Challenges in Evaluating Passive Safety System Performance for Nuclear Power Technologies Under Evolving Hazards

Constantinos Frantzis[a], Kaveh Faraji Najarkolaie[a], Yunfei Zhao[b], Jennifer Irish[c], Mohammad Modarres[b], and Michelle Bensi[a]

[a] Dept. of Civil and Environmental Eng., University of Maryland, College Park, MD, USA, cfrantzi@umd.edu
[b] Dept. of Mechanical Eng., University of Maryland, College Park, MD, USA
[c] Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

Abstract: Advanced nuclear reactor concepts, including light water cooled small modular reactors (SMRs), molten salt reactors (MSRs), liquid metal reactors (LMRs), and high-temperature gas-cooled reactors (HTGRs), promise improved economics and enhanced safety through inherent design features and passive safety systems. These passive systems perform critical functions, particularly decay heat removal, using natural driving forces such as gravity, density differences, and natural convection. Their accelerated deployment is being pursued to provide stable, reliable electrical capacity to a grid whose dependence is amplified by emerging artificial intelligence and data-center infrastructure. Discussions of nuclear safety, however, have traditionally focused on estimating the frequency of catastrophic radiological endpoints. We argue that this framing is potentially incomplete. A plant offline during a regional heat dome, drought, or storm imposes a substantial societal cost on communities, hospitals, water treatment facilities, and data centers even when no radiological release occurs. Generation, in this sense, is itself a potential safety concern.

Both radiological and generational safety concerns are exacerbated by external natural hazards whose frequency and severity are projected to evolve under non-stationary environmental conditions. Passive safety systems, by virtue of relying on weak natural driving forces, are particularly sensitive to the boundary conditions these hazards perturb. Current external hazard Probabilistic Risk Assessment (PRA) frameworks treat hazards as stationary, and Generation Risk Assessment (GRA), the methodology developed to quantify reactor trip and derate frequencies, remains narrowly adopted and has not been generalized to non-stationary hazards. Neither PRA nor GRA, as currently practiced, completely capture the dependency between safety, generation, and the evolving hazard landscape.

In this paper, we examine the implications of these gaps for passive-safe advanced reactors. The literature on passive system robustness supports a nuanced view in which safety margins are broadly preserved against moderate variations, while the probability of derates, protective reactor trips, and extended forced outages is meaningfully more sensitive. GRA is uniquely positioned to capture this sensitivity, as it is the methodology built to quantify the trip, derate, and unavailability outcomes that fall outside the scope of conventional safety PRA. We conclude that broader adoption of GRA, and its extension to incorporate non-stationary external hazard distributions, would help quantify the dual risks to safety and generation that advanced reactors will face under evolving conditions.

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1. INTRODUCTION

Advanced nuclear reactor concepts are widely proposed to improve the economics of nuclear energy through modularization, factory fabrication, and standardization, while enhancing safety through inherent design features and passive safety systems [1], [2]. These passive systems perform critical functions, particularly decay heat removal, using natural driving forces such as gravity, density differences, and natural convection [2], [3].

The accelerated deployment of advanced reactors is being pursued to develop electrical capacity that is stable and reliable [4], [5]. The importance of stable, reliable electrical power is well recognized, and the emergence of artificial intelligence and the associated infrastructure is amplifying its criticality [6], [7]. The dependence of communities and industries on electrical power has implications for how safety is framed. For example, hospitals, water treatment facilities, data centers, and other essential services depend on consistent power, and the loss of generation through reduced thermal efficiency, forced shutdowns, prolonged outages, or more frequent maintenance has direct consequences for public welfare.

Discussions of nuclear safety typically focus on estimating the frequency of severe endpoints such as core damage and large early release. Probabilistic risk assessment (PRA) has been the typical approach by which the frequency of adverse radiological effects has been quantified. However, a plant going offline during a regional heat dome or extended drought imposes societal cost even when no radiological release occurs. Generation is itself a potential safety concern, particularly when electrical capacity margins in a system are limited. To date, generation risk assessment (GRA) has focused primarily on quantifying reactor trip and derate frequencies [8].

