Nuclear Engineering and Technology 50 (2018) 1210–1216

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Topical Issue Article

Development of logical structure for multi-unit probabilistic safety assessment

Ho-Gon Lim*, Dong-San Kim, Sang Hoon Han, Joon Eon Yang

Korea Atomic Energy Research Institute, Daejeon, 34057, Republic of Korea

ARTICLE INFO

Article history:
Received 28 June 2018
Received in revised form
27 September 2018
Accepted 12 October 2018
Available online 13 October 2018

Keywords:
Multi-unit PSA
Multi-unit risk
Site risk
Site CDF
Multi-unit CDF

ABSTRACT

Site or multi-unit (MU) risk assessment has been a major issue in the field of nuclear safety study since the Fukushima accident in 2011. There have been few methods or experiences for MU risk assessment because the Fukushima accident was the first real MU accident and before the accident, there was little expectation of the possibility that an MU accident will occur. In addition to the lack of experience of MU risk assessment, since an MU nuclear power plant site is usually very complex to analyze as a whole, it was considered that a systematic method such as probabilistic safety assessment (PSA) is difficult to apply to MU risk assessment. This paper proposes a new MU risk assessment methodology by using the conventional PSA methodology which is widely used in nuclear power plant risk assessment. The logical failure structure of a site with multiple units is suggested from the definition of site risk, and a decomposition method is applied to identify specific MU failure scenarios.

1. Introduction

Multi-unit (MU) accidents simultaneously challenging two or more than two combination of nuclear reactors or spent fuel pools had been considered as very rare events in a nuclear power plant (NPP) site, and hence in most cases, MU accidents were screened out from the risk profile of an NPP site. However, the Fukushima accident showed that MU accidents can be a major source of threat to the nuclear safety of any region [1]. Also, MU risk in a region can increase if the density of NPPs at a site or the occurrence frequency of MU accidents is relatively high.

Although MU accidents were considered to be very rare in the past, there has been studies for MU risk assessment. The Seabrook station PSA [2] was the first published MU risk assessment for a two-unit NPP site in terms of dependency of the two units. In this assessment, two types of MU initiating events were considered. One is common initiators by which all NPP units at a site experience initiating event simultaneously. The other is the successive occurrence of independent internal initiating events in two or more units. The overall risk assessment methodology was based on single-unit PSA methods except for modeling shared components and common cause failures. For common cause failures, the beta factor model was applied to avoid the complexity of the model. This simple approach can be justified because the number of units is only two and by which the conservatism of the model may be allowable. In the 2000s, MU risk issues were applied to small modular reactor (SMR) design [3] because a numbers of reactor modules are installed in one SMR design by which simultaneous multi-reactor accidents can occur.

After the Fukushima accident, there have been a large number of studies on site or MU risk [4–10]. Although several approaches to site risk assessment have been suggested so far, most of the approaches focused on two-unit sites. However, there already exist a number of NPP sites with even six or more units in several countries including Korea, and the number of such large MU sites can increase in the near future to meet electrical power demands in many countries [11]. Therefore, a systematic approach to MU risk assessment is needed to treat three or more NPP units at a site.

As one of the series of studies [12–15] to develop methods and tools for multi-unit probabilistic safety assessment (MUPSA), this study provides the overall methodology to construct a site or MU risk assessment model. The basic idea is to use each individual unit PSA model as the logic component of site or MU PSA model after treating dependencies among the units at the site. The top structure of MUPSA model is proposed according to the definition of site or MU risk. Then, the decomposition of Boolean logic is applied to identify detailed MU accident sequences without subsuming any of MU sequences. It is due to the fact that, since most of multi-unit

* Corresponding author.
E-mail address: hglim@kaeri.re.kr (H.-G. Lim).

https://doi.org/10.1016/j.net.2018.10.012

accident scenarios are subset of single-unit accident scenarios, the Boolean logic for a site or MU failure logic cannot express specific MU accident scenarios (see Section 3).

This paper is composed of five sections. In Section 2, the similarities and differences between single-unit PSA (SUPSA) and MUPSA are discussed in terms of initiating events (IE), logic model for system failure, reliability data, and failure logic quantification method. Section 3 describes a methodology for constructing site or MU PSA model focusing on the top structure of MUPSA model and decomposition method to avoid subsuming of detailed MU accident scenarios. Finally, in Section 4, some technical challenges of the proposed methodology are discussed to develop a more robust and systematic MUPSA methodology in the future.

