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CHALLENGES IN DEVELOPING A RISK-INFORMED DECISION-MAKING FRAMEWORK TO ADDRESS THE IMPACTS OF EVOLVING CONDITIONS ON ADVANCED NUCLEAR FACILITIES

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INTRODUCTION

Advanced reactor technologies are expected to reduce construction timelines, increase efficiencies, reduce upfront capital and ongoing operating costs, and employ safety-enhancing technologies (DOE, n.d.; IAEA, 2021). Nonetheless, advanced reactor facilities will continue to be exposed to various natural hazards that may affect plant operations or safety, including hydrological and meteorological hazards that may evolve over time. Potential effects may range from an increase in the frequency or characteristics of hazard events (e.g., hurricanes, heavy precipitation), the severity of hazard impacts (e.g., due to sea-level rise), and the duration of adverse conditions (e.g., drought, low water levels, long duration high-/low-temperature events) (US EPA, 2021).

The U.S. Nuclear Regulatory Commission (NRC) defines risk-informed decision-making (RIDM) as a "philosophy whereby risk insights are considered together with other factors to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety" (Gavrilas et al., 2021). Risk-informed approaches lie between the "risk-based" and "purely deterministic" (U.S. NRC, 1999). RIDM provides a structured approach to balance the costs and benefits of risk mitigation, and the nuclear industry has embraced risk-informed approaches and decision-making (U.S. NRC, 2023) as a means of using risk information to complement traditional deterministic, rule-based approaches to safety.

This study investigates the challenges of developing a framework for leveraging probabilistic risk assessment (PRA) and RIDM, considering non-stationary atmospheric and oceanic characteristics and the emerging technologies of advanced nuclear power facilities. The atmospheric and oceanic conditions that drive severe weather are uncertain and evolving, with different technical interpretations regarding potential future scenarios.

In this paper, we discuss the challenges in identifying the effects of long-term shifts in hydrometeorological processes on nuclear power facilities and characterizing the uncertainty and risks associated with natural hazards such as drought, wildfire, flooding, and tropical cyclones (TCs) (U.S. GAO, 2024). We also discuss the main challenges in developing a PRA framework that arise from new technologies, operational models, and policies. Finally, we discuss methods that can be used to address challenges in both categories (evolving climate conditions and advanced reactors) and the interaction between them. These discussions leverage and expand upon previous work (as referenced throughout) and the ongoing work of regulators and other organizations. This paper and the associated presentation intend to seek feedback from the broader PRA community regarding these challenges and to use insights to inform future research activities.

CHALLENGES IN DEVELOPING A RIDM FRAMEWORK

The RIDM process heavily depends on the risk metrics and insights developed through PRA. In this section, we discuss uncertainties associated with the evolving climate conditions and the characteristics of future nuclear power facilities that pose challenges to developing a robust PRA framework and, in turn, could limit the robustness and reliability of decisions made with the RIDM process.

Addressing Non-Stationary Hydrometeorological Processes in RIDM

There is considerable uncertainty about how non-stationary hydrometeorological processes will influence natural hazards, which makes it challenging to identify and incorporate their potential effects into the PRA framework for nuclear power plants (NPPs).

Emissions scenarios such as representative concentration pathways (RCPs) are developed to understand possible future emissions of greenhouse gases, which are widely considered the main cause of global warming in the past few decades (Van Vuuren et al., 2011). These scenarios are inherently uncertain and influenced by policy, demography, economy, geopolitics, and technology, making it challenging to assign probabilities to the likelihood of different RCPs. However, to develop a robust RIDM framework, it is important to incorporate each scenario's likelihood. Official documents that describe RCPs typically do not provide quantitative probabilities for each scenario; instead, they use terms such as "likely" or "unlikely" to describe possibilities. In recent years, a few studies have proposed methods to assign probabilities to these scenarios (Huard et al., 2022). However, some of these studies have methodological limitations, such as sampling errors, insufficient simulation runs, and inconsistent models, which may affect the reliability of their results (Huard et al., 2022).

