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Reliability and Degradation Analysis of Complex Systems Using Stochastic Petri Nets and Monte Carlo Simulations in Modelica

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This study investigates the anticipated transient behavior of molten salt reactors (MSRs), focusing on the effects of a reduction in mass flow caused by primary fuel pump degradation. The analysis evaluates the impact of this degradation on reactor power, core temperature, and overall safety, addressing a gap in existing research on MSRs under such conditions. An integrated approach is employed, combining Stochastic Petri Nets (SPNs) and Monte Carlo simulations within the Modelica environment. SPNs model the probabilistic transitions of the fuel pump between functional, degraded, and failed states using Weibull distributions. These stochastic models are dynamically coupled with the deterministic MSR physical model, which uses validated empirical data to capture continuous system behaviors like heat transfer and mass flow. The results reveal significant power increases and temperature fluctuations in the core during degraded states, providing critical insights into reactor safety and performance under adverse conditions. This work offers a novel framework for modeling the reliability of MSRs under uncertainty, contributing to improved reactor safety, optimized maintenance strategies, and enhanced understanding of transient behaviors in advanced nuclear systems.

Keywords: Reliability, SPN, MSR, Physical model, Monte Carlo simulation.

1. Introduction

Anticipated transients in nuclear reactors, particularly in advanced systems like molten salt reactors (MSRs), require careful study to ensure reactor safety and stability under unexpected operational conditions. One critical scenario that remains underexplored is the behavior of an MSR during a transient without triggering a safety system SCRAM. In this study, we focus on understanding the effects of a reduction in the mass flow rate through the primary fuel pump—a condition that could significantly impact reactor operations. Specifically, we aim to determine how such a transient affects core power, temperature distributions, and, ultimately, the safety of the reactor.

The mass flow rate in an MSR plays a vital role in maintaining thermal equilibrium within the reactor core. A substantial reduction in flow could lead to localized overheating, power increases, and potential challenges to reactor safety. Investigating this scenario requires a detailed understanding of how the reactor responds dynamically to pump degradation, as this is a probable cause of reduced mass flow in operational settings.

Reliability analysis becomes a crucial tool in this context. MSRs, being Generation IV reactors, operate in high temperature, corrosive environments, exposing their components to continuous stress and potential degradation. Among these, the primary pump, which circulates molten salt through the reactor core, is particularly critical. Its degradation whether due to impeller wear, shaft seal deterioration, bearing wear, or molten salt corrosion can directly influence reactor performance. Therefore, modeling the pump's reliability and degradation mechanisms is key to predicting and mitigating the impacts of such transients.

In this work, we combine Monte Carlo simulations and Stochastic Petri Nets (SPNs) to model the degradation of the primary pump. These advanced methods enable the detailed analysis of both deterministic reactor dynamics and stochastic degradation events, capturing real-world operational variability. By simulating the degradation-induced reduction in mass flow, we provide insights into how pump reliability influences reactor safety, power stability, and thermal behavior under transient conditions. This study offers a comprehensive framework for understanding and addressing the challenges posed by anticipated transients in MSRs, contributing to the design of more resilient and reliable reactor systems.

1.1 MSR Technology

Molten salt reactors (MSRs) are a type of advanced nuclear reactor where nuclear fuel is dissolved in a molten salt mixture, typically composed of lithium and beryllium fluorides. Unlike solid-fuel reactors, MSRs use liquid fuel that circulates within the reactor core, allowing for superior thermal management and significantly reducing the risks of core meltdown. This unique liquid fuel system enables MSRs to operate at higher temperatures, improving thermal efficiency and facilitating the use of alternative nuclear fuels, such as thorium. According to Greenwood et al. (2020), such flexibility supports more efficient utilization of fissile resources while minimizing the production of long-lived nuclear waste.

A typical MSR design (Fig. 1) incorporates a primary circuit in which the molten salt circulates through the reactor core, transferring the heat generated by nuclear fission to a secondary circuit via heat exchangers. This secondary circuit then directs the heat to an energy conversion system, commonly a steam cycle, to generate electricity. MSRs offer additional advantages, such as online refueling, which allows for continuous fuel management, and simplified fuel reprocessing due to the liquid nature of the fuel. Additionally, enhanced safety features such as freeze valves allow the liquid fuel to be drained into secure storage tanks in emergencies, where natural convection can safely dissipate residual heat.

