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Expert Perceptions on Human Reliability Analysis for Advanced Reactors

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Abstract: Advanced Power-reactors will deploy more automation, some will be remote operated, need little or no human intervention, utilize varying passive safety systems, and in many cases, operate as multiple units controlled from a single main control room. These and many other features make them significantly different from the conventional power reactors we use today. Human reliability analysis (HRA) methods were developed mainly for the conventional reactors and thus may have to be revisited for suitability for advanced reactors if HRA is at all necessary in these unique contexts. We embarked on a study to interact with 28 experts in the fields of probabilistic safety analysis, human factors, and human reliability analysis across six countries. These experts were affiliated with research institutions, nuclear regulatory bodies, nuclear utilities, technical support organizations, and universities. The results of the study have been organized into operational risks, relevance of HRA, new scenarios and performance shaping factors, organizational approach to HRA, research questions, and open-ended thoughts on HRA for Advanced Reactors. The results highlight that human factors considerations for advanced reactors differ significantly from those associated with conventional designs, thereby presenting new challenges for HRA. Notably, there remains a knowledge gap among experts regarding the operational reliability of the novel systems used in advanced reactors. This uncertainty may contribute to scepticism about the reduced human influence on plant safety often claimed by advanced reactor vendors. While opinions on the role of HRA in advanced reactors vary, there is considerable agreement on key human factor concerns. Overall, the insights from this study offer preliminary guidance for adapting HRA methodologies to advanced reactor contexts, identifying attributes that may inform the development of suitable HRA approaches.

Keywords: Human reliability analysis, safety assessment, advanced reactors, small modular reactors, human factors.

1. Introduction

Advanced reactor designs are anticipated to encompass several distinct characteristics that set them apart from contemporary nuclear power plants. These features include the incorporation of smaller, simpler, and modular reactor configurations, enhanced automation levels, increased reliance on passive safety systems (PSSs), and a transition toward multi-unit (multi-module) operations managed from a single central control room. Although definitions of advanced reactors vary, organizations such as the International Atomic Energy Agency (IAEA), the U.S. Nuclear Regulatory Commission (US-NRC), the United Kingdom government, and the European Union generally agree that these reactors are distinguished by their anticipated enhancements in safety, sustainability, and operational efficiency, marking a significant departure from traditional nuclear reactor designs (Arigi 2025) and this forms the basis for our scope and definition of advanced reactors in this paper. In this paper, the term ‘advanced reactors’ refers to light-water small modular reactors as well as other novel reactor concepts—both proposed and operational—that employ diverse technologies.

Human Reliability Analysis (HRA) and human factors are critical in nuclear safety because human actions can both initiate accidents and provide the last line of defence to prevent or mitigate them, so their contribution must be explicitly modelled and understood. Moreover, probabilistic safety/risk assessments (PSAs/PRAs) are considered incomplete without a systematic identification and quantification of key human-system interactions (Hirschberg 2004). Consequently, human performance should be integrated into safety cases and design improvements, not treated as residual uncertainty, making HRA and human factors indispensable elements of nuclear safety management.

The innovations introduced in advanced reactors are largely intended to reduce the extent to which plant operators must perform safety-related tasks or intervene during accident scenarios, thereby lowering the likelihood of human error. As a result, the operator's role is expected to shift markedly—from actively controlling and managing the plant to primarily supervising and monitoring its systems to ensure they function as intended. Nevertheless, it remains uncertain whether human reliability analysis (HRA) will characterize operator actions in these reactors in the same way it does for conventional nuclear power plants.

According to (O'Hara 2025a) using traditional PSA methods, including HRA, to evaluate advanced reactors presents new challenges compared to their application for large light water reactors. These challenges include limited operating experience and the use of novel technologies, which may lead to greater uncertainty in results. Meanwhile, human performance analysis is applicable to both PSA and deterministic safety analyses (O'Hara 2025a). Additionally, it is essential to ascertain the existence of new human error modes that may be unique to advanced reactor operations, particularly in relation to passive safety mechanisms and human-automation interactions.

This paper continues with a background (section 2) including perspectives from literature on advanced reactor, the human factors issues, and implication for HRA, while section 3 describes the method of data collection. The main objective of this paper is to explore expert perspectives on HRA relevance and adaptation for advanced reactors. This is presented in section 4. Sections 5 and 6 presents brief discussions and conclusions respectively.

