Proceedings of the 35th European Safety and Reliability & the 33rd Society for Risk Analysis Europe Conference
Edited by Eirik Bjorheim Abrahamsen, Terje Aven, Frederic Bouder, Roger Flage, Marja Ylönen

doi: 10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P5542-cd

A Taxonomy of Human Tasks for Human Reliability Analysis of Small Modular Reactors

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Small Modular Reactors (SMRs) represent a radical shift in how nuclear power plants (NPPs) will be operated. SMR designs propose advanced characteristics such as smaller, simpler plants, increased use of automation, and increased reliance on inherent safety properties and passive safety systems. This allows for new operating paradigms such as remote, autonomous and/or multi-unit operation, reduced staffing plans, and alternative applications such as hydrogen production, and district heating. As a result, the role of the human in the operation of SMRs is anticipated to change by comparison to conventional large NPPs. For Human Reliability Analysis (HRA), this means that that our current knowledge and assumptions about human performance may no longer be valid, as these are based on analysis of operator actions at conventional plants. Further, existing HRA approaches may not adequately capture the extent, or impact, of the potential changes to operational tasks and scenarios. At the same time, the role of the operator as a safety barrier in an SMR is expected to be at least as important as at a conventional NPP as it is highly likely that human operators will still form part of the defence-in-depth strategy if automated, inherent, or passive safety systems fail or do not work as required. The Swedish Radiation Authority has recently awarded funding to Risk Pilot AB for a project to investigate the types of tasks that operators will be expected to perform in an SMR plant, with emphasis on the identification of new types of tasks that differ from conventional NPPs. In this paper we will present some key findings from a literature review and how these inform our initial attempts at the development of a task taxonomy to support HRA for SMRs.

Keywords: Human Reliability Analysis, Small Modular Reactors, Nuclear, Human Factors, Taxonomy.

1. Introduction

Small Modular Reactors (SMRs) represent a radical shift in how nuclear power plants (NPPs) will be operated in the future. Many SMR concepts propose advanced design characteristics such as smaller reactor cores, simpler plant systems, the implementation of higher levels of automation compared to contemporary large NPPs, and increased use of inherent safety design features and passive safety systems to manage essential NPP functions including decay heat removal (Blackett et al., 2022a). Not only are these characteristics intended to improve the safety of nuclear power operations, but they are also intended to reduce the cost of running an NPP by enabling the reduction of staffing whilst still meeting the requirements for safe and reliable nuclear operation. A report by the Electric Power Research Institute (EPRI) states that "a key need for SMR economic viability is the ability to safely operate and maintain the plant with an optimized staff" (2016, pp.1-1).

From a Human Factors (HF) perspective, the proposed design advances combined with the intention to reduce staffing means that the role of the human operator in an SMR NPP is anticipated to change by comparison to contemporary conventional NPPs. From the perspective of Human Reliability Analysis (HRA), the changing role of the operator means that there may be new ways in which human error could contribute to risk, and assumptions about the effects of performance shaping factors on human behaviour may no longer be valid for this new operating paradigm. As several SMR concept designs move closer to eventual commercial deployment, it is important that human operators' roles and responsibilities are clearly defined and understood to ensure that the potential for human error is minimised: "One of the more challenging aspects of the introduction of [Advanced SMRs] into the nuclear fleet involves the detailed description of how these plants will be operated and by whom" (INL, 2013, pg.10).

In 2024, the Swedish Radiation Safety Authority (Strålsäkerhetsmyndigheten, SSM) awarded funding to Risk Pilot AB for a project to investigate the types of tasks that operators will be expected to perform in an SMR plant, with emphasis on the identification of new types of tasks that differ from conventional NPPs. In this paper we will present some early findings from a literature review and how these inform our initial attempts at the development of a taxonomy of operator tasks to support HRA for SMRs.

2. Brief Overview of Current SMR Status

The International Atomic Energy Agency (IAEA) defines SMRs as nuclear reactors that "typically have a power capacity of up to 300 MW(e) per unit" (IAEA, 2024, p.8). Some key differences in SMR designs, compared to conventional large NPPs include (Blackett et al., 2022a):

- Approx. 80-90% of the plant fabricated offsite.
- Enhanced utilization of passive safety systems, such as gravity, pressure differentials, and natural circulation.
- Capability for multi-unit operation, where one control room monitors and controls multiple units concurrently.