However, the demanding operating environment of MSRs introduces unique degradation challenges, particularly for critical components like the primary pump. This pump, responsible for circulating the molten salt through the reactor core, is subjected to high temperatures and corrosive conditions that accelerate wear and degradation. Accurately modeling the degradation of the primary pump is vital to understanding its impact on reactor reliability and safety.

In this study, we employ advanced reliability modeling techniques, including Stochastic Petri Nets (SPNs) and Monte Carlo simulations, to analyze the degradation of the primary pump. These methods account for key degradation pathways, such as transitions from a "Functional" to “Degraded” or "Failed" states. SPNs enable detailed representation of these transition stages, while Monte Carlo simulations provide insights into the stochastic nature of degradation under real-world operating conditions. By integrating these models, we capture the dynamic interplay between pump performance and reactor safety, assessing how degradation mechanisms influence key operational metrics like mass flow, power stability, and thermal behavior.

Ensuring the reliability of MSR components through such detailed analyses is critical for maintaining the reactor's structural integrity and operational safety. Failures in primary systems, like the pump, could result in reduced mass flow rates, elevated core temperatures, and increased risks of material degradation. These conditions underscore the importance of proactive reliability assessments to mitigate potential safety concerns and enhance the long-term viability of MSR technology.

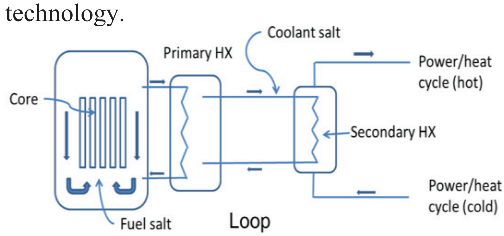

Fig. 1. Molten Salt Reactor.

2. Literature Review

Traditional reliability methods, such as Failure Mode and Effects Analysis (FMEA) and Hazard and Operational Analysis (HAZOP), have long been foundational in analyzing reliability in nuclear reactors. For instance, Burgazzi (2006) applied FMEA to assess the reliability of passive decay heat removal systems in advanced reactors, identifying key accident initiators, failure causes, and mitigation strategies. Ferguson and Lu (2017) applied Fault Tree Analysis (FTA) to assess the reliability of a snake-arm inspection robot for coolant outlet pipe inspection in nuclear power plants, identifying potential failure modes and evaluating the applicability of FTA for robotic inspection systems in the nuclear industry. Also, Leng and Liu (2025) conducted a Fault Tree Analysis (FTA) to evaluate the reliability of the Medium Pressure Safety Injection System (MP-SIS) at Tianwan Nuclear Power Plant, focusing on unavailability and Minimal Cut Sets (MCS) as key metrics. Despite their usefulness, these methods often assume independent failure modes or linear dependencies, which may be inadequate for complex systems.

Petri nets (PNs) offer an alternative that captures dependencies and event sequences crucial in engineering contexts. Yan et al. (2023) demonstrated the effectiveness of Petri nets in assessing nuclear power plant resilience under extreme natural hazards, modeling system health states, mitigation, and recovery processes.

Dynamic Probabilistic Risk Assessment (DPRA), or dynamic reliability, offers a more advanced approach to reliability by integrating both continuous and discrete system dynamics. This approach has seen application in nuclear safety by Zhou et al. (2020), structural engineering by Zhang et al. (2020), and rotating machinery by Chiacchio et al. (2020).

DPRA utilizes modeling techniques like Dynamic Fault Trees (DFTs), Petri Nets (PNs), and Stochastic Hybrid Automata (SHA) in hybrid approaches. For example, Babykina et al. (2014) developed a Stochastic Hybrid Automaton framework to assess the dependability of a nuclear power plant's steam generator, integrating dynamic reliability analysis with Monte Carlo simulations to model stochastic events and continuous system behavior. Taleb-Berrouane et al. (2020) demonstrated a hybrid model integrating Bayesian Networks (BNs) with Stochastic Petri Nets (SPNs) for pump failure events, while Codetta-Raiteri and Bobbio (2005) applied Generalized Stochastic Petri Nets (GSPNs) and Fluid Stochastic Petri Nets (FSPNs) to model a heated tank.

