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Methodology for Evaluating Multi-unit Site Risk

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1. Introduction

Today, probabilistic safety assessment (PSA) is performed under the general assumption that a core damage event can only occur in one reactor at a time, though two-unit risk for the concurrent reactor accidents within a site was evaluated in Seabrook PSA, 1983 [1]. In other words, the multi-unit risk (MUR) within a site has been still ignored with the consensus that the quantitative health objective (QHO) based on the single-unit risk (SUR) would be sufficient to support the risk-informed decision-making (RIDM). Simply speaking, a multi-unit site risk has been regarded as the sum of single-unit risks within a site.

Following the accident that happened at Fukushima, however, the issue of multi-unit site risk is currently spreading over all multi-unit sites composed of two or more operating reactors. This is the reason why the independent risk for one reactor can be significantly underestimated by screening-out or insufficient consideration on the multi-unit initiators (MUIs) concurrently affected with a multiple units within a site.

This paper proposes a new technical basis for estimating the multi-unit site risk, using a generalized mathematical formulation regardless of the number of units at a site. It can provide more comprehensive and more practicable technical platform for estimating multi-unit site risk. Note that the authors give the results of the case study on multi-unit station black-out (MSBO) risk in another paper submitted in the conference [5].

2. Review of the Current Methods

Conceptually, MUR can be defined by the product of frequency and consequence for multi-unit initiator or event (MUI or MUE) like the general definition of risk. MUR has the characteristics that MUI frequency is lower than single-unit initiator or event (SUI or SUE), while MUI consequence (actually, peak of risk) is much higher than SUI. With the results of Seabrook PRA [1], K. Flemming [2] re-raised the importance of multi-unit site risk assessment recently to deal with the problem on the past interpretation of the QHO in the process of developing a risk-informed technology neutral framework for licensing new reactors, especially, small modular reactors.

Two representative methods for evaluating MUR, i.e., Seabrook PSA ([1],[2]) and the scoping estimation ([3],[4]), were proposed up to now. First of all, the methodology for estimating MUR should be able to ensure practicable simplicity with acceptable technical adequacy. Both of the methods adopt the way to estimate from single-unit PSA model in the viewpoint of simplicity.

Seabrook PSA method is based on traditional event tree (ET) approach combined with the inter-common cause failure (CCF) concept between units within a site to quantify the occurrence frequency of the multi-unit common cause initiator (MUCCI). The multi-unit risk profiles for just two units were illustrated in the report. In the viewpoint of the method, however, the ET approach is impractical to apply regardless of the number of units within a site because of the increase of complexity.

The scoping estimation method provides the bounding approach for the multi-unit site risk by mathematical formulation like equation 1.

$$R^{(n)} < n \cdot R_{su,MUI} + n^2 \cdot R_{su,SUI} \qquad (1)$$

where,

$R^{(n)}$= site risk for a site with n identical multi-units (per site year),

$R_{su,MUI}$= risk for multi-unit initiators (MUIs) in a single unit,

$R_{su,SUI}$ = risk for single-unit initiators (SUIs) in a single unit.

Since the site risk in this method is a bounding estimate, it cannot ensure sufficient technical adequacy basically. For example, assume a site has 6 identical units with 1e-5/ry core damage frequency for single-unit and the portion of the MUIs reaches to 40%. The bounding value of site core damage frequency can be simply over-estimated as 2.4e-4/site-year (= 6x0.4x1e-5 + 6^2x0.6x1e-5) from equation 1. It cannot also provide any information of the results detailed, e.g., site risk profile. In addition, the scoping estimate that the portion of MUIs is 0% is n times higher than one that the portion of MUI is 100%. So, the scoping estimation method cannot be applied to domestic sites with 6 operating units and over due to significant over-estimation.

3. A New Method for Estimating Multi-unit Site Risk

As mentioned in previous section, the methodology for estimating MUR should be able to ensure practicable simplicity with acceptable technical adequacy. The new method also follows the way to estimate from single-unit PSA model to ensure practicable simplicity. Thus, comprehension on the SUR structure to estimate through full-scope level 1/2/3 PSA is an important starting point.

