Nuclear Emergency Management using Accident Consequence Analysis Code

Borhan Uddin, Gazi Muhammad*, and Kim, Juyoul**

Abstract

Shin Kori Unit 3 is a new pressurized water reactor in Advanced Power Reactor 1400, which was developed by Korea Hydro and Nuclear Power Co. and commenced commercial operation in December 2016. We calculated the radionuclide concentrations and related radiation doses at the early stage of accidents under the assumption of hypothetical severe nuclear accidents in Shin Kori Unit 3. In this study, the radiological source terms of the accident scenarios were evaluated using the radiological assessment system for consequence analysis code, which has been used as a regulatory software tool for emergency response applications developed by the United States Nuclear Regulatory Commission. In general, the atmospheric transport, dispersion, and deposition processes of radioactive materials can be simulated by the Gaussian model using a straight-line trajectory Gaussian plume model for short distances and a Lagrangian Gaussian puff model for long distances. The most dangerous scenarios were observed during winter when we considered two accident scenarios, namely, long-term station blackout (LTSBO) and loss-of-coolant accident (LOCA), based on the reactor conditions and seasonal effects. The total effective dose equivalent values for LTSBO and LOCA were estimated to be 14 and 0.08 mSv, respectively, in the precautionary action zone of 5 km in two days after the accident. According to Korean regulations on urgent public protective actions, the criteria are 10 mSv in two days for indoor sheltering and 50 mSv in one week for public evacuation. In the LTSBO case, we found that immediate public protective measures were required. Appropriate decisions must be made by the off-site emergency management center under the Nuclear Safety and Security Commission in Korea.

Key words : Nuclear Emergency, Consequence Analysis, LTSBO, LOCA

요 지

신고리 3호기는 한국수력원자력(주)에서 개발한 신형 가압경수로(APR1400)로서 2016년 12월부터 상업운전을 개시하였다. 신고리 3호기에 가상의 중대사고를 가정하여 사고 초기 시간에 따른 방사성 핵종 농도와 방사선량 변화를 계산하였다. 본 연구에서는 미국 원자력규제위원회에서 개발한 방사능방재 비상대응 규제검증 전산코드인 RASCAL을 사용하여 사고 시나리오의 방사선원향을 평가하였다. 일반적으로 방사성 물질의 대기 중 수송, 확산 및 침적 과정은 가우시안 플룸모델로 묘사되는데 근거리에는 직선체적 가우시안 플룸모델, 원거리에는 라그랑지안 가우시안 퍼프모델을 사용하였다. 장기정전사고와 냉각재상실사고 시나리오에 대해 원자로 상태와 계절변화를 고려하여 소외 방사선량을 평가한 결과 가장 위험한 시나리오는 겨울에 발생하였고 사고 후 2일에 예방적보호조치구역인 5 km에서 총유효선량당량의 최대값은 장기정전사고의 경우 14 mSv, 냉각재상실사고의 경우 0.08 mSv로 평가되었다. 긴급주민보호조치에 관한 국내 규제기준은 옥내대피의 경우 이틀간 10 mSv, 주민소개의 경우 일주일간 50 mSv이다. 장기정전사고시 즉각적인 주민보호조치가 필요하며 이 경우 원자력안전위원회 산하 현장방사능지휘센터에서 적절한 의사결정을 내려야 한다.

핵심용어 : 원자력비상, 결말분석, 장기정전사고, 냉각재상실사고

*Member, M.S. Candidate, Department of NPP Engineering, KEPSCO International Nuclear Graduate School (E-mail: borhan_baec@yahoo.com)

**Corresponding Author, Member, Assistant Professor, Department of NPP Engineering, KEPSCO International Nuclear Graduate School (Tel: +82-52-712-7306, Fax: +82-52-712-7375, E-mail: jykim@kings.ac.kr)