2. Background

Advanced reactors include a broad set of technologies—such as advanced water-cooled, gas-cooled, liquid-metal-cooled, and molten-salt designs—that incorporate features distinguishing them from conventional nuclear plants. Many use passive safety systems that reduce reliance on operator intervention, while small modular reactors (SMRs) and micro-reactors emphasize modular construction for faster deployment and lower costs. Several advanced concepts operate at higher temperatures, enabling industrial applications, and some support more efficient fuel use or the utilization of recycled fuels, depending on the design and fuel-cycle strategy. Many often classify SMRs into light-water designs and Generation IV concepts—commonly termed Advanced Modular Reactors (AMRs)—with near-term deployment expected to focus on light-water SMRs, while AMRs remain in development (BEIS 2024) (Nøland et al. 2025) (Arigi and Bye 2024) (BEIS 2024). Advanced reactor control rooms typically feature soft controls, computer-based procedures, advanced alarm systems, modernized workstations, advanced information systems, and evolving communication patterns (Arigi and Kim 2020).

Advanced reactors introduce several significant changes, including the shift toward multi-unit control—where operators may oversee multiple modules from shared interfaces (O'Hara et al. 2012) (NEA 2024) (O'Hara 2025b)—raising challenges for maintaining situational awareness, especially under differing plant states or simultaneous disturbances (Blackett et al. 2022) (Blackett et al. 2023) (Arigi and Blackett 2023). Designs emphasizing reduced staffing through automation and passive safety systems (EPRI 2016) create open questions about workload, situational awareness (Eitrheim et al. 2019), and the safety implications of tasks tied to plant efficiency. Increasingly digitized and automated control rooms pose further questions about unexpected operator responses and human-machine interaction (Jipp & Ackerman, 2016). Computer-based procedures (CBPs), expected to be the standard, improve navigation and integrate plant data (Nilsen and Shin 2011) (Le Blanc and Oxstrand 2013) (Schreck et al. 2025) but introduce new validation challenges as functionalities grow more advanced. With automation shifting the operator's role toward monitoring, proper information presentation remains critical (Boring 2023), especially as reduced engagement may increase category-B human errors (Arigi and Bye 2024). Remote-operation concepts could enable models like single-operator for multiple modules (Morrow et al. 2025), significantly affecting peer-checking and error-recovery assumptions in HRA (Arigi A.M. 2025). Moreso, CBPs and digital communication tools are already reshaping crew interaction, reducing traditional three-way communication and pushing operational exchanges further into digital channels (Kim and Kim 2014) (Hildebrandt and McDonald 2020) (Boring 2023) (Eitrheim et al. 2025).

As automation grows, operators will shift toward monitoring—an activity humans perform poorly according to *MABA–MABA*[a] (Fitts et al. 1951) and as noted by Roth et al. (2019)—requiring new performance shaping factors (PSFs) tailored to PSSs (Park et al., 2025) and granular task analyses to understand human–automation interactions (Arigi and Bye 2024), especially given increased assumptions about reduced human importance (Bye et al. 2022).

Finally, because PSFs depend on specific contextual conditions, human-performance data from existing plants—typically sourced from simulators, experience data, and expert judgement, including SACADA (Chang et al., 2014)—may not fully apply to new operating environments in advanced reactors; only data reflecting similar tasks should be used, though historical data will remain partially relevant when task equivalence exists (Arigi and Bye 2024).

3. Methodology

Given the paucity of publicly available information on the challenges of conducting safety assessments, and performing HRA for advanced reactors, an expert elicitation was considered the most effective option to gain such knowledge.

3.1. *The Interviews*

The experts from some countries with known interest in developing advanced reactors were contacted via e-mail. They were informed about the purpose and procedure of the interviews including ethics and confidentiality matters. After receipt of verbal or written confirmation about intent to participate, the participants were sent the official consent form for their signatures. In some cases where the participants are unable to provide the signed consent forms before the meeting day, the consent forms were re-issued and signed before the interview sessions commenced.

