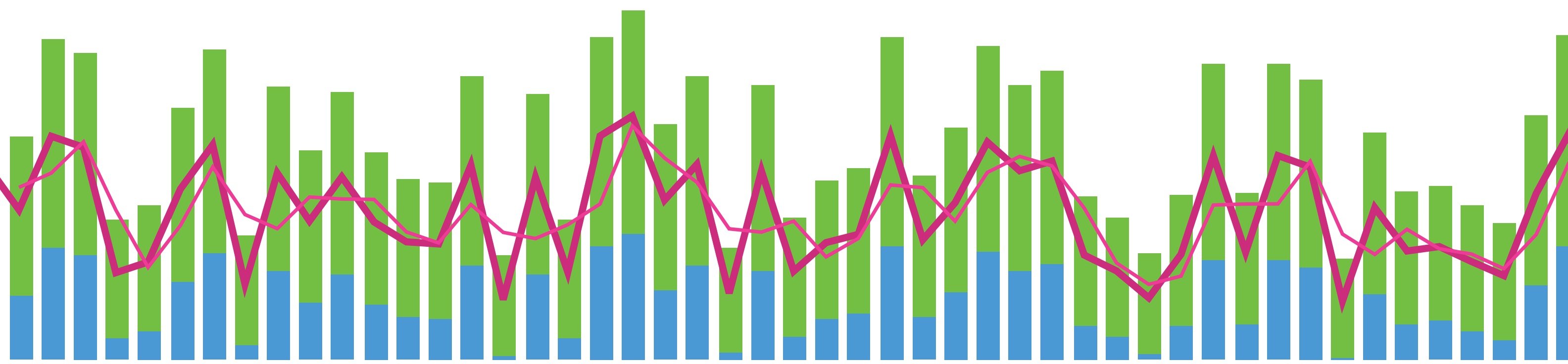
HELPING TO SOLVE THE

PUZZLE:

AN OVERVIEW OF

PROBABILISTIC RISK ASSESSMENT



By Curtis Smith, Andrew Miller, Stephen Hess, and Fernando Ferrante

Probabilistic risk assessments (PRAs) have advanced the safe operation of the U.S. reactor fleet over many decades. Risk insights from PRAs have provided information from many different perspectives, from what is most important to maintain at a facility to a better understanding of how to address new information regarding safety issues. The methods and tools that have supported the creation and enhancement of PRA models were established through multiple decades of research, starting with WASH-1400, *The Reactor Safety Study*,[1] published in 1975, through the comprehensive plant-specific models in use today.

The use of PRA technology has been a critical element in achieving demonstrable improvements in plant safety over time. A recent study[2] by the Nuclear Energy Institute analyzed data from the updates of plant PRA models showing a significant reduction in the average core damage frequency over the previous 30 years of operations. It is notable that these improvements in safety occurred over a time in which the average plant capacity factor increased from about 70 percent to over 90 percent. Further, the risk focus using PRA is an instrumental part of the risk-informed regulatory framework used throughout multiple applications in the United States, including the following:

- Maintenance Rule programs, including plant configuration risk management programs for conducting on line maintenance activities.
- Plant licensing basis changes using a risk-informed approach.
- Ensuring overall baseline plant safety via risk assessment.
- Fire protection programs.
- Risk-managed technical specifications, including completion time and surveillance frequency control programs.
- Programs allowing for alternative regulatory treatments for structures, systems, and components that use a risk-informed categorization process.

Because PRA models are being used to support such a wide array of plant decisions, they are now being applied to analyze an increasing number and diverse set of aspects of the plant, which is well beyond the initial intent envisioned in the 1970s. These demands on PRA methods and tools have led to challenges in further expanding the use of PRAs and have raised the potential for future research into how to address these challenges to ensure continued nuclear safety. In addition to the PRA needs, the domain of computer science has led to advances in computational approaches that may serve to help nuclear power plant PRA applications. These newer technologies have great potential to improve the effectiveness and economics of PRA and are being explored for their potential benefits to the PRA and nuclear power communities.