3.1 Single-unit Risk Model

The single-unit based risk model can be simply represented as equation 2, using the terminology of NUREG-1150 [6].

$$SUR_m = \sum_{l=1}^{nSTC} \left\{ f\left(\sum_{k=1}^{nAPB} \sum_{j=1}^{nPDS} \sum_{i=1}^{n\boldsymbol{E}} \boldsymbol{E}_i \cdot PDS_{ij} \cdot APB_{jk} \cdot STC_{kl} \right) \cdot cSTC_{lm} \right\} \quad (2)$$

where,

SUR_m = annual single unit risk (per reactor year) for consequence measure *m* (e.g., early fatalities, latent cancer fatalities, etc.),

$f(\cdot)$ = annual release frequency (per reactor year) by the *l*-th source term category (STC_l),

$\boldsymbol{E}_i$ = *i*-th initiating event,

PDS_{ij} = accident sequences that $\boldsymbol{E}_i$ will be propagated to the *j*-th plant damage state (PDS_j),

APB_{jk} = accident sequences that PDS_j will result in *k*-th accident progression bin (APB_k),

STC_{kl} = accident sequences that APB_k will be assigned to the *l*-th source term category (STC_l),

$cSTC_{lm}$ = mean (over weather variability, practically) for consequence measure *m* of the *l*-th source term category (STC_l),

$nXXX$ = the number of *XXX* representing *IE, PDS, APB* and *STC,* respectively.

In practice, the equation 2 can be simplified into equation 3 because accident progression bins and source term categories are determined by plant damage state.

$$SUR_m = \sum_{l=1}^{nSTC} \sum_{k=1}^{nAPB} \sum_{j=1}^{nPDS} f\left(\sum_{i=1}^{n\boldsymbol{E}} \boldsymbol{E}_i \cdot PDS_{ij} \right) \cdot pAPB_{jk} \cdot pSTC_{kl} \cdot cSTC_{lm} \quad (3)$$

where,

$f\left(\sum_{i=1}^{n\boldsymbol{E}} \boldsymbol{E}_i \cdot PDS_{ij}\right)$ = annual frequency (per reactor year) of the *j*-th plant damage state (PDS_j) propagated by all kind of initiating events,

$pAPB_{jk}$ = conditional probability that PDS_j will result in *k*-th accident progression bin (APB_k),

$pSTC_{kl}$ = conditional probability that APB_k will be assigned to the *l*-th source term category (STC_l).

3.2 Key Assumptions and Ground-rules (KAG)

The key assumptions and ground-rules (KAGs) to develop MUR estimation structure from single-unit risk model are as follows.

KAG 1: All units within a site are identical.

KAG 2: Level 1/2/3 PSA models and results for a single unit are given.

KAG 3: Single-unit PSA model covers all kind of initiating events to affect a single unit as well as multi-units within a site.

KAG 4: For multi-unit initiators (MUIs), single-unit PSA model includes only the risk impact on the single unit, not multi-units.

KAG 5: Lots of the post-Fukushima action items are being performed including installation of extensive damage mitigation features and so on. Even though these can bring the additional dependencies for multi-units severe accident mitigation, no credit of them is taken because there is no concrete information at this point in time. It means that the progression of severe accident following the core damage is independent between the units within a site, i.e., we can use equation 3 to develop multi-unit risk model.

KAG 6: If the different types of the initiating events induced by a MUI are independently occurred among multiple units within a site, these effects are already included in a single-unit risk model.