2. Considerations for MU risk assessment

The PSA technology as a static risk assessment method can usually be applied to many systems regardless of its complexity if there is no difficulty of quantification of logical failure model. The main difference between a site and its individual unit is the degree of complexity since a site is regarded as a system that is composed of individual NPP units. From this point of view, it is expected that the conventional PSA technology may be applied to develop an MU risk model with minor modifications. As the first step, it is necessary to compare the characteristics between single-unit and MU risk assessment. The following five characteristics are compared with SUPSA to identify anticipated problems in developing an MUPSA methodology. The overall difference and similarities are summarized in Table 1.

2.1. Scope of assessment

The scope of PSA for a single NPP unit (i.e. SUPSA) is generally only the single unit being analyzed. In most SUPSA models, even though a safety system or function for the unit is shared with the other unit(s), its availability is not affected. However, when one considers an MU accident, the whole system at the site should be considered interactively. According to the types of initiating events, an MU accident can affect multiple but not all units at a site or affect all units at the site. Therefore, in an MU risk assessment, all or part of units at a site can be the scope of assessment. As an example, when an MU accident is caused by the failure of a system shared between two specific NPP units, the scope of assessment is the two units. On the contrary, some natural disasters such as earthquake may influence all units at a site simultaneously. In this case, the scope of assessment is all units at the site. Furthermore, if a disaster can affect an extremely wide area (e.g. two adjacent NPP sites), the whole area may be the scope of MUPSA. In this paper, MU accidents are limited to the only one site since the frequency of disasters affecting two or more sites is extremely low in most cases.

2.2. Initiating event considered

In conventional SUPSA, an initiating event (IE) is defined as an event which can potentially lead to core damage or radionuclide release. Such events are mainly grouped into two categories: one for loss of coolant accident (LOCA) and the other for transient events which require the reactor trip. In each category, initiating events are classified into IE groups depending on their characteristics including safety systems or functions used and the similarity of accident progression for convenience of assessment. It is assumed that each IE group has identical accident sequences if the following accident evolution conditions such as safety system/function status are the same.

For an MUPSA, multi-unit initiating events can be defined as those that can lead to core damage in two or more units. The site risk can be calculated by summing single-unit risk and MU risk. MU initiating events can be classified into three categories. The first category includes cases in which independent internal events (one in each NPP unit) occur simultaneously in a specified time interval (e.g. 24 or 72 h). There is no dependency or relation among independent initiating events. As an example, if a LOCA initiating event occurs in Unit 1 and an internal fire initiating event occurs in Unit 2 within a short time interval and each initiating event progresses to reactor core damage or a more severe accident, this case belongs to this category. In general, the contribution to site risk from the simultaneous occurrence of independent single-unit initiating events in two or more units is sufficiently low to be neglected (see Ref. [12] for an example). If it is not, a detailed analysis for this category should be performed.

The second category covers cases in which all units at a site experience a common initiating event. Earthquakes, tsunamis, or typhoons have influence on large area and can induce a common initiating event as seen in the Fukushima accident. The last category involves cases in which an initiating event evolves to radionuclide release in one or more units at a site and the other units at the site

Table 1
Comparison of characteristics between SUPSA and MUPSA.

Characteristics	SUPSA	MUPSA
Scope of System	Only one power generating unit	Two or more units at a site which experience the same initiating event simultaneously (*The scope of MUPSA may increase depending on initiating event such as seismic event)
Initiating Event (IE)	An event which can be progressed to a core damage or radionuclide release accident of a unit	An event which can be progressed to core damage or radionuclide release accident of two or more units at a site. Mainly three categories of IE exist: 1) Simultaneous occurrence of independent initiating events in two or more units; 2) Affected MU events (ex. radionuclide release to neighboring units); 3) Common initiating event (ex. seismic event)
System Failure Modeling	Event Trees/Fault Trees	Event Trees/Fault Trees
Reliability Data	- Structures/systems/components (SSCs) reliability - Human reliability - Hazard frequency	- SSCs reliability - Human reliability - Hazard frequency - Common SSCs reliability - Inter-unit common cause failure data - Inter-unit SSCs fragility correlation - Human performance data related to MU event including organizational factors
Quantification Method	- Minimal cut sets from Boolean equation in terms of fault trees	- Minimal cut sets - Monte-Carlo Sampling (when FT is not treatable due to its large size or the rare event approximation is not applicable)

are affected by the release and eventually experience another initiating event.

2.3. System failure model

Event trees (ET) and fault trees (FT) are widely used in conventional PSA. Usually, ETs are used for accident sequence analysis and FTs are used for safety function/system failure modeling. Since every ET can be transformed into FT structure, the whole system failure modeling is completed by linking ETs and FTs.

