

Operational Challenges in Small Modular Reactors: Insights into Human Factors and Emerging Technologies

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ABSTRACT

Small Modular Reactors (SMRs) introduce new operational concepts and promise both economic and safety benefits, but they also pose challenges for practical implementation and human factors. These challenges include reduced staffing levels, remote personnel, and the centralised management of multiple facilities, among others. The distinctive characteristics of SMRs, and moreover, the potential of emerging technologies, can significantly shape human roles and work practices. Consequently, the role of emerging technologies is becoming increasingly important in supporting safe and efficient SMR operations. This study aims to identify practical needs and solutions for leveraging technology in SMR operations by presenting example cases collaboratively developed with subject matter experts. The study emphasises that the integration of new technologies should be considered already in the design phase, and that the principles of plant design and operational concepts should reflect the effective use of these technologies.

Keywords: Nuclear energy, Small modular reactors, Human factors, Emerging technologies, Operational concepts

INTRODUCTION

The new features and promised benefits of Small Modular Reactors (SMRs) introduce challenges for both operational concepts and practical implementation. Limited operational experience and evolving nuclear industry regulations currently create uncertainties, while the economic advantages promised by SMRs must be realized without compromising safety (Lee, 2024; Blackett et al., 2023).

The roles of operators and other personnel within the SMR context are shifting, with some traditional tasks potentially being replaced by new responsibilities (Blackett et al., 2022). Efforts to minimize staffing levels at SMR facilities raise important questions regarding the responsibilities, information needs, and communication requirements of personnel who may be required on-site when necessary. Furthermore, proposals for remote operations and the centralized management of multiple facilities (multi-site approaches) present additional challenges related to task allocation and communication (Green et al., 2025; Blackett et al., 2023). Considering these challenges, emerging technologies are expected to play an important role in supporting safe and efficient SMR operations.

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To better identify and understand the needs and solutions for leveraging technology, it is first necessary to outline some practical operational characteristics specific to SMR facilities. This paper presents potential practical cases and challenges that are likely to be encountered in SMR operations. The cases were developed collaboratively with experts in the nuclear power sector and technology fields. The results present discussions held with these experts regarding the applicability and significance of the cases within the SMR context, as well as reflections on the utilization of new technologies.

This study does not present comprehensive perspectives or solutions; rather, it brings to the forefront practical issues and challenges that may be partially addressed through the application of new technologies.

In this paper, selected challenges and characteristics related to SMR operations are first presented based on the literature, along with a brief review of relevant technologies. Next, the process of constructing the example cases is described, followed by the presentation of the cases themselves in the results section. Finally, the significance of these cases within the SMR context is discussed, and conclusions are drawn.

OPERATIONAL CHALLENGES IN SMRs

Reduced staffing levels. The operational complexity of SMRs is expected to decrease due to increased use of passive safety systems and advanced automation. Together with simpler designs and smaller reactors, these advancements are expected to enable reduced staffing levels for SMRs, which is also an economic advantage in their deployment. The role of the control room operator may shift towards monitoring and checking, rather than actively intervening in plant operation and management. Under normal operating conditions, operators will have limited tasks unless their traditional role is redefined (Blackett et al., 2023; Hugo, 2021; IAEA, 2001). Overall, the number of personnel present at the facility may be very limited.

Off-site personnel. If the on-site personnel are generally limited, it can be assumed that various off-site personnel will be present at the facility as needed, both in a planned and ad hoc manner performing specific tasks (such as maintenance). One identified concern is that off-site personnel may have limited familiarity with the plant, which could increase the likelihood of errors (ONR, 2021). Furthermore, effective communication and information transfer between on-site and off-site personnel can be expected to become an important issue.

Multi-unit operation. A typical design suggested for SMR facilities involves controlling multiple reactors from a single centralized control room operated by the same operator crew (multi-unit operation). This distinguishes SMR plants from traditional power plants, where each reactor typically has its own dedicated control room and operator crew (Hugo, 2021). The operator crew for a SMR facility may also be smaller than conventional crews. There have been discussions regarding the number of reactors that a single operator can safely monitor, especially during abnormal and emergency situations (Hartmann et al., 2024). It is therefore reasonable to assume that, at least for exceptional circumstances, there will be some form of external support team

(such as an emergency control center) which not only assists local operators during emergencies but also actively monitors the plant's status. Furthermore, considering the multi-unit design, it is possible that multiple identical reactor units located in the same reactor hall could increase potential for human error, such as common cause error (ONR, 2021), or even performing work on the wrong unit.

