The Challenge of Assessing Human Performance and Human Reliability for First-of-a-Kind Technologies

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Abstract: The development of first-of-a-kind (FOAK) technologies such as Small Modular Reactors (SMRs) raise questions about how these plants will be operated, and how operations may differ from conventional nuclear power plants (NPPs). Several design characteristics of SMRs are expected to result in a significant change in the conduct of operations, with concepts such as multi-unit operation, reduced staffing per unit, increased use of passive safety systems and higher levels of automation in the plants. The main goal of these design characteristics is to increase plant safety and efficiency while reducing the likelihood of human error. However, human performance and human reliability assessments will be required to substantiate these claims in advance of operation, as part of the design engineering and regulatory licensing processes. Such assessments typically rely on collecting contextual task performance and environmental data from operating plants, but such data are not available for FOAK plants, at least until the plant has been in operation for some time. In this paper, we argue that generalised human performance data from simulator studies can provide valuable insights into potential new failure modes and human-technology interaction, which can subsequently create the basis for initial reliability assessments for SMRs and other FOAK designs. The Halden Project has a dedicated research activity on human performance in operation of SMRs, which includes an experimental program in an SMR control room simulator. Previous experimental studies in the Halden Man-Machine Laboratory (HAMMLAB) have also yielded results that may be analogous to the potential human performance issues associated with the anticipated changes in operation of SMRs.

1. INTRODUCTION

There is growing interest worldwide in the potential of advanced reactor technologies such as Small Modular Reactors (SMRs) as a more competitive and efficient means of meeting future energy needs. SMRs represent a radical departure from the design of current nuclear power plants (NPP), with the promise of unique design attributes such as a smaller physical plant footprint, a smaller reactor core, simplification of the design, increased use of passive safety systems, and modular construction. Such attributes aim to minimize the potential for severe accidents to occur.

The development of first-of-a-kind (FOAK) technologies such as SMRs inevitably invites consideration of how these new plants will be operated, as compared to current generation plants. For example, the NuScale design proposes a plant of up to 12 SMR modules operated by a minimum shift crew of two senior reactor operators (SROs) and one reactor operator (RO), from a single control room [1]. This is a significant change from current reactor designs that typically feature a minimum crew of three control room operators per reactor, with only one to two reactors operated from a single control room[1]. What effects will this radical change in operating philosophy have on the conduct of operations in the control room, and on human performance and human reliability in operation of the SMR plant? How might human performance and human reliability further be affected by the other unique characteristics of SMR design?

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[1] It is noted that the 1-2 reactor unit per control room setup is *typical*, but there are exceptions to this. For example, there are four Canada Deuterium Uranium (CANDU) reactor plants in operation in Canada which each have 1, 2 or 4 reactor units operated from a single control room.

Human performance and human reliability assessments for current generation plants rely on well-defined and well-documented scenarios within which potential human failure events can be modelled and evaluated, using operating experience as a valuable input to understand how operators typically respond when things go wrong. Predictive risk analyses are required for any new build plant as part of the design engineering and regulatory licensing processes, and these are often informed by operating experience from reference plants of similar design. However, the challenge for FOAK designs is that there is no similar operating experience available yet to verify and validate predictive analyses of human performance and human reliability in these new operating situations.

In 2018, the Halden Project[2] initiated a research activity to understand and investigate the intended conduct of operations for SMR control rooms, and the subsequent effects these new ways of working may have on human performance. Previous experimental studies in the Halden Man-Machine Laboratory (HAMMLAB) have also yielded results that may be analogous to the potential human performance issues associated with the anticipated changes in operation of SMRs. In this paper, we will describe how the Halden project can contribute valuable knowledge to this new area, which can be used to inform human performance and human reliability assessments in the absence of (and, later, in addition to) actual operating experience.

2. AN INTRODUCTION TO SMALL MODULAR REACTORS

2.1 Brief Overview of SMR Concepts

SMRs are scalable plants with a power output below 300 MWe per module. The smaller core, simpler plant design and use of passive safety systems aim to lower the probability of accidents and enable smaller teams of operators to control several modules from a single control room [2]. Passive safety features take advantage of natural forces or phenomena such as gravity, differential pressure, or natural heat convection, and do not rely on external mechanical or electrical power, signals, or forces. Advanced manufacturing techniques enable complete reactor modules to be assembled at the plant site. The power plant can be created from one or several modules as necessary over time.