1. nrc.gov/docs/ML1622/ML16225A002.pdf
2. nei.org/resources/reports-briefs/performance-safety

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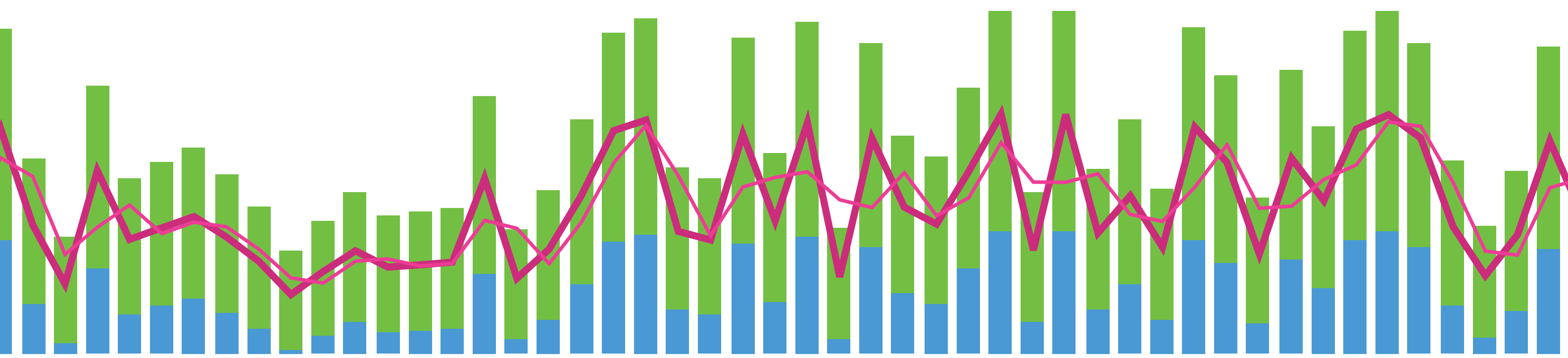
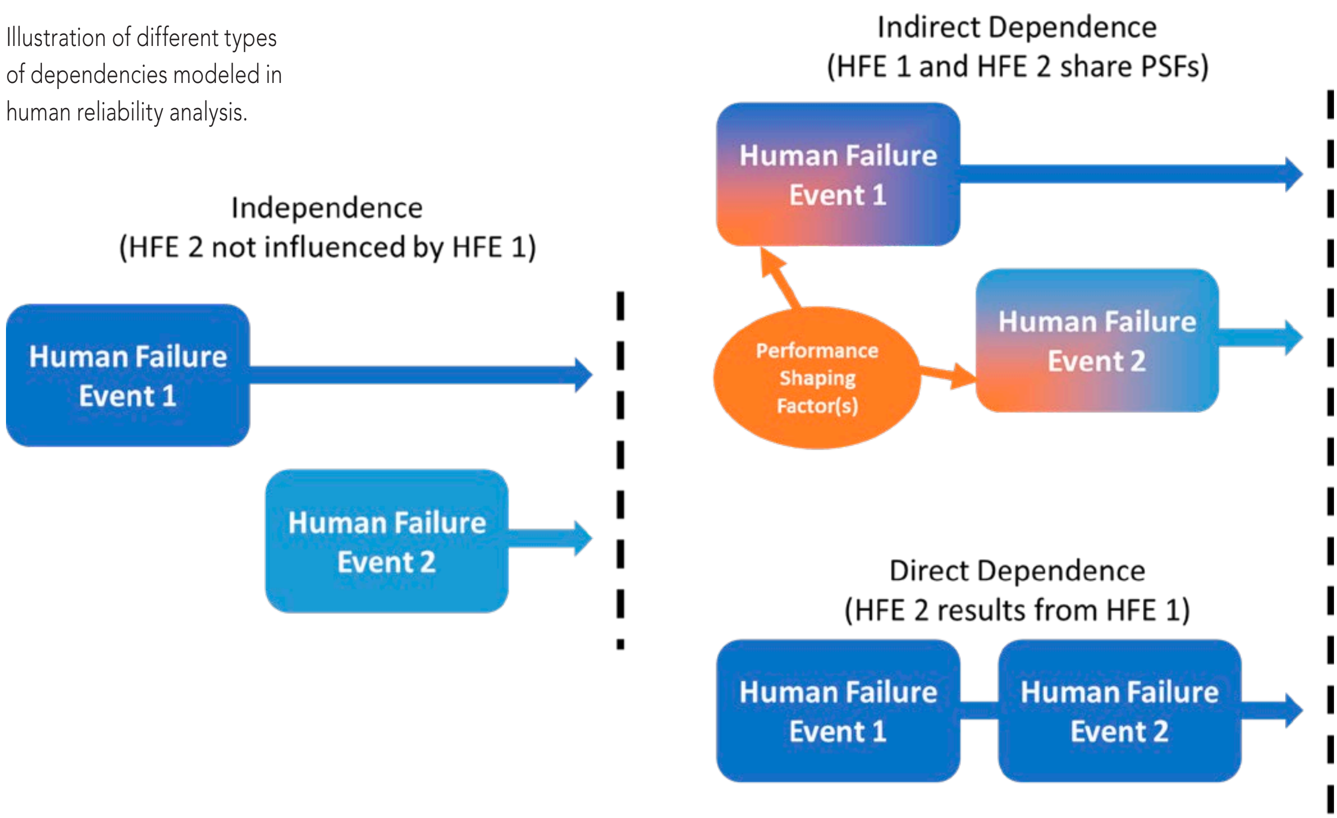