As in the case of MUPSA, if one considers the whole site as a single system in which each unit is a component of the whole system, the same approach can be applied to this system. By treating dependencies among NPP units, one can develop a whole system failure model in terms of ETs and FTs.

2.4. Reliability data in a system failure model

The reliability data for system failure models in conventional PSA are mainly composed of three categories: initiating event frequency, structures/systems/components (SSCs) failure rate or probability, and human error probability. Since MUPSA for an NPP site includes individual unit failure models in a logical structure, the reliability data for a single unit can be used also in MUPSA. In MUPSA, the following additional reliability data are required.

- Common initiating event frequencies
- Reliability data for SSCs shared between multiple units
- Inter-unit common cause failure (CCF) probabilities
- SSC fragility correlation between units (in case of external hazards)
- Resources and human performance data under MU accidents

There are SSCs that are shared between two or more units. Common intake and discharge structures, common switchyard and alternative AC diesel generators (AAC DG) are typical examples of such SSCs. As for inter-unit CCFs, there may be numerous SSCs to be considered. The same type of components (e.g., pumps, valves) used in multiple units should be treated as candidates for inter-unit CCF modeling. Also, some SSCs are considered to have dependency in their fragilities for a specific hazard such as earthquake and tsunami. Since natural disasters are generally the major causes of MU accidents, the dependency of SSC fragilities between units is one of the most important factors in MUPSA. In addition, there can be inter-unit dependencies in human performance and resources in view of MU accidents.

2.5. Quantification of system failure model

In conventional PSA, a system failure model in terms of Boolean logic is generated by the ET/FT linking method. From the whole Boolean logic, one calculate minimal cut sets (MCSs) to investigate system failure scenarios and their frequencies. In case of MUPSA, the same process can be applied if Boolean logic is generated for the whole system (i.e. the NPP site being analyzed). However, the following challenges can arise due to the complexity of the system failure model for MUPSA.

- Increase of the size of the logic model
- Non-applicability of the rare event approximation (REA)

There is a possibility of exponential increase of logic model (see Section 3) depending on the number of NPP units being considered in MUPSA. As the logic model becomes larger, it is difficult to generate MCSs by using conventional FT calculation software. In that case, some other methods such as Monte-Carlo sampling [16,17] can be used as alternatives. When quantifying FTs, the rare event approximation is widely used to generate numerical values such as core damage frequency [18,19]. This approximation is based on the fact that, when failure probabilities are very low, the residual terms except the first term of the inclusion-exclusion formula [20] have very small effects and therefore there is little error in quantifying failure frequency. However, when performing MUPSA for external event (e.g. seismic event), there can be numerous high-probability basic events in the logic model. In this case, quantification using the REA can result in a significant overestimation of the total failure frequency.

3. MUPSA methodology development

3.1. Scope of IE

In this study, the MUPSA methodology development is limited to the following two initiating event categories.

- Simultaneous occurrence of independent internal initiating events in two or more units
- Common initiating events

Although the third category of IE explained in Section 2.2 may be an important source of MU accident scenarios, since this category of IE has dynamic characteristics and the logic structure can be too complex to be analyzed (see Section 4.3), it was excluded in this study.

The first IE category may include all kinds of internal IEs including LOCA, transients, internal fire and flooding. The occurrence of internal events in each NPP unit is considered to be independent. If there is a dependency between each IE, it belongs to category II, common initiating event. Common IE may include all kinds of external disasters affecting two or more NPP units at a site including earthquakes and tsunamis. The simultaneous loss of electrical power or cooling water in two or more units are other examples of IEs that belong to category II.

3.2. Definition of site risk and top structure

The risk of NPPs is quantified based on the assumption that a reactor core damage and/or containment/confinement failure accident occurs. Similarly, an accident in an NPP site may be an event which one or more NPP units are damaged in terms of reactor core and/or containment in a specified time interval. Therefore, a site damage event can be defined as a reactor core and/or containment failure accident occurred in one or more NPP units at a site within a specified time interval. By the definition, site damage event can be logically represented as follows:

$$S = \sum_{i=1}^{n} U_i, \tag{1}$$

where S is site damage event, U_i is damage event of unit i, and n is the number of NPP units at the site. The summation notation in Eq. (1) mean the Boolean summation.

Depending on the definition of an NPP damage event, S means a site core damage event or site radionuclide release event. To estimate site risk, dependencies among NPP units at the site should be carefully reflected in a unit damage event, U. The unit damage event is assumed to include all dependent events, and therefore it can be expressed as the function of unit-specific independent event set and common event set as follows:

$$U_i = U_i(E_i,\ E_c), \tag{2}$$

where E_i is independent event set related to unit i only and E_c is dependent event set related the other units at the site.

