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Assessment of APR-1400 ECCS Performance for Design Basis LOCA Redefinition Applying Combined Deterministic and Probabilistic Procedure

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1. Introduction

As a part of the efforts to develop the risk-informed regulation, alternative rulemaking of 10CFR50.46 is underway. In the rule, USNRC divided the current spectrum of LOCA break sizes into two regions, by determining a transition break size (TBS). LOCAs for any breaks smaller than TBS will continue to be DBA under current 10CFR50.46 ECCS rule. By contrast, it was concluded that LOCAs for any breaks larger than TBS can be regarded as BDBA. It indicates that without any significant erosion of the safety margin a number of possible changes to licensed power reactors can be proposed for extension of diesel generator start times, optimization of accumulator, and power uprates, etc.

In this study, a combined deterministic and probabilistic procedure was proposed for safety assessment of BDBAs. The performance of the APR-1400 ECCS performance was assessed against large break LOCA, under the premise that LOCAs for any breaks larger than transition break size would be regarded as BDBA.

2. Combined Deterministic and Probabilistic Procedure (CDPP) for BDBA Assessment

In the CDPP, the best estimate plus uncertainty (BEPU) method (deterministic approach) is forged into the traditional PSA (probabilistic approach). The definition of conditional core damage probability (CCDP, P(CD)) and core damage frequency (CDF, λ_{CD}) are expressed in equation (1) and (2); where sequence probability (SP, P_{seq}), probability that a sequence of events happens, initiating event frequency (IEF, λ_{IE}), conditional exceedance probability (CEP, $P_{cond,exc}$), probability that core will be damaged for a specific initiating event and its sequence of events. In the CDPP, the CEP obtained by the BEPU method acts as go-between deterministic and probabilistic safety assessments, resulting in more reliable values of CDF and CCDP.

$$P(CD) = P_{seq} \cdot P_{cond,exc} \qquad (1)$$

$$\lambda_{CD} = \lambda_{IE} \cdot P(CD) = \lambda_{IE} \cdot P_{seq} \cdot P_{cond,exc} \qquad (2)$$

In the proposed CDPP for BDBA safety assessment, there are three main stages and thirteen steps as shown in Fig. 1; 1) PSA stage identifying sequence of events and quantifying their probabilities, 2) BEPU stage identifying/quantifying relevant uncertainties and calculating CEP for given sequences, 3) combination stage combining PSA and BEPU results by applying CEP to CDF and CCDP explicitly. Each stage includes corresponding steps.

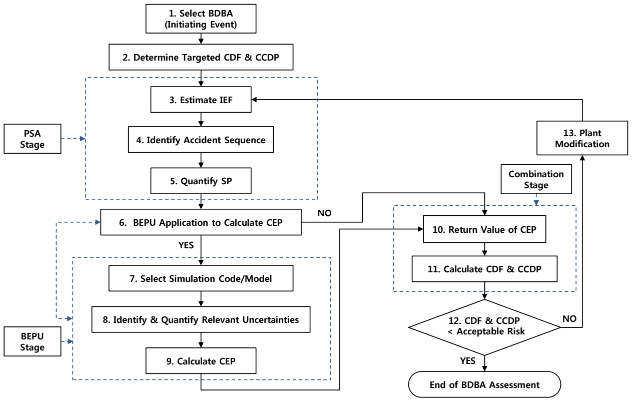


Fig. 1 CDPP for safety assessment of BDBA

3. Premise and Considerations for Assessment

To help establish the TBS, the NRC developed pipe break frequencies as a function of break size using an expert opinion elicitation process as shown in Fig. 2. From this result, a baseline TBS was established that corresponded to a break frequency of 1.0E-5.

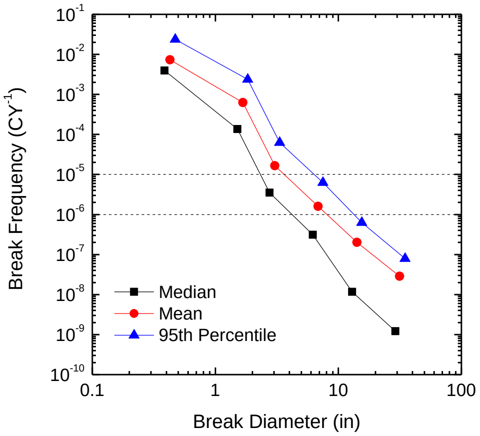


Fig. 2 PWR pipe break frequency according to break size

The cumulative CCDP and CDF for LOCAs of break sizes larger than the TBS are defined as;

$$P(CD|LOCA > TBS) = \int_{TBS}^{DEGB} P_{seq}(z) P_{cond,exc}(z) dz \qquad (3)$$

$$\lambda_{CD}(LOCA > TBS) = \int_{TBS}^{DEGB} \lambda_{IE}(z) P_{seq}(z) P_{cond,exc}(z) dz \quad (4)$$

where z is break size. Assuming the CCDP for a LOCA of any break size larger than TBS be the same as that for the most limiting break size (LBS) LOCA, we can obtain the final form of the CCDP and CDF for BDB LOCAs.

