System Availability Analysis: A Case Study on the Component Cooling Water System of Tsinghua High-Flux Reactor

Yi Wu [1,2,3], Tao Liu [1,2,3], Wang Lin [1,2,3], Zhuohan Wang [1,2,3], Jiejuan Tong [1,2,3]

[1] *Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China*
[2] *Collaborative Innovation Center of Advanced Nuclear Energy Technology, Tsinghua University, Beijing 100084, China*
[3] *The Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Beijing 100084, China*
wuyi23@mails.tsinghua.edu.cn, liu-tao@tsinghua.edu.cn, lw24@mails.tsinghua.edu.cn, wangzhuohan@tsinghua.edu.cn, tongjj@tsinghua.edu.cn

ABSTRACT

System availability analysis is essential for ensuring the reliability and safety of nuclear systems, particularly those characterized by complex configurations, diverse operational modes, and varying maintenance strategies. The Component Cooling Water System (CCWS) of the Tsinghua High-Flux Reactor (THFR) includes continuously operating, standby, and intermittently operated components, making the evaluation of its availability a complex challenge. This study proposes a structured workflow for system availability assessment and identifies critical input parameters such as system configuration, failure and repair rates, mission duration, logical dependencies, and maintenance policies. Traditional Fault Tree Analysis (FTA) provides a static view and fails to capture system state transitions, limiting its applicability under dynamic conditions. To overcome this limitation, a dynamic modeling approach using EMRALD is adopted, enabling the simulation of time-dependent behaviors including equipment failures and repairs over the mission period. Markov modeling is employed for cross-verification, offering a mathematical foundation for analyzing state transitions. The comparative analysis shows that EMRALD delivers a more accurate and adaptable representation of real-world system performance. This research highlights the necessity of dynamic modeling in system availability analysis and offers methodological insights into selecting appropriate tools for nuclear safety and reliability evaluations.

Keywords: system availability, EMRALD, component cooling water system (CCWS), Tsinghua High-Flux Reactor (THFR)

I. INTRODUCTION

To ensure system stability, availability analysis is vital in reliability assessment [1]. It evaluates the system's ability to sustain normal operation over time, reflecting effectiveness in accident prevention and mitigation, especially from failures or disturbances. Availability is the probability that the system is in a working state when needed [2].

Availability depends on functional equipment. In high-throughput reactors, the component cooling water system (CCWS) includes continuously, standby, and intermittently operating components [3]. As the main cooling for thermal equipment, it directly affects core heat removal and equipment operation [4]. Availability changes significantly impact plant reliability, especially during operation and accidents, thus influencing safety margins. Assessment focuses on events from total loss of CCWS [5].

Traditional methods like fault tree analysis (FTA) are still widely used. Yu Yu et al. used the Monte Carlo method to model a high-temperature gas-cooled reactor's CCWS and calculate failure frequency [6]. FTA uses Boolean logic for a clear, intuitive structure. However, as a static method, it struggles with maintenance, switching, recovery, and time-dependent interactions.

Thus, dynamic PSA models were developed. Zhang Binbin et al. applied a Markov model to dynamically evaluate a nuclear plant's CCWS and compared it to FTA [7]. The Markov model simulates random failures/repairs via state transitions. However, it suffers from state space explosion in large systems [8–10] and assumes exponential failure times. To address this, Qi Faqun et al. proposed a semi-Markov model for cold standby systems, allowing both exponential and Weibull distributions [11]. Distefano et al. used stage-type expansion and semi-Markov methods for non-Markovian models [10]. Temraz [12] used semi-Markov and regeneration point techniques for standby systems with general distributions. Wu et al. [13] also used semi-Markov models for repairable standby systems with perfect switching, though the semi-Markov property adds complexity.

With rising demand for dynamic risk assessment, tools like EMRALD, developed by INL, gained attention [14–15]. Combining finite state automata and temporal logic, EMRALD enables dynamic modeling and simulation of system behavior under failure, maintenance, and switching. Its flexibility and scalability provide advantages in availability modeling.

