frontiers | Frontiers in Nuclear Engineering

TYPE Specialty Grand Challenge
PUBLISHED 04 January 2024
DOI 10.3389/fnuen.2023.1346555

OPEN ACCESS

EDITED AND REVIEWED BY
Sergei Dudarev,
United Kingdom Atomic Energy
Authority, United Kingdom

*CORRESPONDENCE
Enrico Zio,
✉ enrico.zio@polimi.it

RECEIVED 29 November 2023
ACCEPTED 12 December 2023
PUBLISHED 04 January 2024

CITATION
Zio E (2024), Advancing nuclear safety.
Front. Nucl. Eng. 2:1346555.
doi: 10.3389/fnuen.2023.1346555

Advancing nuclear safety

Enrico Zio[1,2]*

[1]Centre de Recherche sur les Risques et les Crises, ParisTech École Nationale Supérieure des Mines de Paris, Université de Sciences Lettres de Paris, Sophia Antipolis, France, [2]Energy Department, Politecnico di Milano, Milan, Italy

KEYWORDS

nuclear safety, risk assessment, active and passive safety systems, integrated deterministic and probabilistic safety assessment (IDPSA), dynamic probabilistic safety assessment (DPSA), digital twin (DT), uncertainty and sensitivity analysis (UA and SA), climate change

Safety is a mandatory requirement for nuclear engineering applications in any industrial and medical fields, i.e., for the operation of nuclear power plants, nuclear medical and industrial devices, radioactive waste repositories, nuclear propellers, etc. Then, it is strategic for the development of nuclear engineering.

With a specific focus on nuclear facilities related to energy production, the present paper aims at providing perspectives on a number of issues and topics of safety, which are receiving attention from the researchers and practitioners.

Nuclear safety comprises all measures needed for nuclear facilities to be operated in normal conditions. Such measures aim at preventing accidents of technical, external and human (including malicious) origin, and mitigating the effects that any released radiation may have on the workers, the general public and the environment. For this, technical and organizational measures are put in place for all phases of the lifecycle of a nuclear facility, from design to manufacturing and construction, to operation and decommissioning.

In the current era of strong technological evolution and transition (e.g., energetic and digital), partly motivated by the concerns of climate change, new designs of fission-based nuclear power plants (Small Modular Reactors, SMRs, and Micro Reactors, MRs), and prototype fusion-based facilities for energy production are being put forward. Their licensing for deployment requires verification of the design objectives for operation and safety (Pioro, 2023). With regards to the latter, any new design for safety is expected to conform to the principles of defense in depth, which means it should contain: inherent safety features, passive safety features, specified procedural actions, actions of control systems, actions of safety systems, actions of complementary design features. In particular, passive safety systems are extensively used in most SMRs and MRs because of their simplicity and reliability. However, passive safety systems present some challenges with regards to the assessment of their reliability itself (Di Maio et al., 2021), like lack of data related to relevant functional phenomena, need to know performance under a wide range of conditions and difficult testability to verify the intended function that they must provide. This leads to a significant use of expert judgement and subjective assumptions in the reliability assessment of passive systems and the consequent need of identifying, modeling and propagating the associated uncertainties. This can be done by simulating numerous realizations of the system response under different operating conditions, within a functional failure-based approach based on the integration of Monte Carlo sampling and the mechanistic code of the system physical process, which however requires significant computational efforts. Thus, advanced sampling, empirical metamodelling (e.g., by Artificial Intelligence, AI), advanced sensitivity and uncertainty analyses need to be developed and validated, including efficient and sound Inverse Uncertainty Quantification (IUQ) analyses to find a characterization of the input parameters uncertainty that is consistent with the experimental data, while limiting the associated computational burden (Roma et al., 2022). Clearly, resorting to empirical, fast-computing metamodels for estimating passive systems failure probabilities and for carrying out uncertainty and sensitivity analyses can be very efficient computationally but requires that the regression error be carefully quantified (and possibly controlled), in order to reduce its impact on the quality of the final reliability assessment. Furthermore, the higher the input dimensionality (e.g., when dealing with time series data), the higher the size of the training dataset needed for accuracy, so that approaches to reduce the input dimensionality (e.g., Principal Component Analysis, PCA, or Stacked Sparse Autoencoders) should be applied.

Within the current scenario of nuclear power development, some practical and research issues arise as relevant opportunities and challenges for safety. From the point of view of classical safety assessment, areas of attention are.