If *f(x)* is a frequency estimation function of a Boolean event, *x*, the site damage frequency can be calculated as follows:

$$f(S) = f\left(\sum_{i=1}^{n} U_i\right). \tag{3}$$

To calculate the site risk, one should know the consequence of all site damage state. For the convenience of description, the S_j is *j*-th damage state generated from Eq. (1). Then, the site risk can be defined as follows:

$$R_S = \sum_{j=1}^{m} \left(f(S_j) \cdot C_j\right) \tag{4}$$

where R_S is site risk, C_j is consequence of j-th site damage state, and m is the all possible number of damage state.

If one can calculate the site damage frequency and its consequence, the site risk may be successfully quantified. From Eq. (1), since the frequency of U_i can be calculated by logical tree quantification method such as minimal cut-set of fault tree, also the site damage frequency of *S* can be calculated similarly because the site damage frequency is a Boolean sum of each NPP damage event. There may be an increase of complexity of logical model if the number of NPPs in a site are fairly large. In this paper, only the site damage frequency is discussed. For the quantification of the consequence of the site damage, see reference [14].

3.3. Incorporation of unit damage event structure into a site risk model

To estimate the site risk exhaustively, unit damage event model should include all hazard and all operation mode of the unit. An NPP usually may be in two operational states, one for normal power operation to generate electricity and the other for low power and shutdown (LPSD). In most of PSA, the power operation mode of an NPP is regarded as a single state, in which it is assumed that overall operational parameters including system thermo-hydraulic conditions are fixed to the technically specified values. Single logical failure model are used to assess the risk of this state allowing for the system configuration changes which are minor and no effect on the normal operation of an NPP. LPSD period of an NPP, however, includes various thermos-hydraulic conditions and system configuration changes. For the risk assessment of LPSD period of an NPP, more than 10 plant operational states (POS) are used to consider the variation of T/H conditions and system configuration changes [21]. In each POS, quasi-steady state of T/H condition during predefined time window and fixed system configuration are assumed to construct single logical system failure model. Considering all operation modes of an NPP, the Boolean expression of a unit damage event model can be given as follows:

$$U_i = \sum_{j=1}^{M(i)} \left(p_{ij} \cdot U_{ij}\right), \tag{5}$$

where

M(i): *number* of operation modes of *i*-th NPP in a site,
p_{ij}: event that *i*-th unit is in operation mode *j*,
U_{ij}: damage event of unit *i* in operation mode *j*.

In addition that one should consider all operation mode of an NPP, one also should incorporate all types of initiating events which may invoked by internal causes or external causes such as earthquake and tsunami. Considering all event types from internal and external causes, the damage event of an NPP in a specific operation mode can be expressed as follows:

$$U_{ij} = \sum_{k=1}^{C(i,j)} U_{ijk}, \tag{6}$$

where

C(i,j): number of hazards of unit *i* in operation mode *j*.
U_{ijk}: damage event of unit *i* in operation mode *j* from hazard *k*.

By incorporating Eqs. (5) and (6), the structure of unit damage event model can be written as follows:

$$U_i = \sum_{j=1}^{M(i)} \left(p_{ij} \cdot \left(\sum_{k=1}^{C(i,j)} U_{ijk}\right)\right). \tag{7}$$

By using Eq. (7), the site damage event from Eq. (1) can finally be expressed as follows:

$$S = \sum_{i=1}^{n} \sum_{j=1}^{M(i)} \left(p_{ij} \cdot \left(\sum_{k=1}^{C(i,j)} U_{ijk}\right)\right). \tag{8}$$

3.4. Simplification of site damage event

The site damage event structure in terms of Boolean equation in Eq. (8) is very complicated because the number of operation modes and hazard types are not small. As explained in Section 3.3, in a conventional PSA, more than 10 operation modes are modeled to estimate the risk of an NPP unit. Furthermore, recently, many initiating event groups are used to estimate the risk more realistically. All internal event groups, flooding, fire and seismic events are major parts of hazards which are conventionally assessed to estimate the NPP risk.

There may be two types of simplification methods to reduce the complexity of site damage event model. One method is to reduce the number of operation modes by considering their duration and risk importance. Non-risk-significant operation modes in terms of their duration and risk can be absorbed in other similar operation modes if its risk importance is sufficiently lower than the other similar operation modes. If it is not, however, the conservatism of the model may be attacked and the overall estimation may be underestimated.

