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Technical Paper

Offsite Radiological Consequence Analysis of Hypothetical Accidents for APR1400

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Abstract - About 25% (113 units) of the world's nuclear power plants (NPPs) are operating in Northeast Asia including Korea, China, Japan and Taiwan as of June 2019 based on the power reactor information system (PRIS) of International Atomic Energy Agency (IAEA). Accordingly, the possibility of exposure to unexpected nuclear accidents in Northeast Asia is getting higher and higher. With guidance of lessons learned from previous nuclear disasters such as the Three Mile Island accident in 1979, the Chernobyl accident in 1986 and Fukushima accident in 2011, offsite radiological consequence analysis using computerized software has been considered as one of essential quantitative risk communication in order to identify and discuss public concerns and worries about nuclear safety and public health risk in case of hypothetical nuclear accidents around specific NPPs. In this study, radiological assessment system for consequence analysis (RASCAL) developed by U.S. Nuclear Regulatory Commission (NRC) and Northeast Asia nuclear accident simulator (NANAS) developed by Nuclear Safety and Security Commission (NSSC) in Korea were integrally used to quantify the offsite radiological consequences and to examine the emergency protective measures for the general public around regions of Shin Kori unit 3, the first commercial reactor of advanced power reactor 1400 MWe (APR1400). Comprehensive simulations of radiological source term estimation, atmospheric dispersion analysis and radiation dose assessment to the public have been performed in case of two hypothetical nuclear accidents involving station black out (SBO) and loss of coolant accident (LOCA).

Key words : Hypothetical accident, Consequence analysis, Radiological assessment, RASCAL, NANAS

INTRODUCTION

Nuclear power plants (NPPs) around Northeast Asia' neighbouring countries such as Korea, China and Japan have developed huge concerns and worries towards the public after the major accident at Fukushima in Japan. With aid of lessons learned from previous NPP accidents, radiological consequence analysis could be investigated and predicted for the analysis of hypothetical accident. Analysing NPP accidents in Korea would be useful to calculate risks towards the public and environment. Furthermore, future prediction and estimation of release of nuclear power plants accidents are important as they can be used to assist emergency plans after a postulated accident.

Radioactive materials discharged to the atmosphere could disperse into the air and deposit to the ground during NPP accidents. Various factors affecting these dispersal processes include wind directions, wind speed, atmospheric stability, surrounding temperatures, and so on. All these factors can contribute to the severity of a particular accident in general and vary in term of damage to the public (An *et al*. 2016). Because of limitations to predict the results accurately based on these factors if such accidents would happen, earlier studies or researches could be useful to analyse offsite conse-

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quences of radioactive materials by referring to the past NPP accidents (Pasquill 1961).

The main objective of this research was to investigate the atmospheric dispersion and radiological risk to the public around Shin Kori unit 3 under hypothetical accidents using Northeast Asia Nuclear Accident Simulator (NANAS). By the simulation of NANAS, dose assessments could be performed in accordance with the long-range dispersion and visualized through the map projections and charts for specific regions (Kim *et al*. 2017). In order to investigate the compatibility of NANAS, benchmarking analysis of Fukushima accident was conducted beforehand using data collected on monitoring system in Korea. Some groups of radioactive nuclides (noble gases, halogens and alkali metals) were chosen in which considered to be released to the surrounding environments of NPPs. Atmospheric dispersion was calculated by inputting several factors such as source terms, duration of release and atmospheric stability. Meteorological data of global data assimilation system (GDAS) was used for the first week of April 2011. Map projections with predicted doses at specific locations could be directly extracted from NANAS. The results of this study could facilitate offsite emergency planning for the public nearby Shin Kori unit 3.

MATERIALS AND METHODS

The operation of NPPs require a deliberative attention of safety measures at full length through all operational stages. This study evaluated the radiological consequences of potential accidents at Shin Kori unit 3. Radiological Assessment System for Consequence AnaLysis (RASCAL) and NANAS computer code were used to study the atmospheric dispersion and exposure dose of the public around the NPP according to accident scenarios and weather data.

NANAS consisted of three modules including source-term estimation, atmospheric dispersion prediction and dose assessment (Kim *et al*. 2017). For the prediction of atmospheric dispersion, NANAS used puff and lagrangian particle model embedded in HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. HYSPLIT has been commonly used and worked best to calculate long range dispersion of radionuclides. In addition, calculation of HYSPLIT with GDAS meteorological data displayed good performance in the case of long-distance simulation. Exposure pathways considered in calculation of effective dose were radioactive plume of cloud-shine and ground-shine as external pathways. Airborne particles could be deposited by gravity or precipitation and subsequently, human body could be exposed to the polluted ground. For internal pathway, only inhalation pathway was included at the initial period of nuclear emergency response.