At the time of writing this report, there are a small number of SMRs at an advanced stage of design maturity. According to the Nuclear Energy Agency (NEA) SMR Dashboard (NEA, 2024), there are 3 SMRs deployed and operating in China, Russia and Japan, and construction licenses have been granted for 4 more reactors in Argentina, China and Russia. 2 SMRs have received regulatory design approval in Korea and USA. There are 5 SMRs currently involved in regulatory licensing processes in USA, Canada, Russia and China, and 20 SMRs engaged in pre-licensing activities around the world.

3. The Changing Risk Profile of NPP Operations

It appears from the literature that there will be less reliance on human operator actions as part of the defence in depth strategy for many SMR reactor designs. For example, NuScale states that their design "requires no operator action for 72 hours after any design basis event" (NuScale, 2020, pg.3). The GE Hitachi Safety Strategy for their BWRX-300 reactor also states that, for Design Basis Accidents (DBA), the Fundamental Safety Functions (FSFs) can be performed and maintained for 72 hours without operator action, and that some structures, systems, and components (SSCs) "can perform their necessary functions for a period up to 7 days following DBA" (GE Hitachi, 2022, pg.25).

HRA tends to focus on *post-initiator errors*, i.e., those human errors that directly contribute to an event, or errors that may compromise the effective mitigation of an event. For SMRs, it appears that there will be very few, if any, claims on the reliability of operator actions post-fault. Instead, it is expected that SMR risk assessments will centre on the reliability of the inherent design properties of the reactor, as well as passive safety systems to maintain cooling and containment after an event (Blackett, 2024).

3.1. *From Post-Initiator to Pre-Initiator Human Errors*

It may be tempting to assume that if there are no credited post-initiator actions in an SMR risk assessment, then there is no need for HRA for SMR NPPs: "The passive nature of the safety systems reduces the reliance on operator action, which could imply no inclusion of the operator error in the analysis" (Burgazzi, 2016, pg.6). However, the advancements in SMR designs do not necessarily remove the human contribution to risk and safety of the plant. It is much more likely that the risk will move from post-initiator errors to pre-initiator errors (Blackett, 2024), i.e., errors that indirectly cause the conditions for unwanted events to occur.

For example, to ensure the reliability of inherent design characteristics and passive safety systems, there may now be a greater need to evaluate the potential for human error during normal operation of these systems and plant components to ensure that they will work as required when needed in a post-fault situation (ibid.). Further, the potential for human error as a contributing factor to the initiation of an unwanted event still exists, since most SMR NPP designs still expect to use human operators to some extent in normal operations. Therefore, it is vital to understand what kinds of tasks operators will be expected to perform in these new kinds of plants.

4. Implementation of Automation in SMRs

As noted earlier, the reduction of costs through staff optimization is a key driver for the SMR business case. Some researchers and experts consider that this may be achieved by enabling some tasks to be performed remotely, and by "cross-training" staff in multiple disciplines so that operators can perform multiple roles: "Cross-training of plant staff in multiple disciplines and tasks is essential to operating with an optimum staff size… Cross-training of staff should be the expectation, not the exception." (EPRI, 2016, pg.2-6).

Others have considered the idea that the design advancements for SMR NPPs will fundamentally change the role of the operator: "Advanced reactors will use advanced digital instrumentation and control systems, optimize use of automation and passive components, and integrate new design configurations…. the emerging designs will have different allocation of functions, new operator roles and responsibilities, as well as different requirements for operator knowledge, skills, and abilities, all of which will lead to new operational concepts" (INL, 2014, pg. iii).

There is a common expectation in the open literature that SMRs will experience the implementation of much higher levels of automation when compared to conventional NPPs (US NRC, 2021; Le Blanc et al., 2017; Oxstrand and Le Blanc, 2014), or even fully autonomous operation (Fleming et al, 2020). This may help to explain why there is a reduced reliance on operator actions in post-fault event sequences: "For advanced reactors… the reliance on human intervention in safety-related actions is expected to be reduced or completely replaced by automated actions" (Hamza and Diaconeasa, 2022, pg.1).

4.1. *Allocation of Function for Humans and Automation*

Deciding which tasks should be performed by automation versus humans is typically done using a process called *function allocation*. Function allocation incorporates HF principles to ensure that the safety, reliability, and efficiency of industrial processes is maintained (Bye et al., 1999). According to these principles: "One should allocate functions in order to maximise the operator's situation understanding and ability to handle unexpected events" (ibid., pg.291).