The other method is to use the assumption of exclusiveness among hazard events. These initiating events may also occur simultaneously, however, because their occurrence frequencies are usually very low, they are all treated as exclusive events by which the total risk of an NPP in a specific operation mode can be easily estimated as the algebraic sum of individual risk from each initiating event. Table 2 shows potential IEs that can be considered in MUPSA.

3.5. Decomposition of site damage event

Eq. (1) shows that a site damage frequency can be estimated by Boolean summation of unit risk models. If one wants to know the site risk by simply estimating a frequency of site damage event, the procedure may be similar to the conventional fault tree quantification under the condition that the unit PSA model in terms of FT is

Table 2
Potential IEs to be considered in MUPSA.

MU initiating event category	Potential IEs to be considered in MUPSA
Simultaneous occurrence of independent initiating events in more than one unit	- Internal initiating events - Internal flooding and fire events which are not propagated to the other units
Affected MU events (ex. radionuclide release to neighboring units)	- All types of initiating events
Common initiating event	- All types of external events which influence two or more units (e.g., earthquake, typhoon, tsunami) - Internal events which can challenge two or more units simultaneously

constructed and the dependencies among units are sufficiently considered.

In case that a damage state of a site should be identified to consider the consequence of each damage state, simple frequency calculation may not be applied since direct FT calculation generate minimal cut sets (MCSs) which multiple units failures are subsumed to a simple minimum failure scenario. To avoid this faculty, Eq. (1) should be decomposed into subsets of mutually exclusive events. Eq. (9) shows the exclusive decomposition of Eq. (1) as follows.

$$\begin{aligned} S &= \sum_{i=1}^{n} U_i \\ &= \sum_{i=1}^{n}\left(U_i \cdot \prod_{\theta \neq i}^{n} \overline{U_\theta}\right) + \sum_{i=1}^{n}\sum_{j=i+1}^{n}\left(U_i \cdot U_j \cdot \prod_{\theta \neq i,j}^{n} \overline{U_\theta}\right) + \cdots \\ &+ \sum_{i=1}^{n} \cdots \sum_{l=k+1}^{n} \prod_{\rho=i}^{l} U_\rho \cdot \prod_{\theta \neq i,\cdots l}^{n} \overline{U_\theta} + \cdots + \prod_{\rho=1}^{n} U_\rho \end{aligned} \tag{9}$$

As an example, let a site is composed of three units as shown in the Venn diagram of Fig. 1. The site damage event is decomposed into three type of events as follows: (1) only one unit failure events, (2) two-unit failure events, and (3) three-unit failure event.

$$\begin{aligned} S = &\left(U_1 \cdot \overline{U_2} \cdot \overline{U_3} + U_2 \cdot \overline{U_1} \cdot \overline{U_3} + U_3 \cdot \overline{U_1} \cdot \overline{U_2}\right) \\ &+\left(U_1 \cdot U_2 \cdot \overline{U_3} + U_1 \cdot U_3 \cdot \overline{U_2} + U_2 \cdot U_3 \cdot \overline{U_1}\right) \\ &+U_1 \cdot U_2 \cdot U_3 \end{aligned} \tag{10}$$

Eq. (10) can be expressed by FT using negation as shown in Fig. 2. Since the each sum-of-product in Eq. (10) is mutually exclusive, each term can be separately quantified. Also, the total damage frequency can be algebraically summed up because of the exclusiveness of each sum-of-product. This decomposition can also be accomplished by using ET since ET partitions an event into mutually exclusive subsets. Fig. 3 shows a simple example of the decomposition of a site with three units by using an ET.

4. Technical challenges for MUPSA methodology development

This study developed a methodology for performing MUPSA by using conventional PSA methods that are widely used in an NPP risk assessment. As explained in Section 3, since this methodology is based on conventional static PSA, it does not reflect the dynamic behaviors of MU accident. In addition to this, there are several limitations in performing MUPSA using the methodology. The followings describe possible challenges for the MUPSA methodology proposed in this study.

4.1. The effect of preceding accident

The present method does not provide the accident scenarios for the effect of preceding accident in a MU site. A severe accident of a unit or multiple units in the site can challenge other units unless there are appropriate countermeasure to prepare for harsh environment including radionuclide release from the unit which are progressing severe accident. If this effect is not ignorable, the overall MU risk estimated may be very optimistic one.

To avoid this difficulty, interrelations of each unit PSA especially in term of Level 2 PSA are required. That is, each unit PSA model in term of Level 1 accident sequences should reflect the effect of Level 2 accident sequences of other units. These interrelations may make the whole MUPSA model very complex.

