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Research

A Human Reliability Analysis (HRA) Taxonomy for Small Modular Reactors (SMR) – Part 1 of 2: Mapping the SMR landscape

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SSM 2026:06

SSM perspektiv

Bakgrund

Små modulära reaktorer (SMR) presenteras ofta som en säker och stabil lösning för energi som är snabbare att tillverka än traditionella reaktorer. Teknikens inneboende säkerhetslösningar, högre automationsgrad och ökad användning av passiva säkerhetssystem framhålls ofta som argument till att SMR kräver färre operatörer för den dagliga driften och för att hantera nödsituationer. Än så länge finns dock inte tillförlitliga data (drifterfarenhet) för att stödja detta resonerande.

Denna inledande rapport beskriver bakgrunden för att utveckla en taxonomi för HRA (Human Reliability Analysis – mänsklig tillförlitlighetsanalys), den utgår från en litteraturgenomgång och har kompletterats efter intervjuer med sakområdesexperter. Kunskap och erfarenheter har samlats in för att bättre förstå människans potentiella roller, ansvar och arbetsuppgifter i SMR, samt för att fånga upp faktorer som kan påverka människans prestation; för att ligga till grund för fortsatt utveckling av taxonomin.

Genom arbetsseminarier (workshops) utgående från den bakgrund som presenteras i denna rapport kommer projektet i en avslutande rapport presentera en taxonomi för HRA av SMR och ge förslag på fortsatt utveckling.

Resultat

Resultaten pekar på att graden av automation kommer att ha en stor påverkan på vilka roller och arbetsuppgifter människa kommer att ha i SMR.

Litteraturstudien och intervjuer med experter pekar tydligt på att det inte finns mycket allmänt tillgängliga erfarenheter från drift av SMR. Det är dessutom utmanande att det ä ren brist på information om hur framtida SMR är tänkta att användas.

I förberedelser för att samla in drifterfarenheter från SMR kan det vara nyttigt att utveckla en gemensam förståelse för de utmaningar som därmed uppstår för såväl myndigheter som potentiella tillverkare och tillståndshavare.

Relevans

Mycket av det som är känt om mänsklig tillförlitlighet inom kärnkraftsindustrin kommer från manuell drift av en reaktor från ett centralt kontrollrum. Det är viktigt att identifiera vilka uppgifter det är troligt att SMR-operatörer kommer att utföra och hur deras prestation kan påverkas av ett verkets utformning och användningsområde (ex. produktion av el, värme eller vätgas). Allmängiltiga verktyg, såsom en HRA taxonomi, kan vara användbara för olika intressenter i att jämföra och värdera olika reaktorers design.

Rapporten drar slutsatsen att HRA för SMR kommer att behöva redogöra för latenta fel till en högre grad än vad som traditionellt har behövts. Allteftersom människans roll förändras från att aktivt styra en anläggning till att övervaka och underhålla anläggningen (för att säkerställa att automatiserade funktioner och passiva säkerhetssystem fungerar) – så kommer andra mänskliga felhandlingar (*human error*) komma att behöva mer uppmärksamhet. När människa inte längre aktivt styr anläggningen är det möjligt att antalet felhandlingar minskar i den skarpa änden – men å andra sidan kan det innebära minskade möjligheter för människan att kompensera för latenta fel som inte är omhändertagna i designen. Dessutom kan det manuella arbete och underhåll som fortfarande behöver utföras få en större påverkan på säkerheten än vad de har idag – till följd av att driften av SMR i högre grad baseras på automation och passiva säkerhetssystem. Den inverkan som arbetsuppgifter utförda av driftoperatörer och underhållspersonal har på säkerheten behöver studeras vidare.

Bristen på drifterfarenhet från SMR och empiriska data på människors interaktion med högautomatiserade system gör det utmanande för presumtiva tillståndshavare och granskande myndigheter att bedöma om en SMR-design, inklusive affärsmodell och användningsområde, är tillräckligt säker.

Behov av vidare forskning

Utifrån vad som kommer fram i denna rapport finns det behov av fördjupad förståelse för människans roll i SMR och andra högautomatiserad system, så som fjärrdrift och drift av flera reaktorer från samma kontrollrum. Innan det finns mer drifterfarenhet kan fortsatt arbete med en HRA taxonomi hjälpa till med att förstå manuella uppgifters potential i SMR, vilken påverkan de kan ha och vilka scenarier som kan vara relevanta för tillståndshavare och granskande myndigheter att använda vid värdering av en föreslagen SMR.

Projektinformation

Kontaktperson SSM: Johan Enkvist
Referens: SSM2024-9697 / 4530757

SSM perspective

Background

Small Modular Reactors (SMRs) are typically presented as a solution for safe and reliable energy, requiring less time to construct than the traditional large reactors. The inherent safety features, higher levels of automation and increased reliance on passive safety are often held as reasons for fewer operators being needed in the daily operations and for handling emergencies. However, there are not yet any reliable data (operational experience) to support this assumption.

This report is the first of two, establishing a background for developing a HRA (Human Reliability Analysis) taxonomy, consisting of a literature review and interviews with subject matter experts. This is done to collect information on potential operator roles, responsibilities and tasks in SMRs, as well as on factors that may affect operator performance, that will inform the further development of the taxonomy.

Drawing on experiences from workshops based on the background provided here, a second (final) report will present a taxonomy for HRA of SMRs and give suggestions for further developments.

Results

The results indicate that the level of automation will have a great impact on what role and tasks the human will have in SMRs.

From the literature review and the interviews, it is clear that there is not much publicly available experience from operating SMRs. It is also a challenge that there is a lack of official information regarding how future SMRs are intended to be operated.

In preparation for gathering experience from operating SMRs it could be useful to develop a common understanding of the challenges for vendors, licensees and regulators.

Relevance

Much of what is known about human reliability in the NPP domain is derived from manual operations in a central control room, dedicated to one reactor. It is important to identify what tasks SMR operators are likely to perform and how their performance might be affected by plant design and operating paradigms. Common tools, like a HRA taxonomy, could be useful for different stakeholders in comparing designs and assessments of them.

The report concludes that HRA for SMRs will need to account for latent errors to a higher degree than is needed traditionally. As the human role shifts from actively operating the plant to monitoring and maintaining the plant (making sure that the conditions for the automated functions and passive safety features are upheld), other human errors might need more attention. Without the human in active control, perhaps fewer human errors are made at the sharp end – consequently, the human operator could have less opportunity to compensate for latent errors. Also, the field work and maintenance that still needs to be done could have a larger impact on safety than today due to SMR reliance on automation and passive safety features. The tasks performed by field workers and maintenance personnel need further attention.

The shortage of operating experience from SMRs and empirical data on human interaction with highly automated systems makes it challenging for licensees and regulators to assess if an SMR design, including business model and operating regime, is sufficiently safe.

Need for further research

Given the findings in the report there is a need for deeper understanding of the human role in SMRs and other highly automated designs, including remote and multi-module operation. Until we have more operating experience, further work on an HRA taxonomy can help in understanding the potential human tasks in SMRs, what their impact could be and what scenarios could be relevant for licensees and regulators to use in assessing a proposal.

Project information

Contact person SSM: Johan Enkvist
Reference: SSM2024-9697 / 4530757

Contents

Summary

This report presents the results from work package (WP) 1 of the research study titled “A Taxonomy for Human Reliability Analysis of Small Modular Reactors”. The study is performed by Risk Pilot and is funded by Strålsäkerhetsmyndigheten (SSM). The goal of the study is to develop a taxonomy of generic operator tasks in Small Modular Reactor (SMR) plants to support Human Reliability Analysis (HRA) for these plants. WP1 consisted of a literature review and interviews with subject matter experts to collect information on potential operator roles, responsibilities and tasks in SMRs, as well as factors that may affect operator performance, that will inform the taxonomy development. WP2 will build on these results to identify generic SMR operator tasks and organise these into a taxonomy. A final report from this research project, including the findings from WP2, is planned by fall 2026.

The findings from WP1 indicate that there is likely to be a high level of uncertainty in early HRAs for SMRs. This is due to the changing paradigm of SMR operations and the scarcity of operating experience and human performance data on aspects of this new operating paradigm. This creates a challenge not only for HRA analysts, but also for other stakeholders including vendors, licensees and regulators, regarding how much uncertainty is tolerable at the beginning of this new nuclear era. Some uncertainty can be offset against the increased reliability of the inherently safe designs of SMRs, but it does not remove the need for robust analysis of the potential human contribution to risk. Investigation of the uncertainty challenge is outside the scope of this research project, but it is documented in this report as it is considered a significant finding and an area for future research.

The literature review discovered a lack of publicly available information on how SMRs are expected to be operated in the future, which is a known problem. Nonetheless, a study from Idaho National Laboratory (INL) was uncovered which offered a deep dive into the role of control-room operators at a concept molten salt reactor, including details of how operators are likely to work in a highly automated plant. The findings from both the literature review and the expert interviews indicate that automation will be a key driver in determining the roles and responsibilities of the operator in SMRs, as well as the number of staff available to perform the necessary tasks, which in itself will be heavily influenced by the level of automation.

As for conventional large nuclear power plants (NPPs), there are a wide variety of known factors that will have an impact on determining the operator’s role and performance in that role. However, there are specific factors, some of which are unique to SMRs, that may change the role of the operator in comparison to conventional NPPs. For example, the reactor design itself, the configuration of the reactor (e.g. single unit, multi-module, remote), and the application of the plant (i.e. whether it is used for baseload electricity production, cogeneration, or another application) will all have an impact on what the operator must do and how they do it. All of these factors will have to be taken into consideration when developing the taxonomy.

Sammanfattning

Denna rapport presenterar resultaten från arbetspaket (WP) 1 i forskningsstudien”En taxonomi för analys av mänsklig tillförlitlighet i små modulära reaktorer”. Studien utförs av Risk Pilot och finansieras av Strålsäkerhetsmyndigheten (SSM). Målet med studien är att utveckla en taxonomi för generiska operatörsuppgifter i små modulära reaktorer (SMR) som ska stödja analys av mänsklig tillförlitlighet (HRA).WP1 bestod av en litteraturgenomgång och intervjuer med ämnesexperter för att samla in information om möjliga operatörsroller, ansvarsområden och uppgifter i en SMR, samt faktorer som kan påverka operatörernas prestanda, vilket kommer att ligga till grund för utvecklingen av taxonomin.WP2 kommer att bygga vidare på dessa resultat för att identifiera generiska SMR-operatörsuppgifter och organisera dessa i en taxonomi. En slutrapport från detta forskningsprojekt, inklusive resultaten från WP2, planeras till hösten 2026.

Resultaten från WP1 indikerar att det sannolikt kommer att finnas en hög grad av osäkerhet i de tidiga HRA:erna för SMR:er. Osäkerheten beror på paradigmskiftet med drift av SMR samt bristen på driftserfarenhet och data om mänsklig prestanda. Detta skapar en utmaning när det gäller hur mycket osäkerhet som är acceptabel i början av denna nya kärnkraftsera; inte bara för HRA-analytiker, utan också för andra intressenter, inklusive leverantörer, tillståndshavare och tillsynsmyndigheter. En del osäkerhet kan dock uppvägas av den ökade tillförlitligheten hos SMRs inneboende säkra konstruktioner, men detta eliminerar inte behovet av en robust analys av det potentiella mänskliga bidraget till risken. Att utforska osäkerhetsutmaningen ligger utanför ramarna för detta forskningsprojekt men utmaningen dokumenteras i denna rapport eftersom den anses vara en signifikant upptäckt och ett område för framtida forskning.

Litteraturgenomgången visar att det saknas offentligt tillgänglig information om hur SMR förväntas drivas i framtiden, vilket är ett känt problem. Dock hittades en studie från Idaho National Laboratory (INL) som gav en djupgående inblick i kontrollrumsoperatörernas roll i en konceptuell smältsaltreaktor, inklusive detaljer om hur operatörerna sannolikt kommer att arbeta i en högautomatiserad anläggning. Resultaten från både litteraturgenomgången och expertintervjuerna tyder på att automatisering kommer att vara en viktig drivkraft för att fastställa operatörens roll och ansvar i en SMR, liksom antalet anställda som finns tillgängliga för att utföra nödvändiga uppgifter. Antalet anställda kommer i sig att påverkas starkt av automatiseringsgraden.

När det gäller konventionella kärnkraftverk finns det en mängd kända faktorer som kan påverka operatörens roll och prestation. I en SMR finns det dock vissa unika faktorer som kan förändra operatörens roll jämfört med konventionella kärnkraftverk. Till exempel kommer reaktorns konstruktion, konfiguration (t.ex. fjärrstyrning, *singel unit*, eller *multi-module*) och anläggningens tillämpning (dvs. om den används för baslastproduktion, kraftvärme eller någon annan tillämpning) att påverka vad operatören behöver göra och hur de ska göra det. Alla dessa faktorer måste beaktas när taxonomin utvecklas.

Abbreviations

AdvSMR	Advanced Small Modular Reactor
AI	Artificial Intelligence
AOF	Allocation of Function
BWR	Boiling Water Reactor
CNSC	Canadian Nuclear Safety Commission
ConOps	Concept of Operations
DBA	Design Basis Accident
DSA	Deterministic Safety Assessment
EBR	Experimental Breeder Reactor
EPRI	Electric Power Research Institute
FSF	Fundamental Safety Function
HABA	Humans are Better At
HEP	Human Error Probability
HF	Human Factors
HFE	Human Failure Event
HMI	Human-Machine Interface
HRA	Human Reliability Analysis
HSI	Human-System Interface
HTGR	High-temperature Gas Reactor
HTO	Human Technology Organisation
HTR-PM	High-temperature Reactor-pebble-bed Module
HWR	Heavy Water Reactor
IAEA	International Atomic Energy Agency
IFE	Institute for Energy Technology
INL	Idaho National Laboratory
LOA	Levels of Automation
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MABA	Machines Are Better At
NPP	Nuclear Power Plant
O&M	Operations and Maintenance
OOTL	Out-of-the-loop
OPEX	Operating Experience
PSA	Probabilistic Safety Assessment
PSF	Performance Shaping Factors
PWR	Pressurised Water Reactor
SA	Situation Awareness
SEALER	Swedish Advanced Lead Reactor
SFR	Sodium Fast Reactor
SMR	Small Modular Reactor
SSC	Structures, Systems and Components
SSM	Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority)
US NRC	United States Nuclear Regulatory Commission
WDA	Work Domain Analysis
WP	Work Package

1. Introduction

This chapter describes the background and motivation for the research project, as well as the purpose and scope of this report.

1.1 Background

Small Modular Reactors (SMRs) represent a radical shift in how nuclear power plants (NPPs) will be operated. Many SMR designs propose advanced characteristics such as smaller and simpler plants, integral and modular plant systems, increased use of automation, and increased reliance on inherent safety properties and passive safety systems. These characteristics (explained in more detail in Chapter 3) will have an impact on Human Reliability Analysis (HRA) as they will result in some changes to the operator roles and responsibilities at SMR plants, as well as changes to assumptions about human performance in SMR operation.

The simpler plant designs and higher levels of automation promise reduced complexity and fewer systems or components for operators to oversee. This potentially allows for new operating paradigms such as multi-module operation and/or remote operation, whereby operators could oversee more than one reactor unit at a time and could do so from a control room that is geographically distance from the reactor site. Advances in automation, artificial intelligence (AI) and sensor capabilities potentially enable partial- or fully autonomous operation. Furthermore, SMRs offer the possibility to extend beyond the traditional application of NPPs (i.e. baseload electricity production) and into different applications such as hydrogen production, seawater desalination, district heating, co-production load following with renewable energy systems, industrial heat production, etc.

These advanced characteristics are intended to improve the safety of SMR operations, but also to reduce the cost of running an NPP through staff optimisation whilst still meeting the requirements for safe and reliable nuclear operation. As a result, the role of the operator in SMR NPPs is expected to change significantly by comparison to conventional large NPPs. In a conventional NPP, operators are typically responsible for manually initiating and intervening in plant operation and control. By contrast, SMR NPP operators are expected to be mainly responsible for monitoring and checking automated processes, and only intervening at key process or decision points, or if something goes wrong. It is anticipated that there will be some manual actions for operators to perform, but the number and complexity of these are expected to be greatly reduced by comparison to a conventional large NPP.

HRA is a structured methodology used to analyse potential Human Failure Events (HFE) in a given scenario and to systematically calculate the Human Error Probability (HEP) of those events occurring. HRA uses qualitative data about how tasks in the scenario are performed to determine where there may be vulnerabilities and opportunities for human error. The advanced characteristics and changing operating paradigm of SMRs mean that our current knowledge, experience and assumptions about human performance and human reliability may no longer be valid, as these are based on years of analysis of operator actions at conventional large NPPs. Existing HRA methods and approaches may not adequately capture the extent or impact of the potential changes to operational tasks and scenarios for SMR NPPs. While the simpler design of SMRs and the increased use of automation may simplify tasks or reduce the need for manual actions, the new operating paradigms may introduce complexity elsewhere. The lack of data, the novelty of SMR designs and operational concepts, and the changing risk profile of SMRs may create high levels of uncertainty for HRA analysts. Indeed, even knowing where to start to identify candidate fault scenarios and tasks for analysis may be a challenge.

Furthermore, although there are expected to be fewer claims on operator actions in SMR Deterministic and Probabilistic Safety Assessments (DSA/PSA), it is anticipated that the role of the operator as a safety barrier in an SMR will be at least as important as at a conventional NPP. It is highly likely that human operators will still form part of the defence-in-depth approach if automation or other inherent or passive safety systems fail or do not work as required.

When analysing human reliability and human performance it is important to understand the human contribution to risk for SMR NPPs. Since there are very few commercial SMR NPPs in operation yet, information that would typically be used to inform HRA, such as operating experience (OPEX), functional analyses and operating procedures, are not yet available. Furthermore, to date there has been very little information published in the open literature about the specific roles and responsibilities of operators in SMR NPPs, so it is difficult for HRA analysts to interpret what kinds of tasks operators may have to perform to evaluate where the risk of human error may lie.

A system that identifies and categorises generic SMR operator tasks could provide a valuable input to HRA analysts, especially when detailed documentation is not yet available (e.g. during preliminary analyses at the beginning of design projects). A taxonomy, which is “a means of classifying objects or phenomena in such a way that useful relations among them are established” (Miller, 1967, pg. 167), could provide a useful tool to identify, organise and define the roles, responsibilities, and tasks of operators in SMRs and a clearer framework for how to analyse human interactions with automated systems, passive safety systems and the operational processes of the plant. The goal of this research project is to develop such a taxonomy.

1.2 Project Scope & Goal

The project is divided into three WPs, as follows:

- **WP1 – Map the SMR task landscape:** this WP aims to identify generic tasks that are likely to be performed by human operators in SMR plants, as well as potential Performance Shaping Factors (PSFs) that may influence the performance of those tasks. It comprises a review of publicly available literature and SMR licensing documentation, as well as interviews with subject matter experts.

- **WP2 – Organise tasks and factors into a taxonomy:** this WP aims to collate the findings from WP1 and organise these into a taxonomy. The WP2 will include a workshop with subject matter experts to present an initial draft of the taxonomy for review and discussion.

- **WP3 – Results communication and dissemination:** this WP focuses on organising the documentation of the project results and dissemination via formal reporting to SSM as well as publication of conference papers.

The overall goal of this project is to develop a taxonomy of generic operator tasks in SMR NPPs, that aims to support HRA analysts in performing preliminary analysis of the human contribution to risk. Specifically, the taxonomy aims to support the initial steps of the HRA process: problem definition and task analysis. See Section 4.2 for more details on the need for a taxonomy to support these HRA steps.

The taxonomy will attempt to classify and describe information about SMR operational tasks that may be new or different from typical tasks performed at a conventional large NPP. Where possible, links will be made to potential PSFs that can influence operators' ability to conduct the tasks as required.

