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The Use of Importance Measures for Quantification of Multi-unit Risk

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1. Introduction

A mathematical formulation for evaluating Multi-Unit Risk (MUR) at a site with *n* multi-units was presented in the Jang and Oh [1] as follows.

$$MUR_m^{(n)} \approx n \cdot SUR_m + \sum_{i=1}^{nMUI} \sum_{r=2}^{n} fMUI_{i,r} \cdot \binom{n}{r} \cdot pAS_{r,MUI_i}^{(n)} \cdot cR_{r,m(MUI_i)}^{(n)} \quad (1)$$

,where

$MUR_m^{(n)}$ = multi-unit risk at a site with *n* multi-units for consequence measure *m* (e.g., early fatalities, latent cancer fatalities, etc.),

SUR_m = annual Single-Unit Risk (SUR) per reactor year for consequence measure *m*,

$fMUI_i$ = the frequency of *i*-th Multi-Unit Initiator (MUI) 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 r-units conditional core damage probability for MUI_i, which is combined with Plant Damage State (PDS), Accident Progression Bin (APB), and Source Term Category (STC) scenarios for r-units).

$cR_{r,m(MUI_i)}^{(n)}$ = 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.

Note that the 1st and 2nd terms in the left hand side of the equation have different units of risk measure, i.e., reactor operating year and site operating year, respectively. The total risk of multi-unit reactor accidents concurred by the independent accident sequences each single-unit (the 1st term in the right-hand side of the Equation 1) can approximate the sum of n single-unit risk conservatively. It corresponds to the traditional multi-unit risk profile concept having used since post-PSA era [2]. Simultaneously, the Equation 1 represent that multi-unit risk within a site with n units has been underestimated as much as the amount of the 2nd term (MUR by multi-unit initiators), which consists of three parts: 1) the frequency estimation of a MUI, $fMUI_i$, 2) the quantification of the multi-unit accident sequences frequencies for a MUI, $pAS_{r,MUI_i}^{(n)}$, and 3) the multi-unit consequence analysis for a MUI, $cR_{r,m(MUI_i)}^{(n)}$.

In this paper, we focus on the quantification of the multi-unit accident sequences frequencies, i.e., conditional core damage probability (CCDP) for a MUI from the SUR model. The paper proposes a method for the estimation of the r-units CCDP considered the inter-unit dependency, using importance measures.

2. The Quantification of the CCDP for a MUI

As stated in Jang and Oh [1], we can decompose two terms for all MUI in the SUR model, the frequency of the MUI ($fMUI_i$) and the total CCDP of the MUI ($p(PDS_{ij} \cdot APB_{jk} \cdot STC_{kl}|MUI_i)$). If the letter be independent on MUI_i, the total CCDP for *r* units ($pAS_{r,MUI_i}^{(n)}$) can be simply calculated as the *r*-th power of the single-unit CCDP for the IE involving the MUI_i. Unfortunately, there can be the inter-unit dependencies for the mitigation components and systems. Since it is impossible to treat inter-unit dependencies directly from the enormous combinations of the r-unit accident sequences, their multi-unit risk impact should be considered properly in the process of the estimation of the *r*-unit CCDP.

In this paper, a method for the estimation of the r-units CCDP considered the inter-unit dependency is proposed by a following equation.

$$pAS_{r,MUI_i}^{(n)} \approx \sum_{X_j \in D} \left[\{CCDP(X_j=1)\}^r \cdot P'(X_j) + \{CCDP(X_j=0)\}^r \cdot \left(1-P'(X_j)\right) \right]$$
$$= \sum_{X_j \in D} \left[\{RAW(X_j) \cdot CCDP(IE)\}^r \cdot P'(X_j) + \left\{\frac{CCDP(IE)}{RRW(X_j)}\right\}^r \cdot \left(1-P'(X_j)\right) \right] \quad (2)$$

where, D is the set of the events, X_j's, judged to have inter-unit dependency from the list of minimal cutsets involving the MUI_i in the SUR model. $CCDP(IE)$, defined as the single-unit CCDP for the IE involving the MUI_i, can look up on the results of the SUR model. Therefore, $CCDP(X_j=1)$ and $CCDP(X_j=0)$ stand for the CCDP with the basic event X_j assumed failed and perfectly reliable, respectively. The importance measures, $RAW(X_j)$ and $RRW(X_j)$, are Risk Achievement Worth (RAW) and Risk Reduction Worth (RRW) of the event X_j, respectively. Finally, $P'(X_j) = IUCCF(X_j) \cdot P(X_j)$, where $IUCCF(X_j)$ and $P(X_j)$ are the inter-unit CCF factor and the failure probability of the event, X_j, respectively.

