Re-evaluation of Shin-Kori 1&2 CDF without Quantification Errors

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1. Introduction

The quantification of Probabilistic Safety Assessment (PSA) of Nuclear Power Plants (NPPs) is a complicated process and always has the following two limitations: (1) Approximation Errors (AE) in quantifying Minimal Cut Sets (MCSs) and (2) Truncation Errors (TE) in deleting low-probability cut sets. In practice we can not exactly quantify PSA results without AE and TE. This paper proposes an approach to exactly quantify the risk measures of NPP PSAs using the proposed exact MCS quantification method applicable to large-sized MCS problems and the iterative process of demonstrating that the convergence of risk measures can be considered sufficient.

2. Quantification without AE and TE

2.1 Approximate Solution of SDP: Semi-SDP

Sum of Disjoint Products (SDP) methods [1,2] exactly solve MCS problems. The basic idea of SDP is to transform a set of MCSs into another equivalent set of mutually exclusive events (Disjoint Products: DPs) and then reduce the probability evaluation to a simple summation as:

$$\Pr\{\bigcup_{j=1}^{m}\mathbf{K}_j\} = \sum_{all\ i}\Pr\{DP_i\} \qquad (1)$$

where $\mathbf{K}_1$, …, $\mathbf{K}_m$ are all the identified MCSs of a problem. However, SDP calculations for large-sized MCS problems are very time-consuming. Most NPP PSAs are large-sized MCS problems, so SDP calculations are not practical.

In the proposed SDP algorithm [1], the pivotal decomposition of a Sum Of Products (SOP) makes the equivalent sum of two disjoint terms. Each of them is a Disjoint Product (DP) or a Disjoint Sum Of Product (DSOP). The SDP algorithm is a recursive process of pivotal decompositions. If there are no more SOPs to be decomposed, we finally get a SDP equivalent to the original MCS problem. At any consecutive decomposition of SOPs, we always get a sum of disjoint terms equivalent to the original MCS problem:

$$\bigcup_{k=1}^{m}\mathbf{K}_k = \sum_i DP_i + \sum_j DSOP_j. \qquad (2)$$

Therefore,

$$\Pr\{\bigcup_{k=1}^{m}\mathbf{K}_k\} = \sum_i \Pr\{DP_i\} + \sum_j \Pr\{DSOP_j\}. \qquad (3)$$

Here, each DSOP can be expressed by the product of the corresponding pivotal variable states and the corresponding SOP consisting of minimal terms:

$$DSOP = \prod_i b_i \prod_j \bar{b}_j \times SOP. \qquad (4)$$

Therefore, the probability of the DSOP is

$$\Pr\{DSOP\} = P_b \times \Pr\{SOP\} \qquad (5)$$

where P_b is the branch probability of the DSOP.

"Semi-SDP" method, an approximate solution of SDP, is proposed here. It restricts pivotal decompositions of DSOPs having a very low probability. If P_b of a following DSOP is less than a value C_{BA}, the probability of the following SOP is calculated by the MCUB approximation. Here, C_{BA} is called "Branch-Approximating Criteria" and it is selected by analysts considering computing time. If C_{BA} = 0, the calculation result by the Semi-SDP method is exactly identical to that by SDP methods. For sufficiently low C_{BA}, the results are very close to the exact solution. At any C_{BA}, the Semi-SDP method never underestimates the probability or frequency of a MCS problem.

2.2 Exact MCS Quantification for NPP PSAs

The MCS group of an Initiating Event (IE) is mutually exclusive with that of another IE. Then, the CDF can be written as:

$$CDF = \sum_{i=1}^{all}[F(IE_i) \times CCDP_i] \qquad (6)$$

When event trees with the conditional split fraction method is used, some MCSs can be classified into disjoint MCS groups of the occurrence or non-occurrence of specific conditional events. The Semi-SDP method logically deals with these conditional events.

The Semi-SDP method is implemented by Semi-SDP software. Semi-SDP software automatically classifies MCSs into disjoint MCS groups of different IEs and each of CCDPs is calculated by the Semi-SDP method. Semi-SDP software finally provides an estimate of the risk measure (eg., CDF or LERF). For a sufficiently low C_{BA}, the estimate from Semi-SDP software is very close to its exact solution.

2.3 Evaluation of TE

The ASME standard for PSA [3] requires that accident sequences and associated system models are truncated at a sufficiently low cut-off value that significant dependencies are not eliminated, and final truncation limits are established by an iterative process of demonstrating that the overall model results are not significantly changed and that no important accident sequences are inadvertently eliminated. For example, convergence can be considered sufficient when successive reductions in truncation value of one decade result in decreasing changes in CDF or LERF, and the final change is less than 5%.