Both radiological and generational safety concerns are exacerbated by external natural hazards, including weather and water-related hazards for which the frequency and severity are expected to evolve under non-stationary environmental conditions [9], [10]. Passive safety systems, by virtue of relying on weak natural driving forces, are particularly sensitive to the boundary conditions these hazards perturb [2], [11]. Current external hazard PRA (XHPRA) frameworks treat external hazards as stationary, and GRA methods remain narrowly adopted and and have not been generalized to non-stationary hazards [12]. Neither PRA nor GRA explicitly captures the dependency between safety, generation, and the evolving hazard landscape. Broader adoption and extension of GRA is needed to close this gap.

In this paper, we develop this argument as follows. Section 2 reviews operational experience from the existing fleet, where weather- and water-related events have already imposed substantial generation losses. Section 3 examines current PRA and GRA practice and the stationarity assumption that limits both. Section 4 summarizes the passive decay heat removal systems in water-cooled SMRs, MSRs, and HTGRs and their shared dependence on atmospheric and hydrologic boundary conditions. Section 5 identifies four pathways by which GRA outputs are sensitive to evolving boundary conditions, and Section 6 discusses the implications for operators and regulators and presents our concluding observations.

2. OPERATIONAL EXPERIENCE: GENERATION RISK UNDER EVOLVING HAZARDS

Recognizing the broad impacts of power outages [13], [14], [15], [16], operational experience and recent literature support the framing that generation is itself a potential safety concern.

The OECD Nuclear Energy Agency observes that extreme weather events have already affected nuclear plant operation, and that any increase in cooling water temperature reduces power output through decreased thermal efficiency. They project that the costs of inaction, both at the plant level and indirectly for the electricity system, are likely to exceed the costs of adaptation [10]. Portugal-Pereira et al. [17] identify reduced water-cooling efficiency, biological contamination of cooling streams, and drought-driven water access issues as concrete pathways from evolving hazards to lost output.

The existing fleet provides further insights. For example, Collet et al. [18] document that Electricite de France has reduced or halted output at multiple stations on the Rhone, Garonne, and Gironde rivers during heat waves in 2003, 2018, 2019, 2022, 2024, and 2025. They further project mean annual production losses for the French fleet of approximately 0.3 percent under current conditions, rising to roughly 1.5 percent by mid-century. In the United States, Hurricane Irma in 2017 forced unscheduled outages at Turkey Point and St. Lucie, Hurricane Florence in 2018 caused a nine-day outage at

Brunswick, and the 2020 derecho damaged Duane Arnold cooling towers severely enough that the plant did not return to service [19], [20], [21]. None of these events constituted a radiological incident, yet all imposed substantial generation loss on the grids that depended on the affected plants.

For advanced reactors with passive safety systems, these vulnerabilities are inherited. Because passive system performance is more tightly coupled to ambient conditions than active system performance, advanced reactors will inherit both the availability sensitivities and the safety-margin erosion observed in the existing fleet [22]. Safety and generation cannot be evaluated in isolation, and frameworks are needed that quantify both under non-stationary conditions.

A further consideration is the spatial coherence of these hazards. Heat domes, droughts, and tropical cyclones are regional events that affect multiple plants simultaneously, often within the same balancing authority. When multiple plants with in fleet derate in a single heat wave affecting river water temperatures, or multiple plants are taken offline ahead of one hurricane, generation loss is concentrated in space and time in a way that maximizes its impact on grid reliability [10], [17]. Advanced reactors deployed in multi-unit configurations at a single site, as in current SMR fleet proposals, may compound this risk at the site level [11]. Generation as a safety concern, therefore, extends beyond any individual plant to the regional electricity system that depends on its consistent operation.

3. TREATMENT OF EVOLVING HAZARDS UNDER CURRENT PRACTICE

Quantification of the reliability of passive safety systems has developed over three decades. Frameworks such as Reliability Evaluation of Passive Safety Systems (REPAS), Reliability Methods for Passive Safety Functions (RMPS), and Assessment of Passive System Reliability (APSRA) identify critical thermal-hydraulic parameters, propagate uncertainties through thermal-hydraulic models, and compute functional failure probabilities against defined success criteria [23], [24]. External hazard PRA characterizes external hazards through annual exceedance frequencies, often derived from analysis of historical event records [25]. In both cases, the underlying assumption is that hazard frequencies and intensities, and the parameter distributions feeding T-H analyses, are stationary. This assumption is widely questioned in the literature [10], [17], [26], but no mature methodology has yet displaced stationary return-period framings in regulatory practice.

