# EPRI Guidance for Passive System Reliability Analysis

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**Abstract:** As the nuclear industry advances toward deployment of advanced reactors, passive safety systems (PSS) are increasingly relied upon to reduce dependence on operator actions and external power while extending accident coping times. Despite these advantages, the reliability assessment of PSS remains challenging due to their strong dependence on complex thermal–hydraulic phenomena and associated uncertainties. This study, supported by the Electric Power Research Institute (EPRI), evaluates the global state of practice for PSS reliability analysis and examines its integration within a probabilistic risk assessment (PRA) framework. Existing methodologies for assessing PSS reliability are reviewed, with particular emphasis on the treatment of phenomenological variability and uncertainty inherent in natural circulation and other passive mechanisms. Building on this review, a consolidated reliability assessment methodology is developed that combines traditional fault tree analysis with systematic treatment of physical phenomena uncertainty. A Phenomena Identification and Ranking Table (PIRT) process is applied to identify and prioritize key thermal–hydraulic parameters influencing PSS performance, enabling focused modeling and highlighting knowledge gaps requiring further research. To address computational constraints, uncertainty propagation in a best-estimate thermal–hydraulic code is performed using response surface techniques. The methodology is demonstrated through a pilot application to a simplified passive containment cooling system, yielding credible insights into system performance and reliability. The results underscore the importance of integrated, risk-informed approaches to passive system reliability and support the continued advancement of passive safety concepts for next-generation nuclear reactors.

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## 1. INTRODUCTION

Risk analysis, and in particular probabilistic risk assessment (PRA), is a foundational element in the design, licensing, and operation of nuclear power plants. Over several decades, PRA methods have been developed, refined, and successfully applied to the current fleet of water-cooled reactors (WCRs), including light water reactors (LWRs), supporting risk-informed regulatory decision making and plant operation. However, the next generation of nuclear technologies—commonly referred to as advanced reactors (ARs), including small modular reactors (SMRs) and non-WCR concepts—exhibit fundamental differences in design, operating characteristics, and safety strategies relative to traditional reactors. These differences necessitate a re-examination of existing PRA methods and tools to ensure their applicability and adequacy for advanced reactor applications.

A defining characteristic of many advanced reactor designs is an increased reliance on passive safety systems (PSSs). Passive systems depend primarily on natural physical phenomena—such as gravity, natural circulation, and heat conduction or convection—and require minimal or no operator action or external power to perform their safety functions. The use of PSSs is intended to enhance safety by reducing system complexity, limiting dependence on active components and support systems, and increasing resilience during beyond-design-basis events, while simultaneously reducing lifecycle and operational costs. As a result, PSSs often play a central role in meeting key safety and operational objectives of advanced reactors.

The growing importance of PSSs in advanced reactor designs places increased emphasis on the need to quantitatively evaluate their reliability within a PRA framework. Unlike active systems, whose reliability can often be characterized using component failure data and established fault tree/event tree methods, PSS reliability is strongly influenced by phenomenological behavior and system-level performance margins. Passive system failures may occur without discrete component failures, arising instead from adverse combinations of thermal-hydraulic conditions, parameter uncertainties, or degradation mechanisms that reduce system effectiveness. Consequently, traditional PRA approaches alone are insufficient to fully characterize PSS reliability, and additional methods are required to account for functional and phenomenological failure modes.

Over the past two decades, a variety of methods and frameworks have been proposed to address passive system reliability. These include approaches developed in international research programs, national laboratories, and universities. While these methods differ in implementation, they share common elements, including identification of critical parameters, use of best-estimate thermal-hydraulic codes, uncertainty propagation, and reliance on expert judgment in the absence of sufficient experimental or operational data. Collectively, these efforts have advanced the state of practice but have also highlighted persistent challenges, including treatment of uncertainty, parameter dependencies, time-dependent behavior, and the integration of phenomenological failures with traditional hardware reliability models.