Multi-site approach and mobile personnel. Separate SMR facilities can also be organized as an integrated entity managed centrally (multi-site or fleet approach) (Green et al., 2025). It is possible that the SMR fleet could be supported by a team of mobile personnel who perform work tasks across all operational sites. Their responsibilities may include activities related to EMIT (Examination, Maintenance, Inspection, and Testing) as well as annual maintenance outages. The use of mobile personnel teams operating across multiple sites may introduce risks: an increased likelihood of common cause failures, delayed response times for unplanned EMIT activities due to travel requirements, and a potential for errors due to reduced familiarity caused by variability between SMR sites (ONR, 2021).

Remote operations. In the context of SMRs, the potential for remote operations is also discussed (Blackett et al., 2023). It should be noted that “remote operations”, and “remote monitoring” are distinct concepts. “Remote operations” involves performing command and control activities, whereas “remote monitoring” refers to the collection and observation of plant data. Both cases, however, require data transfer and communication between different locations. It has been suggested that new forms of collaboration should be developed and emerging communication technologies utilized to ensure safe operation. This may encompass communication between remote personnel and both on-site staff as well as off-site personnel who enter the facility as needed (Green et al., 2025).

Technology Considerations

The potential advantages of new and advanced technological solutions have been recognized in the context of SMRs. For example, augmented reality (AR) applications, which combine digital and real-world environments, can enhance a variety of maintenance activities and improve communication among personnel (Hugo, 2021). AR technologies have also been developed for purposes such as route guidance during evacuations (for example MARA Mobile Augmented Reality Application), and remote operations (Helin et al., 2024). In addition, mobile robots, including drones, can perform various inspection and surveillance tasks, thereby support reduced staffing levels and enable work in environments hazardous to humans. The integration of telemetry with advanced automation systems facilitates remote plant monitoring. Remote personnel can furthermore coordinate with on-site and other off-site teams to perform tasks using real-time data and video conferencing (Green et al., 2025; Hugo, 2021).

Furthermore, technologies such as digital twins enable, for example, the prediction of plant aging, allowing for the optimized maintenance of components. The advancement of artificial intelligence (AI) can assist personnel in a range of tasks and help reduce individual workload. From the

perspective of AI and autonomous control, SMR plants should be designed to be as simple as possible to minimize the number of variables requiring control (Rockabrand, 2025; Lee, 2024).

COLLABORATIVE CONSTRUCTION OF SMR CASES

The construction of SMR cases progressed through a collaborative design process. The main stages of this process were as follows:

- *Literature review and researchers' ideas*: Initial SMR case proposals were developed based on existing literature and insights from researchers.
- *Interviews in 2024*: The cases were further developed and refined through interviews. In this first phase of data collection, three individual interviews were conducted with a university researcher who has control room (MCR) operator experience, an SMR professional, and a representative from a nuclear power utility.
- *Workshops in 2025*: The cases were updated and discussed during four workshops. Participants included human factors experts and technology specialists from a research organisation, and SMR professionals from two different SMR companies. In total, seven experts participated in the workshops, with two researchers present in each session to facilitate the discussion.

The individual interviews in the first phase also addressed general challenges related to SMR operations, while the workshops focused more specifically on discussing and evaluating the defined cases.

RESULTS

This chapter presents the developed six SMR cases (titled as Example cases) and the related discussions. Table 1 provides a concise description of the final cases. The content of the cases is further elaborated in the summaries, which draws on the discussions held during the interviews and workshops.

Table 1: SMR cases discussed in the workshops.

Example Case	Description	Explanation
Remote monitoring and diagnostics	Supporting maintenance planning and emergency coordination, among other tasks.	The need for remote diagnostics arises because planning and support activities are also conducted outside the facility.
Mobile robots for operations and security support	Robots supporting inspections & monitoring and performing on-site security tasks.	Robots could support limited on-site personnel in various tasks. Their mobility enables the execution of diverse activities. Robots can also perform tasks that are dangerous for humans.

(Continued)

Table 1: Continued.

