 1 week), distribution of iodine prophylaxis (100 mSv), temporary relocation (prediction of 30 mSv and 10 mSv in the first one month and the following month, respectively) and permanent migration (prediction of 1 Sv during whole lifetime).⁵⁾

2. MATERIALS AND METHODS

2.1. RASCAL

RASCAL code was developed by U.S. NRC for the purpose of independent assessment of dose projections during the response to radiological emergencies. RASCAL could provide the rapid assessment of an incident or accident and help a decision-making process of implementing protective actions.⁶⁾ The source term to dose (STDose) module in RASCAL was used to evaluate projected radiation doses from the plume of the released radioactive substances to the public downwind based on input information of plant conditions. This STDose module first generated time-dependent source terms which then provided the input to an atmospheric dispersion and transport model. In this study, an accident scenario of LTSBO was simulated. In order to calculate the dose to the population, the STDose module included the information on event type, event location, source term, release path and meteorological data. Gaussian plume and Gaussian puff models have been employed for the atmospheric transport, diffusion and deposition of radioactive materials in the vicinity of release point.

The conventional straight Gaussian equation used in RASCAL as follows⁷⁾

$$\chi(x, y, z) = \int_{-\infty}^{\infty} \frac{Q' F_y F_z}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp \left[-\frac{1}{2} \left(\frac{x-ut}{\sigma_x} \right)^2 \right] dt \quad (1)$$

And, a simplified version of the straight-line Gaussian model was expressed as;

$$\frac{\chi(x, y, z)}{Q'} = \frac{F_y F_z}{2\pi u \sigma_y \sigma_z} \quad (2)$$

where,

χ = average concentration,

Q' = release rate,

F_y, F_z = lateral and vertical exponential terms,

x = downwind distance at which χ, σ_x, σ_y and σ_z are evaluated,

u = wind speed,

t = time

RASCAL could not consider the effect of secondary building such as auxiliary building, and hence it did not delay radioactive material's movement between the fuel and containment or between containment and the atmosphere, which was probably the main contribution to the overestimates.⁷⁾ RASCAL also simulated the reduction mechanism as a single filter at the point of release to the atmosphere rather than a time-varying depletion mechanism in containment.⁸⁾ This consequence assessments were based on simple models and had inherent uncertainties for their estimates.

2.2. HYSPLIT

The HYSPLIT model using Lagrangian dispersion formula is a complete system for computing simple air parcel trajectories, as well as complex transport, dispersion, chemical transformation and deposition simulations. HYSPLIT can estimate forward and backward trajectory of air mass by assuming either puff or particle dispersion based on meteorological data. HYSPLIT model is often driven by meteorological data from the Global Data Assimilation System (GDAS) which has a horizontal resolution of 1° which corresponds to about 100 km×100 km and 23 vertical layers. Considering a particle, the particle follows the wind and its trajectory is just the integration of the particle position vector in space and time (t). The final position can be computed from the average velocity (V) at the initial position (P) and first-guess position (P'). The computation of new position at a time step ($t+\Delta t$) due to the mean advection by wind determines the trajectory that a particle or puff will follow.⁹⁾

$$P(t + \Delta t) = P(t) + 0.5[V(P, t) + V(P' t + \Delta t)]\Delta t \quad (3)$$

$$P'(t + \Delta t) = P(t) + V(P, t)\Delta t \quad (4)$$

Equations above are the basis for the calculation of trajectories in HYSPLIT. Only the advection component is considered when running trajectories. The turbulent dispersion component is only needed to describe the atmospheric transport and mixing processes for three-dimensional movement of particles and puffs.¹⁰⁾ Dispersion equations are formulated in terms of the turbulent velocity components. In the three-dimensional model of particles, the dispersion process is represented by adding a turbulent component to the mean velocity obtained from the meteorological data, namely,

$$X_{\text{final}}(t + \Delta t) = X_{\text{mean}}(t + \Delta t) + U'(t + \Delta t)\Delta t \quad (5)$$

$$Z_{\text{final}}(t + \Delta t) = Z_{\text{mean}}(t + \Delta t) + W'(t + \Delta t)\Delta t \quad (6)$$

where,

U' and W' correspond to the turbulent velocity components, X_{mean} and Z_{mean} are the mean components of particle positions,

X_{final} and Z_{final} are the final positions in the horizontal and vertical, respectively.

