A Study for Identifying Multi-Unit Initiating Event and Estimating Frequency

Seungwoo Lee[a*], Ar Ryum Kim[a], Namchul Cho[a], Sokchul Kim[a], Hyowon Kim, Dohyoung Kim[a]
[a] Korea Institute of Nuclear Safety(KINS), Daejeon, Korea
k727lsw@kins.re.kr

Abstract: A purpose of this study is to identify multi-unit initiating event (IE) for probabilistic safety assessment (PSA) and estimate frequency. Two main approaches were used to identify multi-unit IEs. First approach is mainly based on reviewing the operational experience in Korea. OPIS (Operational Performance Information System) data which is a comprehensive database system providing data on events occurred in Korean nuclear power plants (NPPs) were used. Total number of 726 events data occurred during 1978 to 2017 was reviewed. Moreover, a modified event classification scheme was suggested to gain insights on multi-unit risk, especially focusing on the multi-unit IE. From this approach, IEs such as general transient (GTRN), loss of condenser vacuum (LOCV), loss of offsite power (LOOP) and steam generator tube rupture (SGTR) were identified as potential multi-unit IEs. Second approach is mainly based on analyzing the shared structures, systems and components (SSCs). Shared SSCs were identified for the sample NPP site and failure mode and error analysis (FMEA) for shared SSCs was performed to identify potential multi-unit IEs. From this approach, GTRN, LOCV, and loss of instrument air (LOIA) were identified as potential multi-unit IEs. Comprehensive lists of multi-unit IEs were identified and collected from these two approaches and multi-unit IEs subject to detailed analysis were selected by screening criteria suggested in this study. For multi-unit IEs such as GTRN, LOCV and LOOP which have been screened, frequency was estimated using maximum likelihood estimate (MLE) and Jefferey's non-informative prior.

Keywords: Multi-Units, Initiating Event, Operational Experience, Shared SSCs, Frequency

1. INTRODUCTION

According to IAEA (International Atomic Energy Agency) PRIS (Power Reactor Information System) database, approximately 80% of NPP site has more than two reactor units [1]. Especially in Korea, there are four NPP sites and more than six units are operating in each NPP site. As evidenced from Fukushima accident, it has been highlighted among other matters that multi-unit accident can occur in reality [2]. Current situation that all sites in Korea have more than two units raised public's concerns on multi-unit risk. However, there are still lack of understanding about multi-unit risk since traditional safety evaluation has been performed based on a reactor basis. Regarding the current situation that there is increased level of concerns on multi-unit risk, this study aims to identify multi-unit IE which impacts more than one NPP at the site.

Identifying IEs usually forms the basis and a starting point when performing single unit PSA and there is concrete technical backgrounds for addressing IEs for single unit PSA. In one of the international technical documents which are usually referenced when performing PSA, IAEA specific safety guides NO. SSG-3 "Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants" [3] states that the set of IEs should be identified as comprehensive as possible by using different approaches. Although this technical document provides technical background for IE in single unit PSA, it also gives similar insights for multi-unit PSA since it is expected that the fundamentals for the identification process of IEs would not be so different in multi-unit situations. IAEA document also suggests that a systematic process should be used and explains five different approaches such as analytical methods, deductive analysis techniques and etc.

Among these approaches in IAEA specific safety guides No. SSG-3, reviewing the operating experience from the plant and analytical methods such as failure mode and effects analysis (FMEA) was selected to identify multi-unit IEs in this study.
Briefly describing the structure of this study, the first part mainly explains the process for the identification of multi-unit IEs and this part consists of three subparts. In the first subpart, operational experience were analyzed using OPIS data [4] which is a comprehensive database system providing data on events occurred in Korean NPPs. Also, a modified event classification scheme was suggested and applied to have more accurate view of multi-unit IEs. In the second subpart, shared SSCs for NPPs were investigated using design documents between units or at the site and FMEA was performed to identify potential multi-unit IEs from SSCs. In the last subpart, screening criteria for multi-unit IEs were suggested based on the literature review and these criteria were applied to multi-unit IEs collected from two approaches.

Second part mainly explains a process for the estimation of multi-unit IE frequency. Currently, IE frequency in traditional single unit PSA is estimated based on reactor year unit. Since there are only a few research performed for multi-unit PSA and still there is controversy on the definition for the multi-unit IE frequency, a concept of site year with some assumption is used to estimate the multi-unit IE frequency for several case studies.

