Comparative Reliability Analysis of Passive and Active Emergency Core Cooling Systems for Small Modular Reactors

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Abstract: Small Modular Reactors (SMRs) present two fundamentally different safety philosophies for emergency core cooling: passive designs relying on natural circulation and gravity-driven actuation without external power, and active designs employing motor-driven pumps, control logic, and electrical power systems. While both approaches have undergone regulatory review in North America and the United Kingdom, no published study has performed a systematic, quantitative comparison of their reliability for equivalent initiating events through the lens of deployment feasibility in emerging markets. This paper addresses that gap through event tree and fault tree analysis of passive and active SMR emergency core cooling systems — illustrated by the NuScale VOYGR™ reactor vent valve assembly and the BWRX-300 isolation condenser system, respectively — responding to a common initiating event of loss of normal heat removal (LONHR, frequency 10^{-2} to 10^{-1} per reactor-year). Using beta-factor common cause failure modeling ($\beta = 0.10$ passive; $\beta = 0.15$ active) and NUREG/CR-2300 methodology, fault tree quantification yields system failure probabilities of 1.42×10^{-4} (passive) and 2.10×10^{-4} (active) — a 48% difference with NuScale exhibiting lower failure probability. The critical result is qualitative: passive systems exhibit near-total common cause failure dominance (98.9% of total probability), concentrating risk in manufacturing quality assurance and design uniformity across redundant trains, while active systems are dominated by a shared physical heat sink vulnerability (47.6%) that bypasses train-level redundancy entirely. These different failure mode profiles create fundamentally different risk management challenges for newcomer regulatory authorities, project financiers, and operational workforce planning — factors that govern SMR deployment feasibility in resource-constrained markets far more than absolute reliability differences alone. Key Words: Small Modular Reactors; passive safety; active safety; fault tree analysis; probabilistic risk assessment; NuScale; BWRX-300; emerging markets; nuclear financing.

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1. INTRODUCTION

The global nuclear energy landscape is witnessing a strategic pivot toward Small Modular Reactors (SMRs), driven by their promise of reduced capital requirements, shortened construction schedules, and enhanced safety characteristics compared to conventional large reactors. This shift is particularly significant for newcomer and emerging-market countries, where traditional gigawatt-scale nuclear projects present prohibitive financial and technical barriers [1,2]. However, the successful deployment of SMRs in these markets hinges critically on demonstrating quantifiable safety system reliability to satisfy both regulatory authorities and private financiers—stakeholders whose risk perceptions directly influence licensing timelines and cost of capital [3,4].

Contemporary SMR designs embody two fundamentally different safety philosophies. Passive safety systems, exemplified by NuScale's natural-circulation decay heat removal, rely on gravity, natural convection, and large thermal masses rather than active mechanical components or external power sources [5]. In contrast, active safety systems, such as those employed in GE Hitachi's BWRX-300, utilize motor-driven pumps, powered isolation condensers, and complex control logic to achieve safety functions [6]. While both approaches have undergone rigorous regulatory review in North America and the United Kingdom, a critical gap exists in the literature: no systematic, comparative probabilistic risk analysis (PRA) has quantified their relative reliability for equivalent initiating events while interpreting results through the lens of deployment feasibility in resource-constrained markets.

This research gap has profound practical implications. Licensing authorities in newcomer countries—often operating with limited staff and nascent regulatory frameworks—face extended review timelines when evaluating novel safety technologies [7,8]. Project financing in emerging markets commands significantly higher costs of capital (8–12% real discount rates) compared to OECD countries (3–5%), with technical risk perceptions directly influencing these premiums [9]. Operational complexity affects both workforce requirements and long-term operations and maintenance costs that determine project bankability [10].

This paper addresses these challenges through a focused event tree and fault tree analysis comparing NuScale's passive emergency core cooling system against BWRX-300's active system for the common initiating event of loss of normal heat removal. Three objectives drive this work: (1) develop event trees and fault trees for both systems, identifying critical failure sequences; (2) quantify reliability differences using established probabilistic methods and industry failure rate data; and (3) interpret technical findings explicitly connecting reliability metrics to regulatory approval processes, financing risk premiums, and operational constraints in emerging markets.

2. BACKGROUND

There are many different designs for SMRs. The NuScale iPWR and the GE Hitachi BWRX-300 are studied in this paper to highlight the effect of passive and active safety systems on system performance and its implications for deployment in emerging markets.

