



MODELICA Simulation-Based Probabilistic Assessment of i-SMR Containment Integrity under PCCS Performance Degradation

Seong Jun Hong, Riyad Hasan, Yeon Ki Chung, Hyun Gook Kang*

Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7–8, 2026

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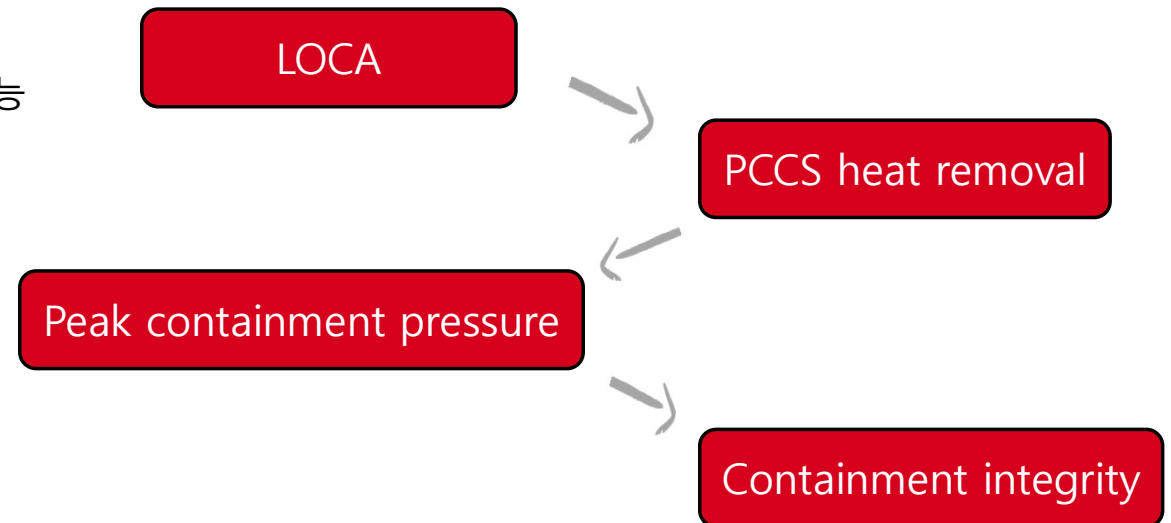
01 Introduction

□ Research Background: Why PCCS matters



Partial PCCS degradation can directly erode containment margin

- Fouling, NCG accumulation, aging 등으로 PCCS 성능 저하가 발생할 수 있음
- 따라서 containment integrity는 PCCS performance 와 직접적으로 연동됨



Objective and Contributions

Problem

PCCS 성능 저하와 containment pressure capacity 불확실성이 동시에 존재

Approach

Dymola/Modelica 해석 + surrogate demand + probabilistic capacity model

Output

SB-LOCA와 LB-LOCA에 대한 조건부 containment failure probability 평가

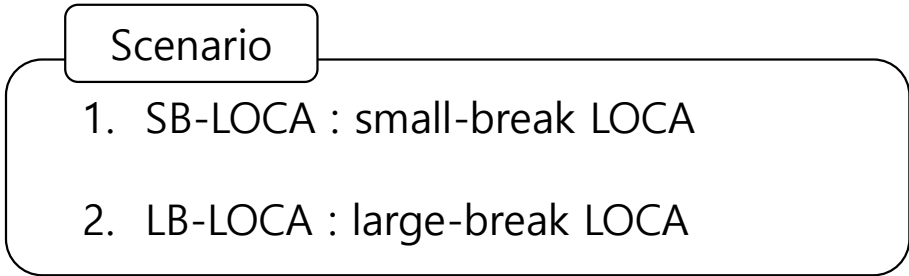
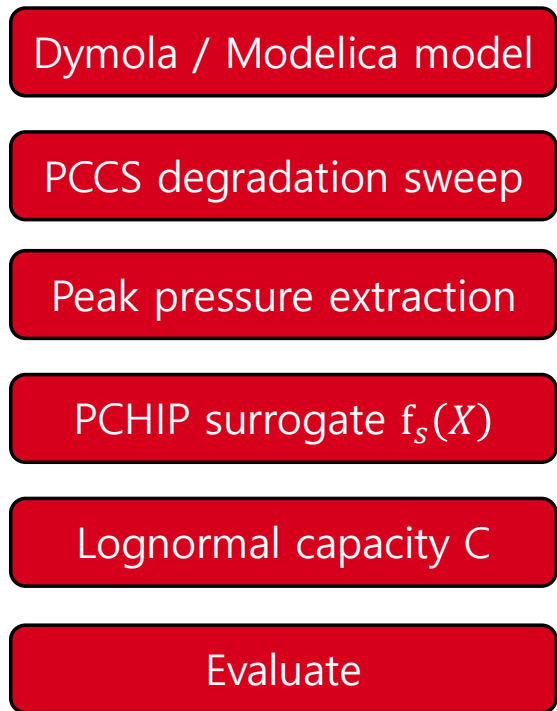
Key Contributions