Based on the reactor coolant type, SMRs can broadly be classified into four major groups of design: water-cooled reactors; gas-cooled reactors; liquid metal cooled reactors; and molten salt reactors [3].

- **Water-cooled**, which are light water reactors (LWR), including integral pressurized water reactors (iPWR), and heavy water reactors (HWR). The reactor coolant may circulate via pumps inside the RPV, or by use of passive safety features, such as natural circulation. The water-cooled reactors can be land-based or marine-based.
- **Gas-cooled**, which use helium as the coolant, and graphite as the neutron reflector and moderator. The fuel has very high integrity which is the primary barrier to the release of radioactivity.
- **Liquid metal-cooled**, which uses either sodium or lead-bismuth that have a high thermal-conductivity and boiling point. These are fast neutron reactors that operate at near atmospheric pressure and have passive safety features.
- **Molten salt-cooled**, which uses molten fluoride salts as the primary coolant, at low pressure. In most designs, the nuclear fuel is dissolved in the coolant itself. MSRs run at higher temperatures and higher efficiencies than water-cooled reactors.

Figure 1 [4] shows an example of the NuScale PWR module (left) and a cutaway of the NuScale plant design (right) showing six modules clustered together to form a multi-module plant.

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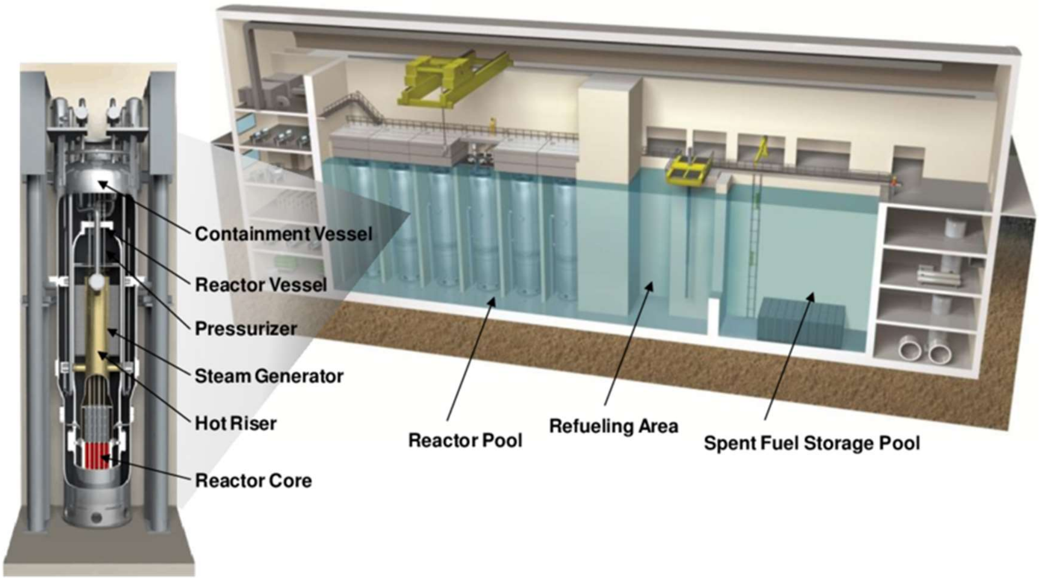
[2] We use the phrase *Halden Project* to refer to the OECD Halden Reactor Project (1958-2020), and the ongoing OECD NEA Halden HTO Project (2021-).

Figure 1: The NuScale SMR power module and multi-module plant design [4]



2.2 Why are SMRs considered to be FOAK?

A first-of-a-kind (FOAK) plant refers to “the first commercial plant of a particular design where prior operational experiences and lessons learned will play a part, but ultimately the majority of experience is to be gained during operation of this specific plant design” [5, pp. 2]. There are several design characteristics of SMRs that differentiate them from conventional (large) nuclear power plants, as shown in Table 1.

Table 1: Differences in design characteristics between SMRs and conventional NPPs