This paper analyzes availability of typical repairable systems (series, parallel, k/n, bypass) using both Markov and EMRALD methods, comparing their consistency. It evaluates availability considering equipment state transitions during operation. EMRALD is used for dynamic modeling, incorporating fault behavior, maintenance, and time constraints; the Markov model verifies and mathematically explains state transitions. Key parameters include equipment structure, task time, failure rate, logical dependency, and maintenance time. A case study of the high-flux reactor's CCWS evaluates the frequency of the initiating event "loss of both trains of CCWS" during power operation.

THFR has high design and operation safety demands [16–17]. High-flux reactors are critical for testing fuels/materials, producing strategic nuclides and isotopes, and are key to national scientific strength. THFR will build a world-class water-cooled high-flux reactor and supporting systems to address the domestic gap in ultra-high-flux neutron sources.

This paper is organized as follows: Section II introduces the methodology for system availability analysis. Section III presents the EMRALD-based event modeling and risk assessment. Section IV explains the availability analysis methods for typical repairable systems. Section V provides a case study on the component cooling water system. Section VI compares the results of three analysis methods. Section VII concludes the paper.

II. METHODOLOGY FOR SYSTEM AVAILABILITY ANALYSIS

System availability analysis requires a structured methodology, especially for complex nuclear systems. This section outlines the evaluation process and modeling techniques, as shown in Fig.1. The first step defines system boundaries and functional requirements by identifying components, subsystems, interfaces, and their interactions, while specifying performance criteria under normal and degraded conditions. Next, essential parameters are collected, including component configuration (e.g., redundancy schemes), failure and repair rates (often exponential or other distributions), mission time, degraded operation duration, maintenance schedules, and logical constraints. Data sources include historical records, expert judgment, and databases. Modeling follows, with dynamic simulation in EMRALD capturing time-dependent behaviors like staggered failures and repairs, while the Markov model is used to verify results. Simulations are executed over a defined mission time (e.g., one year) using Monte Carlo runs to estimate system success probability and unavailability. Finally, results are analyzed and methods compared in terms of system-level availability, modeling complexity, and flexibility, providing guidance for method selection.

