Human Performance in Operation of Small Modular Reactors

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Abstract: The interest in Small Modular Reactors (SMRs) continues to grow worldwide, with over 70 reactor designs in development, one already in operation and 4 more expected to be in operation within the next 5 years. Much of the research focus to date has been on technology development for SMRs, but as the more mature designs progress through licensing processes, attention is turning to the operational side of SMRs and, more specifically, human factors aspects of operation. Design characteristics of SMRs such as the multi-unit operation concept, increased use of passive and automated systems, and an increase in potential deployment use cases are likely to have a considerable impact on how these reactors will be monitored and controlled. As such, there is a vital need to understand the potential effects on human performance to ensure safe operation. In 2018 the Halden Project initiated a research activity to investigate human performance in the operation of SMRs, and in 2019 installed an SMR simulator in the Halden Future Lab to enable the experimental study of important human factors research questions at the heart of this topic. In this paper, we present and discuss the key human performance issues, uncertainties and research topics that have been identified so far in the Halden Project research activity on SMRs. We describe the findings from a first simulator study conducted in 2019 in a basic principle integral pressurised water reactor (iPWR) simulator, and how we intend to expand our experimental program to continue collecting empirical data on human performance in the operation of SMRs in response to the open research questions.

1. INTRODUCTION

The interest in Small Modular Reactors (SMRs) continues to grow worldwide. Today, there are more than 70 SMR designs in development around the world [1], with one marine-based SMR already in operation and four more currently under construction and expected to be in operation within the next 5 years. Despite the advances in SMR technology development, there remain many open questions about the operational side of SMRs, such as the minimum required staffing levels, control room layout and design philosophies, the conduct of operations philosophies and levels of automation to name but a few. Perhaps due to the highly commercial nature of the SMR industry, publicly available information about these aspects of SMR development has been limited to date, resulting in a somewhat "black box" effect for those who wish to understand more about these issues.

A research activity was initiated in 2018 within the Halden Project[1] with the broad objective to identify the potential impacts of SMR control room concepts on human performance, especially where these deviate from how current generation nuclear power plants (NPPs) are monitored and controlled. Our focus is on investigating the cognitive demands on operators in SMR control rooms in different scenarios, and the possible unexpected and unintended operator behaviours that may occur as a result.

2.1 About The Halden Project

The OECD Halden Reactor Project (HRP) was established in 1958 with a joint research programme covering topics related to fuels and materials (F&M) and Man-Technology-Organisation (MTO). It is the oldest project endorsed by the Nuclear Energy Agency (NEA) and is the longest-running nuclear

[1] 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-).

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, including the Halden Man Machine Lab (HAMMLAB). 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 Halden Human Technology Organisation (HTO) was initiated in 2021, supported by 20 organisations in 12 member countries, and is a direct continuation of the HRP MTO programme.

2. DESIGN CHARACTERISTICS OF SMRS

SMRs are most commonly defined as nuclear reactors with a power output of 10-300 megawatt electric (MWe; [2]). The Nuclear Energy Agency (NEA) lists five key design characteristics of SMRs that are shared amongst the majority of SMR designs and are recognised as key safety and economic drivers enhancing the competitiveness of the SMR market. These are (ibid.):

- **Integral designs:** smaller reactor cores enable the use of integral designs that incorporate all the components of the steam supply system into a single vessel, including the steam generator and pressuriser. This design has the advantage of increasing the heat capacity and thermal inertia of the system, which results in a simpler system design, and less complex operation and maintenance of the vessel.
- **Inherent safety:** the lower power output and the smaller reactor core enables increased efficiency of passive safety systems, again allowing for simpler designs, operation and maintenance.
- **Lower core inventories:** the smaller reactor core requires less shielding and reduces radiation exposure doses for workers. The probability of an accident is reduced, and potential radioactive releases would have lower consequences due to the reduced energy driving the release. This means that it may be possible to locate SMRs closer to where energy is needed, reducing the size and complexity of the power grid connection.
- **Improved modularisation and manufacturability:** the smaller vessel sizes and the modular design approach mean that it is possible to construct most of the SMR offsite, reducing the construction costs and times.
- **Enhanced flexibility:** the multi-module operational approach creates greater possibilities for load following, as well as diversity of uses such as heat and electricity generation.

2.1 SMR Design Types and Current Development Status

SMR designs can be broadly divided into four categories, depending on the type of coolant and/or the neutron spectrum adopted, as well as a fifth type, which is the microreactor.