It is anticipated that a taxonomy will enable HRA analysts to better understand the potential operator tasks and PSFs when evaluating risk significant scenarios and tasks for SMRs. The taxonomy is also expected to be useful to stakeholders such as vendors, regulators and licensees by providing a landscape, a common language, and a common understanding of how different SMR designs and operational concepts may affect human tasks, and the overall safety and risk picture for SMR plants. The taxonomy may also be useful for human factors engineering analysts, as part of the identification of important human actions (as described in NUREG-0711 (US NRC, 2012)) which typically takes input from the HRA. However, consideration of the types and presentation of information for human factors engineering is outside the scope of this research project, and so no further consideration is given to how the taxonomy could serve as an input to human factors engineering analyses.

1.3 Purpose of this Report

This report documents the findings from WP1 of the project, titled "Map the SMR task landscape", which focused on data gathering to inform the taxonomy development. The taxonomy will be developed in WP2 and will be reported separately.

1.4 Structure of this Report

The report is structured as follows.

Chapter 2 of this report outlines the methodology used for both data collection and data analysis of the literature review and the interviews with subject matter experts. This chapter also records the limitations of the project which should be taken into consideration when reading the results.

Chapter 3 describes the generic design, operational and functional philosophies of SMRs. The goal of this chapter is to provide a baseline understanding of what SMRs are, how they differ from conventional plants, and some of the unique operational and functional philosophies that are likely to have an impact on operator roles, responsibilities and tasks.

Chapter 4 provides an overview of the generic HRA process, and the two steps of interest for this project, namely problem definition and task analysis. The chapter describes how the unique designs and characteristics of SMRs are likely to change the risk profile when compared to conventional NPPs, and the challenges that these are likely to pose for HRA analysts.

The findings from the literature review are presented in Chapter 5. To set the context for the literature review findings, the chapter focuses first on describing how automation is expected to be implemented in SMRs (Section 5.1). The findings are then presented according to how operator tasks are typically considered in HRA, i.e. operator tasks that are performed in the main control room (Section 5.2), and operator tasks that are performed outside of the main control room (Section 5.3). New operator tasks are also considered (Section 5.4), and a case study from a concept molten salt reactor is summarised as an example of how operator roles may be affected by advanced automation (Section 5.5). Finally, the chapter describes three key PSFs that are likely to impact human performance at SMR NPPs (Section 5.6).

Chapter 6 presents the finding from the subject matter interviews that were conducted in early 2025. The findings are organised according to the main themes that emerged from the interview data analysis, namely:

- Roles and responsibilities for operators in SMRs
- New operator tasks in SMRs
- Main drivers for change in operator roles and responsibilities
- Potential safety challenges for operators in SMRs
- Performance shaping factors in SMRs

Chapter 7 presents a discussion of the findings in relation to the overall objective of the project, which is to develop a taxonomy of operator tasks for SMRs. The chapter documents reflections on the findings from the literature review and interviews, as well as the implications of these findings for HRA for SMRs. The chapter concludes with considerations for developing the taxonomy of SMR tasks.

There are four appendices included in this report, which contain the following:

- Appendix 1 – Tables from the Case Study on Operator Roles in a Molten Salt Reactor (documented in Chapter 5)
- Appendix 2 – Interview documentation
    - Invitation to Interview
    - Interview Consent Form
    - Interview Guide

2. Study Method

This chapter outlines the study method that was applied during WP1 of this project, as well as some limitations of the project. The project is carried out by Claire Blackett and Ella Olson at Risk Pilot, with support from Benjamin Langerak Tottie, also at Risk Pilot.

Data gathering for WP1 was performed across three activities:

- Literature review,
- Licensing documentation review, and
- Interviews with subject matter experts.

2.1 Literature Review Method

The literature review was conducted by searching for international publicly available literature, such as published reports, conference papers, journal papers and articles. The search targeted literature on HRA for SMRs, as well as more general human factors (HF) research related to SMR operations. The literature search focused on identifying publications that describe or provide insights into:

- The potential roles and responsibilities of operators in SMRs,
- The types of tasks that operators may have to perform, and
- The factors that may affect operators in performing these tasks.

The search attempted to identify literature on control room operations as well as field and maintenance activities.

A review was also performed of publicly available licensing documentation, that is, documentation submitted by SMR vendors and/or operating companies to regulators, with the goal of obtaining a nuclear reactor operating license. Licensing documentation was retrieved from the public access pages of the nuclear regulatory authorities in the UK, USA, and Canada. The review of the licensing documentation included:

- Exploration of whether/how operational concepts are defined,
- Whether/how the nuclear power facility will be staffed, and
- Any details on, e.g. control room layout, human-machine interfaces (HMI) etc. that might indicate how the plant will be controlled and operated.

2.2 Literature Data Analysis

The literature review material was analysed using a qualitative, interpretive approach. The objective of the analysis was not to quantify findings, but rather to map existing knowledge on potential operator roles and responsibilities, to identify potential gaps in knowledge, and to extract any insights relevant to what kinds of tasks operators may be expected to perform in SMRs. The focus was on understanding the range and depth of information available, rather than trying to find exact descriptions of future SMR operational tasks.

During the review, relevant sections of the documentation were highlighted and detailed notes summarising key points and quotes were recorded in a separate document. Once all the literature had been reviewed, the notes and summaries were examined to identify recurring themes, conflicting perspectives, and instances where specific operator roles, responsibilities or tasks were mentioned or implied. Differences or conflicts in the literature were reported as observed, as well as gaps in the knowledge.

The extracted information was then synthesised under a set of thematic headings aligned with the main topics of interest in the study. This structured approach enabled a clear and organised presentation of the literature findings, while ensuring alignment with the overall objectives of the research.

2.3 Interview Method

Interviews with subject matter experts were conducted throughout January and February of 2025. Potential interviewees were identified through their contributions to various SMR industry, research, and regulatory fora, such as conferences, technical meetings, etc.

Potential interviewees were sent some documentation in advance of the interviews – see Appendix 2. This included a short summary of the goals and objectives of the SSM study with the invitation to interview. Invitations were sent by email in December 2024, with the goal of conducting interviews in the period January – February 2025. Approximately one week before the confirmed interview date, the participants were sent a consent form, outlining some basic information about the interview process, how the results would be reported, and their right to withdraw at any time. Participants were asked to review, sign, and return the consent form via email in advance of the interview. The interviews were conducted in-person or via Microsoft Teams and were recorded using the Teams in-built recording capability. Microsoft Teams automatically produces a transcript of the recording. Interviewees were informed of this at the beginning of each interview, and the transcript is subject to the same data privacy and data storage rules as the recordings.

A semi-structured approach was utilised for the interviews, allowing for a more flexible and fluid conversational structure following an interview guide that was developed in advance (see Appendix 2). Depending on the flow of conversation and the amount of time available in individual interviews, some questions were dropped to ensure focus on the highest priority questions/topics for discussion.

2.4 Interview Data Analysis

The interview material was analysed using a qualitative, interpretive approach. The objective of the analysis was not to quantify the frequency of particular responses, but rather to identify relevant insights, recurring themes and novel contributions that could inform the overall aims of the study. Considering the diversity of the interviewees' backgrounds, experience and perspectives, the focus of the analysis was on the range and depth of information provided, rather than representativeness.

Following the completion of all the interviews, the detailed notes taken during the interviews were revisited and key points were identified and reviewed in light of the study's core objectives. Information was then collated under five broad headings (see Sections 6.2.1 to 6.2.5) aligned with the major thematic areas in the interview guide. This allowed for a structured synthesis of the material. To ensure confidentiality, the interview content was paraphrased and summarised, rather than directly quoted.

2.5 Limitations of the Project

There are some limitations of this project which should be noted when reading the results.

- A major limitation for any research study on the 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 necessary allocation of function or task analyses. The publicly available licensing documentation for designs where this has been performed is often 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.

- To date, only a small number of control room simulators for SMR design concepts have been built, and access to these simulators (e.g. to explore different kinds of operator tasks) tends to be highly restricted. Data from simulator studies is often proprietary and/or access to the data is restricted to certain membership groups and is not openly published. This project does not have access to an SMR simulator to explore the main ideas, concepts or findings from the project.

Access to proprietary information or simulator data is beyond the scope of this project. The findings documented in this report are based entirely on the open literature and non-proprietary information shared by in the subject matter expert interviews at the time that the work was carried out.

3. SMR Design, Operational and Functional Philosophies

This chapter describes some typical characteristics of SMR designs and also considers the most common operational and functional concepts that are discussed the open literature today.

3.1 Definition of an SMR

For the purposes of this report, we adopt the International Atomic Energy Agency (IAEA) definition of SMR, which is (IAEA, 2022, pg. 2):

"SMRs are advanced nuclear reactors with a power capacity of up to 300 MW(e), and whose components and systems can be factory built and then transported as modules to sites for installation as demand arises."

The smaller power output of SMRs reflects the main defining characteristic of these new types of plants which is that they are significantly smaller in size than the conventional NPPs in operation today. Figure 1 shows an example size comparison of an SMR plant versus a conventional NPP.

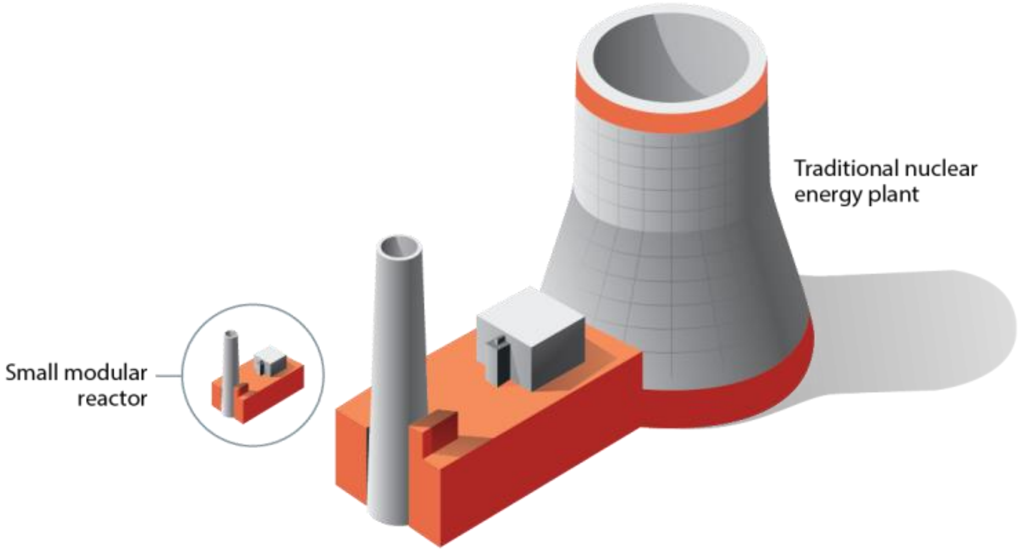


Figure 1: Size comparison of SMR versus conventional NPP (INL, 2025)

The smaller size of the SMR is achieved through several design advancements and changes. For example, many SMRs feature intrinsic, or integral designs where primary components that are traditionally located outside of the reactor pressure vessel are typically integrated into the same vessel as the reactor core (see example in Figure 2).

Furthermore, SMRs have a much smaller reactor core than conventional nuclear reactors, hence the lower power output of SMRs. Many SMRs have simpler, compact designs that use fewer components, fewer electrical systems, and fewer mechanical systems. Instead, safety boundaries are maintained through reliance on inherent safety properties of the design, as well as passive safety systems that use natural phenomena such as gravity, differential pressure, and natural air circulation.

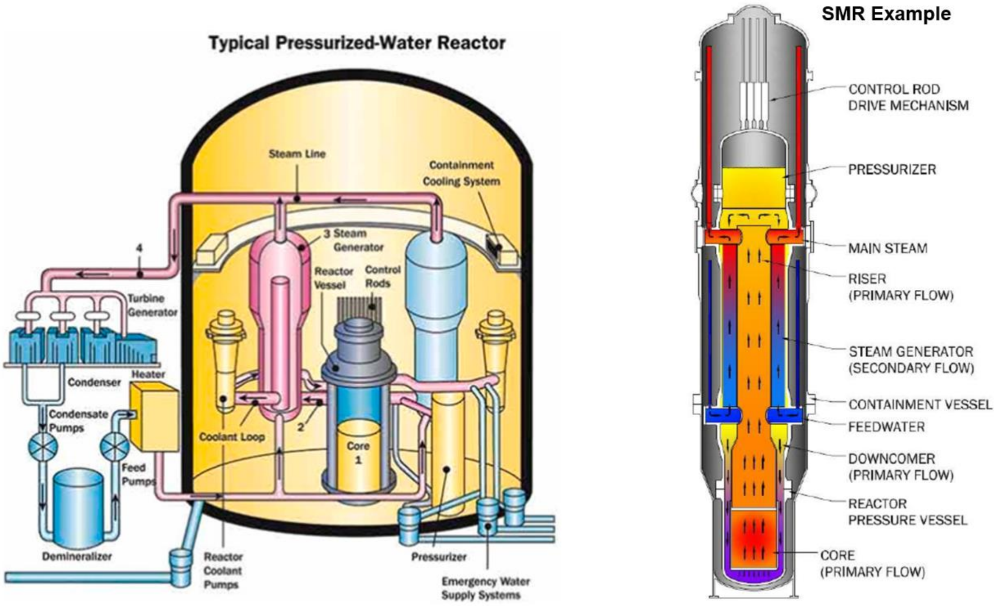


Figure 2: Extrinsic design of a conventional reactor (left; Black et al., 2019) compared to the intrinsic/internal design of an SMR (right; Ingersoll et al., 2014).

There are currently only two commercial SMRs in operation today (IAEA, 2024):

- In China: the high-temperature reactor-pebble-bed module (HTR-PM), which began commercial operation in December 2023. The HTR-PM features two 200 MWe reactors.
- In Russia: the KLT-40S 35 MWe reactor, which is a marine-based pressurised water reactor (PWR) that has been operational since 2020.

3.2 Typical Characteristics of SMR Designs

Table 1 compares several characteristics between SMRs and conventional reactors. Not all SMR designs will include all the characteristics listed here, but many SMR designs will incorporate one or more of these characteristics.

Table 1: Characteristics of SMR NPPs compared to Conventional NPPs (adapted from Blackett et al., 2022)

SMR NPP Design Characteristics	Conventional NPP Design Characteristics
Lower power output (10 – 300 MWe).	Higher power output (700 – 1400 MWe).
Smaller physical footprint (~0.5km^2).	Larger physical footprint (~2km2).
Integral design: primary system components (reactor core, steam generators, pressuriser, etc.) contained within a single vessel.	Extrinsic design: primary system components located outside of the reactor pressure vessel.
Modular design enables factory fabrication offsite, with final ~10% construction/assembly onsite.	Some modular design, but ~70% - 80% of the plant is constructed and assembled onsite.
Scalable design enables easier addition of reactor units to the site over time to increase total power output.	Final number of units must be planned in advance due to large size and long construction times; plants typically designed for 1-4 units in total over the plant lifetime.
Increased reliance of passive safety systems (gravity, pressure differential, natural circulation, etc.).	Reliance on active safety systems that require electrical or mechanical power, signals or forces.
Increased reliance on automation, and less reliance on manual actions by operators; possibility for fully or partially autonomous systems or reactor units.	Less reliance on automation (compared to SMR), with higher reliance on manual intervention and control of the plant by operators.
Capabilities to monitor and control multiple units from a single, centralised main control room, by a single control room operating team (multi-unit operation).	Typically designs to manage between 1-4 reactor units from a single main control room, with one dedicated control room operating team per reactor unit (single unit operation).
Reduced staffing per reactor unit, both within the main control room and throughout the plant, with increased use of cross-trained staff (i.e. staff trained in more than one specific discipline, such as maintenance and chemistry).	Higher number of staff per reactor unit, both in the control room and throughout the plant. Staff typically trained in and working in one discipline only.
Increased possibilities for deployment, including for baseload electricity production, load following, cogeneration, hydrogen production, seawater desalination, district heating, etc.	Typically built only for baseload electricity production, although some conventional NPPs also have capability for hydrogen production.

3.3 Types of SMRs in Development

The IAEA defines six categories of SMR technologies, noting that there are in total 68 active designs in development as of 2024 (IAEA, 2024). The six categories of SMR technologies are as follows:

- **Land-based water-cooled SMRs** (14 active designs) – these are largely based on mature reactor technologies that are prevalent in conventional large reactors. Designs include different types of pressurised water reactors (PWRs) and boiling water reactors (BWRs), utilising light water reactor (LWR) and heavy water reactor (HWR) technologies. Examples include the NuScale VOYGR, the GE-Hitachi BWRX-300, the Rolls-Royce SMR and the EDF-NUWARD, all of which are planned for near-term deployment.

- **Marine-based water-cooled SMRs** (6 active designs) – these are barge-mounted floating power units, designed to offer more flexible deployment options as they are not necessarily fixed to a single geographical location. An example is the KLT-40S reactor on board the Akademik Lomonosov floating NPP, which has been in operation in Russia since 2020.

- **Gas-cooled SMRs** (14 active designs) – these are high-temperature gas-cooled (HTGR) reactors that can provide high-temperature heat (≥ 750°C) for electricity generation, industrial applications and cogeneration (combined heat and power generation). Examples include the high-temperature reactor-pebble-bed module (HTR-PM) which was connected to the grid in China in 2021 and has operated at full power since 2022.

- **Liquid metal-cooled fast-neutron SMRs** (10 active designs) – the coolants for these reactor types may include sodium, pure lead and lead-bismuth eutectic. Examples include a lead-cooled fast reactor by Newcleo in France, a sodium-cooled fast reactor by Oklo in the USA, and the Blykalla SEALER (Swedish Advanced Lead Reactor) lead-cooled reactor in Sweden.

- **Molten salt SMRs** (11 active designs) – these reactors offer enhance safety through the use of low-pressure single-phase coolant systems, which also offer high efficiency and flexible fuel cycles. Examples include Terrestrial Energy in Canada, Moltex Energy in the UK, and Seaborg in Denmark, which has a concept design for a molten-salt reactor on a floating NPP barge (see Figure 3).

- **Microreactors** (13 active designs) – these are the smallest of the SMR designs, the typically generate up to 20MW(e)/30MW(th). They can use a variety of coolants, such as light water, helium, molten salt, liquid metal or heat pipe cooling. Microreactors are targeted at more niche markets such as remote areas and disaster recovery. An example is the Westinghouse eVinci.

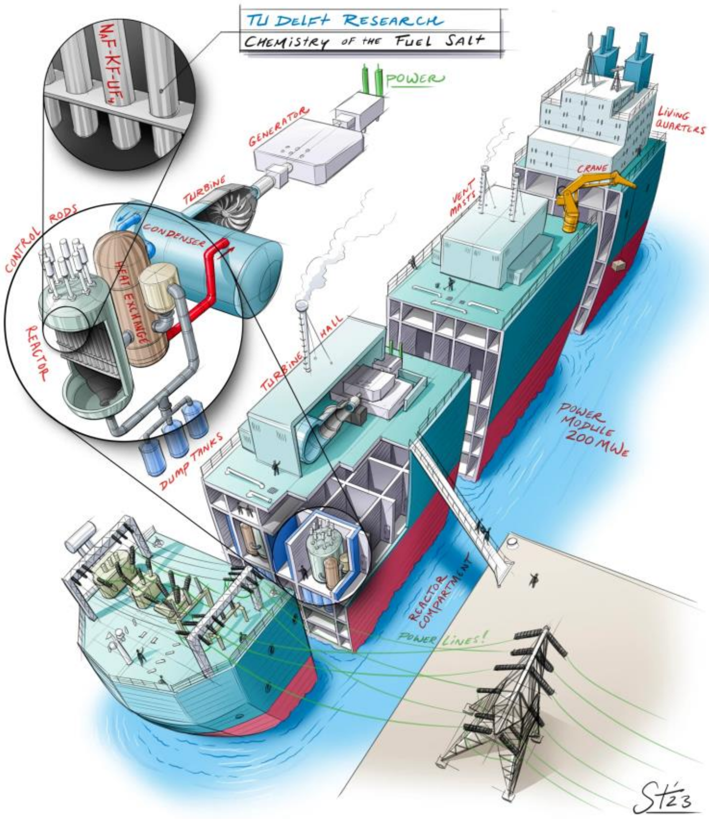


Figure 3: Example of the floating power barge concept for Seaborg (TU Delft, 2023)

3.4 SMR Operational and Functional Concepts

SMRs also differ from conventional NPPs in their operational and functional concepts. Some new concepts are described here as examples, but this is not an exhaustive list. Again, not all SMR designs will include all the concepts listed here, but many SMR designs will incorporate one or more of these.