3.3 The Proposed Model for Estimating Multi-Unit Risk

From KAG 3 and 4, first, SUR models (equations 2 and 3, without the loss of generality) can be divided into two groups of risk contributors (SUI and MUI) as equation 4.

$$SUR_m = SUR_{m,SUI} + SUR_{m,MUI} \quad (4)$$

where,

$$SUR_{m,SUI} = \sum_{l=1}^{nSTC} \left\{ f\left(\sum_{k=1}^{nAPB} \sum_{j=1}^{nPDS} \sum_{g=1}^{nSUI} SUI_g \cdot PDS_{gj} \cdot APB_{jk} \cdot STC_{kl} \right) \cdot cSTC_{lm} \right\}$$

$$SUR_{m,MUI} = \sum_{l=1}^{nSTC} \left\{ f\left(\sum_{k=1}^{nAPB} \sum_{j=1}^{nPDS} \sum_{h=1}^{nMUI} MUI_h \cdot PDS_{hj} \cdot APB_{jk} \cdot STC_{kl} \right) \cdot cSTC_{lm} \right\}$$

$$n\boldsymbol{E} \le nSUI + nMUI.$$

Note that the sum of the numbers of SUI and MUI can be even larger than the number of IE ($n\boldsymbol{E}$) in the original single-unit PSA model, in practice. In a single-unit PSA model, for example, loss of off-site power (LOOP) can include several causes to affect only single unit (e.g., electrical fault within a unit) or multi-units (e.g., external grid collapse). In this case, the LOOP frequency should be divided into two portions according to the causes of SUI and MUI. S. Schroer's work [7] can be helpful to do this.

Finally, the mathematical formula for evaluating multi-unit risk at a site with *n* multi-units can be derived from equation 4 as follows.

$$\begin{aligned} MUR_m^{(n)} &= \sum_{r=1}^{n} \binom{n}{r} \cdot SUR_{r,m}^{(n)} + \sum_{i=1}^{nMUI} fMUI_i \cdot \sum_{r=2}^{n} \binom{n}{r} \cdot pAS_{r,MUI_i}^{(n)} \cdot cR_{r,m\,(MUI_i)}^{(n)} \\ &\approx n \cdot SUR_m + \sum_{i=1}^{nMUI} fMUI_i \cdot \sum_{r=2}^{n} \binom{n}{r} \cdot pAS_{r,MUI_i}^{(n)} \cdot cR_{r,m\,(MUI_i)}^{(n)} \end{aligned} \quad (5)$$

,where

$SUR_{r,m}^{(n)}$ = the risk of consequence measure m due to the independent occurrence of the *r* single-unit initiators (SUIs) in a site with *n* multi-units,

$fMUI_i$ = the frequency of *i*-th multi-unit initiator MUI_i (per site year),

$pAS_{r,MUI_i}^{(n)}$ = the probability that accident sequences occur at *r* units of *n* multi-units within a site by MUI_i

(e.g., it means the multiplication of the probabilities corresponding to PDS, APB, and STC scenario.).

$cR^{(n)}_{r,m\,(MUI_i)}$ = the risk of consequence measure *m* for the STC of the accident sequences affected *r* multi-units by MUI_i in a site with *n* multi-units. It is needed to re-evaluate the off-site consequences with the proper conservatism on source terms from *r* multi-units release accidents.

The total risk of multi-unit concurrent reactor accidents by independent SUIs within a site with *n* units (the 1st term in the left hand side of equation 5) can approximate the sum of n single-unit risk since the concurrent frequencies of independent SUIs are very low relatively. It means that the first term in the left hand side of equation 5 is exactly identical with the traditional multi-unit risk concept having used since post-PSA era. Simultaneously, equation 5 represents that multi-unit risk within a site with n units has been underestimated as much as the amount of the second terms (MUR by multi-unit initiators). Note that the 1st and 2nd terms in the left hand side of equation 5 have different units of risk measure, i.e., reactor operating year and site operating year, respectively.

More details of the equation 5 derivation are provided with the four step procedures for estimating the MUR in the reference [8]. And, a case study on the risk estimation of the multi-unit station black-out according to the proposed method is provided by the authors' another paper [5].

4. Conclusions

This paper proposes a new technical basis for estimating the multi-unit site risk, using a generalized mathematical formulation regardless of the number of units at a site. It can provide more comprehensive and more practicable technical platform for estimating multi-unit site risk.

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