Further difficulty arises when assessing how RCP scenarios may influence natural hazard characteristics. For example, there is uncertainty about how climate change will affect the frequency and characteristics of TCs and hurricanes, such as central pressure (an indicator of TC intensity), radius to maximum wind speed (an indicator of TC size), maximum wind speed, forward speed, genesis point, and track. Multiple studies have investigated the potential changes in these factors for TCs (Bloemendaal et al., 2022; Patricola & Wehner, 2018; T. R. Knutson et al., 2013; Xi & Lin, 2021; Kang & Elsner, 2015; Gori et al., 2022; Jewson, 2023; Xi et al., 2024; T. Knutson et al., 2020), highlighting uncertainties and inconsistencies when using climate projections to model future TC characteristics. Most studies have focused on intensity and frequency. Few studies have explored other TC characteristics or how statistical relationships between TC characteristics will evolve. These other characteristics and statistical relationships provide key information for probabilistic characterizations for TC-induced hazards. For instance, a stronger TC may produce more intense wind hazards and pressure differentials. However, historical data suggest that stronger TCs tend to be smaller. As a result, it is unclear whether a shift towards stronger storms will increase or decrease the frequency of severe TC hazards for NPPs located in coastal areas.

Despite uncertainty in atmospheric phenomena, the effects of factors such as changes in baseline coastal water levels and coastal erosion are known to exacerbate the impacts of TCs. Nonetheless, further research is needed to understand strategies to probabilistically model these effects and integrate them with TC-induced coastal hazards. For example, existing studies provide varying estimates regarding the magnitudes of longer-term oceanic water level increases due to differences in assumptions, models, and emission scenarios (Grandey et al., 2024). Research is also needed to define better strategies to accurately model local water level effects, which are influenced by uncertain phenomena in coastal areas, such as subsidence, uplift, coastal erosion, and the impact of melting ice, and can vary significantly across different regions.

Non-stationary hydrometeorological processes might alter the likelihood of combined/compound hazards. The challenge of considering compound/combined hazard effects in PRA is neither new nor unique to advanced reactors, and it is generally recognized that a combination of hazards can have a more adverse impact on plant safety compared to one hazard (Brinkman et al., 2022). In addition, advanced reactors could add new aspects to the challenges associated with combined hazards, such as those that may arise due to new siting and operational conditions (Gurpinar & Johnson, 2024).

Challenges in Applying a RIDM Framework for Advanced Nuclear Power Facilities

The new technologies used in advanced reactors have substantial performance advantages, but that can make developing and applying the RIDM framework challenging. Some of these challenges are:

- **Limited data and operational experience**: Developing robust PRAs depends on having high-quality data from operational experience and failures. The newly designed systems lack operating experience, which leads to data sparsity, limiting the data available to inform PRA.
- **Evolving design and technologies:** The design and technologies of advanced reactors evolve rapidly, including system configurations, dependencies, and classifications. It is challenging to develop a PRA that is robust to changes in design and can be updated easily to reflect design iterations (Zhang et al., 2024). Regulatory process uncertainties further compound the impacts of design uncertainties.
- **New operational models:** New operational models increasingly rely on autonomous systems and may offer capabilities for remote operations. Relying on automated operational models is expected to reduce the likelihood of human failure events but could introduce new failure modes. Moreover, the need to understand human-system interactions persists (Ramos & Mosleh, 2021). Research gaps exist related to identifying and correctly incorporating failure modes associated with using autonomous systems and human-system interactions into PRA.
- **New siting criteria for advanced reactors:** There is a new paradigm in choosing locations for sites of new advanced reactors. Reflecting the enhanced safety profile of advanced reactors, the sites might be closer to population centers. They may also be built on sites exposed to higher-intensity natural hazards than those previously used for large light water reactor sites, including previous industrial and fossil fuel facility sites (Belles et al., 2019). Also, portable reactors and microreactors could be employed in locations that may increase their exposure to certain natural hazards (U.S. NRC, n.d.).
- **Interaction between external hazards and advanced reactors:** The interactions between natural hazards and the structures, systems, and components (SSCs) might differ significantly from those in conventional reactors. For instance, using the passive system in advanced reactors decreases the reliance on offsite power, making a loss of offsite power due to natural hazards less significant for NPPs. However, passive systems rely on weak driving forces like gravity, pressure differences, and natural circulation, which might be more vulnerable to external hazards (Burgazzi, 2009).

