HOW ARTIFICIAL INTELLIGENCE AND SMALL MODULAR REACTORS WILL SHAPE THE FUTURE OF EMERGENCY PREPAREDNESS AND RESPONSE

Author: Ryan Rockabrand
Affiliation: United States, Department of Energy, National Nuclear Security Administration, Office of Counterterrorism and Counterproliferation
Email: ryan.rockabrand@nnsa.doe.gov

Abstract:

The purpose of this research is to enhance requirements for personnel considering Artificial Intelligence (AI) capabilities during the adoption of Small Modular Reactors (SMR) in the context of nuclear Emergency Preparedness and Response (EPR) activities. The goal is to understand how AI might integrate into the emergency response organizations for SMR deployments to improve decision-making and crisis management strategies. Approaches to EPR requirements must undergo a profound transformation to adequately address the complex challenges and opportunities presented by the deployment of SMRs and AI by specifically evolving current frameworks and response plans.

In the realm of SMR deployments, AI may serve as a crucial ally in enhancing EPR measures. At the same time, allowing for new considerations such as remote or in-the-vicinity operations, staffing plans, qualifications, and training specifically for SMR expertise, scenario simulations to include digital twins of facilities, responding to communication challenges for remote operations centers, and the management of SMR maintenance and modifications.

1. INTRODUCTION

The intersection of AI and SMRs will reshape the future of EPR. In a world where one technology (nuclear power) is heavily regulated, the other (AI) has minimal oversight, meanwhile recent innovations are poised to imminently impact the nuclear industry in ways we are just beginning to explore. This research is investigating the intersection of these technologies and historical theories through a modified Delphi study.

This research study is being conducted through four rounds of surveys over the course of the 2024 calendar year. The aim of round one was to assess the awareness and knowledge by emergency management professionals of AI and SMRs. Round two, executed in the second quarter of calendar year 2024, identified how AI could enhance emergency preparedness and response before, during, and after SMR emergencies. Subsequently, round three builds on the first two rounds by identifying how industry is preparing to engage communities for the deployment of SMRs. Ultimately, the final round four outlines what AI and EPR actions will be necessary by establishing a framework for the successful implementation of SMRs leveraging AI.

2. RESEARCH

At the IAEA International Conference on Nuclear Security (ICONS) event in May 2024, a paper submission was approved and released, and an accompanying oral presentation was provided. The author provided ICONS participants with the findings from round one, an overview of round two results thus far, and a preliminary outline of recommendations established to date for consideration.

Fig 1: Ryan Rockabrand presenting at #ICONS2024 on May 22, 2024, on 'AI and SMRs Shaping the Future of EPR'

It was evident after round one that the utilization of AI in the context of SMRs involves key aspects that significantly enhance emergency preparedness and response measures. AI algorithms are crucial in accident prediction as they analyze large amounts of data to identify patterns and anomalies, allowing for early prediction of potential issues. Additionally, AI systems determine immediate fault diagnosis, rapidly identifying abnormalities within SMR environments which initiate quick and accurate responses to potential emergencies.

AI technologies help with real-time monitoring by continuously assessing SMR parameters. This gives operators direct insights into SMR conditions and potential risks. As part of enhanced decision support systems, AI assists operators and emergency response teams can make well-informed decisions during crisis situations. This is attributed to the fact that AI will streamline communication and information sharing between different stakeholders, including plant operators, regulatory agencies, emergency response teams, and local jurisdictions. This will help to ensure that all parties have access to the latest information, fostering better coordination in managing the SMR.

3. ROUND 2 RESULTS

In round two, participation was narrowed down to a select panel comprised of 30 domestic and international subject matter experts representing industry, government, academia, advocacy or professional associations, and the military. As identified below in Figure 2, the results were equitable in that less than 20% having had experience with or observed the utility of AI before, during, or after accidents or incidents.