$$P(CD|LOCA > TBS) \approx P_{seq}(LBS) P_{cond,exc}(LBS) \qquad (5)$$

$$\lambda_{CD}(LOCA > TBS) = P(CD|LOCA = LBS) \int_{TBS}^{DEGB} \lambda_{IE}(z) dz \quad (6)$$

The total IEF of break sizes larger than TBS in eqn. (6) can be obtained by using either the results of NUREG-1829 as shown in Fig. 2. The integral value of IEF is estimated to be 1.08E-5 for median, 2.72E-5 for mean, and 4.50E-5 for 95th percentile data. In this study, integral IEF value for 95th percentile data is chosen conservatively; then, the CDF for BDB LOCA can be described as:

$$\int_{TBS}^{DEGB} \lambda_{IE}(z) dz = 4.50 \times 10^{-5} \qquad (7)$$

$$\lambda_{CD}(LOCA > TBS) = (4.50 \times 10^{-5})\, P(CD|LOCA = LBS) \quad (8)$$

4. CDPP Application to APR-1400 BDB LOCA

The APR-1400 ECCS consists of four safety injection pumps (SIPs), four safety injection tanks (SITs) with fluidic device and in-containment refueling water storage tank (IRWST) which is the coolant source. The APR-1400 ECCS performance against the BDB LOCA is assessed according to the developed procedure.

Step 1.Select BDBA

The LOCA by a double-ended guillotine break at the reactor coolant pump discharge leg which are the limiting break size and location was selected as initiating event.

Step 2. Determine targeted CDF & CCDP

The targeted CDF and CCDP for the BDB LOCA were set to be 1.0E-7 and 2.0E-3, respectively based on PSA data.

Step 3.Estimate IEF

In this study, the IEF, frequency of LOCAs for break sizes larger than the TBS, can be estimated to be 4.5E-5 using the results of NUREG-1829.

Step 4 & 5. Identify sequence of events & Quantify SP

The PSA results were utilized to identify the sequence of events and to quantify the SP. Figure 3 shows the event tree in which IEF, unavailability of components, sequence probability for BDB LOCA are specified. As shown in this figure, there are three sequences.

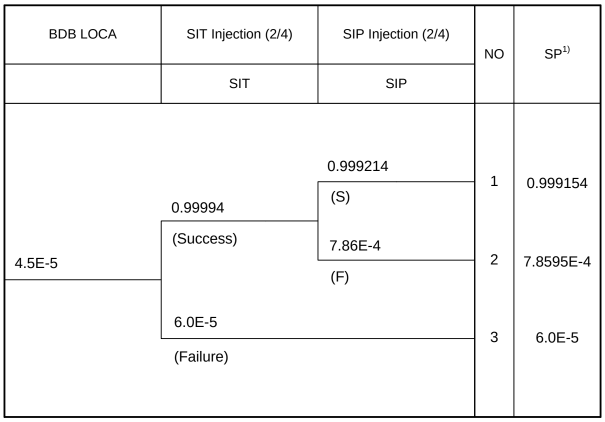
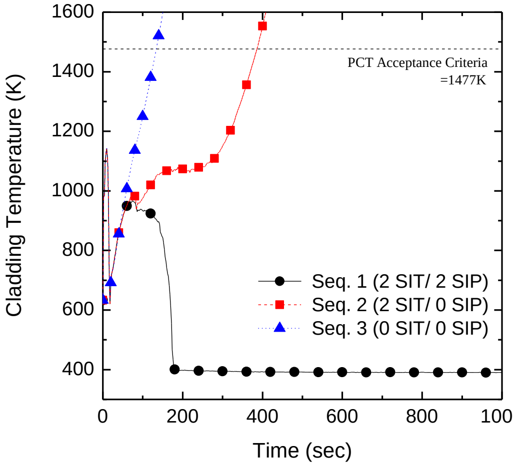


Fig. 3 Event tree of APR-1400 BDB LOCA

Step 6. BEPU application to calculate CEP

In this step, the importance of CEPs in a sequence is evaluated, and a preliminary CEP is estimated through the engineering judgments or the simplified calculations to make a decision whether to apply the BEPU method for sequences given in event tree. Figure 4 shows the cladding temperature behavior of BDB LOCA sequences. As shown in Fig. 4 (a), in case that only two SITs are available in sequence 2 and neither SIT nor SIP are available in sequence 3, since the ECCS cannot supply the coolant to the core sustainably during the accident, the cladding temperatures exceed the safety limit of 1477 K. As shown in Fig. 4 (b), in case that two SITs, one SIP are available in sequence 2 and one SIT, one SIP are available in sequence 3, since the coolant capacity delivering to core is not sufficient to remove decay heat, the cladding temperatures exceed the 1477 K. Therefore, the CEPs for sequence 2 and 3 can be estimated to be approximately unity without application of BEPU method. However, in case of sequence 1, the base case analysis result is not sufficient to determine the CEP, so the application of BEPU method is necessary.