1. Introduction

Since the Three Mile Island accident in 1979, Chernobyl accident in 1986 and Fukushima accident in 2011, a great emphasis has been put on assessing emergency response capabilities for different types of stakeholders including electric utilities, regulatory bodies and local communities. Estimation of radioactive materials released to the atmosphere, which is usually termed as source term estimation, constitutes an important part of nuclear emergency response. This source term can provide a necessary input for the consecutive simulation of atmospheric dispersion and radiological dose assessment to the public. Based on the dose assessment, corresponding emergency response actions could be recommended such as whether people should be guided by evacuation or shelter-in-place protective actions (Zhao et al., 2015). Radiological source term estimation, atmospheric dispersion analysis and radiation dose assessment have been considered as the most important safety concerns in the area of emergency response after a nuclear accident. Therefore, public concerns after nuclear accidents emphasized an absolute necessity to identify and address potential health effects which were closely related with the accurate dose assessment to the public around nuclear power plants (NPPs) (Ahangari et al., 2017).

The siting of NPP is one of important parameters from the point of view of emergency preparedness and response. There are two kinds of site, i.e., on the site (on-site) and off the site (off-site). The on-site area is the area under the control of operators or first responders, and the off-site area is the area beyond that area. In addition, for the off-site, there are two kinds of emergency planning zone (EPZ), precautionary action zone (PAZ) and the urgent protective action planning zone (UPZ). Protective actions within PAZ are to be taken before or shortly after a release of radioactive materials on the basis of conditions at NPPs, and protective actions within UPZ are to be mainly taken on the basis of environmental monitoring. The EPZ is divided into PAZ and UPZ which have a radius of 5 km and a radius of 20–30 km from the nuclear facility, respectively (Lee et al., 2016).

Radiation exposure following the release of radioactive materials in nuclear accident can occur through various pathways of exposure. Total effective dose equivalent (TEDE) can be generally calculated from three pathways including external cloud shine, external ground shine and internal inhalation which contributes committed dose equivalent (CDE). In this study, we estimated off-site radiological doses

for severe nuclear accidents of Shin Kori unit 3 which is named an advanced power reactor 1400 (APR1400), a two-loop pressurized water reactor (PWR) with rated thermal output of 4,000 MWt or electrical power of 1,400 MWe. It is located at the latitude of 35.3236° and the longitude of 129.2915° in the administrative district of Ulsan city. The elevation of the site is 9.5 m from the sea level. The geological location and reactor design parameters of Shin Kori unit 3 are shown in Fig. 1 and Table 1, respectively, according to design control documents of APR1400 (KEPCO and KHNP, 2014). The residential population around Shin Kori unit 3 and the relevant meteorological data are shown in Tables 2 and 3, respectively (KMA, 2019). Using the information above, the effectiveness of emergency management for Shin Kori unit 3 was addressed in terms of radiological source term, TEDE and thyroid CDE by a regulatory accident consequence analysis code. Multiple simulations were performed for two accidents of long-term station blackout (LTSBO) and loss of coolant accident (LOCA) considering the atmospheric conditions in the time of morning and evening of four seasons. Through the preliminary analysis, the evening time of winter was found to have the most significant effect on the accident (Uddin, 2019). The worst scenario in the evening time of winter was chosen and analyzed for two hypothetical accidents of LTSBO and LOCA in this study.

2. Materials and Methods

Radiological assessment system for consequence analysis (RASCAL) is the software developed by United States Nuclear Regulatory Commission (NRC) emergency operations center to estimate projected doses from radiological emergencies (U.S. NRC, 2017a). The code can provide the rapid dose assessment for an incident or accident and help any decision-making process such as whether the public should be considered shelter-in-place or immediate evacuation. RASCAL can compute nuclear reactor's source terms, airborne transport of activities through both Gaussian plume and puff models, and the resulting off-site doses (Athey et al., 2015).