U.S. Nuclear Regulatory Commission (NRC) developed RASCAL which could evaluate releases from nuclear power plants, spent fuel storage pools and casks, fuel cycle facilities, and radioactive material handling facilities for the purpose of dose estimation during radiological emergencies. The system could support various evaluations based on plant situations. For nuclear facilities including commercial nuclear power plants and research reactors, the main concerns were radioactive materials released into the atmosphere and radiation exposures to the public, especially during severe accidents. Hence, investigation of anticipated doses to the public within emergency planning zone (EPZ) and surrounding regions in the event of accidents was one of essential requirements for the safety operation of nuclear facilities (Ramsdell *et al*. 2012; Athey *et al*. 2017a; Athey *et al*. 2017b). In this study, we used the RASCAL code to analyse the consequences of the hypothetical accident's scenarios for station black out (SBO) and loss of coolant accident (LOCA) at Shin Kori unit 3. Consequently, in order to find source terms of APR1400 type of reactor, Barakah NPPs of United Arab Emirates (UAE) of RASCAL code were used as reference models because the plant information of Barakah NPPs had been embedded to input deck of RASCAL code (Ramsdell *et al*. 2012; Athey *et al*. 2017a; Athey *et al*. 2017b).

Benchmarking analysis is a specific type of research that allows sets of data to be compared with existing results alongside calculation or measurement data that fits overall approach for continuous and compatibility. Benchmarking analyses often rely on both quantitative and qualitative measures to generate significant results. Quantitative analysis can provide metric-based outcomes, while qualitative comparisons often reveal best practices. The benchmarking process usually encompasses four steps starting with estimation, investigation, action and assessment (Invernizzi *et al*. 2017).

For the benchmarking analysis, simulation of NANAS was performed using source terms from Fukushima accident, and the radiological environmental impacts to Korean peninsula was analyzed in terms of the comparison with real measurement data provided by nationwide radioactivity monitoring posts of Korea Institute of Nuclear Safety (KINS) at the time

Table 1. Benchmarking analysis with Fukushima accident

Release Point – Fukushima Daiichi, Japan	
Year	2011
Month	4
Day	1
Hour	00:00
Calculation period	161 hr
Sampling interval	3 hr
Meteorological data file	gdas1.apr11.w1
Nuclides	^{131}I ^{134}Cs ^{137}Cs

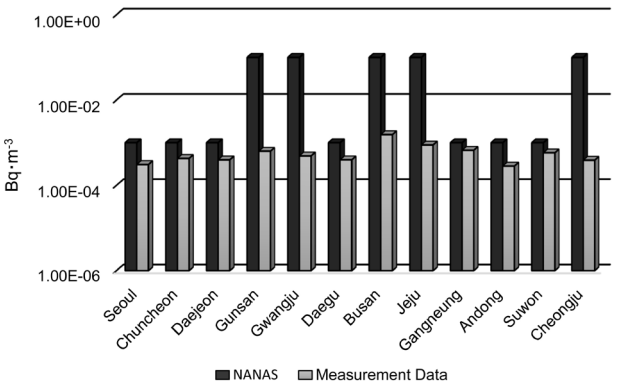

Fig. 1. Comparison of NANAS and measurement data for ^{137}Cs from 24th March to 7th April, 2011.

of Fukushima accident in 2011 (MEST 2011). The information of input data for benchmarking process was presented in Table 1. Time, meteorological data and source term followed the exact sets of measurement data to be compared. Source terms of ^{131}I, ^{134}Cs and ^{137}Cs were taken from UNSCEAR report of 2013 Annex A, Table B4 and B5. Fig. 1 shows the comparison results between NANAS and measurement data for ^{137}Cs starting from 24th March to 7th April 2011 and the measurement data of ^{137}Cs are shown in Table 2. Since radioactivity concentrations measured at the nationwide radioactivity monitoring posts of KINS were taken around 1.5 m above the ground surface, calculated activities deposited on the ground from NANAS were compared with the measurement data.