(a)

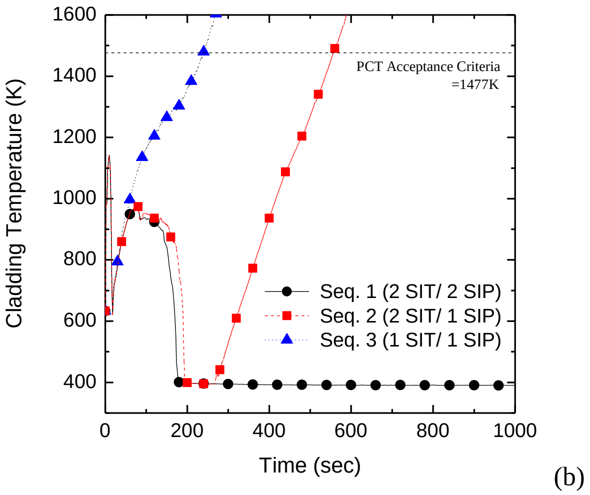


Fig. 4 Cladding temperature for BDB LOCA sequences; (a) 2 SITs/ 2 SIPs in sequence 1, 2 SITs/ No SIP in sequence 2, No SIT/ No SIP in sequence 3 (b) 2 SITs/ 2 SIPs in sequence 1, 2 SITs/ 1 SIP in sequence 2, 1 SIT/ 1SIP in sequence 3

Step 7. Select simulation code/model

A thermal-hydraulic system code, MARS-KS 1.2 was used for a realistic simulation of BDB LOCA with uncertainty propagation.

Step 8. Identify & quantify relevant uncertainties

Table 1 shows the uncertainty parameters affecting BDB LOCA analysis and quantification information.

Table 1. Uncertainty Parameter and Quantification Information

No	Parameter	Associated phenomenon	Distribution	Mean	Uncertainty[1)]
1	Gap conductance (Clad roughness)	Gap conductance	Uniform	0.95	0.55
2	Fuel thermal conductivity	Stored energy	Uniform	1	0.153
3	Core power	Stored energy	Normal	1	0.0065
4	Decay heat	Decay heat	Normal	1	0.0214
5	Critical heat flux	Rewet	Normal	1	0.178
6	Nucleate boiling heat transfer	Reflood heat transfer	Normal	0.995	0.1505
7	Transition boiling criteria	Rewet	Normal	1	0.149
8	Liquid convection heat transfer	Reflood heat transfer	Normal	0.998	0.127
9	Vapor convection heat transfer	Reflood heat transfer	Normal	0.998	0.127
10	Film boiling heat transfer	Reflood heat transfer	Normal	1.004	0.1864
11	Break C_D	Critical flow	Normal	0.945	0.07
12	Pump two phase head multiplier	Pump two phase performance	Uniform	0.5	0.5
13	Pump two phase torque multiplier	Pump two phase performance	Uniform	0.5	0.5
14	SIT actuation pressure (MPa)	Reflood	Normal	4.245	0.0696
15	SIT water inventory (m^3)	Reflood	Normal	49.95	1.505
16	SIT water temp. (K)	Reflood	Uniform	308.0	14
17	SIT loss coefficient	Reflood	Normal	18	2.33
18	HPSI water temp. (K)	Reflood	Uniform	302.5	19.5

Step 9. Calculate CEP

In this step, the probability density function (PDF) of the load (key safety parameter) is determined from the BEPU calculation. Then, the CEP, defined as the probability for a given sequence that the load PDF exceeds the capacity of PCT 1477 K, is calculated.

In this study, to obtain the CEP, 1,000 input sets were made by simple random sampling for uncertainty parameters shown in Table 1, and for sequence 1, the corresponding calculations were performed using Monte-Carlo method.

Figure 5 shows the PDF and cumulative probability of PCT for sequence 1. As shown in this figure, the PDF of PCT is similar to normal distribution, and there is not the case beyond PCT limit of 1,477 K; therefore, the CEP of sequence 1 is estimated to be nearly zero.