One of the most commonly used approaches to function allocation is the *compensatory* approach (ibid.) in which the strong and weak characteristics of humans versus machines (or automation) are compared and functions are assigned based on the best fit according to these characteristics. This approach is also often referred to as the "Fitts List" (based on a report by Fitts et al., 1951) which included tables of human and machine capabilities) or *Men-are-better-at/Machines-are-better-at* (MABA–MABA).

This approach is still popular today, especially in the development of autonomous technologies (Roth et al., 2019). Despite its popularity, there has been a lot of criticism of the Fitts/MABA-MABA approach, including that replacing a previously manual action with an automated action fundamentally changes the nature of the work and creates *new* tasks for the human who now must interact with that automation. As pointed out by Roth et al. (ibid., pg.3): "These new tasks (e.g., monitoring system states and functioning) may, ironically, require what the Fitts report originally stated humans are bad at doing—namely, tasks requiring vigilance and little activity."

Furthermore, the MABA-MABA approach encourages a technology-centric approach, whereby functions are typically allocated to the automation first, with the remaining actions then "left-over" for the human. Roth et al., make a valuable point that: "This method of function allocation accommodates the limits of the automation, but not the human, which can lead to performance problems" (ibid. pg.3). They give the example that when automation fails (e.g., due to encountering a set of conditions that it was not designed for), then the expectation is that the human should take over the automation's functions. However, if the system is in a state where the automation fails, then it is likely that the human is already experiencing high workload, and the requirement to take over the functions previously performed by the automation may cause serious human performance detriments and increase the risk of human error.

4.2. *Function Allocation in Contemporary SMR Designs*

While high levels of automation seem to be a common characteristic across the range of SMR NPPs, it is less clear which function allocation approach is being used by the different designers and vendors. Function allocation reports for NPPs are typically not made available in the open literature for security reasons, and the literature that is openly available is highly redacted. Nevertheless, some insights can be gleaned.

Examples include the Human Factors Engineering Program Plan submitted by GE Hitachi to the Canadian Nuclear Safety Commission (CNSC) for the BWRX-300 Darlington New Nuclear Project (GE Hitachi, 2023). The chapter on Allocation of Function (AOF) states that: "AOF establishes a plant control scheme that enhances plant safety and reliability by taking advantage of human and machine strengths and avoiding human and machine limitations" (ibid., pg.20). This appears to conform to the compensatory or MABA-MABA approach. However, the document further states that "The AOF strives to provide personnel with logical, coherent, and meaningful tasks, and establishes a design that maintains human vigilance and situational awareness. The goal of the AOF is to provide acceptable workload levels per job role that minimize periods of human underload and overload to the extent possible" (ibid., pg.20). This indicates good awareness of the potential conflicts and risk of performance decrements described previously with respect to allocation functions between automation and humans.

Another example is a Human Factors Engineering Functional Requirements Analysis and Function Allocation Plan issued by NuScale to the US Nuclear Regulatory Commission (US NRC), which describes a more specific approach and includes a table of example criteria for function allocation (NuScale, 2015). The table indicates that designers should tend towards automation if, for example: the required response time is too short for an operator to react; there is a high probability of operator error; or, very precise control is required. Designers should tend towards operator functions if, for example: human knowledge and judgement are essential to ensure reliability system function performance; operating experience indicates that the function should be manual; or operator situation awareness must be optimized.

Again, the NuScale approach appears to adopt the compensatory / MABA-MABA approach, while acknowledging that maintaining operators' situation awareness is an important aspect of the function allocation approach.

5. Operator Roles and Responsibilities in a Highly Automated Plant

Seymour et al. (2022) note that a new Concept of Operations (ConOps) will be needed to describe, amongst other attributes, the new roles and responsibilities of human operators in SMR NPPs. They agree that the role of the operator is likely to be shaped by the degree and use of automation and other technological factors but argue that: "even within the context of a fully autonomous design, the need might still exist for human actions under certain circumstances, such as, perhaps, for the purpose of defense-in-depth" (ibid., pg.3).

5.1. *Operator Tasks in the Main Control Room*

It seems logical that reducing the requirements for tasks to be performed manually, instead allocating these to automated systems, will push the role of the operator towards one of monitor or supervisor, with only occasional requirements to manually intervene and manipulate plant components (Blackett et al., 2022a). Even if there are no claims on operator actions in the first 72 hours after a DBA, it is likely that operators will still be required to be present in the control room during this time to monitor and ensure that passive safety systems and automated systems have actuated and are performing as expected (Blackett, 2024).