As shown in Fig. 1, comparison of NANAS and measurement data at seven cities showed the similar trends even though there were differences of 10∼100 times at five cities due to the shortage of available information at the time of Fukushima accident. Because NANAS included a long-range atmospheric dispersion model based on HYSPLIT, the differences in results were expected to happen considering

Table 2. Concentrations of ^{137}Cs ($Bq \cdot m^{-3}$) measured in Korea

Date	Seoul	Chuncheon	Daejeon	Gunsan	Gwangju	Daegu	Busan	Jeju	Gangneung	Andong	Suwon	Cheongju
March 24, 2011		1.8×10^{-4}										
April 2, 2011			1.04×10^{-4}	7.9×10^{-5}							1.06×10^{-4}	7.8×10^{-5}
April 3, 2011	7.5×10^{-5}						7.4×10^{-5}	4.3×10^{-5}				
April 4, 2011	6.2×10^{-5}	9.6×10^{-5}	9.2×10^{-5}	1.44×10^{-4}	7.2×10^{-5}	2.4×10^{-5}	6.2×10^{-5}	1.08×10^{-4}	7.85×10^{-4}		7.05×10^{-5}	
April 5, 2011		1.3×10^{-4}	6.9×10^{-5}	1.1×10^{-4}		1.02×10^{-4}	1.57×10^{-4}	1.82×10^{-4}	1.71×10^{-4}	7.2×10^{-5}	1.81×10^{-4}	1.97×10^{-4}
April 6, 2011	1.71×10^{-4}	2.02×10^{-4}	1.31×10^{-4}	2.98×10^{-4}	4.17×10^{-4}	2.71×10^{-4}	1.25×10^{-3}	5.5×10^{-4}	2.13×10^{-4}	1.54×10^{-4}	2.16×10^{-4}	1.13×10^{-4}
April 7, 2011									905×10^{-5}	5.7×10^{-5}		
Total	3.08×10^{-4}	4.28×10^{-4}	3.96×10^{-4}	6.31×10^{-4}	4.89×10^{-4}	3.97×10^{-4}	1.543×10^{-3}	8.83×10^{-4}	6.64×10^{-4}	2.83×10^{-4}	5.78×10^{-4}	3.88×10^{-4}

some limitations encountered which are the release time, period and rate of source term, and uncertainty of long-range weather data. Fig. 2 shows the Bland-Altman plot of NANAS calculations and measured data. From the data used for both measurement data and NANAS calculations, the value of standard deviation (SD) was 0.0508. As the pivoting point, the value of median data (MD) was −0.0417 and thus producing a plot between MD + SD of +0.0579 and MD − SD of −0.1412. From the dots shown in the Bland-Altman plot, it could be concluded that similar trends were found with different absolute values for two results.

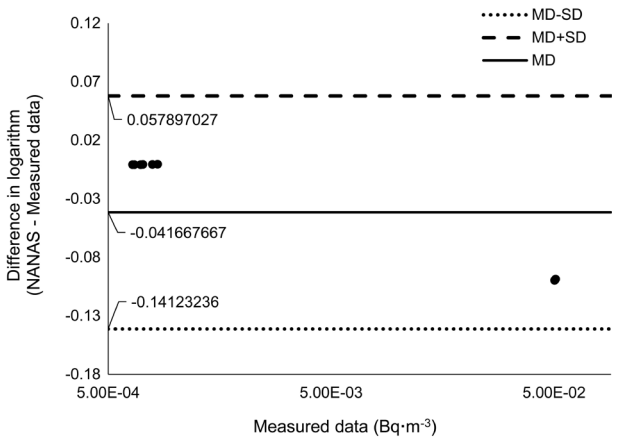

Fig. 2. Bland-Altman plot between NANAS and measurement data.

RESULTS AND DISCUSSION

RASCAL has been used by response personnel to conduct an independent evaluation of dose, consequence projections and training purposes. The model was developed to allow consideration of the dominant aspects of source term, transport, dose and consequences. Source term calculations in RASCAL can estimate the amount of radioactive materials released based on a wide variety of potential radiological accident scenarios (Athey *et al*. 2017a; Athey *et al*. 2017b). In RASCAL, radioactive materials accidents could be categorized as fuel-cycle facility accidents, uranium fires and explosions, criticality accidents and isotopes releases. The source term calculations performed in this study belonged to fuel-cycle facility accidents. Before inputting source term into NANAS code, extensive researches were done with RASCAL code considering various factors including types of accidents, parameters of specific reactor, release pathways, meteorological conditions, height of release and time.