The expert elicitations were done within the months of October to December 2024 in the form of semi-structured interviews in two ways: (1) In-person at a designated office space, and (2) Online at designated times during the regular work hours. The in-person interviews were conducted in 11 sessions involving 18 participants with minimum of one (1) and a maximum of six (6) persons per session. The online interviews were conducted in 4 sessions involving 10 participants with a minimum of one (1) and a maximum of four (4) persons per session.

The sessions typically began with introductions of both the participants and the interviewer(s). The interviewers then outlined the purpose of the project and the interview, explained the interview structure, reviewed the consent form, and provided the necessary ethical information. Participants were given the opportunity to ask questions for clarification. After this, the interviewer proceeded with the interview questions, and the participants responded accordingly.

The interview questions were structured in three phases.

- In the first part, we attempt to get the respondents' independent opinion about the relevance of HRA for advanced reactors and its challenges.
- In the second part, we asked about the planned approach of the respondent's organization / country for handling HRA/PRA for their advanced reactors.
- In the third part, we asked for the other opinions of the respondents not covered by the previous questions.

The semi-structured interview format was selected for several reasons. First, it provides a predefined set of core questions while still allowing the interviewer to probe more deeply and request clarification when needed. Second, it offers flexibility for the interviewer to adjust the sequence and flow of the conversation in response to the interviewee's answers, ensuring that all key topics are addressed without constraining the dialogue. Third, the format is less rigid than fully structured interviews, fostering a more natural and conversational interaction that may encourage participants to respond more openly

[a] MABA-MABA referring to the concept 'Men Are Better At – Machines Are Better At'

and candidly. Consequently, interviewers did not demand direct answers to every question as initially phrased.

3.2. *Participants*

There were 28 participants from six (6) countries. The participants have expertise in one or more of three main areas: PSA/PRA, human factors (HF), and HRA. Sixteen (16) participants had expertise in two of the three areas. None of the participants claimed expertise in all three areas. Participants were drawn from a variety of organizations including research institutes, universities, technical support organizations (including nuclear systems design consultancy), nuclear power plant utilities, and regulatory agencies.

3.3. *Data Collection and Analysis*

An audio record of each session was made via a table-top battery-powered (3Volts) audio recorder (SONY IC recorder ICDPX470) alongside note taking by the interviewer(s). The audio records were uploaded unto a secured database managed by the interviewers' organization via a dedicated virtual private network (VPN) immediately after each session and thereafter deleted from the audio recorder to prevent unauthorized access. The duration of the in-person interviews was a range of 33 minutes to 63 minutes while the online sessions lasted between 62 minutes and 83 minutes excluding the introductions.

Although notes were taken during the interviews, the analysis mainly relied on the audio recordings to make qualitative analysis of the interviewee responses. In cases where there was more than one interviewee in a session, the notes were written on the same file, but the participants' responses were coded as P1 (for participant 1), P2 (for participant 2), and the like.

4. Expert Views

After a qualitative analysis of the expert perspectives the following is a summary of the opinions expressed, organized in specific themes. These are based on the understanding of the author without directly quoting the participants.

4.1. *Envisaged Operational Risks*

Participants expressed concerns that advanced reactor designers focus heavily on core physics and passive safety while giving limited attention to operational aspects such as HMIs, control systems, and time-critical operator actions. Several participants reported that vendors sometimes rely on implicit or outdated assumptions, which only become visible under detailed scrutiny and can undermine the credibility of the safety case.

They also highlighted the lack of operating experience with new technologies, particularly passive systems, raising doubts about whether all potential failure modes—especially under external or cogeneration-related hazards—are fully understood. According to participants, maintenance activities may introduce additional risks due to compact designs and multi-unit configurations, increasing the likelihood of latent or pre-initiating human errors.

Participants further pointed to challenges associated with remote operations, reduced staffing, and expanded human-technology collaboration. In their view, although advanced reactors may have lower potential consequences, their reliability is currently less established than that of the existing fleet. This, they suggested, places greater importance on human performance and increases the impact of human errors on overall plant risk.

4.2. *Relevance of HRA*

Divergent opinions on necessity and scope. Participants offered differing views on the risk significant human actions in advanced reactors. Some argued that humans will remain essential, noting that operators will still be required to detect and correct unforeseen conditions, as has historically been the case in conventional plants. They emphasised that system designs are based on incomplete knowledge, that utilities may expect earlier operator intervention than safety cases imply, and that humans will still be needed to monitor automation and manage accidents—especially when automation fails.