2.3. FDNPP accident

In order to understand the modeling of atmospheric dispersion of radionuclide releases in the event of a severe

NPP accident, benchmarking of FDNPP accident was performed. This FDNPP accident involved very complicated accident sequences and large atmospheric radioactive releases. The accident was due to the Japan earthquake and tsunami of March 2011 that led to LTSBO and damaged the nuclear reactor's safety features. FDNPP experienced core melt, hydrogen explosions (unit 1 and unit 3) and the releases of significant radioactive materials from 12th to 15th March 2011. Reactor cores of unit 1 and unit 3 were uncovered for more than 12 hours. **Table 1**, **Table 2** and **Table 3** showed the time sequences of FDNPP unit 1, unit 2 and unit 3, respectively, immediately after the accident. Reactors of FDNPP were boiling water reactors (BWRs) designed with Mark I containment. The source term merge tool in RASCAL was used to calculate source term by combining consequences of multi-reactor events for two or more reactors at a single site. The simulation considered a period of 11th to 15th March 2011 and the releases were observed for 96 hours after the core melt. Drywell and direct releases were considered as the release pathway. Leak rates were adjusted according to the accident sequence in the report of Institute of Nuclear Power Operations (INPO)¹¹⁾ and they were used in RASCAL. RASCAL's default leak rate for BWR was 0.5% volume per day. This leak rate was changed from 0.5% volume per day to 1% volume per hour at the beginning phase of core

Table 1. Accident sequence of FDNPP unit 1.

Date	Japan Local Time	Event
11/3/2011	14:46	Reactor shut down
11/3/2011	14:47	Emergency Diesel Generators (EDGs) automatically started, Isolation Condenser initiated
11/3/2011	15:37	EDGs off due to tsunami, Alternating Current (AC) and Direct Current (DC) were lost Isolation condenser (IC) stopped
11/3/2011	18:10	Core uncover
12/3/2011	14:30:	Start Venting, opening valve
12/3/2011	15:36:	Explosion of reactor building

Table 2. Accident sequence of FDNPP unit 2.

Date	Japan Time	Event
11/3/2011	14:46	Loss of offsite power, Reactor shut down
11/3/2011	14:50	Start of core cooling by Reactor Isolation Cooling System (RICS)
11/3/2011	14:47	EDGs automatically started
11/3/2011	15:35	Tsunami, EDGs off due to tsunami
13/3/2011	16:00	Manual operation of RICS was terminated
13/3/2011	11:46	Core uncover
13/3/2011	01:06	Core recovery
15/3/2011	02:00	Start Venting, opening of valve
15/3/2011	12:00	End Venting, closure of valve

Table 3. Accident sequence of FDNPP unit 3.

Date	Japan Time	Event
11/3/2011	14:46	Reactor shut down
11/3/2011	15:37	Tsunami hit: AC power was lost but DC power was available. Reactor core isolation cooling (RCIC) was kept in operation with operator's control
12/3/2011	11:36	RCIC operation was terminated
13/3/2011	9:20	Start Venting, opening valve
13/3/2011	12:46	Core uncover
13/3/2011	15:06	Core recovery
13/3/2011	20:10	Start venting
14/3/2011	1:00	End venting
14/3/2011	6:00	Start venting
13/3/2011	6:00	End venting
14/3/2011	11:01	Explosion

Table 4. Accident sequence of Shin Kori unit 3.

Date	Korea local time	Event
2018/08/10	01:00	Reactor shut down due to loss of offsite power
2018/08/10	01:00	Sprays off. Emergency core cooling system (ECCS) available for 8 hours under station battery power
2018/08/10	17:00	Core uncover (core release). 16 hours after shut down
2018/08/10	17:00	Leak rate of 10 % vol/day considered. Core uncovered for 4 hours
2018/08/10	21:00	Core recovered

Table 5. Accident sequence of Shin Kori unit 4.

