2026 International Nuclear Atlantic Conference - INAC 2026
Escola de Guerra Naval, Rio de Janeiro, RJ, August 24 - 28, 2026

Putting Nuclear Risk into Perspective: Comparing NuScale SMR Accident Metrics with Natural Disasters

E. Moraes[1], L. Kulay[2], M. S. Rocha[3] and E. E. S. Lora[4]

1. *eduardo.moraes@unifei.edu.br - Institute of Mechanical Engineering, Federal University of Itajubá (UNIFEI) - Brazil*
2. *luiz.kulay@usp.br - Department of Chemical Eng., Polytechnic School of the University of São Paulo - Brazil*
3. *msrocha@ipen.br - Nuclear Engineering Center (CEENG), Institute of Energy and Nuclear Research (IPEN)- Brazil*
4. *electo@unifei.edu.br - Institute of Mechanical Engineering, Federal University of Itajubá (UNIFEI) – Brazil*

1. Introduction

Nuclear safety has become a central criterion in the design and licensing of modern nuclear power plants, quantified through Probabilistic Risk Assessment (PRA) methodologies. For Small Modular Reactors (SMRs), particularly the NuScale VOYGR integral Pressurized Water Reactor (iPWR), probabilistic safety metrics indicate accident frequencies several orders of magnitude lower than those of conventional Generation II reactors.

However, public perception of nuclear risk frequently diverges from quantitative evidence, a phenomenon described in risk psychology as the social amplification of risk (Kasperson et al., 1988; Slovic, 1987), in which rare technological events are perceived as more threatening than frequent natural hazards with significantly larger societal impacts.

In parallel, the global energy transition increasingly demands reliable low-carbon baseload generation capable of complementing variable and intermittent renewable sources and supporting grid stability. In this context, SMRs have been identified in the literature as a potentially strategic technology for decarbonization and long-term energy systems security (IAEA, 2022; IEA, 2022).

Despite the extensive use of PRA in nuclear licensing and safety evaluation, quantitative comparisons between modern nuclear accident frequencies and the probabilities of natural hazards routinely accepted by society remain relatively uncommon in the technical literature. Such comparisons may provide a useful framework for contextualizing nuclear risk and supporting evidence-based risk communication, particularly in discussions involving advanced reactor technologies.

This paper presents a structured PRA framework applied to the NuScale 12-module VOYGR plant, compares probabilistic nuclear accident metrics with occurrence probabilities of selected extreme natural events, and discusses the implications of these comparisons for nuclear risk communication and the prospective role of SMRs in low-carbon energy systems and global warming mitigation strategies.

2. Methodology

The probabilistic framework adopted in this study is based on Probabilistic Risk Assessment (PRA), which is widely used by regulatory authorities and reactor vendors to quantify nuclear safety performance. PRA is traditionally organized into three hierarchical levels: (i) *Level 1* - evaluates the Core Damage Frequency (CDF), defined as the annual probability of fuel damage leading to core degradation or melt. (ii) *Level 2* - evaluates the probability of significant radioactive releases to the environment, commonly expressed as Large Release Frequency (LRF) or Large Early Release Frequency (LERF). (iii) *Level 3* - evaluates the potential off-site consequences of accident scenarios, including radiological doses, environmental contamination, economic losses, and societal impacts. For the NuScale design, however, the U.S. Nuclear Regulatory Commission (NRC) adopted LRF as the principal *Level 2* safety metric due to the comparatively small radioactive inventory associated with each reactor module Consequently, Level 2 metrics are considered sufficient to demonstrate compliance with the principal safety objectives for licensing purposes, while detailed Level 3 consequence analyses play a less prominent regulatory role (NuScale, 2020; USNRC, 2023)

Within this framework, total expected risk (R) can be obtained by integrating accident probabilities and associated consequences over all relevant accident scenarios (Equation 1):

$$R = \sum_i (P_i \times C_i) \quad (1)$$

where $P_i$is the probability of accident scenario (i) and $C_i$represents its associated consequence.