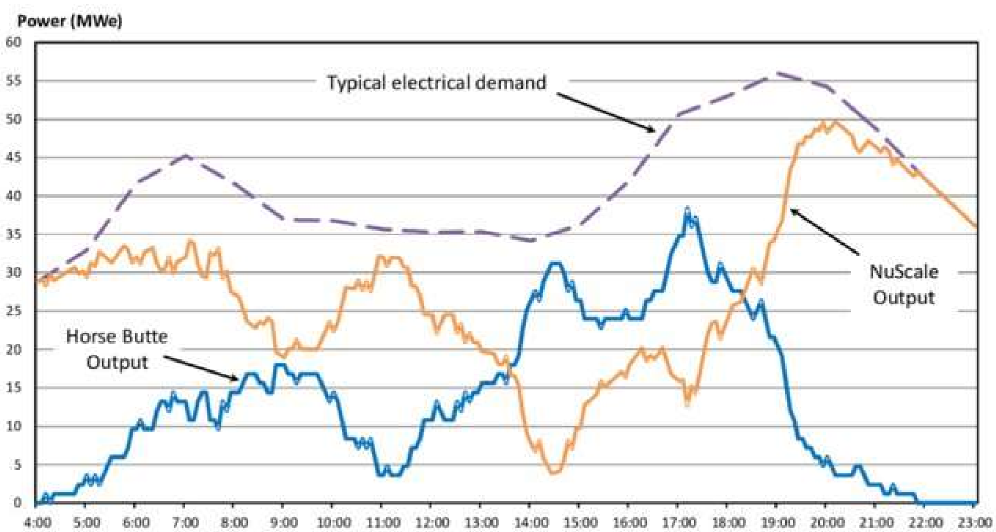
- **Water-cooled (including light water reactor, LWR; heavy water reactor, HWR; pressurised water reactor, PWR):** these designs represent the most mature technology, and the closest to the large conventional plants in operation today. In 2020, there were a total of 31 water-cooled SMRs designs worldwide, with one in operation - the KLT-40S on board the Akademik Lomonosov barge (Russia) – and one under construction and expected to be in operation by 2023 – the CAREM-25 (Argentina).
- **High-temperature gas-cooled (HTGR; including pebble bed reactor, PBR):** there are 14 HGTR SMR designs worldwide. A demonstration module of the HTR-PM was connected to the grid in China in late 2021, and the dual-reactor unit is expected to be fully operational in mid-2022. The XE-100 HTGR PBR built in the US is expected to be operational by 2027.
- **Fast neutron (including liquid metal fast reactor, LMFR; gas modular fast reactor, GMFR):** there are 11 fast neutron-type reactors in various stages of design development around the world. The BREST-OD-300 (Russia) lead-cooled fast neutron reactor is under construction and is expected to be in operation by the end of 2026.

- **Molten salt (including chloride salt cooled reactor; fluoride salt-cooled, FHR):** there are 10 molten salt SMR designs worldwide. This SMR type promises “enhanced safety due to salt’s inherent property, low-pressure single-phase coolant system that eliminates the need of large containment, a high-temperature system that results in high efficiency, and flexible fuel cycle” [1, pg. 4]. Several molten salt SMR designs are progressing through preliminary licensing activities in Canada, the UK and the USA.
- **Microreactor:** very small SMRs designed to generate electrical power up to about 10 MWe, with different types of coolant. There are 6 microreactor designs in development worldwide.

2.2 Potential Uses of SMRs

The design characteristics of SMRs (listed in Section 2) open up new use cases for this novel technology that go beyond how conventional NPPs have traditionally been utilised, though the most prominent use case is still the production of electricity for the power grid. A key advantage of SMRs over conventional NPPs is the possibility of more efficient and economical load following in response to fluctuating energy demands as requested by the grid operator [3]. Although not impossible for conventional plants, load following is not desirable since it can “reduce fuel utilization efficiency, increase the maintenance cost or reduce the lifetime of the plant due to thermal cycling” [ibid., pp. 27]. SMRs, on the other hand, are more suited to load following due to design characteristics such as the smaller core size, increased number of rod control cluster assemblies, simpler designs and use of digital instrumentation and control systems. Figure 1 [4] shows an example model of how a NuScale SMR module could be utilised for load following to compensate for fluctuations in generation from a wind farm.