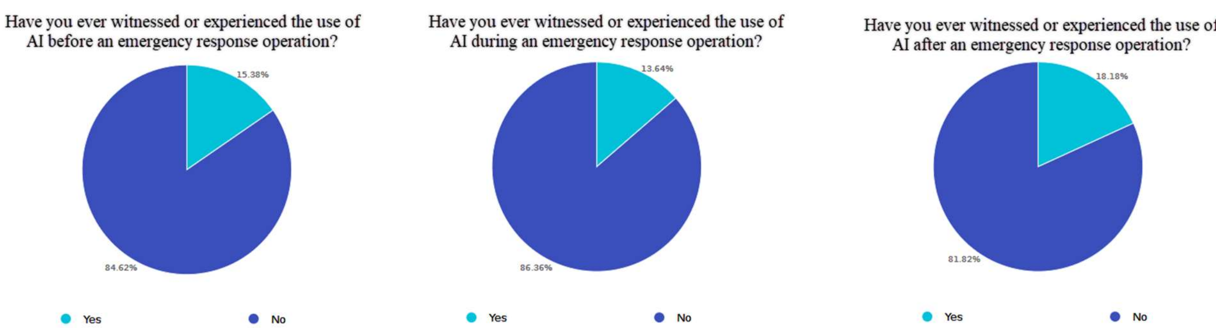

Fig 2: Panel results representing experiences with AI either before, during, or after disasters.

Approximately 23% of participants identified as having familiarity with AI enhancements for EPR and in turn, an extrapolation of their responses captured the following perspectives on AI response factors. In Figure 3, an overall CSAT (customer satisfaction) key performance indicator score assessed whether AI is currently meeting expectations in certain areas. Using this method, expectations were high that the pre and post emergency phases of an incident most benefit from AI due to modeling tools that evaluate strategic recommendations, and that predicting and mitigating situations are well positioned for adoption. It also helps to identify areas of underperformance to allow for necessary improvements enhancing the utility of AI chiefly in the areas of familiarity and response operations.

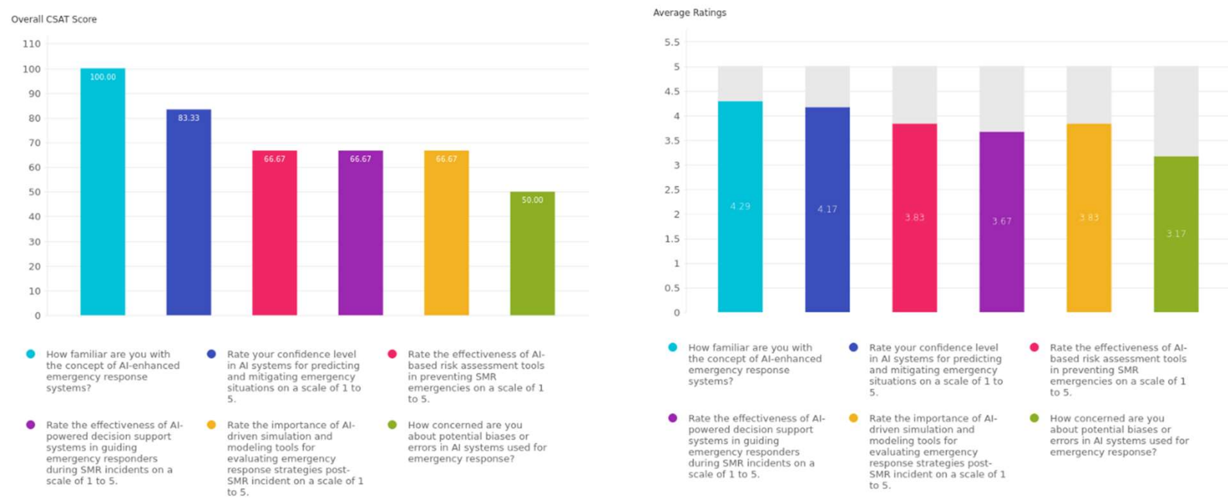

Fig. 3: Panel results for Overall CSAT Score and Average Ratings based on AI familiarity for EPR systems

Summarizing open-ended submissions, participants felt that using AI before, during, and after a SMR accident or incident presents a multifaceted approach to risk mitigation and response. Before an incident, AI can play a crucial role in analyzing near-real-time data streams and integrating them with other sources. This integration enables the identification of conditions where probabilities, vulnerabilities, and potential consequences converge, thereby providing early warnings to mitigate risks effectively. During the initial phases of a response, AI tools can assist in discerning essential data from less critical information. This capability empowers decision-makers to focus on relevant data, facilitating more informed and timely decision-making processes. Furthermore, AI applications can aid in identifying probable locations of undetected hazards by integrating diverse data streams and survey results. This proactive approach allows for the anticipation of potential human health and environmental impacts, enabling preemptive measures to be implemented. In the aftermath of an incident, AI can contribute to the prediction and monitoring of chemical, biological, or radiological plumes by tracking known air streams and considering building wake effects. This predictive capability enhances the accuracy of plume prediction and enables more effective monitoring and application of mitigation strategies in affected areas.