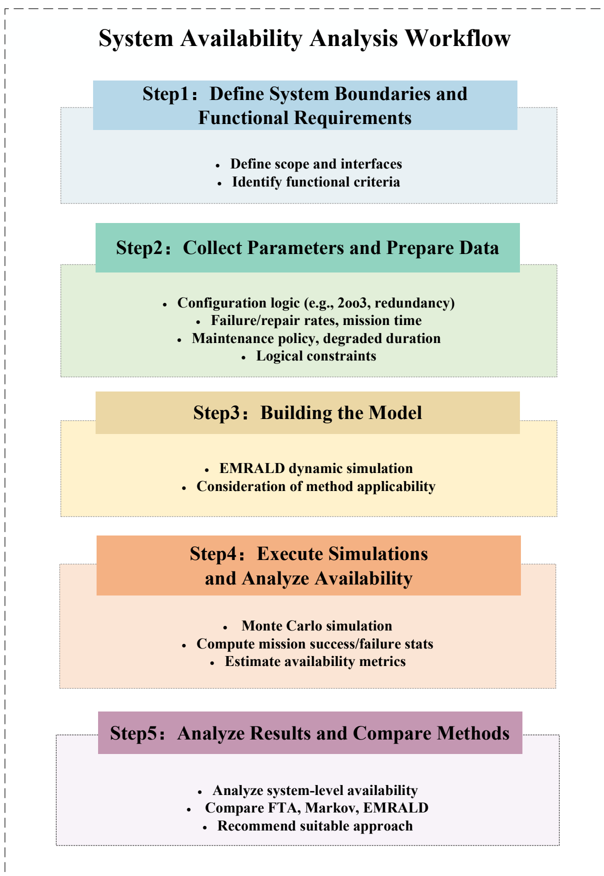

FIGURE 1. Workflow for System Availability Analysis Using EMRALD

III. EVENT MODELING RISK ASSESSMENT USING LINKED DIAGRAMS (EMRALD)

EMRALD, developed by INL, is a software tool for dynamic PRA (probabilistic risk assessment), considering time factors to more accurately assess operational risks. It has been updated to integrate with external physics-based simulation tools for external hazard PRA. Its goal is to provide modeling concepts for traditional PRA, a simple interface for complex interactions, and coupling functions for dynamic PRA challenges [18]. EMRALD uses three-stage discrete event analysis without fixed or variable time steps—simulation advances to the next event in time [19]. Results are derived statistically from Monte Carlo simulation runs. As shown in Fig. 2, its core elements are states, events, actions, and arrows.

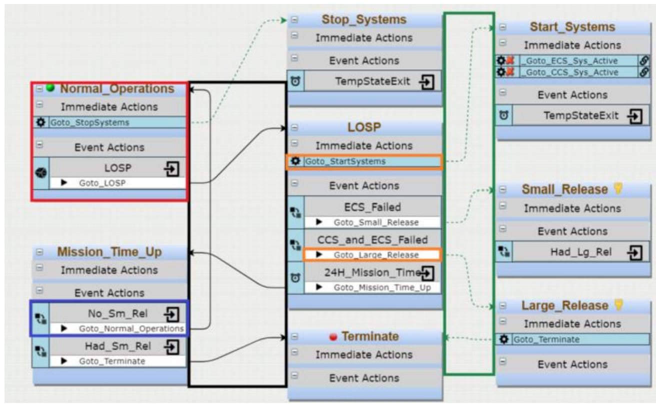

FIGURE 2. Elements of A Representative EMRALD Diagram. (Red) State S, (Orange) Actions A, (Blue) Events E, (Black) State Transition to Different State RB, (Green) State Transition to Current State RG.

This example illustrates the diagram's internal structure, including a state transition diagram with elements and set notation in Equation (1) [20]. The expected outputs are mean time to failure (MTTF) and fraction of key states.

$$\mathrm{EMRALD} \coloneqq < \mathrm{S}, \mathrm{E}, \mathrm{A}, \mathrm{R_B}, \mathrm{R_G}, \mathrm{D} > \tag{1}$$

IV. AVAILABILITY ANALYSIS METHOD of TYPICAL REPAIRABLE SYSTEM

For typical systems like series, parallel, k/n, and bypass systems [2], if the life and maintenance time of each unit follow an exponential distribution. This paper uses the Markov and EMRALD modeling methods to analyze the availability of these four systems and compare the consistency of the results, the Markov model can be applied for availability analysis..

IV.A. Availability of Repairable Series Systems

IV.A.1. Availability of 2-Unit Series System

Assume that the repairable series system consists of 2 units, whose failure rates are λ_1 and λ_2, and whose maintenance rates are μ_1 and μ_2. The maintenance strategy is one maintenance worker (or one group of maintenance workers), that is, the possible states of the system are: 0 state - both units work normally, the system is normal; 1 state - any one of the two units fails and is repaired, the other unit works normally, and the system fails; 2 state - both units fail, the system fails. EMRALD Modeling Diagram is shown in Fig. 3. The results are compared to the corresponding EMRALD model as shown in Table 1.