Figure 1: Example model of SMR load following capability [4]



The load following capabilities of an SMR can also be combined with cogeneration, where excess thermal energy is not converted into grid power but is instead used for some other purpose, such as district heating, water desalination, or the production of another product, such as hydrogen [5]. Desalination of seawater to produce drinking water in arid regions has been explored as a concept for cogeneration and several coupling schemas have already been proposed [6]. The generation of hydrogen through water electrolysis [5] and the production of synthetization of biofuel from microalgae [7] has also been discussed as possible non-electrical applications of SMR technologies. Other cases that have been discussed are the production of gasoline, diesel-like fuels from plastic pyrolysis, or wooden pellets from leftover wood. It should be noted that if desired, SMRs can be used fully for the beforementioned activities without using any of the energy created for electricity production.

3. HUMAN FACTORS ASPECTS OF SMRS

In addition to the design characteristics that differentiate SMRs from current generation large NPPs, the conduct of operations (i.e., how the plant is operated and managed) is also likely to represent a significant departure from current practices. Although some microreactor designs aim for autonomous operation, most SMR designs do still depend on human operators to some extent. As such, it is important to understand the impact that the SMR conduct of operations may have on human factors. To date, there has been little publicly available information about the planned conduct of operations for SMRs, perhaps in part due to the relatively early development phase of the majority of SMR designs and in part due to the highly competitive nature of the SMR industry. However, the available literature helps to shed light on some potential human factors aspects of interest.

3.1 A New Concept of Operation

One of the key differences between conventional NPPs and SMRs is the common design intention to operate multiple SMR units as a single plant, from a single, centralised control room. For example, a NuScale staffing plan report submitted to the United States Nuclear Regulatory Commission (US NRC) for review and approval [8] proposes a plant design of up to 12 modules, controlled from a single main control room (see Figure 2 [9]). This concept of operation is vastly different from today's conventional NPPs which typically feature one or two reactor units are controlled from a single main control room. Canadian NPPs have up to four reactor units controlled from a single main control room, and so provide some valuable experience about the multi-unit operation and human performance aspects.

Figure 2: The NuScale concept main control room [9]

To achieve the multi-unit goal of SMR designs, consideration must be given to human factors engineering aspects such as the distribution of functions and tasks for multiple module operation, the design of control room layouts and human-system interfaces (HSI) to support operators in multi-unit operation, and the staffing policy to ensure there are enough operators available to monitor and control the plant in all operational states, as well as during potential disturbances.

3.2 The Changing Role of the Operator

The design intention to utilise passive safety systems for reactivity control, as well as potentially higher levels of automation, could result in a considerable change in the role of the operator in the SMR plant. Passive safety systems are those in which the safety function is achieved "through reliance on laws of nature, material properties, and energy stored within the safety systems, structures, or components (SSC)" [10, pg. 10]. Such systems do not require human intervention to maintain a safe state.

In addition to increased reliance on passive safety systems, it is anticipated that SMRs will incorporate higher levels of automation than the existing NPP fleet [11, 12, 13]. It is argued that this will support reduced staffing levels for SMRs, which is one of the key economic drivers for the SMR business case, as well as taking advantage of technological developments for this next generation of NPP, although details of how this will be achieved are not yet available in the public domain. It may be the case that some functions and tasks are shared between the operator and the automated systems, in which case it will be vital to understand "how the operator and the automation work as a team to ensure effective and safe plant operation, also known as the human-automation collaboration" [13, pg. viii]. Regardless, the increased reliance on passive safety systems, as well as the higher levels of automation, are likely to change the role of the operator to one of monitoring and checking, rather than actively intervening in plant operation and management.

3.3 Variability in SMR Deployment Applications

One of the main reasons for the rapidly increasing worldwide interest in SMRs is due to the flexibility offered by the design for load following, and deployment in different sectors, including electrical, heating, hydrogen production and seawater desalination, as mentioned in Section 2.2. It is possible in the future that multi-unit SMR plants could serve a range of purposes, with some units dedicated to baseload electricity generation, other units dedicated to load following, and still other units dedicated to non-electrical purposes. A key human factors aspect will be to determine whether/how the different units or groups of units will be monitored and controlled. For example, will there be separate control rooms depending on the use case for the different units, or will all units still be managed from a single control room? Will there be different staff, with different training and qualifications for the different units, or will control room staff need a range of competencies and qualifications to manage any/all of the units? What could be the effects on human performance for staff in these different situations?