CHALLENGES IN EXPANDING RISK ASSESSMENT AND MANAGEMENT TOOLS

Efforts have been made to reach out to a spectrum of industry PRA users to identify potential issues with the current PRA methods and tools. The intent was to determine which issues were most significant with respect to supporting timely and efficient risk-informed decision-making. Based on the feedback, several challenges were identified that could prevent the further use of risk insights from PRA models based on current PRA practices:

- **Quantification speed and efficiency.** One of the most cited issues was the fact that current PRA software methods and tools take hours to solve for many models. This stems from the increased complexity and details of the models, requiring greater computing power and memory. An example of this issue is the time required for fire PRA models, which can be as long as several days for quantification. Enhancements to the time it takes to solve PRA models has been a continuing issue over the past two decades, and further improvements are needed.
- **Dependency analysis.** Another frequently mentioned issue is related to how dependency is represented for human reliability analysis. Typically, in PRA models, multiple human actions may exist in a single scenario representing core damage. However, dependencies may exist between these events, such as the same crew performing multiple actions, or the time needed to perform actions being shared across different activities. The current practice is to create complex relationships in the PRA model to look for these dependencies and then modify the results as needed. Not only are these dependency models complex and difficult to understand, they slow down the analysis, increasing the overall quantification time.
- **Model development, maintenance, and updates.** The process of managing and updating PRA models is mostly a manual, labor-intensive, and specialized activity, and in many cases, multiple PRA models must be maintained to represent the different risk-informed applications. An automated way of providing, managing, and checking the PRA model would benefit many day-to-day risk-related activities.
- **Risk aggregation.** Risk aggregation consists of activities combining different elements of the PRA to develop insights and metrics to support decision-making. The aggregation of risk is challenging in terms of

Illustration of different types of dependencies modeled in human reliability analysis.



decision-making (e.g., how to understand the implications of different inputs with different levels of detail, confidence, and uncertainties). With the expansion of PRA models into multiple types of hazards—including internal fire, external flood, pipe breaks, high winds, and seismic events—as well as considering the possible impact of a single hazard (or a combination of hazards) on a site with multiple units and multiple potential sources of radiological release, properly comparing the overall collective risk, and the contribution from individual hazards, can be challenging.

■ **Uncertainty analysis.** One benefit of using risk assessment is the ability to address inherent uncertainties in our state of understanding. Most PRA models include the capability to explicitly incorporate uncertainties considered for failure parameters, including common-cause failure probability, failure rates, and initiating event frequencies. However, most PRAs treat uncertainties related to physical phenomena (success criteria, the margin between success and failure, and the causal mechanisms to failures) in diverse ways via sensitivities, bounding assessments, expert elicitation, and other approaches. Given that uncertainties in physical phenomena may drive uncertainty in current PRAs, improving methods to account for an integrated understanding of the overall contributions is essential.