Date	Korea local time	Event
2018/08/10	01:00	Reactor shut down due to loss of offsite power
2018/08/10	01:00	Sprays off. ECCS available for 8 hours under station battery power
2018/08/11	09:00	Core uncover (core release)
2018/08/11	09:00	Leak rate of 10 % vol/day considered. Core uncovered for 3 hours
2018/08/11	12:00	Core recovered

damage. It was changed to 25% volume per hour for 1 hour for the containment venting and to 50% volume per hour for 1 hour following the hydrogen explosions of unit 1 and unit 3. After the containment venting and hydrogen explosions, the leak rate was returned to 1% volume per hour.¹¹⁾

2.4. Hypothetical accidents at Shin Kori NPPs

This study analyzed radiological consequences that would occur if both unit 3 and unit 4 at Shin Kori NPP underwent a core melt. Unit 3 and unit 4 of Shin Kori NPP are APR1400 type reactors which are two-loop PWRs supplying a rated thermal output of 4,000 MWt or electrical output of 1,400 MWe, respectively. An accident scenario of LTSBO imbedded in RASCAL was applied to derive source terms as shown in **Table 4** and **Table 5**. This scenario considered unmitigated scenario which would occur if operators failed to carry out key mitigation measures to prevent the accident from

progressing. Ulsan's wind data from Korea Meteorological Administration (KMA) for the year of 2018 was analyzed using wind rose as shown in **Fig. 1**. It was observed that the frequent wind direction of the east occurred in the month of August and would cause the most harmful effect on the atmospheric dispersion and ground deposition of radionuclides into the inland of Korea after the event of an accident. Because most NPPs in Korea were located at coasts, sea-land breeze effect was relatively high. Therefore, it was expected that wind direction and wind speed had a large effect on the atmospheric dispersion of radioactive materials in the case of a severe accident.

3. RESULTS AND DISCUSSION

3.1. Benchmarking study of FDNPP accident

Total amount of source terms released from FDNPP to the

Fig. 1. Wind rose diagram of Ulsan region during August 2018.

atmosphere was estimated to be 1.3×10^{18} Bq using RASCAL code. Noble gases consisted of significant parts in the early releases from FDNPP. However, noble gases did not contribute to ground depositions and their releases had minor influences on the radiological consequences to the general public. ^{131}I and ^{137}Cs were found to be the most important radionuclides

because they had a high activity of 100~400 PBq for ^{131}I and 7~20 PBq for ^{137}Cs .¹²⁾ These two radionuclides adversely affected human health through the contamination of air, water, soil and food.¹³⁾ **Table 6** and **Table 7** showed source terms for radionuclides important to the exposure doses and accumulated doses, respectively. ^{133}Xe had the highest source term because of its large inventory of 61% at the point of reactor shutdown.¹²⁾ Additionally, **Fig. 2** and **Fig. 3** illustrated total releases of the main radionuclides important to the exposure doses with time and foot print of the accumulated TEDEs within 8 km and 40 km, respectively. According to the simulation results above, it was found that the population

Fig. 2. Release amount of source term over time for FDNPP accident.

Table 6. Source terms (Bq) for FDNPP accident.

Nuclide		Nuclide		Nuclide	
^{140}Ba	8.0×10^{15}	^{133}I	7.7×10^{16}	^{89}Sr	4.4×10^{15}
^{134}Cs	2.7×10^{16}	^{140}La	1.1×10^{15}	^{90}Sr	3.5×10^{14}
^{136}Cs	9.7×10^{15}	^{99}Mo	5.6×10^{16}	^{127m}Te	3.0×10^{15}
^{137}Cs	1.8×10^{16}	^{103}Ru	1.9×10^{16}	^{129m}Te	1.2×10^{16}
^{131}I	1.7×10^{17}	^{106}Ru	5.6×10^{15}	^{132}Te	1.8×10^{17}
^{132}I	1.9×10^{17}	^{127}Sb	1.4×10^{16}	^{133}Xe	5.7×10^{18}

Table 7. Estimated doses (Sv) for FDNPP accident.