The definitions and the complementary applications of the importance measures are introduced in many references ([3],[4],[5]). The Equation 2 can be delivered inductively from the linear equation of the risk importance measures, $R(X_j) = aX_j + b$, suggested by Wall [5].

The equation underlines the point that the r-unit CCDP is predominated by the events with inter-unit dependency, compared with any combination of the multi-unit accident sequences. Note that the n-unit combined impact on the single-unit risks for all MUIs are already included in the MUR model of the equation 5. The identification of the multi-unit risk-significant events is very important thing in the process of the analysis. They can be identified by the investigation on their characteristics related to the inter-unit dependencies, such as the shared components/systems, extra equipment, site-common recovery actions, the causes stated in the paper [6], and so on.

Seabrook PSA [7] introduced the concept of IUCCF with two examples for emergency diesel generator (EDG) and motor operated valve (MOV). However, we recommend a bounding analysis using the conservative assumption on unity IUCCF (perfectly correlated) for the inter-unit dependent events identified because we can operate additively with the increase of the size of the event set (D) up to the criteria such as the predetermined coverage of the core damage accident sequences for the MUI, and so on. Henceforward the refinement of the IUCCF can be performed if needed.

3. Conclusions

The paper proposes a method for the estimation of the r-units CCDP considered the inter-unit dependency, using importance measures. It can facilitate the treatment of the inter-unit dependencies in the multi-unit risk model and can give more comprehensive and more practicable technical platform for estimating multi-unit site risk.

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Appindix: The Proof of the Equation 2

Suppose that X is an event with inter-unit dependency. All minimal cutsets for a MUI in the SUR model can be expressed by Boolean equation used in Wall [5] as follows:

$R(X) = aX + b$

,where aX represents the cutsets containing the specific event X, meanwhile b stands for the minimal cutsets not containing X.

Under the assumption that 1) X is perfect correlated between multi-units and 2) all events except X are inter-unit independent events, i.e., both a and b are independent, the maximum impact of the event X on the two-unit CCDP is expended from the Boolean logic extended by the equation (3) as follows:

$\Pr\{(R(X)^2\}$
$= \Pr\{(aX+b)^2\}$
$= \Pr\{a^2X^2+2abX+b^2\}$
$= \Pr\{a^2X+2abX+b^2\}$, by assumption 1
$= \Pr\{(a^2+2ab)\} \Pr(X) + \{\Pr(b)\}^2$
$= \Pr\{(a^2+2ab+b^2)\}\Pr(X) - \{\Pr(b)\}^2 \Pr(X) + \{\Pr(b)\}^2$
$= \{\Pr(a+b)\}^2 \Pr(X) + \{\Pr(b)\}^2\{1-\Pr(X)\}$
$= \{CCDP(X=1)\}^2 \Pr(X) + \{CCDP(X=0)\}^2 \{1-\Pr(X)\}$

For three units,

$\Pr\{(R(X)^3\}$
$= \Pr\{a^3X^3+ 3a^2bX^2+3ab^2X+b^3\}$
$= \Pr\{(a^3+ 3a^2b+3ab^2)\} \Pr(X) +\{\Pr(b)\}^3$
$= \{\Pr(a+b)\}^3 \Pr(X) + \{\Pr(b)\}^3\{1-\Pr(X)\}$
$= \{CCDP(X=1)\}^3\Pr(X) + \{CCDP(X=0)\}^3\{1-\Pr(X)\}$

…

For r units, inductively

$\Pr\{(R(X)^r\}$
$= \{\Pr(a+b)\}^r \Pr(X) + \{\Pr(b)\}^r \{1-\Pr(X)\}$
$= \{CCDP(X=1)\}^r \Pr(X) + \{CCDP(X=0)\}^r \{1-\Pr(X)\}$

After the process stated above are repeated for all events with inter-unit dependency, the summation of these results can be a good estimate of the multi-unit CCDP. Here, we can substitute Pr(X) into Pr'(X) = IUCCF(X)·Pr(X) when the inter-unit dependency of the event X should be modeled with correlation defined as inter-unit common cause failure factor, IUCCF(X). The use of Pr'(X) provides an approximation of the maximum impact on the r-unit CCDP for the event X. Also, note that CCDP(X=1) = RAW(X) * Pr{R(X)}, and CCDP(X=0) = Pr{R(X)} / RRW(X) = (1-FV(X)) * Pr{R(X)}.