1. PCCS 불확실성을 1차원 변수 X 로 parameterization
2. binary counting 대신 expected-fragility 기반 희귀 사건 평가
3. U / H / L 성능 가정에 대한 screening 민감도 분석 수행



02 Methodology

□ Integrated Evaluation Framework



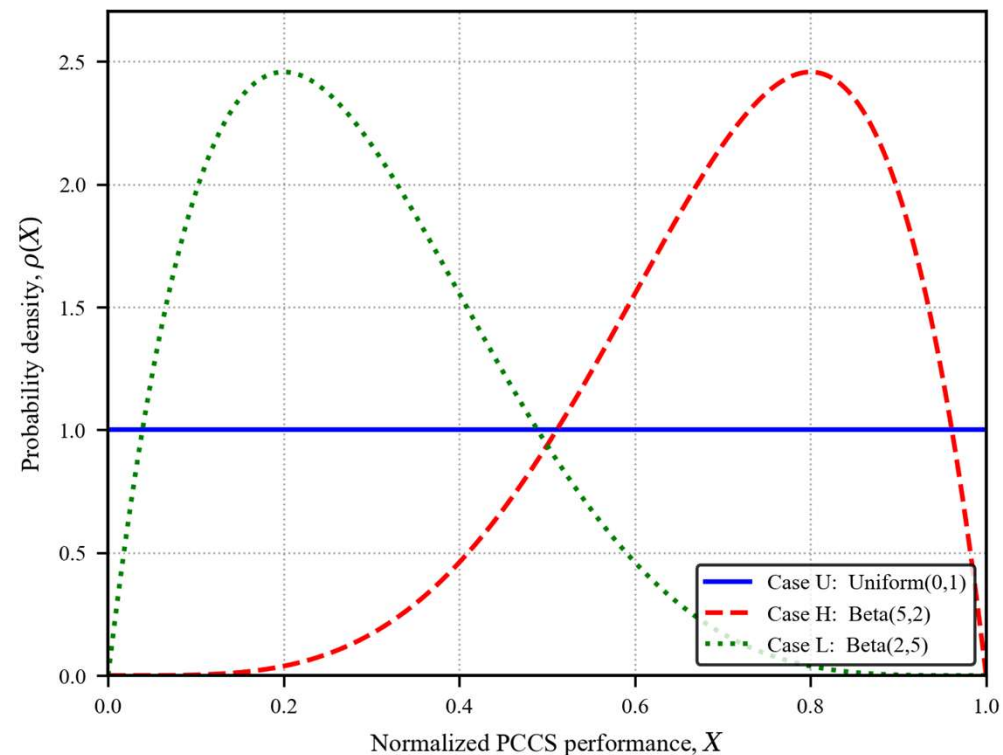
$$F_C(p) = \mathbb{P}(C < p) = \Phi\left(\frac{\ln(p/P_m)}{\beta_C}\right)$$

Peak containment pressure is used as the structural load metric

□ PCCS performance uncertainty parameterization



- PCCS degradation은 normalized effective cooling capability $X \in [0,1]$ 로 표현
 - $X = 1$: nominal PCCS performance
 - $X = 0$: fully degraded PCCS performance
- Dymola에서는 active parallel tubes / conduction component 수를 바꿔 성능 저하를 모사
- screening case는 U, H, L 세 가지를 비교
 - Case U : Uniform
 - Case H : High biased performance
 - Case L : Low biased performance