4.2. Inter-unit common cause failure

As explained in Eq. (2), each individual unit PSA model should have inter-unit dependency including CCFs among the units at a site. For inter-unit CCFs, if there are many systems or components related to CCF, the number of CCF events can increase explosively. As an example, if each unit has four identical components and there are six NPP units at a site, one should consider CCF groups of 24 components. If the beta factor model is used to avoid the complexity of CCF modeling like the Seabrook station PSA [2], there may be a severe conservatism in MU risk assessment because the whole failure of identical component may contribute the MU risk assessment. On the contrary, if one uses the alpha factor model [22], one should generate (2^{24}−1) numbers of events to model these component's failure.

To avoid this difficulty, a hybrid method which can remove

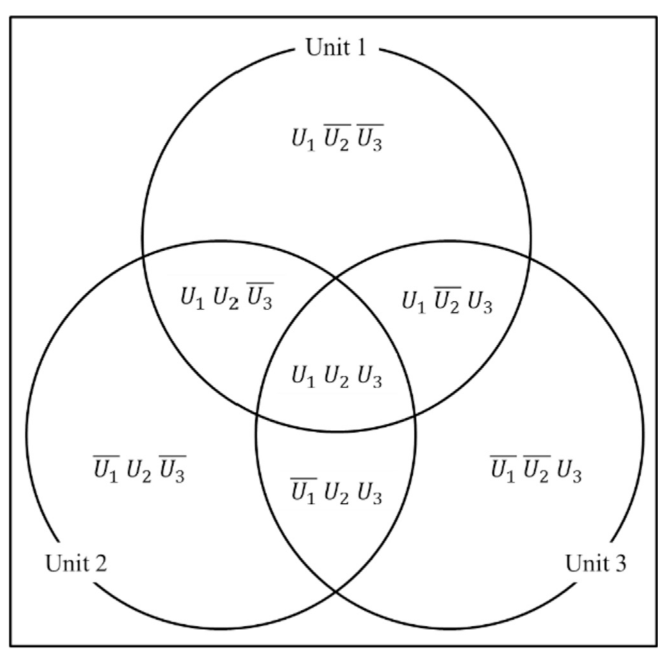

Fig. 1. Decomposition of failure events of three units to exclusively represent MU failures.

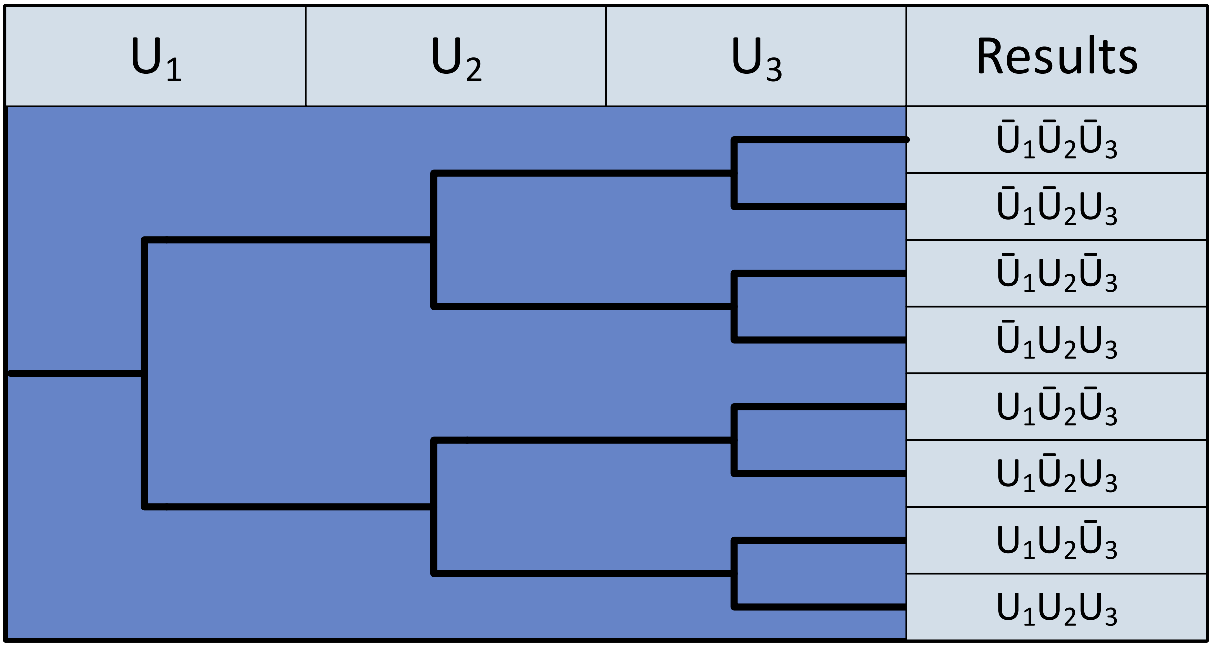

Fig. 2. Decomposition of failure events of three units using event tree.