STATIONARY RIDM FRAMEWORKS AND RISK METRICS

Current regulatory approaches are based on stationary metrics that are calculated under the assumption of stationary hazard frequency (typically based on historical data) (Caruso et al., 1999; U.S. Nuclear Regulatory Commission, 2002). One of the primary principles of RIDM, based on NRC guidance, is that "when proposed changes result in an increase in core damage frequency (CDF) and/or risk, the increases should be small and consistent with the intent of the Commission's Safety Goal Policy Statement (U.S. Nuclear Regulatory Commission, 2002)." Accordingly, the changes in CDF and large early release frequency (LERF) as surrogates to the quantitative health objectives (QHOs) of NRC's Safety Goals are evaluated against established thresholds to make decisions on whether the proposed changes are acceptable. Beyond risk metrics, risk importance measures (e.g., Fussell-Vesely, risk reduction worth, risk achievement worth) help to identify safety-significant SSCs and provide insight into how changes could alter the result of PRA (CDF or LERF).

There are shortcomings associated with these RIDM metrics when used to assess risks related to non-stationary hydrometeorological processes. CDF, LERF, and risk importance metrics calculated using a static and stationary PRA do not account for changes in hazard frequency or intensity over time, which might lead to an underestimation of long-term risks to NPPs. For example, the relative risk contributions of SSCs may change/evolve with changes in natural hazard frequencies, intensities, or other characteristics of the hazards, such as duration of impacts. Some component failures might be quantified as low-risk under current conditions and knowledge but may become safety-significant in the future. This is particularly relevant when external hazards contribute significantly to the overall risk profile of NPPs and can influence the dominant accident sequences. The changes in natural hazard characterization may shift these dominant sequences over time. Moreover, an evolving climate may increase the likelihood of simultaneous failure of multiple components (i.e., common cause failures) due to the higher stress it might pose on NPPs.

ADDRESSING NON-STATIONARITIES IN RIDM

This section discusses several potential strategies for addressing non-stationarities within RIDM, some of which are being considered by regulators and international organizations. These strategies are discussed in the context of this conference paper to elicit discussions and insights from conference participants.

Development of Time-dependent Risk Measures

A straightforward approach to address non-stationarities is to recompute risk metrics and importance measures considering a single representation of the evolution of future hazards (e.g., calculating yearly CDF and LERF under a given scenario). This provides point-in-time estimates that can inform decision-making. However, the estimates are highly uncertain. Moreover, the trade-offs between current benefits and future risks are not explicitly considered: Should we not construct NPPs today because the (highly uncertain) risk in 50 years will be too high?

A more complex approach involves constructing time-varying or cumulative risk metrics, explicitly integrating over uncertainties in time. This provides a more robust option, but it is computationally challenging and may be difficult to interpret and use as input to RIDM under established criteria.

Deterministic Scenario-based Approaches

Alternatively, by using scenario-based approaches, it is possible to assess the risk posed by multiple potential climate scenarios (e.g., RCPs) and mitigation scenarios (e.g., construction of protective barriers of varying configurations) and evaluate the safety of SSCs. A primary limitation of this approach is its reliance on a limited set of predefined scenarios, which may not fully capture rare but high-consequence events, especially considering that climate change is a developing and non-stationary phenomenon that may not be fully or accurately represented in the developed scenarios. Conversely, scenarios may be designed that are overly conservative. Specifically, while scenario-based deterministic approaches can address conservative design criteria, they are not as probabilistically robust or informative as the PRA methods (IAEA, 2024). This can be costly and may lead to inefficient use of resources (Chen, 2000).