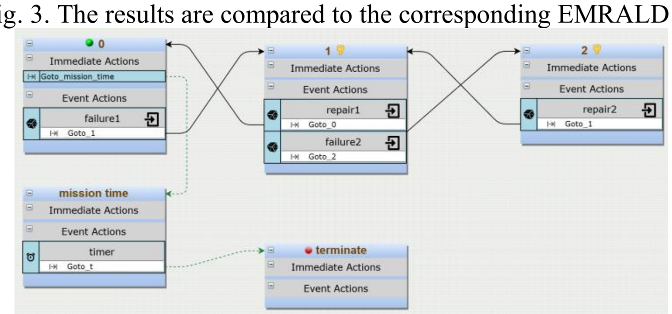

FIGURE 3. EMRALD Modeling Diagram of A Repairable Two-Unit Series System

TABLE Ⅰ. Availability of A Repairable Two-Unit Series System

Failure Rate	Repair Rate/time	Mission Time	Number of Runs	EMRALD Availability	Analytical Availability
1/10days	1/day	1000days	100000	0.81932	0.81967

IV.B. Availability of Repairable Parallel Systems

IV.B.1. Availability of A Parallel System of Identical Distribution Units

Assume that the system consists of two identical distributed units in parallel, with a failure rate of λ and a maintenance rate of μ. If one unit fails, a repairman will immediately repair it until it is repaired, and the system will still work normally. The possible states of the system are: State 0 - Both units work normally, and the system is normal; State 1 - Any one of the two units fails and is repaired, and the other unit works normally, and the system is normal; State 2 - Any one of the two units fails and is repaired, and the other unit fails and is waiting for repair, and the system fails. EMRALD Modeling Diagram is shown in Fig. 4. The results are compared to the corresponding EMRALD model as shown in Table 2.

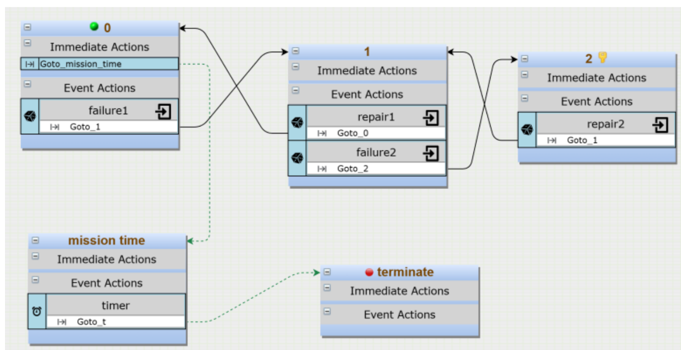

FIGURE 4. Repairable 2-Unit Parallel System EMRALD Modeling Diagram

TABLE Ⅱ. Availability of A Repairable 2-Unit Parallel System

Failure Rate	Repair Rate/time	Mission Time	Number of Runs	EMRALD Availability	Analytical Availability
1/10days	1/day	1000days	100000	0.9911	0.9836

IV.C. Availability of Repairable k/n Systems

IV.C.1. Availability of 2/3 Systems with the Same Distribution Unit

A 2/3 system composed of identically distributed units has a unit failure rate of λ and a maintenance rate of μ. With 1 repairman, the possible states of the system are: State 0 - All 3 units are working properly, and the system is normal; State 1 - Any one of the 3 units is repaired, and the system is normal; State 2 - Any one of the 3 units is repaired, and the other unit is waiting to be repaired, and the system is faulty. EMRALD Modeling Diagram is shown in Fig. 5. The results are compared to the corresponding EMRALD model as shown in Table 3.

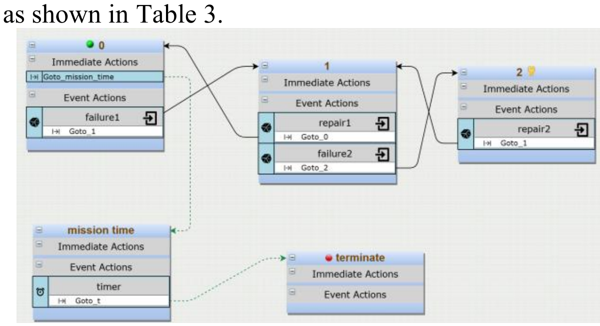

FIGURE 5. EMRALD Modeling Diagram of 2/3 System with 2 Identical Distributed Units