Example Case	Description	Explanation
Mobile personnel for maintenance support	Mobile personnel conducting maintenance (etc.) activities across multiple SMR sites.	Deploying mobile personnel across multiple facilities reduces overall staffing needs. Limited site familiarity and inter-facility differences may increase the risk of errors, and the need for communication and information access can become more evident.
Route guidance and work verification	Support for route planning and work location verification at the plant.	Verifying routes and work locations through technology can be particularly important for temporary personnel unfamiliar with the facility.
Personnel situational overview	Real-time monitoring of personnel position and status.	Information about the exact position and status of both on-site and distributed off-site personnel could be particularly important in the SMR context.
Support for operators in off-normal and emergency conditions	Remote support for on-site operators in multi-unit operation.	On-site operators may require remote support in various abnormal situations, when staffing levels are insufficient for tasks such as operating multiple reactors.

Remote monitoring and diagnostics. This first example case prompted discussion about dividing tasks between local and remote control rooms. Under normal operating conditions, the number of personnel in the local control room was assumed to be minimal. However, the personnel there would still bear the responsibility for the plant safety. The data from plants, then, could be widely utilised in diagnostics, such as monitoring changes in system operation, heating and air conditioning, which would facilitate predictive maintenance. For remote monitoring, a fleet metaphor was used: the remote control room could coordinate several tasks, including maintenance and fuel supply.

From a technological implementation perspective, it was noted that an SMR plant is expected to provide more data for external use compared to a conventional plant. This is essential for aspects such as remote operation and multi-site coordination. Data security is therefore a critical concern. For distributed functions (onsite vs. offsite), selective filtering of information for different roles and end-user devices would be beneficial. From a comprehensive digital model of the plant, such as a digital twin, data can be extracted and visualised to meet specific user needs, with artificial intelligence (AI) assisting in the filtering process. The digital model as a whole can be monitored and managed from a possible centralised organisation.

Mobile robots for operations and security support. Utilising mobile robots raised interest, though certain risks and challenges were also identified. Robots were considered useful for special situations and operations, such as for radiation leaks and for sampling or changing filters in a radiated area. They could be deployed in periodic inspections, to minimize human exposure and to save human resources. Mobile robots and drones in particular could also

enhance plant security through external monitoring. Identified risks include falling to dangerous areas, such as a fuel tank, and therefore, pre-defined routes for the robots were proposed. In addition, the fire compartmentation was identified limiting the operational area of the robots and thereby their potential benefits.

From technology perspective, the technology specialists noted that a robot could routinely traverse designated routes to collect relevant parameters for predicting potential issues or verifying that variations remain within acceptable limits. If the route needed to be adjusted, it would be easier than installing new fixed sensors, as they may be needed in areas challenging for human access. Integrating sensing and security functions was also identified as a promising approach to enhance cost-effectiveness.

Mobile personnel for maintenance support. The third example case raised discussion on the allocation of responsibilities between the local and remote control rooms. The shift manager of the local control room was considered to have the overall responsibility of the maintenance, and particularly the nuclear safety of the plant. Even though the maintenance manager of the central organisation oversees the maintenance operations, the shift manager needs to understand and communicate relevant restrictions to the external maintenance manager. As the local plants may be unique, the external maintenance organisation requires plant-specific information, such as details on radiation zones and technical specifications. Beyond maintenance, mobile personnel were identified valuable also for other tasks, such as technical planning and installations, fuel procurement, and plant chemistry. One additional challenge highlighted was ensuring the commitment of mobile personnel to plant safety and the potential role of technology in supporting this objective.

In terms of technological applications, AR and VR solutions were identified as clearly beneficial for both training and situational awareness. Personnel can be trained centrally in a VR environment to ensure consistency across operations at different plants. Alternatively, AR applications can provide plant-specific information when required. These technologies can also support the onboarding of mobile personnel upon arrival at a facility. Furthermore, VR environments could be utilised for pre-job briefings and post-job reviews, while simultaneously capturing observations into a shared digital model to prevent errors.

Route guidance and work verification. This example case was considered relevant in the SMR context due to the increased likelihood of human error when multiple nearly identical small reactors are present. Effective communication between the local control room and the maintenance personnel was identified critical, not only for ensuring accurate route guidance and instructions, but also for occupational safety to verify, for example, that the workstation's electrical system is properly isolated. Route guidance was identified necessary when entering and exiting the worksite but also during transitions, for example when a route from the work site to a warehouse is needed. In addition to leveraging mobile technology, the need for familiarisation in advance and entering the premises together with local

staff were highlighted. Furthermore, the need for illuminated exit routes, powered independently in case of electrical failure, was emphasized for emergency situations.