SMR Design Characteristics	Conventional NPP Design Characteristics
Lower power output (10-300 MWe)	Higher power output (900-1400 MWe)
Smaller physical footprint (~7 hectares)	Larger physical footprint (~259 hectares)
Integral design (primary system components (reactor, steam generators, pressurizer, etc.) contained within a single vessel)	Extrinsic design (steam generators, coolant pipes, pressurizer etc. located outside of the reactor pressure vessel)
Modular design enables fabrication offsite, with final ~10% construction/assembly onsite	Some modular design, but ~70-80% of plant constructed on site
Scalable design enables addition of reactor units to the site to increase total power output	Typically designed for 1 to 2 reactor units for the lifetime of the plant, due to large size.
Increased use of passive safety systems (gravity, pressure differential, natural circulation)	Reliance on active safety systems that require electrical power, signals, or forces
Increased use of automation, and possibly even autonomous systems/reactor units	Low levels of automation, with high reliance on manual intervention and control by operators
Ability to monitor and control multiple units from a single, centralized main control room	Typically designed to manage 1 to 2 reactor units from a single main control room
Reduced staffing need (per unit) in main control room (e.g., 3 senior reactor operators to manage 12 units)	Typical control room staff of 1 senior reactor operator, 1 balance of plant operator and 1 unit supervisor to manage 1 unit)
Increased deployment potential of SMRs (e.g., baseload, load following, hydrogen production, seawater desalination, district heating)	Typically built only for baseload electricity production, although some NPPs now also used for hydrogen production.

As Table 1 demonstrates, the SMR design represents a significant departure from the conventional NPP, which will likely result in “radically different concepts of operations” [6, pg. 45]. The increased use of passive safety systems and automation, as well as the multi-unit approach with reduced staffing levels per unit in the control room, are likely to significantly change the role of the operator. In conventional NPPs, the operator is actively engaged in the management and control of the NPP; in the SMR, the role of the operator is likely to be that of monitor or supervisor of passive and automated functions, with occasional intervention in abnormal situations.

2.3 A New Conduct of Operations for SMRs

The design differences in Table 1 (i.e., simpler plant designs, higher levels of automation, increased use of passive safety systems, etc.) are also likely to result in a fundamental change in the conduct of operations (COO) for SMR NPPs [3]. Since the SMR industry is still at a relatively early maturity level [2], and due to the highly competitive nature of the industry, specific details of how these design differences will be realised are not widely disseminated. However, we can infer some details based on recent reports that have been released into the public domain.

Perhaps the most evident change will be the increased number of reactor units that will be operated from a single control room, and the new staffing model that will be needed for multi-unit SMR design concepts. Several designs boast an overall reduction in the number of staff needed to monitor and control the plant. A NuScale staffing plan submitted to the United States Nuclear Regulatory Commission (US NRC) in 2020 gives an indication of what this may look like in practice. The plan [1] proposes a plant design of up to 12 modules, monitored and controlled from a single, centralised control room by a crew complement of three senior reactor operators. This is a radical departure from the typical setup in most conventional NPPs, with a single unit being monitored and controlled by a crew complement of three to four – typically a senior reactor operator, a balance of plant/turbine operator, a unit supervisor and a shift technical advisor. We do not suggest that the NuScale plan is a benchmark for all SMR staffing strategies, but regardless of whether other plants adopt a similar staffing concept to NuScale, it is clear that the SMR model will change how operators monitor and control units, how they distribute and prioritise work tasks across units, and maybe even how they work and communicate as a team. Thus, the effects of these changes on human performance and human reliability are important to understand.

The increased use of passive safety systems for reactivity control is another key feature of SMR designs that may have an impact on the COO. Although there is little publicly available literature at the moment on how the passive safety systems will be realised, a Sandia National Laboratory report on microreactors (i.e., reactors with a power output <10 MWe) gives some insight into how this might work, noting that "with a passive safety system, a microreactor design would not require significant human or automation intervention to maintain a safe state. Thus, human and/or automated tasks may serve as a secondary safety check rather than a primary function to operate the reactor" [7, pp. 10]. SMRs are expected to be more highly automated than conventional NPPs, as automated technologies can provide advantages in terms of safety and efficiency. The combination of passive and automated systems is likely to shift the role of the operator from active initiation of/intervention in control tasks, to one of monitoring/supervising tasks carried out by these systems, raising questions about how to maintain the "human-in-the-loop" during operations and especially complex or abnormal situations.

The scalability and flexibility of SMR deployment may also have a significant impact on the COO over time. The scalability concept means that additional SMR units could be added to the power plant over time to replace the original units and/or to increase the power output from the plant. It is possible that later units will have incorporated some design differences from the earlier units, as time and experience inevitably result in improvements for the sake of increasing safety and/or efficiency. Flexibility in deployment means that SMRs could be used for different purposes, beyond electricity production, which may also change how the SMR should be monitored and controlled. Although it is not yet clear whether a single plant could include a combination of functions (e.g., some SMR units used for load following, some SMR units used for district heating and some SMR units used for hydrogen production), it is a possibility that must be considered at this time. This means that over time there may be situations where operators are responsible for monitoring and controlling units with different design features and/or different functions from a single control room. This raises questions about how to maintain operator familiarity and competence with different types of units, and also the potential effects on operator performance during disturbances, especially multi-unit disturbances of different reactor types.