- Active and Passive Safety Systems
- Deterministic Safety Assessment (DSA)
- Probabilistic Safety Assessment (PSA)
- Integrated Deterministic and Probabilistic Safety Assessment (IDPSA)
- Dynamic Probabilistic Safety Assessment (DPSA)
- Multi-Unit Risk Assessment and Risk Aggregation
- Multi-Hazard Risk Assessment and Risk Aggregation
- External Events Risk Assessment in the realm of Climate Change

For what concerns active and passive safety systems, it is important that their design and testing be advanced in a way to address hazards and vulnerabilities characteristic of the new reactors technological solutions, in terms of materials, components and systems therein adopted. For the passive systems (IAEA, 2009), in particular, also the effects of climate change on their functionality need to be considered in the expected time frame of operation (Sahlin et al., 2015; Vagnoli et al., 2018; https://utilitiesone.com/the-impact-of-climate-change-on-nuclear-power-plant-safety).

This requires also the advancement of deterministic and probabilistic safety assessment capabilities, to allow relaxing excessive conservatism for more realistic analysis (e.g., by Best Estimate Plus Uncertainty, BEPU methods; D'Auria, 2019; Sun et al., 2020), on one side, and verifying and validating (V&V) the quality of the methods used for the assessment, on the other side (Paul et al., 2016). These advancements should regard also the confirmation of the added value of integrated deterministic and probabilistic safety assessment (IDPSA, Zio, 2014; Di Maio et al., 2015; Heo et al., 2021) and dynamic probabilistic safety assessment (DPSA, Wiltbank and Palmer, 2021; Parhizkar et al., 2022), in certain cases and for certain scenarios to be definitely identified, and their final deployment based on the power of computational risk assessment (CRA, Sezen et al., 2019). Indeed, BEPU, IDPSA, DPSA and CRA are expected to contribute significantly to robust risk-informed decision making for nuclear safety in practice, by enabling the integrated consideration and treatment of the time-dependent interactions of the stochastic processes of hardware component failures, the deterministic responses of the system process, the effects of the control and operator actions, software and firmware. Yet, to bring these computational frameworks to industrial use requires further efforts to increase their efficiency for the generation of multiple scenarios of system behavior by combining advanced Monte Carlo simulation with AI metamodelling for guided design of experiment (DoE) and system response simulation. Also, transparent post-processing by clustering (e.g., by AI) of the multiple scenarios output is necessary for classification (e.g., by Machine Learning, ML) so as to render the results treatable and useable for risk-informed decision making. Finally, in very practical terms it is needed that the computational codes be user-friendly and easy to link with existing PSA/DSA codes.

Within the safety assessment of existing multi-units and future modular nuclear installations, two issues that are still open and, thus, deserving attention are multi-hazard and multi-unit risk assessment, for achieving a scientifically solid evaluation of the aggregated site risk (Yoo et al., 2021; Ming et al., 2022; Hochrainer-Stigler et al., 2023). This puts under the spotlight also the assessment of the risk contribution from external events, e.g., earthquakes and extreme meteorological events (also in relation to the climate change that is being experienced and which increases the relevance of the latter), and the resilience of nuclear power plants (Di Maio et al., 2022; 2023).

From another perspective, there are continuous advancements in sensor electronics for component and process state monitoring, AI analytics and machine learning ML algorithms for elaborating the monitored data, and computational power availability to fuel these elaborations (Zio, 2018). This exciting combination offers a stream of opportunities for advanced solutions of operation and maintenance of nuclear facilities, e.g., autonomous operation supported by digital twins (DTs) and data-driven condition-based or predictive maintenance (Coble et al., 2012; Hu et al., 2022; Zio, 2022; Kim et al., 2023; Kropaczek et al., 2023). Yet, the issues of the qualification and V&V of AI models and ML algorithms, which are typically black boxes, for their safe use is still very much open even if they were used "only" to assist the operators and decision makers, and not for autonomous operation (Huang et al., 2023). On one side, this calls for a proper treatment of the uncertainty in the predictions used in the decision making, e.g., by Bayesian neural networks and deep gaussian processes. On another side, the safety criticality of the application of AI models and ML algorithms in the nuclear field motivates research for improving the transparency and interpretability of the predictions so as to build trust on their use. Methods for injecting physical information in learning models and algorithms, *post hoc* sensitivity approaches and visualization techniques need to be further developed and used to provide interpretability from different perspectives, including explaining the learned input-output relation representations, explaining the individual outputs, explaining the way the output is obtained. Regarding digital twins, one challenge is the seamless integration of DTs with existing systems and processes. Ensuring that DTs can communicate and share data with existing systems and methods can be a complex task, as it may require the development of new interfaces and protocols. On the other hand, interoperability is one of the most promising features that DTs can offer. It is crucial to ensure that data is being shared effectively so that it can be used to support decision-making and control tasks to fully exploit this technology. Also, the role of operators and users in using and implementing DTs must be carefully considered.