Regarding mobile technology, the technology specialists discussed the potential of providing route guidance with an AR-based map that could be incorporated into the safety glasses of the personnel. They also suggested the use of headphones for providing audio instructions. When at a site, verification of the target could be achieved through QR code scanning. Nonetheless, SMR professionals emphasised that any application providing route guidance and work verification should be integrated with the existing mobile communication devices used at the facility to avoid the need for personnel to carry additional equipment.

Personnel situational overview. In the SMR context, the need for real-time personnel location information was debated. Current nuclear plants already track entry and room occupancy via access control, and operators generally know who is on site and what tasks are underway. Consequently, the necessity of precise position information for any off-site central control in the SMR context was questioned. Moreover, exact positioning of mobile and off-site personnel was considered less relevant, whereas within the plant itself, accurate location information becomes more important for safety and coordination. Two main purposes were identified: security, ensuring that authorized personnel are in permitted areas, and operational awareness of ongoing maintenance work. While the added value of detailed location data under normal conditions was questioned, SMR-specific features, such as underground reactor halls with limited evacuation routes, highlight its potential importance in emergencies. In such scenarios, knowing exactly who is in hazardous areas and maintaining rapid communication can be critical.

The technological implementation is determined by the required level of accuracy for personnel location data. When fully real-time information is not necessary, alternatives such as QR codes can provide sufficient detail. In addition, various annotations—including documentation—can optionally record a person's location within a possible digital model. Privacy must be carefully considered in all solutions involving personnel location tracking.

Support for operators in off-normal and emergency conditions. The SMR professionals concurred that operational responsibility during off-normal and emergency scenarios resides with the local control room. The remote control room would serve in a supporting role by monitoring the situation and providing information derived from situational analysis. In case of a serious disruption, an emergency organisation was expected to be convened to analyse the situation based on their expertise and advice the operator shift on appropriate strategies. This emergency organisation would also maintain communication with the radiation and nuclear safety authorities and local agencies. The operator shift was expected to focus on the immediate fault, while the remote control room assists by monitoring other reactors.

Regarding supporting technologies, artificial intelligence was identified as a potential tool for enhancing situational awareness and highlighting institutional emergency procedures. Beyond off-normal and emergency conditions, also the importance of adopting a preventive approach was

noted – operational processes utilizing technology should be designed to support operator vigilance so that monitoring responsibilities would include active engagement, such as explicit reception or approval of tasks.

SIGNIFICANCE OF THE CASES IN SMR CONTEXT

Each example case was perceived as containing elements significant to the SMR context. The personnel situational overview (Case 5) and associated real-time localisation generated the most questioning regarding their practical benefits, particularly among SMR professionals. It is also noteworthy that many technological solutions—such as AR and VR applications and artificial intelligence—can support operations in conventional power plants and are therefore not limited exclusively to SMRs. Remote diagnostics and remote assistance in off-normal situations (Cases 1 and 6), mobile personnel (Case 3), and the indication of work locations and routes (Case 4) were regarded as both significant and natural especially in SMR operations. For SMR professionals, the utilisation of mobile robots (Case 2) represented a relatively novel concept, and their benefits for SMRs were not immediately evident. Nevertheless, it may be assumed that emerging robotic solutions could prove valuable in scenarios where the aim is to minimise the number of personnel at the plant. Furthermore, with respect to personnel position and status information, it is worth considering whether its importance will increase if the role of mobile personnel expands, particularly in multi-site operations involving several plants. The required accuracy of location data may be influenced by safety requirements and industry regulations.

CONCLUSIONS

This study aimed to identify practical needs and solutions for leveraging technology in SMR operation by outlining operational characteristics and presenting relevant example cases. The cases were collaboratively developed with nuclear power and technology experts.

It is important to note that while advanced technological solutions—such as augmented reality, mobile robots, digital twins, and artificial intelligence—offer significant potential for SMR operation, their benefits are not exclusive to SMRs and can also be applied in conventional power plants. However, in SMRs, the integration of new technologies should be considered during the design phase rather than as retrofits, and the principles of plant design and operational concepts should reflect the adoption and effective use of these technologies.

Each example case presented could be further explored in future research. At a more general level, supporting the work of operators as well as other personnel through technological solutions in multi-unit operating situations is likely to be essential in the SMR context. Moreover, the effect of novel solutions and related practices on human factors engineering (HFE) is also a critical subject of examination. Furthermore, future research should explore how to maintain operator vigilance and motivation during normal operation, supported by technological solutions, as this is an important area for investigation.

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