2.1. Small Modular Reactor Technology Approaches

NuScale VOYGR™ Power Module (Passive Safety Design). NuScale's 77 MWe power module represents the first light-water SMR to receive standard design approval from the U.S. Nuclear Regulatory Commission (NRC), with the 50 MWe design certified in August 2020 and the uprated 77 MWe version approved in May 2025 [5,11]. The design features a fully passive ECCS and decay heat removal system that operate without pumps, diesel generators, or operator actions for at least 72 hours following an accident [12]. Core decay heat is removed through natural circulation within the containment vessel, transferring thermal energy to a large reactor pool via convective and conductive pathways. Critical passive components include reactor vent valves (RVVs) and reactor recirculation valves (RRVs) that open automatically on demand without electrical power. This passive philosophy eliminates entire classes of active failure modes while introducing uncertainties related to natural circulation flow stability and common-cause failures affecting shared heat sinks [13].

BWRX-300 Design (Active Safety with Passive Features). GE Hitachi's BWRX-300 is a 300 MWe boiling water reactor leveraging decades of BWR operational experience [14]. The reactor retains active emergency core cooling systems alongside isolation condensers (ICs) for decay heat removal. While ICs operate passively once initiated, their actuation depends on control signals and DC power [6]. The design completed Step 2 of the UK Generic Design Assessment in December 2024 [15]. In Canada, Ontario Power Generation selected BWRX-300 for the Darlington New Nuclear Project [16]. The active safety approach introduces dependencies on electrical power, control logic, cooling water systems, and human actions that must be factored into reliability assessments.

2.2. Regulatory and Financing Context for Emerging Markets

Regulatory Challenges in Newcomer Countries. Emerging-market countries confront regulatory capacity constraints that significantly extend licensing timelines. Newly established nuclear regulatory bodies often operate with limited staff experienced in probabilistic safety assessment, digital I&C review, or passive system performance evaluation [7]. They rely heavily on vendor-supplied safety cases and IAEA mechanisms, introducing scheduling uncertainties [2]. Regulators must balance apparent design simplicity against the need to independently verify vendor safety claims—a challenge amplified when staff lack thermal-hydraulic analysis tools or operational experience databases available to mature regulatory authorities [17].

Financing Constraints and Cost of Capital Impacts. Nuclear projects in emerging markets face substantially higher financing costs than OECD projects, with real discount rates of 8–12% versus 3–5%—differences that fundamentally alter project economics [9]. These elevated costs stem from perceived construction risk, operational risk, currency and political risk, and residual severe-accident risk [3,4]. The Canadian SMR Roadmap's Economics and Finance Working Group explicitly identifies cost of capital as the dominant factor in SMR levelized cost of electricity and recommends government-backed risk mitigation to address first-of-a-kind technical uncertainties [18]. Quantitative reliability assessment becomes a critical input to financial structuring—enabling more accurate risk pricing and potentially supporting public sector guarantees that lower overall project costs.

3. METHODOLOGY

This section presents the analysis procedure for both NuScale and BWRX-300 emergency core cooling systems, starting with selecting a common initiating event, followed by fault tree and event tree construction and common cause analysis. Both qualitative and quantitative analysis are performed and the limitations and constraints are identified.

3.1. Analytical Framework

This analysis employs established PRA methodology following NRC guidelines (NUREG/CR-2300, NUREG-2150) and IAEA safety standards [2,19]. The methodology comprises four integrated phases: (1) event tree construction to identify accident sequences; (2) fault tree development to model component-level failure logic; (3) quantification using industry failure rate databases and common-cause failure models; and (4) comparative interpretation through the lens of deployment constraints in emerging markets.

3.2. Initiating Event Selection

The initiating event is Loss of Normal Heat Removal (LONHR), defined as an event where the normal residual heat removal pathway becomes unavailable, requiring actuation of dedicated emergency core cooling or decay heat removal systems. Both NuScale and BWRX-300 address decay heat removal using fundamentally different approaches—passive natural circulation versus active motor-driven systems—making LONHR an ideal discriminating event. Based on NUREG/CR-6928 [20,21], LONHR occurs at estimated frequencies of 10^{-2} to 10^{-1} per reactor-year, a moderately frequent initiating event category where reliability differences meaningfully affect overall plant risk profiles.

3.3. Event Tree Analysis Approach

Event trees were constructed following NUREG/CR-2300 [19]. For NuScale, four safety function headings were defined: (1) RVV actuation; (2) RRV opening; (3) natural circulation establishment; and (4) reactor pool heat sink adequacy. For BWRX-300: (1) isolation condenser actuation; (2) ECCS pump operation; (3) electrical power availability; and (4) suppression pool capacity. Success criteria were defined based on design-basis safety analyses in vendor submissions to regulatory authorities [5,6,12,15].