2. Identification of Multi-Unit IE

2.1. Identification of Multi-Unit IE Using Operational Experience

One of the widely used method to identify IE is to review operational experience from the plant. However, it should not be limited to the identification of IEs but could have more accurate view of a multi-unit risk. In this sense, S. Schroer et al., [5] developed an event classification schema to evaluate site risk and six main dependence classifications such as initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies were considered in the event classification schema. Using this schema, licensee event reports (LERs) that is submitted to U.S NRC (Nuclear Regulatory Commission) from 2000 through 2011 were evaluated to confirm that the proposed classification includes all potential events that may link multiple units.

Although this event classification scheme gives fruitful insight on multi-unit risk in a broad range, this is only limited to investigate IEs that has dependency between units. Since there more than one type of multi-unit IE, for example, accident occurring concurrently and propagating accident from one NPP to another NPP, this event classification scheme only considers IE that has dependency between units. Hence, this event classification scheme is modified to focus more on the causes and types of the multi-unit IEs.

In modifying the event classification scheme, 'internal factor' and 'external factor' were considered. 'Internal factors' are divided into 'hardware factor' and 'software factor'. 'Hardware factor' is also divided into 'identical component' and 'shared component', in which 'identical component' refers to the accidents occurred due to the components that have same design, operation, the operating environment in multiple units, whereas 'shared component' refers to the accidents occurred due to the links that physically connect SSCs of multiple units. 'Software factor' is divided into 'individual factors' and 'organizational factors', in which 'individual factor' refers to the accidents occurred due to individual human error such as maintenance error, whereas 'organizational factors' refers to the accidents occurred due to latent error in the organization such as safety culture, procedure and etc. Moreover, 'external factors' are also considered while internal factors were considered to focus on the hardware and human factors point of view. Seven factors such as lightening, severe climate change, external fire, external flooding, strong wind (typhoon), beyond design earthquake and marine organisms were considered in the 'external factors'.

Moreover, types of multi-unit IE were considered to find the characteristics of multi-unit IE. ORNL (Oak Ridge National Laboratory) [6] suggested the types of multi-unit accident and three types of multi-unit IEs such as independent multi-unit events, cascading multi-unit events and common cause multi-unit events were considered in this study. An example of modified event classification scheme which was used in this study is shown in Figure 1.

Internal	Software	Individual error	Accident due to individual human error such as maintenance error	External	1. Lightening	5. Strong Wind(Typhoon)
		Organizational error	Accident due to organization's error such as safety culture, procedure and etc.		2. Severe Climate Change	6. Beyond Design Earthquake
	Hardware	Identical system	Accident due to components that have same design, operation, the operating envrionment in multiple units		3. External Fire	7. Maritime Organsims
		Shared system	Accdient due to links that physically connect SSCs of multiple units		4. External Flooding	

No.	Unit	Date of events	Case	Operation mode	실제발생/발생가능	Identical	Individual	Organizational	Shared	MU Events	Evidence	발생원인	Effects on System	Result	Possible Initiating Event	Types of events (1: Independent, 2:Propagating, 3: Common casue)
7	월성4호기	2016-09-12 19:44	경주 인근지역 지진발생에 따른 월성 4호기 지진감시기 작동 및 원자로 수동정지	75%	실제발생						실제 지진이 발생하는 경우 인근 원전에 동일한 영향 발생 가능	지진		원자로 수동정지		3
8	월성3호기	2016-09-12 19:44	경주 인근지역 지진발생에 따른 월성 3호기 지진감시기 작동 및 원자로 수동정지	86%	실제발생						실제 지진이 발생하는 경우 인근 원전에 동일한 영향 발생 가능	지진		원자로 수동정지		3
9	월성2호기	2016-09-12 19:44	경주 인근지역 지진발생에 따른 월성 2호기 지진감시기 작동 및 원자로 수동정지	86%	실제발생						실제 지진이 발생하는 경우 인근 원전에 동일한 영향 발생 가능	지진		원자로 수동정지		3
10	월성1호기	2016-09-12 19:44	경주 인근지역 지진발생에 따른 월성 1호기 지진감시기 작동 및 원자로 수동정지	94%	실제발생						실제 지진이 발생하는 경우 인근 원전에 동일한 영향 발생 가능	지진		원자로 수동정지		3
11	신월성1호기 외 1개 호기	2016-09-12 19:44	경주 인근지역 지진발생에 따른 월성본부 지진감시기 작동(해당호기 : 신월성1,2호기)	100%	실제발생						실제 지진이 발생하는 경우 인근 원전에 동일한 영향 발생 가능	지진		10% 출력감발		3