Atmospheric dispersion is generally governed by a differential equation called the diffusion equation. With a set of assumptions that can be reasonably applied to the atmospheric processes, this diffusion equation has a specific and closed-form algebraic solution of Gaussian function. In a Cartesian coordinate system with x and y axes in the horizontal plane and z in the vertical, the normalized concentration in the vicinity is as follows.

Fig. 1. Geographic Information Around Shin Kori Unit 3

Table 1. Location and Parameters of Shin Kori Unit 3

Location	
City	Seosaeng-myeon, Ulju-gun, Ulsan
Latitude/Longitude/Sea level	35.3236 °N, 129.2915 °E, 9.5 m
UTC offset	9 hrs
Reactor parameters	
Reactor power	3,983 MWt
Average burnup	28,914 MWd/MTU
Containment type	PWR dry ambient
Containment volume	3.13×10^6 ft ³
Design pressure	50 lb/in ²
Design leak rate	0.10 %/d
Coolant mass	2.92×10^5 kg
Assemblies in core	241
Type of steam generator	U-Tube
Water mass of steam generator	218,000 kg
Release pathway	
Type	PWR dry containment leakage or failure
Release height	60 m

Table 2. Residential Population Around Shin Kori Unit 3

Distance (km)	Population
0~2	2,367
2~4	6,338
4~6	5,068
6~8	15,185
8~10	22,308
10~20	551,853
20~35	3,464,351
Total	4,067,470

Table 3. Meteorological Information in this Study

Season	Time	Type	Direction (degree)	Speed (m/s)	Stability Class	Temp (°C)
Winter	2017/12/12; 09:00	Obs	320	3.8	B	-5.8
	2017/12/12; 10:00	Obs	290	4.4	B	-4.6
	2017/12/12; 11:00	Obs	290	4.4	B	-3.4
	2017/12/12; 12:00	Obs	290	4.1	B	-2.1
	2017/12/12; 13:00	Obs	320	5.0	C	-1.8
	2017/12/12; 14:00	Obs	320	5.0	C	-1.5
	2017/12/12; 15:00	Obs	320	4.5	B	-0.9
	2017/12/12; 16:00	Obs	290	4.1	B	-1.1
	2017/12/12; 17:00	Obs	270	3.8	B	-1.9
	2017/12/12; 18:00	Obs	290	2.8	B	-2.5
	2017/12/12; 19:00	Obs	360	1.5	A	-3.3
	2017/12/12; 20:00	Obs	320	2.6	B	-3.5
	2017/12/12; 21:00	Obs	320	2.4	B	-3.8
	2017/12/12; 22:00	Obs	320	1.7	A	-4.1
	2017/12/12; 23:00	Obs	340	2.1	B	-4.4
	2017/12/13; 00:00	Obs	320	2.2	B	-4.9
	2017/12/13; 01:00	Obs	340	2.6	B	-4.8
	2017/12/13; 02:00	Obs	320	1.6	A	-5.6
	2017/12/13; 03:00	Obs	360	3.0	B	-5.5
	2017/12/13; 04:00	Obs	360	2.9	B	-4.4
	2017/12/13; 05:00	Obs	290	6.9	C	-4.1
	2017/12/13; 06:00	Obs	290	6.2	C	-4.8
	2017/12/13; 07:00	Obs	340	3.1	B	-5.2
	2017/12/13; 08:00	Obs	70	2.2	B	-5.6
	2017/12/13; 09:00	Obs	90	2.5	B	-3.9
	2017/12/13; 10:00	Obs	320	4.3	B	-2.5
	2017/12/13; 11:00	Obs	320	4.4	B	-1.0
	2017/12/13; 12:00	Obs	290	5.0	C	0.4
	2017/12/13; 13:00	Obs	290	5.7	C	1.6
	2017/12/13; 14:00	Obs	290	4.6	B	2.5
	2017/12/13; 15:00	Obs	340	3.4	B	2.5
	2017/12/13; 16:00	Obs	360	3.2	B	1.9
	2017/12/13; 17:00	Obs	340	2.0	A	0.5