Also, clearly the ongoing digitalization of the industry increases the attention to cybersecurity of nuclear installations (Kim et al., 2020). Indeed, cyber risk analysis of digitalized assets is still an immature field with unproven techniques due, in part, to the continuously changing threat environment. On the other hand, nuclear installations continue to digitalize and, thus, it becomes increasingly important to have techniques of analysis whose outcomes can support risk management decisions for implementation of prioritized security controls to prevent and mitigate cyber risk within the unique constraints of the nuclear industry (Ayodeji et al., 2023).

Given the critical role that safety plays for the development of nuclear power to the benefit of sustainable progress, the expectation is to develop significant advances, both in theory and in practice, in the areas discussed above.

Author contributions

EZ: Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

References

Ayodeji, A., Mohamed, M., Li, Li, Di Buono, A., Pierce, I., and Ahmed, H. (2023). Cyber security in the nuclear industry: a closer look at digital control systems, networks and human factors. *Prog. Nucl. Energy* 161, 104738. ISSN 0149-1970. doi:10.1016/j.pnucene.2023.104738

Coble, J. B., Ramuhalli, P., Bond, L. J., Hines, W., and Upadhyaya, B. (J. (2012). *Prognostics and health management in nuclear power plants: a review of technologies and applications (PNNL–21515)*. United States.

D'Auria, F. (2019). Best estimate Plus uncertainty (BEPU): status and perspectives. *Nucl. Eng. Des.* 352, 110190. ISSN 0029-5493. doi:10.1016/j.nucengdes.2019.110190

Di Maio, F., Bani, L., and Zio, E. (2023). Seismic resilience assessment of small modular reactors by a three-loop Monte Carlo simulation. *Nucl. Eng. Des.* 410, 112385. ISSN 0029-5493. doi:10.1016/j.nucengdes.2023.112385

Di Maio, F., Pedroni, N., Tóth, B., Burgazzi, L., and Zio, E. (2021). Reliability assessment of passive safety systems for nuclear energy applications: state-of-the-art and open issues. *Energies* 14, 4688. doi:10.3390/en14154688

Di Maio, F., and Zio, E. (2022). The role of nuclear small modular reactors for the resilience of integrated energy systems. *Findings*. doi:10.32866/001c.37211

Di Maio, F., Zio, E., Smith, C., and Rychkov, V. (2015). Integrated deterministic and probabilistic safety analysis for safety assessment of nuclear power plants. *Sci. Technol. Nucl. Installations* 2015, 1–2. Article ID 136940. doi:10.1155/2015/136940

Han, R., Li, P., and Shi, Z. (2022). "Implementation strategy of predictive maintenance in nuclear power plant," in 2022 Prognostics and Health Management Conference (PHM-2022 London), London, UK, May 27-29, 2022, 143–146.

Heo, G., Baek, S., Kwon, D., Kim, H., and Park, J. (2021). Recent research towards integrated deterministic-probabilistic safety assessment in Korea. *Nucl. Eng. Technol.* 53 (11), 3465–3473. ISSN 1738-5733. doi:10.1016/j.net.2021.05.015

Hochrainer-Stigler, S., Trogrlić, R. Š., Reiter, K., Ward, P. J., Marleen, C. de R., Duncan, M. J., et al. (2023). Toward a framework for systemic multi-hazard and multi-risk assessment and management. *iScience* 26 (5), 106736. ISSN 2589-0042. doi:10.1016/j.isci.2023.106736

Hu, Y., Miao, X., Si, Y., Pan, E., and Zio, E. (2022). Prognostics and health management: a review from the perspectives of design, development and decision. *Reliab. Eng. Syst. Saf.* 217, 108063. ISSN 0951-8320. doi:10.1016/j.ress.2021.108063

Huang, Q., Peng, S., Deng, J., Zeng, H., Zhang, Z., Liu, Yu, et al. (2023). A review of the application of artificial intelligence to nuclear reactors: where we are and what's next. *Heliyon* 9 (3), e13883. ISSN 2405-8440. doi:10.1016/j.heliyon.2023.e13883

IAEA (2009). *Passive safety systems and natural circulation in water cooled nuclear power plants*. IAEA-TECDOC-1624.