GRA was developed by EPRI in the early 2000s as an asset management tool to model the frequencies of reactor trips and derates resulting from balance-of-plant and nuclear steam supply system failures, supporting equipment reliability, maintenance optimization, and economic decision-making [8]. GRA models include both safety-significant and non-safety SSCs that contribute to availability and explicitly track derates, defined as any drop in power from full output, in addition to full trips [8], [27]. Despite these features, GRA has been narrowly adopted across the industry, with implementations limited to a small number of plants, and the peer-reviewed literature on GRA implementation and sensitivities is scarce relative to that on safety PRA [12]. Recent work on tools such as the Versatile Economic Risk Tool [12] aims to simplify and automate GRA modeling, but extension to incorporate non-stationary external hazard distributions is not part of standard practice.

The combined effect is that neither PRA nor GRA, as currently practiced, explicitly captures the dependency between plant endpoints and evolving external hazards. PRA captures adverse radiological safety endpoints, typically under historical hazard assumptions. GRA quantifies reactor trip and derate frequencies under similar historical equipment and operating data. Neither, as deployed today, propagates non-stationary hazard distributions through the dependencies that determine both safety margin and generation availability.

4. PASSIVE SAFETY SYSTEMS AND BOUNDARY-CONDITION DEPENDENCE

Passive decay heat removal systems differ across reactor classes in working fluid, geometry, and driving mechanism, but share a common feature: the chain of heat rejection terminates in atmospheric or hydrologic conditions, and the driving forces are, by construction, weak. Table 1 summarizes and compares passive decay heat removal systems (DHRS) across three broad reactor types most commonly discussed in the literature.

This paper focuses on light-water reactor (LWR) variants of water-cooled SMRs. LWRs are the dominant technology in the existing US fleet, and the vast majority of advanced SMR designs currently under licensing review and near-term deployment in the United States are LWR-based [28], [29]. Pressurized heavy-water reactor (PHWR) variants, although significant in some international contexts, are not the focus of current US advanced SMR programs. Their passive decay heat removal pathways and boundary-condition dependencies are sufficiently similar to those of LWR-SMRs that the discussion that follows applies broadly to both.

Table 1. Comparison of passive DHRS across water-cooled SMRs, MSRs, and HTGRs

Reactor type	Passive system	Heat transfer mechanism	Ultimate heat sink	Key boundary conditions	Refs
Water-cooled SMR	Reactor pool, DHRS	Natural circulation boil-off air convection	Atmosphere (via pool)	Pool inventory, pool temperature, ambient air temperature	[30], [31]
MSR	RVACS[1], DRACS[2], Freeze valve, drain tank, coolant at atmospheric pressure	Gravitational drain natural circulation heat pipes	Atmosphere	Ambient air temperature, freeze valve thermal margin	[32], [33], [34], [35]
LMR	RVACS, DRACS, coolant at atmospheric pressure	Natural circulation thermal radiation convection	Atmosphere	Ambient air temperature	[24], [36], [37]
HTGR	Reactor Cavity Cooling System (RCCS)	Thermal radiation Natural convection	Atmosphere	Ambient air temperature	[38], [39], [40], [41], [42]

[1]Reactor Vessel Auxiliary Cooling System, [2]Direct Reactor Auxiliary Cooling System

Many water-cooled Small Modular Reactor (SMR) designs rely on natural circulation in the primary loop and on passive heat transfer to a pool that serves as the ultimate heat sink [3], [30]. In the NuScale design, the pool transitions through water cooling, boiling, and finally passive air cooling as boil-off progresses [31]. Pool inventory, pool temperature, and ambient air temperature are therefore the primary boundary conditions, with importance shifting from water to air temperature on multi-day timescales. While not an SMR, the same physics also governs the AP1000 passive containment cooling system, for which Yu et al. [11] demonstrated measurable shifts in functional failure probability across plausible atmospheric inputs.

Molten Salt Reactor (MSR) designs use a different strategy. Fuel salt is gravitationally drained to subcritical drain tanks when a freeze valve melts under decay heat. Drain tank cooling is then provided by passive natural circulation heat rejection systems such as the Reactor Vessel Auxiliary Cooling System (RVACS) and the Direct Reactor Auxiliary Cooling System (DRACS) via thimbles and heat pipes, with heat ultimately rejected to ambient air [32], [34]. The freeze valve must hold the plug against inadvertent dislodging at elevated ambient temperatures, and the drain tank heat rejection capacity depends directly on ambient temperature conditions [32], [33]. In addition to drain-based shutdown, MSRs benefit from passive features intrinsic to the coolant: molten salts have high volumetric heat capacity that provides thermal inertia, and operate at near-atmospheric pressure, reducing the risk of pressure-driven loss-of-coolant events [43]. The intrinsic atmospheric-pressure feature is largely insensitive to evolving boundary conditions, but the heat-rejection chain itself still terminates in the atmosphere.