For multi-module reactor facilities such as the NuScale VOYGR 12-module plant, three complementary probabilistic metrics were considered. *Metric 1* corresponds directly to the certified per-

ISBN: 978-65-272-2398-6

module Core Damage Frequency (CDF), expressed in events per reactor-year, and represents the primary safety indicator reported by the NRC. *Metric 2* evaluates the probability distribution of independent core damage events occurring within the plant. Assuming statistical independence among modules for internal initiating events and neglecting common-cause failures, the occurrence of core damage events can be represented by a Poisson process (Equation 2):

$$P(k,t) = \frac{e^{-\lambda_p.t}.(\lambda_{p.}.t)^k}{k!} \quad (2)$$

where (k) is the number of core damage events within the considered time interval, (t) is the time interval (year), and (λ_p) is the aggregated mean occurrence rate for the plant, calculated as: $\lambda_p = N_m \times CDF$, where N_m*:* is the number of reactor modules in the plant. This general formulation allows the probability of exactly (k) events to be calculated directly, while cumulative conditions, such as "at least" - one event ($k \geq 1$), two events ($k \geq 2$), or (m) events ($k \geq m$), are derived from the complementary cumulative probability of the same Poisson distribution. Given the extremely low event frequencies associated with the evaluated SMR design, exact and cumulative probabilities are numerically indistinguishable for most practical purposes.

The *Metric 3* evaluates the probability of simultaneous core damage affecting multiple modules. For this purpose, a binomial formulation may be employed (3):

$$P(k,N) = C(N,k)\ .\ p^k.(1-p)^{N-k} \quad (3)$$

where (N) is the total number of modules and (p) is the probability of core damage for an individual module. This formulation provides a useful framework for evaluating hypothetical multi-module accident scenarios and common-cause events affecting more than one reactor unit. Although the binomial model assumes statistical independence among modules, the results may also provide a first-order approximation for assessing the potential implications of shared system failures or correlated external events capable of affecting multiple units simultaneously, such as large earthquakes, tsunamis, floods, or other extreme natural hazards.

The present study provides a broader societal perspective by comparing probabilistic indicators derived from nuclear safety assessments with occurrence probabilities of most common extreme natural hazards compiled from publicly available and scientifically recognized databases, including USGS, NOAA, UNESCO-IOC, and EM-DAT/CRED. Although nuclear accidents and natural hazards arise from different causal mechanisms and represent distinct risk constructs, their comparison on a common probabilistic scale provides a valuable framework for contextualizing relative event likelihoods. Such an approach contributes to a more balanced discussion and understanding of nuclear risk, and supports evidence-based risk communication regarding the role of advanced nuclear technology in low-carbon energy systems.

3. Results and Discussion

Table I summarizes representative PRA safety targets and accident frequencies reported for major reactor technologies developed over the last five decades, illustrating the substantial reduction in Core Damage Frequency (CDF) achieved through successive generations of reactor design. Generation II PWRs typically operated with CDF values in the range of 10^{-4}-10^{-5}reactor.year^{-1}, whereas passive Generation III+ reactors, including passive design such as the AP1000 and the active safety - based design EPR, achieved values of 10^{-6}-10^{-7}reacto,year^{-1}. Advanced SMRs, including the NuScale VOYGR, report CDF values between 10^{-8} and 10^{-10}reactor.year^{-1}, reflecting the increasing role of passive safety systems and integral primary circuit configurations in modern reactor concepts (USNRC, 2023; Skolik et al., 2021).

For the NuScale 12-module plant, the certified per-module CDF for internal events is approximately 3.3×10^{-10} reactor·year^{-1}. Applying Equation 2 with $\lambda_p = 12 \times 3.3\times10^{-10} \approx 3.96\times10^{-9}$, the probability "at least one" module experiences core damage within a one-year reference period is approximately 3.96×10^{-9}, which means recurrence for a plant level CDF event every 2,53 x 10^8 plant·years of operation. These safety performance levels are largely attributed to the integrated iPWR

ISBN: 978-65-272-2398-6

design, in which the reactor core, pressurizer, and steam generators are housed within a single reactor pressure vessel (RPV) submerged in a pool at atmospheric pressure. Combined with passive safety features based on natural circulation, gravity, and differential pressure, this configuration enables long-term core cooling under loss-of-power scenarios without reliance on operator actions, external power supplies, or active safety equipment.