3.4. Fault Tree Construction and Logic Development

Fault tree construction followed the deductive, top-down approach prescribed in IEEE Std 352 [23] and NUREG/CR-2300 [19]. For NuScale, the top event "both RVV trains fail to open on demand" decomposes through intermediate train-level events to basic events: mechanical valve failure, plugging/fouling, and test/maintenance errors. For BWRX-300, the top event "both IC trains fail to remove decay heat" decomposes through four intermediate categories per train: (1) valve failures; (2) heat exchanger failures; (3) electrical power failures; and (4) instrumentation and control failures [6,14].

3.5. Common-Cause Failure Modeling

Common-cause failures (CCFs) are modeled using the beta-factor method per NUREG/CR-5497 [22,30,31]. The CCF probability is $Q_{CCF} = \beta \times Q_{total}$. Beta factors: $\beta = 0.10$ for NuScale passive valve groups (lower susceptibility to common design, maintenance, and environmental stressors) and $\beta = 0.15$ for BWRX-300 active component groups (higher vulnerability to calibration errors and power supply dependencies). To avoid double-counting, independent train probabilities are adjusted as $Q^{Ind} = (1-\beta) \times Q_t$, consistent with NUREG/CR-5497 [30].

3.6. Component Failure Rate Data

Component failure probabilities were sourced from NUREG/CR-6928 [20,21] as the primary reference. Supplementary sources included IAEA TECDOC-930 and TECDOC-478 [26,27] for international cross-validation, and IEEE Std 500 [31] for electrical and I&C component failure rates. Human error probabilities used NUREG/CR-1278 [25] screening values. Failure rate data are presented in Tables 4 and 6.

3.7. Quantitative Analysis and Minimal Cut Set Generation

Fault tree quantification employs the rare-event approximation. The top event probability is:

$$\mathbf{Q_{top} \approx \Sigma\, Q(MCS_i) = \Sigma \prod Q_j} \tag{1}$$

where Q_j is the failure probability of basic event j within cut set i. Minimal cut sets (MCS) were generated through Boolean algebraic reduction. Importance measures including Fussell-Vesely (FV), Risk Achievement Worth (RAW), and Risk Reduction Worth (RRW) were calculated for dominant basic events [35]. All quantification was performed manually using arithmetic and verified by cross-checking MCS probability sums against top event totals.

3.8. Limitations and Assumptions

Key limitations: (1) failure rate data for novel SMR-specific components relies on analogous component analogies, introducing epistemic uncertainty; (2) beta factors represent generic industry estimates rather than design-specific assessments; (3) human reliability analysis uses screening-level error probabilities rather than detailed THERP or SPAR-H task analysis; (4) scope encompasses internal events only, excluding seismic, flooding, and fire hazards; and (5) mission time is 72 hours for NuScale and 8 hours for BWRX-300. These limitations are consistent with preliminary Level 1 PRA methodology [19] and do not compromise the validity of comparative insights.

4. EVENT TREE ANALYSIS

This section presents the detailed event tree construction and analysis for both NuScale and BWRX-300. The comparative results for the event trees for these two different designs, one passive and the other active, are summarized.

4.1. NuScale Passive Safety System Event Tree

Figure 1 presents the NuScale event tree for LONHR [5,11,12]. The tree generates five distinct sequences: SEQ-1 and SEQ-2 achieve core cooling; SEQ-3, SEQ-4, and SEQ-5 lead to core damage. SEQ-5—complete RVV failure—represents the most severe consequence because containment cannot be vented, eliminating all recovery paths.

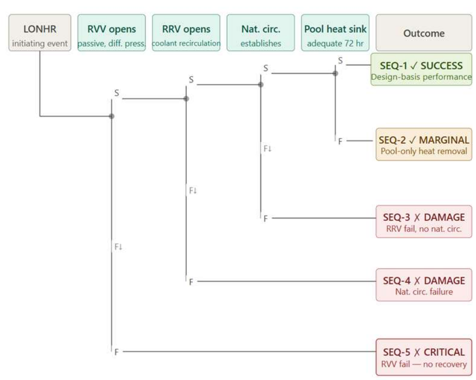

Figure 1. NuScale VOYGR™ event tree for loss of normal heat removal initiating event