3. HUMAN PERFORMANCE AND HUMAN RELIABILITY ASSESSMENT FOR SMRS

Human reliability analysis (HRA) plays a key part in the design engineering and regulatory licensing processes. HRA is a well-established tool within the nuclear industry because “despite the high reliability of safety systems of NPPs, human actions still play an important role in NPP safety. Evaluation of human reliability is therefore important for a full-scope probabilistic safety assessment (PSA) and risk analysis” [8, pp. 178]. Even though SMRs are expected to have higher levels of automation and increased use of passive safety systems, human operators will still be responsible for overseeing operations and thus human performance and human reliability must be evaluated. At their core, all HRA methods include a systematic evaluation of human performance shaping factors (PSFs) to better understand how human operators can contribute to (and prevent/mitigate) the overall risk and safety of the plant, under different operating conditions and in different circumstances.

PSF values are estimated based on contextual information about where, when, and how a specific operator task is performed, and these values are used to adjust nominal human error probabilities (NHEPs) to give a more realistic estimation of the probability of human error for a given event scenario. Determining which PSFs contribute (either positively or negatively) to the human error probability, and the extent to which they contribute can be a challenge for HRA analysts. Hallbert et al. note that “considerable analyst judgment is required to identify factors that may affect the reliability of a candidate human activity and to estimate their effects on the conditional expectation of success or failure” [9, pp. 2]. A report on Quantified HRA (QHRA) by the Energy Institute states that “it may be argued that only data collected from the actual context in which a task is performed should be used to predict future failures in that situation. This is because human performance is extremely dependent upon task conditions” [10, pp. 16].

The task context that analysts use to inform their judgement is typically collected through talk-/walk-throughs with experienced operators, interviews with subject matter experts, task observations and reviews of documented operating experience. This is because there may be some differences between how the task was designed to be performed, or how it is described in operating procedures, and how it is actually performed in practice. The HRA aims to evaluate the actual risk from human error, and so contextual task information is vital to ensuring a realistic and trustworthy HRA. However, as noted by Porthin et al., “While operating experience reflects the real situation, many relevant data are often not properly recorded or not even observable in real-life situations. For example, information about environmental conditions and the number of successfully performed tasks may be hard to retrieve. Also, data for analysing rare events are usually very scarce or even non-existing. Interviews with subject matter experts are highly recommendable and certainly help the HRA analyst in understanding the phenomena on a qualitative level, but the benefits for quantification may be limited” [11, pp. 8].

The situation is perhaps worsened for FOAK plants because, until the plant is in operation, there will be no documented operating experience, no possibility to collect contextual data in situ, and the knowledge of subject matter experts is theoretical at best until some time has been spent operating the plant. The analyst cannot make estimates on the human performance effects of multi-unit operation, staffing strategies, automation, passive safety systems or scalable designs, as there are very few, if any, plants in operation with these unique design characteristics. This does not mean that the analyst cannot perform HRA; rather, it means that they must look elsewhere for the contextual data that are needed to inform the HRA. In such cases, full-scope simulator studies can provide an invaluable source of data for analysts because “they provide an environment and human behaviour similar to the real world, but [at] the same time controllable and observable conditions” [11, pp. 8].

4. AN OVERVIEW OF SIMULATOR STUDIES IN THE HALDEN PROJECT

4.1 Introduction to the Halden Project

The OECD Halden Reactor Project (HRP) was established in 1958 as a joint research programme covering topics related to (i) fuels and materials (F&M) and, later, (ii) Man-Technology-Organisation (MTO). It is the oldest project endorsed by the Nuclear Energy Agency (NEA) and is the longest-running nuclear research project in the world. The Institute for Energy Technology (IFE) in Halden, Norway both administrates and executes the project, and it has been funded by over 100 organisations in 20 countries worldwide. As part of the Halden Project, IFE owned and operated the Halden Boiling Water Reactor (BWR) and the Halden MTO research laboratories. The Halden BWR was shut down in 2018 after 60 years of service. The HRP F&M programme will end in 2023 with the completion of the final project in this programme. The OECD NEA Halden Human Technology Organisation (HTO) Project was initiated in 2021, supported by 20 organisations in 12 member countries, and is a direct continuation of the HRP MTO programme.