An in-depth examination by Idaho National Laboratory (INL, 2013) of potential function allocations for an advanced reactor considers that the automation may have primary responsibility during an unwanted event (if the shutdown sequence is fully automated): "The human operator would have almost no control functions assigned to him or her in this failure mode, but would have many supervisory functions to perform… The operator's function would then be to monitor the relevant performance variables and to verify the performance of the automated safety systems" (ibid., pg.53).

Seymour et al. (2022) state that: "irrespective of any degree of automation, certain important administrative functions that must be implemented by a human being (e.g., technical specification implementation, configuration control, authorizing emergency-related departures from facility license conditions, notifications to offsite authorities, etc.) would still be required at any foreseeable advanced reactor facility, thus requiring that human roles continue to be considered outside of purely operational contexts" (ibid., pg.3).

5.2 *Operator Tasks in the Field*

As noted earlier, there is likely to be increased focus on pre-initiator human errors in the HRA for SMR NPPs, and thus there is a need to identify potential operator tasks that could contribute to unwanted events. A report by EPRI (2016) examined where and how technology may be used to support staff reduction across ten different technical areas. Of particular interest for HRA are maintenance and operations as these tend to impact plant safety more directly. For maintenance, the EPRI report notes that the use of standardized components will reduce plant complexity, and "enable a rapid remove-and-replace overall maintenance philosophy" (ibid. pg.3-6). This should simplify many maintenance tasks, both in terms of the task performance itself and verification afterwards. Presumably, plant components that are removed can then be repaired elsewhere (e.g., a workshop or offsite). Furthermore, the report notes that tasks such as maintenance work planning, tracking and management will be automated, removing the need for manual preparation of work orders, revision and approval, worker tracking, etc.

For operations, the EPRI report considers the use of 3D models (presumably akin to a digital twin) to allow: "determination of the physical status of plant configuration at any time. This results in minimizing the need for field verifications and for operators to physically go to specific locations confirming status of components" (ibid., pg.3-11). The report also states that automation will be used to monitor and analyse plant data: "to allow enhanced plant automated functions, the effective use of electronic procedures and automation of plant logs including narrative entries" (ibid.). The overarching concept is "to automatically and remotely monitor plant conditions and to apply electronic, automated processes to minimize operational staff time spent on routine, repetitive required functions" (ibid.). It is assumed that monitoring of these automated functions may then be performed by a reduced number of field operators, potentially the same operators located in the main control room (assuming these operators are appropriately cross-trained).

5.3 *New Operator Tasks at an SMR NPP*

A further aspect that must be considered is the potential for new operator tasks at an SMR NPP, as a result of the new use cases for SMRs, such as hydrogen production, district heating, etc. The INL report (2013, pg.10) notes: "It seems clear that operators will be faced with new tasks due to the increased ability of multi-modular plants to load-follow, to distribute load demand among multiple units, and to transition among different product streams." At the same time, the INL report states that: "This will be achieved through operational concepts that would include high levels of automation, advanced human-system interface technologies, computerized procedures, and on-line maintenance of multiple reactor units" (ibid.).

So, it seems that the tasks assigned to operators for these new kinds of use cases will still largely consist of monitoring automated processes, albeit for an extended set of plant systems and/or functions. To date, the literature review has not identified any completely novel operator tasks associated with SMR NPPs, although, again, this may be because of the lack of open literature on HF / HRA aspects of SMR operation.

5.4. *Factors Affecting Operator Task Performance*

There are several factors that may affect operator performance in SMR operations, and that should be considered when exploring operator tasks in SMR NPPs. For example, one major factor is the potential for multi-unit operation of SMRs; that is, the ability to operate multiple units as a single plant, from a single, centralised control room (Blackett et al., 2022b). The number of units that a single operator can safely manage alone will depend on the operating state of the different reactors, as well as the complexity of the operating scenario (Hartmann et al., 2024). The level of automation utilised at the plant will also have a significant impact, since presumably if operators are primarily responsible for monitoring highly automated units, then they should be able to oversee more than one unit concurrently. However, Hartmann et al. note that multi-unit operation can create high cognitive workload for operators because of having to repeatedly switch mentally between multiple reactors (ibid.).