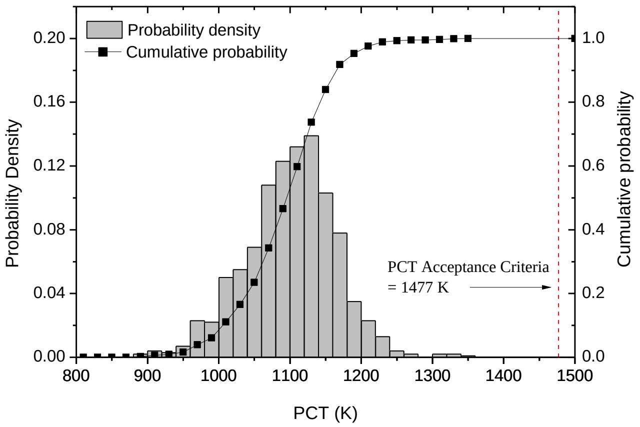


Fig. 5 PDF and cumulative probability of PCT for sequence 1

Step 10 & 11. Return value of CEP & Calculate CDF & CCDP

Table 2 shows calculated probability and frequency results of each sequence, and CDF and CCDP for BDB LOCA obtained by summing pre-determined values.

Table 2. Probability and Frequency results for APR-1400 BDB LOCA

Sequence No.	IEF	SP	CEP	CCDP	CDF
1	4.5E-5	0.999154	~ 0.0	~ 0.0	~ 0.0
2	4.5E-5	7.8595E-4	~ 1.0	7.8595E-4	3.537E-8
3	4.5E-5	6.0E-5	~ 1.0	6.0E-5	2.7E-9
			Sum	**8.4595E-4**	**3.807E-8**

Step 12. CDF & CCDP < acceptable risk

The calculated values of CDF and CCDP for BDB LOCA meet the acceptable risk specified in step 2. Therefore, it is confirmed that current APR-1400 ECCS design has capability to mitigate BDB LOCA by analyzing ECCS cooling performance for BDB LOCA.

5. ECCS Performance Assessment for Plant Design Modification

Under the premise of design basis LOCA redefinition, a wide scope of design or operational changes can be considered. Potential design changes include the extension of diesel generator start times, power uprates, changes in the required number of accumulators, modification of containment spray design, and modifying core peaking factor, etc. Some of these design and operational changes could increase plant safety because the system could be modified to better mitigate the more likely smaller LOCAs. However, the ECCS performance should be assessed to demonstrate that some design modifications would be made within the acceptable risk against BDB LOCA. In this assessment, the extension of diesel generator start times and power uprating are considered out of a number of possible NPP changes.

In original APR-1400 design, when the low pressurizer pressure (LPP) signal is automatically generated after the break, the emergency diesel generator (EDG) starts up within 20 seconds. Then, SIP 1 and 3 are loaded onto EDG after 5 and 10 seconds, respectively, and after 10 seconds the coolant is injected into reactor vessel. The extension of EDG start time delays the coolant injection time through SIP. Assuming that the power uprating would not affect the accident scenarios and unavailability of components, the PSA results for the original design of the rated thermal power 3,983 MWt were used in this assessment, as can be seen in Fig. 3. In this figure, the CEPs of sequences 2 and 3 are nearly unity and do not change by the design modification. However, the CEP of sequence 1 would vary with the design changes, and the variation of the CEP is allowed within the probability specified to meet targeted CDF and CCDP.

For sequence 1, calculations with 1,000 input sets were performed for each design modification case to calculate the CEP. Figure 6 shows the ECCS performance assessment results of BDB LOCA for plant design modification. The unacceptable design changes are plotted in cross symbols.

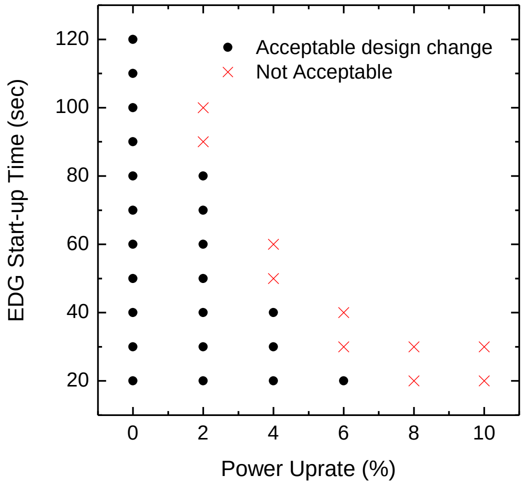


Fig. 6 ECCS performance assessment results of BDB LOCA for plant design modification

6. Conclusion

A combined deterministic and probabilistic procedure was proposed for safety assessment of the BDBAs. The performance of the APR-1400 emergency core cooling system performance was assessed against large break LOCA by applying CDPP, under the premise that LOCAs for any breaks larger than transition break size would be regarded as BDBA. The proposed CDPP was also applied to design changes of the emergency diesel generator (EDG) start time extension and power uprates with simplified assumption that the PSA data are still valid. Discussions were made for acceptable nuclear power plant changes.

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