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An Extrapolation Method for Estimating Truncation Errors in PSAs

Jongsoo Choi
Korea Institute of Nuclear Safety, 19 Guseong-dong Yuseong-gu Daejeon 305-338; k209cjs@kins.re.kr

1. Introduction

The quantification of a Probabilistic Safety Assessment (PSA) of a Nuclear Power Plant (NPP) is a complicated process and always has the Truncation Errors (TEs) in deleting low-probability cut sets. In practice it is extremely difficult to quantify PSA results without TEs.

This paper proposes an approach to estimate the TEs in NPP PSAs which is based on the least square fitting and the extrapolation of risk increments. The proposed TE measure is reasonable and conservative. The proposed method can be helpful in demonstrating that the convergence of risk measures is sufficient.

2. Truncation Error Evaluation

2.1 Truncation Errors in PSAs

In NPP PSAs, it is impossible to enumerate all the MCSs of a specific risk measure due to high memory requirements and long computing time. To determine a set of MCSs with a manageable size, truncation neglecting low-probability (or low-frequency) cut sets is applied. In this cutoff procedure, MCSs with probabilities (or frequencies) less than a specified cutoff value are discarded. The selection of the cutoff value (i.e., truncation limit: TL) depends on the judgment of the analyst. The application of the cutoff entails the need to estimate the truncation error, i.e., the additional risk related to the discarded cut sets.

The ASME standard for PSA [1] requires that accident sequences and associated system models are truncated at a sufficiently low cutoff 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. The standard says that 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 cutoff value and proving the convergence of risk measures. By comparing the change of a risk measure caused by successive reductions in cutoff 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. For example, Fig. 1 shows the CDF increments of Shin-Wolsong 1&2 PSA caused by successive reductions in cutoff value of one decade.

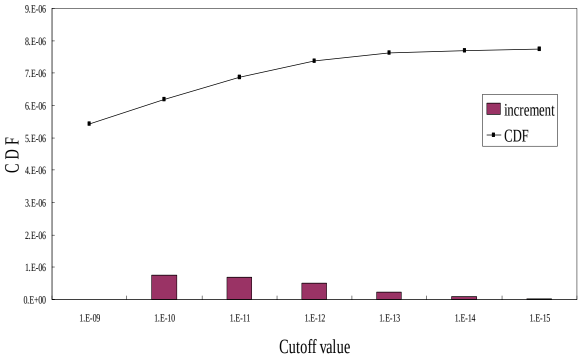

Fig. 1. CDF and its increment vs. cutoff value

2.2 Least Square Fitting of Risk Increments

Here, the risk increment *I(k)* is defined as

$$I(k) = Risk(k) - Risk(k-1) \quad (1)$$

where *Risk(k)* is the risk measure quantified at the cutoff value 1.0E-k. The plot of risk increments vs. cutoff values is very useful to show the convergence of the risk measure as shown in Fig. 1.

We can say that the TE of *Risk(k)* is the sum of all the unknown risk increments as

$$\begin{aligned} TE(k) &= Risk(\infty) - Risk(k) \\ &= \sum_{i=k+1}^{\infty} I(i). \end{aligned} \quad (2)$$

At a sufficiently low cutoff value, *I(k)* must be very small. It seems very likely that risk increments with *k* have exponential dependencies as

$$f(x) = A\,e^{-Bx} \quad (3)$$

Curve fitting is the process of constructing a mathematical function that has the best fit to a series of data points. Using EXCEL, we can easily get a fitted curve of *I(k)* as shown in Fig. 2.

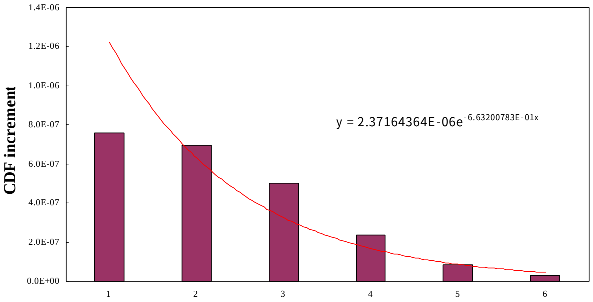

Fig. 2. Least Square fitting to an exponential function

2.3 Proposed Upper Bounds of Truncation Errors

If exponential fitting can provide the best fit of the unknown risk increments, the truncation error can be reasonably estimated with the following integral equation:

$$TE(k) \approx \int_{X_{next}}^{\infty} f(x)\,dx = \frac{A}{B} e^{-BX_{next}}. \qquad (4)$$

Using Eq. (4), the non-truncated CDF is estimated by

$$CDF = CDF(k) + TE(k). \qquad (5)$$

In Fig. 3, the line 'Upper' is the estimation of non-truncated CDFs calculated by Eq. (5).