Other participants believed it is possible to demonstrate safety cases in which human actions are not risk significant, particularly for designs with few moving parts, such as some microreactors, or when licensing frameworks rely on probabilistic arguments showing that events rarely progress to stages requiring human intervention. A third group maintained that it is not yet possible to determine whether human actions will be more or less risk significant in advanced reactors compared to conventional reactors, given the unpredictability of new technologies and the likelihood that more complex designs will involve more personnel than currently indicated.

Most participants agreed that HRA remains relevant wherever humans contribute to the reactor lifecycle, but many felt its scope will need to expand beyond conventional assumptions. They identified potential areas for attention, including new error databases, software design and coding errors, monitoring and maintenance activities, calibration-related category-A errors, and accident sequences involving passive safety systems and automation limits. A few participants suggested that HRA might become unnecessary only if its scope is defined narrowly, but not when considering the full lifecycle from design to decommissioning.

4.3. *New Scenarios and Performance Shaping Factors*

Participants generally found it difficult to identify event scenarios unique to advanced reactors, largely due to limited familiarity with the details of emerging designs. Nonetheless, several believed that many important scenarios would involve PSSs, expressing concern that reliance on physical phenomena alone may be insufficient. Some also pointed to multi-unit configurations as a potential source of novel challenges, noting that external hazards affecting units in different operational modes could create unforeseen complex situations for operators and complicate HRA modelling.

Many participants anticipated that errors of commission (EOCs) (actions that inadvertently compromise safety) would be prominent in advanced reactors. They described situations in which operators might intervene to prevent safety system actuation perceived as harmful, or take actions aimed at asset protection that unintentionally compromise safety. These behaviours were viewed as important to capture in future HRA.

Participants did not identify entirely new PSFs but suggested that several known PSFs may become more influential in advanced reactors. These included training quality, communication demands, automation and passive function transparency, procedure interaction, teamwork dynamics, attention fatigue, HMI design, and information adequacy. Collectively, these were seen as factors that could significantly affect human error probabilities in the context of advanced reactor operation.

4.4. *HRA Methods Applicability for Higher Automation and Passive Safety Systems*

Participants expressed differing views on which HRA methods are suitable for analysing human interaction with high-level automation and PSSs. Some felt that existing methods could still be applied, but only with significant enhancements—both in their underlying methodological structure and in the data required to support them. Others maintained that none of the current approaches are appropriate because they were not developed with the characteristics of advanced automation or PSSs in mind.

Several participants instead outlined features they believed an effective method should possess. They emphasised a need for approaches grounded in Bayesian networks that explicitly link PSFs, failure mechanisms, and failure modes, particularly given the new operational paradigms expected in advanced reactors. They also stressed that any method used should remain conservative, flexible enough to combine PSF multipliers, capable of addressing EOCs, and sensitive to ergonomic considerations.

Participants further noted that the method should evaluate scenarios with long response windows, focus more on the nature of tasks rather than engineered system characteristics, and support the identification of failure modes rather than rely solely on predefined ones. Simplicity and accessibility were also highlighted as desirable attributes of the HRA method for practical application.

4.5. *Organizational Approach to HRA*

Participants reported that most national regulatory frameworks—being risk-informed—already require licensees to complete a PRA, which in practice necessitates an accompanying HRA. Some participants noted that utilities commonly follow standards such as American Society of Mechanical Engineers (ASME)-PRA, and that in some countries HRA is embedded within broader human-factors regulations. Several participants expected that even where regulation is not explicitly risk-informed, defence-in-depth principles would still require identifying human actions, at least qualitatively.

Many also observed that regulators are still developing specific rules for SMRs and other advanced reactors, and that no single HRA method is formally mandated. According to the participants, organizations are beginning to reassess existing HRA approaches for their suitability to new technologies, considering the addition of new failure modes while retaining current ones. Some also pointed to ongoing discussions with utilities about challenges in applying traditional HRA methods to digital control rooms, with lessons expected to be relevant for advanced reactor HRAs.

4.6. *Research topics*

Although participants were invited to propose research topics related to HRA for advanced reactors, most instead highlighted several broader areas spanning both human-factors and HRA considerations.