4. SMR RESEARCH IN THE HALDEN PROJECT

In 2018, the Halden Project established a research activity on the topic of "Human Performance in Operation of SMRs", which continues through the current Halden Project 3-year program cycle 2021-2023. The main objective of the research activity is to identify the possible impacts of SMR control room concepts on human performance, and how these can be captured in human factors validation studies.

4.1 White Paper on Small-scale Simulator Studies on Multi-Unit Operation

Two important documents were issued at the beginning of the research activity which helped to inform and shape the work going forwards. The first was a white paper issued in 2018 [14] titled "*Small-scale simulator studies on multi-unit operation*" which outlined some of the human factors challenges and research questions for multi-unit operation as understood at that time, including topics such as:

- Operator vigilance in highly automated plants.
- The effects of distractions and interruptions in a multi-unit control room environment.
- The cognitive effects of multi-tasking when monitoring and controlling multiple units.
- The workload dichotomy of underload as a result of long periods of monitoring where operators are more prone to boredom and errors, to overload as a result of responding to simultaneous failures on multiple units.
- The effects on human performance of task switching between units and between passive monitoring to active control.

The white paper also considered methodological requirements for empirical data collection on human performance in a simulated SMR control room environment, which have been used as a basis for consideration in the development of the SMR experimental program for the Halden Project.

4.2 Halden Work Report on Operation of Multiple Reactors from a Single Control Room: Experiences from Nuclear and Other Industries

The second document that greatly informed the research activity was a Halden Work Report (HWR, [15]) issued in 2019 titled "*Operation of multiple reactors from a single control room: Experiences from nuclear and other industries*" which contained a review of a range of control room designs and crew compositions for multi-unit operation in the nuclear and other industries. The report investigated CANDU nuclear reactors, hydropower plants, air traffic control and petroleum installations, with the goal of identifying human performance challenges and possible mitigation strategies that could be of interest for the SMR research activity.

For example, the report identified that the multi-unit control room concept is also gaining popularity across these other industries and that many of these forecast that operations will become highly automated, with less human intervention. While these concepts can reduce (conventional) operator workload and the resources needed to monitor and control the plants, they may also introduce new operator demands for supervising and understanding the automated systems, to identify whether human intervention is needed. The report also identified a trend towards remote operation concepts amongst these other industries, which would introduce another set of challenges for operators, such as how to maintain knowledge of each plant and collect information about the current state of the plant.

The report also considered the ways in which multi-unit control room concepts differ from single-unit designs, the potential risk implications for one operator monitoring two or more units in parallel and for a team of operators monitoring multiple units in parallel, and which design principles exploit the operator resources for monitoring multiple units. The lessons learned from existing multi-unit concepts, and the available information about future concepts indicated that these issues will depend on "(i) the complexity of each unit, (ii) any differences and dependencies between units, and (iii) the expected need for human supervision and interventions at different operational states" [15, pp. 23].

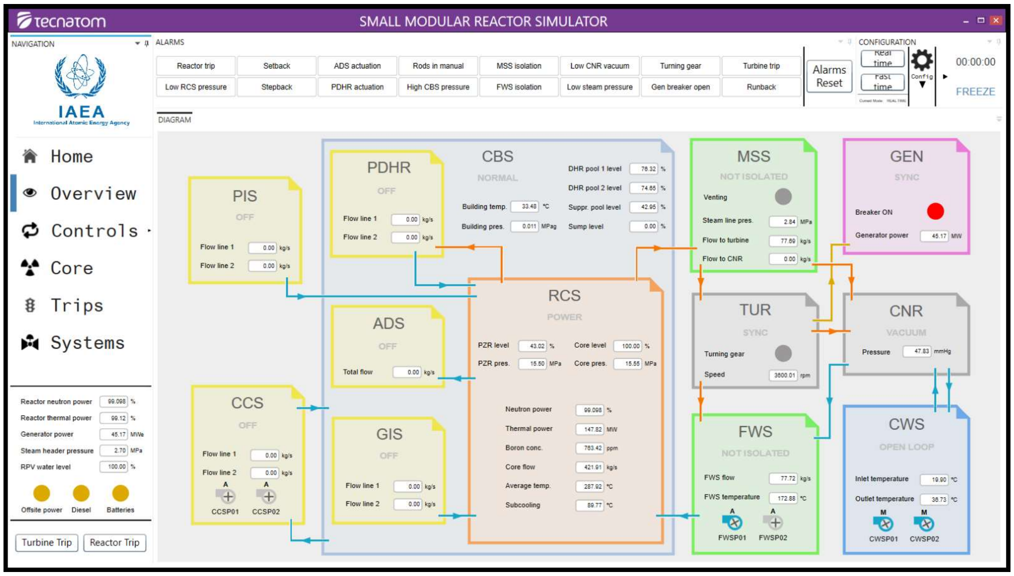
4.3 Installation of an SMR Simulator in the Halden HTO Laboratories