Liquid Metal Reactor (LMR) designs, most commonly sodium-cooled fast reactors (such as TerraPower's Natrium and Oklo's Aurora) [29], employ pool-type primary systems in which the reactor core is submerged in a large sodium pool that serves as both the working fluid and an integral heat reservoir. Like MSRs, LMR designs use coolants with high volumetric heat capacity that operate at near-atmospheric pressure, providing intrinsic thermal inertia and reducing the risk of pressure-driven loss-of-coolant scenarios [43]. Passive decay heat removal is provided by natural-circulation systems such as RVACS and DRACS, in which decay heat is transferred from the core through the reactor vessel or through a dipped heat exchanger and ultimately rejected to ambient air [24], [36]. As with MSRs, the chain of dependence terminates in the atmosphere, and ambient air temperature is the principal boundary condition. The intrinsic atmospheric-pressure feature is largely insensitive to evolving boundary conditions, but the heat rejection chain is subject to the same non-stationarity concerns discussed for the other reactor classes [37].

High Temperature Gas Reactor (HTGR) designs rely on the Reactor Cavity Cooling System (RCCS) as the principal passive feature, with decay heat conducted through the graphite core to the reactor pressure vessel and transferred across the cavity primarily by thermal radiation and natural convection to ambient air [42]. Of the three classes, HTGR RCCS performance has the most direct functional dependence on ambient air temperature. Design analyses commonly assume a fixed bounding ambient near 40 degrees Celsius, and operational data from HTR-PM confirm that small ambient variations measurably affect heat removal performance [41].

The existing literature on passive system robustness under varying boundary conditions presents a nuanced picture. Detailed thermal-hydraulic analyses show that passive safety systems retain their safety functions across substantial ambient variations. Fakhraei et al. [35] confirmed that the NuScale design retains sufficient margin during extended station blackout sequences even with concurrent emergency core cooling system failure. Park et al. [44] showed that natural-circulation heat removal effectively dissipates decay heat across credible boundary-condition variations. At the same time, reliability analyses identify sink and environment temperatures as among the most influential parameters for performance, and Nayak et al. [23] note that they vary in time and cannot reasonably be treated as fixed.

Thus, available literature suggests safety margins are broadly preserved against moderate variations in ambient conditions. However, the magnitude of those margins and the probability of derates, protective reactor trips, and extended forced outages are sensitive to boundary-condition statistics that are no longer stationary. Existing literature has not thoroughly explored the extent to which these changes will meaningfully affect generational risk.

5. GRA IMPLICATIONS OF EVOLVING BOUNDARY CONDITIONS

GRA quantifies generation risk through reactor trip and derate frequencies that depend directly on the boundary conditions that determine passive system performance. This direct dependence makes GRA outputs particularly sensitive to non-stationary hazard distributions through four distinct pathways:

1. **Thermal efficiency loss,** representing when efficiency falls at heat sink temperature rises.
2. **Administrative output reduction**, representing operator derating to preserve safety limits as passive heat rejection capacity degrades.
3. **Protective shutdowns**, including reactor trips due to loss of offsite power, drought-driven water unavailability, or other factors such as smoke loading.
4. **Elevated maintenance unavailability**, due to more frequent inspection, cleaning, and repair of components operating closer to performance limits.

Thermal efficiency of any thermodynamic cycle depends on the temperature difference between the heat source and the heat sink. As ambient air or cooling water temperatures rise, Carnot efficiency falls and net electric power output is reduced even at full thermal power [45]. The OECD Nuclear Energy

Agency notes that any increase in cooling water temperature reduces power output through decreased efficiency [10], and this effect compounds over the long operating life of an advanced reactor as ambient distributions shift.

Under the second pathway, passive heat rejection capacity is reduced by elevated ambient temperatures. Operators may need to reduce reactor power to preserve margin to safety limits and avoid challenging passive system performance envelopes [46]. This pathway translates degraded passive system effectiveness directly into derates, even before any safety-relevant threshold is approached, and is by construction invisible to traditional safety PRA.