$$\frac{\chi(x,y,z)}{Q} = \frac{1}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} \times \exp\left[-\frac{1}{2}\left(\frac{x-x_o}{\sigma_x}\right)^2\right] \quad (1)$$

$$\times \exp\left[-\frac{1}{2}\left(\frac{y-y_o}{\sigma_y}\right)^2\right] \times \exp\left[-\frac{1}{2}\left(\frac{z-z_o}{\sigma_z}\right)^2\right]$$

where χ is the concentration (Ci/m³ or g/m³) and Q is the amount of material released (Ci or g). σ is the dispersion parameter (m) which is a function of distance from the release point. When combined with a transport mechanism to move the center of the puff (x_o , y_o , z_o), Eq. (1) is a simplified version

of the puff model in RASCAL (Ahangari et al., 2017).

The basic scenario of LTSBO was assumed to have been initiated by an external event which caused the loss of offsite and onsite AC power at Shin Kori unit 3. It was assumed that the reactor was shut down at 5:30, 12 December 2017. Reactor cooling was maintained for a period of several hours but was ultimately lost, at which point the coolant boiled away. Core damage and releases from the core began after core uncover. Emergency diesel generators (EDGs) were providing the electric power and emergency core cooling systems (ECCS) were available and operating for 5 hrs. These

inputs were combined with the shutdown time to determine when the reactor coolant would begin to boil off. Then, RASCAL added a fixed boil-off duration of 8 hrs according to NUREG-1935 to determine the time of core melt and release (U.S. NRC, 2012). EDGs became inoperable after 5 hrs and the core began to heat to the point of meltdown. The containment sprays then became inoperable which increased containment pressure and leakage to a release rate of 5% per day. Power was restored at 21:00 and the core was recovered. Containment pressure was reduced by 04:30 of the next day and then containment leakage was stopped (U.S. NRC, 2017b).

In case of LOCA, it was also assumed that there was a major rupture in the primary coolant system after the extreme natural disaster. As a result, the reactor was tripped at 18:00, 12 December 2017. Due to significant loss of coolant passed into the containment building, the core was uncovered at 19:00. Release from the containment to the atmosphere was assumed to follow the leak rate of design control documents of APR1400 (KEPCO and KHNP, 2014). Release rate was assumed to be 3% per day. At 01:00 of the next day, operators were able to recover the core. Containment remained at high pressure which kept the release ongoing and pressure was not reduced until 05:00 of the next day. At that time, the release rate was set to be 0.1% per day (U.S. NRC, 2017c).

3. Results and Discussion

The accident scenario and radiological source terms for LTSBO were shown in Table 4. Noble gases, iodine and particulate

nuclides were remarkably released to the atmosphere. Among the released activities to the atmosphere, the proportional portion of noble gases was higher by 51.4% and that of iodine was 27.7%. This was because the reactor core was melted in the case of LTSBO. It was observed that activities were increasing until the time of 21:00 as shown in Figs. 2 and 3. After that, the activities of ^{135}Xe , ^{132}I and ^{132}Te were decreasing slowly because of their relatively short half-lives which were 9.1 hrs, 2.3 hrs and 3.2 days, respectively. But, ^{133}Xe remained steady after reaching the maximum point compared to others. ^{133}I and ^{131}I were showing the similar characteristics and they decreased rapidly with half-lives of 20.8 hrs and 8 days, respectively. ^{135}I had a half-life less than 7 hrs and it shortly decayed to ^{135}Xe . It was also observed that the radioactive plume was moving towards the south-east direction from Shin Kori unit 3 and accumulated TEDEs during 48 hrs since 18:30 of 12 December were shown in Fig. 4. TEDE and thyroid CDE for LTSBO were shown in Tables 5 and 6, respectively. TEDE and thyroid CDE were 14 mSv and 160 mSv, respectively, at about 5 km of PAZ in the evening time of winter season. Calculated values of TEDE and thyroid CDE in PAZ were higher than the Korean regulations on the indoor sheltering of 10 mSv in 2 days and thyroid protection level of 100 mSv, and therefore it was found that indoor sheltering and distribution of iodine prophylaxis should be immediately implemented for short-term protective measures. In this situation, an immediate evacuation should be decided by the off-site emergency management center (OEMC) which was responsible for emergency decision-making process under the nuclear safety and security commission (NSSC) in Korea.