■ **Communication of risk insights.** Commercial nuclear power plants are complex, and, consequently, their associated PRA models are becoming increasingly complex. In addition, the process of creating, maintaining, and deploying PRA requires a high level of specialized knowledge and experience, limiting the ease of communication behind risk insights and drivers of results. Further, the computer support tools currently used rely on decades-old basic visualization methods and approaches. Communication of the results of PRA models and their implications is essential to permit effective decision-making by a broad array of stakeholders, including plant managers and regulatory authorities. This is particularly critical because many of the intended stakeholders and decision-makers are not experts in the details of PRA methods. As a result, substantial benefits can be obtained by the development of improved methods to display data and results from PRAs. An example of risk communication using visualization from the Nuclear Regulatory Commission's Accident Sequence Precursor Program dashboard[3] is shown below.

3. nrc.gov/about-nrc/regulatory/research/asp.html#dashboard

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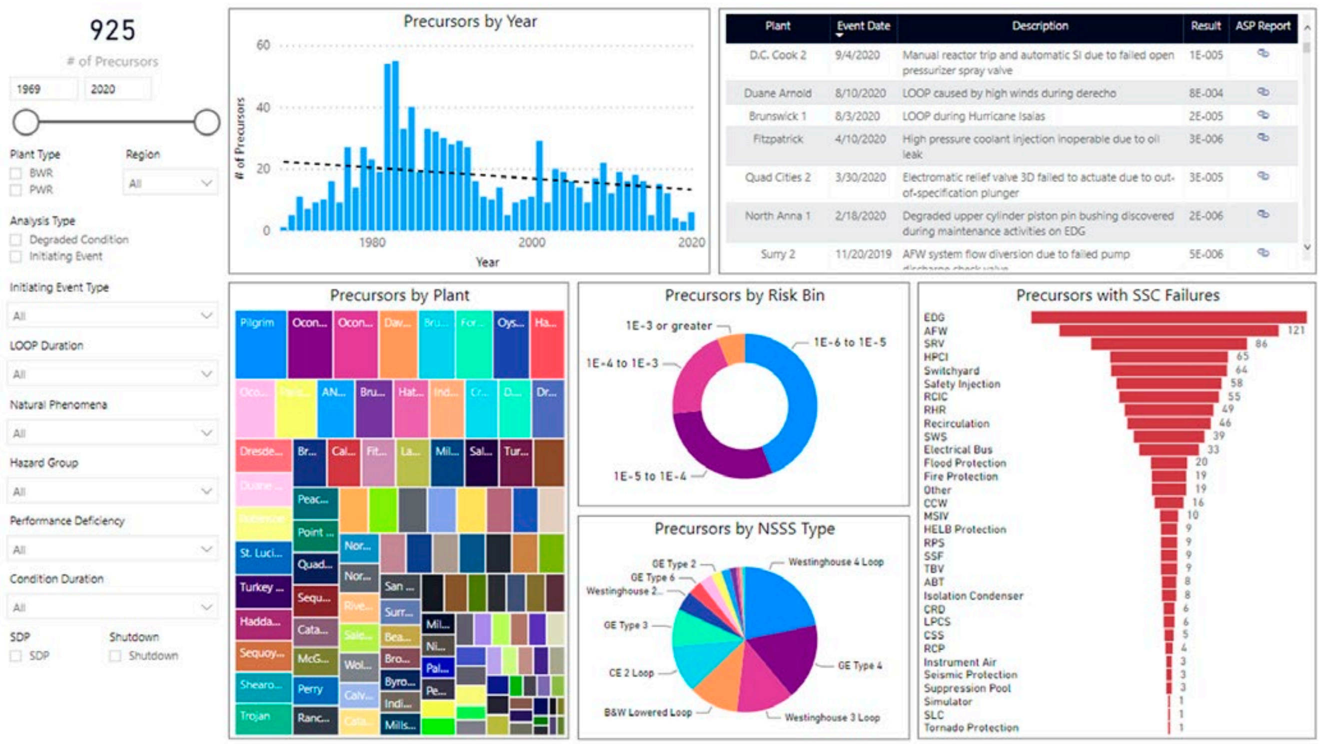


Example communication dashboard showing risk insights from the Nuclear Regulatory Commission's Accident Sequence Precursor Program.