Third, protective shutdowns arise from a range of evolving hazards that GRA inputs typically treat as low-frequency events. Loss of offsite power during heat domes and storms, drought-driven cooling water unavailability, intake clogging from biological contamination of warmer surface waters [17], wildfire smoke loading on air-cooled passive system intakes [47], and severe precipitation or storm surge are all hazards whose frequencies are expected to evolve [48]. Each translates into reactor trip frequencies that current GRA implementations, using historical data, are likely to underestimate.

Fourth, prolonged or more frequent forced maintenance is an indirect but substantial pathway. Passive systems operating closer to performance limits, balance-of-plant equipment exposed to more frequent thermal extremes, and intake structures fouled by warmer water [49] or biological contamination [50] all impose more frequent inspection, cleaning, and repair, which appear in GRA as elevated unavailability rates rather than discrete reactor trip events.

These pathways are largely independent of, but coupled to, the safety endpoints PRA quantifies. A plant can preserve safety margin while losing efficiency, reducing output, suffering protective reactor trips, and incurring extended maintenance. The cumulative effect on availability for a community depending on that plant is substantial.

6. DISCUSSION AND CONCLUSION

Passive safety systems in advanced reactors depend on environmental boundary conditions that are no longer stationary, and the existing literature supports a nuanced perspective in which safety margins are broadly preserved against moderate variations while generation availability is meaningfully more sensitive. Because communities, essential services, and, increasingly, data centers depend on consistent power, the loss of generation through reduced thermal efficiency, administrative derates, protective shutdowns, and elevated maintenance imposes a substantial societal cost even when no radiological event occurs. Generation, in this sense, is itself a potential safety concern.

Utilities and plant operators have a direct economic interest in availability, and the case for broader GRA adoption may strengthen for plants relying on passive safety systems. Stability and performance of these systems in conventional PRA could mask the risks to public welfare and the economic impacts of generation disruptions. While current operators use GRA for asset management at a handful of plants, advanced reactor operators may derive insights from GRA-style analyses that characterize the sensitivities of generation capacity when performance may shift under evolving hazards. The four pathways identified in Section 5 collectively define an availability envelope that current GRA practice, with its reliance on historical equipment and operating data, may overestimate.

Regulators have traditionally focused on catastrophic safety endpoints, and for the existing fleet, this focus has served well. Two considerations may now warrant broader engagement with GRA. First, the defense-in-depth interpretation of safety holds that margin erosion is a concern even when safety limits are not exceeded. Hazard-driven degradation of passive system performance can potentially erode margin in this sense, particularly for designs whose safety case rests on passive heat rejection to ambient environments. Second, as nuclear capacity is positioned as stable low-carbon generation, the societal stake in generation availability is increasingly a public safety concern. A plant safely shut down during a heat dome does not constitute a radiological event, but a regional fleet simultaneously offline does constitute a grid reliability event with potential consequences for the communities that depend on it.

In summary, current PRA and GRA practice does not explicitly capture the dependency between safety and generation endpoints and the evolving external hazards that drive them. GRA in particular remains narrowly adopted and methodologically static. Combined operator–regulator interest in extending GRA to incorporate non-stationary external hazard inputs offers a strong organizational basis for closing this gap. Broader adoption of GRA, and its extension to incorporate non-stationary external hazard distributions could help quantify the dual risks to safety and generation that advanced reactors will face under evolving conditions.

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References

[1] Committee on Laying the Foundation for New and Advanced Nuclear Reactors in the United States *et al.*, *Laying the Foundation for New and Advanced Nuclear Reactors in the United States*. Washington, D.C.: National Academies Press, 2023, p. 26630. doi: 10.17226/26630.

[2] International Atomic Energy Agency, "Use of Passive Safety Features in Nuclear Power Plant Designs and their Safety Assessment," IAEA, Feb. 2017. Accessed: May 29, 2026. [Online]. Available: http://www.iaea.org/topics/design-safety-nuclear-power-plants/passive-safety-features

[3] International Atomic Energy Agency, "Passive Safety Systems in Water Cooled Reactors: An Overview and Demonstration with Basic Principle Simulators," IAEA, Sep. 2019. Accessed: Apr. 17, 2026. [Online]. Available: http://www.iaea.org/publications/13530/passive-safety-systems-in-water-cooled-reactors-an-overview-and-demonstration-with-basic-principle-simulators

[4] "Small Modular Reactors: Adding to Resilience at Federal Facilities," Energy.gov. Accessed: May 29, 2026. [Online]. Available: https://www.energy.gov/ne/articles/small-modular-reactors-adding-resilience-federal-facilities

[5] U. S. G. A. Office, "Technology Assessment: Nuclear Reactors: Status and Challenges in Development and Deployment of New Commercial Concepts | U.S. GAO." Accessed: May 29, 2026. [Online]. Available: https://www.gao.gov/products/gao-15-652

[6] A. Shehabi *et al.*, "2024 United States Data Center Energy Usage Report," Dec. 2024, doi: 10.71468/P1WC7Q.