Adaptive Engineering Approaches

Across multiple sectors, a promoted strategy to address non-stationary changes is adaptive design. In this approach, the capacity to modify/alter SSCs is incorporated into the facility design (e.g., adjustable protection systems or components that can be moved or upgraded). The concept of adaptive design is tied to the idea of iterative risk management, which could include actively monitoring the changes in hydrometeorological processes, updating the input data for PRA, rerunning the PRA incorporating the input changes, and changing/modifying plant design if found necessary (National Research Council, 2011).

The adaptive design approach would require tracking how external hazard characterizations shift over time and having criteria in place to identify when physical or administrative changes are needed. In the U.S., NRC has the POANHI framework for systematically monitoring new information on natural hazards to determine whether it is safety significant (U.S. NRC, 2024). Non-U.S. plants are often required to perform periodic (typically 10-year) safety reviews (PSRs) (IAEA, 2003). These frameworks can potentially be used to track changes in natural hazards and gather insight into the safety significance of non-stationary evolving climate for NPPs over time.

The adaptive design approach is potentially effective for addressing deep uncertainty associated with non-stationary changes due to its capability to implement alterations if supported by the data; however, it requires "upfront" effort in which the potential for adaptive change is considered and implemented in the design and construction phase. Thus, this solution might not be effective for the existing fleet of NPPs or plants in advanced design stages, given structural and (potentially) regulatory constraints.

Alternative Decision-Making Paradigms

Challenges related to adaptation and mitigation of the effects of climate change are being tackled across many sectors outside the nuclear industry (Curran et al., 2024; V. A. Marchau et al., 2019; Stanton & Roelich, 2021; Tolk, 2022). For example, Dittrich et al., (2016) surveyed decision-making approaches, recognizing that many standard approaches (e.g., cost-benefit and multi-criteria analysis), which often require known probabilities and defined outcomes, are challenging to apply under the substantial uncertainties associated with the magnitude and effects of a changing climate. These conventional frameworks may not be well-suited to the low-probability, high-consequence-focused safety assessments performed for nuclear power facilities. However, they may provide useful structures for operational continuity and reliability assessments (i.e., assessments focused on continuity of operations to provide electricity rather than safety-related decisions).

Alternatives to the conventional approaches have been proposed. For example, robust decision-making (RDM) focuses on decision-making under deep uncertainty, linked to the concept of minimizing regret, which could potentially be adapted to focus on severe safety outcomes (Groves et al., 2019). Other strategies that look at balancing trade-offs (e.g., real option analysis) may be useful for general applications that are financially motivated but perhaps less useful in low-probability, high-consequence contexts focused on safety. However, these decision structures could help understand the financial trade-offs in building adaptive capacity at the design phase (i.e., is it worth investing in putting in adaptive features not to avoid future shutdowns?).

SUMMARY AND CONCLUSION

This paper discusses challenges to understanding the risks a non-stationary evolving climate may pose to plant safety while also recognizing that building future energy infrastructure should not be discouraged due to deeply uncertain long-term projections. This study aims to provide potential solutions that support the sustainable development of NPPs by identifying, reviewing, and discussing strategies to address deep uncertainties.

We first discussed uncertainties arising from evolving hydrometeorological hazards. Studies have demonstrated increased baseline water levels in certain coastal areas in the U.S. (Sweet et al., 2017). Other studies suggest that the frequency of TCs will decline in general, but their projected intensity will increase (T. Knutson et al., 2020). Nonetheless, additional research is needed to understand the implications of these changes on site-level hazards.

We also reviewed current RIDM practices in NPPs and identified potential challenges in incorporating the influence of non-stationary climate conditions on external hazards. Then, we provided possible solutions that could be incorporated into the RIDM framework. We also discussed alternative decision-making processes and their merits and limitations compared to RIDM.

As the next step in this study, we will use a case study to show how the impacts of evolving climate conditions can be adequately and accurately incorporated into a RIDM framework. Research efforts will use insights gleaned from engagement with the PRA community as a result of this paper/presentation and other activities.

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