In response to the complex reliability demands of MSRs, this paper proposes an integrated framework using Stochastic Petri Nets (SPNs) and Monte Carlo simulations within Modelica. This approach combines SPNs for probabilistic state transitions and Monte Carlo sampling to account for both physical degradation and probabilistic event-driven processes inherent in MSR systems. This methodology enables interaction between physical behaviors (e.g., temperature variations) and stochastic state transitions, offering a comprehensive reliability assessment with metrics like Mean Time to Failure (MTTF) and degradation rates.

The study demonstrates the utility of this framework in predicting reliability under uncertainty, highlighting its potential in identifying vulnerabilities, optimizing maintenance, and enhancing MSR resilience.

3. General Methodology

This paper presents a hybrid modelling approach that overcomes the limitations of traditional reliability analysis by integrating the physical behavior of critical components, such as the primary pump, with stochastic events that influence its degradation throughout the MSR's operational life. The approach combines two complementary sub-models: a deterministic sub-model and a stochastic sub-model, which simulates random events and variability in degradation rates.

Together, these interconnected sub-models form a robust framework that enables a detailed analysis of the primary pump's reliability, accounting for degradation mechanisms such as impeller wear, shaft seal deterioration, bearing wear, corrosion from molten salt, and operational temperature fluctuations. The deterministic sub-model provides a foundation for modelling the baseline operational behavior under controlled conditions, while the stochastic sub-model introduces randomness to reflect real-world uncertainties and operational variability.

The following sections discuss each sub-model in detail, beginning with the deterministic model, followed by the stochastic petri nets model.

3.1. *Deterministic model in modelica*

The physical model of MSR using Modelica in the Dymola environment is depicted in Fig. 2. All input data for this model are empirical and validated by Greenwood et al. (2020).

This model presents a high-level overview of essential subsystems, including the Off-Gas System & Drain Tank, Primary Fuel Loop (PFL), Decay Heat Removal System, Primary Coolant

Loop (PCL) and Power Conversion Loop. These subsystems perform vital functions like gas extraction, molten salt circulation, heat dissipation, and heat transfer to power systems, all of which are crucial for maintaining safe reactor operation.

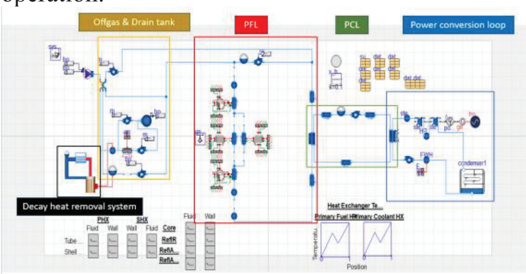

Fig. 2. Physical modelling of MSR.

3.2. *Stochastic modelling*

The stochastic sub-model focuses on modelling the degradation and potential failures of key components within the molten salt reactor (MSR) system, specifically addressing the primary pump's reliability. This component of the hybrid model operates in the discrete-time domain and uses Stochastic Petri Nets (SPNs) to represent various degradation stages and failure events over the reactor's lifespan. Through SPNs, we model critical degradation mechanisms impacting the pump, such as leak or rupture or functional failure. These degradation processes are simulated with SPN transitions that capture the progression from functional to degraded or failed states, providing a detailed representation of the primary pump's reliability within the overall MSR system.

Petri nets serve as a powerful graphical and mathematical modelling tool used to depict a wide range of systems and processes. A Petri net consists of a bipartite graph with two types of nodes: places and transitions. The collection of places reflects the potential states of the system, while transitions between these places represent the various events occurring during the system's operational life. Tokens move between places through transitions, and the system's state at any given moment is defined by the distribution of tokens across the places. Transitions are activated when specific conditions are satisfied, and in this model, all transitions are timed, meaning each has an associated delay that comes into play once the firing conditions are met. The timing for transitions may either be random or predetermined. In graphical representations, places are illustrated as circles, and transitions as rectangles.

Several software tools exist for constructing and simulating Petri Nets, but since the deterministic sub-model has been developed using the Modelica language, utilizing a Petri net library within this framework is ideal. For this purpose, the PNlib library developed by Proß & Bachmann (2012) is employed to construct the stochastic sub-model. This open-source library contains the code and graphical representations for all essential Petri net elements.