The typical approach to deal with the TEs of NPP PSAs is the iterative process of truncating at a sufficiently low cut-off value and proving the convergence of risk measures. By comparing the change of a risk measure caused by successive reductions in cut-off value of one decade (i.e., the increment of the risk measure), we can demonstrate that the convergence of the risk measure is achieved and the unidentified MCSs can be considered negligible.

3. Re-evaluation of Shin-Kori 1&2 CDF

The CDF model for Shin Kori 1&2 [4] has 16 initiating events. The Truncation Limit (TL) used in the PSA report is 10^{-11}.

Table I: MCS size vs. truncation limit

TL (10^{-k})	# MCSs	CDF by RE (M)	Exact value[a]	M^k/M^{k-1}
1E-10	2,767	5.9605E-6	5.88078E-6	116.48 %
1E-11	13,450	6.6217E-6	6.50538E-6	111.05 %
1E-12	61,711	7.1352E-6	6.99512E-6	107.76 %
1E-13	254,028	7.3702E-6	7.21520E-6	103.29 %
1E-14	968,128	7.4517E-6	7.28945E-6	101.11 %

[a]by Semi-SDP software with $C_{BA} = 10^{-13}$

Table I shows MCS size versus TL and the MCS quantification results calculated by the RE approximation and the Semi-SDP method. In Table I, it is shown that the number of MCSs grows exponentially with reductions in TL, and for equal to and less than 10^{-13} in TL the changes in CDF is less than 5% in compliance with the requirement of ASME standard. So, it is recommended that the TL of the CDF model should be less than **10^{-13}**.

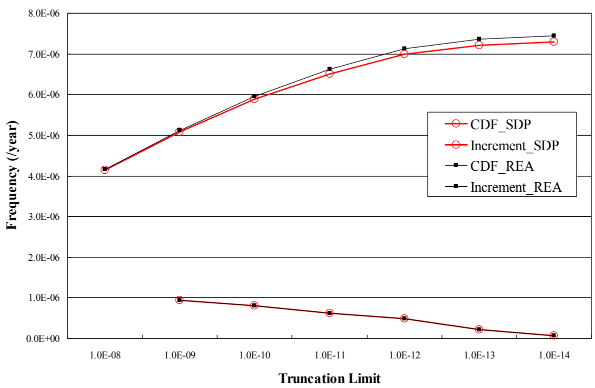

Fig. 1. CDF and its increment vs. truncation limit (TL)

Fig. 1 shows CDF and its increment versus TL for the CDF model. It shows that when TL = 1.0E-14, the convergence of CDF has been achieved. Because the CDF difference (i.e., the increment of CDF) between 1.0E-13 and 1.0E-14 in TL is close to zero relatively to the CDF, it is convinced that the convergence of CDF is achieved at the TL of 1.0E-14, and the unidentified MCSs (and the truncation error) are negligible. Therefore, the exact CDF of the model must be very close to **7.28945E-6/yr** which is calculated by the Semi-SDP method with a sufficiently low C_{BA}. Fig. 2 shows the characteristics of Semi-SDP calculations.

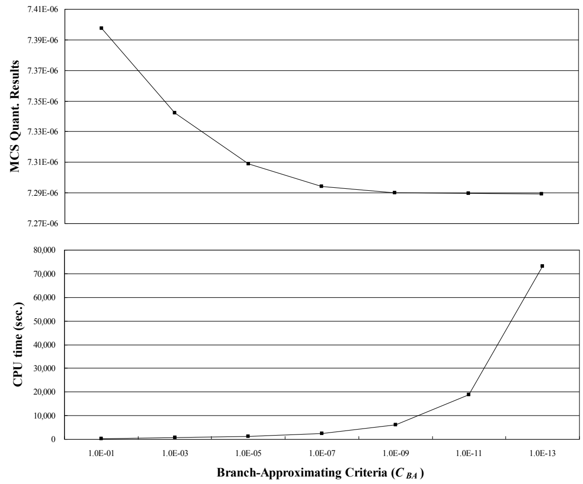

Fig. 2. Semi-SDP calculations (TL=10^{-14})

4. Conclusions

This paper focuses on exact quantification of the risk measures of NPP PSAs without AE and TE. The Semi-SDP method, an exact MCS quantifier, is proposed here. From this study, we can draw the following conclusions.

- The newly proposed Semi-SDP method is practically applicable to exact quantification of large-sized MCS problems.
- By calculating MCSs based on the Semi-SDP method and demonstrating convergence of the risk measure estimates, we can evaluate the risk measures of NPP PSAs without AE and TE.

REFERENCES

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