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Application of Various Protective Actions for Multi-unit Accidents

Sunghyun Park, Mina Cho, Seokwoo Sohn and Moosung Jae*
Department of Nuclear Engineering, Hanyang University, Seoul, 04763, Republic of Korea
**Corresponding author: jae@hanyang.ac.kr*

1. Introduction

Nuclear plant licensee should prepare protective actions for the radioactive plume exposure area, including evacuation, sheltering, and consideration of potassium iodide (KI). However, these protective actions are based on a single unit accident.

Since the Fukushima accident, the possibility of multi-unit accidents has been identified although it is very unlikely. Therefore, appropriate protective actions for multi-unit accidents have been needed, but it is very complex and difficult to be developed because of the beginning of protective actions and exposure areas.

In this study, we applied the methodology for evaluating the protective actions for single unit accidents [1] into multi-unit accidents. The objectives of this study are to evaluate the various protective actions, to assess whether the implementation of alternative protective actions could reduce potential health effects, and to gain a better insight into the protective actions.

2. Methods

In this section, how to select multi-unit source term, protective actions, and consequence modeling are described.

2.1 Multi-unit Source Terms

In order to apply the protective actions for single unit accidents to multi-unit accidents, we utilized the previous results of multi-unit probabilistic safety assessment (MU-PSA) [2].

The source term for the multi-unit accident can be classified into two categories by the release characteristics; the first is the rapidly evolving source term (RE-ST) and the second is the progressively evolving source term (PE-ST). The RE-ST has the characteristic of releasing a large amount of I-131 in a relatively short time, and the PE-ST has the characteristic of releasing I-131 gradually over a relatively long period of time.

In order to select the RE-STs and the PE-ST from the previous results of MUPSA, we considered multi-unit loss of offsite power for two units (2MU-LOOP), three units (3MU-LOOP), and four units (4MU-LOOP).

Next, we selected the top ten source terms by frequency for each multi-unit accident. In order to select the RE-ST and PE-ST from the top ten source terms, we considered the duration between public notification time and release time and the total amount of I-131 released. The selected source terms information and its type are presented in Table I.

2.2 Various Protective Actions

In general, various protective actions should be

Table I: Source Term Information

Initiating Event	Accident Sequence	Frequency (/yr)	Earliest Warning Time (sec)	Earliest Release Time (sec)	Total Amount of I-131 (Bq)	Type
2MU-LOOP	K3-S20 + K4-S20	1.21E-07	21,139	21,404	1.17E+18	RE-ST
	S3-S10 + S4-S10	4.43E-08	167,514	259,200	2.55E+18	PE-ST
3MU-LOOP	K2-S13 + K3-S20 + K4-S20	1.08E-09	4387	4,495	1.48E+18	RE-ST
	S1-S2 + S2-S2 + S3-S14	1.33E-10	180,002	181,751	2.03E+18	RE-ST
4MU-LOOP	K2-S2 + K3-S2 + S3-S14 + S4-S10	1.86E-13	991	2,375	3.31E+18	RE-ST
	K3-S20 + K4-S20 + S1-S2 + S2-S2	1.04E-13	21139	21,404	1.17E+18	RE-ST

K2-S2	: No containment failure in Kori 2
K2-S13	: Isolation failure in Kori 2
K3-S2	: No containment failure in Kori 3
K3-S13	: Late containment failure (rupture) in Kori 3
K3-S20(=K4-S20)	: Isolation failure in Kori 3
S1-S2(=S2-S2)	: No containment failure in Shin-kori 1
S3-S10(=S4-S10)	: Late containment failure (rupture) in Shin-kori 3
S3-S14	: Containment failure before vessel breach in Shin-kori 3

limited to a few effective options because decision-makers may not have sufficient time and/or information to sort through several different and potentially complex protective action strategies [3].

Hence, the following five strategies were considered in this study.

1. Radial evacuation (baseline)
2. Lateral evacuation
3. Staged evacuation
4. Shelter-in-Place (SIP) followed by radial evacuation
5. SIP followed by lateral evacuation

For the radial evacuation, people travel directly toward the boundary and receive no further dose after they cross it. For the lateral evacuation, people travel azimuthally (around the compass) until they emerge from the plume [1].

2.3 Consequence Modeling

In this study, we utilized the WinMACCS version 3.11.2 developed by Sandia National Laboratories (SNL). Also, this study covered only the consequence calculated by the emergency phase, which is typically one week. The emergency phase with major input parameters is shown in Fig. 1.