Table 4. Scenario and Source Term for LTSBO

Accident scenario		
Type	Long Term Station Black Out	
Shutdown	2017/12/12; 05:30	
Release from core starts	2017/12/12; 18:30	
Core recovered	2017/12/12; 21:00	
Release events		
2017/12/12; 18:30	Leak rate (% vol) 5.0 %/d	
2017/12/12; 18:30	Sprays off	
2017/12/13; 04:30	Leak rate (% vol) 0.1 %/d	
Activities released to the atmosphere		
	Bq	% of total
Noble gas	1.5×10 ¹⁷	51.4
Iodine	8.1×10 ¹⁶	27.7
Particulate	6.1×10 ¹⁶	20.9
Total	2.92×10 ¹⁷	100.0

Fig. 2. Source Terms of ^{133}Xe , ^{135}Xe , ^{132}I and ^{132}Te for LTSBO

Fig. 3. Source Terms of ^{133}I , ^{131}I , ^{99}Mo and ^{135}I for LTSBO

Fig. 4. Contour Plot of TEDE for LTSBO

Table 5. TEDE for LTSBO and LOCA in Winter

Distance from release (km)	TEDE (mSv)			
	LTSBO		LOCA	
	Morning	Evening	Morning	Evening
3.22	16	28	0.093	0.170
4.83	7.4	14	0.043	0.080
6.44	4.8	9.3	0.031	0.057
8.05	3.8	7.4	0.030	0.053
11.3	2.8	6.4	0.031	0.060
16.1	2.0	5.2	0.024	0.042
24.1	1.4	3.9	0.019	0.031
32.2	1.3	2.8	0.017	0.023

Table 6. Thyroid CDE for LTSBO and LOCA in Winter

Distance from release (km)	Thyroid CDE (mSv)			
	LTSBO		LOCA	
	Morning	Evening	Morning	Evening
3.22	170	330	0.61	0.92
4.83	79	160	0.28	0.46
6.44	51	110	0.18	0.31
8.05	39	86	0.14	0.24
11.3	31	80	0.12	0.26
16.1	23	66	0.09	0.21
24.1	16	49	0.08	0.16
32.2	15	35	0.08	0.13

The accident scenario of LOCA and top eight radionuclides released to the atmosphere for both accidents of LTSBO and LOCA were shown in Tables 7 and 8, respectively. Among the released activities to the atmosphere, the proportional portion of noble gases was higher by 99% but that of iodine was smaller by 0.3% unlike LTSBO. This was because reactor core was not melted in case of LOCA. It was observed that released activities were increasing very fast to their maximum values within 2 hrs and then, the activities were decreasing slowly until 05:00 of the next day as shown in Figs. 5 and 6. ^{133}Xe and ^{135}Xe were showing almost similar characteristics and decreased slowly with 5.2 days and 9.2 hrs of half-lives, respectively. The behaviors of ^{88}Kr and $^{85\text{m}}\text{Kr}$ were different because both particles' half-lives were relatively short, i.e., 2.8 hrs and 4.5 hrs, respectively. ^{87}Kr decreased very quickly with a short half-life of 76.3 minutes and there was little contribution to the

population to radiation exposure during the early phase of a nuclear accident. $^{135\text{m}}\text{Xe}$ also decreased very fast to an unstable isotope of xenon with a half-life of 9.2 hrs. As shown in Fig. 7, the radioactive plume whose TEDE was above 10 mSv did not reach to the distance of 8 km (5 miles) from the facility. TEDE and thyroid CDE were 0.08 mSv and 0.46 mSv, respectively, at about 5 km of PAZ in the evening time of winter season. Both values were sufficiently low when compared with the criteria of 10 mSv for 2 days because most radioactive isotopes released to the atmosphere belonged to noble gases. The accident scenario of LTSBO proved to be more dangerous than that of LOCA in this study, As shown in Figs. 8 and 9, this result could be convinced by the fact that estimated TEDEs of Shin Kori unit 3 for LTSBO and LOCA showed similar trends with those of Arkansas unit 2 and Braidwood unit 1 in the United States, whose reactor powers were 3,026