Stochastic Petri Nets model as shown in Fig.3 have been created for degraded and failure mode of the primary fuel pump in the MSR system. To establish the delays associated with the transitions, the times to failure for the components are modelled using a two-parameter Weibull distribution. According to O'connor and Kleyner (2011), this distribution is frequently used in reliability engineering due to its adaptability in fitting various other probability distributions. The unreliability function F(t), which characterizes the probability of component failure over time, is given by:

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \qquad (1)$$

where β is the shape parameter and η is the scale parameter. The firing intervals for each transition mode, t_{fire}, can be derived by rearranging and taking the logarithm of both sides of the unreliability equation:

$$t_{fire} = \eta\left[-ln\left(1 - F(t)\right)\right]^{\frac{1}{\beta}} \qquad (2)$$

In this study, β is initially fixed at 1 for all failure modes, assuming a constant failure rate. This assumption is supported by reliability data from Smith (2005) and Moss (2005), which account for early-life failures being eliminated through rigorous pre-installation testing and end-of-life failures being avoided through scheduled maintenance and component replacement. As a result, many industrial reliability models apply an exponential failure distribution (β = 1) for components operating within their useful life period, where failures occur randomly at a constant rate.

However, degradation is typically a progressive process, where the failure rate increases over time due to wear and aging effects. In Weibull-based reliability modeling, this is represented by a shape parameter $\beta > 1$, indicating a time-dependent increase in failure probability. While this study primarily assesses degradation effects using an extrapolated η parameter, future iterations will incorporate $\beta > 1$ to better capture the physics of wear-related degradation and its impact on MSR operation.

Degradation in this study refers to the gradual reduction in the primary fuel pump's performance due to mechanical wear, leaks, or flow obstruction, which affects the mass flow rate and, consequently, the reactor's thermal and neutron flux behavior. In the stochastic Petri net (SPN) model (see Fig. 3), degradation and failure are represented by two separate transitions (T2 and T3), both governed by Weibull-distributed times to transition.

- C2_W represents the initial fully functional state of the pump.
- T2 (Degradation Transition) models the shift from a functional to a degraded state (C2_DM), where mass flow is reduced but the pump remains operational.
- T3 (Failure Transition) models the transition from a functional state directly to failure (C2_FM), where the pump ceases operation entirely.

The transition times in the SPN, dictated by the Weibull-distributed time-to-failure Eq. (2), determine the positioning of tokens and thus control the stochastic evolution of degradation and failure. By linking this stochastic model with the deterministic MSR model, pump degradation events influence process variables such as mass flow rate, core temperature, and power output. When a token occupies a degraded or failure state (C2_DM or C2_FM), a corresponding signal is generated using the Modelica Standard Library. This signal is then relayed to the deterministic MSR model, triggering changes in mass flow, thermal dynamics, and reactor feedback mechanisms. Through this integrated approach, the impact of progressive degradation and sudden failures on MSR performance can be systematically analyzed, providing insights into operational reliability and necessary maintenance strategies.

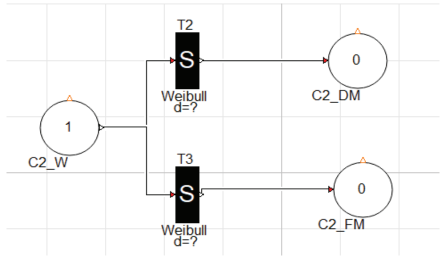

Fig. 3. Petri Net representation of fuel pump degraded and failure modes using PNlib in Modelica.

This integration is illustrated in Fig. 4, showing the hybrid model's layout. The lower section of Figure 4 depicts the MSR model, with an SPN module connected to the fuel pump to monitor its operational states. The upper part of Fig. 4 displays the Stochastic Petri Net (SPN) structure, which represents the pump's degradation and failure modes. This SPN includes transitions labelled "Degradation" and "Failure," as well as three states: Functional, Degraded, and Failed. The pump's state is determined by token placement in the Degraded and Failed states, with the Integer-to-Boolean and TriggeredTrapezoid blocks processing these states to generate the fault signal F(t). This fault signal is then fed into the fuel pump as an input to simulate its degraded or failed behavior.