Multi-unit operation could also increase the need for flexible and dynamic allocation of tasks between operators, as needed by the different units' operating states or operating processes occurring. For example, if one specific unit requires more attention, then operators will (re)distribute the workload between them to enable this (Hugo et al., 2014). Multi-unit operation is more likely to require multi-tasking and repeated mental switching (between units/processes), which can increase the cognitive workload and negatively impact the situational awareness (O'Hara et al., 2012; Hugo et al., 2014; Hartmann et al., 2024).

The level of automation (LOA) deployed in an SMR NPP may help to decrease the operators' cognitive workload, but Hugo et al. (2014) argue that it may also hinder situational awareness and stress the importance of keeping the human in the loop. O'Hara et al. (2012) consider learnings from non-nuclear systems and how these learnings may be applied to SMRs, specifically regarding automation. The authors suggest that the reliability of an automated system may affect the operator's performance and trust in automation.

7. Considerations for a Taxonomy of Operator Tasks in SMR NPPs

The main purpose of the research project funded by SSM is to develop a taxonomy of operator tasks for SMR NPP operations. A taxonomy: "is a means of classifying objects or phenomena in such a way that useful relations among them are established" (Miller, 1967, pg.167). In the absence of operating experience of SMRs, a taxonomy can help to describe and classify information about SMR operational tasks which may be new and/or different from tasks at conventional large NPPs. This may enable HRA analysts to better understand the potential operator tasks and performance influencing factors when evaluating risk significant scenarios and tasks for SMR design and licensing processes.

Table 1 outlines some potential attributes that a taxonomy of operator tasks for SMRs may need to consider, based on early findings from the literature review and expert interviews.

Table 1. Potential attributes to consider for the taxonomy.

Attribute	Examples
Reactor type	Light water, molten salt
Design concept	Single unit, multi-unit, remote
Function	Baseload, hydrogen production
ConOps	LOA, passive safety
Operation mode	Full power, low power, refuelling
Scenario	Normal ops, emergency, offline
Task location	Control room, field, remote

The taxonomy will be developed in the next phase of the project, based on inputs from the literature review and expert interviews. Both activities sought to identify the potential roles, responsibilities, and task activities of SMR operators, within different operating paradigms (single unit, multi-unit, etc.) To develop the structure of the taxonomy, existing human error taxonomies, and performance influencing factor taxonomies (e.g., Embrey, 1986; Kim and Jung, 2003) will be reviewed for inspiration.

8. Limitations of this research study

A major limitation for any research study on operation of SMRs is the lack of publicly available information on how the plants will be operated. Depending on the maturity of the different reactor designs, the designers/vendors may not yet know themselves how the plant will be operated as they may not have yet performed the necessarily AOF or task analyses. The publicly available licensing documentation for those designs where this has been performed is heavily redacted, meaning that detailed descriptions of operator roles, responsibilities or tasks are not open to the public.

There is also a lack of publicly available information on whether/how operator roles, responsibilities or tasks may change depending on the specific functional application of the reactor, i.e., whether it will be used for baseload electricity production or some other function such as hydrogen production, process heat, etc. To the best of our knowledge, no regulatory license applications have yet been submitted for such cases and so knowledge is limited in this area.

Furthermore, the number of control room simulators for different SMR designs are also limited, and access to these simulators tends to be highly restricted. Data from simulator studies tends to be proprietary and not openly published, again restricting access for the purposes of projects such as this one. This project does not have access to an SMR simulator to validate the taxonomy; instead, we plan to present the taxonomy in a workshop format with subject matter experts to collect feedback and suggestions for improvement.

9. Conclusions & Future Work

SMRs represent a paradigm change in how NPPs may be operated in the future, for reasons such as simpler reactor designs and higher levels of automation, as well as multi-unit operation and non-nuclear application. Analysis of the human contribution to risk requires a clear understanding of the roles and responsibilities for human operators in this new paradigm.

This paper presents some early results from a 2-year research study funded by the Swedish nuclear regulator, SSM. We present key findings from a literature review and initial thoughts on the potential attributes to consider when developing a taxonomy of tasks for SMR operations. At the time of writing, interviews are being conducted with Subject Matter Experts (SMEs) who will also provide valuable insights to the taxonomy.

Due to the limited availability of open literature and information on SMR operations, the taxonomy is likely to be speculative in nature. Validation of the taxonomy e.g., in an SMR simulator is unfortunately beyond the scope of this study. However, the aim is to present the taxonomy in a workshop with SMEs in the latter part of 2025 to collect feedback and suggestions for improvement. The results from the study will be published in two reports, an interim report in 2025 and a final report in 2026.

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