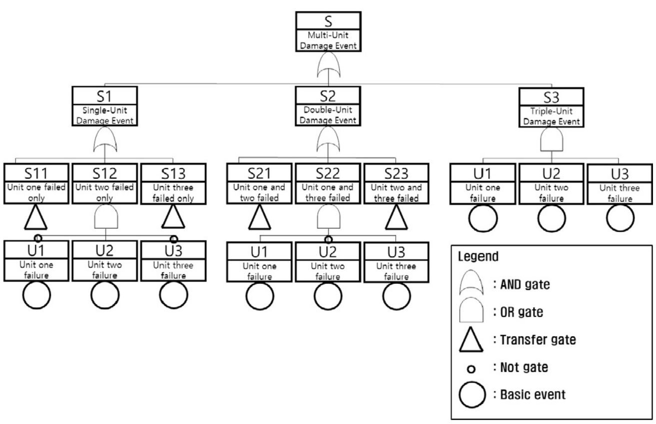

Fig. 3. Fault tree of decomposed site damage event for a site with three units.

excessive conservatism and can avoid complexity of CCF modeling are needed. A CCF model which has partially beta factor' characteristic and behave alpha factor' characteristics overall may be a desirable example of inter-unit CCF modeling to avoid conservatism and complexity simultaneously.

4.3. Use of delete-term approximation in a top structure of MU failure logic

As explained in Eq. (9), to identify MU accident scenarios, a decomposition method was employed in the MU failure logic model. Delete-Term Approximation [23] is widely used in the quantification of failure logic of a system. In conventional PSA, del-terming is applied to the success of a safety function/system and it usually makes the risk assessment optimistic [24]. In the MUPSA methodology proposed in this study, since the negation of unit failure logic is used in the top structure, unit NPP failure logics are del-termed in the whole MU failure logic quantification. It can also make the whole risk assessment results optimistic. Therefore, one should carefully examine whether this del-terming process gives optimistic results.

4.4. Modeling of human performance and resource allocation among units

As elaborated in Ref. [25], there are many additional issues to characterize the multi-unit accident risk. One of the major issues is to handle the human performance related to multi-unit accident. Staffing, command and control at the site level, and organizational factor are the examples to be investigated in the area of human reliability analysis. Also, since various movable safety systems for cooling water or electrical power supply have been introduced after Fukushima accident, the human reliability analysis for the operation of these new safety systems is the new challenging area for the multi-unit risk assessment

When a NPP site shares safety resources such as electrical power and cooling water among units and the resources are not sufficient to cover whole units, the modeling of resource allocation may be the critical problem to reasonably assess the multi-unit risk

5. Conclusion

This study proposed an overall methodology for MU risk assessment by using conventional PSA technology. It was shown that, under the condition that NPP unit failure logic is treated to include dependency among all NPP units, the top structure of MUPSA can be easily constructed according to the definition of site or MU risk. Then, to avoid subsuming of detailed MU accident scenarios into single unit accident scenarios, a decomposition method of Boolean logic was proposed. The proposed MUPSA methodology was applied to construct MUPSA model for a pilot NPP site with six units. The details are described in the series of the papers to develop MUPSA methodology and tools [12,13].

Although this methodology has its limitations as explained in Section 4, it is expected that the main features of MU risk can be identified using the methodology.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT: Ministry of Science and ICT) (No. 2017M2A8A4015287).