3.4.1. Operational Concepts

The following operational concepts are commonly referred to when talking about SMRs:

- **Multi-module operation** – refers to the monitoring and control of multiple reactor modules from a single control room, by a single control room operating team. Most conventional NPPs have one control room & operating team per reactor module. Some conventional NPPs may share a control room between modules, but within that room, each module has a physically separated set of control stations and a dedicated control room operating team per reactor module (e.g. CANDU plants in Canada).

- **Highly automated or partially/fully autonomous operation** – refers to the expectation that SMRs will utilise much higher levels of automation compared to conventional (Generation III) NPPs in operation today. Some SMRs, particularly microreactors, are being designed with the expectation that they will be partially or fully autonomous in the future, meaning that very little or no manual actions will be needed to operate the reactors. Partial autonomy may also mean that some systems or sub-systems within the plant are autonomous while others are not. It is expected that new build conventional sized plants (Generation IV+) will also take advantage of much higher levels of automation, although partial/full autonomy may not be utilised as widely as for SMR NPPs.

- **Remote operation** – refers to the concept where an SMR NPPs may be geographically remote from the control room where it is monitored, controlled and/or operated. The remote control room may oversee one or multiple reactor modules, which may be co-located or may be distributed across several geographical locations.

3.4.2. Functional Concepts

The following functional concepts are commonly referred to when talking about SMRs:

- **Cogeneration** – refers to the simultaneous production of both electricity and functional heat from a single reactor. Heat is produced during electricity production but is not normally used for other purposes (i.e. considered a waste product of the electricity production process). Many SMR functional concepts intend to utilise the heat produced during electricity production for other purposes which could include, e.g. district heating, industrial processes such as chemical production, for cooling and refrigeration, seawater desalination etc.

- **Hydrogen production** – refers to the increased opportunity for cost-effective industrial production of hydrogen, which is increasingly seen as a viable alternative to fossil fuels in transportation, maritime, etc. Although there are some conventional NPPs that produce hydrogen today, SMRs are considered particularly suitable to this function due to the flexibility offered by SMR design, enabling them to more easily switch between electricity and hydrogen production based on market demand.

- **Local energy production** – refers to the flexibility that SMRs offer regard siting, especially in locations where it would be difficult to build a conventional large-sized NPP. The smaller footprint of SMRs, and the modular, factory-fabricated concept, means that it may be easier to site SMRs in locations to provide energy and/or heat for use at a local level, rather than to a national grid. This may be particularly useful for remote communities and industries that might not be connected to a national power grid and thus may be reliant on fossil fuels for energy and heating.

The operational and functional concepts are noted here because these are likely to have an impact on the roles and responsibilities of SMR operators, as well as impacting the potential risk from operation of SMRs. The potential impacts will be explored further in this report.

3.5 A Note on Terminology

Throughout this report, terminology related to reactor types and configurations is used as consistently as possible, but it is important to note that definitions can vary by country and context. The acronym *SMR* most commonly refers to *Small Modular Reactors*, but in some contexts, it may also be used to denote *Small and Medium-Sized Reactors*.

Similarly, the term *Advanced Reactor* is used in some countries to mean reactors that use molten salt, liquid metal or inert gases as reactor coolant, and/or that use fuel or material designs that differ from what is typically used historically. The term Advanced Reactor may include SMRs but is not limited to SMRs. *Microreactors* are often considered a subset of SMRs due to their small size and modularity, but they are sometimes treated as a distinct category.

In addition, the terms *multi-unit* and *multi-module* are sometimes used interchangeably, although they have subtly different meanings. Multi-unit generally refers to separate reactor units (plus necessary supporting systems) co-located at a site, while multi-module typically describes integrated systems with multiple reactor modules sharing physical infrastructure such as safety systems, major electrical components, control room, ultimate heat sink etc.

4. HRA for SMR NPPs

This chapter outlines what HRA is and what kind of information is needed to perform HRA. Further, the chapter explains how the risk profile for SMR NPPs is changing, compared to conventional NPPs, and the potential impact this will have on HRA and analysis of the human contribution to risk.

4.1 Brief Overview of HRA

HRA is a systematic approach to analysing potential human failure events in a fault scenario, often with the goal of quantifying a human error probability (HEP). The HEP can be integrated with the PSA to assess the effect of the human contribution to risk on the overall plant safety. Figure 4 shows a generic HRA process which most HRA methods generally follow.

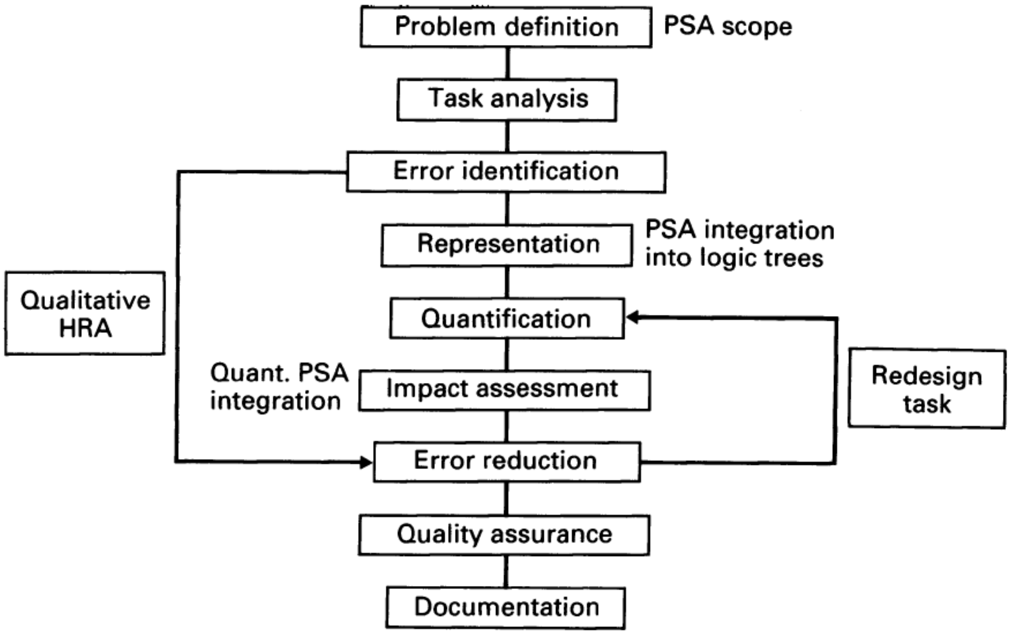


Figure 4: The HRA process (Kirwan, 1994)

HRA uses qualitative data about how human tasks and actions in the fault scenario are performed to determine where there may be vulnerabilities and therefore opportunities for human error. Factors that could potentially influence the performance of those tasks are also examined, such as the working environment in which the tasks are performed, the human-system interfaces that are used by operators performing those tasks, the potential for time pressure while performing the task, etc. Such PSFs can support the operator in succeeding in the task, or could be detrimental to successful task performance, or may not have any effect either way. The HRA process systematically evaluates all this information against existing models of human behaviour and human performance and uses this information to estimate the probability of human error in the scenario.

There are many different HRA quantification methods that analysts can use, which range from placing the focus of the analysis on low-level manual actions through to higher-level cognitive decision making. The methods differ in terms of the underlying data informing the quantification calculations, and the range of PSFs that may be used to adjust the underlying data to the specific scenario(s) of interest. This project does not consider any specific HRA methodology in connection with the analysis that will be performed for SMR NPPs, and it is assumed that different organisations will use different methods according to organisational and/or national regulatory preferences. The focus for this project is on the qualitative part of the HRA that is performed prior to the quantification, and specifically on the first steps of the generic HRA process – problem definition and task analysis.

4.2 Focus on HRA Problem Definition and Task Analysis

Problem definition is perhaps the most important step in the HRA (Bye et al., 2016) as it defines the scope and boundary of the HRA that shapes the subsequent qualitative and quantitative analyses that will be performed. This step also defines the scenario(s) that will be investigated in the HRA (i.e. the set(s) of tasks and/or actions of interest). The scenario may be identified by the PSA based on specific fault sequences that are modelled and that include some human actions. And/or the scenario may be determined by a specific human performance problem that has been identified, or as part of some other safety improvement initiative (Kirwan, 1994).

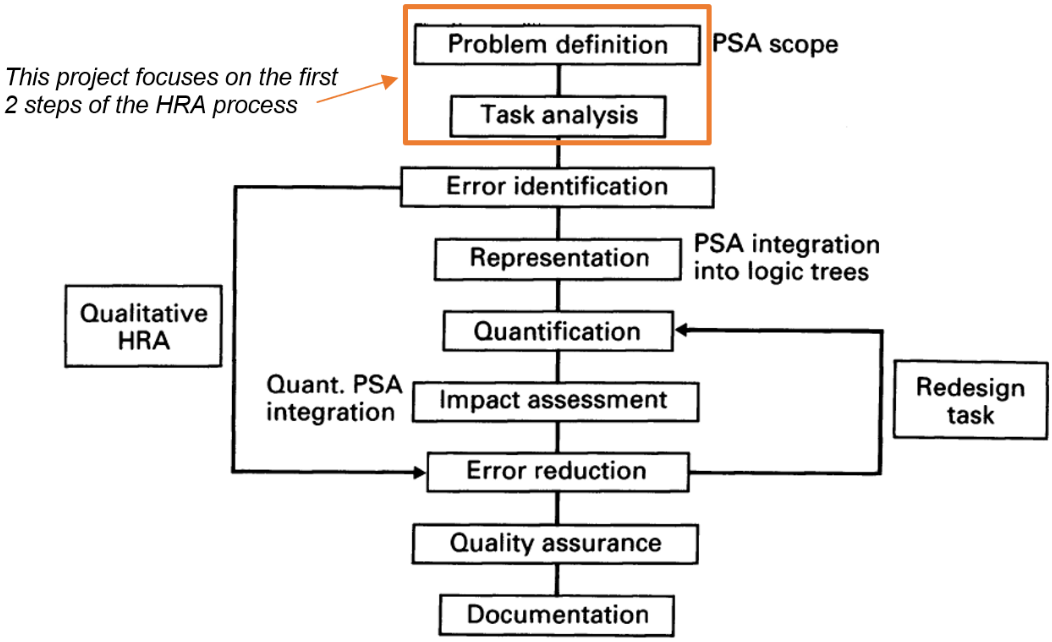


Figure 5: The HRA process showing the areas of focus for this project (adapted from Kirwan, 1994)

In the problem definition step, the analyst will try to collect as much information as possible about the scenario of interest. This will include details such as the operating mode/state of the reactor and plant, the initiating conditions for the scenario, and the operator role and required actions. For example, Hugo et al. (2013) describes a scenario analysis produced for the purpose of function allocation that closely mirrors the kind of information that is also required for HRA problem definition, including (but not limited to):

- Related system: the name of the affected system(s) in this scenario.

- Personnel involved: the titles of all of the personnel that will be involved in the scenario.
- Operator role: the role of the operator(s) in resolving the scenario and returning the plant to a safe state.
- Task location: the location in the plant in which the scenario occurs, which may include secondary locations where important operator task actions are performed.
- Operator main functions: the tasks and actions that the operator(s) will perform in line with the previously described role.

The next step in the generic HRA process is task analysis which builds the foundation for the subsequent error identification, representation, and quantification steps. The task analysis “describes what an operator is required to do, in terms of actions or cognitive processes (or both), to achieve the system’s goal” (ibid, pg. 49). The task analysis involves collecting information about the operator tasks, and systems and tools that the operator uses to perform those tasks. This information is organised such that it can be subsequently used to identify potential human errors and analyse the factors that may make those errors more or less likely to occur.

Both problem definition and task analysis steps require knowledge of the roles and responsibilities of operators within the specific fault scenario(s), and what kinds of tasks and/or actions each operator will be required to perform.

4.3 The Changing Risk Profile for SMR Operations

Information on SMR design concepts indicate a desire to reduce the number of operations and maintenance (O&M) staff on site. O&M staff and activities are cited as one of the highest costs for an operating plant (Wood et al., 2017). Staff reductions are likely to be achieved via simpler designs and increased use of automation during normal operations, and increased reliance on automation, inherent safety properties and passive safety systems during abnormal or emergency situations. These design features are expected to increase the overall safety of SMRs and reduce the likelihood of events.

Even if unplanned events do occur, some SMR vendors have stated that their designs do not require operator intervention after a design basis event. 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).

At first glance, statements such as these could lead one to assume that operators will not perform any actions after an event. However, these statements are more correctly interpreted as meaning that there are no claimed post-fault human actions, i.e. the PSA places the reliability for post-fault event management on designed systems (e.g. automation, passive safety systems, inherent safety properties of the reactor design). Nevertheless, it is highly likely that some manual actions will be required, e.g. ensuring that gravity-fed cooling pools maintain an adequate water level to supply cooling to the reactor, monitoring automated and passive safety systems to ensure that they do initiate when required and perform as expected, etc., but these will not be claimed in the PSA. It is also likely that the operators will be required to intervene in the event of a failure of an automated or passive safety system, and/or if these systems are unable to operate due to a beyond design basis event.

From an HRA perspective, this implies that the risk profile for SMR operations is changing with respect to human error. Reducing the need for human intervention post-fault does not mean that the risk of human error is removed from the system; it merely changes where and how human error may impact plant risk and safety.

In PSA and HRA, human errors are typically divided into three groups (Vaurio, 2009):

- Type A: these are errors that are made during normal operations prior to any initiating event occurring. Such errors typically occur during maintenance or testing activities. These are also known as latent errors or pre-initiator errors.
- Type B: these are errors or actions that cause an initiating event to occur. Such errors typically occur during maintenance or testing activities and can also occur during normal plant operation activities. These are also known as initiator errors.
- Type C: these are errors that occur after an initiating event, during the actions that are intended to recover from the initiating event. These are also known as post-initiator errors.

Figure 6 illustrates where in an event sequence these different types of errors may occur.

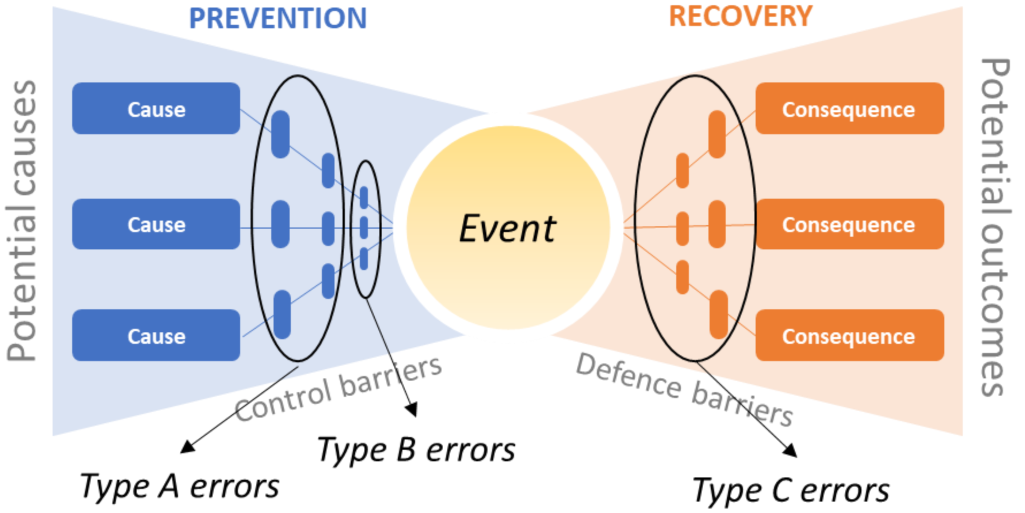


Figure 6: Diagram illustrating the three human error types in relation to when they may occur in an event sequence

Traditionally, HRA has tended to focus on analysing post-initiator (Type C) human errors (Park & Boring, 2023). These are errors that could occur when performing manual actions in response to an event at an NPP, that could compromise the mitigation of event consequences. For example, an operator failing to close a valve after a pipe break could result in release of radioactive material after a Loss of Coolant Accident (LOCA) would be considered a post-initiator human error and would be analysed using HRA to determine the likelihood of this error occurring in such a situation.

For SMRs, it is assumed that such manual actions will now be handled by the automated, inherent, or passive safety systems that have been designed to manage the actions required to mitigate events. From the PSA perspective, the risk of post-initiator human error is effectively removed by not having any required manual actions. However, the reliability of those automated, inherent, or passive safety systems may be reduced by pre-initiator human errors, which can insert latent failures into these systems that affect whether/how they operate when required after an event. For example, when performing maintenance, testing or inspection tasks on these systems, the operator could fail to de-isolate a system after testing meaning that the system is not available if an event were to occur.

Such errors are not exclusive to SMRs and can also occur in conventional NPPs. However, in conventional NPPs, human operators are typically credited with a significant role in detecting and responding to plant faults and in returning the plant to a safe state. In contract, the design philosophy of SMRs places primary reliance on automated and passive systems, with minimal (if any) credit given to human intervention. This may introduce challenges because automated systems can only respond to the conditions they are designed and programmed to recognise, which makes them vulnerable to sensor failures or erroneous data inputs – risks highlighted by incidents such as the Boeing 737 MAX accidents (Jamieson et al., 2022). Furthermore, by reducing the operators’ role in post-fault management, SMRs risk leaving humans “out of the loop”, potentially delaying their ability to detect, diagnose, and mitigate unanticipated faults. As a result, latent (Type A) failures such as maintenance errors and/or errors that result in non-availability of automated or passive safety systems may carry greater consequences in SMRs than in conventional NPPs, where human action remains a more integral layer in the defence-in-depth strategy.

Thus, the human contribution to risk of the plant safety has not been removed for SMR designs; it has changed from focusing almost exclusively on post-initiator (Type C) errors and now is likely to also require examination and inclusion of pre-initiator (Type A) and initiator (Type B) errors.

4.4 Challenges for HRA Analysts

There are likely to be several challenges for HRA analysts responsible for performing analysis of SMR plants. For example:

- **The lack of operational data:** as noted earlier, there are a very small number of SMRs currently in operation meaning that there is a significant lack of real-world operational data that HRA analysts can use as a basis for their analysis. Operational data would typically be used to support problem definition and task analysis, enabling the analyst to specify exactly what operators are required to do, when and how they are required to do it. As a result, HRA analysts may be reliant on training simulators (of which there are very few), expert judgement or data from similar nuclear or non-nuclear systems to make informed predictions about human performance in SMR operations (Blackett et al., 2022). The lack of operational data also significantly increases uncertainty in HRA in terms of predicting how humans will interact with SMR technologies and where failures may occur (Hugo et al., 2014).

- **Novel work tasks and an increase in complexity:** the increased use of automation and the design characteristics of SMRs are used by many SMR designers and vendors to justify reductions in the numbers of staff needed to operate the plant safely, as well as changing how those staff operate when compared to conventional large NPPs. Tasks that operators previously performed manually are now either removed through design or are automated, changing the role of the operator from “doer” to “monitor of automation” to ensure it works as required (Hugo et al., 2013). Furthermore, the utilisation of automation and passive safety features increases the complexity of the systems that humans are meant to oversee (Roth et al., 2019). For HRA, this may mean that the standard models of human cognition and behaviour that are currently used in HRA methods may need to be updated to understand how humans interact with more advanced automated systems and the potential effect this has on how operators perform their tasks (Fleming et al., 2020).