Types of PRAs

Probabilistic risk assessment is a concept, not one tool or method. PRA is a risk assessment approach that relies on quantitative risk modeling, informed by additional qualitative inputs, used to assess the risk of a current design or operation, as well as to identify performance shortfalls.

- **Traditional, classical, or legacy PRAs:** These are PRAs that are based on event trees to define potential accident sequences and probabilities and fault trees to represent the branch points as one follows a sequence through the event tree. The outcome of a traditional PRA for a nuclear power plant is a set of minimal cut sets (i.e., combinations that, if seen, will result in the accident condition being modeled) that reflect ways to experience the condition being analyzed, which for a nuclear power plant typically is core damage and large early release of fission products. The term "safety case" is sometimes confused with PRA. A safety case is a structured approach relying on evidence to argue that a system is safe. While a PRA is not required to be part of a safety case, often the evidence supporting the safety case takes the form of a PRA. It has been shown that using probabilistic approaches can complement deterministic ones, strengthening the overall nuclear safety approach.
- **Dynamic PRAs:** These PRAs are typically created to capture timing information into what is normally a static model. Dynamic PRAs were initially created in the late 1970s and early 1980s and over time have expanded to include physical phenomena in the scenario modeling. Historically, many different approaches have been used to represent dynamic PRA, including the extension of fault trees and event trees with time, graph-based models, Markovian-based approaches, and various simulation techniques.
- **Computational risk assessments (CRAs):** These are simulations that represent the operations, timing, likelihoods, and physics of scenarios. The output of a CRA includes scenario information such as physical parameters (e.g., core temperature and pressure), detailed time histories, margin to failure or success, and the probabilities of experiencing a variety of outcomes ranging from success to failure. Since a rich variety of information can be provided by a CRA, including the physics of an operational facility, it can be used for making a detailed engineering design, supporting a safety case, identifying important physical phenomena, uncertainty quantification, and risk-informed applications.

- **Integration of new technologies and existing models.** Existing PRA approaches rely on a framework that was built using methods mostly developed during the 1970s. As new advanced technologies develop (e.g., use of parallel processing, multi-physics modeling of phenomena, and simulation to capture timing), the integration and acceptance of these advanced methods needs to be considered for enhancing the current state of practice and continuing to foster innovation.

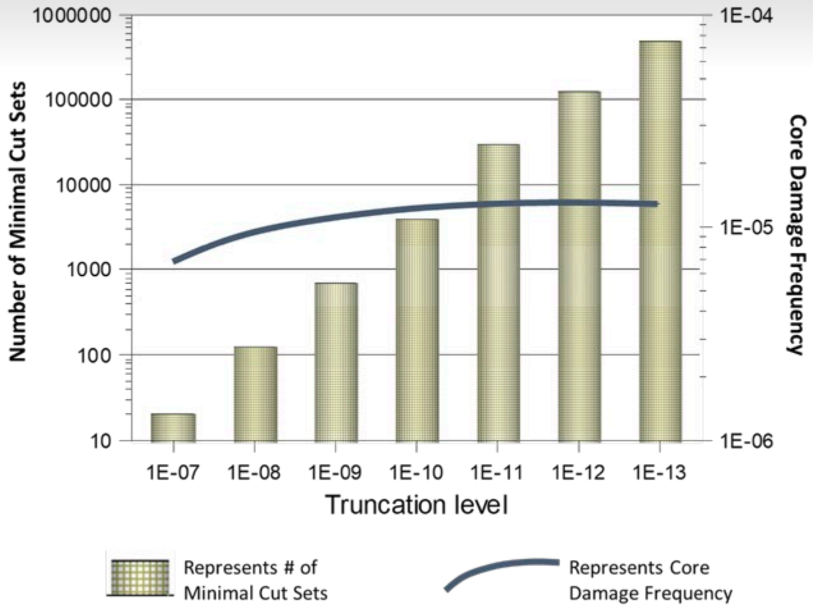
RESEARCH NEEDS AND ROAD MAP

The challenges presented highlight the key areas where research is needed to enhance the technical capabilities and cost-effectiveness of PRA technology. We note that some of the challenges may be difficult to address in the near term (over the next one to two years). Nonetheless, we believe that risk research from the nuclear community can bring about enhancements and solutions to today's challenging PRA issues.