Distance (km)	0.8	1.61	2.41	3.22	4.83	6.44	16.1	24.1	32.2
TEDE*	2.9×10^0	7.6×10^{-1}	3.4×10^{-1}	1.9×10^{-1}	8.7×10^{-2}	5.1×10^{-2}	2.3×10^{-2}	1.7×10^{-2}	1.6×10^{-2}
Thyroid CDE**	3.3×10^0	8.3×10^0	3.8×10^0	2.1×10^0	9.6×10^{-1}	5.6×10^{-1}	2.3×10^{-1}	1.7×10^{-1}	1.5×10^{-1}
Inhalation CEDE***	1.9×10^0	4.8×10^{-1}	2.2×10^{-1}	1.2×10^{-1}	5.5×10^{-2}	3.2×10^{-2}	1.3×10^{-2}	9.7×10^{-3}	8.8×10^{-3}
Cloud-shine	4.1×10^{-2}	1.3×10^{-2}	3.3×10^{-3}	1.9×10^{-3}	8.4×10^{-4}	4.7×10^{-4}	4.2×10^{-4}	3.1×10^{-4}	2.8×10^{-4}
4-day Ground-shine	1.0×10^0	2.7×10^{-1}	1.2×10^{-1}	6.8×10^{-2}	3.1×10^{-2}	1.8×10^{-2}	9.8×10^{-3}	7.2×10^{-3}	6.5×10^{-3}
Interphase of 1st year	1.6×10^1	4.1×10^0	1.9×10^0	1.1×10^0	4.8×10^{-1}	2.8×10^{-1}	9.6×10^{-2}	7.2×10^{-2}	6.5×10^{-2}
Interphase of 2nd year	8.5×10^0	2.2×10^0	9.9×10^{-1}	5.6×10^{-1}	2.5×10^{-1}	1.5×10^{-1}	5.3×10^{-2}	4.0×10^{-2}	3.6×10^{-2}

* TEDE = Inhalation CEDE + Cloud-shine + 4-day Ground-shine

** Thyroid committed dose equivalent (CDE) is the dose to the thyroid glands after an intake of radioactive material by an individual during the 50-year period.

*** Inhalation committed effective dose equivalent (CEDE) is the internal dose received through inhalation by an individual during the 50-year period.

Fig. 3. Radiation exposure map within 8 km (left) and 40 km (right) for FDNPP accident.

Fig. 4. Comparison of source terms between this study and existing research results for FDNPP accident.

within 30 km would receive radiation doses greater than 10 mSv in the first 4 days and would require immediate protective actions for sheltering-in-place. In this study, only source terms for ^{131}I and ^{137}Cs were compared with other previous results as shown in Table 8 and Fig. 4.¹⁴⁻¹⁹⁾ Further, comparisons of release rates between this study and previous estimates using inverse modeling were carried out in order to find the correlation as shown in Fig. 5.²⁰⁾ The highest peaks of the release rates were observed due to the explosions on 12th and 14th March of unit 1 and unit 3, respectively. The differences were attributed to the assumed values of leakage rates,

Fig. 5. Comparison of total release rate for FDNPP accident during 11~15 March, 2011.

mathematical models, computer codes and uncertainties in the measured values. Along with the leakage rates used in this study, the high concentration of ^{137}Cs and ^{131}I might be attributed to RASCAL because it could not consider an effect of secondary building, and thus there was no delay in the movement of radioactive materials between the reactor fuel and containment or between containment and the atmosphere. The source terms published by IAEA in 2015 were derived using inverse modelling and accident progression.¹²⁾ Inverse

Table 8. Comparison of source terms between this study and existing research results for FDNPP accident.

	This study	U.S. Nuclear Regulatory Commission ¹⁵⁾	International Atomic Energy Agency ¹²⁾	Terada ¹⁶⁾	Winiarek ¹⁷⁾	Chino ¹⁸⁾	Morino ¹⁹⁾	Nuclear and Industry Safety Agency (NISA) ¹⁴⁾
^{131}I (Bq)	1.7×10^{17}	2.0×10^{17}	$1 \sim 4 \times 10^{17}$	1.50×10^{17}	1.90×10^{17}	1.5×10^{17}	1.42×10^{17}	1.6×10^{17}
^{137}Cs (Bq)	1.8×10^{16}	2.17×10^{16}	$7 \sim 20 \times 10^{15}$	1.3×10^{16}	1.20×10^{16}	1.30×10^{16}	9.94×10^{15}	1.5×10^{16}
Estimation method	RASCAL 4.3	RASCAL 4.2	Accident progression plus inverse modeling	Inverse modelling	Inverse modelling	Inverse modelling	Inverse modeling	Accident progression

Fig. 6. Airborne concentration for FDNPP accident during 11~15 March, 2011.