In 2019, the Halden Project obtained a basic principle integral pressurised water reactor (iPWR) simulator from the International Atomic Energy Agency (IAEA), which was developed by Tecnatom. The IAEA simulator design is largely based on the Idaho National Engineering and Environmental Laboratory's Multi-Application Small Light Water Reactor (MASLWR), which is the basis for NuScale [16]. Certain parameters have been modified to make the design more representative of several design variants being pursued around the world [ibid.].

The reactor is a 150MWth, 45MWe light water pressurized water reactor. The simulator is designed with passive safety systems that include an Automatic Depressurization System, Pressurized Injection System, Gravity Injection System, and a natural circulation Passive Decay Heat Removal system. The iPWR simulator has two plant operating modes (turbine leading mode and reactor leading mode) and two core cooling options (natural circulation with no reactor coolant pumps (RCPs) or forced circulation with four RCPs). The cooling option is determined by the initial condition selected, i.e., the specific state of the plant. The secondary side systems include a single turbine, main generator, condenser cooled by a lake, condensate system, and feed water system.

The simulator is intended for educational purposes and thus comes with a simplified graphical user interface, that enables a basic understanding of an integral pressurized water reactor (iPWR). The HSI for the iPWR simulator is made up of eleven displays. All displays have the same configuration menu and alarm information at the top, and key plant parameters and a navigation area to the left; see an example of the overview display in Figure 3. The displays can be opened as separate windows and organized side-by-side on several screens. Trends can be opened in separate windows, and it is possible to display several curves in each trend area. The configuration menu provides a dropdown list of functionalities such as loading initial simulator conditions, modifying specific parameters, and activating malfunctions. It should be noted that all configurations are performed on the computer and screens in which the simulator is running and cannot be accessed remotely. Sixteen key alarms, for example, reactor trip, low reactor coolant system pressure and feed water isolation, are indicated by flashing orange tiles on top of all displays. There is no alarm sound provided by the iPWR.

Figure 3: Example overview display from the basic principle IAEA iPWR



Three instances of the iPWR simulator were installed in the Future Lab in Halden in 2019, as shown in Figure 4. As noted previously, the simulator was developed for the IAEA as an educational simulator to enable demonstration of the basic principles of SMR operation. Thus, there are clear limitations in terms of the capabilities of the simulator for the purposes of experimental human performance research. In 2021, IFE awarded a contract to Tecnatom to provide an advanced version of the simulator to better suit our experimental needs.

Figure 4: The basic principle iPWR simulator setup in the Halden Future Lab

4.4 A First Simulator Study on Multi-Unit Operation

The first study on operating SMRs was conducted in the Halden Future Lab in 2019 to investigate monitoring strategies and prioritization of taskwork when one operator attends more than one reactor at a time [17]. The main purpose of the study was to clarify and possibly develop new research questions beyond topics identified in previous reports [14, 15].

Two participants were tested individually in the Future Lab. Although one operator working in isolation is not a realistic staffing policy for an SMR control room, this approach enabled investigations of workload and task prioritization for an operator responsible for multiple reactors. The data collection included four scenarios designed to be gradually more complex with parallel tasks and disturbances occurring on three reactors. The first scenario was a baseline monitoring scenario in which three reactors operated at full power without any disturbances introduced. The subsequent scenarios involved operator tasks such as start-up, load manoeuvring, and boron concentration adjustments. Disturbances such as reactor trip, steam head break and steam generator tube rupture were introduced on one or more reactors. The study also included a secondary task of categorizing sequential sounds to evaluate spare capacity.

Given the novelty of the simulated process and the SMR test environment, qualitative assessments of participants' understanding, and task performance were conducted. These included observations of task execution compared to pre-scenario expectations and debriefing interviews to document the participants' experiences of the test environment and scenarios.