- **Novel working environments:** SMRs offer opportunities for novel working environments with concepts such as multi-module operation, remote operation, cogeneration, etc. This can introduce new ways of working, new cognitive demands and new potential error modes that current HRA methods and approaches may not adequately capture. Analysts may need to adapt existing methods and approaches or develop new ones to effectively model how operators will work in SMR NPPs (Kim & Jung, 2003).

- **Focus shift from post-initiator to pre-initiator human errors:** as described in Section 4.3, the utilisation of enhanced automation, passive safety systems and simpler operations are expected to further reduce the likelihood of unwanted events and greatly reduce the risk of post-initiator human errors. As a result, there is likely to be a greater focus placed on the risk of pre-initiator human errors, which could lead to an initiating event in the first place, or which could compromise the integrity or reliability of the designed safety systems to manage the event (Sim & Vasilenko, 2018). HRA has tended to focus on the analysis of post-initiator human errors and so there is limited methodological guidance, data and experience on how to identify or analyse pre-initiator candidate scenarios and tasks (Park & Boring, 2023).

- **Focus shift from control room to field operations:** Historically, HRA has tended to focus on manual actions performed in the control room, since this is where most post-initiator actions take place in conventional NPPs. However, in SMRs operators are likely to spend more time performing tasks in the field, such as maintenance, system checks and environmental monitoring, to ensure that automated and passive systems remain within safe limits. This can be challenging for HRA analysts because of the wide variety of potential field tasks that need to be considered, and face that these kinds of tasks are less well documented in HRA databases (Woods & Cook, 2002; Leveson, 2011).

5. Findings from the Literature Review

This chapter describes the findings from the literature review activity of WP1, which includes the review of SMR vendor licensing documentation. The review was performed between September 2024 and March 2025. A major finding from the literature review is that the implementation of more advanced automation (in terms of automation ability and/or complexity, compared to conventional NPPs) is expected to be a primary driver of change to the roles and responsibilities of operators in SMR NPPs. Consequently, the presentation of the findings in this chapter focuses first on how automation is expected to be implemented in SMR NPPs to help provide some context within which the subsequent findings on operator tasks are presented (Section 5.1).

For the purposes of HRA, it is important to incorporate some nuance into the description of operator task types beyond simply noting that operators will “monitor” automated systems. Analysts need more details of what actions are involved in such monitoring tasks in order to effectively define the problem (HRA Step 1) and develop a sufficiently detailed task analysis (HRA Step 2) to allow for subsequent error identification, representation, quantification, etc. The literature review aimed to uncover details of task actions that would support these two HRA steps.

The results are divided into three categories: tasks in the main control room (Section 5.2), tasks outside of the main control room (Section 5.3), and novel operator tasks (Section 5.4). HRA has traditionally focused on quantifying operator tasks that are performed in the control room as this is where the majority of actions that could lead to Type C errors would take place. However, considering the earlier discussion of the changing risk profile of SMR operations (Section 4.3), it is prudent to also consider tasks that could result in Type A and B errors. These tasks typically take place in the field but may also include some control room tasks.

Finally, as noted earlier, the design and characteristics of SMRs may also result in novel tasks that are not typically performed at conventional NPPs. These may also be relevant to HRA as they may require the addition of novel task types to existing HRA models, and/or they may result in new or different types of PSFs that should also be incorporated into HRA models.

5.1 Implementation of Automation in SMRs

The reduction of costs through staff optimisation is a key driver for the SMR business case. This is expected to primarily be achieved through automation of the majority of plant functions: “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” (Hugo et al., 2014, pg. iii).

A common theme throughout the literature is the expectation that SMRs will implement higher levels of automation when compared to conventional large-sized NPPs (US NRC, 2021; Le Blanc et al., 2017; Oxstrand and Le Blanc, 2014). Fully autonomous operation of SMRs is also considered, especially for microreactors (Fleming et al, 2020).

Furthermore, SMRs are anticipated to incorporate more advanced and more complex automation than currently implemented in conventional NPPs (IAEA, 2017). This will have profound implications for human operators, not only in terms of the tasks that they will now perform in such highly automated plants, but also in terms of how they interact with and supervise these complex automated systems (O’Hara et al., 2012).

In highly automated environments, the operator role is typically that of supervisor, responsible for monitoring system performance and intervening only in abnormal or failure conditions (Parasuraman et al, 2000). While automation can reduce workload for operators, it can also reduce situation awareness, and result in degradation of operator skills. This can lead to operators being “out-of-the-loop”, and so it is important that systems are designed to ensure that these kinds of human performance costs are minimised (ibid.).

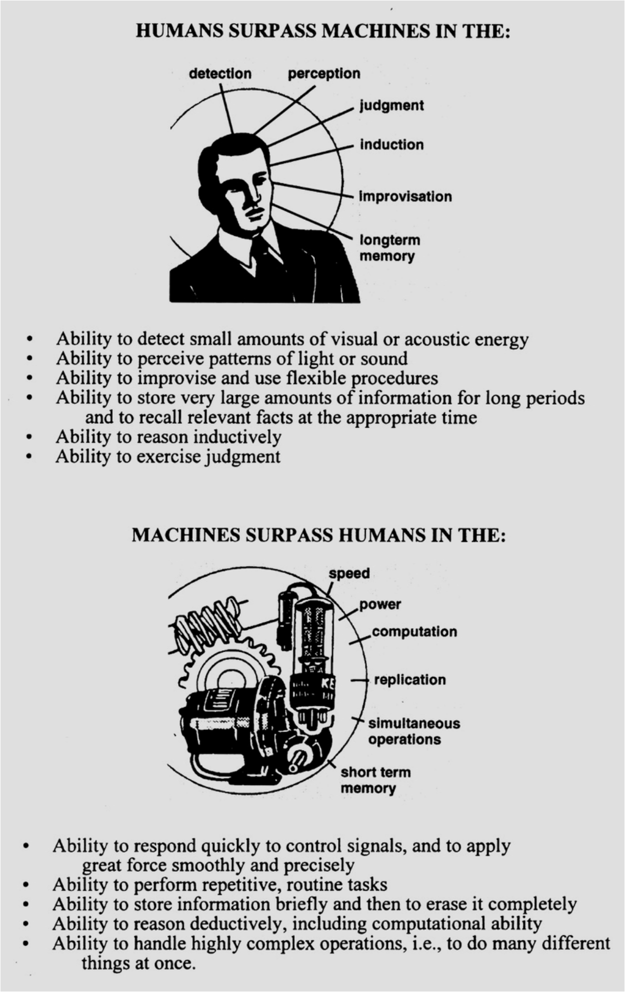
Challenges related to operators being “out-of-the-loop” are especially relevant in SMRs where increased automation is expected to significantly reduce the frequency of direct operator intervention: “For advanced reactors […] the reliance on human intervention in safety-related actions is expected to be reduced or completely replaced by automated actions” (Hamza and Diaconeasa, 2022, pg. 1). It is expected, however, that operators will still be required to intervene in the case of an automation failure or in a beyond design basis event (Blackett et al., 2023). Such events are expected to be rare, making them even more cognitively demanding for operators to identify, characterise and manage. Understanding what kinds of tasks operators will be expected to perform in highly automated plants – routinely and non-routinely – is important to ensure that design and operational concepts effectively support the new operational landscape.

5.1.1 AOF Between Humans and Automation

Deciding which tasks should be performed by automation versus humans is typically done using a process called allocation of function (AOF). AOF 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).

Early Methods of Function Allocation

The earliest formal methods for function allocation were based on task-oriented taxonomies such as Fitts List (Figure 7). Fitts proposed a set of principles for abilities in which humans are better than machines, such as perception, detection, and improvisation (Fitts, 1951). Conversely, Fitts proposed that machines are better at tasks requiring, for example, speed, power, deduction, and performance of simultaneous operations. Interestingly, Fitts cautions against “assuming that men can successfully monitor complex automatic machines and take over if the machines break down”, and notes that “both men [sic] and machines are likely to break down or become unstable if overloaded” (ibid., pg. 11). Despite this, Fitts states that “one of the greatest advantages of including human elements in a system is increased flexibility” (ibid., pg. 11), noting that humans can more easily adapt to the introduction of new equipment to the system, or the sudden failure of equipment, or to the occurrence of unique and unforeseen problems.

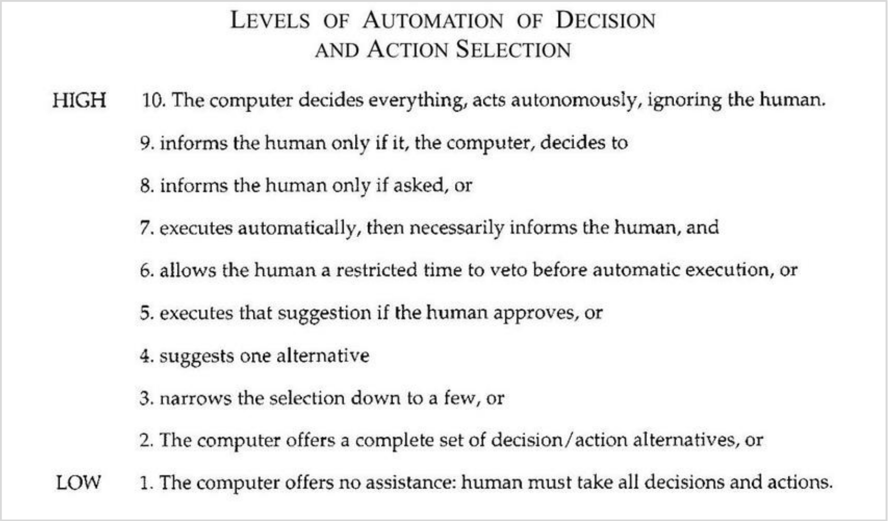


- Ability to detect small amounts of visual or acoustic energy
- Ability to perceive patterns of light or sound
- Ability to improvise and use flexible procedures
- Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time
- Ability to reason inductively
- Ability to exercise judgment

- Ability to respond quickly to control signals, and to apply great force smoothly and precisely
- Ability to perform repetitive, routine tasks
- Ability to store information briefly and then to erase it completely
- Ability to reason deductively, including computational ability
- Ability to handle highly complex operations, i.e., to do many different things at once.

Figure 7: Illustration of the original Fitts List (Hoffman et al., 2002)

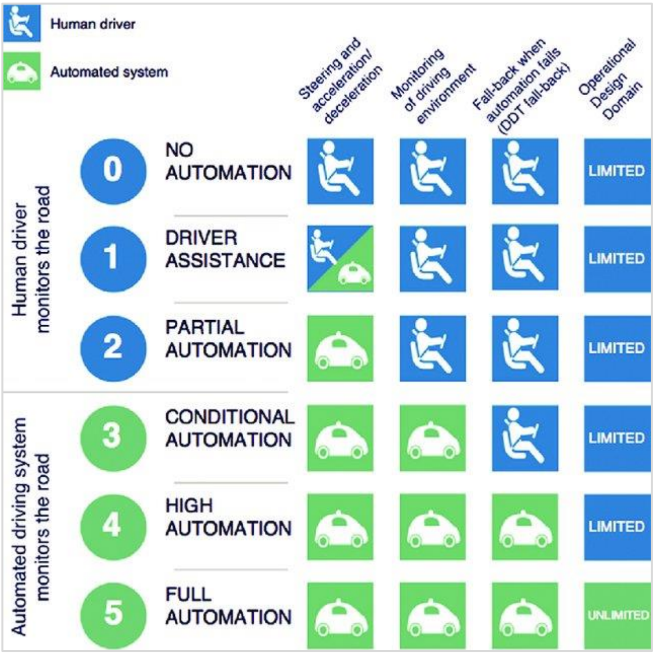
Such approaches to function allocation are often known as HABA-MABA - Humans-are-better-at/Machines-are-better-at, or substitution-based function allocation methods (Dekker & Woods, 2002). These types of approaches are still popular today, and is often seen in, for example, the development of autonomous technologies such as the Levels of Automation (LOA) model (Figure 8). LOA models have been favoured by designers and manufacturers wishing to develop autonomous technologies, not least within the automotive industry where in recent years there has been a huge push to develop so-called “self-driving” cars (Roth et al., 2019; Blackett, 2022 ; Figure 9).



LEVELS OF AUTOMATION OF DECISION
AND ACTION SELECTION

HIGH 10. The computer decides everything, acts autonomously, ignoring the human.
9. informs the human only if it, the computer, decides to
8. informs the human only if asked, or
7. executes automatically, then necessarily informs the human, and
6. allows the human a restricted time to veto before automatic execution, or
5. executes that suggestion if the human approves, or
4. suggests one alternative
3. narrows the selection down to a few, or
2. The computer offers a complete set of decision/action alternatives, or
LOW 1. The computer offers no assistance: human must take all decisions and actions.

Figure 8: Levels of Automation table (Parasuraman et al., 2000)



🟦 Human driver
🟩 Automated system

			Steering and acceleration/deceleration	Monitoring of driving environment	Fall-back when automation fails (DDT fall-back)	Operational Design Domain
Human driver monitors the road	0	NO AUTOMATION	🟦	🟦	🟦	LIMITED
	1	DRIVER ASSISTANCE	🟦🟩	🟦	🟦	LIMITED
	2	PARTIAL AUTOMATION	🟩	🟦	🟦	LIMITED
Automated driving system monitors the road	3	CONDITIONAL AUTOMATION	🟩	🟩	🟦	LIMITED
	4	HIGH AUTOMATION	🟩	🟩	🟩	LIMITED
	5	FULL AUTOMATION	🟩	🟩	🟩	UNLIMITED

Figure 9: Example of an LOA model used for driving tasks (Serban et al., 2020)

A common criticism of LOA models is that they can tend to be overly simplistic in the way that human and automated functions are described, and that they are misleading in the implication that functions can be swapped between humans and automation in a linear “like for like” manner. LOA models can often imply that in the event of an automation failure, humans can simply “take over” the automation’s functions and steer the system back towards a safe state. “This assumption does not take into consideration the intricate cognitive processes required for a human to go from a state of disengagement to being fully engaged, aware and able to safely resume a previously automated task, in a real-world environment” (Blackett, 2022, pg. 4).

Another criticism of HABA-MABA or substitution-based functional approaches is that it does not recognise that replacing a previously manual action with an automated action fundamentally changes the nature of the work and often creates new tasks for the human who now must interact with that automation (Dekker & Woods, 2002). As pointed out by Roth et al. (2019, 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 HABA-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 (Hollnagel & Bye, 2000). Roth et al., makes a valuable point that: "This method of function allocation accommodates the limits of the automation, but not [of] the human, which can lead to performance problems" (2019. 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.

Adaptive and Dynamic Function Allocation

A disadvantage of the HABA-MABA approach is that it is static, meaning that once functions have been allocated between machines and humans, those allocations do not typically change. Other models of function allocation have since emerged that are more adaptive and dynamic, taking advantage of developments in automation and Artificial Intelligence (AI) technologies.

Adaptive function allocation refers to when tasks are allocated and re-allocated between humans and machines based on specific, pre-defined operating conditions such as system state, operator workload or other environmental factors. In this way, the AOF between humans and machines will be context based but will follow a structured rule-based decision process. For example, if the operator workload is high, the automation may take over some tasks to help ease the burden on the operator and then return those tasks when the operator is ready to take them over again (Parasuraman et al., 2000; Kaber & Endsley, 2004).

Wickens et al. (1998) write that "Adaptive automation may involve either *task allocation*, in which case a given task is performed either by the human or the automation in its entirety, or *partitioning*, in which case the task is divided into subtasks, some of which are performed by the human and others by the automation" (pg. 39). The decision to allocate or partition tasks may be performed by an intelligent system, based on a pre-defined operating model, or it may be the responsibility of the human operator. Strictly speaking, adaptive automation refers to the situation where an intelligent system makes the decision on whether tasks, or parts of tasks, should be performed by the automation or the human. When the human decides, this is referred to as *adaptable automation*.

Dynamic function allocation refers to a more flexible allocation of tasks between humans and machines that is done in real-time (i.e. not pre-defined) based on the specific scenario, the operators' workload and the system needs (Dearden et al., 2000; Wright et al., 2000). It works by continuously adjusting the level of control by both the human and the automation, allowing for more fluid, real-time collaboration between machines and humans (Atashfeshan et al., 2021; Hildebrandt & Harrison, 2002). It may be achieved using machine learning and AI-driven decision aids which can monitor the operators' workload, the performance of the system and the operator, and the environmental conditions, and then anticipate when the automation needs to take over control, or when it can be handed back to the human (Kaber & Endsley, 2004).

There are advantages and disadvantages to both adaptive and dynamic AOF. Billings and Woods (1994, as cited in Wickens et al., 1998) note that systems with adaptive automation may create more human performance vulnerabilities if they do not have sufficient transparency, and if operators are not aware of the adaptive automation state, and state changes. They argue that adaptable automation is preferable because the operators can tailor the level and type of automation depending on their own needs.

Kaber and Endsley (2004) argue that adaptive automation "may provide performance benefits to operators involved in monitoring, psychomotor and dynamic control tasks. These benefits appear to result from maintaining operator involvement in active control and managing workload, which may serve to prevent OOTL [out-of-the-loop] performance problems including complacency, vigilance decrements, and a loss of SA [situation awareness] and manual skills" (pg. 126). Although SMRs are expected to be highly automated, with minimal tasks allocated to human operators, it is important to bear in mind the need for the operator to remain in the loop, and to retain situation awareness and manual skills so that they can intervene in the event of failure of an automated or passive safety system. To maintain these human capabilities, system designs may decide to allocate some functions or tasks to humans. Wickens et al. note that "If an automated system always carries out a high-level function, there will be little incentive for the human operator to be aware of or monitor the inputs to the function and may consequently not be able to execute the function well manually if he or she is required to do so at some time in the future" (1998, pg. 38).

5.1.2 AOF in Contemporary SMR Designs

The unique design goals and operational contexts for SMRs must be considered when developing the functional allocation analyses for these NPPs. SMR features such as smaller plant size, reduced staffing, increased use of passive safety systems, the potential for remote operation and modular deployment strategies creates both opportunities and challenges in determining how responsibilities should be divided between human operators and automated systems.

In conventional NPPs, function allocation often follows a relatively stable model with a well-defined division between automated systems (e.g. for control and monitoring) and human operators (e.g. for oversight, diagnostics and decision-making). However, the goal of minimal staffing and simplified operations in SMRs leads to greater reliance on automation to handle not just routine control tasks but also aspects of fault detection, system diagnostics and even decision support (O'Hara et al., 2012). Rather than simply automating as much as possible, designers should carefully assess which functions can and should be allocated to automation (e.g. functions requiring rapid response, consistency, or routine monitoring of large amounts of data), and which functions are essential for human operators to retain to preserve cognitive strengths such as adaptability and complex judgement in uncertainty (Sheridan & Parasuraman, 2005).

It is difficult to determine from the open literature which function allocation approaches are being, or will be, employed by SMR designers. Many SMR designs are simply not yet mature enough for function allocation analyses, and those that are mature do not typically make the analyses available in the open literature, likely for commercial and/or security reasons. The few reports that are available are heavily redacted, meaning that it is only possible to infer some insights into how SMR designers may be approaching the issue of AOF in these highly automated plants. Two examples are discussed here.

The first example comes from 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) includes a chapter on AOF which 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). 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).

The second example comes from the 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; Figure 10). The table indicates that designers should tend towards automation if, for example: the required response time is too short for an operator to react, or if there is a high probability of operator error. Conversely, designers should tend towards operator functions if, for example: human knowledge and judgement are essential to ensure reliability system function performance, or if operator situation awareness must be optimized.