TABLE Ⅲ. Availability of 2/3 Systems with Two Identical Distributed Units

Failure Rate	Repair Rate/time	Mission Time	Number of Runs	EMRALD Availability	Analytical Availability
1/10days	1/day	1000days	100000	0.95509	0.95588235

IV.D. Availability of Repairable Bypass Systems

IV.D.1. Availability of Repairable Bypass Systems

Only one of the n units in the system works. When the working unit fails, it is connected to another normal standby unit through the fault monitoring and conversion device to continue working. The system will not fail until all units fail. Such a system is called a bypass system. Suppose a bypass system composed of two different distributed units is maintained by a maintenance worker, with failure rates of λ_1 and λ_2, and maintenance rates of μ_1 and μ_2. According to the analysis of the system's working process, the possible states of the system are: State 0 - Unit 1 is working, Unit 2 is on standby, and the system is normal; State 1 - Unit 1 is repaired, Unit 2 is working, and the system is normal; State 2 - Unit 1 is on standby, Unit 2 is working, and the system is normal; State 3 - Unit 1 is working, Unit 2 is repaired, and the system is normal; State 4 - Unit 1 is repaired, Unit 2 is on standby, and the system is faulty; State 5 - Unit 1 is on standby, Unit 2 is repaired, and the system is faulty. EMRALD Modeling Diagram is shown in Fig. 6. The results are compared to the corresponding EMRALD model as shown in Table 4.

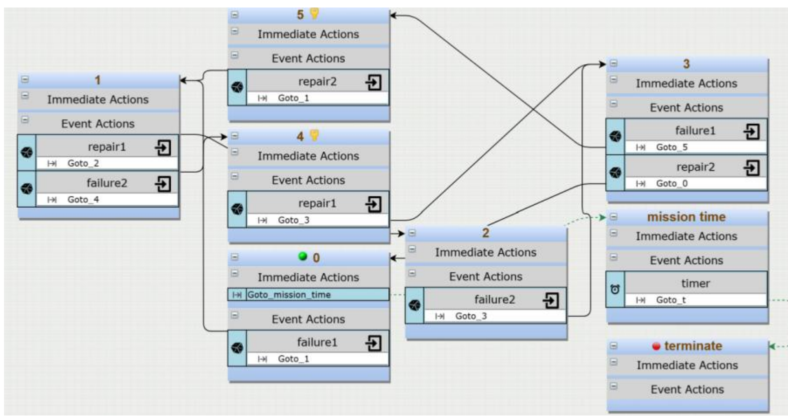

FIGURE 6. EMRALD Modeling Diagram of Two Different Distributed Unit Bypass Systems

TABLE Ⅳ. Availability of Two Different Distributed Unit Bypass Systems

Failure Rate	Repair Rate/time	Mission Time	Number of Runs	EMRALD Availability	Analytical Availability
1/10days	1/day	1000days	100000	0.9966	0.990991

The theoretical value here refers to the result calculated by the Markov model. Due to its random sampling characteristics, the result cannot be completely consistent with the theoretical calculation value. However, from the comparison results, the calculation results of EMRALD are highly consistent with the theoretical value, indicating the effectiveness and accuracy of its method in this problem.

V. A CASE STUDY on the COMPONENT COOLING WATER SYSTEM

V.A. EMRALD Model of Component Cooling Water System

This paper uses EMRALD software for dynamic modeling, and evaluates the frequency of the initiating event of "loss of both trains of the component cooling water system" during the power operation stage. The component cooling water system is a typical redundant backup system, and the failure of both trains is a typical support system initiating event. As shown in Fig. 7, it is a schematic diagram of typical component cooling water system in high flux reactor. The system consists of two independent series A and B. Each series includes two 100% capacity single-stage centrifugal pumps, one 100% capacity plate heat exchanger, and a water tank.