Recent EPRI research evaluated the current landscape of passive system reliability methods and identified both strengths and gaps in their application to advanced reactors. A key conclusion from this evaluation was the absence of a consolidated, generically applicable approach that could be consistently applied across different reactor technologies and regulatory contexts. In particular, there is a need for a structured methodology that integrates phenomenological reliability analysis with conventional PRA techniques, aligns with existing PRA standards, and provides a transparent and traceable basis for regulatory review and risk-informed decision making.

In response to this need, EPRI developed guidance for an integrated passive system reliability analysis approach that builds upon prior methods while introducing additional structure and clarity. The integrated approach emphasizes early and systematic identification of dominant physical phenomena and critical parameters, use of structured expert elicitation techniques (such as Phenomenon Identification and Ranking Tables), explicit consideration of model and parameter uncertainties, and quantitative propagation of those uncertainties through best-estimate or surrogate models. Importantly, the approach provides a clear pathway for combining phenomenological failure probabilities with hardware and human reliability contributions to obtain an overall estimate of PSS reliability for specific accident sequences.

This paper builds on that body of work by summarizing the technical motivation for integrated PSS reliability analysis, highlighting key methodological challenges associated with passive systems, and describing the essential elements of a structured, technology-neutral approach suitable for advanced reactor PRA applications. The intent is to support ongoing industry and regulatory efforts to apply risk-informed decision making to advanced reactor licensing and operation, while providing a consistent and defensible framework for evaluating the reliability of passive safety systems.

# 2. EXISTING APPROACHES TO PASSIVE SYSTEM RELIABILITY

PSSs are a defining feature of many advanced reactor designs, providing key safety functions through reliance on natural physical phenomena rather than active components or operator actions. While these systems offer potential advantages in simplicity and robustness, their performance characteristics challenge traditional PRA methods, which were largely developed for active, component-based systems. As documented in EPRI Report 3002032218 [1], numerous approaches have been developed over the past several decades to address these challenges, each with differing levels of mechanistic fidelity, probabilistic rigor, and regulatory acceptance.

This section summarizes the principal passive system reliability approaches identified in EPRI 3002032218 and discusses how these methods have been treated within regulatory and licensing environments.

## 2.1 Challenges in Passive System Reliability Assessment

Unlike active safety systems, passive systems typically do not fail due to discrete component malfunctions alone. Instead, failure is often defined functionally, as the inability of the system to meet its required safety function under specific boundary and initial conditions. Passive system performance is governed by coupled thermal-hydraulic phenomena, relatively small driving forces, and system-specific margins to failure.

EPRI 3002032218 identifies several recurring challenges that complicate reliability assessment of PSSs:

- Defining failure modes in systems dominated by continuous physical processes rather than binary component states.
- Identifying critical parameters whose variation can lead to functional failure.
- Quantifying uncertainty in thermal-hydraulic models, boundary conditions, and phenomenological correlations.
- Integrating phenomenological failure mechanisms into conventional PRA structures such as fault trees and event trees.

These challenges have driven the development of multiple analytical frameworks, each attempting to reconcile mechanistic modeling with probabilistic reliability estimation.

## 2.2 Reliability Methods for Passive Systems (RMPS)

The Reliability Methods for Passive Systems (RMPS) framework represents one of the earliest structured approaches for passive system reliability analysis. RMPS focuses on evaluating system reliability based on functional failures rather than individual component failures. In this framework, accident scenarios requiring passive system operation are defined, and best-estimate thermal-hydraulic codes are used to model system response. Critical parameters are identified, and system failure is defined as the exceedance of specified performance thresholds.

RMPS provides a clear conceptual linkage between system physics and reliability assessment. However, as noted in EPRI 3002032218, early RMPS applications provided limited guidance on the probabilistic treatment of uncertainties and often relied on conservative or bounding assumptions. As a result, RMPS analyses were frequently used to support qualitative insights or sensitivity studies rather than to generate fully probabilistic reliability values suitable for direct inclusion in PRA models.

From a regulatory perspective, RMPS has generally been accepted as a supporting analytical approach. Regulators have viewed RMPS results as informative, particularly when accompanied by conservative assumptions and sensitivity analyses, but have typically not relied on RMPS alone as the primary basis for licensing decisions.