The Halden HTO research laboratories include the Halden Man-Machine Laboratory (HAMMLAB), which was established in 1983. The HAMMLAB comprises two full-scope nuclear power plant control room simulators, a control room where professional crews operate the simulated plants, and a gallery from where the experimental team controls the scenarios, observes crew behaviour, and evaluates human performance. Figure 2 shows a model of the Halden Project research laboratories, indicating (1) the HAMMLAB control room, (2) the observation gallery, (3) the Virtual Reality/Augmented Reality centre, and (4) the combined FutureLab and simulator test facility. A Cybersecurity Centre is located in the neighbouring building. The HAMMLAB is largely considered to be at the core of the experimental research performed by the Halden Project. It enables the researchers to study licensed operators performing tasks in a highly realistic operational environment, under a variety of different conditions, to better understand how human performance can impact safety and risk [11].

Figure 2: The Halden Project advanced research laboratories

4.2 Halden Project Research on Human Performance in SMR Operations

Initiated by the international committee Halden Board of Management, “Operation of multiple SMRs” was proposed and approved as a new research activity in the HRP programme 2018-2020. The purpose of the activity was to investigate potential safety issues associated with operation, human-system interfaces (HSIs) and staffing in multi-unit control room environments. In the early phase of the project a white paper [12] was issued outlining human factors challenges and design considerations for multi-unit operation, The white paper proposed ideas for specific research questions and discussed methods for conducting empirical, simulator-based studies to answer these. The white paper also identified the issues of knowledge gaps and limited operational experience concerning the attentional demands for operators monitoring two or more reactors at a time, and performance decrements following periods of too high or too low workload (overload and underload respectively).

Given the sparse information on operational concepts for SMRs, and due to many concepts still being in the early design phase, experiences and operational concepts from multi-unit operation in other industries were also reviewed [3]. The supplementary perspectives were based on industry visits and lessons learned from IFE projects within petroleum, power production and air transportation. Experiences from CANada Deuterium Uranium (CANDU) nuclear power plants showed that operational concepts can change substantially over time. This should be reflected by ensuring flexibility to accommodate future needs, such as additional staff working across units. Flexible allocation of operators is also seen in air traffic control, in which air space sectors are staffed dynamically depending on traffic load, complexity and workload. However, different plant designs and/or functions may require specialized competencies, which challenges dynamic staffing strategies. To some extent, sufficient competence could be ensured through shift planning and support centres that serve multiple units. Our experience in the Halden Project indicates that simulator studies can provide knowledge about the performance benefits and potential risk implications of different staffing strategies in different scenarios. Research can also enhance the understanding of operator cognitive demands, which will be an important basis for evaluating staffing in multi-unit operation.

The first simulator-based study on operation of SMRs was conducted in the HTO Future Lab in 2019. The study used a basic principle integral pressurized water reactor (iPWR) simulator developed by Tecnatom for the International Atomic Energy Agency (IAEA). The simulator is intended for educational purposes and enables a basic understanding of general principles and operator interventions relevant to controlling iPWRs but does not constitute a full-scope simulator. Still, the simplified test set-up allows for the collection of observational data, qualitative assessments of task execution and debriefing interviews. The purpose of the 2019 study was to investigate monitoring strategies and prioritization of taskwork when one operator attends more than one reactor at a time. Two participants were tested individually while operating three iPWRs simultaneously. Four scenarios were designed to be gradually more complex with parallel tasks and disturbances occurring in three reactors. Although they had limited familiarity with the iPWR process, the participants were able to control the three reactors even in challenging scenarios. The results of the study indicated that workload increased but did not seem to impede task completion. The explorative study enabled a better understanding of prioritized topics for future research, requirements for participant training and simulator capabilities in future studies.

Our 2019 study highlighted that a full-scope research simulator with an alarm system, procedures and a separate instructor station is needed in order to implement complex scenarios on multiple units and collect human performance data in different crew and control room configurations. In 2021, IFE contracted Tecnatom to provide an advanced, full-scope version of the iPWR simulator that is expected to be installed in mid-2022. The new simulator will allow investigation of more complex scenarios for between one- and twelve-unit configurations. The simulator is not a direct replica of any specific SMR plant design but is expected to be functionally similar and provide comparable results to other water-cooled SMR simulators.

4.3 Examples of Relevant Human Performance Data from Other Halden Project Experiments

Although the SMR-specific research activity is relatively new to the Halden Project, there have been several research activities and simulator studies in the past as well as in the current programme that are highly relevant to SMR operation and, in particular, the anticipated new COO for SMRs.