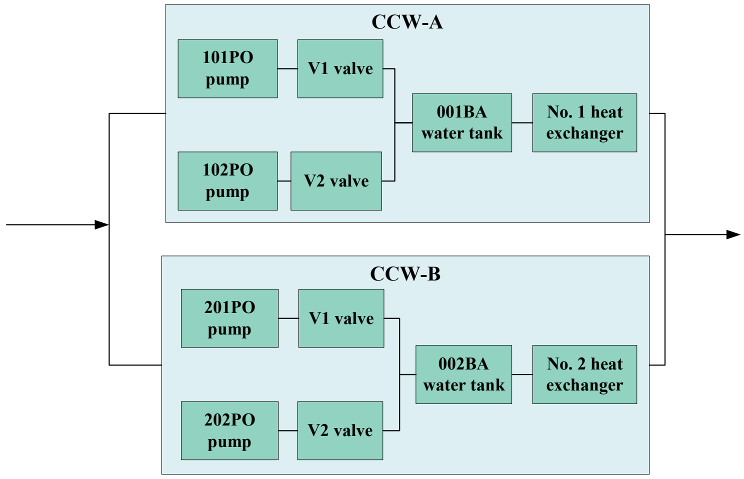

FIGURE 7. Component Cooling Water System Diagram

Assuming that the demand time of the chilled water system is 8760 hours, the operation procedures clearly stipulate the corresponding measures to be taken under different system configurations to ensure that the system availability meets the operation requirements. Under normal operation, the system is put into operation in one loop, and each loop must have at least 1 pump, 1 heat exchanger, and 1 water tank in an available state. The maintenance time after a single pump failure is assumed to be 36 hours. In this study, a fixed value was used for simplicity and consistency with the Markov model, which assumes constant rates.

The reliability data refers to the China Nuclear Power Plant Equipment Reliability Data Report [21], IAEA General Reliability Database [22], and NUREG/CR-5750 [23].

Based on the structure of the equipment component water system, the system operation procedures, and potential maintenance activities following equipment failure, the state transition diagram of the system is shown in Fig. 8. The system may be in 5 different states. If the system is in the P1 normal state, the standby train is activated when the running train fails completely. If two pumps in the running train fail, the standby train's heat exchanger and water tank are activated. When a pump or water tank/heat exchanger fails, the train is considered unavailable. From the normal state (P1), the system transitions to P2 due to a cooling pump failure. After the pump is successfully repaired, the system returns to P1. Similarly, P4 can transition to P3. When both pumps in a train fail, the train is considered failed, and maintenance of the pumps is not considered, so P3 cannot return to P2. The EMRALD modeling interface and calculation results are shown in Fig. 9.