Table I: Representative CDF and LRF/LERF values for major reactor technologies.

Reactor Type	CDF (1/year)	LRF/LERF (1/year)	Source
PWR Gen-II (1970–80)	10^{-4} - 10^{-5}	10^{-5} - 10^{-6}	USNRC (1975–1990)
Gen-III+ (AP1000, EPR)	10^{-6} - 10^{-7}	10^{-7} - 10^{-8}	Westinghouse FSAR (2011); EDF EPR (2012)
SMRs (NuScale, BWRX-300)	10^{-8} - 10^{-10}	10^{-9} - 10^{-11}	USNRC/IAEA PSA (2020–2023)
Gen-IV (Na, He)	10^{-7} - 10^{-9}	10^{-8} - 10^{-10}	GIF (2014); OECD-NEA (2015–2020)

The significance of these values becomes clearer when compared with the occurrence frequencies of selected natural hazards (Table II). A major hurricane (Category 4 -5) making landfall along the Florida coast carries an estimated annual probability on the order of 10^{-2} (NOAA, 2021), a value roughly seven orders of magnitude greater than the per-plant core damage probability estimated for the NuScale facility. Similarly, a magnitude-9.0 or greater earthquake in the United States or in Japan presents an annual probability on the order of 10^{-3}-10^{-4} (USGS NSHM, 2023; HERP,2020), remaining several orders of magnitude more frequent than the multi-module CDF calculated for the NuScale plant. Although these events differ substantially in nature and consequences, the comparison provides a useful perspective on the rarity of severe accident scenarios predicted for advanced SMR designs under current probabilistic safety assessment frameworks.

Table II: Annual probabilities of natural catastrophes and NuScale CDF metrics.

Event / Metric	Annual Probability	Source
Hurricane Cat 4-5 (Florida)	10^{-1} - 10^{-2}	NOAA (2021)
Earthquake Mw 9.0	10^{-3} - 10^{-4}	USGS NSHM (2023)
Tsunami ≥20 m	10^{-4}	NOAA/IOC (2018)
Tsunami ≥ 10m (Nankai-type scenarios)	10^{-2}	ERC (2025)
100-year flood (local)	10^{-2}	USGS (2010)
NuScale CDF - per module	3.3×10^{-10}	NuScale/USNRC (2023)
NuScale (12-module) CDF - per plant (any module)	3.96×10^{-9}	Aggregate mean occurrence rate

A simplified expected-risk calculation further illustrates this contrast. Using the Fukushima Daiichi accident, with approximately US$150 billion in estimated economic losses, as a reference consequence, and adopting the historical empirical core damage frequency for Generation II BWR Mark I reactors (approximately 7.6×10^{-4} reactor·year^{-1}), the expected annual financial risk for a single reactor is approximately US$ 114 million per plant-year, corresponding to undiscounted cumulative expecteded risk over a nominal 40-year operating life roughly to US$ 4,56 billion.

Nevertheless, the Fukushima accident was not driven by independent reactor failures but by a rare external common-cause event. The tsunami, initially estimated to have a recurrence interval on the order of 1,000 to 100,000 years, became the dominant risk contributor by simultaneously disabling key safety functions across multiple reactor units. Following Fukushima, hazard reassessments substantially revised the estimated occurrence frequencies of large subduction-zone earthquakes and tsunamis affecting the Japanese coast. Current estimates place the annual probability of such events in the range of approximately 4.5×10^{-2} to 5.6×10^{-2}, corresponding to mean recurrence intervals of roughly 18 to 22 years, a finding that fundamentally reframed the risk profile of coastal nuclear facilities in seismically active regions of Japan.