For example, multi-unit SMR plants are expected to reduce the number of control room staff per reactor unit. Reduced staffing in nuclear control rooms has been investigated in two HAMMLAB experiments conducted in 2000 and 2009. Hallbert et al. [14] collected human performance data on a simulated PWR plant model implemented in a training simulator and in HAMMLAB, serving as conventional and advanced plants respectively. A four-operator crew configuration participated in both plant types. This was compared to a three-operator crew in the conventional plant, and a two-operator crew in the advanced plant. Four-operator crews performed better than three-operator crews in the conventional plant; conversely, two-operator crews performed better than four-operator crews in the advanced plant. These findings illustrate the need for considering control room design features, automation and plant-specific characteristics when deciding on staffing levels in FOAK plants such as SMRs. Conventional plants have been designed for larger control room staffing levels. Passive safety systems, automation and more compact, integrated control room designs may better accommodate flexible and possibly smaller crew configurations with new operator roles.

The feasibility of alternative staffing strategies and new operator roles was investigated in the 2009 HAMMLAB experiment [15]. The experiment tested whether a three-operator crew can simultaneously control two nuclear processes. For comparison, three-operator crews controlled one nuclear process. The findings favoured the latter crew configuration operating a single nuclear process. However, operators also managed to complete a considerable number of tasks when responsible for two nuclear processes. Notably, their situation awareness was higher when controlling two nuclear processes compared to being responsible for one plant only. Possible explanations could be that operators prioritized situation awareness at the expense of other tasks and that the increased workload encouraged participants to utilize dedicated tools for monitoring automation activities introduced in the study. Some participants reported that the reduced staffing level per unit simplified crew communication.

Another example from the current Halden Project programme is on the topic of automation. SMRs are expected to feature higher levels of automation than conventional NPPs, but details of how this automation may be realised are not yet available. Studies on the effects of automation on human performance have been investigated by the Halden Project since the mid-1990s. These have included nine full-scope simulator studies on human-automation interaction in the HAMMLAB, covering topics such as levels of automation, operator trust in automation, automation transparency, out-of-the-loop unfamiliarity, and automation malfunction [16]. Further, the FutureLab was established in Halden with the purpose of prototyping plausible conceptual control room designs for operation of highly automated plants, with the goal of further understanding how operators might realistically work in such environments. More recently, in-depth exploration of knowledge from other safety-critical domains, as well as high-profile automation-related accidents in the aviation and transportation industries, have helped to identify nine important automation research topics for nuclear control rooms, including, for example, automation transparency, automation failure, reliance and trust in automation, and human-automation communication [16]. The goal of this research is to understand, through simulator studies, how different implementations of these aspects of automation may affect human performance.

5. USING EXPERIMENTAL KNOWLEDGE AND DATA TO SUPPORT HRA FOR FOAK DESIGNS

As noted earlier, predictive analyses of human performance and human reliability are required for new build plants as part of the design engineering and regulatory licensing processes. For conventional design plants, operating experience data from reference plants of similar design is often used to inform these analyses. The challenge for FOAK designs is that reference plant operating experience does not yet exist, and thus predictive risk analyses for new builds can have very high levels of uncertainty. This issue may be compounded for SMRs since the unique design characteristics of SMRs are expected to change how plants are operated and controlled, and thus there are questions about whether new error modes may be introduced and/or which factors may (negatively or positively) drive human performance.

Qualitative and quantitative data and knowledge from simulator studies have been used as inputs in many HRA methods to define nominal human error probabilities (NHEPs), as well as the effects on NHEPs of different PSFs. However, we argue that experimental simulator studies, such as those performed by the Halden Project, can provide even greater value for human reliability assessments of FOAK designs, as direct inputs to the predictive analyses themselves, providing the necessary task context within which one can observe operator performance and make more informed predictions about the human contribution to risk at the specific plant of interest.

The experimental studies summarised in 4.2 and 4.3 can provide valuable information about the different factors that can affect human performance and the extent to which these effects were observed. Furthermore, such studies can help to identify the potential for unanticipated human performance effects, and even new error modes that may result from the changes to design, technology and/or COO.