4. REMOTE SMR OPERATIONS

In examining the communication implications inherent in remote operations, several critical considerations come to light. It’s important to begin by realizing that the traditional paradigm of operations within a protected and isolated environment undergoes a fundamental shift with SMRs. Operations now transcend the confines of a protected boundary, extending across multiple geographically dispersed sites. This necessitates seamless coordination among remote, on-site, and in-the-vicinity personnel. However, this expanded communication network also amplifies vulnerabilities and attack surfaces, underscoring the imperative of robust security measures.

Furthermore, potential use cases may involve situating reactors in areas with limited communication infrastructure and physical accessibility. Addressing logistical challenges associated with remote locations becomes imperative for ensuring timely response and effective planning. Even with dedicated communication systems in place, the risk of failure or compromise remains. Continuous monitoring of communication channels becomes essential to promptly identify and address any disruptions. Operators must anticipate communication interruptions and devise contingency plans to enable informed decision-making during such scenarios.

In the event of an interruption, how operators access and interpret information to make informed decisions becomes paramount. Solutions provided by vendors, leveraging existing telecom industry infrastructure, may offer a pathway forward but require additional coordination to ensure seamless integration into the operational framework.

In exploring the implications of remote operations, a performance-based approach to human factors engineering (HFE) and staffing emerges as pivotal. This approach hinges on fulfilling safety functions, prioritizing necessity over tradition. Interestingly, there's no strict mandate on the physical location of operators or Human-System Interfaces (HSIs). Instead, the emphasis lies on proving the adequacy of the proposed method, considering design-specific factors. Furthermore, certain requirements such as self-reliant mitigation facilities and load following gain prominence within this framework. These elements are deemed particularly pertinent in ensuring the effectiveness of remote operations. Looking ahead, this approach lays the groundwork for future concepts in remote operations, fostering innovation and adaptability. However, it's crucial to note that while this approach addresses key aspects, other considerations like cybersecurity remain significant challenges to be addressed.

In the context of these remote operations scenarios, four critical tasks are paramount. First, operators must be able to seamlessly receive plant operating data, encompassing vital information ranging from reactor parameters to data essential for evaluating emergency conditions. This real-time access to comprehensive data ensures operators remain informed and capable of making informed decisions. Second, in the event of an emergency, operators must possess the capability to swiftly initiate a reactor shutdown from their remote location. This immediate response mechanism is crucial in mitigating potential risks and ensuring the safety of the facility and surrounding areas. Third, the ability to promptly dispatch operations and maintenance personnel is essential. Remote operators must possess the means to mobilize necessary personnel efficiently, ensuring that any required actions or interventions can be carried out swiftly and effectively. Lastly, remote operators must be equipped to implement their responsibilities under the facility's emergency plan without delay. This includes executing predefined protocols and procedures as dictated by the emergency plan, ensuring a coordinated and effective response to any emergency situations that may arise.

Notional AI and Autonomy Levels in Commercial Nuclear Activities

Level	Notional AI and Autonomy Levels	Potential Uses of AI and Autonomy in Commercial Nuclear Activities
Level 0	**AI Not Used**	No AI or autonomy integration in systems or processes
Level 1	**Insight** Human decision-making assisted by a machine	AI integration in systems is used for optimization, operational guidance, or business process automation that would not affect plant safety/security and control
Level 2	**Collaboration** Human decision-making augmented by a machine	AI integration in systems where algorithms make recommendations that could affect plant safety/security and control are vetted and carried out by a human decisionmaker
Level 3	**Operation** Machine decision-making supervised by a human	AI and autonomy integration in systems where algorithms make decisions and conduct operations with human oversight that could affect plant safety/security and control
Level 4	**Fully Autonomous** Machine decision-making with no human intervention	Fully autonomous AI in systems where the algorithm is responsible for operation, control, and intelligent adaptation without reliance on human intervention or oversight that could affect plant safety/security and control

Human Involvement
Machine Independence

Fig 4: NRC AI Strategic Plan Notional Levels for Human Involvement vs. Machine Independence