Two hypothetical accident simulations were conducted using RASCAL to evaluate source term data for Shin Kori unit 3. Input parameters in RASCAL were referred from RASCAL manual guide. The first simulation conducted using RASCAL was station blackout accident scenario and the sec-

Table 3. Input parameters for running RASCAL simulation

Input parameters		
Reactor parameters	Reactor power	3983 MWth
	Average burnup	28914 MWd/MTU
	Containment type	PWR dry ambient
	Containment volume	3.13×10^6 ft^3
	Design pressure	60 lb/in^2
	Design leak rate	0.10%/d
	Coolant mass	2.92×10^5 kg
	Assemblies in core	241
	Steam generator type	U-tube
	SG water mass	218,000 kg
SBO	Shutdown	00:00, May 3
	Release from core starts	12:00, May 3
	Core damage estimated by	Core recovered status
	Core recovered	13:00, May 3
	End of calculations	14:00, May 3
	Leakage release height	60 m
LOCA	Shutdown	00:00, May 6
	Release from core starts	04:00, May 6
	Core damage estimated by	Core recovered status
	Core recovered	04:35, May 6
	End of calculations	06:00, May 6
	Leakage release height	60 m
Meteorology	Dataset name:	Standard condition (D stability,1.8 m · s^{-1}, 70°F, no precipitation)

ond was loss of coolant accident scenario. Table 3 presents the input parameters of RASCAL simulation for both station blackout and loss of coolant accident scenarios by taking default values embedded in RASCAL following the same type of reactor chosen with APR1400 of Barakah NPPs in UAE (Athey *et al*. 2017a; Athey *et al*. 2017b). Table 4 shows list of radionuclides released with total activity of source term from the accident scenarios.

Simulations of NANAS for SBO and LOCA were conducted for all four seasons with constant wind speed of 1.8 $m \cdot s^{-1}$ and D stability using standard meteorological RASCAL input data as shown in Table 3. In this study, GDAS meteorological data were used for the first week of July 2018 (for summer season) and first week of October 2018 (for autumn season) which could be freely downloadable from National Oceanic and Atmospheric Administration (NOAA), ftp://arlftp.arlhq.noaa.gov/pub/archives/gdas1. Consecutively, for winter and spring season, GDAS meteorological data for the first week of January 2019 and April 2019 were inputted, respectively. Deposition covers for a total 7 days of simulation according to specific season. During summer, spreading of radionuclides covered a large area because wind direction blown from south and shifted towards south southwest (SSW) affecting southern parts of Korean peninsula in the first two days. Some regions in the eastern part of Korean peninsula were affected during 7 days of simulation and dose assessment was performed in cities of Daejeon, Gwangju, Incheon, Suwon and Ulsan. During autumn, spreading of radionuclides covered most cities in Korea as shown in Fig. 3 and the wind direction started from west towards east for the first two days. After day 3, some of concentration of activity could be seen circled back into Korean peninsula affecting major cities in Korea and radioactive nuclides could be clearly deposited inside Korean peninsula. Major regions in Korea were affected in the 7 days of simulation and output from dose assessment was investigated in cities, particularly, Busan, Daegu, Daejeon, Gwangju, Incheon, Jeju, Suwon and Ulsan as shown in Fig. 4. Output of dose assessment could be seen from Fig. 5 and Fig. 6 in Busan, and Fig. 7 and Fig. 8 in Ulsan. During winter, spreading of radionuclides only

Table 4. List of radionuclides released with activities for hypothetical accidents

SBO		LOCA	
Nuclide	Activity (Bq)	Nuclide	Activity (Bq)
^{133}Xe	5.70×10^{12}	^{133}Xe	3.50×10^{13}
^{133}I	1.80×10^{11}	^{133}I	6.60×10^{11}
^{131}I	1.30×10^{11}	^{131}I	4.70×10^{11}
^{134}Cs	1.70×10^{10}	^{134}Cs	5.70×10^{10}
^{137}Cs	1.20×10^{10}	^{137}Cs	3.90×10^{10}
^{106}Ru	1.40×10^{8}	^{106}Ru	6.20×10^{8}
^{90}Sr	1.70×10^{7}	^{90}Sr	7.70×10^{8}
^{95}Nb	8.90×10^{3}	^{95}Nb	1.90×10^{8}
^{95}Zr	8.70×10^{3}	^{95}Zr	1.90×10^{8}
^{144}Ce	7.00×10^{3}	^{144}Ce	3.80×10^{8}
^{241}Pu	6.30×10^{2}	^{241}Pu	3.40×10^{7}
Total	6.04×10^{12}	Total	3.62×10^{13}

