

Degradation-Informed Functional Reliability Assessment of Natural Circulation in an SMR Primary Coolant System

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1. Introduction

Passive safety functions in advanced water-cooled reactors and small modular reactors (SMRs) often rely on gravity, convection, and natural circulation. Natural circulation can transport core heat without continuously operating pumps, but its relatively small driving head makes performance sensitive to changes in hydraulic resistance [1].

Conventional reliability models commonly emphasize discrete component failures. Passive functions, however, can lose capability progressively while components remain mechanically available. Deposits, flow-path restriction, surface deterioration, and localized obstruction can increase hydraulic resistance and reduce natural-circulation flow. Ageing-management guidance therefore emphasizes degradation mechanisms and condition information from operation, inspection, surveillance, and maintenance [2].

This study presents a degradation-informed functional reliability framework for the natural-circulation function of an SMR primary coolant system under normal operation. The target is the ability of the primary flow path to sustain natural-circulation flow. Hydraulic degradation states are mapped to normalized degradation variables (NDVs), component performance indices (CPIs), a system performance index (SPI), and a functional performance index (FPI), with uncertainty propagated by Monte Carlo simulation.

Three hydraulic degradation modes are considered: flow-area restriction, surface/friction degradation, and localized hydraulic resistance. Their effects on retained natural-circulation flow capability are compared. The analysis is a methodological demonstration based on explicit scenario assumptions, not a plant-specific reliability assessment.

2. Methodology

Conventional reliability analysis usually begins with discrete component failure events. Here, degradation mechanisms are the uncertain inputs, and their progressive hydraulic effects are propagated to natural-circulation capability before component failure. The sequence is degradation mechanism, physical-parameter change, CPI, SPI, FPI, and conditional functional

reliability. The framework therefore complements component-based reliability.

2.1 Natural-Circulation Flow-Path Degradation

The analyzed flow path comprises four representative series regions: core flow region, hot riser, primary-side heat-exchanger flow region, and cold return/downcomer. Performance is defined as attainable natural-circulation flow relative to nominal under an approximately unchanged driving head. Detailed heat-source and heat-sink behavior is outside the screening model. Degradation alters effective flow area, distributed friction, or localized resistance.

Flow-area restriction was represented by the normalized degradation variable

$$\delta_A = \frac{A_0 - A}{A_0} \quad (1)$$

where A_0 and A are the nominal and degraded effective flow areas, respectively.

Surface/friction degradation was represented as

$$\delta_f = \frac{f - f_0}{f_0} \quad (2)$$

where f_0 and f denote the nominal and degraded friction factors.

Localized hydraulic degradation was defined as

$$\delta_K = \frac{K - K_0}{K_0} \quad (3)$$

where K_0 and K are the nominal and degraded local loss coefficients, respectively.

For the baseline demonstration, the following scenario ranges were adopted:

Scenario ranges: flow-area restriction 0-0.20, friction increase 0-0.20, and localized-loss increase 0-0.15.

These are illustrative scenario bounds, not universal degradation limits.

2.2 Natural-Circulation Performance Indices

Each CPI represents normalized hydraulic performance of a representative primary flow-path element under one degradation mode. Natural-circulation flow is approximated as inversely proportional to the square root of hydraulic resistance at approximately unchanged driving head. For area restriction, flow area scales with the square of hydraulic diameter and representative circular-path resistance with approximately the inverse fifth power, yielding the exponent in Eq. (4). The CPIs were represented by

$$CPI_A = (1 - \delta_A)^{\frac{5}{4}} \quad (4)$$

$$CPI_f = (1 + \delta_f)^{-\frac{1}{2}} \quad (5)$$

$$CPI_K = (1 + \delta_K)^{-\frac{1}{2}} \quad (6)$$

For the combined screening case, each mode-specific normalized resistance was obtained as the inverse square of its CPI and combined as

$$r_{H,comb} = 1 + (r_A - 1) + (r_f - 1) + (r_K - 1) \quad (7)$$

Here, $r_{H,comb}$ is the ratio of degraded total hydraulic resistance to nominal hydraulic resistance. At nominal conditions $r_A = r_f = r_K = 1$, so each $(r_i - 1)$ term is the incremental normalized resistance from one degradation mode. The additive relation is a first-order screening approximation that neglects interaction terms. SPI is then calculated as

$$SPI_{NC} = \frac{1}{\sqrt{r_{H,comb}}} \quad (8)$$

The functional performance index (FPI) compares the retained natural-circulation capability represented by SPI with the selected minimum required fraction:

$$FPI_{NC} = \frac{SPI_{NC}}{SPI_{req}} \quad (9)$$

An illustrative retained-flow requirement of 0.80 was adopted; it is not a design, licensing, or plant-specific limit. SPI measures how much natural-circulation performance remains relative to nominal, whereas FPI compares that retained performance with the requirement. Thus, $SPI < 1$ indicates degradation but not necessarily failure, while $FPI = 1$ is the functional threshold and $FPI \geq 1$ denotes success.

2.3 Monte Carlo Functional Reliability

The degradation variables were sampled independently from bounded uniform distributions because plant-specific joint distributions were unavailable.

A total of 100,000 Monte Carlo samples were generated and propagated through the resistance, SPI, and FPI models. Independence is a demonstration simplification because common degradation mechanisms may correlate the variables.

$$R_{NC} = N_{success} / N_{MC} = P(FPI_{NC} \geq 1) \quad (10)$$

This quantity is the conditional probability that degraded natural-circulation capability meets the selected requirement; it depends on the assumed distributions, independence, reduced-order model, and threshold.