Table 1. NuScale VOYGR™ critical sequences and outcomes

Seq.	RVV Opens	RRV Opens	Nat. Circ.	Pool Heat Sink	Outcome

SEQ-1	Success	Success	Established	Adequate	**SUCCESS:** Design-basis; natural circulation with pool. No operator action for 72 h.
SEQ-2	Success	Success	Fails	Adequate	**MARGINAL:** Pool alone provides heat removal. Reduced safety margin.
SEQ-3	Success	Fails	Fails	Inadequate	CORE DAMAGE: RRV failure; decay heat removal inadequate.
SEQ-4	Success	Success	Fails	Inadequate	CORE DAMAGE: Natural circulation fails; pool insufficient.
SEQ-5	**FAILS**	**N/A**	**N/A**	**N/A**	**SEVERE CD:** RVV failure prevents venting; no recovery path. Most risk-significant sequence.

4.2. BWRX-300 Active Safety System Event Tree

Figure 2 presents BWRX-300's event tree [6,14,15]. Seven sequences are generated. Three (SEQ-1, SEQ-2, SEQ-4) achieve cooling success through different system combinations, demonstrating operational flexibility [14]. Four (SEQ-3, SEQ-5, SEQ-6, SEQ-7) result in core damage when critical dependencies fail.

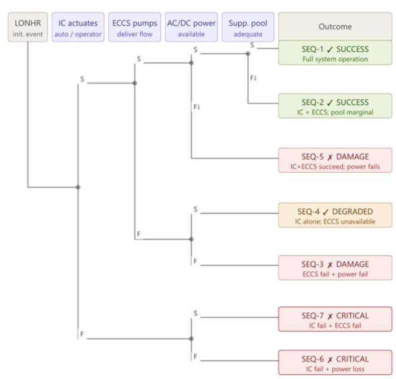

Figure 2. BWRX-300 event tree for loss of normal heat removal initiating event

Table 2. BWRX-300 critical sequences and outcomes

Seq.	IC Actuates	ECCS Pumps	Power Avail.	Supp. Pool	Outcome
SEQ-1	Success	Success	Available	Adequate	SUCCESS: Nominal; all systems functional.
SEQ-2	Success	Fails	Available	Adequate	SUCCESS: IC sufficient without ECCS pumps.
SEQ-3	Success	Fails	Available	Inadequate	CORE DAMAGE: ECCS fails; pool inadequate.
SEQ-4	Success	Success	Lost	Adequate	SUCCESS: IC operates passively despite AC loss.

SEQ-5	Success	Fails	Lost	Inadequate	CORE DAMAGE: Multiple system failures converge.
SEQ-6	**FAILS**	**N/A**	**Lost**	**N/A**	**SEVERE CD:** IC failure with power loss; no recovery path.
SEQ-7	**FAILS**	**Fails**	**N/A**	**Inadequate**	**SEVERE CD:** IC failure with ECCS failure and pool inadequacy. Dominant risk sequence.

4.3. Comparative Event Tree Assessment

NuScale achieves simplicity through elimination of failure modes [5,12]—zero active components and no power dependencies remove entire failure categories. BWRX-300 provides operational flexibility through three distinct success path combinations [14,15]. Both designs exhibit single-point vulnerabilities: RVV failure for NuScale (SEQ-5) and IC failure for BWRX-300 (SEQ-6, SEQ-7). Table 3 summarises these structural differences.

Table 3. Event tree structural comparison: NuScale vs. BWRX-300

Parameter	NuScale VOYGR™	BWRX-300
Total sequences	5	7
Success sequences (%)	2 (40%)	3 (43%)
Core damage sequences	3	4
Decision points	4	4
Active components in safety system	0	8+
Power dependencies	None	DC + AC (EDGs)
Operator actions (72 h)	None required	Manual backup available
Single-point vulnerability	RVV failure (SEQ-5)	IC failure (SEQ-6, SEQ-7)
Basic events in dominant FT	7	~20

5. FAULT TREE ANALYSIS

This section presents the detailed fault tree construction and analysis for both NuScale and BWRX-300. Through this study, the top event and core damage probabilities are obtained. Furthermore, the Risk Importance Measures (RIM) and sensitivity analysis revealed the major contributing factors for system safety.

5.1. NuScale Reactor Vent Valve Failure Analysis

Figure 3 presents the NuScale RVV fault tree [12]. The top event—both RVV trains fail to open on demand—connects through an AND gate to two intermediate events (Train A and B failures). Each train failure connects through OR gates to three basic event categories [19]. A common cause failure event feeds directly to the top event [22,30].