[7] "Advantages and Challenges of Nuclear-Powered Data Centers," Energy.gov. Accessed: May 29, 2026. [Online]. Available: https://www.energy.gov/ne/articles/advantages-and-challenges-nuclear-powered-data-centers

[8] "Generation Risk Assessment (GRA) Plant Implementation Guide," Electric Power Research Institute, Palo Alto, CA, 1008121, 2004. Accessed: Feb. 17, 2026. [Online]. Available: https://www.epri.com/research/products/1008121

[9] Intergovernmental Panel On Climate Change (Ipcc), *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report*

of the Intergovernmental Panel on Climate Change, 1st ed. Cambridge University Press, 2023. doi: 10.1017/9781009157896.
[10] H. Kromp-Kolb *et al.*, "Climate Change: Assessment of the Vulnerability of Nuclear Power Plants and Approaches for their Adaptation," Organisation for Economic Co-Operation and Development, Nuclear Energy Agency - OECD/NEA, 46, quai Alphonse Le Gallo, 92100 Boulogne Billancourt (France), NEA--7207, 2021. Accessed: May 27, 2026. [Online]. Available: https://inis.iaea.org/records/99aha-qkc32
[11] Y. Yu, W. Feng, G. Liu, F. Niu, Y. Dong, and K. Yu, "Analysis of climatic conditions effect on passive containment cooling system reliability in AP1000 for multi-unit nuclear power plant site," *Progress in Nuclear Energy*, vol. 170, p. 105129, May 2024, doi: 10.1016/j.pnucene.2024.105129.
[12] J. Miller, S. Ercanbrack, and C. L. Pope, "Versatile Economic Risk Tool," *Nuclear Technology*, vol. 209, no. 11, pp. 1666–1679, Nov. 2023, doi: 10.1080/00295450.2022.2129273.
[13] I. S. Wing *et al.*, "A Method to estimate the economy-wide consequences of widespread, long duration electric power interruptions," *Nat Commun*, vol. 16, no. 1, p. 3335, Apr. 2025, doi: 10.1038/s41467-025-58537-4.
[14] D. Thomas and J. Fung, "Power Disturbances: An Examination of Short-Term Losses in the Downstream Supply Chain," in *AEA Conference*, Jan. 2023. Accessed: May 29, 2026. [Online]. Available: https://www.nist.gov/publications/power-disturbances-examination-short-term-losses-downstream-supply-chain
[15] D. Ai, C. L. Crago, and J. T. Mullins, "Heat, power outages, and mortality in the United States," *Journal of Environmental Economics and Management*, vol. 137, p. 103275, May 2026, doi: 10.1016/j.jeem.2025.103275.
[16] G. B. Anderson and M. L. Bell, "Lights out: impact of the August 2003 power outage on mortality in New York, NY," *Epidemiology*, vol. 23, no. 2, pp. 189–193, Mar. 2012, doi: 10.1097/EDE.0b013e318245c61c.
[17] J. Portugal-Pereira, M. Esteban, and K. Araújo, "Exposure of future nuclear energy infrastructure to climate change hazards: A review assessment," *Energy Strategy Reviews*, vol. 53, p. 101365, May 2024, doi: 10.1016/j.esr.2024.101365.
[18] L. Collet *et al.*, "Future nuclear power outages in a changing climate - A case study on two contrasted French power plants," *Energy*, vol. 320, p. 135207, Apr. 2025, doi: 10.1016/j.energy.2025.135207.
[19] "Hurricane Irma cut power to nearly two-thirds of Florida's electricity customers - U.S. Energy Information Administration (EIA)." Accessed: May 29, 2026. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=32992
[20] "U.S. nuclear plant outages increased in September after remaining low during summer - U.S. Energy Information Administration (EIA)." Accessed: May 29, 2026. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=37252
[21] "U.S. nuclear capacity outages were 35% higher in summer 2020 than 2019 - U.S. Energy Information Administration (EIA)." Accessed: May 29, 2026. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=45176
[22] "Climate Vulnerability Considerations for the Power Sector: Nuclear Generation Assets," Electric Power Research Institute, Palo Alto, CA, 3002026313 June 2023, 2023. [Online]. Available: https://restservice.epri.com/publicdownload/000000003002026313/0/Product
[23] A. K. Nayak, A. Chandrakar, and G. Vinod, "A Review: Passive System Reliability Analysis – Accomplishments and Unresolved Issues," *Front. Energy Res.*, vol. 2, Oct. 2014, doi: 10.3389/fenrg.2014.00040.