Kim, J., Lee, S., and Seong, P. H. (2023). *Autonomous nuclear power plants with artificial intelligence*. ISBN 978-3-031-22385-3. doi:10.1007/978-3-031-22386-0

Kim, S., Heo, G., Zio, E., Shin, J., and Song, J. g. (2020). Cyber attack taxonomy for digital environment in nuclear power plants. *Nucl. Eng. Technol.* 52 (5), 995–1001. doi:10.1016/j.net.2019.11.001

Kropaczek, D. J., Badalassi, V., Jain, P. K., Ramuhalli, P., and Pointer, W. D. (2023). "Digital twins for nuclear power plants and facilities," in *The digital twin*. Editors N. Crespi, A. T. Drobot, and R. Minerva (Cham: Springer). doi:10.1007/978-3-031-21343-4_31

Ming, X., Liang, Q., Dawson, R., Xia, X., and Hou, J. (2022). A quantitative multi-hazard risk assessment framework for compound flooding considering hazard inter-dependencies and interactions. *J. Hydrology* 607, 127477. 127477, ISSN 0022-1694. doi:10.1016/j.jhydrol.2022.127477

Parhizkar, T., Utne, I. B., and Vinnem, J. E. (2022). "Dynamic probabilistic risk assessment," in *Online probabilistic risk assessment of complex marine systems* (Cham: Springer). Springer Series in Reliability Engineering. doi:10.1007/978-3-030-88098-9_2

Paul, S., Lamb, R., Panzeri, M., Bowman, H., Hall, J., Horritt, M., et al. (2016). "Believe it or not? The challenge of validating large scale probabilistic risk models," in 3rd European Conference on Flood Risk Management (FLOODrisk 2016), Volume 7, Lyon, France, 17-21 October 2016. Article Number 11004. doi:10.1051/e3sconf/20160711004

Pioro, I. L. (2023). "Handbook of generation IV nuclear reactors," *Woodhead publishing series in energy*. 2 (Swanson, United Kingdom: Woodhead Publishing). Page iv, ISBN 9780128205884. doi:10.1016/B978-0-12-820588-4.09996-5

Roma, G., Antonello, F., Di Maio, F., Nicola, P., Zio, E., Bersano, A., et al. (2022). Passive safety systems analysis: a novel approach for inverse uncertainty quantification based on Stacked Sparse Autoencoders and Kriging metamodeling. *Prog. Nucl. Energy* 148, 104209. ISSN 0149-1970. doi:10.1016/j.pnucene.2022.104209

Sahlin, U., Di Maio, F., Vagnoli, M., and Zio, E. (2015). *Evaluating the impact of climate change on the risk assessment of Nuclear Power Plants*. doi:10.1201/b19094-342

Sezen, H., Hur, J., Smith, C., Aldemir, T., and Denning, R. (2019). A computational risk assessment approach to the integration of seismic and flooding hazards with internal hazards. *Nucl. Eng. Des.* 355, 110341. ISSN 0029-5493. doi:10.1016/j.nucengdes.2019.110341

Sun, D., Zhang, Z., Li, X., Li, L., Wang, H., Xu, A., et al. (2020). An improved best estimate Plus uncertainty method for small-break loss-of-coolant accident in pressurized water reactor. *Front. Energy Res.* 8, 188. doi:10.3389/fenrg.2020.00188

Vagnoli, M., Di Maio, F., and Zio, E. (2018). Ensembles of climate change models for risk assessment of nuclear power plants. *Proc. Institution Mech. Eng. Part O J. Risk Reliab.* 232 (2), 185–200. doi:10.1177/1748006X17734946

Wiltbank Nathan, E., and Palmer Camille, J. (2021). Dynamic PRA prospects for the nuclear industry. *Front. Energy Res.* 9. ISSN 2296-598X. doi:10.3389/fenrg.2021.750453

Yoo, H., Jin, K., and Heo, G. (2021). Study of combinations of site operating states for multi-unit PSA. *Nucl. Eng. Technol.* 53 (10), 3247–3255. doi:10.1016/j.net.2021.04.016

Zhao, X., Kim, J., Warns, K., Wang, X., Ramuhalli, P., Cetiner, S., et al. (2021). Prognostics and health management in nuclear power plants: an updated method-centric review with special focus on data-driven methods. *Front. Energy Res.* 9, 9–2021. doi:10.3389/fenrg.2021.696785

Zheng, X., Tamaki, H., Sugiyama, T., and Maruyama, Yu (2022). Dynamic probabilistic risk assessment of nuclear power plants using multi-fidelity simulations. *Reliab. Eng. Syst. Saf.* 223, 108503. ISSN 0951-8320. doi:10.1016/j.ress.2022.108503

Zio, E. (2014). Integrated deterministic and probabilistic safety assessment: concepts, challenges, research directions. *Nucl. Eng. Des.* 280, 413–419. ISSN 0029-5493. doi:10.1016/j.nucengdes.2014.09.004

Zio, E. (2018). The future of risk assessment. *Reliab. Eng. Syst. Saf.* 177, 176–190. ISSN 0951-8320. doi:10.1016/j.ress.2018.04.020

Zio, E. (2022). Prognostics and Health Management (PHM): where are we and where do we (need to) go in theory and practice. *Reliab. Eng. Syst. Saf. Part A* 218, 108119. ISSN 0951-8320. doi:10.1016/j.ress.2021.108119