Figure 1. An Example of Modified Event Classification Scheme

As stated in the introduction, total number of 726 events data from 1978 to 2017 were analyzed to identify multi-unit IEs. Number of analysts who have more than 10 years of operating experience at NPP participated and multi-unit IE was identified in two options. First option was to identify the multi-unit IE that actually occurred and second option was to identify potential multi-unit IE that actually not occurred in reality, but could possibly progress to the multi-unit IE. Reasons for considering two options was to identify the multi-unit IE as comprehensive as possible and gain some insights not only from the actual multi-unit accidents but also from near-miss multi-unit accidents. Multi-unit accident due to manual trip because of the seismic events were not included in the scope of this study.

For the 1st option, total number of 14 multi-unit accidents actually happened in Korea and it was investigated that multi-unit IEs would be GTRN, LOOP, and LOCV as is shown in Table 1.

Table 1. Multi-Unit IEs for the First Option

	NPP	Date of Occurrence	Internal and External Factors	Multi-Unit IE
1	Kori 1,2	2010.07.16	External Factors(Lightening)	General Transient (GTRN)
2	Kori 1,2,3,4	2003.09.13	External Factors(Typhoon)	
3	Hanbit 5,6	2002.11.03	External Factors(Lightening)	
4	Hanul 1,2	1993.11.23	Internal Factors(Shared System)	
5	Kori 1,2	1987.04.21	Internal Factors(Shared System)	
6	Kori 1,2	1986.10.10	Internal Factors(Shared System)	
7	Hanul 1,2	1986.10.10	External Factors(Strong Wind)	Loss of Offsite Power (LOOP)
8	Kori 1,2,3,4	1997.01.01	External Factors(Typhoon)	
9	Kori 3,4	1987.07.16/17	External Factors(Typhoon)	
10	Hanul 1,2	1986.08.28	External Factors(Marine organism)	Loss of Condenser Vacuum (LOCV)
11	Hanul 1,2	2006.05.18	External Factors(Marine organism)	
12	Hanul 1,2	2001.05.01	External Factors(Marine organism)	
13	Hanul 1,2	1997.12.28	External Factors(Marine organism)	
14	Hanul 1,2	1997.02.01	External Factors(Marine organism)	

For the 2nd option, accidents which could progress to multi-unit accidents were identified and it was investigated that potential multi-unit IEs could be LOCV, LOOP and SGTR. It was shown that GTRN identified from the 1st option was included in the LOOP from the 2nd option since the most of the GTRN occurred due to the shared systems such as switchyard.

After identifying multi-unit IEs from operational experience, a modified event classification scheme is applied to multi-unit IEs identified from 1st and 2nd option. Table 2 shows risk profile for multi-unit IEs from 1st and 2nd option.

Table 2. Risk Profile for Multi-Unit IEs using a Modified Event Classification Scheme

Types of Initiating Event		Actual Multi-Unit Initiating Event			Possible Multi-Unit Initiating Event		
Initiating Event		GTRN	LOOP	LOCV	LOOP	LOCV	SGTR
Int.	Shared Systems	0%	0%	0%	0%	0%	0%
	Identical Systems	50%	0%	0%	52%	0%	0%
	Individual	0%	0%	0%	0%	0%	0%
	Organizational	0%	0%	0%	3%	0%	100%
Ext.	Lightening	33%	0%	0%	21%	0%	0%
	Climate Change	0%	0%	0%	0%	0%	0%
	External Fire	0%	0%	0%	7%	0%	0%
	External Flooding	0%	0%	0%	0%	14%	0%
	Strong Wind	17%	100%	0%	17%	14%	0%
	Beyond Design Earthquake	0%	0%	0%	0%	0%	0%
	Marine Organism	0%	0%	100%	0%	72%	0%

As is shown in Table 2, approximately 80% of multi-unit IEs occurred due to external factors in case of 1st option, whereas external factors and internal factors occupy approximately 60% and 40% in case of 2nd option, respectively. Because of a small number of example, a number which is shown in Table 2 cannot be representative value for multi-unit risk profile. However, it is be shown that risk profile for multi-unit IEs can be gained using this modified event classification scheme and it is expected that more accurate view can be obtained with more operational experience.