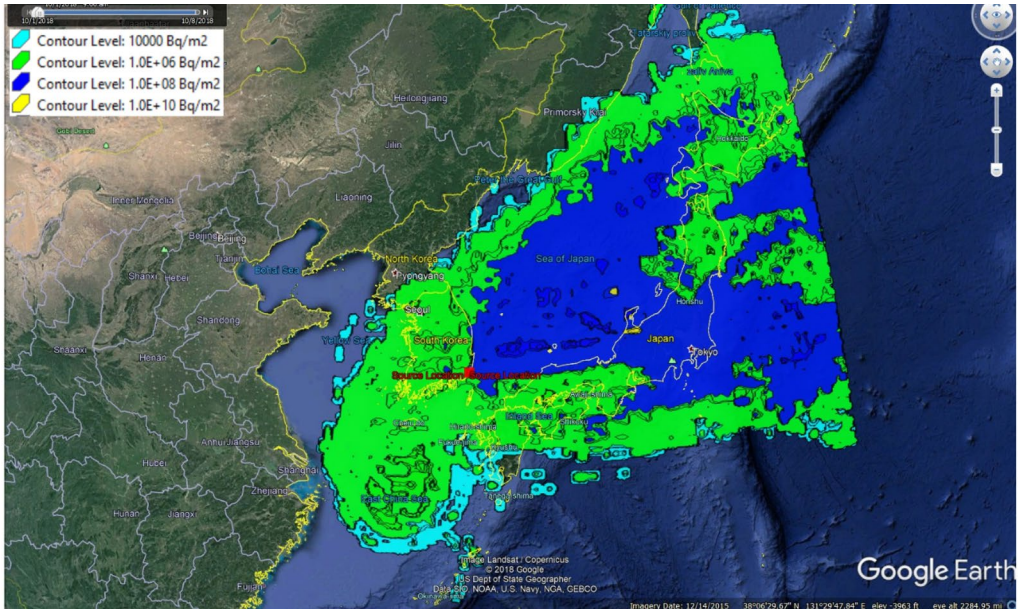

Fig. 3. Calculated deposition patterns of ^{134}Cs, ^{137}Cs and ^{131}I for autumn season (Google Earth 2018).

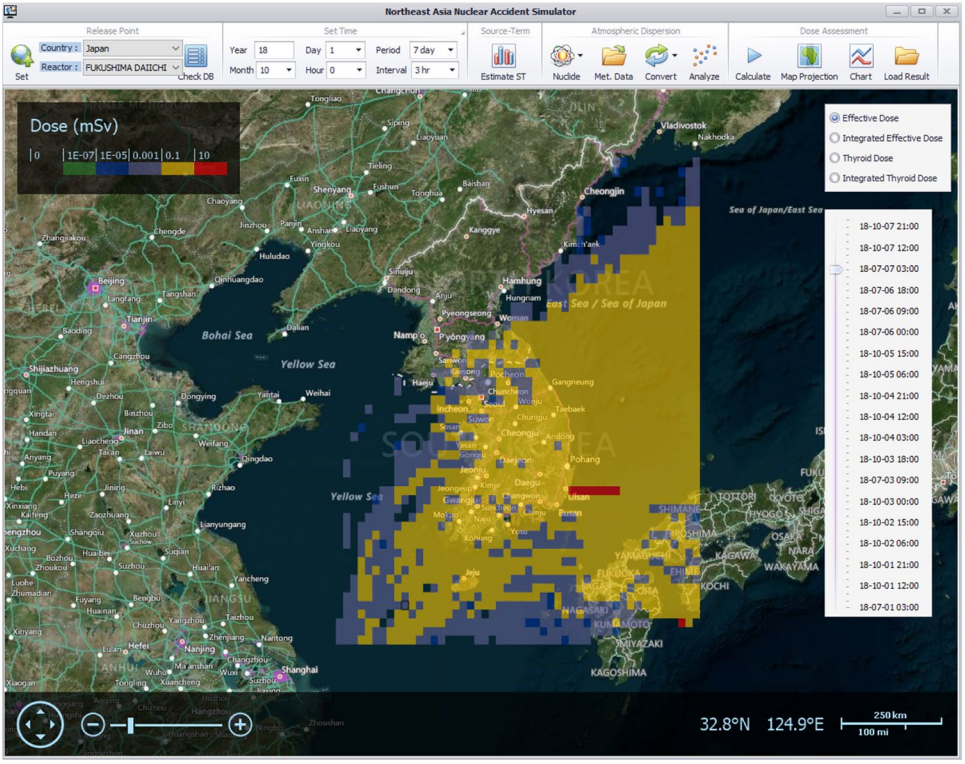

Fig. 4. Map projection for the spatial distribution of effective dose.