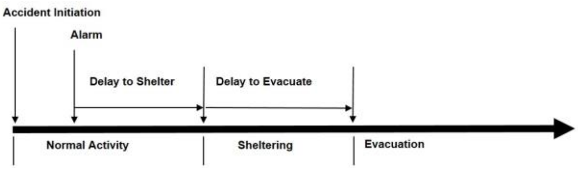

Fig. 1. Timeline of the Emergency Phase in WinMACCS [4]

Major input parameters or assumptions for the modeling are as follows:

1. A 16 km radius was used as the outer boundary for dose calculations.
2. Keyhole evacuation was used to simulate the lateral evacuation.
3. ‘Delay to shelter’ was assumed to be 15 minutes.
4. Sheltering periods of 4, 6, 8, and 10 hours were considered.
5. People in the Exclusion Area Boundary (EAB) are excluded from the calculation, and EAB is assumed 0.5 km from reactor.
6. Evacuation Time Estimates (ETEs) include 4, 6, 8, 10 hours.
7. For the staged evacuation scenario, the evacuation speeds were varied over three-time intervals, such that the population would travel a little faster speed for the first 2 km, slower for the next 5 km, and even slower for the next 9 km.
8. Protective factors used in NUREG/CR-6953 were used [1].

The evacuation speeds for each ETEs are presented in Table II and Table III. In Table III, calculation of evacuation speed only for 4-hours ETE is described.

Table II: Evacuation Speed of Radial and Lateral Evacuation

ETE	Evacuation Speed (m/s)
4-hrs	1.08 = (16000-500)/(4·3600)
6-hrs	0.72 = (16000-500)/(6·3600)
8-hrs	0.54 = (16000-500)/(8·3600)
10-hrs	0.43 = (16000-500)/(10·3600)

Table III: Evacuation Speed of Staged Evacuation

ETE	Evacuation Speed
4-hrs	3.00 = (2000-500)/(500) 1.25 = (5000)/(4000) 0.91 = (9000)/(9900)
6-hrs	2.00, 0.83, 0.61
8-hrs	1.50, 0.63, 0.46
10-hrs	1.20, 0.50, 0.37

3. Results

In this section, the various protective actions for each multi-unit source term are evaluated compared to radial evacuation. Each protective action can be evaluated as ‘less benefit’ or ‘significantly less benefit’. If a certain protective action is evaluated to be less than twice the baseline, it was assumed the same as the baseline. Also, if a certain protective action is evaluated to be more than ten times the baseline, it was assumed ‘significantly less benefit’, and the others was assumed ‘less benefit.’

3.1 Protective Actions for Two Units

The RE-ST and PE-ST were selected for the two units accident. In the case of PE-ST, the Early Fatality population-weighted risk (EF-risk) was not calculated, and the Latent Cancer Fatality population-weighted risks (LCF-risk) for all protective actions were not different. Therefore, we suggest only the RE-ST result in this paper. The EF-risk and LCF-risk results are shown in Table IV and Table V, respectively.

Table IV: EF-risk Result for the RE-ST for Two Units

Protective Action	Benefit
Radial Evacuation	Baseline (not significantly different from baseline)
Lateral Evacuation	
Staged Evacuation	
SIP-4hrs/ETE-4,6,8,10hrs/Radial Eva.	Less benefit
SIP-4/ETE-4,6,8,10/Lateral Eva.	
SIP-6,8,10/ETE-	Significantly less

4,6,8,10/Radial Eva.	benefit (more ten times greater than baseline)
SIP-6,8,10/ETE-4,6,8,10/Lateral Eva.	

Table V: LCF-risk Result for the RE-ST for Two Units

Protective Action	Benefit
Staged Evacuation	Baseline (not significantly different from baseline)
Radial Evacuation	
Lateral Evacuation	
SIP-4,6,8,10/ETE-4,6,8,10/Radial Eva.	Less benefit
SIP-4,6,8,10/ETE-4,6,8,10/Lateral Eva.	

3.2 Protective Actions for Three Units

Two RE-ST were selected for the three units accident. The EF-risk and LCF risk results are shown from Table VI to Table VIII, respectively.