2.2. Identification of Multi-Unit IEs using FMEA

According to the Article 16 (Sharing of SSCs) of Regulation of Technical Standards for Nuclear Reactor Facilities Etc., in Korean Law [7], the SSCs important to safety shall not be shared among than two nuclear facilities. However, the SSCs important to safety may be shared in case where such facilities meet all the following requirements :

1) For each nuclear facilities, all the safety requirements for the relevant shared facilities are satisfied and
2) In the accident conditions of one of the units sharing SSCs, an orderly shutdown, cooldown, and residual heat removal of the other units shall be achievable.

Although most NPPs in Korea do not have significant degree of shared SSCs, there exists possibility that multi-unit IEs can occur from shared SSCs. Due to this reason, a process described in Figure 4 is adopted to identify multi-unit IE from shared SSCs. To briefly explain the process, shared SSCs were investigated using design documents. Since then, these SSCs are further reviewed if these SSCs cause directly reactor trip or cause initiating events and component failure. After that, FMEA which is widely known as analytical method is performed to find out the failure mode of components and their effect on the NPP. While performing FMEA, potential multi-unit IEs are also identified with reviewing whether these IEs can occur at single unit or multi-units.

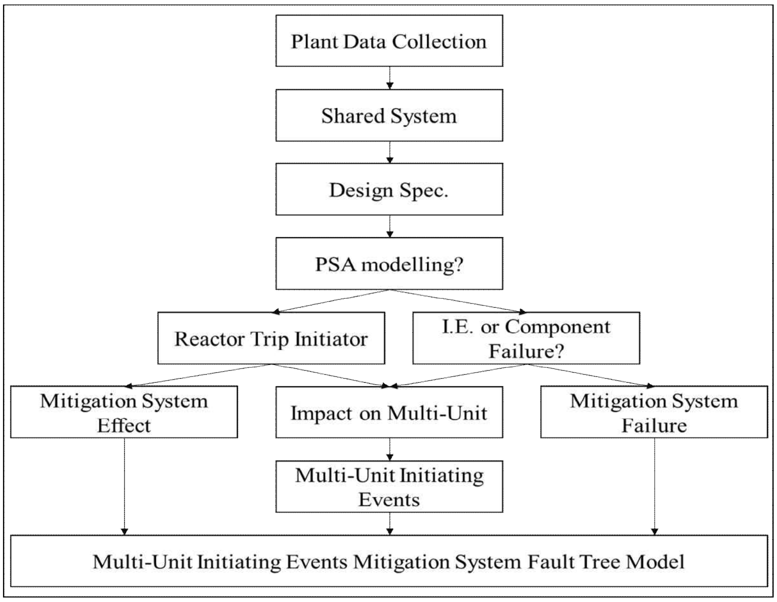

Figure 2. A Process for Identification of Multi-Unit IE from Shared SSCs

In this study, one sample NPP site in Korea was selected and it was investigated that four systems such as offsite power system, circulating water system, instrument air system and seismic monitoring system were shared systems between units or at the site. Also, components for each system were identified and FMEA was performed. Table 3 shows an example of FMEA result for circulating system which was investigated as one of the shared SSCs in this study.