There are approximately 30 SMR developers currently working roughly 80 distinct design concepts for SMRs and around 50 companies who will serve as suppliers as SMR energy market matures. With so many variations in design, it's clear that a vast range of technical expertise will be required to manage these critical tasks. This is coupled with the level of competency and flexibility that will be required of emergency response teams in the event of an accident or incident. Before any SMR implementation occurs, developers must standardize and institutionalize the notional AI and autonomy level for SMRs, as well as coordinate with local officials from a response standpoint. This requirement is derived from the NRC AI Strategic Plan for FY 2023-2027, which is presented in Figure 4 above [1]. To provide one extreme innovative example, the French company DCNS (now Naval Group) developed the Flexblue concept project. The project involved placing a seabed-moored multi-unit SMR offshore and controlling it from an onshore control room while tethering it with a cable for remote management. This novel subsurface marine approach as one can imagine poses challenges from an inspection, access, and environmental perspective yet at the same time offering benefits such as a natural cooling, protection against external hazards, and no land-based footprint requirements [2].

AI's diverse capabilities can act as a powerful safeguard for SMRs, contributing to enhanced safety, efficiency, and preparedness across various aspects of their operation. However, in contemplating the integration of remote operations for future SMR deployments, a delicate balance between cost-efficiency and safety considerations emerges as vital. Primarily, the adoption of remote operations holds the promise of streamlining expertise centralization, potentially yielding substantial cost savings. This centralized approach enables the consolidation of specialized skills and resources, thereby harnessing economies of scale, particularly in overseeing multiple reactors. Through remote operations, efficiencies can be realized across various facets of reactor oversight, facilitating a more cost-effective operational framework. Nevertheless, this pursuit of cost efficiency must be juxtaposed with the imperative of upholding stringent safety standards, particularly concerning human factors.

5. SMR STAFFING CONSIDERATIONS

When formulating the staffing plan for SMRs, careful consideration is essential to ensure comprehensive coverage across various functional areas. This entails addressing key aspects such as the plan must delineate how the allocation of personnel, including their numbers, positions, and corresponding responsibilities, will sufficiently support all critical functions. These functions span diverse domains such as plant operations, equipment surveillance and maintenance, radiological protection, chemistry control, fire brigades, engineering, security, and emergency response.

The staffing plan must ensure that each area receives adequate attention and expertise to guarantee the safe and efficient operation of the SMR. Furthermore, a crucial element of the staffing plan involves always ensuring the availability of engineering expertise to on-shift operating personnel, regardless of plant conditions. This provision is indispensable for addressing unforeseen situations that may arise beyond the scope of standard procedures or training. By having engineering support readily accessible, operators can receive timely guidance and assistance, enhancing their ability to effectively manage and resolve any challenges encountered during operations.

In navigating the landscape of remote operations staffing, several pivotal considerations emerge such the establishment of robust data and voice communication infrastructure, coupled with stringent security measures including cybersecurity, stands as foundational. These elements form the backbone of remote operations, facilitating seamless communication and safeguarding against potential cyber threats. Secondly, defining the responsibilities of these remote operators hinges on various factors, including the degree of automation, the balance between human and automated actions, and the time constraints associated with human interventions. These parameters shape the role of remote operators, dictating their involvement in meeting operational criteria and addressing potential risks. Third, while remote operations offer significant advantages, the presence of an on-site or nearby crew remains indispensable. This arrangement ensures swift response capabilities and enhances overall operational resilience within the remote operations paradigm.

Additionally, ensuring the physical security of both the site and the remote control room is fundamental. This entails implementing measures to safeguard against unauthorized access and potential security breaches, bolstering the overall integrity of the operational infrastructure. Moreover, communication challenges inherent in remote operations introduce novel uncertainties, necessitating innovative approaches for resolution. Emerging technologies such as physics-based and machine learning systems play a pivotal role in modeling and evaluating reactor behavior, augmenting operators' capabilities beyond traditional monitoring and control tasks. Concepts like digital twins and advanced Human-Machine Interfaces (HMIs) offer enhanced information assurance and diagnostic capabilities to remote operators, further fortifying the operational framework against uncertainties.

In delineating the roles and responsibilities of personnel and automation within the operational framework, several key inquiries emerge. Clarification must be sought regarding the roles of personnel in executing and ensuring the attainment of plant safety and emergency response functions. Additionally, there is the question regarding the involvement of plant personnel in other mission functions of the facility. It is necessary to clearly define these roles and functions, specifying where personnel will operate to execute these obligations.