ISBN: 978-65-272-2398-6

Applying the same consequence value to the NuScale 12-module plant, a deliberately conservative assumption given the substantially smaller radioactive inventory per module, and combining it with the calculated per-plant CDF probability (3.96×10^{-9} plant·year^{-1}), the resulting expected annual financial risk is approximately US$ 594 per plant·year, or roughly US$ 35,640 over a nominal 60-year operating life. Under these assumptions, for an undiscounted cumulative estimate, the expected financial risk associated with the NuScale configuration is approximately five orders of magnitude lower than that estimated for historical Generation II reference systems, a reduction consistent with the several-decade advancement in passive safety design philosophy embodied in the iPWR concept.

The International Nuclear and Radiological Event Scale (INES) classifies nuclear events on a logarithmic scale ranging from 0 to 7. Only two events have reached the maximum Level 7 classification: Chernobyl (1986) and Fukushima Daiichi (2011). The majority of reported nuclear events worldwide remain within Levels 0–2 (IAEA,2023). This distribution reflects the effectiveness of modern defense-in-depth safety strategies and underscores the rarity of severe nuclear accidents.

The social amplification of risk framework (Kasperson et al., 1988) and psychometric studies (Slovic, 1987) help explain the persistent asymmetry between quantitative risk and public perception. Technological and involuntary hazards are often perceived as more threatening than familiar natural hazards, even when their probabilities are substantially lower. Millions of people voluntarily reside in hurricane-prone regions such as Florida, where the annual probability of a major hurricane landfall exceeds the probability of severe core damage in a NuScale plant by several orders of magnitude. This contrast illustrates the continuing gap between perceived and calculated risk and reinforces the importance of evidence-based nuclear risk communication.

4. Conclusions

This study demonstrates that the annual core damage probabilities associated with advanced SMR technology are substantially lower than the annual occurrence probabilities of major natural hazards affecting regions where large populations routinely live, work, and invest despite chronic exposure to such risks. The results provide a quantitative framework supporting evidence-based risk communication and may contribute to improved public understanding of nuclear risk perception, one of the principal challenges to the broader acceptance and expansion of nuclear energy worldwide.

In the extended context of climate change mitigation, these findings also contribute to the ongoing discussion on SMR deployment and its potential role in achieving deep decarbonization. As a source of reliable, low-carbon electricity, SMRs may complement renewable energy sources by supporting grid stability and long-term electricity supply, benefits that, taken together with the safety performance levels demonstrated here, reinforce the case for advanced nuclear technology as a component of sustainable energy transitions.

Acknowledgements

The first author gratefully acknowledges and expresses sincere thanks to Prof. Dr. Electo Eduardo Silva Lora, Prof. Dr. Marcelo da Silva Rocha and Prof. Dr. Luiz Kulay for their continuous scientific guidance, technical support, and valuable contributions to the development of this research.

References

This study includes 17 bibliographic references, which will be presented in the complete research paper.

[5] Kasperson, R. E. et al. "The Social Amplification of Risk: A Conceptual Framework," Risk Analysis, vol. 8, no. 2, pp. 177–187 (1988).

[7] NOAA. "Atlantic Hurricane Season Outlook," National Oceanic and Atmospheric Administration, Silver Spring, MD (2021).

[10] Ritchie, H. and Roser, M. "What Are the Safest Sources of Energy?" Our World in Data, https://ourworldindata.org/safest-sources-of-energy (2020).

[11] Skolik, K. et al. "Probabilistic Safety Assessment of Passive Safety Systems in the NuScale Integral Pressurized Water Reactor," Annals of Nuclear Energy, vol. 150, 107856 (2021).

[12] Slovic, P. "Perception of Risk," Science, vol. 236, pp. 280–285 (1987).

[13] UNDRR. "The Human Cost of Disasters: An Overview of the Last 20 Years (2000–2019)," United Nations Office for Disaster Risk Reduction, Geneva (2020).