Representative screening distributions of PCCS performance

□ Structural capacity model and failure formulation



Demand Side

- 65개 discrete degradation state에 대해 simulation 수행
- 각 state의 최대 압력을 추출
- PCHIP으로 continuous surrogate 구성

Capacity Side

- Containment capacity는 lognormal random variable로 모델링
- Median capacity: 10.1324 MPa
- Baseline $\beta_c = 0.15$
- Sensitivity range: 0.12 / 0.15 / 0.18

Final probability formula

$$P_{fail} = E_X[P(f_s(X) > C)]$$

PCHIP : Piecewise Cubic Hermite Interpolating Polynomial



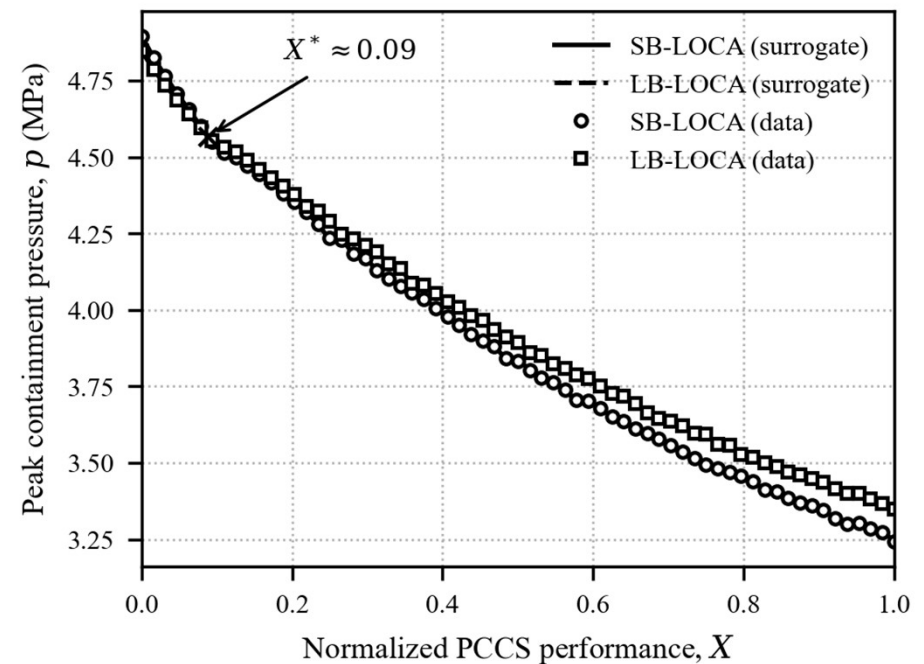
03 Case Study

□ Peak pressure response and SB-LB crossover



Under severe PCCS degradation, peak pressure under SB-LOCA exceeds LB-LOCA near $X \approx 0.09$.

- PCCS 성능이 좋아질수록 peak containment pressure는 감소
- X 가 대략 0.09보다 작을 때 SB-LOCA에서 더 높은 최대 압력 값이 관찰됨.

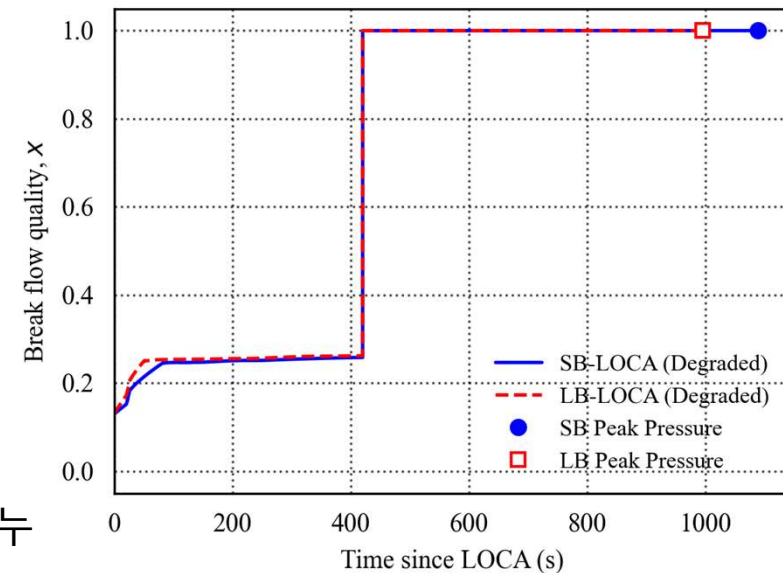


□ Physical interpretation: Why SB can exceed LB?