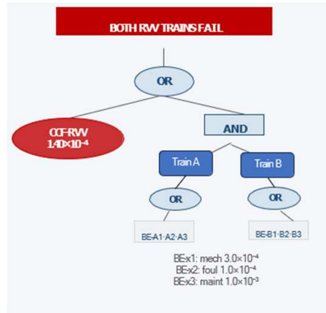

Figure 3. Fault tree for NuScale RVV system failure

Table 4. NuScale RVV basic events and failure probabilities

Event ID	Description	Probability & Source
BE-A1, BE-B1	Mechanical valve failure (stuck closed, spring failure)	3×10^{-4} /demand (NUREG/CR-6928 [24])
BE-A2, BE-B2	Plugging/fouling (boron deposits, debris)	1×10^{-4} /demand (IAEA TECDOC-930 [26])
BE-A3, BE-B3	Test/maintenance error (misalignment, improper reassembly)	1×10^{-3} /demand (NUREG/CR-6928 [24])
CCF-RVV	**Common cause: both trains (design, manufacturing, environment)**	**$\beta = 0.10$; $Q_{CC}{}^{f} = 1.40\times10^{-4}$ (NUREG/CR-5497 [30])**

Table 5. NuScale RVV minimal cut sets

MCS	Order	Events	Probability	% Total
MCS-1	**1**	**CCF-RVV**	**1.40×10^{-4}**	**98.9%**
MCS-2	2	BE-A3 ∩ BE-B3	8.10×10^{-7}	0.57%
MCS-3	2	BE-A1 ∩ BE-B3	2.43×10^{-7}	0.17%
MCS-4	2	BE-A3 ∩ BE-B1	2.43×10^{-7}	0.17%
MCS-5	2	BE-A2 ∩ BE-B3	8.10×10^{-8}	0.06%
MCS-6	2	BE-A3 ∩ BE-B2	8.10×10^{-8}	0.06%
MCS-7	2	BE-A1 ∩ BE-B1	7.29×10^{-8}	0.05%
MCS-8–10	2	Remaining 2nd-order combinations	$\sim3.55\times10^{-8}$	<0.03%
		TOTAL	**1.42×10^{-4}**	**100.0%**

CCF is the overwhelmingly dominant risk contributor at 98.9% of total RVV failure probability (FV = 0.989) [30,31]. Manufacturing quality assurance, design diversity between trains, and staggered maintenance become paramount risk management priorities [22]. Adjusted independent probabilities $Q^{Ind} = (1-\beta)\times Q_t$ are applied to all 2nd-order cut sets to avoid double-counting per NUREG/CR-5497 [30].

5.2. BWRX-300 Isolation Condenser System Failure Analysis

Figure 4 presents the BWRX-300 IC fault tree [14]. Complexity is significantly greater: the top event decomposes through four intermediate failure categories per train (valves, heat exchanger, power, control/logic), yielding approximately 20 basic events [19].

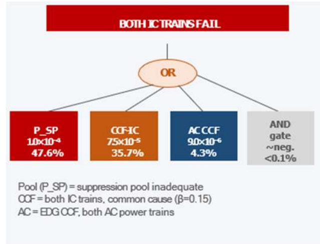

Figure 4. Fault tree for BWRX-300 IC system failure

Table 6. BWRX-300 IC system basic events and intermediate failure probabilities (per train)

Event ID	Category	Component Failures	Prob./Train	Source
IF-A1/B1	Valves	Inlet + outlet MOV (2 per train), passive position failure	1.0×10^{-4}	NUREG/CR-6928 [24]
IF-A2/B2	Heat Exch.	Tube plugging, rupture, fouling	3.0×10^{-5}	IAEA TECDOC-930 [26]
IF-A3/B3	Power	DC battery + AC/EDG combined	2.5×10^{-4}	NUREG/CR-6928 [24,31]
IF-A4/B4	Control	Sensor error, logic fault, manual actuation fails	1.2×10^{-4}	IEEE Std 500 [31]
P_SP	Shared	Suppression pool inadequate — defeats both trains simultaneously	1.0×10^{-4}	IAEA TECDOC-478 [27,33]
CCF-IC	**CCF**	**Both IC trains — common cause failure (β = 0.15)**	**7.50×10^{-5}**	**NUREG/CR-5497 [30]**

Table 6. BWRX-300 IC system basic events and intermediate failure probabilities (per train)