Examples of Criteria for Function Allocation	**If YES, Then Bias Towards:**
Operator capabilities	
Required response time too short for an operator to react?	automation
High probability of operator error?	automation
Repeated action distracts operator?	automation
Repeated action consumes too much of operator's time?	automation
Very precise control required?	automation
Functions, or parts of them, will be allocated to personnel when human knowledge and judgment are essential to ensure reliable system function performance.	operator
Can an operator maintain situation awareness with automated function?	automation
Machine or automation capabilities	
Automation of function is technically feasible?	automation
Automation of function is practical?	automation
Automation of function is cost-effective?	automation
Other criteria	
Are consequences acceptable for automation to backup operator functions that might be shed?	operator
Does function have existing practices?	existing practices
Operating experience analysis indicates function should be automated?	automation
Operating experience analysis indicates function should be manual?	operator
Operating experience review of operating nuclear facilities to assign allocation	lessons learned
Operating experience review of non-nuclear facilities to assign allocation	lessons learned
Does function have regulatory requirements?	per regulations
Safety-related system function reliability optimization?	automation
PRA risk significant function reliability optimization?	automation
Operator situation awareness must be optimized.	operator
Individual modules may be in different modes of operation (startup, shutdown, power operation or refueling).	automation
The aggregate of system functions allocated to one operator must be within their workload capability (counter objective to following objective).	automation
The aggregate of system functions allocated to one operator must allow the operator to remain vigilant (counter objective to previous objective).	operator
Operation by consent and operation by exception allocations allow operator involvement in the execution of a system function while still allowing automation to provide the primary execution of the function.	automation

Figure 10: Extract from NuScale Criteria for Function Allocation (NuScale, 2015, pg. 6)

Both of these examples appear to show a tendency towards traditional, HABA-MABA approaches, comparing the strengths and weaknesses of humans and automation and then making decisions about where functional control/responsibility should be assigned. The examples both indicate good awareness of the potential conflicts and risk of performance decrements described previously with respect to allocation functions between automation and humans.

It is important to state that these are just two examples of many and are not necessarily representative of the approach that will be used in the SMR industry as a whole. However, it must also be noted that both GE-Hitachi and NuScale are leaders in the field, with mature designs that are likely to be amongst the first commercial SMRs deployed. As such, it is natural that these examples may set a precedent for SMR development, whether intentional or not. It remains to be seen whether the traditional HABA-MABA approach to AOF will be successful in SMR deployment, or whether experience will show that other approaches such as scenario-based AOF and/or adaptive/dynamic AOF may be more appropriate.

5.2 Operator Tasks in the Main Control Room

It is important to understand what tasks are involved in the operator's expected monitoring/supervision role in order to effectively model potential fault scenarios in an HRA. As noted earlier, a goal of the literature review was to identify details of potential operator tasks beyond high level descriptions such as "operator monitors the automation". Some reports identified in the literature review contain more detailed descriptions of operator tasks that allow for interpretation in the context of a highly automated plant. For example, a report by the Idaho National Laboratory (INL; Hugo & Farris, 2015) considers a potential operational concept for a hypothetical sodium fast reactor (SFR) as one type of SMR that may be implemented in the future. In this report, the authors note that in conventional NPPs, operators are typically responsible for manual actions during start-up and shutdown regimes such as manual generator synchronization, manual diagnostic checks and tests, etc. However, in advanced reactors such as the SFR, it was anticipated that the start-up and shutdown regimes would be automated.

Such automated sequences will likely include pre-programmed hold points or pauses, where manual operator authorization is required for the automation to continue to the next step or sequence of steps. Thus, even though the role of the operator is primarily to monitor the automated processes, there is some requirement for the operator to not only maintain vigilance and situation awareness, but also to effectively understand what the automation is doing in order to be able to provide the correct authorisation at the relevant hold points.

Hugo and Farris consider that during normal operations, when the cognitive demand on the control room operators is expected to be low, operators are likely to perform higher-level tasks "such as production planning, and system optimization" (ibid. pg. 9). They also expect that, for facilities with remote-control capabilities, during periods of higher workload (such as outages, security events or accidents), remote operator assistance could be provided to take over routine operational activities with lower safety significance. This would allow the on-site control room operators to concentrate on safety functions, freeing up cognitive capacity to focus on monitoring automated sequences and/or passive safety systems.

Oxstrand et al. (2013) note that automation is typically used to replace human cognitive functions and identify two sets of generic cognitive functions that operators would normally perform, shown here in Table 2 .

Table 2: Generic cognitive functions (adapted from Oxstrand et al., 2013)

Parasuraman et al. (cited in Oxstrand et al., 2013)	**Endsley and Kaber (cited in Oxstrand et al., 2013)**
• Information acquisition (e.g. the gathering of process information)	• Monitoring: scanning displays and indications to perceive system or process status
• Information analysis (e.g. calculations)	• Generating: formulating options or strategies to achieve operational goals
• Decision and action selection (e.g. evaluating step logic, conditions, or providing recommendations)	• Selecting: making a decision on a particular option or strategy
• Action implementation (taking a control action such as opening a valve)	• Implementing: carrying out the selected option.

Further exploration of these cognitive functions led the authors to the below taxonomy of cognitive functions developed by O’Hara et al. (as cited in Oxstrand et al., 2013, pg. 15):

- **Monitoring and detection** refer to the activities involved in extracting information from the environment. Monitoring is checking the state of the plant to determine whether it is operating correctly, including checking parameters indicated on the control panels, monitoring those displayed on a computer screen, obtaining verbal reports from other personnel, and sending operators to areas of the plant to check on equipment. An alarm system is an example of automation applied to monitoring and detection.

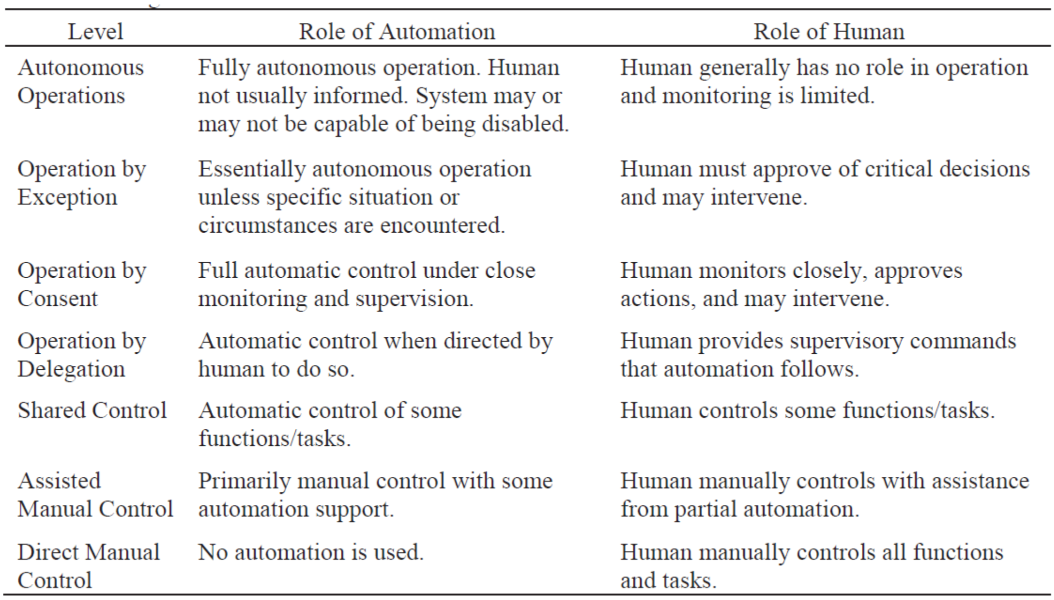
- **Situation assessment** is evaluating current conditions to assure their acceptability or determining the underlying causes of any abnormalities (e.g. diagnosis). An example of automation applied to a situation assessment is a disturbance analysis system and other computerized operator-support systems.

- **Response planning** refers to deciding on or choosing a course of action to address the current situation. In an NPP, procedures usually aid response planning. An example of automation applied to response planning is a computer-based procedure system.

- **Response implementation** is undertaking the actions specified by response planning. They include selecting a control, providing control input, and monitoring the responses of the system and process. An example of automation applied to implementing a response is an automatic safety system such as soft controls.

- **Interface management** encompasses activities such as navigating or accessing information at workstations and arranging various pieces of information on the screen. An example of applying automation to interface management is automatic identification of a display appropriate to the ongoing situation (e.g. identification of an emergency-procedure display upon detecting any of the procedures entry conditions). In this context, HSI notifies the operator of the availability of the display (i.e. by a blinking icon at the bottom of the screen), rather than disrupting the operator’s ongoing activity by obtrusively showing the display.

As discussed in Section 5.1.1, LOA models are often used to describe the division of responsibilities or functions between automation and humans. Oxstrand et al. give the example of a well-known LOA framework based on the aviation industry that is also relevant to nuclear control room operations – see Figure 11.



Level	Role of Automation	Role of Human
Autonomous Operations	Fully autonomous operation. Human not usually informed. System may or may not be capable of being disabled.	Human generally has no role in operation and monitoring is limited.
Operation by Exception	Essentially autonomous operation unless specific situation or circumstances are encountered.	Human must approve of critical decisions and may intervene.
Operation by Consent	Full automatic control under close monitoring and supervision.	Human monitors closely, approves actions, and may intervene.
Operation by Delegation	Automatic control when directed by human to do so.	Human provides supervisory commands that automation follows.
Shared Control	Automatic control of some functions/tasks.	Human controls some functions/tasks.
Assisted Manual Control	Primarily manual control with some automation support.	Human manually controls with assistance from partial automation.
Direct Manual Control	No automation is used.	Human manually controls all functions and tasks.

Figure 11: Billings' levels of automation (cited in Oxstrand et al., 2013, pg. 16)

Considering both the list of cognitive functions and the example LOA shown above, one can start to extrapolate about what kinds of tasks operators may have to perform, even in the role as automation supervisor. It is likely that the cognitive functions listed above are still performed by the operator, but now they are directed towards the automation, rather than nuclear processes. For example, in the case of “Operation by Exception” from Figure 11 above, the automation must wait for operator approval of critical decisions when operating the plant. For the operator to approve these critical decisions, the operator tasks may involve:

- **Monitoring and detection** – monitor the progress of the automation in a specific task and detect that a critical decision point has been reached,
- **Situation assessment** – evaluate the plant state and conditions to gain an understanding of the situation and the potential outcomes of the different critical decision paths, which may require some **interface management**,
- **Response planning** – determine which critical decision path is most appropriate in this situation, and
- **Response implementation** – approve the relevant critical decision in the automated system.

A report by Hugo et al. (2014), related to the INL study discussed in Section 5.5, identifies a set of eight “high-level supervisory performance criteria” (pg. 19):

1. The ability to detect out-of-tolerance conditions. This will require the availability of appropriate operational information, as described in item 8 below.
2. The ability to adjust the system or stay on course as a function of plant conditions and various context topologies.
3. Maintaining the balance of goals and means for complex goal topologies.
4. The ability to perform goal and goal status assessments in a timely manner.
5. Conducting effective and accurate information search as required by conditions.
6. Successfully apply procedural guidance within regulatory bounds.
7. Intervene and override automation as required, and exercise control at various levels of systems performance.

8. Adapt to varying levels of automation associated with various reactor systems (for example some automation will have hold points and others will be fully automated).

Although these criteria specify abilities rather than actions, one can extrapolate from this list a set of actions that operators may be responsible for when supervising automated systems. For example, operators may monitor the progression of automation to ensure that the resulting effects on the system do not conflict with operational goals (item 3) or regulatory bounds (item 6).

In addition to monitoring automated systems, operators in the main control room of SMR NPPs are likely to also have other roles or functions that they are responsible for. Seymour et al. (2022) lists a set of administrative functions that will still be required in advanced reactors, such as SMRs, and that (from a regulatory perspective) will still require implementation by a human, rather than automation. For example (ibid., pg. 3): “technical specification implementation, configuration control, authorizing emergency-related departures from facility license conditions, notifications to offsite authorities, etc.”

A draft white paper by the US NRC further explains the administrative responsibilities that are necessary for regulatory compliance and are important to safety. These include (US NRC, 2021, pg. 36): “compliance with technical specifications, operability determinations, NRC notifications, emergency declarations, risk assessment, maintenance oversight, and radiological release limit compliance.”

5.3 Operator Tasks Outside of the Main Control Room

The technological advancements in SMR design and the shift towards automation do not only affect operations inside a main control room. Seymour et al. (2022) state that “the NRC staff have identified that, for advanced reactors, important tasks such as maintaining and fulfilling safety functions may not necessarily be performed only in a traditional control room” (pg. 5). They note that “tasks needed to ensure the fulfilment of safety functions… may extend beyond those tasks only associated with plant operations and might also encompass maintenance, testing, and inspection-related activities as well” (pg. 5).

This aligns with our earlier hypothesis that 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 the Electric Power Research Institute (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 (including field operations) as these tend to impact plant safety more directly and thus are more likely to be represented in HRA fault scenarios. 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 likely 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 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).

A 2008 report by the US NRC takes an interesting perspective on how maintenance tasks may change in NPPs that are becoming increasingly digital and automated (US NRC, 2008). The report notes that the introduction of complex digital and automated technologies is likely to change the concept of maintenance. For example, digital systems are more likely to have unique features that will make them more challenging to maintain, especially as digital technology evolves at such a rapid pace. Most troubleshooting and maintenance activities are now likely to be performed using software at a workstation, rather than requiring physical field work.

Furthermore, as more complex automation and information systems are introduced, the report predicts a merging of the maintenance and operations functions, noting that “on-site personnel who are charged with operating the plant also will increasingly need to act as the first line of defense when faults are detected, or failures occur in the I&C systems. With digital systems, the distinction between I&C maintenance and operations tends to become blurred in the early stages of fault response” (ibid., pg. 31).

Additionally, the expectation of simpler plant designs that are easier and less expensive to perform maintenance on (i.e. the remove-and-replace philosophy suggested in EPRI, 2016), might result in “maintenance being more quickly performed by [field] operations personnel without the checks and balances done by maintenance departments” (US NRC, 2008, pg. 31). This approach could also support the staff-reduction philosophy, whereby more staff are cross-trained in multiple disciplines. including maintenance, as noted earlier in this report.

5.4 Novel Operator Tasks at an SMR NPP

A further aspect that must be considered is the potential for new operator tasks at an SMR NPP because of new reactor configurations, such as multi-modular operation or remote operation, and/or new applications of the reactor technology, such as for hydrogen production or district heating.

The report by Hugo et al. (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 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., pg. 10). 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.

There are also likely to be requirements for new or different knowledge, skills, and abilities for operators because of the introduction of more advanced digital technologies. In the later report by Hugo et al. (2014, p. iii) it is stated that “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”

Unfortunately, this literature review has not identified any further information on completely novel operator tasks at SMR NPPs, which is likely as a result of lack of maturity of very new or very different SMR NPP designs and/or lack of open literature on human factors aspects of SMR operations related to new designs.

5.5 Case Study on Operator Roles in an Advanced SMR

One of the most comprehensive studies of potential operator tasks identified during this literature view was performed by INL between 2012 and 2015 and reported in a series of technical reports and peer-reviewed articles. The purpose of the INL Advanced SMR (AdvSMR) program was to investigate human factors issues in AdvSMR Concept of Operations (ConOps) and included the development of a Functional Analysis framework use to analysis (Hugo et al., 2013). One aspect of this work involved an in-depth examination of the characteristics and attributes of the AdvSMR ConOps and how the role and function of humans in the plant might be affected by advanced technologies such as automation.

The AdvSMR concept used in this study is based on design information and operating experience from a sodium-cooled Experimental Breeder Reactor-II (EBR-II) reference plant. The EBR-II design was used to extrapolate operating principles to a modern sodium-cooled reactor design, making assumptions about modularity, plant layout, levels of automation, etc. For example, the authors assumed that for emerging sodium-cooled reactor designs, there would be a high level of automation in all normal operating scenarios, but operators could still manually intervene and take over control of components, systems, and processes as necessary.

The authors also assumed that advanced digital instruments, controls, and human-system interfaces (HSIs) would be found in the control room. The report further explains that for the EBR-II, manual control of systems and processes was the norm, as automation only existed at component level due to technological limitations at the time. However, for the AdvSMR sodium-cooled design, the expectation is that automation would be implemented at the system and/or process levels, and that this will likely be the norm. The authors note that dual control capability (human and automation) as well as fully manual control capability would still be required for abnormal or emergency situations.

The authors of the study had the possibility to access operating procedures, drawings, and system descriptions for the EBR-II. With this information, the authors used cognitive work analysis to evaluate the types of functions and activities that would take place within the different operating domains of the concept AdvSMR plant. Specifically, the study used work domain analysis (WDA) as the foundational methodology to identify the functional and structural characteristics of the work domain, as well as any constraints that the work domain might impose on workers and systems.

Based on documentation from the EBR-II archives, the authors developed a state-transition diagram for the EBR-II (Figure 12), and this was used together with the documentation as a basis for identifying important normal and abnormal operating conditions. The WDA performed for the EBR-II was then translated to an AdvSMR design.

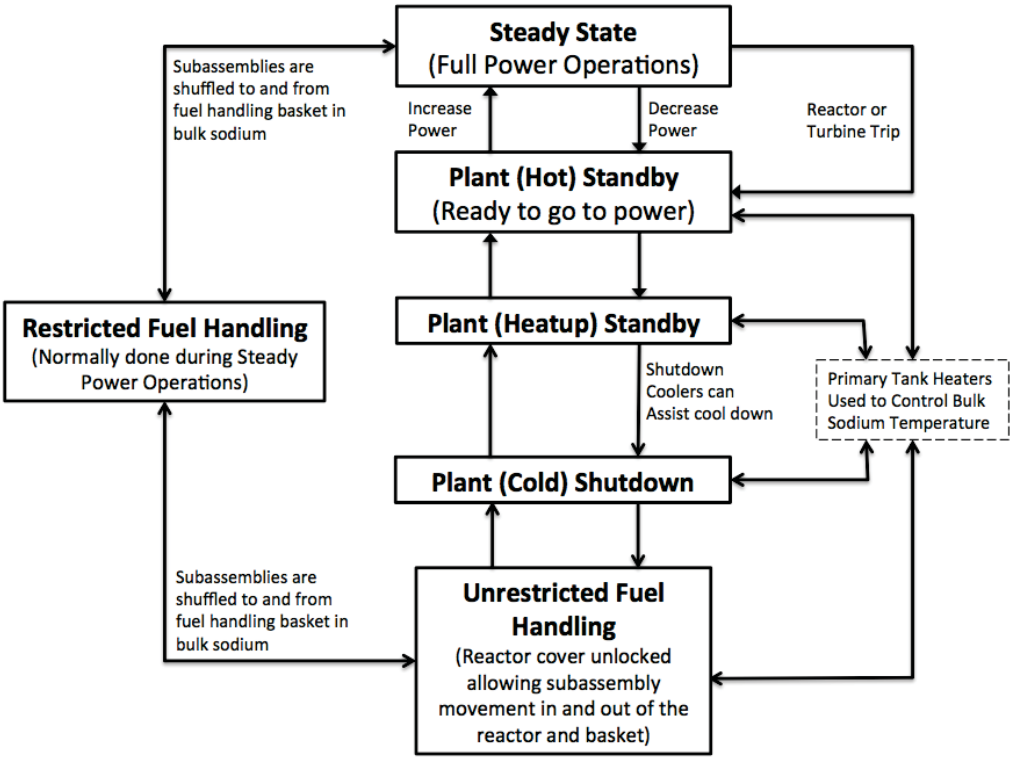


Figure 12: The EBR-II state transition diagram (Hugo et al., 2013, pg. 21)

The next major step in the study was to develop a function allocation framework for the AdvSMR. The study notes the need for a more dynamic allocation of function between humans and automation because there are many ways in which failures can occur. In some situations, such as complete failure of the automation, the human should be allocated all control functions to bring the reactor to a safe state. In other situations that might lead to an automatic shutdown, then the automation should be allocated most of the control functions, with the human supervising the overall system. The authors note that: “The consequence of this issue is that the allocation of functions and responsibilities cannot remain static in an AdvSMR, due to the fact that different design basis accidents are already identified as requiring differing levels of human and/or automation involvement” (ibid., pg51).