Table 3. An Example of FMEA Result for Circulating System

Failure Mode	Effect	Possible I.E	Multi-Unit Effect
Loss of component cooling water due to mechanical failure	- Reactor trip due to loss of RCP seal cooling - Partial loss of related system(RCP, charging pump, RHR/SDC system, containment heat removal system, essential chilled water system and EDG)	Partial loss of component cooling water	Single Unit
Loss of essential service water due to mechanical failure	- Reactor trip due to loss RCP seal cooling - Partial loss of related system(RCP, charging pump, RHR/SDC system, containment heat removal system, essential chilled water system and EDG)	Partial loss of component cooling water	Single Unit
Loss of circulating water due to mechanical failure	- Turbine trip due to loss of condenser vacuum - Partial loss of relevant system(Turbine building, component cooling water, main feedwater, air compressor, non-safety system HVAC)	Loss of condenser vacuum Loss of feedwater Loss of instrument air	Single Unit
Loss of condenser pump	- Turbine trip due to loss of condenser vacuum - Loss of main feedwater pump	Loss of condenser vacuum	Single Unit
Loss of ultimate heat sink due to external hazards	- Reactor trip due to loss of RCP Seal cooling - Partial loss of relevant system(Turbine building, component cooling water, main feedwater, air compressor, non-safety system HVAC)	Total loss of component cooling water Loss of condenser vacuum	Multi Unit

FMEA was performed for the remaining three shared SSCs following the process described above and it was shown by the FMEA results that multi-unit IEs such as LOOP, LOFW, LOIA and GTRN would be the multi-unit IEs from shared SSCs. Table 4 shows shared systems, components and possible multi-unit IE analyzed in this study.

Table 4. Potential Multi-Unit IEs from Shared SSCs

Shared System	Components	Potential Multi-Unit IE
Offsite Power System	Switchyard, Transmission line, etc.	LOOP
Circulating Water System	Circulating water system discharge line	LOFW
Instrument Air System	Connection line between units	LOIA
Seismic Monitoring System	Seismic Monitor	GTRN

2.3. Suggestion of Screening Criteria for Multi-Unit IEs

Total number of six potential multi-unit IEs are collected from two processes. Although, one of the purpose was to collect multi-unit IEs as comprehensive as possible, some of these multi-unit IEs need to be screened if such an event has very rare probability of occurrence or model simplification is required for some purpose. In this sense, screening criteria is required to select multi-unit IEs subject to detailed analysis.

Likewise the situation for multi-unit PSA, there were few research conducted on screening criteria. ASAMPSA (Advanced Safety Assessment Methodologies PSA) [8] performed research on extended scope of PSA and one of their work was related to the development of methodology for selecting initiating events and hazards for consideration in an extended PSA which suggested screening criteria for external hazards. Although, this screening criteria is suggested for external hazards, valuable insight can be gained in multi-unit situations because external hazards was identified as one of the main causes that mostly occurred multi-unit accidents as is shown in Table 2. Table 5 shows a part of screening criteria introduced by ASAMPSA.

Table 5. Part of Screening Criteria Suggested in the ASAMPSA

Reference	Screening Criteria
IAEA SSG-3	· Dependent on the intensity of the hazard, no initiating event will be triggered. · The scenario develops slowly, there is sufficient time to control event, adverse consequences are very unlikely · The hazard scenario can be subsumed into another hazard · The hazard scenario has a significantly lower frequency of occurrence than other hazards, which lead to similar or worse consequences; simultaneously, the uncertainty of the frequency estimation is not significant for the risk assessment.
Western European Nuclear Regulators Association	· It is not physically capable of posing a threat to nuclear safety. · The frequency of occurrence of the external hazards is higher than pre-set criteria
OECD/NEA	No specific guidance on screening criteria for external hazards
ASME/ANS RA-S 2013	The event is of equal or lesser damage potential than the events for which the plant has been designed. · The event has significantly lower mean frequency of occurrence than another event and the event could not result in worse consequences than the consequences from the other event · The event cannot occur close enough to the plant to affect safety. · The event is included in the definition of another event. · The event is slow in developing allowing sufficient time for adequate response
Canada	· A phenomenon which occurs slowly or with adequate warning with respect to the time required to take appropriate protective action · A phenomenon which in itself has no significant impact on the operation of an NPP and its design basis · An individual phenomenon which has an extremely low probability of occurrence. · The NPP is located at a sufficient distance from or above the postulated