Event ID	Category	Component Failures	Prob./Train	Source
IF-A1/B1	Valves	Inlet + outlet MOV (2 per train), passive position failure	1.0×10^{-4}	NUREG/CR-6928 [24]
IF-A2/B2	Heat Exch.	Tube plugging, rupture, fouling	3.0×10^{-5}	IAEA TECDOC-930 [26]
IF-A3/B3	Power	DC battery + AC/EDG combined	2.5×10^{-4}	NUREG/CR-6928 [24,31]
IF-A4/B4	Control	Sensor error, logic fault, manual actuation fails	1.2×10^{-4}	IEEE Std 500 [31]
P_SP	Shared	Suppression pool inadequate — defeats both trains simultaneously	1.0×10^{-4}	IAEA TECDOC-478 [27,33]
CCF-IC	**CCF**	**Both IC trains — common cause failure (β = 0.15)**	**7.50×10^{-5}**	**NUREG/CR-5497 [30]**

Table 7. BWRX-300 IC dominant minimal cut sets

MCS	Order	Events / Description	Probability	% Total

MCS-1	**1**	**P_SP: Suppression pool inadequate — shared event; defeats both trains**	**1.00×10^{-4}**	**47.6%**
MCS-2	**1**	**CCF-IC: Both IC trains fail — common cause failure**	**7.50×10^{-5}**	**35.7%**
MCS-3	1	Q_AC_CCF: Both EDGs fail to start (CCF, $\beta = 0.05$)	9.00×10^{-6}	4.3%
MCS-4+	1–2	Remaining CCF terms and 2nd-order cross-train combinations	~2.60×10^{-5}	12.4%
		TOTAL	**2.10×10^{-4}**	**100.0%**

Suppression pool inadequacy (MCS-1, 47.6%) and CCF (MCS-2, 35.7%) together account for 83.3% of total failure probability [26]. The suppression pool is a shared resource whose failure affects both IC trains simultaneously despite train-level redundancy—fundamentally different from NuScale's profile where CCF dominates but no shared physical component creates single-point failure [12]. Active component CCF ($\beta = 0.15$) exceeds NuScale's ($\beta = 0.10$), reflecting higher susceptibility to calibration errors and power source commonalities [22,30,31].

5.3. Quantitative Reliability Comparison

Table 8. Comparative top event failure probabilities and key metrics

Metric	NuScale RVV	BWRX-300 IC
Top event probability (Q_{tot})	1.42×10^{-4}	2.10×10^{-4}
Uncertainty range (±50% BE)	$0.71–2.13\times10^{-4}$	$1.05–3.15\times10^{-4}$
Number of basic events	7	~20
Order-1 MCS count	1 (CCF-RVV)	3 (P_SP, CCF-IC, AC CCF)
Dominant contributor	CCF (98.9%)	Pool inadequacy (47.6%)
FV of dominant contributor	0.989	0.476
Beta factor (CCF)	0.10 (passive)	0.15 (active)
Relative failure probability	1.00× (baseline)	1.48× (48% higher)

NuScale's passive RVV system achieves 32% lower failure probability than BWRX-300's active IC system (1.42×10^{-4} versus 2.10×10^{-4}). NuScale's 98.9% CCF dominance makes the entire top event probability essentially equal to a single first-order cut set. BWRX-300's suppression pool single-point vulnerability bypasses train redundancy entirely, creating a persistent floor on failure probability regardless of individual component quality [26,31].

5.4. Importance Measures

Table 9. NuScale RVV importance measures

Event	FV	RAW	RRW	Interpretation
CCF-RVV	**0.989**	**7,063**	**89.2**	**Eliminating CCF reduces Q_{tot} by 89×**
BE-A3/B3	0.008	6.8*	1.008	Maintenance error; marginal
BE-A1/B1	0.003	3.1*	1.003	Mechanical failure; low
BE-A2/B2	0.001	1.6*	1.001	Fouling; lowest

* RAW for individual basic events computed as Q_{tot}(event = 1, train A fails) / Q_{tot}, reflecting conditional increase if a single train's event is certain.