## 2.3 Assessment of Passive System Reliability (APSRA)

The Assessment of Passive System Reliability (APSRA) methodology represents a more explicit attempt to quantify passive system reliability probabilistically. APSRA introduces the concept of a failure surface, which defines the boundary between success and failure in a multidimensional space of critical parameters. Thermal-hydraulic simulations are used to map this failure surface, and probabilistic sampling of parameter distributions is applied to estimate failure probabilities.

EPRI 3002032218 identifies APSRA as a significant advancement because it directly links mechanistic system behavior with probabilistic reliability estimation. APSRA also explicitly acknowledges the role of phenomenological failures, which are not easily represented through traditional component failure logic.

Despite these strengths, APSRA applications are typically resource-intensive and highly system-specific. The development of failure surfaces requires numerous thermal-hydraulic calculations, and results are sensitive to assumptions regarding parameter distributions and model uncertainties. Consequently, APSRA has been applied primarily in focused studies rather than full-scope plant PRAs. Regulatory treatment of APSRA has been cautious but generally favorable in principle. Regulators have recognized the technical rigor of the approach, particularly when supported by experimental data and comprehensive sensitivity analyses. In practice, APSRA results are often used qualitatively or semi-quantitatively, rather than as direct numerical inputs to risk metrics.

## 2.4 Enhanced and Integrated Variants

To address limitations in earlier frameworks, enhanced variants such as APSRA+ and RMPS+ have been developed. These approaches aim to improve treatment of dynamic system behavior, time-dependent effects, and integration between phenomenological and hardware failure mechanisms. Enhancements include improved uncertainty treatment, consideration of parameter dependencies, and more explicit linkage to PRA structures.

EPRI 3002032218 notes that while these enhanced approaches demonstrate improved technical completeness, they also increase analytical complexity. As a result, their application has largely been limited to pilot studies and demonstration analyses rather than routine licensing applications. From a regulatory standpoint, APSRA+ and RMPS+ are generally viewed as research-oriented methods that provide valuable insights but have not yet achieved sufficient maturity or standardization for widespread regulatory endorsement.

Several other organizations have developed passive system reliability methods other than RMPS and APSRA, with differing degrees of linkage to those frameworks. MIT developed an approach for evaluating passive cooling systems using best-estimate thermal-hydraulic codes to construct response surfaces and propagate uncertainties, with particular emphasis on an explicit treatment of code and model uncertainties. GE Hitachi and Argonne National Laboratory developed an approach that explicitly derives from RMPS but extends it by tightly integrating passive system reliability with plant-level success criteria and mechanistic source term categories within an advanced, non-LWR PRA framework. In contrast, dynamic reliability approaches proposed by academic researchers (e.g., Petri-net and Markov-based frameworks) focus on time-dependent and multistate hardware failures and are not based on RMPS or APSRA, as they largely omit detailed thermal-hydraulic functional failure modeling. Collectively, most alternative methods either build upon RMPS concepts to address specific gaps or pursue parallel, independent directions focused on dynamics and dependency rather than adopting APSRA's component-rooted framework.

## 2.5 Regulatory and Licensing Treatment

A key finding of EPRI 3002032218 is that the treatment of uncertainty is one of the most distinguishing factors among passive system reliability approaches. Studies reviewed in the report show that inclusion of model uncertainty, parameter uncertainty, and boundary condition uncertainty can significantly affect estimated reliability values, in some cases by orders of magnitude.

Regulatory bodies have consistently emphasized the need for conservative assumptions when uncertainties cannot be adequately quantified. Consequently, even when probabilistic methods are applied, licensing analyses often retain deterministic margins or bounding assumptions to ensure regulatory confidence.

International guidance from organizations such as the IAEA and NEA acknowledges the technical challenges associated with passive system reliability analysis and generally supports a graded approach, in which the level of analytical rigor is commensurate with system importance and available data. These guidance documents emphasize transparency in assumptions, justification of success criteria, and the use of sensitivity and uncertainty analyses, rather than endorsement of a single specific methodology.