	phenomenon · A phenomenon that is already included or enveloped by design is another phenomenon
France	· Applicability : The hazard cannot occur on the site or sufficiently close to have an impact. · Inclusion : The hazard is included in the definition of other hazards analyzed for the site. · Severity : The hazard can only generate potential damage lower than or equal to that caused by similar events for which the plant was sized. · Initiating event : the hazard doesn't generate any PSA initiating event. · Kinetics : The hazard has sufficiently slow kinetics to demonstrate that there is sufficient time to either eliminate the effects or to implement a suitable response. · Frequency : The hazard has a frequency of occurrence lower than indicative target in order of a few 10-7 per reactor year. · Contribution : The risk contribution of the hazard is lower than indicative targets of a few 10-7 per reactor year for fuel meltdown, or of a few 10-7 per reactor year for large releases.
Japan	· The frequency of the hazard is apparently extremely low. · No hazard occurs in the proximity of the plant to have any impact. · Time scale for hazard progression is sufficiently longer than the time required to take countermeasure of the plant. · It is apparent that no hazard, assuming it has reached the plant, will cause any initiating event leading to core damage.
U.S.A	· The contributor or hazard cannot occur close enough to the plant to affect it. Application of this criterion must take into account the range of magnitudes and frequencies of the hazard. · Screening of contributor or hazards from a PRA based on the fact that core damage would not occur during selected mission time (e.g., 24 hours) and core damage would not occur later, assuming no credit is taken for any compensatory measures that are implemented after the mission time is expected. · The contributor or hazard is included in the evaluation of another hazard or event. [NUREG-1855]

Although Table 5 shows part of screening criteria, all the screening criteria which were suggested by ASAMPSA were reviewed and four screening criteria for multi-unit IE are suggested in this study.

1) Accident Progression : The sequence of accident is sufficiently slow to demonstrate that there is sufficient time to eliminate the effects of accident by using suitable measure.
2) Frequency : The accident has significantly low frequency of occurrence shown by results of bounding analysis.
3) Severity : The accident is not physically capable of posing a threat to plant's safety.
4) Proximity : The contribution of accident cannot occur close enough to have an impact on nearby plants.

Using above screening criteria, potential multi-unit IEs were screened. To briefly explain the results, SGTR which was identified as potential multi-unit IE from operational experience was screened out using screening criteria 2. This SGTR only occurred at single unit during maintenance team's eddy current testing (ECT) on steam generator tubes. This event is screened out because among the causes that could possibly occur SGTR, it was concluded that possibility that multi-unit SGTR will occur due to same reason such as error from the same maintenance team would very low. For the LOIA and GTRN which are identified as potential multi-unit IEs from FMEA for shared SSCs, these multi-unit IEs were screened out using screening criteria 3 and 4. Cross-tie line of instrument air was originally installed for the preparation of loss of instrument air at nearby plants, and it was concluded that this event does not propagate accident to nearby plants. For GTRN, it was concluded that seismic monitoring system does not cause direct reactor trip by in-depth analysis. However, it should be noted that GTRN from operational experience is not screened out because GTRN screened out is multi-unit

IEs from FMEA for shared SSCs. Three potential multi-unit IEs such as GTRN, LOOP and LOCV are identified after screening process.

3. Estimation of Multi-Unit IE Frequency

In a PSA carried out for a single unit, the frequency basis for initiating events and accident sequence is events per reactor calendar year. Reviewing the multi-unit PSA studies, Seabrook Station which was completed in 1983 used site based risk metrics so as not to confuse reactor based risk metrics such as CDF (Core Damage Frequency) and LERF (Large Early Release Frequency). Although 'site year' as a frequency units is recommended in some studies, there is still controversy on the exact definition of site year.

If we assume that there are number of NPPs at same site which has different initial date of operation, it is difficult to define which initial date of operation should be used as reference date when estimating the site year at this site. Since there are still technical issues for site year, two key assumptions were made when estimating site year. Firstly, site year considering from the time when the first NPP at the site went operation to current date as of September, 30, 2017 was estimated. Secondly, site year considering the time when the second NPP at the site went operation to current date used in above assumption was estimated to consider actual possibility of multi-unit accident. For the site, two cases were considered where one case is that new NPPs such as Shin-Kori and Shin-Wolsong were considered to be located at separate sites, and the other case is that new NPPs are considered to be located at the same existing sites. By combining two assumptions for site year and two assumptions for site, results for four cases are shown in Table 6.