Table 10. BWRX-300 IC system importance measures (dominant contributors)

Event	FV	RAW	RRW	Interpretation
P_SP (supp. pool)	**0.476**	**4,762**	**1.91**	**Removing pool risk halves Q_{tot}**
CCF-IC	**0.357**	**4,762**	**1.56**	**CCF elimination reduces Q_{tot} by 1.56×**
Q_AC_CCF	0.043	4,762	1.04	EDG CCF; low-moderate contributor
Other (MCS 4+)	0.124	varies	1.14	Distributed individual CCF terms

5.5. Core Damage Frequency Estimates

Table 11. CCF contribution summary

Parameter	NuScale RVV	BWRX-300 IC
Beta factor (β)	0.10	0.15
Single-train failure rate (Q_t)	1.40×10^{-3}	5.00×10^{-4}
CCF probability ($Q_{ccf} = \beta \times Q_t$)	1.40×10^{-4}	7.50×10^{-5}
CCF as % of Q_{tot}	98.9%	35.7%
Independent double failure (Q^{Ind})	1.59×10^{-6}	1.81×10^{-7}
Q_{tot} without CCF	1.59×10^{-6}	1.35×10^{-4}
RRW(CCF)	89.2	1.56

Table 12. Accident sequence frequencies per reactor-year (LONHR, IE = 10^{-2}/RY)

Seq.	Cond. Probability	Freq. (/RY)	Outcome
NuScale VOYGR™ sequences			
SEQ-1	~0.950	$\sim9.50\times10^{-3}$	Success
SEQ-2	~0.049	$\sim4.90\times10^{-4}$	Marginal success
SEQ-3	$\sim5.5\times10^{-9}$	$\sim5.5\times10^{-11}$	Core damage (minor)
SEQ-4	$\sim5.0\times10^{-5}$	$\sim5.0\times10^{-7}$	Core damage
SEQ-5	1.42×10^{-4}	1.42×10^{-6}	Severe core damage
NuScale CDF (SEQ-4 + SEQ-5) = 1.92×10^{-6} /RY			
BWRX-300 sequences			
SEQ-1	~0.897	$\sim8.97\times10^{-3}$	Success
SEQ-2	~0.085	$\sim8.5\times10^{-4}$	Marginal success
SEQ-3	$\sim4.3\times10^{-4}$	$\sim4.3\times10^{-6}$	Core damage
SEQ-4	$\sim3.0\times10^{-3}$	$\sim3.0\times10^{-5}$	Degraded (ECCS fails, IC ok)

SEQ-5	~1.0×10^{-5}	~1.0×10^{-7}	Core damage
SEQ-6	~5.0×10^{-5}	~5.0×10^{-7}	Severe core damage
SEQ-7	2.10×10^{-4}	2.10×10^{-6}	Severe core damage
BWRX-300 CDF (SEQ-3, 5, 6, 7) = 7.00×10^{-6} /RY			

NuScale yields a CDF of 1.92×10^{-6}/RY versus BWRX-300's 7.00×10^{-6}/RY—a ratio of approximately 3.6×. Both values satisfy advanced reactor safety goals (CDF < 10^{-5}/RY) for this initiating event category.

5.6. Sensitivity Analysis

Beta-factor sensitivity analysis confirms the robustness of findings. For NuScale, varying β from 0.05 to 0.20 changes Q_{tot} by −49% to +98% relative to baseline, remaining CCF-dominated throughout. For BWRX-300, the same range yields only −24% to +24% variation because the fixed suppression pool term (P_SP = 1.0×10^{-4}) anchors the total. Table 13 presents the reliability ratio Q_{tot}(BWRX)/Q_{tot}(NuScale) across all beta combinations, confirming NuScale's advantage is robust wherever $\beta_{E}^{Lx} \geq \beta_{P}^{s} + 0.05$.

Table 13. Reliability ratio Q_{tot}(BWRX) / Q_{tot}(NuScale) across beta combinations (* base case)

	NS β = 0.05	NS β = 0.10	NS β = 0.15	NS β = 0.20
BW β = 0.05	2.23×	1.13×	0.76×	0.57×
BW β = 0.10	2.58×	1.31×	0.88×	0.66×
BW β = 0.15*	2.93×	**1.48×***	0.99×	0.75×
BW β = 0.20	3.27×	1.66×	1.11×	0.84×

BWRX> = BWRX-300 has higher failure probability; NS> = NuScale has higher failure probability.

6. IMPLICATIONS FOR EMERGING MARKET DEPLOYMENT

6.1. Synthesis of Reliability Analysis

NuScale's failure probability concentrates near-totally in CCFs (98.9%), making manufacturing quality and design diversity paramount while keeping operational surveillance minimal [22,30]. BWRX-300's failure probability distributes between a shared heat sink vulnerability (47.6%) and CCF (35.7%), concentrating 83.3% of risk into two mechanisms requiring different mitigation strategies [26]. Despite 3× greater system complexity, BWRX-300 achieves near-comparable reliability through redundancy and diversity [8,14]. These distinctions manifest differently across regulatory review, financial risk assessment, and operational execution—the three critical barriers in emerging markets [4,18,26].