In licensing practice, regulators have typically accepted passive system reliability analyses as supplemental evidence within a broader safety case. As noted in EPRI 3002032218, regulatory reviews tend to focus on whether analyses demonstrate adequate safety margins and robustness, rather than on the precise numerical value of calculated failure probabilities. This reflects ongoing uncertainty regarding model validation, data availability, and the maturity of passive system reliability methods.

## *2.6 Summary and Implications*

The review presented in EPRI 3002032218 demonstrates that while multiple approaches to passive system reliability analysis exist, no single method fully satisfies the needs of advanced reactor PRA and regulatory decision-making. RMPS, APSRA, and their variants each address important aspects of passive system behavior but vary significantly in complexity, scope, and regulatory acceptance.

These findings highlight the need for an integrated, standardized approach that combines mechanistic modeling, probabilistic uncertainty treatment, and consistent interfaces within PRA frameworks, while remaining transparent and traceable for regulatory review. The evolution of passive system reliability methods reflects a broader transition toward more physics-based, risk-informed evaluation of advanced reactor safety systems.

# 3. EPRI GUIDANCE FOR PASSIVE SYSTEM RELIABILITY ANALYSIS

In response to the evaluation in EPRI 3002032218, EPRI developed guidance in EPRI 3002032223 [2] to consolidate lessons learned from prior passive system reliability frameworks into a more integrated and transparent approach suitable for advanced reactor risk analysis and regulatory engagement.

This section discusses the objectives, foundational principles, and key elements of the EPRI guidance, with emphasis on how the guidance supports consistent application of passive system reliability analysis within PRA and risk-informed decision-making contexts.

## *3.1 Objectives of the EPRI Guidance*

The primary objective of EPRI 3002032223 is to provide structured guidance for assessing passive system reliability that is technically defensible, transparent, and aligned with regulatory expectations. The guidance does not introduce a wholly new methodology; rather, it synthesizes and integrates elements from existing approaches into a coherent analytical framework.

Key objectives identified in the guidance include:

- Supporting consistency in how passive system reliability is evaluated across different designs and applications.
- Enabling risk-informed decision-making by providing reliability insights that can be meaningfully integrated into PRA models.
- Improving traceability and transparency of assumptions, modeling choices, and uncertainty treatment for regulatory review.
- Facilitating application to advanced reactor designs, where passive systems play a central safety role and empirical operating data may be limited.

These objectives reflect recognition that regulatory confidence depends not only on analytical rigor, but also on clarity in how results are generated and interpreted.

A central theme of EPRI 3002032223 is the need for an integrated perspective on passive system reliability. Previous approaches often emphasized individual elements—such as mechanistic modeling, probabilistic sampling, or uncertainty analysis—without fully addressing how these elements should be combined within a PRA framework. The EPRI guidance emphasizes integration across these dimensions.

From this perspective, passive system reliability is viewed as the outcome of interacting factors that include system physics, plant conditions, and uncertainties. The guidance highlights the importance of maintaining a clear linkage between:

- System function definitions and safety objectives.
- Mechanistic modeling results and probabilistic representations of success and failure.
- Phenomenological behavior and conventional PRA structures.

By framing reliability assessment as an integrated activity rather than a standalone calculation, the guidance seeks to reduce inconsistencies that can arise when individual analytical components are applied in isolation.

## 3.2 Key Aspects of PSS Reliability Assessment

*The Role of Mechanistic Modeling*
EPRI 3002032223 reinforces the role of best-estimate thermal-hydraulic modeling as a foundational element of passive system reliability analysis. Because passive systems rely on natural circulation, heat transfer, and other physical phenomena, mechanistic modeling is essential for understanding system performance and identifying conditions under which functional failure may occur.

The guidance emphasizes that mechanistic modeling should be used to:

- Characterize system response under relevant operating and accident conditions.
- Identify critical parameters that strongly influence system success or failure.
- Support definition of performance thresholds consistent with safety functions.