Table 6. Site Year Estimation with Assumptions on 'Site Year' and 'Site'

NPP Site	Initial Date*	Site Year	Initial Date**	Site Year	Initial Date*	Site Year	Initial Date**	Site Year
Kori	1978.04.29	39.5	1983.07.25	34.2	1978.04.29	39.5	1983.07.25	34.2
Hanul	1988.09.10	29.1	1989.09.30	28.0	1988.09.10	291.	1989.09.30	28.0
Hanbit	1986.08.25	31.1	1987.06.10	30.3	1986.08.25	31.1	1987.06.10	30.3
Wolsong	1983.04.22	34.5	1997.07.01	20.3	1983.04.22	34.5	1997.07.01	20.3
Shin-Kori***	2011.02.28	6.6	2012.07.20	5.2				
Shin-Wolsong***	2014.07.31	3.2	2015.07.24	2.2				
	Total Site Year	144.04	Total Site Year	120.2	Total Site Year	134.24	Total Site Year	112.8

* : Initial date considering when the first NPP went operation at the site
** : Initial date considering when the second NPP went operation at the site
*** : New NPPs

Thus, frequency of three multi-unit IEs can be estimated for four cases using Table 6 and results are shown from Table 7 to Table 10. In estimating multi-unit IE frequency, maximum likelihood estimation (MLE) and Jefferey's Non-Informative Prior was considered for the Bayesian update.

Table 7. Multi-Unit IE Frequency for Case 1

Multi-Unit IEs	Number of Occurrence	Site Year	Initiating Frequency(/Site-Year)			
			MLE*	Gamma Distribution		
				Mean**	α	β
GTRN	6	144.04	4.17E-02	4.51E-02	6.5	144.04
LOOP	3	144.04	2.08E-02	2.42E-02	3.5	144.04
LOCV	5	144.04	3.47E-02	3.81E-02	5.5	144.04

* (the number of event occurrence) / (site-year)
** (the number of event occurrence + 0.5) / (site-year)

Table 8. Multi-Unit IE Frequency for Case 2

Multi-Unit IEs	Number of Occurrence	Site Year	Initiating Frequency(/Site-Year)			
			MLE*	Gamma Distribution		
				Mean	α	β
GTRN	6	122.02	4.99E-02	5.41E-02	6.5	122.2
LOOP	3	122.02	2.50E-02	2.91E-02	3.5	122.2
LOCV	5	122.02	4.16E-02	4.57E-02	5.5	122.2

Table 9. Multi-Unit IE Frequency for Case 3

Multi-Unit IEs	Number of Occurrence	Site Year	Initiating Frequency(/Site-Year)			
			MLE*	Gamma Distribution		
				Mean	α	β
GTRN	6	134.24	4.47E-02	4.34E-02	6.5	134.24
LOOP	3	134.24	2.33E-02	2.61E-02	3.5	134.24
LOCV	5	134.24	3.72E-02	4.10E-02	5.5	134.24

Table 10. Multi-Unit IE Frequency for Case 4

Multi-Unit IEs	Number of Occurrence	Site Year	Initiating Frequency(/Site-Year)			
			MLE*	Gamma Distribution		
				Mean	α	β
GTRN	6	112.8	5.32E-02	5.76E-02	6.5	112.8
LOOP	3	112.8	2.66E-02	3.10E-02	3.5	112.8
LOCV	5	112.8	4.43E-02	4.88E-02	5.5	112.8

Although these values represent multi-unit IE frequency at the sample site, it can be shown that the frequencies of multi-unit IEs can be estimated using above process

4. CONCLUSION

In this research, it was shown that multi-unit IEs can be identified using two processes such as reviewing operational data and FMEA for shared SSCs. Moreover, a modified event classification scheme is suggested to gain insight on risk profile for multi-unit IEs. For the comprehensive lists of multi-unit IEs, a screening process was performed using screening criteria suggested in this study. Multi-unit IEs such as GTRN, LOCV and LOOP were finally identified. For three multi-unit IEs, multi-unit IE frequency was estimated for four cases. Although the estimated multi-unit IE frequency is not a representative value for the sample site, it could be shown that multi-unit IE frequency can be estimated process described in this study. It is expected that more precise multi-unit IE frequency can be estimated when there is more supporting technical backgrounds for assumptions made in the estimation. A process shown to identify multi-unit IEs and estimate frequency in this research could be used to develop a technical foundation for estimating multi-unit risk.

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