[24] A. J. Brunett, D. Grabaskas, M. Bucknor, and S. Passerini, “A Methodology for the Integration of Passive System Reliability With Success Criteria in a Probabilistic Framework for Advanced Reactors,” presented at the 2016 24th International Conference on Nuclear Engineering, American Society of Mechanical Engineers Digital Collection, Oct. 2016. doi: 10.1115/ICONE24-60749.
[25] *Probabilistic Risk Assessment Standard for Advanced Non Light Water Reactor Nuclear Power Plants - ASME*, ASME/ANS RA-S-1.4, 2021. Accessed: May 29, 2026. [Online]. Available: https://www.asme.org/codes-standards/find-codes-standards/probabilistic-risk-assessment-standard-for-advanced-non-light-water-reactor-nuclear-power-plants
[26] T. M. Coscia, F. Di Maio, G. Heo, and E. Zio, “Probabilistic safety assessment of nuclear power plants considering climate change,” *Reliability Engineering & System Safety*, vol. 265, p. 111590, Jan. 2026, doi: 10.1016/j.ress.2025.111590.
[27] T. Saito and M. Yoneyama, “Case Study: A Comparison of Generation Risk Assessment and Failure Modes and Effects Analysis Methodologies at TEPCO’s Nuclear Power Plants,” Electric Power Research Institute, TEPSYS, Tokyo, Japan, 1016461, Jun. 2008. [Online]. Available: https://restservice.epri.com/publicdownload/000000000001016461/0/Product
[28] S. Johnson and W. Walsh, “Small modular reactors and microreactors under development in the United States - U.S. Energy Information Administration (EIA),” Today in Energy. Accessed: Jun. 12, 2026. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=67584
[29] “US Advanced Reactors Under Development,” US Department of Energy, Factsheet DOE/NE-0149, Jan. 2020. [Online]. Available: https://www.energy.gov/documents/011620-advanced-reactor-types-factsheetpdf
[30] S. G. Lim, H. S. Nam, D. H. Lee, and S. W. Lee, “Design characteristics of nuclear steam supply system and passive safety system for Innovative Small Modular Reactor (i-SMR),” *Nuclear Engineering and Technology*, vol. 57, no. 10, p. 103697, Oct. 2025, doi: 10.1016/j.net.2025.103697.
[31] K. Welter, J. N. Reyes, and A. Brigantic, “Unique safety features and licensing requirements of the NuScale small modular reactor,” *Front. Energy Res.*, vol. 11, Apr. 2023, doi: 10.3389/fenrg.2023.1160150.
[32] S. Wang *et al.*, “A passive decay heat removal system for emergency draining tanks of molten salt reactors,” *Nuclear Engineering and Design*, vol. 341, pp. 423–431, Jan. 2019, doi: 10.1016/j.nucengdes.2018.11.021.
[33] M. Ilham, I. Kuncoro Aji, and T. Okawa, “Numerical investigation on the effects of fundamental design parameters on freeze plug performance in molten salt reactors,” *Nuclear Engineering and Design*, vol. 403, p. 112144, Mar. 2023, doi: 10.1016/j.nucengdes.2022.112144.
[34] D. Holcomb, R. Kisner, and S. Cetiner, “Instrumentation Framework for Molten Salt Reactors,” ORNL/TM-2018/868, 1462848, Jun. 2018. doi: 10.2172/1462848.
[35] A. Fakhraei, F. Faghihi, M. Amin-Mozafari, and A. Sadegh-Noedoost, “Safety analysis of an advanced passively-cooled small modular reactor during station blackout scenarios and normal operation with RELAP5/SCDAP,” *Annals of Nuclear Energy*, vol. 143, p. 107470, Aug. 2020, doi: 10.1016/j.anucene.2020.107470.
[36] G. Vaidyanathan, “Decay heat removal in sodium cooled fast Reactors-An overview,” *Annals of Nuclear Energy*, vol. 205, p. 110554, Sep. 2024, doi: 10.1016/j.anucene.2024.110554.
[37] J. Liang, D. Lu, J. Fu, H. Zhao, X. Luo, and Y. Zhang, “Three-dimensional numerical research on natural circulation characteristics of decay heat removal system in pool-type