5.1 Challenges and Opportunities for Use of Simulator Data for FOAK Design Assessment

A key challenge when considering when and how to utilise experimental simulator data in assessments concerns the ecological validity or generalisability of the data. For example, the Halden Project studies on staffing strategies and automation (see 4.3) have been performed in control room simulators of conventional design NPPs, and as such one could question whether the findings are valid and translatable to new settings such as FOAK designs and, specifically, multi-unit SMR plants. A fundamental belief in experimental psychology research is that there are basic human capabilities that will be affected by the environment in which tasks are performed. Thus, if we can find similar dimensions and factors of that environment in other settings, we can assume that the results from our simulator study can be generalised to those other settings. The experimental studies performed within the Halden Project research laboratories aim to recreate realistic operating scenarios within a high-fidelity environment and recruit licensed and experienced nuclear operators as participants, thus ensuring high ecological validity and generalisability to other settings.

There is a question about the extent to which human performance in FOAK designs such as SMRs will diverge from the generalised data collected from studies of conventional plant designs. There are some design characteristics of SMRs, such as multi-unit operation, that are not represented (or not to the same extent) in earlier experimental studies. Analysts need to understand which performance data can be generalised, and which is more dependent on specific aspects of the FOAK design. For example, it may be difficult to extract generalised data and context from studies on workload for a team of three operators in a single-unit conventional NPP for analysis of a team of three operators in a 12-unit SMR NPP. How, and in which ways, does workload change as the number of reactor units per control room is increased, and the number of operators per reactor unit is decreased? It can be difficult to extrapolate an answer from previous, single-unit HAMMLAB studies as workload is unlikely to increase linearly or exponentially, but rather will probably depend on several performance shaping factors and not just the number of units that the operator is responsible for overseeing. Other study topics such as human performance when using computerised procedure systems are likely to be more readily translatable to the SMR environment.

An important advantage of simulator studies is the ability to explore safety-critical situations in an environment that is controllable and observable. For example, one may manipulate complexity in a scenario and study the interaction with teamwork and the impact on the operator's performance [17]. This is much more difficult to do in an operational setting on site, as the risk of unintended consequences on plant operation and safety is much higher. In addition, the experimental study approach allows for tighter control over variables that may affect performance, and thus it can be easier to determine specifically which factors (or combinations of factors) affect performance, and by how much. The previous HAMMLAB studies can also provide an important benchmark to understand how FOAK designs can affect human performance, and whether these new designs can create different or new failure modes that require additional evaluation, or even new evaluation methods.

6. CONCLUSIONS

Analysis of human performance and human reliability assessment is not new to nuclear; in fact, these are well-established methods for understanding the human contribution to risk and the potential effects of human error on safety. The fundamental changes to the conduct of operations in SMRs will require a new understanding of human performance and human reliability because of the introduction of new and advanced technologies in the design of these reactors and plants. It is vital to understand how operators interact with these technologies in practice, and how the role of the operator will change to ensure that new reactor and control room designs support the operators in maintaining safety.

Operating experience is an important input to understanding human performance and assessing human reliability. However, the introduction of advanced technologies may result in new failure modes that have not been seen before in conventional NPPs. As such, there is a gap between the operating experience that can be collected from conventional NPPs, and what is needed to identify and understand the effects of these new failure modes on human performance. In such cases, the generalised information provided from simulator studies can give a sufficient indication of the human contribution to risk, until such time that contextual data is available for input to the analysis. Further, because a fundamental aspect of FOAK designs is the utilisation of new technology to increase safety and reduce the risk of human error, it is vital to understand the interaction and effect this will have on operating crew roles and teamwork [18]. Simulator studies can provide invaluable information about potential new failures modes related to multi-unit operation, higher levels of automation, increased use of passive safety systems, and other characteristics of SMRs as described previously.

The Halden Project has over thirty years' experience in conducting simulator studies to understand human-technology interaction and the subsequent effects on human performance in different operating situations. For example, previous studies on reduced staffing in nuclear control rooms, and the current research activities on automation transparency and automation failure will provide useful insights for SMRs. In 2018 the Halden Project initiated a specific research activity on human performance in operation of SMRs, which included a study in 2019 on a basic principle iPWR simulator. IFE is in the process of obtaining a full-scope SMR simulator which will enable the continued study of human performance in complex multi-unit operation scenarios in the future.

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8. REFERENCES

[1] NuScale. "*NuScale Control Room Staffing Plan*", Report No. TR-0420-69456-NP Rev. 0, NuScale Power LLC, 2020, Corvallis, Oregon, USA. Retrieved on 13.02.2022 from: https://www.nrc.gov/docs/ML2016/ML20163A556.pdf

[2] International Atomic Energy Agency (IAEA). "Advances in Small Modular Reactor Technology Developments", International Atomic Energy Agency, 2020, Vienna, Austria.