The explorative study enabled a better understanding of what to prioritize in future research, requirements for participant training and test environments for conducting such studies. Although the participants had backgrounds from conventional single-unit plants and had limited exposure to the iPWR simulator before the study, they were both able to operate the three SMRs even in challenging scenarios with several disruptions. This indicates that future studies are feasible without necessarily needing to recruit operators that are licensed to operate SMRs specifically; licensed operators for conventional NPPs may also participate.

Surprisingly, the risk of unit confusion discussed above [15] was not observed in the current study, not even during the most challenging scenarios with multiple tasks and disturbances occurring at a time. Findings from an explorative study with two participants in a simplified simulator environment should be interpreted with caution but this could indicate that unit confusion may be less critical than originally anticipated. Results also indicated that workload increased when participants performed tasks on multiple reactors but did not seem to impede task completion. The secondary task measure was sensitive to changes in participants' spare capacity and should be further developed in future studies.

The study identified several aspects worth further investigation, such as monitoring strategies when overlooking several reactors at a time; means to support monitoring of reactors in different operating modes; detection of multi-unit failures; and team organization to support planned, parallel operations and safe prioritizations of tasks.

4.5 Future Plans for Experimental Simulator Studies

As noted in the previous section, IFE has purchased an upgraded iPWR simulator that will enable the continuation and expansion of experimental simulator studies into the future, as part of the Halden Project. The upgrade will increase the scope and configurability of the simulator, allowing us to run more complex scenarios in a single-unit, six-unit or twelve-unit control room setup.

Building on the previous work in the Halden Project, the experimental program will continue to investigate the novel challenges and work processes introduced by SMRs. Because there is so little information available about how SMRs will be monitored and operated (the so-called "black box" effect mentioned earlier), we have had to adopt an explorative approach to the investigation of possible human performance issues. However, our experience from experimental studies in the Halden Project positions us well to make informed estimations about what kinds of challenges may be faced by SMR operators. In addition, we continue to monitor industry reports and published literature to stay up to date with developments (e.g., the NuScale staffing plan [8]). The main research questions for the next 3-year research activity on SMRs in the Halden Project are currently defined as:

- What are the impacts of expected staffing strategies (e.g., a 3-person crew for a 12-unit plant) on operating monitoring strategies across multiple units?
- What are reliable monitoring strategies for operators overlooking several reactors at the same time, that can minimise the risk of unit confusion?
- What are effective means for detecting single-unit and multi-unit failures?
- How can adaptive human problem-solving capabilities be utilized while ensuring safe prioritizations of tasks in multi-unit environments?
- To what extent will proposed control room layouts, user interfaces and staffing plans support operators' ability to maintain attention/stay alert, and/or how could these have a detrimental impact on human performance?

Further elaboration and prioritisation of these research questions will be conducted in parallel with the development of appropriate scenarios for experimental testing in the new Halden SMR simulator.

5. CONCLUSIONS & NEXT STEPS

In this paper, we have considered how specific characteristics common to many SMR designs represent a significant change from conventional NPP operation, and thus are likely to change how operators will monitor and control SMR plants. The smaller reactor, simpler design, and increased use of passive and automated systems are expected to reduce the overall complexity of operation. However, the resulting changes in minimum staffing levels, roles and responsibilities, and human-system interaction may have a detrimental effect on human performance. The multi-unit concept as well as the increased diversity of deployment opportunities for SMRs have the potential to create new error modes for operators. Furthermore, the scalability aspect of SMRs (i.e., the ability to add or remove units from operation to increase or decrease output) will mean that the development of operational concepts for SMRs needs to consider changes in operational demands and staffing levels in the short term and long term.

Our research activity on human performance in operation of SMRs continues through the current Halden Project 3-year program, which runs from 2021 to 2023, and we are currently developing the work plan for the next 3-year program after that (2024-2026). As SMR designs continue to mature across the world, our goal is to continue updating our knowledge on the human factors and human performance challenges and opportunities of SMRs. Particular attention is being paid to those designs that are nearing the finalisation of the licensing process and beginning operation, as these processes yield greater details about control room design philosophies and the planned conduct of operations as they move closer to commissioning. In parallel, we aim to continue investigating research questions in our iPWR simulator in Halden, as a means to empirically evaluate and measure human performance and the potential impact on the safety of SMR operation.

6. ACKNOWLEDGEMENTS

Funding: This work was supported by the OECD Nuclear Energy Agency (NEA) Halden Human-Technology-Organisation (HTO) Project. Thanks to the members of the Programme Review Group of the Halden HTO Project for review and constructive comments.

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