References

[1] IAEA, The Fukushima Daiichi Accident: Report by the Director General, International Atomic Energy Agency, 2015.
[2] Pickard Lowe, Garrick, Inc., Seabrook Station Probabilistic Safety Assessment – Section 13.3 Risk of Two Unit Station, Prepared for Public Service Company of New Hampshire, PLG-0300, 1983.
[3] K.N. Fleming, On the issues of integrated risk—a PRA practitioners perspective, in: Proceedings of the ANS International Topical Meeting on Probabilistic Safety Analysis, San Francisco, CA, USA, 2005.
[4] S. Samaddar, K. Hibino, O. Coman, Technical approach for safety assessment of MU NPP sites subject to external events, in: Proceedings of Probabilistic Safety Assessment and Management (PSAM 12), Honolulu, Hawaii, 2014.
[5] K.N. Fleming, On the risk significance of seismically induced MU accidents, in: Proceedings of the ANS International Topical Meeting on Probabilistic Safety Assessment and Analysis, ID, USA, 2015.
[6] K. Ebisawa, T. Teragaki, S. Nomura, H. Abe, M. Shigemori, M. Shimomoto, Concept and methodology for evaluating core damage frequency considering failure correlation at multi units and sites and its application, Nucl. Eng. Des. 288 (2015) 82–97.
[7] C.S. Kumar, V. Hassija, K. Velusamy, V. Balasubramaniyan, Integrated risk assessment for MU NPP sites – a comparison, Nucl. Eng. Des. 293 (2015) 53–62.
[8] T.D. Le Duy, D. Vasseur, E. Serdet, Probabilistic safety assessment of twin-unit nuclear sites: methodological elements, Reliab. Eng. Syst. Saf. 145 (2016) 250–261.
[9] S. Zhang, J. Tong, J. Zhao, An integrated modeling approach for event sequence development in MU probabilistic risk assessment, Reliab. Eng. Syst. Saf. 155 (2016) 147–159.
[10] M. Modarres, T. Zhou, M. Massoud, Advances in MU nuclear power plant probabilistic risk assessment, Reliab. Eng. Syst. Saf. 157 (2017) 87–100.
[11] IAEA, Nuclear Power Reactors in the World, Reference Data Series No. 2, International Atomic Energy Agency, 2017, 2017.
[12] D.-S. Kim, S.H. Han, J.H. Park, H.-G. Lim, J.H. Kim, Multi-unit Level 1 probabilistic safety assessment: Approaches and their application to a six-unit nuclear power plant site, Nucl. Eng. Technol. 50 (2018) 1217–1233.
[13] J. Cho, S.H. Han, D.-S. Kim, H.-G. Lim, Multi-unit Level 2 probabilistic safety assessment: Approaches and their application to a six-unit nuclear power plant site, Nucl. Eng. Technol. 50 (2018) 1234–1245.
[14] S.-Y. Kim, Y.H. Jung, S.H. Han, S.-J. Han, H.-G. Lim, Multi-unit Level 3 probabilistic safety assessment: Approaches and their application to a six-unit nuclear power plant site, Nucl. Eng. Technol. 50 (2018) 1246–1254.
[15] S.H. Han, K. Oh, H.-G. Lim, J.-E. Yang, AIMS-MUPSA software package for multi-unit PSA, Nucl. Eng. Technol. 50 (2018) 1255–1265.
[16] S.H. Han, H.G. Lim, Top event probability evaluation of a fault tree having circular logics by using Monte Carlo method, Nucl. Eng. Des. 243 (2012) 336–340.
[17] K. Oh, S.H. Han, J.H. Park, H.G. Lim, J.E. Yang, G. Heo, Study on quantification method based on Monte Carlo sampling for multiunit probabilistic safety assessment models, Nucl. Eng. Technol. 49 (2017) 710–720.
[18] W. Vesely, J. Dugan, J. Fragola, J. Minarick, J. Railsback, Fault Tree Handbook with Aerospace Applications, National Aeronautics and Space Administration, 2002.
[19] E. Ruijters, M. Stoelinga, Fault tree analysis: a survey of the state-of-the-art in modeling, analysis and tools, Comp. Sci. Rev. 15–16 (2015) 29–62.
[20] J. Kahn, N. Linial, A. Samorodnitsky, Inclusion-exclusion: exact and approximate, Combinatorica 16 (4) (1996) 465–477.
[21] KHNP, LPSD Internal Events Level 1 PSA Report for Hanul Units 3&4, Korea Hydro & Nuclear Power, Co. Ltd., 2015.
[22] U.S. Nuclear Regulatory Commission, Guidelines on Modeling Common-cause Failures in Probabilistic Safety Assessment (NUREG/CR-5485), Washington, D.C, 1998.
[23] W.S. Jung, J.E. Yang, J.J. Ha, A new method to evaluate alternate AC power source effects in multi unit nuclear power plants, Reliab. Eng. Syst. Saf. 82 (2003) 165–172.
[24] S. Epstein, A. Rauzy, Can we trust PSA? Reliab. Eng. Syst. Saf. 88 (2005) 195–205.
[25] S. Schroer, M. Modarres, An event classification schema for evaluating site risk in a multi-unit nuclear power plant probabilistic risk assessment, Reliab. Eng. Syst. Saf. 117 (2013) 45–51.