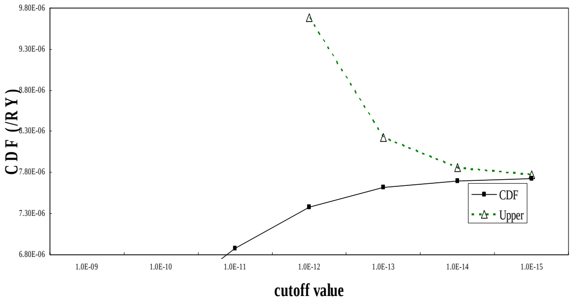

Fig. 3. CDF and upper bounds vs. truncation limit

From its application to many domestic PSAs, it seems very likely that the proposed TE measure expressed by Eq. (4) is always an upper bound of TE.

By using this method, we can demonstrate at least that the convergence of the risk measure is achieved and the unidentified MCSs can be considered negligible.

3. Re-evaluation of Internal Event Level 1 PSAs

Fig. 4 is the re-evaluation of the CDF model for Shin Wolsong 1&2 based on the proposed method. It shows that the TE is very small when TL = 1.0E-15.

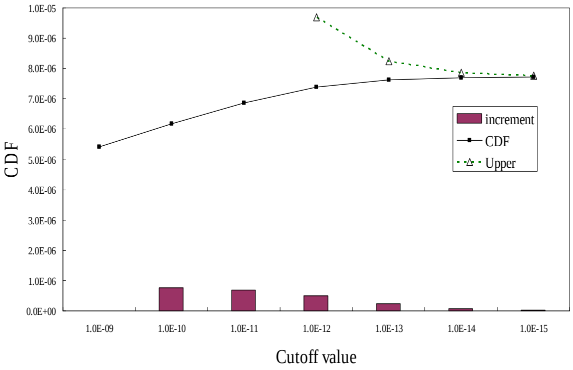

Fig. 4. Truncation error evaluation on SWS 1&2 PSA

"Semi-SDP" method [2,3] can exactly solve MCS problems. Fig. 5 is the MCS quantification by Semi-SDP for TL=1E-15. The 'Lower' line is a set of lower bounds of the frequency of all the MCSs based on the exponential fitting technique.

Table I shows the re-evaluation results for 11 level 1 PSAs for internal events based on the proposed method.

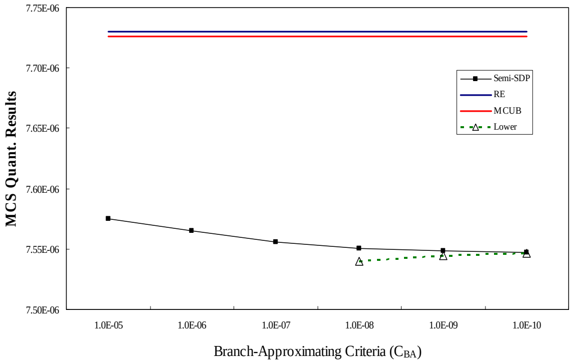

Fig. 5. MCS quantification by Semi-SDP for TL=1E-15

Table I: Re-evaluation of domestic PSAs

Internal L1 PSA	**TL**	**AE**	**TE**	**Reported / exact**
SWS 1,2	1.E-11	1.944%	12.412%	91.011%
-2010	1.E-15	2.307%		
SKR 1,2	1.E-11	1.787%	13.002%	90.481%
-2009	1.E-15	2.246%		
YG 1,2	1.E-12	1.709%	0.332%	101.389%
-2008	1.E-15	1.726%		
WS 1	1.E-13	0.364%	0.389%	99.990%
-2008	1.E-16	0.380%		
KR 1	1.E-11	2.486%	1.803%	100.787%
-2007	1.E-15	2.604%		
KR 2	1.E-11	1.494%	0.964%	100.556%
-2007	1.E-15	1.526%		
WS 2,3,4	1.E-13	0.660%	1.095%	99.598%
-2007	1.E-16	0.689%		
YG 5,6	1.E-12	0.955%	0.864%	100.171%
-2006	1.E-15	1.037%		
UC 5,6	1.E-12	1.024%	0.821%	100.287%
-2006	1.E-15	1.111%		
YG 3,4	1.E-12	1.004%	0.933%	100.146%
-2005	1.E-15	1.080%		
UC 3,4	1.E-12	1.032%	0.860%	100.256%
-2005	1.E-15	1.119%		

4. Conclusions

This paper focuses on the measure of TE based on curve fitting and extrapolation of risk increments. From this study, we can draw the following conclusions.

- The newly proposed TE measure is conservative and best fitted to known information in PSAs.
- Using the proposed method, we can evaluate the risk measures of NPP PSAs without truncation errors and approximation errors.

REFERENCES

[1] ASME/ANS RA-Sa-2009: Standard for Probabilistic Risk Assessment for Nuclear Power Plant Applications, American Society of Mechanical Engineers, 2009.

[2] J. Choi, An Approach to Evaluate Quantification Errors in PSAs, PSAM 10, Seattle, June 7-11, 2010.

[3] J. Choi, Re-evaluation of Shin-Kori 1&2 CDF without Quantification Errors, KNS Spring Meeting, Pyeongchang, May 27-28, 2010.