[3] Eitrheim, M. H. R., Skraaning, G. & Hurlen, L. "*Operation of Multiple Reactors from a Single Control Room: Experiences from Nuclear and Other Industries*", Report No. HWR-1251, OECD Halden Reactor Project, 2019, Halden, Norway.

[4] Ingersoll, D. T., Houghton, Z. J., Bromm, R. & Desportes, C. "*Integration of NuScale SMR with Desalination Technologies*", Proceedings of the ASME Small Modular Reactors Symposium (SMR2014), April 15-17, 2014, Washington, D.C., USA.

[5] Boldin, L. M. & Sabharwall, P. "*Small Modular Reactor: First-of-a-Kind (FOAK) and Nth-of-a-Kind (NOAK) Economic Analysis*", Report No. INL/EXT-14-32616, Rev. 0, Idaho National Laboratory, 2014, Idaho Falls, Idaho, USA.

[6] US NRC. "*Risk-Informed and Performance-Based Human-System Considerations for Advanced Reactors (Draft white paper)*" United States Nuclear Regulatory Commission, 2021, Washington, D.C., USA. Retrieved on 13.02.2022 from: https://www.nrc.gov/docs/ML2106/ML21069A003.pdf

[7] Fleming, E. S., Nyre-Yu, M. & Luxat, D. L. "*Human Factors Considerations for Automating Microreactors*", Report No. SAND2020-5635, Sandia National Laboratories, 2020, Albuquerque, New Mexico, USA.

[8] Voronov, R. & Alzbutas R. "*Human reliability analysis for probabilistic safety assessment of a nuclear power plant*", In Energetika. Vol. 56, Nr. 3–4, pp. 178–185, (2010).

[9] Hallbert, B. P., Gertman, D. I., Marble, J., Lois, E. & Siu, N. "*Using Information from Operating Experience to Inform Human Reliability Analysis*", Proceedings of International Conference on Probabilistic Safety Assessment and Management (PSAM7), June 14-18, 2004, Berlin, Germany.

[10] Energy Institute. "Guidance on Quantified Human Reliability Analysis (QHRA)", The Energy Institute, 2012, London, England. Retrieved on 13.02.2022 from: https://www.hpog.org/assets/documents/QHRA-Guidance.pdf

[11] Porthin, M., Liinasuo, M. & Kling, T. "*Effects of digitalization of nuclear power plant control rooms on human reliability analysis – A review*", In Reliability Engineering & System Safety, Vol. 194, February 2020, 106415.

[12] Skraaning Jr., G. & Bye, A. "*The Purpose of HAMMLAB and the Theoretical Basis for Experimental Research*", In Skjerve, A. B. & Bye, A. (Eds.) *Simulator-based Human Factors Studies Across 25 Years: The History of the Halden Man-Machine Laboratory*, pp. 45-56, Springer, 2011, London, England.

[13] Eitrheim, M., Fernandes, A., Hurlen, L. and Skraaning, G. "*Small-scale simulator studies on multi-unit operation*", Report No. HWhP-069 Issue 1, OECD Halden Reactor Project, 2018, Halden, Norway.

[14] Hallbert, B., Sebok, A., Morisseau, D. *A Study of Control Room Staffing Levels for Advanced Reactors*", Report No. NUREG/IA-0137, U.S. Nuclear Regulatory Commission, 2000, Washington, DC, USA.

[15] Eitrheim, M. H. R., Skraaning, G., Lau, N., Karlsson, T., Nihlwing, C., Hoffmann, M., & Farbrot, J. E. *"Staffing Strategies in highly automated future plants: Results from the 2009 HAMMLAB Experiment"*, Report No. HWR-938, OECD Halden Reactor Project, 2010, Halden, Norway.

[16] Skraaning, G. & Blackett, C. "*The HTO 4.2 Experimental Program: Research Topics and Test Platforms"*, Report No. HTOR-003, OECD NEA Halden HTO Project, 2022, Halden, Norway.

[17] Braarud, P.Ø., Johansson, B. "*Team Cognition in a Complex Accident Scenario*", Report No., HWR-955, OECD Halden Reactor Project, 2010, Halden, Norway.

[18] Bye, A. "*Future Needs of Human Reliability Analysis: The Interaction between New Technology, Crew Roles and Performance*". In Safety Science, 2022 (in press).