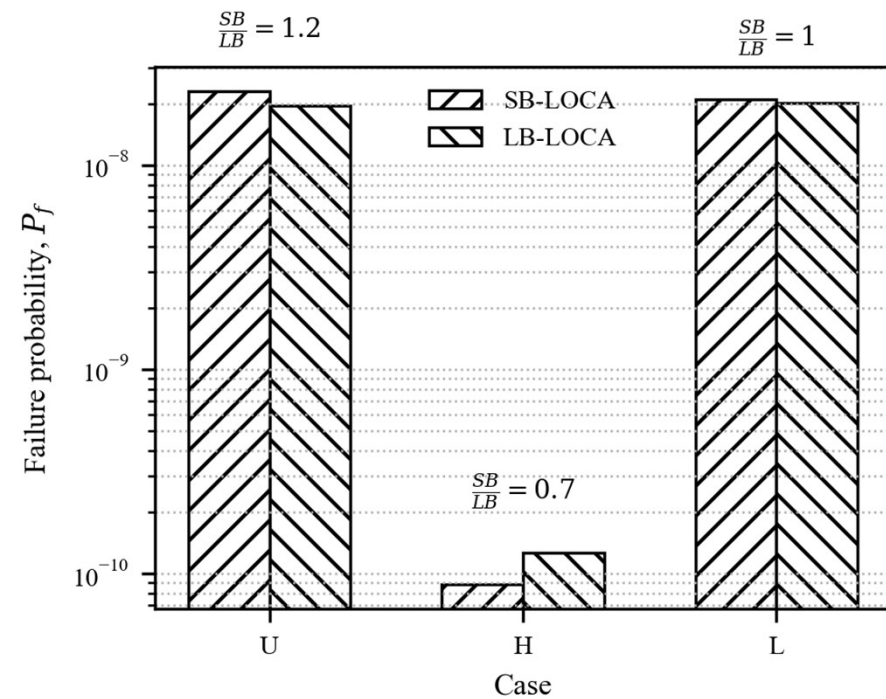
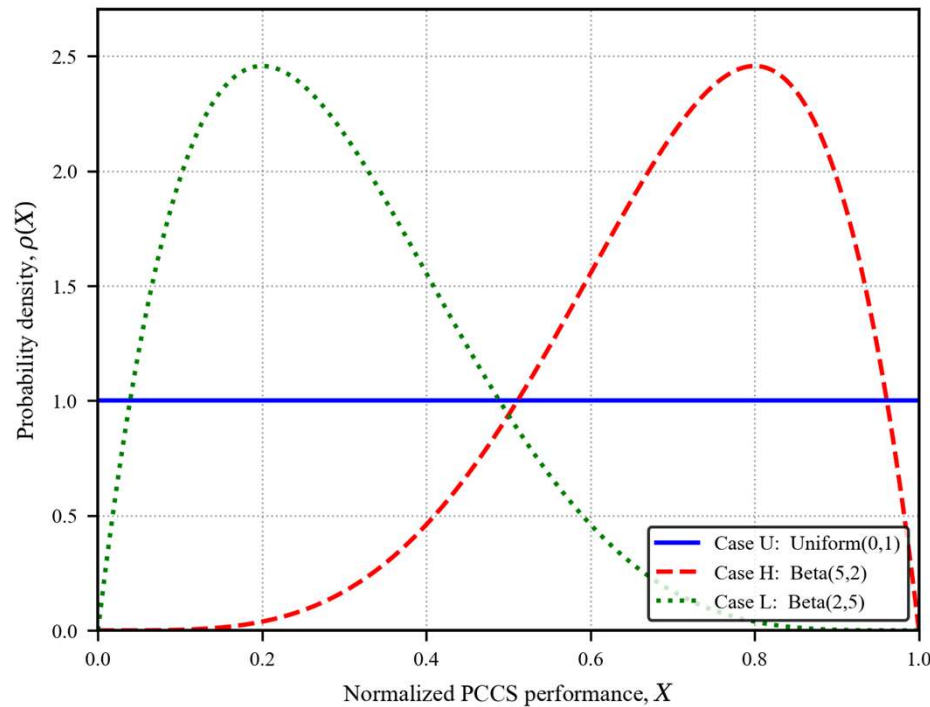