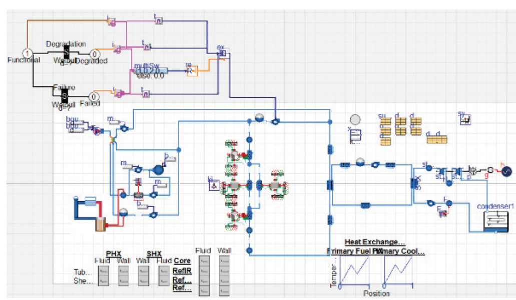

Fig. 4. Arrangement of blocks to translate the state of Petri net into the dynamic variables of the fuel pump of the overall MSR model.

4. Monte Carlo simulation

In this study, simulation-based reliability analysis is employed to evaluate the impact of primary fuel pump degradation and failure on the reactivity and power output of the MSR system. This analysis utilizes the Monte Carlo method, a robust approach for exploring systems with significant uncertainty in their parameters. The method enables the investigation of various scenarios of the pump's lifetime evolution by iteratively generating random input parameters, such as time to failure derived from the Weibull distribution and applying them to the coupled SPN-MSR model.

Through repeated simulations, the deterministic model evaluates the pump’s degradation and failure modes and their effects on reactor dynamics. By recording and analyzing the outputs of these simulations, statistical insights into the reliability of the pump and its influence on the thermal stability, neutron flux, and overall system performance are obtained. This approach provides a comprehensive understanding of how pump behavior affects the long-term operation and safety of the MSR under varying conditions.

4. Simulation design

The durability target for a Molten Salt Reactor (MSR) system is typically designed for decades of operation under optimal conditions. However, simulating the full operational life of an MSR is computationally prohibitive. Therefore, for this study, the simulations were limited to a runtime of 10,000 seconds. The parameter η was extrapolated to 10, representing a scale factor for the Weibull distribution, to investigate the impact of pump degradation and failure within this timeframe.

To conduct the Monte Carlo simulations, the Modelica Standard Library (MSL) 3.2.2 was used, leveraging its built-in package, Math.Random.Generators. Given the limited number of required simulations, the xorshift64* generator was selected for its efficiency and suitability for the given scale. The entire Monte Carlo simulation was implemented in the Modelica environment.

The process logic involves simulating the degradation and failure behavior of the primary fuel pump and its effects on the MSR's reactivity and power output. Each iteration uses randomly generated input parameters from the Weibull distribution to evaluate the deterministic SPN-MSR model. The simulation continues until the predetermined runtime of 10,000 seconds is reached. To ensure accurate results, ten Monte Carlo simulations were performed. While there is no universal rule for determining the total number of Monte Carlo iterations, the number of simulations was chosen based on the need to gather statistically meaningful results for the system’s performance.

Though the primary focus was on evaluating the degradation and failure modes of the pump, additional simulations could offer more detailed insights into the system’s behavior under various failure scenarios. However, due to the integration of the SPN model with the MSR system, the current simulation effort effectively captures the critical dynamics between pump degradation and reactor performance, including thermal behavior and power fluctuations.

5. Simulation results

In this study, few scenarios were simulated to enhance understanding of the steady-state and transient behavior of MSR. Using the empirical and validated data by Greenwood et al. (2018), some of the results obtained for the steady state conditions are shown in Fig. 5. The subsequent tests begin from the result of this simulation.

In the MSR model (see Fig. 5), the mass flow rate of the primary fuel pump at steady state is 5544 kg/s. The core temperature initially rises to 605°C before stabilizing at its steady state, and the total core power (Q_{total}) at steady state is ~ 400 MW.

However, when integrating the SPN model to simulate pump degradation (see Fig. 6), where the mass flow decreases by ~50%, significant deviations were observed:

- The core temperature rose to ~ 625°C before stabilizing, a rise of ~3.3% compared to the 605°C observed in the non-degraded scenario.
- The total core power (Q_{total}) is ~500 MW, representing a substantial rise in thermal load.

These results were consistent across 10 simulation iterations, with variations observed only in the transition times (see Table 1) between functional and degraded (T_{deg}) or failed states (T_{fail}).

