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Advancing Nuclear Reactor Safety Analysis: Methodological Innovations And Results From Dynamic Probabilistic Safety Assessment

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This study revolutionizes nuclear reactor safety analysis through a pioneering application of Dynamic Probabilistic Safety Assessment (DPSA), utilizing advanced dynamic fault trees (DFTs) and Markov models (Dugan, 1993). By meticulously modeling the probabilistic and temporal dependencies among system components, we assess the implications of operational scenarios on reactor safety. Our investigation zeroes in on critical insights into reactor operation, particularly focusing on quantifying the probabilities of core damage and radiological releases, thereby delineating a time-dependent risk profile of reactor operation. Through sensitivity and uncertainty analyses, the research identifies pivotal components and operational strategies essential for minimizing risk, providing a robust framework for informed decision-making in nuclear safety management.

The catastrophic potential of nuclear accidents necessitates a rigorous approach to safety analysis. Traditional Probabilistic Safety Assessments (PSA) often fall short in capturing the dynamic interactions and temporal aspects of reactor operations. Our research addresses this gap by implementing a DPSA methodology, integrating dynamic fault trees (DFTs) and Markov models to offer a nuanced understanding of reactor behavior under various operational scenarios (Verma et al., 2022).

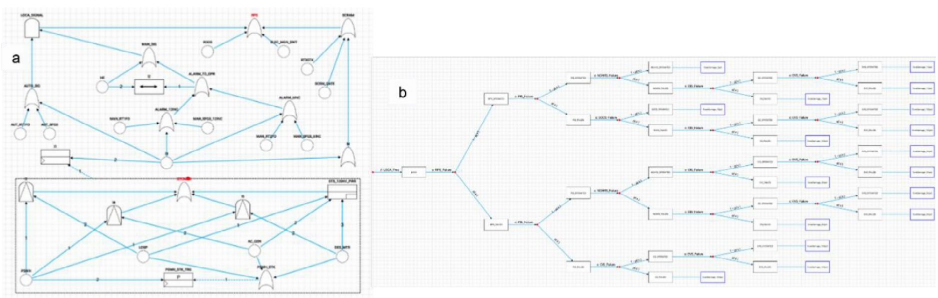

Fig. 1. Resulting Dynamic Fault Trees (a) and event Trees (b) generated in this study using SAFEST tools (Volk et al., 2024).

At the core of our methodology is the construction of DFTs that encapsulate the complex interactions between reactor components. These DFTs are adeptly translated into Markov models, enabling a sophisticated analysis of the system's dynamic behavior (Volk et al., 2024). The methodology leverages:

- Model Checking of Markov Models: To systematically verify safety and reliability properties.
- Efficient State Space Generation: Utilising Binary Decision Diagrams (BDDs) to manage computational complexity.
- Custom Metrics Application: Focusing on Mean Time to Failure (MTTF) among other safety metrics.

Our results underscore the efficacy of the DPSA methodology in enhancing reactor safety analysis:

- Core Damage Frequency (CDF) Analysis: Reveals a significant variation in CDF over operational time, with a pronounced peak at 20,000 hours.
- Sensitivity and Uncertainty Analysis: Demonstrates the critical impact of the Pool Isolation System (PIS) and Emergency Core Cooling System (ECCS) on overall safety. A sixfold increase in PIS failure rate could potentially escalate CDF by up to six times. Meanwhile, a 20% uncertainty in Emergency Core Cooling (ECCS) operations translates to nearly a 10% variation in CDF.

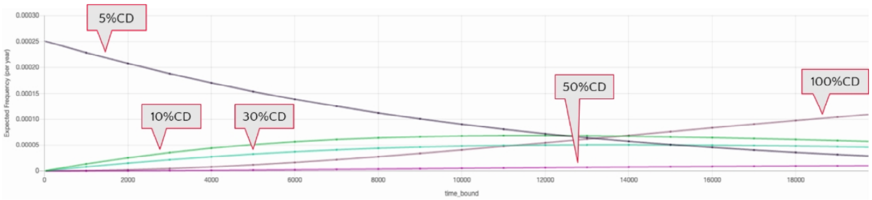

Fig. 2. Expected Core Damage Frequency (CDF) varies with LOCA occurrence time (hrs), LOCA Freq: 2.51E-04 per year

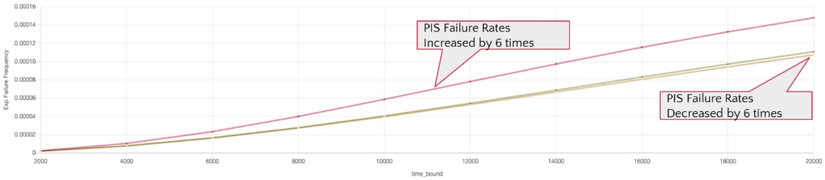

Fig. 3. Sensitivity analysis: 100% CDF depends on failure rates of Pool Isolation System (PIS), LOCA occurrence Freq: 2.51E-04 per year

The study's findings illuminate the paramount importance of dynamic safety assessment in nuclear reactor operations. By pinpointing critical periods and components susceptible to failure, the DPSA methodology facilitates the development of targeted maintenance and emergency response strategies, significantly mitigating risk (Zhang et al., 2020). Our research marks a significant stride toward advancing nuclear reactor safety analysis. The dynamic and probabilistic lens through which reactor operations are examined not only enriches the understanding of inherent risks but also empowers stakeholders with actionable data for enhancing safety protocols.

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