Parameter	LB-LOCA	SB-LOCA
Time to Peak Pressure	3,000 s	3,089 s
Total Discharged Mass	66,012 kg	51,571 kg
Liquid Mass in CV	44,017 kg	29,222 kg
Peak Vapor Mass in CV	21,994 kg	22,349 kg

- LB-LOCA는 총 방출 질량은 더 크지만 액체 비중이 큼
- SB-LOCA는 감압이 느려 증기 건도가 더 높고 냉각수 누출 시간도 더 김.
- PCCS의 성능이 심하게 저하되면 긴 시간 누적된 증기가 빠져나가는 SB-LOCA일 때 더 높은 압력 값을 기록됨.



Failure Probability under Screening Assumptions



□ Sensitivity to structural capacity uncertainty



Distribution Case	LOCA Scenario	$\beta_C = 0.12$	$\beta_C = 0.15$ (Base)	$\beta_C = 0.18$
Case U (Uniform)	SB-LOCA	1.53×10^{-11}	2.31×10^{-8}	1.51×10^{-6}
	LB-LOCA	1.07×10^{-11}	1.96×10^{-8}	1.42×10^{-6}
Case H (Optimistic)	SB-LOCA	8.40×10^{-15}	8.89×10^{-11}	2.33×10^{-8}
	LB-LOCA	1.15×10^{-14}	1.27×10^{-10}	3.33×10^{-8}
Case L (Pessimistic)	SB-LOCA	9.32×10^{-12}	2.10×10^{-8}	1.77×10^{-6}
	LB-LOCA	7.56×10^{-12}	2.01×10^{-8}	1.81×10^{-6}

- Sensitivity to probability of failure P_f : The probability changes significantly depending on the change in the logarithmic standard deviation (β_C).
- Distribution Tail Dependence: The probability of rare accidents is absolutely dominated by the extreme 'tail shape' of the capacity distribution.
- The relative risk ranking between SB and LB is maintained.



04 Conclusion

□ Key conclusions and future work

Conclusion

- MODELICA 기반 시스템 시뮬레이션과 probabilistic structural capacity를 결합해 i-SMR containment reliability를 평가함
- PCCS 성능 분포 가정이 failure probability에 큰 영향을 줌
- PCCS가 심각하게 열화된 조건에서는 SB-LOCA가 LB-LOCA보다 더 불리할 수 있음
- 설계가 업데이트되면 surrogate만 다시 생성해 framework를 쉽게 재활용할 수 있음

Future work

- 통합실험데이터 기반 PCCS 성능 분포의 확률 밀도 함수를 보완
- multi-dimensional uncertainty 확장
- scenario frequency까지 결합한 integrated risk metric으로 확장

□ Q&A





Thank you!

Seong jun Hong
(presenter)
hsjun5847@hanyang.ac.kr

Hyun gook Kang
(corresponding author)
kangh6@rpi.edu

이 논문은 정부(과학기술정보통신부)의 재원으로 한국연구재단의 지원을 받아 수행된 연구임(No. RS-2025-02363036)

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□ Appendix 1

1. $p = f_s(X), s \in \{SB, LB\}, X \in [0,1]$
2. $P_f(s) = \mathbb{E}[F_C(f_s(X))]$
3. $n \in \{0,1, \dots, n_{\max}\}, n_{\max} = 64$
4. $X \in [0,1]$
5. $F_C(p) = \mathbb{P}(C < p) = \Phi\left(\frac{\ln(p/P_m)}{\beta_C}\right)$
6. $P_f(s) = \mathbb{E}_X[\mathbb{P}(C < f_s(X) \mid X)] = \mathbb{E}_X[F_C(f_s(X))]$

□ Appendix 2