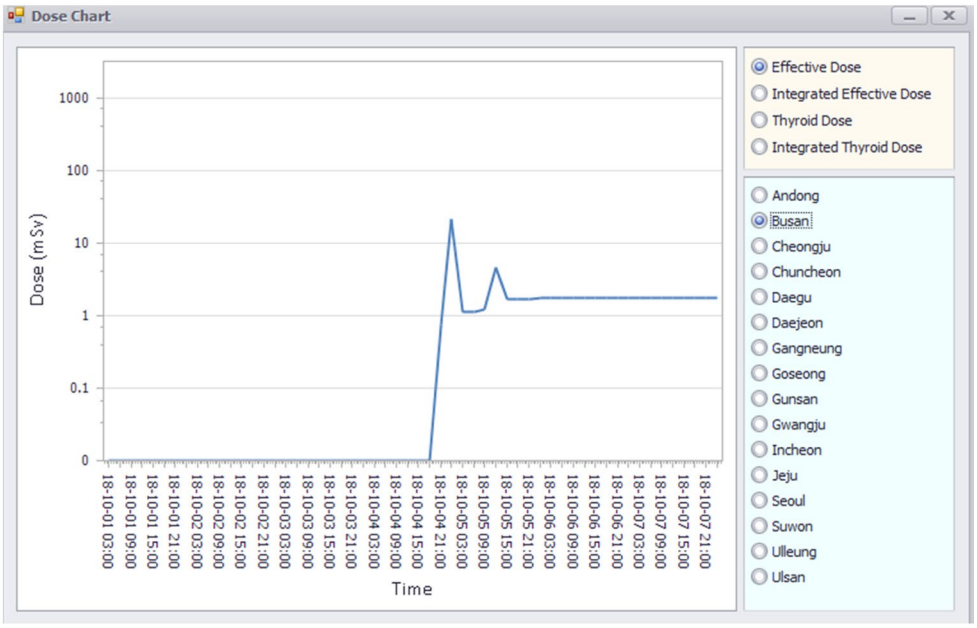

Fig. 5. Effective dose with time at Busan city.

scattered through single direction of dispersion. This simulation started with wind direction from west towards east for the whole 7 days. Under this situation, Japan was mostly contaminated and Korean peninsula was not affected. After 7 days of simulation, dose assessment at major cities in Korea could not be done. During spring, spreading of radionuclides scattered towards direction away from Korea peninsula. The simulation blows wind direction started from north towards

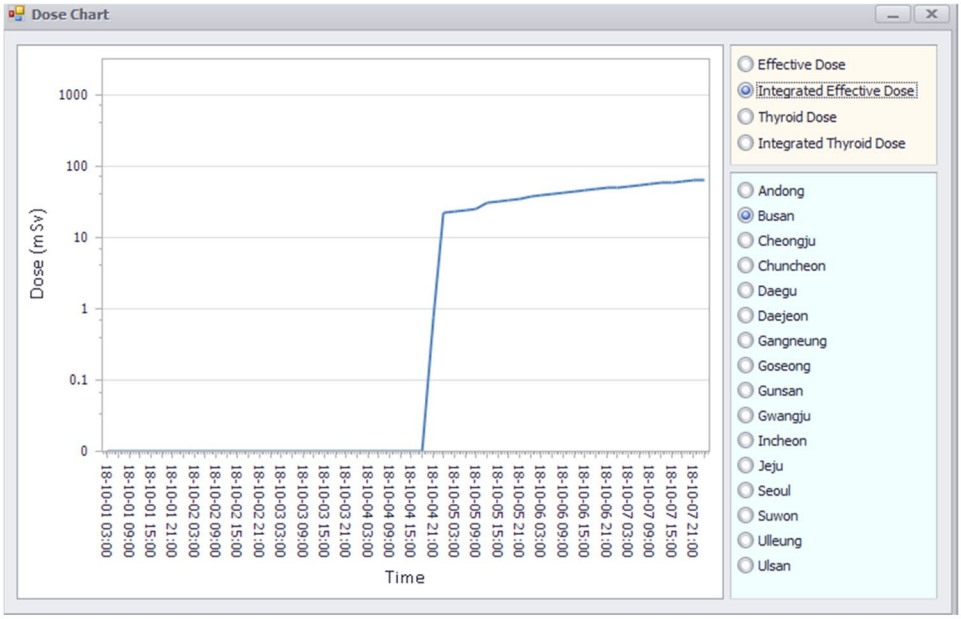

Fig. 6. Time-integrated effective dose at Busan city.