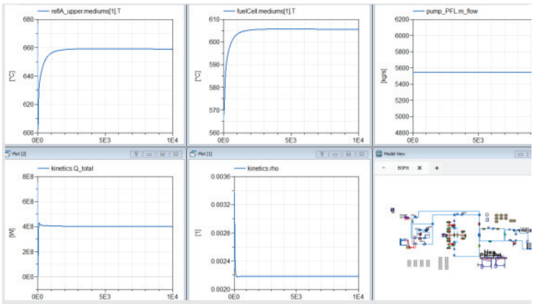

Fig. 5. A plot of the physical behavior model of MSR showing the temperature of the core, mass flow of the primary fuel pump, total power and total reactivity feedback in the functional state.

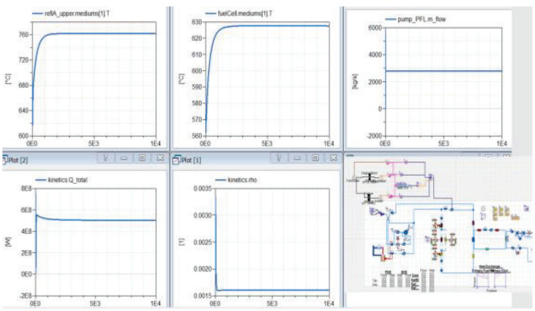

Fig. 6. A plot of the physical behavior model of MSR showing the temperature of the core, mass flow of the primary fuel pump, total power and total reactivity feedback in the degraded state.

The comparison between the MSR model (see Fig. 5) and the SPN-MSR model (see Fig. 6) underscores the relationship between reduced mass flow ($\Delta\dot{m}$) and reactor performance metrics. The 50% reduction in mass flow resulted in a higher core temperature and increased power output, suggesting reduced heat removal efficiency and heightened thermal feedback. This indicates that while MSRs are designed with inherent safety features, such as passive temperature regulation, prolonged operation under degraded conditions could challenge these safety margins.
While the MSR's design mitigates catastrophic outcomes, these findings emphasize the importance of real-time monitoring, redundancy in critical systems, and pre-emptive maintenance strategies to sustain safe operation.
By integrating stochastic degradation models with deterministic reactor behavior, this study provides valuable insights into MSR reliability, offering a foundation for enhancing reactor safety and optimizing operational strategies under transient conditions.

Table 1. Different transition times observed across 10 simulation iterations.

Simulation number	Transition time (s)
1	T_{deg}= 12.1924 T_{fail}= 7.38462
2	T_{deg}= 15.3878 T_{fail}= 12.3633
3	T_{deg}= 36.3234 T_{fail}= 14.3657
4	T_{deg}= 12.3517 T_{fail}= 28.7210
5	T_{deg}= 22.1388 T_{fail}= 14.2259
6	T_{deg}= 23.3297 T_{fail}= 5.42396
7	T_{deg}= 16.3261 T_{fail}= 6.64184
8	T_{deg}= 13.3837 T_{fail}= 6.99179
9	T_{deg}= 52.1985 T_{fail}= 5.32069
10	T_{deg}= 7.13695 T_{fail}= 12.0723

6. Conclusion

This study presented a comprehensive modeling approach for assessing the reliability of molten salt reactors (MSRs) by integrating deterministic system dynamics with stochastic degradation and failure mechanisms. The deterministic model represents the continuous-time behavior of key reactor components and their interactions. Stochastic Petri Nets (SPNs) were employed to simulate discrete-time events, such as degradation and failure of the primary fuel pump—a critical component in maintaining reactor performance.
By coupling SPNs with Monte Carlo simulations, the approach enabled the evaluation of the impact of pump degradation on MSR performance metrics, including core temperature, mass flow rate, and total power output. Simulations demonstrated that a ~50% reduction in pump mass flow caused significant changes in reactor behavior, such as a rise in core temperature and increased total power output. These findings reveal the sensitivity of the reactor to pump

performance, underscoring the importance of real-time monitoring and predictive maintenance to mitigate potential safety risks.

The proposed modeling framework offers a robust tool for understanding the dynamic reliability of MSRs under various operating conditions. It provides valuable insights into the interaction between component degradation and overall system behavior, contributing to the development of enhanced safety strategies and operational guidelines for advanced nuclear reactors. Future work could extend this approach to include additional reactor components, dynamic ambient conditions, and more sophisticated failure mechanisms to further refine reliability assessments and optimize MSR safety and efficiency.

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