Table VI: EF-risk Result for the RE-ST(1) for Three Units

Protective Action	Benefit
Radial Evacuation	Baseline (no calculated)
Lateral Evacuation	
Staged Evacuation	
SIP-4/ETE-4,6 /Radial Eva.	
SIP-4/ETE-4,6 /Lateral Eva.	
SIP-4/ETE-8,10 /Radial Eva.	Less benefit
SIP-4/ETE-8,10 /Lateral Eva.	
SIP-6,8,10/ETE-4,6,8,10/Radial Eva.	Significantly less benefit
SIP-6,8,10/ETE-4,6,8,10/Lateral Eva.	

Table VII: LCF-risk Result for the RE-ST(1) for Three Units

Protective Action	Benefit
Radial Evacuation	Baseline (not significantly different from baseline)
Staged Evacuation	
Lateral Evacuation	
SIP-4,6,8,10/ETE-4,6,8,10/Radial Eva.	Less benefit
SIP-4,6,8,10/ETE-4,6,8,10/Lateral Eva.	

Table VIII: EF-risk Result for the RE-ST(2) for Two Units

Protective Action	Benefit
Radial Eva. (ETE-4)	Baseline (no calculated)
Lateral Eva. (ETE-4)	
Staged Eva. (ETE-4)	
Staged Eva. (ETE-6)	Less benefit
Radial Eva. (ETE-6)	
Lateral Eva. (ETE-6)	
The others	Significantly less benefit (SIP-10/ETE-10 is the worst case that is more 5,000 times than the case of radial evacuation (ETE-10))

Table IX: LCF-risk Result for the RE-ST(2) for Two Units

Protective Action	Benefit
Staged Evacuation	Baseline (not significantly different from baseline)
Radial Evacuation	
Lateral Evacuation	
SIP-4,6,8,10/ETE-4,6,8,10/Radial Eva.	Less benefit
SIP-4,6,8,10/ETE-4,6,8,10/Lateral Eva.	

3.3 Protective Actions for Four Units

Two RE-ST were selected for the four units accident. In the case of the first RE-ST, EF-risk was not calculated, and all LCF-risks were not significantly different from baseline. Hence, we suggest the only result of the second RE- ST, shown in Table X and Table XI.

Table X: EF-risk Result for the RE-ST for Four Units

Protective Action	Benefit
Radial Evacuation	Baseline (no calculated)
Lateral Evacuation	
Staged Evacuation	
SIP-6/ETE-4 /Lateral Eva.	
SIP-4/ETE-4,6,8/Radial Eva.	Less benefit
SIP-4/ETE-4,6,8/Lateral Eva.	
SIP-4/ETE-10 /Radial Eva.	Significantly less benefit (More 10 times greater than SIP-4/ETE-4)
SIP-4/ETE-10 /Lateral Eva.	
The others	

Table XI: LCF-risk Result for the RE-ST for Four Units

Protective Action	Benefit
Staged Evacuation	Baseline (not significantly different from baseline)
Radial Evacuation	
Lateral Evacuation	
SIP-4,6,8,10/ETE-	Less benefit

4,6,8,10/Radial Eva.	
SIP-4,6,8,10/ETE-4,6,8,10/Radial Eva.	

3.4 Discussion

The radial evacuation, which is the baseline, is the most effective protective action in terms of EF-risk and LCF-risk. In addition, lateral evacuation and staged evacuation are not significantly different from the baseline.

In the view of EF-risk, SIP effectiveness has been identified for some scenarios. In particular, for the four units scenario, SIP with a longer sheltering period of 6 hours is more effective than SIP with a shorter sheltering period of 4 hours. Plus, it is disadvantageous in terms of early fatality by the exposure from ground-shine as the sheltering period increases.

In the view of LCF-risk, all SIP-protective actions were evaluated as 'less benefit.'

4. Conclusions

The development of appropriate protective actions in multi-unit accidents is very complex and challenging. For the basic research, we applied the protective actions considered in the single-unit accident into multi-unit accident scenarios. This study was based on the methodology used in NUREG/CR-6953 to evaluate several protective actions in multi-unit accidents. We selected the RE-ST and PE-ST for multi-unit accidents; 2MU-LOOP, 3MU-LOOP, and 4MU-LOOP.

Early fatality population-weighted risk and latent cancer fatality population-weighted risk were used as the measure of the protective actions. A radial evacuation was evaluated as the most effective protective action. Lateral evacuation and staged evacuation are not significantly different from the radial evacuation. SIP effectiveness has been identified for some scenarios.

For the future work, the following studies will be needed: (1) more detailed source term analysis, (2) more realistic modeling of protective actions for multi-unit accidents, and (3) use of other measurements to evaluate the protective actions.

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