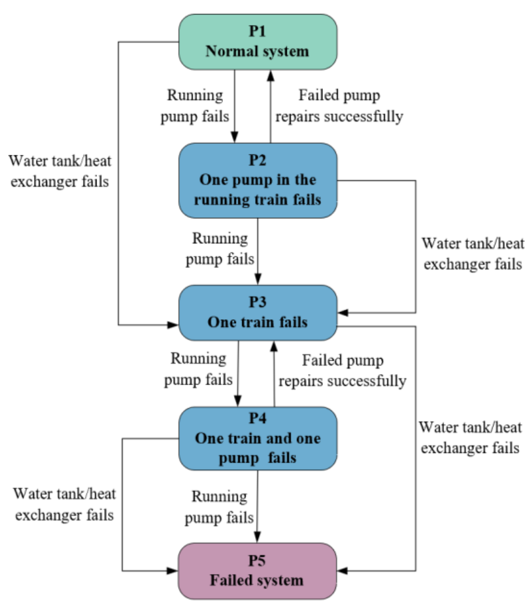

FIGURE 8. State Transition Diagram

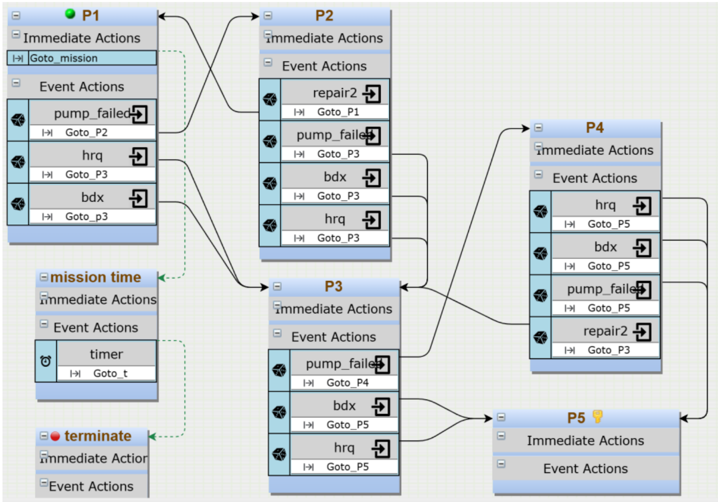

FIGURE 9. EMRALD Modeling Interface

V. B. Solution

Since the probability P of system failure within the required time can be approximately expressed by the Poisson distribution with its failure frequency F as parameter, the following formula can be obtained: f=-ln(1-P).

For 1,000,000 simulation runs with a mission time of 8760 hours, the key state "P5" occurred 355 times, resulting in a rate of 0.000355. The solution is that when the system is in the P1 state at the "current moment", the failure frequency of the system is 3.55E-04 times/reactor·year.

VI. COMPARISON of the RESULTS of THREE ANALYSIS METHODS

The EMRALD method yields a calculation result of 3.55E-04 times/ reactor·year, providing a more accurate description of the system's dynamic behavior compared to the fault tree analysis method (7.90E-04 times/ reactor·year) and the Markov method (3.64E-04 times/ reactor·year). Comparative analysis reveals that while the fault tree analysis method is computationally efficient, it struggles to dynamically model state changes due to the lack of maintenance consideration. Although the Markov method can account for maintenance, it faces challenges with state space explosion and high modeling complexity. The EMRALD method, with its event-driven approach, offers enhanced modeling flexibility and dynamic behavior simulation while maintaining calculation accuracy. Therefore, it demonstrates superior applicability for nuclear power system reliability and availability analysis, providing a more accurate and efficient modeling tool for related research. Future work can focus on expanding EMRALD's application and optimizing its computational performance to enhance its practical use in nuclear engineering safety analysis.

VII. CONCLUSIONS

In conclusion, this study presents a comprehensive system availability analysis of the component cooling water system (CCWS) in a high-flux reactor, highlighting the limitations of traditional fault tree analysis (FTA) in capturing dynamic behaviors such as maintenance, switching logic, and fault recovery. The EMRALD modeling approach, based on discrete event simulation and state transition logic, effectively represents complex system behaviors and allows integration of key factors such as mission time, failure and repair rates, and maintenance policies. The consistency between EMRALD and Markov model results for typical system configurations (series, parallel, k/n, bypass) confirms the reliability of the dynamic modeling approach. Applying these methods to the high-flux reactor's CCWS shows that EMRALD can effectively evaluate the frequency of critical initiating events, such as the loss of both cooling trains, thus offering valuable insights for risk-informed design and safety assessment. Overall, the research underlines the importance of adopting dynamic modeling techniques like EMRALD for availability analysis in nuclear systems and provides guidance for future applications in probabilistic safety assessments.

REFERENCES

[1] J. C. LEE and N. J. MCCORMICK, *Availability and Reliability of Systems with Repair*, pp. 109–139, Wiley, United States (2012).

[2] X. JIN, *System Reliability and Availability Analysis Methods*, National Defense Industry Press, Beijing, China (2007).

[3] L. W. BEI and J. Zhao, *Fault Tree Analysis of Initiating Events Due to Loss of Component Cooling Water System in CAP1400* [Dissertation], Tsinghua University, Beijing, China (2019).

[4] S. P. XING and Y. SUI, "Dynamic Reliability Assessment Method for Component Cooling Water System in Nuclear Power Plants," *Science Technology and Engineering*, 22(23), 10092–10101 (2022).