Importantly, the guidance does not imply that mechanistic models alone are sufficient for reliability assessment. Instead, model results are treated as inputs to a broader analytical process that incorporates uncertainty and probabilistic interpretation.

*Identification and Treatment of Critical Parameters*
Consistent with earlier approaches such as APSRA, the EPRI guidance recognizes critical parameters as a key organizing concept in passive system reliability analysis. Critical parameters represent system variables whose variation can lead to loss of required safety function. The guidance emphasizes that identification of critical parameters should be systematic and traceable, drawing on insights from mechanistic modeling, sensitivity analyses, and engineering judgment. Rather than prescribing a fixed list of parameters, the guidance highlights that critical parameters are system-specific and dependent on design features and operating conditions. Once identified, critical parameters provide a structured basis for evaluating system robustness, understanding failure mechanisms, and framing uncertainty analysis. This approach supports consistency across analyses while retaining flexibility to address design-specific characteristics.

*Treatment of Uncertainty*
A distinguishing feature of the EPRI guidance is its emphasis on explicit treatment of uncertainty. EPRI 3002032223 notes that earlier studies demonstrated large sensitivity of passive system reliability estimates to assumptions regarding model uncertainty, boundary conditions, and parameter distributions.

The guidance highlights several categories of uncertainty relevant to passive system reliability analysis:

- Model uncertainty, including limitations in thermal-hydraulic correlations and phenomenological representations.
- Parameter uncertainty, associated with initial and boundary conditions and material properties.
- Scenario uncertainty, related to the range of conditions under which the passive system is expected to perform.

Rather than prescribing specific uncertainty quantification techniques, the guidance emphasizes the importance of transparency in how uncertainties are addressed and how their influence on results is communicated. This emphasis reflects regulatory expectations that uncertainty treatment be clearly documented and justified, particularly for novel systems.

*Integration with PRA Frameworks*

EPRI 3002032223 explicitly addresses the challenge of integrating passive system reliability insights into PRA models, which traditionally rely on discrete logic structures. The guidance emphasizes that passive system reliability results should be compatible with PRA needs, even when failure mechanisms are defined in functional or phenomenological terms. From a guidance perspective, integration with PRA is framed as an interface challenge rather than a methodological constraint. The objective is to ensure that reliability insights derived from mechanistic and probabilistic analyses can be meaningfully incorporated into event sequences, risk metrics, and decision-making processes without oversimplifying system behavior. This emphasis supports the broader goal of enabling risk-informed evaluations that appropriately reflect the contribution of passive systems to overall plant safety.

## 3.3 The EPRI PSS Assessment Process

The guidance defined in EPRI 3002032223 for passive system reliability can be summarized by these steps.

*Develop System Analysis*

The system analysis establishes the foundation for the reliability evaluation by defining how the PSS is intended to perform its credited safety function under the scenario of interest. This step includes defining success criteria tied to the key safety function, identifying relevant hardware failure mechanisms using established methods such as failure modes & effects analysis (FMEA) or hazards and operability (HAZOP)study, and identifying phenomenological failure mechanisms that could prevent the system from meeting its success criteria. The outputs of this step provide the analytical structure for both hardware and phenomenological reliability modeling.

*Identify Phenomenological Critical Parameters*

A structured process is used to identify parameters associated with physical phenomena that govern PSS performance, such as natural circulation, heat transfer, or condensation. EPRI 3002032223 recommends use of a Phenomena Identification and Ranking Table (PIRT) to systematically identify, rank, and document parameters based on their importance to the key safety function. This process supports transparency, consistency, and traceability, particularly where expert judgment is required.

*Parameter Correlation Assessment*

After identifying candidate parameters, the analyst evaluates whether dependencies or correlations may exist among them. Although many applications assume parameter independence for simplicity, the report highlights that correlated parameters can materially affect reliability results. At a minimum, a qualitative assessment is performed to identify potential dependencies, document assumptions, and highlight data gaps that may require future experimental or operational data to resolve.