Fig. 7. Ground deposition for FDNPP accident during 11~15 March, 2011.

modelling involved a comparison of measurements in the environment with estimates derived from simulations. The release rates of source terms obtained from RASCAL were then applied to HYSPLIT code. The top six radionuclides of ^{137}Cs , ^{134}Cs , ^{133}Xe , ^{131}I , ^{132}Te and ^{132}I were analyzed because they were important to the public doses in the first week of a nuclear accident.^{21,22)} The air parcel forward trajectories using HYSPLIT code showed that air parcels originating from FDNPP after the accident moved into Pacific Ocean on 12 March and continued to move mostly to the northeastward as shown in Fig. 6 and Fig. 7. Most releases were dispersed over Pacific Ocean whereas some of the releases were dispersed over Japan's main land causing areas of significant deposit. Airborne concentrations ranged from 3.2×10^6 to $1.4 \times 10^{16} \text{ Bq} \cdot \text{m}^{-3}$ whereas maximum and minimum depositions of $1.7 \times 10^8 \text{ Bq} \cdot \text{m}^{-2}$ and $6.3 \times 10^{-15} \text{ Bq} \cdot \text{m}^{-2}$, respectively, in 96 hours were estimated in this study.

3.2. Simulation of hypothetical accidents at Shin Kori NPPs

Source terms of Shin Kori NPP unit 3 and unit 4 were

calculated through the simulation of 4 days using RASCAL as shown in Table 9. Total amount of radioactive materials released was estimated to be $4.1 \times 10^{16} \text{ Bq}$ which was less than source terms of FDNPP, $1.3 \times 10^{18} \text{ Bq}$ as previously mentioned. ^{133}Xe contributed the highest fraction of the source term because this radionuclide was attributed to the large inventory within the nuclear reactor. Additionally, ^{131}I was the radionuclide of concern due to the source of internal exposure of thyroid gland and its amount was estimated to be $9.3 \times 10^{14} \text{ Bq}$. The merging technique of source terms provided a means to calculate radiation doses of gaseous releases from multiple units at a single site as shown in Table 10. It was found that estimated TEDEs within PAZ (5 km) ranged from 11 mSv at 4.83 km to 50 mSv at 1.61 km from Shin Kori NPPs. And, the release rates of the main radionuclides important to the radiation doses and TEDEs within 8 km and 40 km were depicted in Fig. 8 and Fig. 9, respectively. No deterministic effects would be expected since the maximum TEDE fell below 100 mSv. And, deterministic thyroid effects would not be expected to occur because the highest thyroid CDE received by a person in 50 years was

Table 9. Source terms (Bq) for hypothetical accidents at Shin Kori NPPs.

Nuclide		Nuclide		Nuclide	
^{134}Cs	1.2×10^{14}	^{99}Mo	2.9×10^{14}	^{90}Sr	4.4×10^{11}
^{136}Cs	4.8×10^{13}	^{103}Ru	3.3×10^{13}	$^{127\text{m}}\text{Te}$	1.5×10^{13}
^{137}Cs	8.5×10^{13}	^{106}Ru	9.0×10^{12}	$^{129\text{m}}\text{Te}$	6.3×10^{13}
^{131}I	9.3×10^{14}	^{127}Sb	6.0×10^{13}	^{132}Te	1.1×10^{15}
^{132}I	1.1×10^{15}	^{89}Sr	5.8×10^{12}	^{133}Xe	3.6×10^{16}
^{133}I	6.6×10^{14}				

Table 10. Estimated doses (Sv) for hypothetical accidents at Shin Kori NPPs.