In a situation where the AOF has assigned almost all of the control functions to the automation, the division of roles might be as shown in Table 3.

Table 3: Potential roles for automation and operators in a highly automated operating scenario (adapted from Hugo et al., 2013)

Automation role	Operator role
• Monitor the plant state • Control electricity generation process in-line with pre-defined operating parameters	• Monitor and verify the performance of safety systems • Maintain communication with relevant onsite and offsite personnel • Initiate recovery actions following an event • If necessary, initiate reactor shutdown by manual scram, or manual activation of the automated shutdown system

In this situation, the operator is clearly in a supervisory role, with the requirement that the operator can intervene to initiate automated functions or perform manual functions when necessary. The authors further describe how this division of function would work in two generic failure modes (Table 4): (i) automatic shutdown of the NPP, and (ii) failure mode requiring human operator intervention, such as loss of coolant accident (LOCA) in a light-water cooled NPP (ibid, pg. 53).

Table 4: Specification of automated and operator functions/tasks in two generic failure modes (adapted from Hugo et al., 2013)

Failure mode	Automated functions/tasks	Operator functions/tasks
1. Automatic shutdown	• Initiate the shutdown sequence for the reactor	• Detect that the new desired end state is a safely shut down reactor (i.e. that automatic shutdown has been triggered) • Monitor the relevant performance variables • Verify the performance of the automated safety systems.
2. Operator-initiated shutdown (e.g. LOCA)	• Execute the actions as directed by the operator.	• Detect the information presented (i.e. relevant operating parameters) • Diagnose situation (based on training and procedures) • Decide what actions to take (i.e. shut down the reactor) • Give orders to other operators and/or the automation to perform the required actions.

With these examples, the authors illustrate their belief that a more dynamic function allocation is appropriate in systems with high levels of automation, where the roles and functions of the automation and the operator are determined by the operational state of the plant, and that different operational states will require different levels of automation, depending on the desired outcome of that state.

One of the most relevant aspects of the study for this literature review relates to the authors' attempts to determine major functions associated with the EBR-II reactor, from which they extrapolate how these functions might be realised in the AdvSMR, given expected advances in automation. This is considered especially relevant for this project because it starts to form a picture of what kinds of tasks operators may have to perform in an SMR control room, beyond the high level "monitor the automation" task. The authors identified four functions that are typical of normal operations at the EBR-II that they assume will also occur at the AdvSMR plant (ibid., pg. 77):

- Drive the turbo generator, to convert mechanical energy to electrical energy,
- Maintain fast fission, converting potential energy to nuclear energy,
- Maintain reactor cooling, utilising sodium coolant to remove reactor heat, and
- Manage and control plant operations.

The authors then identified two plant operating states, which were steady state (normal) operations, and restricted fuel handling. These two states were selected because during steady state operations one can expect that many previously manual functions will now be performed by automation (e.g. load following, sodium temperature monitoring, etc). Conversely, during restricted fuel handling, although it is still considered a normal operation, it is more complex and there are more manual actions with safety-related requirements that require a high degree of situation awareness from the operators. The authors note that workload is moderate to high during restricted fuel handling, so their expectation is that some aspects of this would be automated in the AdvSMR to ease the workload of the operators, e.g. robotic control of the fuel handling crane.

A table was developed to compare crew responsibilities for the two selected normal operation scenarios in the EBR-II and AdvSMR designs, according to the four typical functions identified – see Table 5 in Appendix 1. Where the operating crew responsibility is documented as "monitoring" the automated system, one can assume that the operator is checking that automated system processes have initiated as required, and that the system is being operated within the expected performance parameters.

The authors of the INL report further extended this analysis to consider an emergency operating scenario, in this case a water-to-sodium leak. The authors note that, whilst this scenario would not directly threaten the reactor as it does not involve the primary sodium system or the reactor itself, it could result in a fire and/or hydrogen explosion, damage to equipment and property, and considerable financial loss. As a result, it is considered to be a challenging scenario for operators.

In the case of a water-to-sodium leak, the reactor would be tripped and decay heat removal from the reactor would be initiated. The secondary sodium system would be isolated by stopping flow through the heat exchangers and operators would drain the secondary sodium system. This is expected to be done automatically in the AdvSMR concept.

The following important functions were identified in this scenario (ibid., pg. 80):

- Maintain equipment integrity,
- Maintain a habitable and safe environment,
- Ensure containment of fission products,
- Manage and control operations,

- Provide electrical power,
- Maintain reactivity control,
- Maintain coolant circulation, and
- Maintain environmental control (HVAC; heating, ventilation, and air conditioning).

Table 6 in Appendix 1 shows the primary responsibilities for the automation and the crew in the EBR-II and, by comparison, in the AdvSMR design concept, for this emergency scenario.

Utilising this approach, the authors observed some differences in operator roles between the EBR-II design and the AdvSMR concept. For example, in maintaining equipment integrity in the AdvSMR concept, many of the monitoring duties that would normally be performed manually by operators are now expected to be automated. In the EBR-II design, operators would have manually monitored equipment and process status information, but for the AdvSMR this will now be done by automation that will also perform diagnostic and prognostic analyses on the data. Whereas before operators would have had to perform mental calculations on integrated data to assess the status of equipment and the progression of system processes, this will now be done automatically. The control room HSIs for the AdvSMR are expected to feature smart displays and trends, providing the operator with information about the automated diagnostics and prognostics, which will support operator situation awareness and communications. Other formerly manual actions such as operator actuation of scram, building evacuation, draining sodium and actuating the argon vent valve are also expected to be automated, further reducing the operators’ role.

Conversely, some functions such as maintaining a habitable environment, containment of fission products, etc. will not change significantly in the AdvSMR concept for this scenario. This is largely because this specific event occurs outside of the main control room and reactor building.

Overall, the authors of the INL study conclude that, compared to the EBR-II reactor design, operators of the AdvSMR concept would be responsible for significantly less control actions, but a larger number of system monitoring activities. They note that: “Operators will have the capability to manually intervene in many cases, but this will be the exception to the rule of monitoring and supervising highly automated systems” (ibid., pg. 88).

5.6 Performance Shaping Factors in SMRs

PSFs are used in HRA to modify the qualitative and quantitative analyses to reflect the influence of factors related to the task, environment and individual conditions that can influence human error – positively or negatively. Moreover, the design and operational characteristics of SMRs may possibly introduce some novel PSFs and/or change the level of influence of existing PSFs on human performance and human error probability. Although the taxonomy objective of this project is focused on the early steps of the HRA process, and treatment of PSFs tends to occur later in the HRA process, many HRA practitioners will already consider potential PSFs from the first step as these may affect how the practitioner thinks about operator tasks and what kinds of data the practitioner seeks to collect. Thus, information identified during the literature review on potential PSFs is documented here for consideration during the development of the taxonomy.

The literature review identified that, similarly to conventional NPPs, there are several factors that may have an impact on operator performance in SMR operations, and that should be considered when exploring operator tasks for these NPPs. It is expected that most of the PSFs that exist in conventional NPPs will still be relevant for SMRs in cases where the basic operator roles and responsibilities are not expected to change significantly. The following sections describe the findings from the literature review on the PSFs that are expected to have the most significant impact on operator performance in SMRs. This is not intended to be a comprehensive list of PSFs for SMRs; rather, the goal is to document novel or significantly different PSFs, as compared to conventional NPPs.

5.6.1 Impact of Multi-Module Operation

One major factor is the potential for multi-module operation of SMRs; that is, the ability to operate multiple modules as a single plant, from a single, centralised control room (Blackett et al., 2022). However, how many modules one operator can safely handle is still under debate. According to Hartmann et al. (2024) this depends on which state the reactors are in, noting that an increase in complexity decreases the number of reactors that can be managed by a single operator. One operator could potentially handle 3-5 reactors that are undisturbed, 1-2 reactors that are in refuelling mode or startup/shutdown operations, and only one reactor that is engaged in accident management. Hartmann et al. argue that the reason for this is the high cognitive workload of having to repeatedly switch mentally between multiple modules. According to NuScale (2020) a 12-module power plant may be operated safely by a minimum of three operators from a single control room, even during high-workload conditions. Although, the staffing may not be the same throughout the lifetime of the plant, in the beginning more resources/staffing may be required since there might be a higher workload (due to establishing procedures, training the staff, less experience, new environment etc.; IAEA, 2001).

Moreover, O’Hara et al. (2012) suggest that when the workload is high it should be possible to add additional staff to the control room, for example during startup/shutdown operations. It must be noted, however, that this strategy can come with challenges related to quickly ensuring adequate situation awareness for the newcomers to enable them to effectively provide support when and where needed, as evidenced by, for example, studies on situation awareness during shift handover (Carvalho et al., 2012). Arigi et al. (2019) note the importance of considering situation awareness at multi-module sites because of the increased complexity of events at multi-module sites compared to single unit sites, and because of the increased use of shared systems and components between modules.

Multi-module operation could also increase the need for flexible and dynamic allocation of tasks between operators, as needed by the different modules’ operating states or operating processes occurring. For example, if one specific module requires more attention, then operators will (re)distribute the workload between them to enable this (Hugo et al., 2014). Bye (2023) suggests that the more complex tasks get, the more does (bad) teamwork impact performance.

The design of the control room needs to facilitate teamwork and communication in multi-module plants. SMRs are likely to be equipped with an entirely digital interface which, according to Bye (ibid.) is suspected to result in operators having less overview of their colleagues’ activities compared to analogue control rooms. According to Bye (ibid.) the reason for this is that in an analogue control room the physical position of an operator (for example in front of the safety panel) indicates that the operator is working on that panel. The operators in a digital control room are generally at their desk regardless of which system they are operating or monitoring.

The design of the control room, and overall system design, becomes even more important when considering multi-module SMR plants. A multi-module plant may require the operator to multi-task and repeatedly mentally switch between tasks which can result in both cognitive overload and cognitive underload which will impact the situational awareness (O’Hara et al., 2012; Hugo et al., 2014; Blackett et al., 2023; Hartmann et al., 2024). O’Hara et al. (2012) mention the importance of having differences in system interface design between the different modules to support situational awareness and separation of the individual modules. According to Hugo et al. (2014) the possibly high cognitive workload may challenge the view that one operator can handle multiple modules at the same time.

5.6.2 Impact of Automation

The level of automation utilised at the plant will also have an impact on operator performance, since presumably if operators are primarily responsible for monitoring highly automated modules, then they should be able to oversee more than one module concurrently (Blackett et al., 2022). Hugo et al. (2014) argues that even though automation may decrease the cognitive workload it may hinder situational awareness, and the authors stress the importance of keeping the human in the loop.

Blackett et al. (2021) looked at high-profile automotive and aviation accidents and how to consider the human in highly automated systems. When designing an SMR, and particularly the control room, a human-centred design process should be implemented to ensure that human-automation interaction requirements are appropriately considered. The risk of over-reliance on automation is important to consider in SMRs since the main responsibility of the control-room operator is checking and verifying that the automation work as intended. If the operator places too much trust in the automated system, they may not apply an appropriately questioning attitude to indications that the automation might be on the verge of failing or operating out-of-bounds. Furthermore, over-reliance on automation might cause the operator to disengage and fail to appropriately monitor the automated systems.

A way to counteract over-reliance in automation can be to ensure that operators are fully informed of the abilities as well as the limitations of the systems, and that there is sufficient transparency of automated functions to allow the operator to see what is happening. The control room interface should be designed to support automation transparency, and as noted by O’Hara et al. (2012), operators should be trained to ensure that they understand how the automation works.

Several papers (O’Hara et al., 2012; Hugo et al., 2014, Blackett, 2022; Jamieson et al., 2022) suggest further research into human-automation collaboration, considerations and limitations. As automation capabilities advance, there is still a tendency to rely on humans to act as the backup to failure of the technology: “Research tells us that even in highly automated systems, manual intervention is often still relied upon in the case where automation fails, and that human-automation interaction is a complex and multi-faceted concept that requires careful consideration especially in high-hazard and/or safety related systems.” (Blackett et al., 2023, pg. 3). Moreover, even though there is an assumption that the technology capabilities exist for fully autonomous SMRs, regulation and liability will probably always require a human operator to have an oversight over the SMR and the automation (ibid.).

5.6.3 Impact of Remote Operations

Remote operations are another SMR operating paradigm that may have an impact on operator performance. When considering lessons learned from other industries that have implemented remote operation (e.g. oil & gas, maritime (specifically autonomous ships) and aviation (specifically air traffic controllers)), Blackett et al. (2023) noted several lessons learned that may be applicable to the SMR industry.

One of the major considerations for remote operations is the clarification of command-and-control responsibilities between the remote control centre and the module. This will be influenced by the level of automation at the site, and level of intervention expected from a human operator under different conditions. Deciding whether responsibility and control lies with the operators in the remote control centre or operators at the site, and under which conditions, is essential and may affect the types or nature of tasks that should be included in the HRA.

Furthermore, considerations must be given to whether there will be some personnel (such as maintenance personnel, field operators etc.) at the remote site. Problem-solving without any personnel on the physical site may be difficult and compensatory measures implemented to aid problem-solving remotely may introduce new challenges rather than making it easier.

6. Findings from the Expert Interviews

In addition to the literature review, interviews were conducted with 21 individuals considered to be subject matter experts (SMEs) on the topic of SMRs. Potential interviewees were identified through their contributions to various SMR industry, research, and regulatory fora, such as conferences, technical meetings, etc. The SMEs were then recruited via Risk Pilot's own networks and were invited to participate in a video interview. 28 invitations were sent, of which 21 individuals agreed to participate in an interview.

6.1 Information About the Interviews

The invitations to interviews were targeted across a selection of individuals working within the nuclear industry, and who were considered to have some knowledge of SMRs or SMR-related topics. The goal was to interview a range of individuals to collect a broad spectrum of knowledge, experiences, and opinions on the topics of interest to this study.

Participants were informed that the data would be handled confidentially and not attributed to individuals or organizations, to encourage open and candid discussions. Personal data collected about the interviewees was limited to their current country location (Figure 13), the type of organisation they work for (Figure 14) and the number of years' experience with SMRs or advanced reactors (Figure 15). Interviewees were also asked about the type of SMR experience they had, and whether it was towards a specific SMR technology or more general concepts of SMRs.

To preserve the confidentiality of the interviewees, the findings documented in this report are aggregated and are not attributed to an individual person or organisation, nor are the results related to any specific reactor technology.

As shown in the following figures, participants from seven countries were interviewed, coming from five different organisation types: regulatory bodies, vendor companies, nuclear power plant operator companies, research organisations and consultants working in the nuclear industry. Their experience working with topics related to SMRs and/or advanced reactors ranged from 0-5 years to more than 15 years.

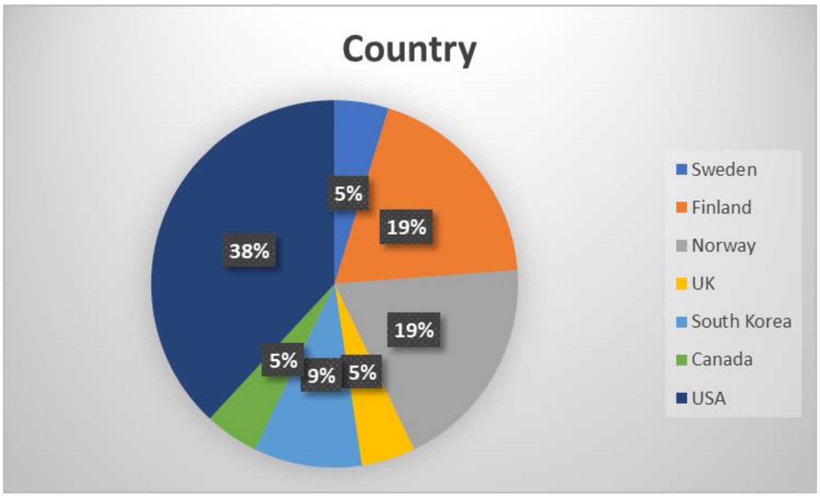


Figure 13: Location of interviewees by country

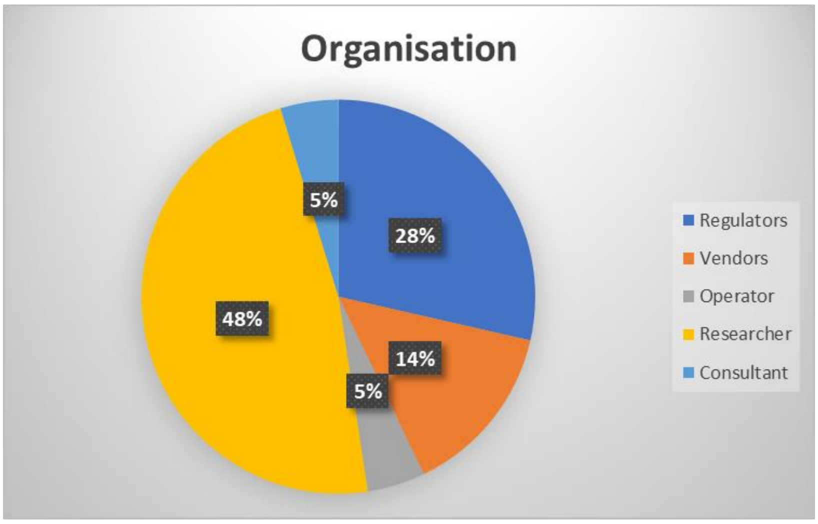


Figure 14: Organisation type of interviewees

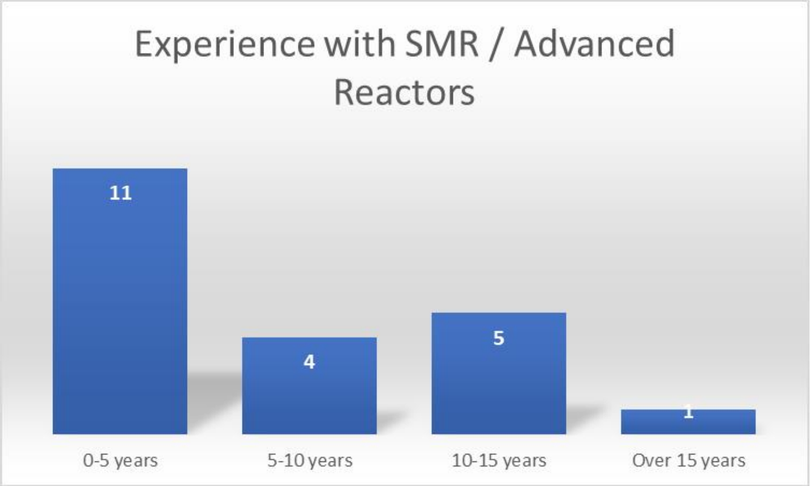


Figure 15: Number of years' experience of interviewees

6.2 Interview Findings

The following sections present the aggregated findings from the SME interviews, grouped according to five main themes:

1. Roles and responsibilities for operators in SMRs
2. New operator tasks in SMRs
3. Main drivers for change in operator roles
4. Potential safety challenges for operators in SMRs, and
5. Performance shaping factors in SMRs

An important point that was stressed by several of the interviewees is that any discussion of these themes must acknowledge the wide variety between the SMR designs and concepts that are in development today. As such, it is difficult to be specific about potential operator roles, responsibilities, new tasks, challenges, or PSFs since these could vary significantly between one design/concept and another. As such, the interviewees tended to prefer to speak more generically about how they think SMRs will be operated in the future.

It should also be noted that the findings presented here are primarily focused on control room operations, unless stated otherwise.

6.2.1 Roles and Responsibilities for Operators in SMRs

When asked about the roles and responsibilities for operators in SMRs, most of the interviewees responded that the role of the operator will mainly be to monitor automation and inherent and/or passive safety systems. The operator’s responsibility will be to ensure that these systems perform the functions that they are supposed to perform.