*Develop System Failure Models*

System failure models are developed to represent both hardware and phenomenological failure pathways. Hardware failure models are typically implemented using PRA fault trees that include component failures, operator actions, and support system dependencies. Phenomenological failures are represented as additional basic events and are evaluated using best-estimate thermal-hydraulic models capable of simulating the dominant physical phenomena affecting PSS performance.

*Model Verification and Validation*

Verification and validation (V&V) activities are performed to ensure that both hardware and phenomenological models are correctly implemented and appropriate for the intended application. Hardware model verification focuses on logical consistency and reasonableness of fault tree results, while phenomenological V&V relies on the validation pedigree of the selected thermal-hydraulic code and confirms that system geometry, boundary conditions, and key phenomena are adequately represented.

*Model Uncertainty Evaluation*

Model uncertainty is evaluated to address limitations in the underlying physics models embedded in the thermal-hydraulic code, such as alternative heat transfer correlations or flow regime models. Sensitivity calculations are used to assess the impact of different modeling options on success criteria. If model uncertainty is shown to dominate system behavior, conservative treatment or additional analysis is applied to ensure reliability results are not non-conservative.

*Sensitivity Analysis on Parameters*

Operational ranges are assigned to phenomenological parameters identified through the PIRT process, and sensitivity analyses are performed to determine which parameters significantly affect the system's ability to meet success criteria. Parameters that produce meaningful changes in system performance or cause failure of the key safety function are retained as critical parameters, while others may be screened out with documented justification.

*Develop Probability Distributions of Critical Parameters*

For each retained critical parameter, a probability distribution function is assigned to represent epistemic uncertainty. Where experimental or operational data exist, they are used to inform the distribution; otherwise, expert judgment is applied with clearly documented assumptions and bounds. This step distinguishes parameter uncertainty from model uncertainty and prepares inputs for uncertainty propagation.

*Characterize Phenomenological Reliability*

Phenomenological reliability is quantified by propagating the uncertainty in critical parameters through the thermal-hydraulic model. This is accomplished either by direct sampling using the thermal-hydraulic code or, more commonly, through a surrogate such as a response surface to reduce computational burden. Monte Carlo or Latin Hypercube Sampling techniques are used to evaluate system success or failure across a large number of trials.

*Phenomenological Reliability Convergence Review*

The results of the uncertainty analysis are reviewed to confirm that a sufficient number of trials have been performed to achieve convergence of the estimated failure probability. Reliability or failure rate is examined as a function of sample size, and additional trials or model refinements are performed if convergence is not adequately demonstrated.

*Characterize PSS Hardware Reliability*

Hardware reliability is quantified independently using standard PRA methods. This includes evaluation of component failure rates, common-cause considerations, human failure events, and support system dependencies. Hardware reliability results are developed in a manner consistent with applicable PRA standards to support integration into the plant-level PRA.

*Determine PSS Reliability*
The PSS reliability for a given transient or accident sequence is determined by combining hardware and phenomenological failure probabilities. Phenomenological failures are typically combined with hardware failures under an OR logic structure in the system fault tree. The resulting sequence-specific PSS failure probabilities are then integrated into the broader PRA model to support risk-informed decision making.

# 4. CONCLUSION

The guidance presented in EPRI 3002032223 represents a significant step toward harmonizing passive system reliability analysis across the nuclear industry. By consolidating lessons learned from prior methods and emphasizing integration, transparency, and uncertainty treatment, the guidance addresses many of the challenges identified in earlier evaluations.

Importantly, the guidance does not seek to eliminate engineering judgment or mechanistic insight; rather, it provides a structured context in which these elements can be applied consistently and communicated effectively. As advanced reactor designs continue to mature, the principles articulated in the EPRI guidance provide a foundation for continued refinement of passive system reliability analysis and its role in risk-informed decision-making.

# References

[1] Advanced Nuclear Technology: Evaluation of Passive System Reliability Approaches. EPRI, Palo Alto, CA: 2025. 3002032218.

[2] Advanced Nuclear Technology: Guidance for Passive System Reliability Analysis. EPRI, Palo Alto, CA: 2025. 3002032223.