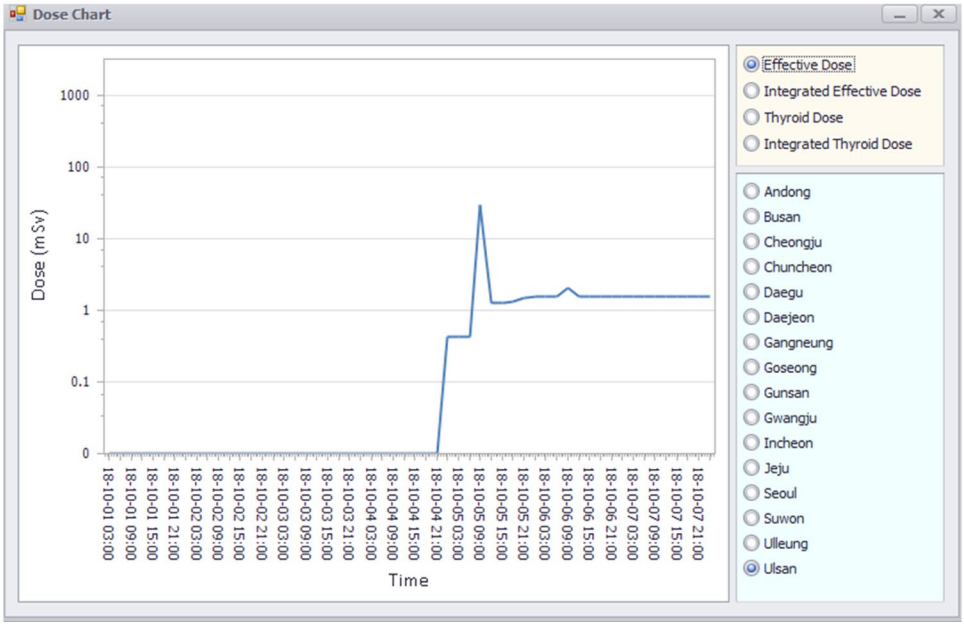

Fig. 7. Effective dose with time at Ulsan city.

north north-west (NNW) for the whole 7 days. For the simulation during winter and spring, atmospheric dispersion of radioactive materials did not affect Korean peninsula. From simulations of all four seasons, the highest recorded value of integrated effective dose was found to be 64 mSv in Busan. Major nuclides of source terms taken into consideration were ^{131}I, ^{133}Xe, ^{134}Cs and ^{137}Cs based on UNSCEAR report (UNSCEAR 2014). In this study, the total activities of SBO and LOCA with core recovery for both scenarios were calculated to be 6.04×10^{12} Bq and 3.62×10^{13} Bq, respectively.

As shown in Fig. 5, Fig. 6, Fig. 7 and Fig. 8, although the amount of ^{131}I, ^{134}Cs and ^{137}Cs released into the atmosphere during SBO and LOCA scenarios was $10^5 \sim 10^6$ times smaller than that of Fukushima accident, the cumulative doses at Busan and Ulsan exceeded the sheltering criteria of 10 mSv. These findings could be explained as follows. Estimated total