Some interviewees considered that operator roles will not vary significantly from today, due to the high levels of automation that already exist in modern NPPs in operation today and the fact that many operator tasks are already performed via digital interfaces. However, these interviewees noted that the difference for SMRs will be in terms of the number of people needed to perform these roles, which in turn will depend on the operational concept and the control room design. It may be possible to combine some roles to achieve the desired lower staff levels, although it is currently unclear which roles could be combined; there are too many unknown dimensions as of today to be able to speculate on this.

When considering this theme in terms of safety, some interviewees noted that the role of the operator may be very small because of automation, inherent safety properties and passive safety systems. The operator may only have a role if something goes wrong with one of these. Further, when considering the role of the operator from a production perspective – particularly in cases where the SMR is used to produce outputs other than baseload electricity – it becomes less clear what the operator will be required to do, and whether production responsibilities could conflict with safety responsibilities.

When the interviewees were prompted to consider the role of the operator in more detail, the majority noted that operators are likely to have a simpler role, but there will still be plenty for the operator to do. For example, if the plant is in operation, at or near 100% power/production, then operators will still be involved in a cycle of preventative maintenance, corrective maintenance, surveillance, testing, reporting, etc. Some of the interviewees likened the role of the SMR control-room operator to that of resource manager or work management coordinator, overseeing and coordinating work performed by different disciplines across the plant. In terms of plant operation itself, operators are expected to have a lower task inventory, and will mainly be responsible for monitoring, detecting and interpreting alarms, and for starting and the observing automated function sequences.

From the perspective of safety and reliability, interviewees noted that it will be important to keep operators in the loop. Although humans will no longer actively control the plant or perform physical manipulations of the plant, they should still be responsible for making critical decisions, for example, to approve or initiate safety critical functions. As the technology advances, it may no longer be necessary for humans to monitor the automation all of the time, but this will depend on the reactor design and the level of autonomy.

An interesting point raised by a small number of interviewees relates to whether it is better to rely on automation or have an operator intervene in abnormal or emergency situations. Many SMR concepts put forward the case that no operator actions will be needed for an extended period of time (e.g. 72 hours – see Section 4.3). In such a situation, the operators should let the plant trip automatically, and (by design) it will end up in a passively safe state. But from an economic point of view this may not be desirable because, for example it might involve the actuation of single-use passive safety systems which must then be replaced or reset, resulting in a longer period where the reactor is offline. If the operator could intervene relatively easily to manage the scenario and bring the reactor to a safe state without actuating passive safety systems, then that may be desirable even if those operator actions are not credited in the plant risk analysis or safety case.

6.2.2 New Operator Tasks in SMRs

Whilst it is difficult to state exactly whether/what kinds of new operator tasks might be created in SMRs, some interviewees did suggest that increased automation and/or more advanced automation could create new tasks and require new capabilities from the operators. Some new operational concepts, such as load following, could also create new types of tasks for operators, although it was not possible to be more specific about what kinds of tasks.

The multi-module concept came up in a number of interviews as potentially creating new tasks, or new ways of working, for operators. For example, multi-module operation might require a more dynamic work style as operators need to more flexibly allocate their attention and effort across multiple reactor modules. Furthermore, the multi-module concept may require operators to have a wider and more generalised knowledge, since individual operators may now be responsible for entire reactor modules, rather than being responsible for only the reactor or balance of plant systems as in today’s control rooms. As noted in the previous section, control room operators may take on more of a work management role, as they may be responsible for coordinating work across modules to ensure that the work is sequenced correctly and there is not too much happening in parallel. At the multi-module plant, some interviewees suggested that the plant could always be in outage, i.e. outage would be staggered across modules so that there would always be one preparing for, in outage, or coming back online after outage. This would require more vigilance on behalf of control room operators, as well as more continuous maintenance work going on.

Some interviewees also discussed the fleet maintenance concept that could introduce new tasks at an SMR. This is the idea that, instead of having dedicated maintenance personnel at each SMR plant, there could instead be a central pool of competent people who could be sent to different modules across the fleet as needed. Whilst this might have the advantage of further reducing the number of staff on site, the interviewees did note some potential disadvantages to this concept. For example, the concept may only work for preventative maintenance tasks that can be pre-planned and pre-scheduled, meaning that you may still need some maintenance staff on site to perform corrective maintenance as necessary. In addition, some concepts discuss this as a service provided by an external party, such as a reactor vendor organisation. This might not be ideal from a regulatory perspective as there is a risk that plant knowledge and competence would then be held by the service provider rather than the licensee.

6.2.3 Main Drivers for Change of Operator Roles

The interviewees considered a number of different factors that may act as drivers for change in operator roles and responsibilities in SMRs. Several interviewees stated that the level of automation and the number of modules to be managed will be a key determinant of future roles and responsibilities. There may be more variability in the operator role in the multi-module concept because operators are now responsible for overseeing the entire module and/or because different modules may have different output goals, as in the cogeneration concept discussed earlier in this report.

Some interviewees raised an interesting question with respect to this concept and operator licensing: how similar or different do reactor modules need to be before an operator would need a different license to operate them? This relates not only to the cogeneration concept, but also the issue of homogeneity of modules being used for the same purpose. For example, if not all modules at a plant have been built at the same time (e.g. two modules built first and another two modules added some years later), and/or with maintenance over the years (e.g. replacing the same component but now made by a different vendor), it is possible that there will be differences between modules over time. It is unclear at the moment how this may affect licensing regulations, and also the effect it may have on operator roles and responsibilities over time.

The simplified reactor designs and new fuel technologies, as well as increased use of and reliability upon inherent safety properties of the module and passive safety systems will also result in a major change to the role and responsibilities of operators in abnormal or emergency events. With these systems in place, the safest thing for operators to do might be nothing. Some interviewees noted that this is difficult for humans as we tend to want to intervene in situations to see if we can help.

Additional factors that will affect roles and responsibilities will be the number of staff on site. Several interviewees noted that, to be economically viable, SMRs cannot have large numbers of staff on site. This may result in pressure to consolidate roles to keep the numbers of staff lower, as well as pressure to centralise control and introduce fleet service models. Centralisation of control could look like a control centre that monitors several remotely located plants, as is done in the air traffic control and petroleum industries (see, for example, Blackett et al., 2023). The fleet service model could be introduced not only for maintenance, as discussed previously, but even for some routine operational services as well, such as inspection and testing.

6.2.4 Potential Safety Challenges for SMR Operators

Some interviewees considered that multi-module operation could create potential safety challenges for operators, especially in countries that do not have prior experience of this kind of operational concept. The challenge may come from when different modules are in different operating conditions/modes, even if they are all in “normal” operational mode. The interviewees discussed how operators will have to deal with different situations simultaneously, e.g. one module could be in startup mode, whilst another is in steady state, whilst third is preparing for outage. This may be challenging for operators and is a key reason why automation will be necessary to support multi-module operations.

When thinking about automation, a small number of the interviewees raised the issue of having to consider unique situations that might be created by the automation. An example of this is the Boeing 737 MAX 8 accidents that occurred in 2018 and 2019, where automation masked a sensor data failure and resulted in two fatal accidents (Jamieson et al., 2022). In both cases, the automation functioned exactly as designed, but the human operators were unable to recognise what was happening and so could not intervene. Such situations create challenges both regarding how to manage human-automation interaction, but also in how to identify such potential accident scenarios during the design of SMRs.

The changing risk profile of SMRs (see Section 4.3) is also recognised by some interviewees as creating potential safety challenges for operators. It may become even more important to focus on identifying errors of commission (as well as errors of omission) that could introduce latent failures into the system. When combined with reduced staffing levels, this could mean that there are less people on site to detect potential latent failures before they become initiating events. Some interviewees pointed out that risk analyses/safety cases for SMRs will have basic assumptions around the design basis and operating envelopes for passive safety systems, but if, for example, an error is made when returning systems to service after routine maintenance, then it may challenge those assumptions that technical specifications are based on.

Some interviewees discussed how the complexity of the organisational landscape could further exacerbate this situation, for example, if the fleet services/maintenance model is implemented. Maintenance and field personnel are the ones who are out in the plant regularly and who are more like to identify issues before they become problems. But if the maintenance or field personnel are not employees of the licensee and are just there to do a job, will they be familiar enough with the plant to identify potential problems? Will they feel the same sense of ownership of the plant or responsibility to the licensee to inform them of potential issues? This may also present a challenge in terms of knowledge capture and knowledge transfer.

Sustaining situation awareness for operators in highly automated plants was mentioned as a challenge by several interviewees. This is especially the case when the operator role has shifted from active operation to passive monitoring. For multi-module operations, there may be a challenge regarding how to distribute work between operators and how to monitor several different processes and/or modules simultaneously. Some interviewees pointed out that humans are not good at multi-tasking or dividing attention between different things so this may be a challenge.

Operators in highly automated systems are also going to be presented with much more data than in conventional plants. Much of the raw data coming from sensors and instruments will be aggregated, integrated, and processed for presentation to the operators in a way that is understandable. But some interviewees pointed out that this increases the cognitive distance between the operating personnel and the reactor and makes it more complex for humans to understand what is actually happening. This may be especially challenging in cases where the operator has to intervene because the automation has failed or is in a beyond design basis situation. At this point the data may become unreliable, and the human may not be familiar with what the automation has been doing (see again the Boeing 737 MAX 8 accidents).

The emphasis on reduced staffing might also create challenges if emergency response resources are outsourced. Normally security and fire-fighting resources would be part of the staff on site, but this is likely to be outsourced to help keep staff costs down. However, there are unique challenges that must be considered when responding to a nuclear emergency which might result in needing more specialised training and response resources offsite, thus increasing the cost. There is a trade-off-that needs to be considered. Reduced staffing levels could also result in people working alone on tasks where there previously would have been two persons. This may have an impact on the ability to perform peer checking/independent verification as well as affecting personal safety.

6.2.5 Performance Shaping Factors in SMRs

The interviewees were asked about what they considered would be the factors that would most likely influence operator performance in SMRs. Many interviewees mentioned workload as an important performance influencing factor (PIF), specifically the risk of sustained underload for operators in highly automated plants, occasionally interjected with periods of extreme overload in abnormal or emergency situations. Interviewees noted that when there is no active role for operators in the day-to-day running of the plant, then it is difficult to expect a lot from operators in the event of an automation failure or beyond design basis situation. One interviewee considered that in such situations, the operators may be ill-equipped to take over control of the plant due to the need to switch from being an out-of-the-loop supervisor of automation to suddenly needing to be in-the-loop and in control of the entire plant.

Workload may also be affected by new or unique SMR processes, for example, cogeneration or multi-module operation. In these cases, the operators will need to be able to understand and maintain awareness of different process models and operating modes at the same time. Some interviewees further discussed how operators will be reliant on being able to understand and interpret sensor data, as well as what the automation is doing. SMR operation will require a lot of trust in automation on behalf of the operators.

Other factors mentioned by interviewees that will affect operator performance include advances in technology, which will presumably reduce the operators’ workload and mental burden. The size of the reactor, the number of modules, and how remote the plant is will also have an impact on operator performance for the reasons already discussed in previous chapters of this report.

A small number of interviewees commented that underload will not be a problem for operators, as there is always something to do in an NPP – referencing the large amount of administrative and routine testing tasks that operators often have to do, as well as the newer work management role that operators may have to take on.

7. Discussion & Conclusions

This chapter discusses the findings derived from the literature review and interviews with subject matter experts and considers the implications for the development of a taxonomy of tasks for HRA of SMRs.

7.1 Reflections on Findings

The literature review and the expert interviews converge on the central theme that operator roles and responsibilities in SMRs will experience some changes, and that these changes will largely be driven by the level of automation that will be implemented at the plant and the staffing plans of the operating organisation or licensee.

Automation and staffing are tightly coupled factors in SMR operations. Most SMR designs propose to use advanced automation to perform the majority of functions at the plant, which means that less people are needed to perform the remaining human actions. At the same time, economic pressure to reduce costs through having less staff on site means that there is an increased need for automation to pick up the workload burden.

What is interesting for this research study is that both of these factors are likely to change the operating paradigm, i.e. change the way operators perform their tasks and/or change what tasks need to be performed, likely introducing new tasks. The research also identified that the move towards higher levels of automation may introduce new levels of complexity for operators, which may in turn be further compounded by the reduced staffing levels because operators may have a wider role, overseeing more systems than in a conventional NPP.

One of the aims of the literature review was to try to provide more detail to the hypothesis that the role of the operator will change from “doer” to “monitor of automation”. From an HRA perspective, there is a need to understand what task actions are involved in monitoring, to be able to decompose this task to a level that allows a robust examination of the potential errors that could occur. The INL study documented in Section 5.5 provides a valuable example of how this might be achieved in practice and is expected to be a key input to the taxonomy development. Although this study is based on a conceptual SMR design, it nonetheless describes in some detail how the role of the operator in a highly automated control room might be realised in terms of the actual task actions they may have to perform. Together with the understanding of how automation is implemented to replace human cognitive functions, this should provide a good grounding for how to think about the role of the operator in different situations and operating scenarios.

The research identified that the operator role will also be shaped by the level of supervisory control that is required, which in turn may be shaped by the reactor type, the level of risk involved, the operating context and regulatory expectations. Some critical task steps may purposefully remain within the control of the human operator, while others may be fully automated. For example, microreactors may be more suited to near-autonomous operation due to the simpler design and lower risk profile of the reactor. Some remote monitoring may be required for such reactors, but even this may not need to be continuous and rather focus on overseeing transitional states such as start up or shut down. Conversely, the larger SMRs will likely require more involvement from the operators in their oversight roles, with operators still mostly responsible for diagnostic decisions-making and safety-critical interventions. Operators may be responsible for deciding which automation sequences should be performed, initiating these sequences, monitoring the sequences, and then approving continuation of these at pre-determined hold points. This may have the added advantage of keeping the operator in the loop during automated operations, which may increase their ability to intervene, if necessary, in abnormal or emergency situations.

The research identified the importance of understanding the implications of function allocation, especially for those SMRs that are expected to be highly automated. The traditionally technology-centric approach – allocating functions primarily based on automation capability, leaving the residual tasks to humans – risks producing systems that are poorly matched to human strengths and limitations. The Boeing 737 MAX 8 accidents serve as a cautionary example to illustrate how design that favour automation and neglects human factors can have catastrophic consequences, and how automation can mask problems as they unfold. The parallels to SMR design highlight the importance of ensuring that operators remain meaningfully in the loop and that the automation supports, rather than undermines, human decision-making across all operating conditions.

The findings emphasise a need for a human-centred approach that explicitly incorporates human cognitive capabilities and constraints. This includes designing for more adaptive and flexible working arrangements, which may be particularly relevant for multi-module SMRs where workload distribution may need to shift dynamically based on the operational status of the different modules.

The challenge of maintaining human engagement and situation awareness also emerges from the findings of both the literature review and the expert interviews. Both emphasize the risk of the operator being “out-of-the-loop” when their primary responsibility is to monitor automated processes. This issue may be especially critical during situations where the automation fails or cannot handle a beyond-design-basis situation, and the operator must rapidly assume manual control. Such situations can coincide with high cognitive load and stress for the operator, which can potentially overwhelm them especially if they have not been engaged in the run up to the situation. This may be further complicated in multi-module SMR plants due to the complexity involved in overseeing multiple modules that are potentially in different operating modes, expanding cognitive demands beyond what would traditionally be expected for a control-room operator.

An interesting point was raised in the expert interviews around practical considerations for the operator in emergency situations. In theory, the automation and/or passive safety systems should be able to handle emergencies largely without human intervention. However, this may contrast with operators’ instinctual desire to intervene and “help”, especially if it means avoiding using costly one-time passive safety systems. In fact, the current emphasis on the need to prove the cost-effectiveness of SMRs may already be subtly shaping future SMR operators’ expectations and beliefs about operational goals and the need to be cost-effective. Designers and licensees may need to consider whether operators will be able to remain “hands-off” for the specified post-fault period, or whether some operator involvement should be deliberately built into emergency response protocols to satisfy the human need to help and avoid more unpredictable and uncontrolled interference that could undermine the reliability of the designed safety features.

Unfortunately, the literature search did not uncover much information about the roles and responsibilities of field operations or maintenance personnel at SMRs. The information that was identified tended to note only that, in line with staff reduction efforts, aspects of these roles may be combined to reduce the number of personnel required onsite. Licensees often do not have to specify the numbers or roles and responsibilities of field or maintenance personnel in applications to the regulator, and so it is possible that the lack of literature reflects a more general lack of examination of these roles with respect to SMR design and license applications. However, considering the need to examine potential latent failures as part of the shifting risk profile of SMRs (Section 4.3), this knowledge gap is likely to present challenges for HRA analysts in the near future.

7.2 Implications for HRA in the SMR Context

The findings from the literature review have some significant implications for HRA in the SMR context. Increased implementation of advanced automation is one of the dominating drivers for change in operator roles. This will introduce a swathe of human-automation interaction tasks for which human performance data is currently scarce. The majority of HRA methods in use today were developed during primarily analogue operations, and even those developed for analysis of fault scenarios involving digital HSIs have limited consideration of automation in the control room, let alone plant-wide automation.

This data gap may constrain the development or refinement of HRA methods that adequately capture the new types of errors and cognitive demands that operators will face in SMR NPPs. It will also have implications for human error quantification as the majority of the existing error quantification models do not include data on errors from complex human-automation interactions.

There is an expectation that HRA for SMRs will need to account for both Type A and Type B (see Figure 6) human errors in order to assess the potential impact of latent errors on the availability and reliability of the automated and passive systems that will now be credited within the PSA. However, very little information is available in the publicly accessible literature regarding what these tasks will actually involve in advanced, highly automated plants. In conventional NPPs, these kinds of activities have traditionally been quite manual in nature, but it is unclear whether this will hold true for SMRs. Field operations and maintenance tasks may increasingly include cognitive components such as interpreting sensor data and performing diagnostic reasoning on automated systems and components.

Consequently, HRA for SMRs may need to draw on different human performance models to capture the full spectrum of the human contribution to risk, using manually oriented models for analysis of field operations and maintenance, and using cognitively oriented models for analysis of control room operations. The degree of on-site maintenance may further influence HRA modelling as a “remove-and-replace” maintenance philosophy could simplify the maintenance task while shifting the risk focus to ensuring correct post-maintenance plant alignment and verification.

Overall, the greatest challenge for HRA in this context currently lies in the lack of available knowledge on how field operations and maintenance will actually be conducted. Extrapolation of HRA operating experience and findings from conventional large-size NPPs who have implemented some human-automation interaction tasks is possible, but the diversity of SMR designs, configurations and potential applications may make it difficult to directly use these data for SMR HRA. This will also be true as the industry starts to collect data and operating experience from the first years of SMR operation. The analyst will need to be skilled at extrapolating and interpreting data for application in the specific cases they are working on.