Our research organizations have been collaborating on a prioritized list of issues. Most recently, with support from the Department of Energy's Light Water Reactor Sustainability Program and the Electric Power Research Institute, we have been focusing on three near-term research activities: (1) quantification speed to support decision-making, (2) dependency modeling of human-related basic events, and (3) integration of multi-hazard models.

Quantification speed to support decision-making

PRA quantification speed continues to represent the most significant challenge to more effectively and efficiently using these models to support risk-informed decision-making. Quantification speed affects all aspects of how a PRA can be used, modified, and checked. Thus, the largest benefit to both the PRA community and the nuclear industry can be obtained from research to decrease quantification times while maintaining acceptable levels of accuracy. As an example of the type of complexity seen in nuclear power plant PRAs, see the figure at right, where the number



Representation of a nuclear power plant PRA output in terms of number of core damage combinations and the associated core damage frequency.

of minimal cut sets (i.e., different combinations of ways the plant can experience core damage) grows very large as additional details are captured by lowering the PRA model quantification truncation level to smaller and smaller values wherein combinations are not considered below this frequency level.

There are a few potential options to address quantification speed. One option is to have a tailored, case-specific approach to higher truncation values, thereby decreasing quantification times. Another approach is to develop a better understanding of the details of the PRA structure and its impact on quantification times. A third potential option is to leverage the computer science investment in high-performance computing and advance software development to solve PRA models using new methods.

Dependency modeling of human-related basic events

Human reliability analysis modeling is an accepted and required element in legacy PRAs representing human actions as part of a PRA scenario. However, a significant challenge exists when multiple human actions appear in a single scenario (which occurs frequently). A key question is how these separate events interact dependently through factors such as events occurring close in time or relying on the use of the same plant staff to accomplish multiple required tasks. Current approaches to human reliability analysis focus on manually determining the degree of dependency through the application of simple "if-then" types of rules. This approach is suboptimal, since it may have to rely on conservative assumptions, the rules themselves can become complex, and scrutiny from external reviewers may lead to further conservatism and/or complexity, which may or may not yield additional insights.

Similar to the case of quantification speed research, there are multiple potential solutions to the human dependency issue. For example, one approach may be to create an automated rule-based process to identify and apply dependency factors. Another approach might be to apply machine learning methods to find and apply the dependency factors. A third potential approach might be to move the dependency model directly into the fault or event trees where possible, thereby bypassing the rule-based approach entirely.

Integration of multi-hazard models

Increasingly, multi-hazard models are being developed and used to support plant operational needs. The ability to assess the risk that occurs due to all potential hazards, understand their individual contribution, and recognize what risk insights are most optimal to address is critical to properly implementing risk-informed decision-making. However, the full integration of multi-hazard models can be cumbersome to perform, maintain, and use. In addition, aggregating risk insights into a single output can often lead to additional communication challenges without providing a better understanding of how the individual PRA models have been integrated and what specific component, scenario, or uncertainty is driving the risk. A useful research activity could focus on how to more effectively integrate various hazards into existing PRA models without overly complicating the original model. In addition, this research ties back to the quantification speed issue and associated research, since adding additional elements will increase—sometimes greatly—the overall analysis time.