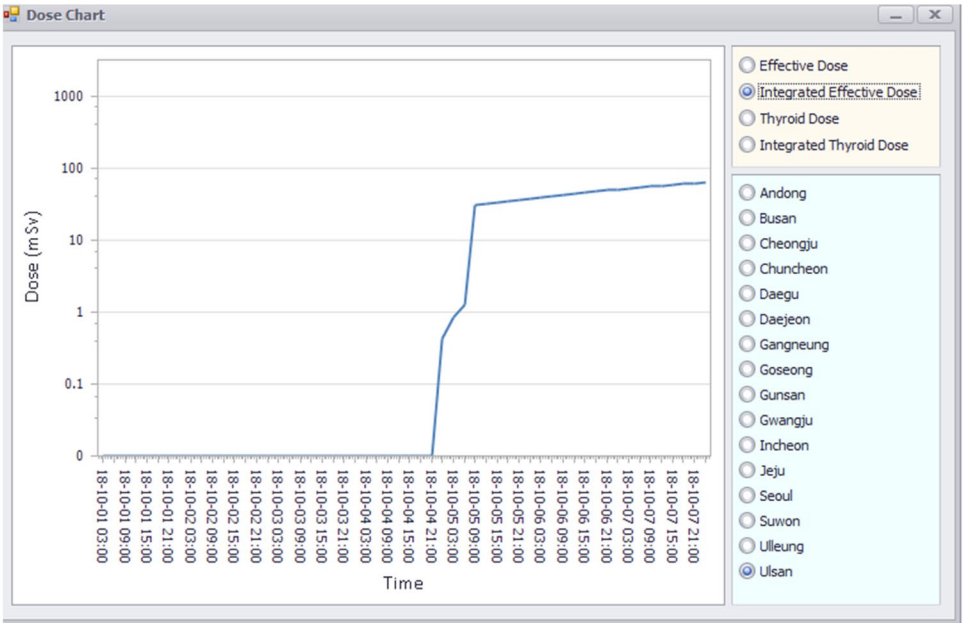

Fig. 8. Time-integrated effective dose at Ulsan city.

amounts of ^{131}I, ^{134}Cs and ^{137}Cs released to the atmosphere during the Fukushima accident were 1.24×10^{17}, 9.01×10^{15} and 8.83×10^{15}, respectively, as shown in Table B4 of UNSCEAR Report 2013 Annex A. These were estimates during the period of about 50 days from March 12 to May 1, 2011 according to Table B5 of UNSCEAR Report 2013 Annex A. Most of the radiation doses around Fukushima NPPs were 1~10 mSv due to long-term atmospheric dispersion. However, the effective doses at Namie town and Itate village (about 30 km away from Fukushima NPPs) were reported to be 10~50 mSv (WHO 2012). The duration times of accidents in this study were 14 hours and 6 hours for SBO and LOCA, respectively, as shown in Table 3 according to accident scenarios of Barakah NPPs (APR1400, the same reactor type as Shin Kori unit 3) which were provided by RASCAL code. The cumulative effective doses at Busan and Ulsan, located at a radius of 20~30 km from Shin Kori unit 3, were estimated to maximum values of 64 mSv and 62 mSv, respectively, although radiological source terms were smaller than that of Fukushima accident but were released in a relatively short period of release time.

CONCLUSION

Based on the benchmarking results of NANAS and measurement data collected in Korean peninsula at the previous Fukushima nuclear accident, the compatibility of NANAS program was proven to be useful in terms of providing significant simulations of hypothetical accidents for Shin Kori unit 3. From the simulation conducted with RASCAL, total amount of source terms for SBO and LOCA scenarios with core recovery were 6.04×10^{12} Bq and 3.62×10^{13} Bq, respectively, as shown in Table 4. Source terms for both accident scenarios were consecutively used as inputs to NANAS in order to perform the atmospheric dispersion analysis and dose assessment. The results showed that LOCA posed the highest integrated effective dose with a value of 64 mSv at the city of Busan in four days after the accident. According to simulations conducted by NANAS during seven days of both accident scenarios in the season of spring, summer, autumn and winter in the particular year of interest, 2018, the likelihood of highest severity of accidents was found to be coming from autumn season. During this season, major cities in Korea were polluted by the atmospheric dispersion of radionuclides along with wind direction starting from west towards east for the first two days, and at day three, some activities were circled back into Korean peninsula. Two major cities mostly affected during autumn in 2018 were found to be Busan and Ulsan. The cumulative effective doses at the city of Busan and Ulsan which were located within a radius of 20~30 km from Shin Kori unit 3 were estimated to maximum values of 64 mSv and 62 mSv, respectively. The main reason was that radiological source term of Shin Kori unit 3 was released to the atmosphere in a relative short period of release time when

compared with that of Fukushima accident. Furthermore, according to the standards that have been enacted by the NSSC, the urgent public protective actions of evacuation should be carried out in response to accidents, which was confirmed by the results of NANAS in which exceeded the limit of 50 mSv for seven days at the city of Busan and Ulsan. It was concluded that the results obtained in this study could help the offsite radiological consequence analyses of hypothetical nuclear accidents in Korea and could be benefited for future research and development needs.

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