Table 7. Scenario and Source Term for LOCA

Accident scenario		
Type	Loss of Coolant Accident	
Shutdown	2017/12/12; 18:00	
Release from core starts	2017/12/12; 19:00	
Core recovered	2017/12/13; 01:00	
Release events		
2017/12/12; 19:00	Leak rate (% vol) 3.0 %/d	
2017/12/12; 19:00	Sprays on	
2017/12/13; 05:00	Leak rate (% vol) 0.1 %/d	
Activities released to the atmosphere		
	Bq	% of total
Noble gas	1.287×10 ¹⁷	99.0
Iodine	3.4×10 ¹⁴	0.3
Particulate	9.2×10 ¹⁴	0.7
Total	1.3×10 ¹⁷	100.0

Table 8. Top eight Source Terms for LTSBO and LOCA

	LTSBO		LOCA	
	Nuclide	Bq	Nuclide	Bq
1	^{133}Xe	1.1×10^{17}	^{133}Xe	8.7×10^{16}
2	^{135}Xe	3.2×10^{16}	^{135}Xe	2.7×10^{16}
3	^{132}I	2.8×10^{16}	^{88}Kr	7.2×10^{15}
4	^{132}Te	2.7×10^{16}	$^{85\text{m}}\text{Kr}$	4.1×10^{15}
5	^{133}I	2.5×10^{16}	^{85}Kr	3.4×10^{14}
6	^{131}I	2.1×10^{16}	$^{133\text{m}}\text{Xe}$	2.6×10^{15}
7	^{99}Mo	8.0×10^{15}	$^{135\text{m}}\text{Xe}$	2.5×10^{15}
8	^{135}I	6.8×10^{15}	^{87}Kr	1.5×10^{15}

Fig. 5. Source Terms of ^{133}Xe , ^{135}Xe , ^{88}Kr and $^{85\text{m}}\text{Kr}$ for LOCA

Fig. 6. Source Terms of ^{85}Kr , $^{133\text{m}}\text{Xe}$, $^{135\text{m}}\text{Xe}$ and ^{87}Kr for LOCA

Fig. 7. Contour Plot of TEDE for LOCA

Fig. 8. Comparison Between Shin Kori Unit 3 and Arkansas Unit 2 for LTSBO

Fig. 9. Comparison Between Shin Kori Unit 3 and Braidwood Unit 1 for LOCA

MWt and 3,645 MWt, respectively, and other reactor design parameters were similar with Shin Kori unit 3 (U.S. NRC, 2017b, 2017c).

4. Conclusions

The objective of this study was to analyze the off-site radiological consequences from hypothetical severe accidents of Shin Kori unit 3 along with the emergency protective levels in Korea. In order to investigate the effect of released radioactive materials to the public, TEDE and thyroid CDE were evaluated

using a regulatory software tool developed by U.S. NRC. Multiple simulations were performed considering reactor conditions and seasonal effects. In the event of LTSBO, TEDE and thyroid CDE were estimated to be 14 mSv and 160 mSv, respectively, at about 5 km of PAZ in the evening time of winter season. Estimated values of TEDE and thyroid CDE in PAZ were higher than the Korean regulations on the indoor sheltering of 10 mSv in 2 days and thyroid protection level of 100 mSv, and therefore it was found that more careful public protective measures of emergency management should be taken in the accident of LTSBO.

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