Those relevant for HRA include: identifying which of the many possible EOCs are most safety-significant; determining an effective HRA process for new advanced reactors to ensure all relevant human errors are captured; understanding how combinations of PSFs contribute to specific cognitive failure modes; establishing criteria for selecting suitable HRA methods for different advanced reactor types; gathering design-specific human performance data when unique PSFs are present; and adapting data from the current light water reactor fleet to reflect the characteristics of advanced reactors.

4.7. *Open-ended thoughts*

Participants raised several open considerations for HRA in advanced reactors. Some argued that current methods do not adequately capture human–computer interaction errors in advanced digital interfaces, while others felt that risks in the control room may decrease because operators have limited direct influence over passive systems. They also emphasised the importance of conducting HRA early in the design phase to guide design decisions and reduce later uncertainty.

Several participants expressed concern that increased automation may reduce some error types but heighten the likelihood of latent, configuration-related errors (category A human errors)—especially when passive components cannot be tested until demanded. Others questioned whether HRA should expand to include design-related failures and errors by non-nuclear personnel, noting that both could introduce previously unrecognised hazards under new operational models.

Many participants cautioned against overconfidence in passive safety claims, arguing that real-world physical conditions may challenge assumptions about flow, margins, and operability. They also stressed that data and human performance insights from current reactors may require adjustment for advanced designs, and that qualitative understanding of how people work in new operational contexts is essential. Additional concerns included accounting for security-related constraints and the limited availability of qualified human factors / HRA experts to evaluate increasingly complex systems.

5. Discussion

The interviews point to persistent uncertainties in the operational risk landscape of advanced reactors. Advanced reactor vendors often emphasise reactor core safety while providing limited detail on operational behaviours, resulting in safety claims that may not withstand detailed scrutiny. Limited experience with passive systems, combined with new co-generation applications and compact multi-unit designs, introduces unfamiliar failure modes and maintenance challenges. Overall, the findings suggest a trade-off: although consequences of accidents may be reduced, the intrinsic reliability of advanced reactors is not yet proven, elevating the importance of human factors and consideration of latent errors.

These findings collectively indicate that HRA remains relevant for maintaining robust safety margins as reactors adopt technologies who's real-world performance remains only partially validated. While some designs reduce the need for operator intervention, human involvement remains essential for monitoring automation, managing unforeseen events, and compensating for design uncertainties. The scope of HRA will need to expand to include software-related errors, maintenance-driven failures, and new human error categories for which existing databases are insufficient.

Key modelling challenges for HRA include multi-unit scenarios, dominant errors of commission, and amplified effects of established PSFs such as communication, training, automation transparency, and HMI quality. Although few advocate for entirely new HRA methods, there is clear support for approaches that remain conservative, flexible, able to treat EOCs explicitly, and capable of representing causal mechanisms in novel operating contexts, and methods that focus on task characteristics.

The study highlights broader human-factor issues, including human-automation function allocation, operator engagement in highly automated settings, and the need to account for design-related human errors and non-nuclear on-site personnel. Research needs include identifying significant EOCs, refining HRA processes for new builds, linking PSFs to cognitive mechanisms, and adapting light-water-reactor data to advanced technologies. A cross-cutting concern is the uncertain performance of non-testable passive systems and how this shapes operator trust and action tendencies.

6. Conclusion

Findings from interviews with 28 experts from various countries on HRA needs for advanced reactors, including SMRs have been presented. Key human factors issues identified include multi-unit operation, reduced staffing, increased automation, remote operation, increased monitoring roles, and the use of computer-based procedures. The research highlighted that while automation and PSSs may reduce the number of human tasks, the remaining tasks become more critical, especially for safety.

Experts expressed concerns about limited operational experience, unforeseen failure modes, and the challenges of analysing EOCs. There was consensus that HRA remains relevant, particularly for monitoring automation and mitigating design uncertainties, even as human intervention decreases. We also noted a reluctance among experts to adopt entirely new HRA methods, favouring flexible adaptation of existing approaches. More data for HRA in advanced reactor is needed, especially on ex-control room actions and novel control room contexts.

Future work should prioritise deeper investigation into design-related human errors, specific consideration of non-testable PSSs, multi-unit operator roles, and the adaptation of existing human-performance data to new technologies. These directions reflect areas of expert-identified need rather than prescriptive conclusions, signalling where research and methodological refinement should focus next.

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