fast reactor CEFR," *Nuclear Engineering and Design*, vol. 383, p. 111424, Nov. 2021, doi: 10.1016/j.nucengdes.2021.111424.
[38] C. Fang, R. Morris, and F. Li, "Safety Features of High Temperature Gas Cooled Reactor", doi: 10.1155/2017/9160971.
[39] B. Mays, L. Lommers, S. Yoder, and F. Shahrokhi, "Sensitivity of SC-HTGR Conduction Cooldown to Reactor Cavity Cooling System Failure," *Nuclear Technology*, vol. 208, no. 8, pp. 1311–1323, Aug. 2022, doi: 10.1080/00295450.2021.1947664.
[40] K. Takamatsu, T. Matsumoto, and K. Morita, "New reactor cavity cooling system (RCCS) with passive safety features: A comparative methodology between a real RCCS and a scaled-down heat-removal test facility," *Annals of Nuclear Energy*, vol. 96, pp. 137–147, Oct. 2016, doi: 10.1016/j.anucene.2016.05.012.
[41] X. Xu, Y. Ye, Y. Wu, and Y. Zheng, "Study on the Influence of Ambient Temperature and RPV Temperature on Operation Performance of HTR-PM Reactor Cavity Cooling System," *Journal of Nuclear Engineering*, vol. 6, no. 4, p. 48, Dec. 2025, doi: 10.3390/jne6040048.
[42] D. Petti, J. Kinsey, and D. Alberstein, "Modular High Temperature Gas-Cooled Reactor Safety Basis and Approach," INL/EXT--13-30872, 1149009, Jan. 2014. doi: 10.2172/1149009.
[43] C. W. Forsberg, P. F. Peterson, and P. S. Pickard, "Molten-Salt-Cooled Advanced High-Temperature Reactor for Production of Hydrogen and Electricity," *Nuclear Technology*, vol. 144, no. 3, pp. 289–302, Dec. 2003, doi: 10.13182/NT03-1.
[44] J. Lee, S.-S. Jeon, J.-Y. Park, and H. K. Cho, "Effect evaluation on performance issues of passive safety system– Part II. Passive emergency core cooling system," *Nuclear Engineering and Design*, vol. 411, p. 112446, Sep. 2023, doi: 10.1016/j.nucengdes.2023.112446.
[45] S. I. Attia, "The influence of condenser cooling water temperature on the thermal efficiency of a nuclear power plant," *Annals of Nuclear Energy*, vol. 80, pp. 371–378, Jun. 2015, doi: 10.1016/j.anucene.2015.02.023.
[46] Q. Liu and T. Homma, "Sensitivity analysis of a passive decay heat removal system under a post-loss of coolant accident condition," *Journal of Nuclear Science and Technology*, vol. 49, no. 9, pp. 897–909, Sep. 2012, doi: 10.1080/00223131.2012.712481.
[47] Y. Okano and H. Yamano, "Numerical simulations of forest fire propagation and smoke transport as an external hazard assessment methodology development for a nuclear power plant," *Mechanical Engineering Journal*, vol. 3, pp. 15–00592, Jan. 2016, doi: 10.1299/mej.15-00592.
[48] A. Ahmad, "Increase in frequency of nuclear power outages due to changing climate," *Nat Energy*, vol. 6, no. 7, pp. 755–762, Jul. 2021, doi: 10.1038/s41560-021-00849-y.
[49] K. K. Satpathy, "Effects of bio-fouling on the cooling water quality of a nuclear power plant," *Bulletin of Electrochemistry*, vol. 15, pp. p143-147, Mar. 1999.
[50] X. Liu, W. Meng, L. Lu, and J. Li, "Research on the Prevention and Control System of Jellyfish in Nuclear Power Plants Cooling Water System," Nov. 2022. doi: 10.1115/ICONE29-92507.