Regarding staffing, qualifications, and training, there is a need to outline the planned number and qualifications of both onsite and remote staff. Anticipated changes in the staffing plan over the facility license period should also be addressed. We also need to understand where and how personnel will be trained and qualified, whether at the reactor facility, a remote operations facility, or another location. For example, NuScale Power is currently the only NRC-certified SMR design in the United States and underwent stringent reviews to achieve certification. During one of many evaluations it was revealed that their licensed operator SMR training program encompassed the following characteristics and components:

- developed using a systems approach to training, as described in 10 CFR Part 55 [3]
- the math, physics, thermodynamics, and component design topics that are of specific relevance to the operation of a nuclear power plant
- training for mitigating core damage
- plant specific training, including:
    - plant systems
    - plant specific reactor technology (including core physics data)
    - plant chemistry and corrosion control
    - reactor plant materials
    - reactor plant thermal cycle
    - transient/accident analysis
    - emergency procedure

Notably however, their test results determined that only a site-specific training program could guarantee all these elements. Furthermore, NuScale had to go through an exemption process and revised staffing plan validation test since their original application which called for six licensed operators to manage twelve power modules did not meet the minimum federal staffing requirements [4]. These are just a couple examples of the nuances that each SMR design will have to overcome to achieve certification and approval to proceed with implementation.

When managing normal operations, outlining the roles of personnel in tasks such as monitoring and controlling normal operational phases like start-up, power level control, shutdown, and refueling must be established. It is imperative to specify where personnel will carry out these duties to perform their roles effectively. Similarly, in managing off-normal conditions and emergencies, the roles of personnel in responding to such situations need clarification. Additionally, the location from which personnel will perform these duties must be identified. Contingencies for dispatching personnel to the reactor site in response to off-normal or emergency conditions also need to be outlined. Furthermore, strategies for managing a loss or degradation of communications between the reactor facility and remote operations facility must be devised.

Lastly, in managing tests, inspections, and surveillances, the roles of personnel in these activities need to be defined, along with the locations where they will undertake these responsibilities. Although SMRs are taking a more integrated approach to safety, security, and safeguards, commonly referred to as “3S by Design”, addressing current regulatory hurdles which call for certain physical protection requirements with fixed numbers of security staff and on-site responders defeats the purpose of remote control room functionality and the benefits of cost reductions [5]. Concerning the management of maintenance and modifications, the roles of personnel in executing these tasks require clarification, along with the locations where these duties will be performed.

6. CONCLUSION

In conclusion, this research captures the significant potential of Artificial Intelligence (AI) to revolutionize Small Modular Reactor (SMR) emergency preparedness and response (EPR) measures. Ongoing studies aim to enhance EPR requirements by understanding how AI will integrate into emergency response organizations and improve decision-making and crisis management. Four key findings from this research include:

- **AI's potential to significantly enhance EPR**: AI can provide valuable insights for accident prediction, fault diagnosis, real-time monitoring, and decision support.
- **Challenges and opportunities of remote SMR operations**: Remote operations present unique communication challenges and require robust security measures.
- **Staffing considerations for SMRs**: A comprehensive staffing plan is essential to ensure adequate coverage across various functional areas, including remote operations.
- **Importance of standardization and institutionalization**: SMR developers need to standardize AI and autonomy levels and coordinate with local officials for effective response.

Most importantly, the transition to remote operations necessitates heightened coordination across multiple sites, introducing complexities that could potentially compromise safety and security protocols. The increased reliance on multi-site coordination demands meticulous attention to human factors considerations to mitigate risks effectively. Ultimately, this will require both onsite and offsite emergency response organizations to critical think about communications strategies from a tactically perspective and the coordination of how best to utilize AI tools when disseminating messages with the communities in which these sites are located.

Beyond enhancing decision-making and crisis management, AI can enable new operational paradigms, such as remote or in-the-vicinity operations, and support strategic planning for staffing, qualifications, and training tailored to SMR expertise. Additionally, AI-powered tools like digital twins can facilitate scenario simulations and address the unique communication challenges of remote operations centers. Safeguarding against complacency and ensuring robust communication and coordination mechanisms are imperative to sustain high levels of safety amidst the evolving operational landscape. By addressing these critical areas, AI can play a pivotal role in ensuring the safety and efficiency of SMR deployments.

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