3. Results and Discussion

3.1 Component Performance under Degradation

At maximum assumed degradation, the CPI values were 0.757 for flow-area restriction, 0.913 for surface/friction degradation, and 0.933 for localized resistance, corresponding to performance reductions of 24.3%, 8.7%, and 6.7%, respectively.

Table I: Mode-specific CPI values at maximum assumed degradation

Degradation phenomenon	Maximum NDV	CPI	Performance reduction
Flow-area restriction	0.20	0.757	24.3%
Surface/friction degradation	0.20	0.913	8.7%
Localized hydraulic resistance	0.15	0.933	6.7%

Within the selected ranges and reduced-order model, natural-circulation performance is most sensitive to effective flow-area reduction.

3.2 Natural-Circulation Functional Performance

At the maximum combined state, $SPI=0.691$, meaning 69.1% of nominal attainable natural-circulation flow. With the illustrative requirement of 0.80, $FPI=0.863 < 1$.

For flow-area restriction alone, the threshold was crossed at $s=0.817$, corresponding to approximately 16.3% effective flow-area reduction.

For combined degradation, the threshold occurred at $s=0.579$, corresponding to 11.6% flow-area restriction, 11.6% friction increase, and 8.7% localized-resistance increase. Thus, simultaneous moderate degradation can exhaust functional margin before any variable reaches its maximum assumed value.

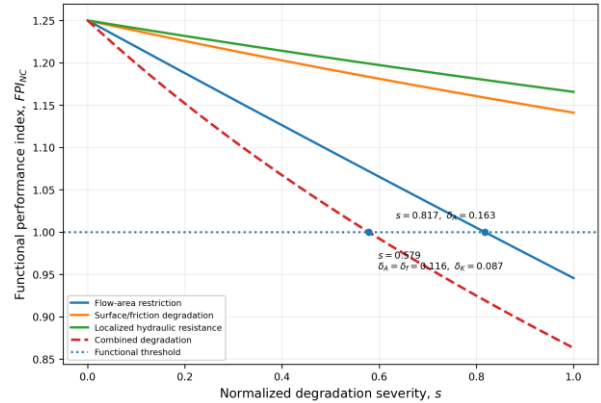


Fig. 1. Natural-circulation functional performance under individual and combined degradation conditions.

The FPI reductions from nominal were 0.304 for flow-area restriction, 0.109 for surface/friction degradation, and 0.084 for localized hydraulic resistance. The individual ranking was therefore flow-area restriction > surface/friction degradation > localized hydraulic resistance.

Flow-area restriction was identified as the dominant individual degradation mode within the assumed ranges and equations, while the combined case produced the largest overall performance reduction.

3.3 Conditional Functional Reliability

The Monte Carlo simulation gave a 0.60945 (60.9%) conditional probability that degraded natural-circulation capability satisfies the illustrative 0.80 requirement; the corresponding failure probability was 39.1%.

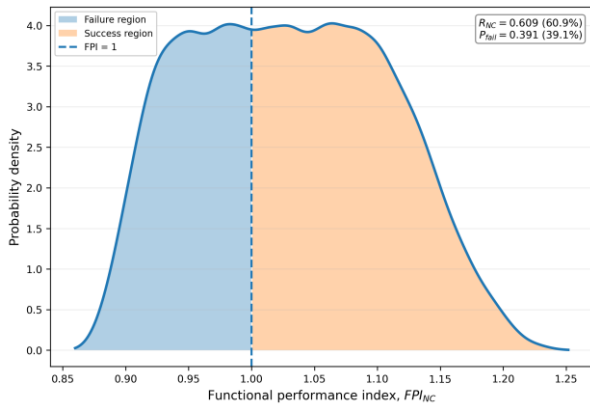


Fig. 2. Monte Carlo distribution of natural-circulation functional performance with the threshold at FPI = 1.

The result depends on the illustrative threshold. Success probabilities were 85.6%, 60.9%, and 36.1% for retained-flow requirements of 0.75, 0.80, and 0.85, respectively. Thus, 60.9% is a scenario-based conditional reliability, not reliability of the complete primary coolant system.

3.4 Practicability and Applicability

Flow and differential-pressure measurements may indicate changes in natural-circulation hydraulic capability, while inspection can indicate deposits, blockage, material loss, or localized obstruction. Distinguishing individual degradation modes requires additional diagnostics or an inverse model. These monitoring routes are consistent with ageing-management practices [2].

Because the variables are normalized, another natural-circulation primary system can replace the illustrative flow area, friction, local-loss, degradation-distribution, and acceptance-criterion inputs without changing the assessment sequence.

Engineering Measurements → NDVs → CPIs → SPI → FPI
→ Functional Reliability

4. Conclusions

A degradation-informed framework was applied to the natural-circulation function of an SMR primary coolant system under normal operation. Three hydraulic degradation modes were propagated through NDVs, CPIs, SPI, and FPI.

Within the assumed ranges, flow-area restriction produced the greatest individual performance reduction,

while combined degradation produced the largest overall reduction.

With 100,000 samples and an illustrative retained-flow requirement of 0.80, the conditional probability of satisfying the requirement was 60.9%. It depends on the assumed degradation ranges, independent sampling, additive-resistance approximation, and threshold, and is not the reliability of a complete plant system.

The framework complements component-failure reliability by treating degradation mechanisms as uncertain inputs and propagating their hydraulic effects to conditional functional reliability. Future validation should use plant-specific hydraulic data, correlated degradation models, and design-based criteria.

Acknowledgement

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