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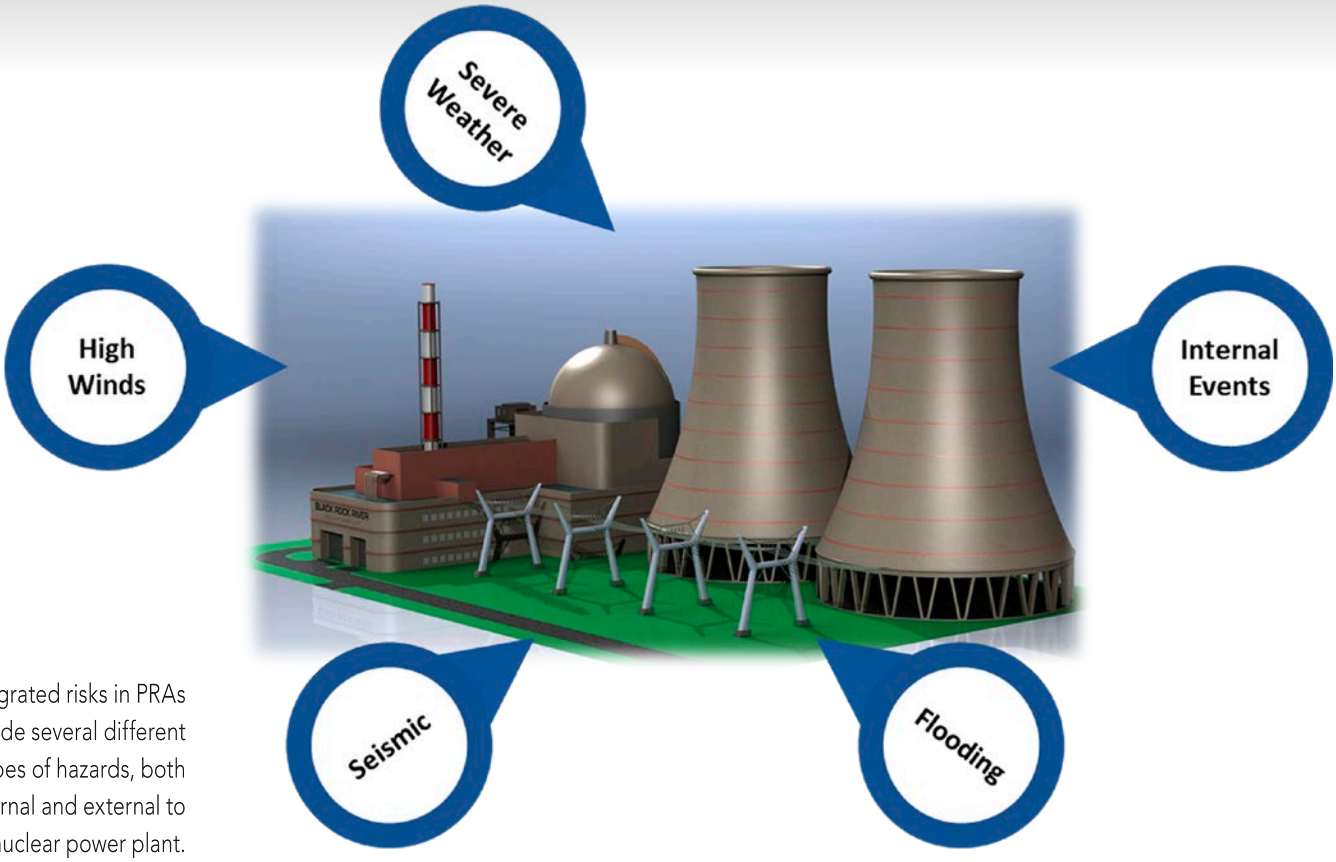

Integrated risks in PRAs include several different types of hazards, both internal and external to the nuclear power plant.

NEXT STEPS

PRA has provided the nuclear industry with an effective tool to manage risks when operating a complex facility such as a nuclear power plant. This process, though, is not without challenges and limitations in terms of continued progress in PRA usage expansion and improvement of risk-informed decision-making. Through feedback from industry practitioners, we have identified and prioritized current issues when developing and using PRAs for risk-informed applications. We are now applying resources to investigate and solve some of the more vexing outstanding issues. As these solutions are created, they will be integrated into current and new PRA approaches used to further strengthen the United States' investment in risk technology while continuing to ensure the safety of the nuclear reactor fleet.

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