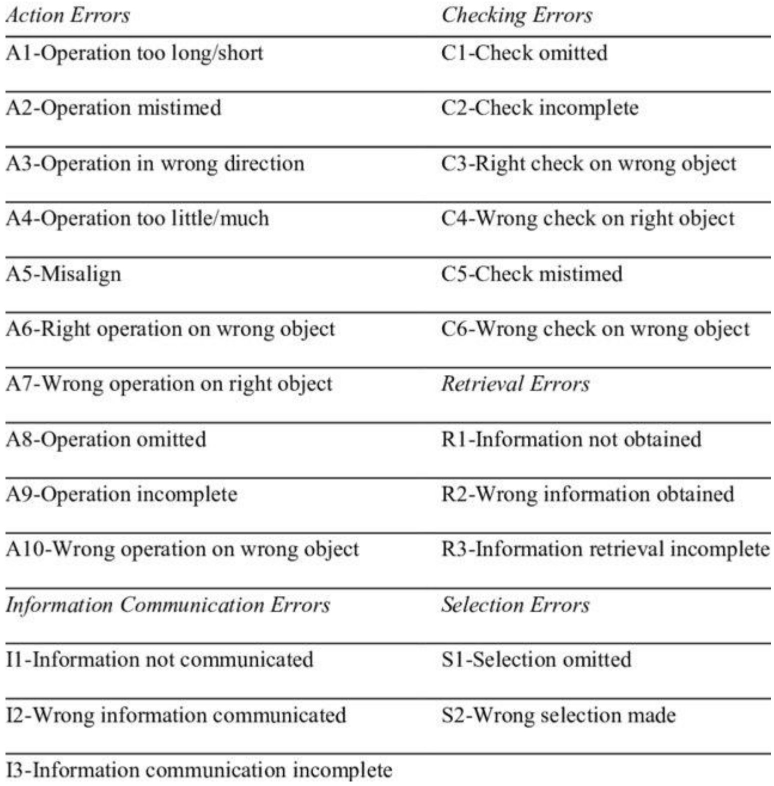
This points to an underlying challenge that will affect not only HRA analysts but also licensees and regulators; that HRA for SMRs is likely to involve high levels of epistemic uncertainty (Abrahamsson, 2002), primarily due to the limited operational experience and lack of empirical data on human interaction with advanced automation systems. Knowledge-based uncertainty arises from incomplete understanding and insufficient data and is particularly problematic in novel systems. As noted by Abrahamsson, in the absence of historical evidence, risk analyses tend to rely heavily on expert judgement which introduces potential biases such as overconfidence and anchoring, whereby people tend to fixate on an initial value and then work from this value even if it is incorrect. Furthermore, applying traditional HRA models calibrated for conventional large-sized NPPs to SMRs without adaptation introduces significant model uncertainty, as the assumptions underpinning these models may no longer be valid in the context of highly automated operation.

This raises the question about how much uncertainty is tolerable within HRA for the different stakeholders – primarily licensees and regulators. In principle, the inherent safety features of SMRs (e.g. passive safety systems, smaller core inventory, modularity, reduced system complexity) reduces the need for operator intervention as reliance is placed on the technical systems. This could offset some of the consequences of uncertainty in HRA because fewer human actions are needed to prevent escalation of an event, and because the plant should be able to get to a passively safe state without operator intervention. However, reducing the frequency or severity of human-initiated events or escalation does not eliminate the uncertainty of the human response. The novelty inherent in SMR designs may increase the cognitive load on operators as well as changing the nature of the human role, and there is scarce data on how humans will perform in these toles. Humans are still likely to be involved in responding to initiating events in some capacity, and automation can introduce new levels of complexity that are not yet modelled in HRA space.

So, while SMR designs and safety features might mitigate the impact of HRA uncertainty in some contexts, they do not eliminate the need for a robust examination of the human role, or the need for a robust uncertainty treatment. Investigation of the uncertainty issue is beyond the scope of the current research project but is documented here to acknowledge this challenge and to highlight it as an area for future research.

7.3 Considerations for Developing a Task Taxonomy

The main purpose of this research project 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). Taxonomies are often used in HRA, especially for error identification (e.g. the SHERPA error taxonomy (Embrey, 1986; see Figure 16)), assessment of factors influencing human performance (Kim and Jung, 2003), etc.



Action Errors	*Checking Errors*
A1-Operation too long/short	C1-Check omitted
A2-Operation mistimed	C2-Check incomplete
A3-Operation in wrong direction	C3-Right check on wrong object
A4-Operation too little/much	C4-Wrong check on right object
A5-Misalign	C5-Check mistimed
A6-Right operation on wrong object	C6-Wrong check on wrong object
A7-Wrong operation on right object	*Retrieval Errors*
A8-Operation omitted	R1-Information not obtained
A9-Operation incomplete	R2-Wrong information obtained
A10-Wrong operation on wrong object	R3-Information retrieval incomplete
Information Communication Errors	*Selection Errors*
I1-Information not communicated	S1-Selection omitted
I2-Wrong information communicated	S2-Wrong selection made
I3-Information communication incomplete	

Figure 16: The SHERPA error taxonomy (in Boring, 2015)

In the absence of operating experience for SMRs, a taxonomy is needed to describe and classify information about SMR operations which may be new and/or different from operations at conventional large NPPs. This will enable HRA analysts to better understand the potential operator tasks and performance shaping factors when evaluating risk significant scenarios and tasks for SMR design and licensing processes.
Based on the findings from the literature review and expert interviews, the taxonomy will need to consider that the range of operator tasks may vary depending on:

- Reactor type, e.g. light water reactor, molten salt reactor.
- Configuration, e.g. single unit, multi-module, locally operated, remotely operated.
- Application, e.g. baseload electricity production, load following, district heating, industrial heat production, hydrogen production.
- Concept of operations, e.g. level of automation, use of passive safety systems.
- Operational mode, e.g. full power, low power, refuelling, shutdown.
- Operational conditions, e.g. normal operations, abnormal/emergency operations, online/offline maintenance.
- Location of the task, e.g. main control room, field operations.
- Nature of the task, e.g. supervisory, administrative, action tasks.

Careful consideration will need to be given to the structure of the taxonomy, to determine how best to capture the potentially wide variability in task types based on the above list of attributes, while at the same time ensuring that the taxonomy remains useful and useable.

The literature review reveals that most control-room operator tasks will involve monitoring of automated systems. A practical starting point for the development of the taxonomy may be to categorise and describe generic human-automation interaction tasks that operators would be expected to perform in a highly automated control room. From there, the different attributes listed above could be considered to determine whether this may change or add to the list of generic tasks.

Due to the aforementioned lack of literature and knowledge on operator roles and responsibilities in SMRs, especially with respect to field operators and maintenance personnel, there is a risk that the taxonomy may contain substantial gaps. This is unavoidable due to the limitations of the research study and the reliance on open access literature. Nevertheless, the authors still expect to be able to make some progress with developing a taxonomy that more accurately describes the actions that are performed by operators when “monitoring” automation, which in itself is expected to contribute to reducing the level of uncertainty inherent in HRA for SMRs. It is hoped that the initial taxonomy resulting from this work may be expanded in future years as more operating experience and data from SMR operations are produced.

The taxonomy development is ongoing throughout 2025, building on the results presented in this report. A final report from this research project, including the findings from the taxonomy development, is planned by fall 2026.

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Appendix 1 – Case Study on Operator Roles in an Advanced SMR

This appendix contains tables referred to in Chapter 5.5, with details from the case study on operator roles in an Advanced SMR.

Table 5: Operating crew responsibilities for EBR-II and AdvSMR normal operating scenarios (reproduced from Hugo et al., 2013, pg. 78)

Scenarios	**Steady State**		**Restricted Fuel Handling**	
Functions	**EBR-II**	**AdvSMR**	**EBR-II**	**AdvSMR**
Drive turbo generator	• Monitor turbo generator • Communication with load dispatcher (LD)	• Monitor turbogenerator and automated control system • Communication with load dispatcher (decreased communication, LD→MCR in baseload mode, increased communication LD↔MCR in load following mode)	• Monitor turbogenerator • Communication with load dispatcher	• Monitor turbogenerator and automated control system Communication with load dispatcher (decreased communication, LD→MCR in baseload mode, increased communication LD↔MCR in load following mode)
Maintain fast fission	• Monitor reactivity manually • Manual rod control (automatic control rod control available but not trusted or used)	• Automated system monitors reactivity • Operator monitors the automated system and reactivity • Automatic control rod control	• Monitor reactivity manually • Manual rod control (automatic control rod control available but not trusted or used)	• Automated system monitors reactivity • Operator monitors the automated system and reactivity • Automatic control rod control
Maintain reactor cooling	• Manually monitor ΔT (the difference between the intermediate heat exchanger (IHX) inlet and outlet temperature)	• Automated system monitors ΔT • Operator monitors the automated system and ΔT	• Manually monitor ΔT	• Automated system monitors ΔT • Operator monitors the automated system and ΔT

Scenarios	Steady State		Restricted Fuel Handling	
Functions	**EBR-II**	**AdvSMR**	**EBR-II**	**AdvSMR**
Manage and control operations	- Monitor manually all systems per a surveillance schedule (increased monitoring during online maintenance[1] activities) - Manual, expert-based diagnosis (mental, knowledge-based integration of data and diagnosis) - Manually control train-switching (often during online maintenance activities) - Communication within MCR and between MCR and field/maintenance operators	- Automation monitors the system, processes, and components, gathers data, and reports to the operators via the HSI - Automation (operational advisor system) conducts smart diagnostics, prognostics, trending, and data analysis - Operator monitors the automation and shares responsibility for diagnosis of trends prior to thresholds - Train-switching is automated.	- Manual movement of fuel subassemblies, using crane and subassembly equipment - Manual grappling of subassembly in and out of the fuel basket and interbuilding coffin (IBC) - Manual/haptic verification of subassembly positive capture - Manual movement of subassemblies to fuel processing facility via IBC - Communication between fuel handlers (two operators were required) - Otherwise same as steady state	- Automated fuel handling system, some robotics possibly involved - Operators monitor fuel handling system and robotics, manual intervention as necessary[2] - Automated movement of subassemblies in and out of the fuel basket - Automated movement of subassemblies to and from the fuel processing facility - Automated verification of positive subassembly capture - Communication between fuel handler (one operator required to monitor the system) and I&C technician - Otherwise same as steady state

Notes:

1. *Plants will often deal with planned or emergent maintenance activities while at power to save time during outages. This often involves switching active system trains to conduct maintenance on the train that is out of service. This is often the only activity that occurs during normal steady- state operations.*
2. *We expect that in AdvSMR designs, operators will not take manual control of the fuel handling system, but that they will call in an instrumentation and control (I&C) technician in the case of a malfunction.*

Table 6: Operating crew responsibilities for EBR-II and AdvSMR emergency scenario (reproduced from Hugo et al., 2013, pg. 81)

Scenario	**Secondary Sodium System: Water to Sodium Leak**	
Functions	**EBR-II**	**AdvSMR**
Maintain equipment integrity	• The primary system and reactor integrity is not affected; primary and secondary systems are physically separated systems with heat transfer occurring in the IHX (heat exchanger). • Monitor alarms (hydrogen monitoring system alarm, cover gas meter leak detector alarm, tube sheet leak detect or alarm, secondary sodium relief header flow alarm, secondary sodium relief valve/ flow detector alarm, and secondary sodium rupture disk alarm, secondary cover gas pressure alarm), trending data, verification of leak. • Diagnosis: crew must manually and mentally integrate the above information into a diagnosis of a sodium-water reaction. • Communication: SRO will verify with chemistry technician whether any cold trap operations that introduced air and/or moisture into the secondary sodium system have been underway. • Diagnosis: the SRO must watch the indications to verify if a sodium-water reaction is occurring. • Control actions: SRO will scram the reactor when the sodium-water reaction is confirmed. • Recovery/mitigation actions: Secondary sodium operator (SSO) will manually actuate alarm to evacuate the sodium building. • Recovery/mitigation actions: Crew will manually actuate sodium building fire push button, which will stop all secondary sodium pumps and flow in the secondary sodium system.	• The primary system and reactor integrity is not affected; primary and secondary systems are physically separated systems. • Automation monitors the system parameters and alarms (likely to be the same or similar parameters and alarms as EBR-II) and provides integrated data, trends, and displays • Operators monitor the automation and data supplied by the HSI. • Diagnosis: the automation performs data analysis, diagnostics and prognostics, provides more integrated data and diagnosis information to the crew. • Indications will provide chemical system status (so SRO will know if there has been any chemistry operations (cold trap operations in the secondary sodium system). • Communication: SRO may verify status of the secondary sodium chemistry system with the chemistry technician. • Automatic reactor scram • Automatic sodium building evacuation alarm • Automatic actuation of sodium fire protocols, including stopping all secondary sodium pumps and isolation of the feedwater and main steam system (tripping the feedwater pumps and MISVs) • Automatic draining of the secondary sodium system and backfilling with argon. • Automatic isolation and draining of the feedwater and main steam systems and backfilling with argon.

Scenario	Secondary Sodium System: Water to Sodium Leak	
Functions	**EBR-II**	**AdvSMR**
	• Recovery/mitigation actions: crew will manually secure feedwater and close the MISVs. • Recovery/mitigation actions: crew will manually drain the secondary sodium system into the sodium dump tank, and dump water from the steam system into an external tank. • Recovery/mitigation actions: crew will manually actuate sodium-argon vent valve to backfill secondary system with argon. • Recovery/mitigation actions: crew will manually backfill feedwater and main steam systems with argon.	• Operator role is to anticipate required automatic actions, monitor automation, and verify necessary recovery actions occurred as expected and required.
Maintain habitable and safe operating environment	• The main control room is unaffected, no actions to maintain habitability are required. • Recovery/mitigation actions: evacuate the sodium boiler building (SBB) (manual alarm actuation).	• The main control room is unaffected, no actions to maintain habitability are required. • Recovery/mitigation actions: evacuate the (SBB) (automatic alarm actuation).
Ensure containment of fission products	• Not applicable; primary system and reactor are safely shutdown and are not adversely affect ed by secondary sodium system events.	• Not applicable; primary system and reactor are safely shutdown and are not adversely affect ed by secondary sodium system events.
Manage and control operations	• Intermediate heat exchanger (IHX) is inoperable; shutdown coolers louvers automatically open at preset primary sodium temperature providing for natural circulation cooling of the bulk sodium. • Operator role is to monitor shutdown cooling.	• IHX is inoperable; shutdown coolers louvers automatically open at preset primary sodium temperature providing for natural circulation cooling of the bulk sodium. • Operator role is to monitor shutdown cooling.
Provide local electrical power	• Offsite power is available. • Operator role is to monitor.	• Offsite power is available. • Operator role is to monitor.
Maintain reactivity control	• Not applicable; reactor is scrammed. • Operator role is to monitor/verify rod bottoms lights and zero reactor power.	• Not applicable; reactor is scrammed. • Operator role is to monitor/verify rod bottoms lights and zero reactor power.
Maintain coolant circulation	• Reactor cool ant pumps are operating and remove reactor decay heat to bulk sodium. • Shutdown coolers automatically start	• Reactor cool ant pumps are operating and remove reactor decay heat to bulk sodium. • Shutdown coolers automatically start

Scenario	Secondary Sodium System: Water to Sodium Leak	
Functions	EBR-II	AdvSMR
	• Provide cooling of the bulk sodium. • Operator role is to monitor reactor decay removal.	• Provide cooling of the bulk sodium. • Operator role is to monitor reactor decay removal.
Maintain environmental condition control	• Reactor building and MCR are nominal, no recovery or mitigating actions are necessary. • SBB habitability based on the severity of the event and speed of mitigating actions. • Emergency response team(s) responsible for assessing severity of event and planning response. • HVAC for Reactor Building and MCR remains operable – providing habitability. • Fire crews take action on the sodium fire, if accessible (lay down silica sand), and combat any non-sodium fires that may have started as a result of the sodium fire. • No operating crew role unless designated as emergency response team members.	• Reactor building and control room are nominal, no recovery or mitigating actions are necessary • SBB habitability based on the severity of the event and speed of mitigating actions • Emergency response team(s) responsible for assessing severity of event and planning response • HVAC for Reactor Building and MCR remains operable – providing habitability • Fire crews take action on the sodium fire, if accessible (lay down silica), and combat any non-sodium fires that may have started as a result of the sodium fire • Possible automatic carbon dioxide fire suppression actuation (to fight/prevent other combustible fires; will not affect the sodium fire) • No operating crew role unless designated as emergency response team members.

Appendix 2 – Interview documentation

This appendix contains the documentation that was prepared in relation to the interviews with SMRs (see Section 2.3).

Invitation to Interview

Risk Pilot (Sweden) is conducting a 2-year research project on the topics of "A Taxonomy for Human Reliability Analysis of Small Modular Reactors". The project is funded by The Swedish Radiation Safety Authority (Strålsäkerhetsmyndigheten, SSM) and will run from 2024 until 2026.

The goals of the project are to:

- Identify the tasks that human operators will likely perform in an SMR plant, considering the new/advanced design characteristics and operating paradigms, and the factors that may affect human performance,
- Organize these tasks and factors into a taxonomy to support human reliability analysis (HRA) of future plant designs and applications.

The overall objective is to develop a tool to support analysis of the human contribution to risk for SMR designs and applications. The tool is expected to also be of use to other stakeholders who wish to understand and examine the potential safety risks from different SMR designs and operational philosophies, including regulators, licensees, designers, researchers etc.

As part of the project, my colleagues and I wish to interview subject matter experts (SMEs) who have been working on topics related to SMRs and/or Advanced Reactors, to collect your experiences and insights on how SMRs are likely to be operated in the future. We would like to invite you to participate in an interview at a time that is convenient for you between January – March 2025. The interview can be conducted by Microsoft Teams and should take no longer than 45 – 60 minutes.

Interview Consent Form

Name & organization of interviewee	
Name of interviewer(s)	
Date of interview	

Thank you for agreeing to be interviewed as part of this research project.

Background:
The goal of this project is to develop a taxonomy to support analysts in conducting Human Reliability Analysis (HRA) for Small Modular Reactor (SMR) applications. The project is funded by The Swedish Radiation Safety Authority (Strålsäkerhetsmyndigheten, SSM) and is carried out by Risk Pilot in Sweden.

An objective of the project is to conduct interviews with subject matter experts (SME) who have worked or are currently working with topics related to SMRs and/or Advanced Reactors. You have been identified as an SME who may be able to provide valuable insights and information to this project.

About the interview:
Please read the following information about the interview before signing this form to indicate your consent to continue:

- The interview is expected to take approximately 45 – 60 minutes.
- The interview will be recorded, but a transcript will not be produced. The recording will be used to supplement the interviewers' notes and will be deleted after the research project has been completed (end of 2026).
- Access to the interview recording and notes will be limited to the interviewers and colleagues working on this research project only.
- The findings from the research project will be aggregated and published in open access literature (via technical reports to SSM and conference papers). Any summary interview content or direct quotations from the interview will be anonymized so that neither you nor your organization can be identified in either the technical reports or conference papers.
- If you are directly quoted in a technical report or conference paper, you will have an opportunity to first review the section of the report or paper where you are quoted, and you have the right to withdraw your quote if you do not agree to it being used.
- You have the right to terminate the interview and withdraw your consent at any time without consequence; in this case, all notes and recordings will be deleted effective immediately.

By signing this form, I confirm that I have read the above information and consent to being interviewed for this research project.

---------------------------------- ----------------------------------

Signature of interviewee Date & place

Interview Guide

Name & organization of interviewee	
Name of interviewer(s)	
Date of interview	

General background information:

1. What is your current job role?
2. How long have you been working with topics related to SMRs or Advanced Reactors?
3. What types and configurations of SMRs have you been working with so far? (e.g. light water, molten salt, single unit, multi-unit etc.)

Understanding operator roles in SMR operations:

4. Based on your expertise and knowledge, what roles do you think human operators will have in day-to-day operation of SMRs? Are there specific tasks that you think will be performed by operators versus e.g. automated systems?
5. How different is this from conventional NPPs?
6. What do you think will be the main drivers of change for operator roles and responsibilities in SMRs?
7. Are there specific regulatory requirements that may shape the roles and responsibilities for operators in SMRs?
8. Do you think that roles/responsibilities might change after there has been some experience of operating SMRs? (e.g. 5 years, 10 years)?

Safety/regulatory considerations:

9. What unique safety challenges do you foresee for human operators in SMRs, and how do you think these should be addressed?

Performance influencing factors:

10. What kinds of factors do you think will influence operators in performing their roles and responsibilities in an SMR?
11. How do you think these factors can be most effectively managed?

Closing questions:

12. What do you consider to be the biggest advantage of SMRs?
13. What do you consider to be the biggest disadvantage or challenge of SMRs?
14. What is your main concern or your greatest challenge in relation to your work on SMRs?
15. What would help you most in your work to address this concern or challenge?

The Swedish Radiation Safety Authority (SSM) works proactively and preventively with nuclear safety, radiation protection, nuclear security, and nuclear non-proliferation to protect people and the environment from the harmful effects of radiation, now and in the future.

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