[5] B. GUO, *Research on the Estimation Method of Initiating Event Frequency in Online Risk Monitoring System* [Dissertation], Harbin Engineering University, Harbin, China (2016).

[6] Y. YU, J. J. TONG, J. ZHAO, et al. "Application of Monte Carlo Method to Simulate the Frequency of Initiating Events of Loss of Component Cooling Water System in Nuclear Power Plants," *Nuclear Power Engineering*, 31(4), 57-59 (2010).

[7] B. B. ZHANG and J. HE, "Research on the Calculation of the Frequency of Initiating Events Using Markov Model," *Proc. 2012 Nuclear Energy Probabilistic Safety Analysis Symposium*, Beijing, China, pp. 125–129, China Nuclear Energy Association (2012).

[8] L. XINGX, A. SHRESTHA, Y DAI, "Exact Combinatorial Reliability Analysis of Dynamic Systems with Sequence Dependent Failures," *Reliability Engineering & System Safety*, 96(10), 1375-1385 (2011).

[9] A. PEIRAVI, M. A. ARDAKAN, E. ZIO, "A New Markov-based Model for Reliability Optimization Problems with Mixed Redundancy Strategy," *Reliability Engineering & System Safety*, 201, 106987 (2020).

[10] S. DISTEFANO and K. S. TRIVEDI, "Non-Markovian State-Space Models in Dependability Evaluation," *Quality and Reliability Engineering International*, 29(2), 225-239 (2013).

[11] F. Q. QI, H. M. ZHONG, J. H. PANG, et al. "Optimization of Cold Standby System Maintenance Strategy Based on Semi-Markov Process," *China Mechanical Engineering*, 31(03), 336-343 (2020).

[12] N. S. Y. TEMRAZ, "Comparison of fuzzy semi-Markov models for one unit with mixed standby units with and without preventive maintenance using regenerative point method," *Heliyon*, 7(8) (2021).

[13] X. WU and J HILLSTON, "Mission reliability of semi-Markov systems under generalized operational time requirements," *Reliability Engineering & System Safety*, 140, 122-129 (2015).

[14] "git clone," https://github.com/inl-labtrack/EMRALD.git.

[15] "EMRALD - Overview," https://emrald.inl.gov/SitePages/Overview.aspx.

[16] M. CEPIN, Assessment of Power System Reliability: Methods and Applications, pp. 89–99, Springer, London, UK (2011).

[17] J. L. LIU, Probabilistic Safety Analysis of High Flux Engineering Test Reactor [Dissertation], University of Science and Technology of China, Hefei, China (2016).

[18] S. PRESCOTT, C. SMITH, L. VANG, "EMRALD, Dynamic PRA for the Traditional Modeler," *Proc. 14th International Probabilistic Safety Assessment and Management Conference,* Los Angeles, CA (2018).

[19] M. PIDD, "Object-orientation, Discrete Simulation and the Three-phase Approach," *Journal of the Operational Research Society*, 46(3), 362-374 (1995).

[20] A. EARTHPERSON, C. M. OTANI, D. NEVIUS, et al, "A combined strategy for dynamic probabilistic risk assessment of fission battery designs using EMRALD and DEPM," *Progress in nuclear energy (New series)*, 160(C), 104673 (2023).

[21] China Nuclear Energy Association, *Reliability Data Report of Equipment in Chinese Nuclear Power Plants (2022 Edition) [Technical Report]*, China Nuclear Energy Association, Beijing, China (2022).

[22] International Atomic Energy Agency (IAEA), *Generic Component Reliability Data for Research Reactor PSA* [Technical Report], IAEA-TECDOC-930, Vienna, Austria (1997).

[23] U.S. Nuclear Regulatory Commission (NRC), *Rates of Initiating Events at U.S. Nuclear Power Plants, 1987–1995* [Technical Report], NUREG/CR-5750, Washington, DC (1999).