6.2. Regulatory Approval and Licensing Timeline Impacts

NuScale's 98.9% CCF dominance means regulators must scrutinize manufacturing quality assurance programs and vendor testing protocols with particular rigor, potentially requiring IAEA peer reviews that extend licensing timelines [22,30]. However, zero active components requiring periodic testing and no operator actions for 72 hours substantially reduces the volume of technical specifications and emergency operating procedures requiring review [5,11,12]. BWRX-300 leverages proven BWR technology precedent, enabling regulators to reference established surveillance requirements and well-understood failure modes [6,15,20], though its complexity demands multidisciplinary regulatory expertise that newcomer countries may lack [7,26].

6.3. Project Financing and Cost of Capital Impacts

NuScale's lower failure probability should reduce technical risk premiums, and the absence of active components eliminates surveillance testing and calibration cost categories, providing O&M cost certainty that debt financiers value [3,28]. However, the 98.9% CCF concentration introduces uncertainty for conservative financiers lacking operational experience data [24]. BWRX-300's higher failure probability is partially offset by decades of BWR operational data providing actuarial confidence in failure rate predictions, and the 47.6% suppression pool vulnerability is quantifiable and addressable through enhanced instrumentation at modest capital cost [1,6,14].

6.4. Operational Staffing and Workforce Requirements

NuScale's passive design reduces the need for specialized I&C technicians and calibration experts scarce in developing countries [12], and the 72-hour grace period eliminates time-critical operator actions that introduce human error risk [23]. BWRX-300 requires comprehensive multidisciplinary staffing across mechanical, electrical, I&C, and digital control disciplines [6,16], though extensive real-time instrumentation can compensate for limited operational experience through automated decision support [2,30].

6.5. Technology Selection Guidance for Emerging Markets

For countries with minimal nuclear infrastructure, NuScale's passive approach offers compelling advantages: fewer regulatory review systems, staffing requirements aligned with constrained labor markets, and simplified procedures. The critical success factor becomes manufacturing quality assurance—countries must develop confidence in vendor QA programs or structure contracts with warranty provisions that transfer CCF risk to vendors [22,27]. For countries with established technical universities or regional nuclear cooperation, BWRX-300 provides operational flexibility and technology transfer opportunities through the shared BWR knowledge base [16,18,29]. Financing structures should align with technology risk profiles: NuScale projects benefit from government loan guarantees covering passive component performance risk [1,3]; BWRX-300 projects benefit from long-term O&M contracts converting variable costs into fixed schedules [6,16]. The 48% reliability difference and 3.6× CDF ratio should inform but not solely dictate technology selection; regulatory capacity, workforce availability, and financing structure alignment are equally decisive [4,18,26].

7. CONCLUSIONS

This paper presents a systematic comparative reliability analysis of passive versus active SMR emergency core cooling systems through the lens of emerging market deployment constraints [4,26]. NuScale's passive RVV system achieves a failure probability of 1.42×10^{-4} compared to 2.10×10^{-4} for BWRX-300's active IC system—a 48% difference—with a 3.6× difference in LONHR-induced CDF (1.92×10^{-6} versus 7.00×10^{-6} per reactor-year), both satisfying advanced reactor safety goals for this event category. The more important finding is qualitative: NuScale concentrates 98.9% of its failure probability in a single first-order CCF cut set, demanding rigorous manufacturing QA and design diversity; BWRX-300 distributes 83.3% across a shared heat sink vulnerability (47.6%) and active component CCF (35.7%), requiring different and operationally addressable mitigation strategies. NuScale's passive simplicity reduces regulatory review complexity and operational staffing requirements—critical advantages in newcomer countries [7,26]—while BWRX-300's active approach provides operational flexibility and diagnostic capability valuable in countries with growing technical workforces [16,29]. Country-specific regulatory capacity, workforce availability, and financing structure alignment are as decisive as the absolute reliability difference [4,18,26]. Future work should complete remaining safety system fault trees for full CDF calculations [19,32], conduct Monte Carlo uncertainty analysis [26,27,34], and develop quantitative decision frameworks integrating reliability with economic, regulatory, and workforce parameters for specific country profiles.

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