Distance (km)	1.61	2.41	3.22	4.83	8.05	11.3	16.1	24.1	32.2
TEDE	5.0×10^{-2}	3.0×10^{-2}	2.0×10^{-2}	1.1×10^{-2}	4.8×10^{-3}	1.2×10^{-3}	5.2×10^{-4}	1.7×10^{-4}	7.8×10^{-5}
Thyroid CDE	8.1×10^{-2}	3.6×10^{-2}	2.0×10^{-2}	8.6×10^{-3}	3.3×10^{-3}	2.8×10^{-3}	1.9×10^{-3}	1.2×10^{-3}	7.4×10^{-4}
Inhalation CEDE	3.5×10^{-3}	1.6×10^{-3}	8.4×10^{-4}	3.5×10^{-4}	1.3×10^{-4}	1.0×10^{-4}	6.8×10^{-5}	4.0×10^{-5}	2.4×10^{-5}
Cloud-shine	1.3×10^{-4}	3.4×10^{-5}	1.9×10^{-5}	*	*	*	*	*	*
4-day Ground-shine	4.6×10^{-2}	2.8×10^{-2}	1.9×10^{-2}	1.1×10^{-2}	4.7×10^{-3}	1.1×10^{-3}	4.4×10^{-4}	1.3×10^{-4}	5.2×10^{-5}
Interphase of 1 st year	4.8×10^{-1}	3.0×10^{-1}	2.0×10^{-1}	1.1×10^{-1}	4.8×10^{-2}	9.6×10^{-3}	3.1×10^{-3}	5.2×10^{-4}	1.3×10^{-4}
Interphase of 2 nd year	2.8×10^{-1}	1.7×10^{-1}	1.2×10^{-1}	6.6×10^{-2}	4.1×10^{-2}	*	5.3×10^{-3}	1.6×10^{-3}	1.9×10^{-4}

* indicates values less than 10 μ Sv

Fig. 8. Release amount of source term over time for hypothetical accidents at Shin Kori NPPs.

below 100 mSv as shown in **Table 10**. Based on Korean standards for emergency response, sheltering-in-place would be required in the early phase of accident because TEDEs were estimated to be 11~50 mSv within PAZ of 5 km around Shin Kori unit 3 and unit 4. Korean standards recommended sheltering-in-place for the projected radiation dose of 10 mSv in 2 days and evacuation for 50 mSv in 1 week.

The air parcels showed that most radionuclides were transported northwards due to southern winds and some of

the air masses moved westwards towards the main land of Korea as shown in **Fig. 10**. Radioactive materials released to the atmosphere were largely dispersed over the main land of Korea due to the frequency of eastern winds. Noble gases did not get deposited and therefore the airborne concentrations were expected to remain high and further transported into other areas outside of Korea depending on their half-lives. The airborne concentrations at ground level were estimated to be between 1.4×10^{-5} and 1.2×10^2 Bq·m⁻³ while the ground depositions ranged from 9.7×10^{-9} to 7.7×10^4 Bq·m⁻² as shown in **Fig. 11** and **Fig. 12**, respectively. The ground depositions were mainly contributed by ¹³⁷Cs and ¹³⁴Cs and the precipitation on 10th and 11th August 2018 according to the weather data from KMA.

4. CONCLUSION

Benchmarking analysis of FDNPP accident indicated that RASCAL could give reasonable results of radiological source terms in the case of a nuclear emergency although high values and some inconsistencies were observed, which were attributed

Fig. 9. Radiation exposure map within 8 km (left) and 40 km (right) for hypothetical accidents at Shin Kori NPPs.

Fig. 10. Trajectory of air mass from Shin Kori NPPs during 10~14 August, 2018.

Fig. 11. Airborne concentration for hypothetical accidents at Shin Kori NPPs during 10~14 August, 2018.

to the assumed information of leakage rates and limited functions of used model. RASCAL also could not reflect an effect of moving radioactive materials between compartments inside buildings and thus there were no delayed releases of radioactive materials into external environment. These might have led to the overestimation of radiological source terms. In case of severe accidents at Shin Kori NPPs, it was observed that total amount of 4.1×10^{16} Bq was estimated to be released to the atmospheric environment. The airborne concentrations at ground level ranged from 1.4×10^{-5} to 1.2×10^2 Bq·m⁻³ whereas the ground depositions ranged from 9.7×10^{-9} to 7.7×10^4 Bq·m⁻² which were mainly contributed by the precipitation on 10th and 11th August 2018. It was found that

Fig. 12. Ground deposition for hypothetical accidents at Shin Kori NPPs during 10~14 August, 2018.

estimated TEDEs within PAZ of 5 km around Shin Kori unit 3 and unit 4 ranged from 11 mSv to 50 mSv, and therefore urgent public protective actions would be implemented according to Korean regulatory standards which recommended sheltering-in-place and public evacuation if the projected radiation dose exceeded 10 mSv and 50 mSv in the first 2 days and 1 week after the accident, respectively.

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