Needs for change of human reliability analysis for new advanced reactors

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Abstract: Efforts to implement the innovative advanced reactor designs have been consistent for the past few years and some of the light water based advanced reactors are very close to implementation and operation. The designs of these advanced reactors and their applications are different from those of conventional nuclear power plants, including more inherent passive safety features and more automation. Subsequently, the in-control room and ex-control room operations may be radically different. The human role will be different in a highly automated plant in which the claim is that there will be fewer safety related actions by humans. The prediction is that the human role will be characterized by more monitoring and less procedure execution and thus much less hands-on actions. Safety assessments are indispensable for nuclear power plant licensing and operations. Until now, there is very little known about how the new forms of operations and work practices would affect the human reliability aspects of safety assessments that should be done for the various advanced reactors. How is this presumably more monitoring role analyzed? This paper brings to the fore, issues that have been discussed in the human reliability analysis (HRA) community based on current knowledge about how humans might work with the new advanced reactors. Literature reviews have been conducted to gather thoughts from stakeholders on the characteristics of new advanced reactor designs and how they might affect the way we do HRA in the future. A systematic analysis of the change needs for HRA to deal with the issues raised are presented.

Keywords: PSA, human reliability analysis, advanced reactors, HRA.

1. INTRODUCTION

Human reliability analysis (HRA) evaluates human actions and inactions that can significantly influence system reliability. Typically, HRA encompasses all intricate industrial systems that depend on human-machine interactions for effective operation, maintenance, and management. Consequently, human errors during operation, management, or maintenance tasks are typically considered in Nuclear Power Plants (NPPs), whereas errors from the plant designer, such as poor design or inappropriate material selection for equipment, are excluded.

The need for human reliability analysis emerged in the 1960s as probabilistic risk/safety assessment (PRA/PSA) methods were first applied to nuclear power plants. Early HRA methods like the Technique for Human Error Rate Prediction (THERP) (Swain & Guttman, 1983) were developed "to quantify human error probabilities based on task analyses and performance shaping factors" (Boring, 2015). These initial approaches treated humans as components that could fail, and they had limited ability to model cognitive causes behind human errors and the context in which they occurred (Bowie, et al., 2015).

Subsequent HRA methods aimed to better represent cognitive processes and error mechanisms. Methods like A Technique for Human Event Analysis (ATHEANA) used an underlying model of human information processing to identify error-forcing contexts (Bowie, et al., 2015). Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) incorporated performance shaping factors like workload and complexity (Bowie, et al., 2015). A few methods were developed that treated PSFs slightly differently, and frameworks of "internal PSFs" and "external PSFs" were developed (Williams, 1986). A common denominator for many of the early HRA methods was that they were quantification methods. They did not incorporate a proper process for performing the qualitative HRA, meaning the human factors methods and techniques needed to get a proper basis for the quantification. This was part of the basis for conclusions such as "*challenges remained in addressing complex human-system interaction and integrating HRA into PRA models*" (Bowie, et al., 2015).

Newer methods have provided a more structured framework for incorporating the qualitative HRA process into the HRA, as part of the method. ATHEANA is a good example of this, but even methods based on a classic PSF model have incorporated this. These methods typically describe a framework for how to do task analysis, error identification and error modelling as a basis before a detailed quantification is done that relies on this process. See Figure 1 in the Petro-HRA method for an overview of this process (Bye, et al., 2017). The first example of a structured incorporation of qualitative HRA is probably the HRA process type of work done in the UK, where British Energy (now EDF-Energy) applied Human Error Assessment and Reduction Technique (HEART) and Nuclear Action Reliability Assessment (NARA) (Williams, 1986) (Kirwan & Gibson, 2007) for quantification in a structured HRA process, the latter though as part of an internal qualification routine and leaving only the HEART as a quantification method as a public method.

Later methods have taken the approach to incorporate the qualitative HRA into the HRA method description itself, most prominent examples are Petro-HRA (ibid.), Phoenix (Ekanem, et al., 2016) and IDHEAS-ECA (Xing, et al., 2022) .Another key attribute with some of the newer methods is that they rely more on data and a structured way of incorporating data into both their basic foundations, such as the nominal PSF multiplier values, and into their applied use, such as giving users a proper example background and example values as part of the guidelines of the method. IDHEAS-ECA (ibid.) is a good example of this. EMBRACE (Kim, et al., 2019) (Kim, et al., 2020) is another example of a method that uses data to systematically underly the method.

Despite improvements, traditional HRA methods still face several key limitations. Most techniques were developed based on experience from current light water reactor designs, which may not translate well to advanced reactor concepts with higher autonomy, increased digital instrumentation and controls (Kirwan, et al., 2004), and remote operations. Existing HRA dependency models struggle to account for increased automation and potential for new error modes (Kirwan, et al., 2004) (Bowie, et al., 2015). There is also a lack of guidance on evaluating cognitive workload, situation awareness, and human-system interface issues for advanced human-system integration concepts (Bowie, et al., 2015). As such, new HRA approaches tailored to advanced reactor characteristics are needed (Bowie, et al., 2015).

The importance of rigorous safety assessments for new advanced reactors, especially PSAs, cannot be overstated. Complex systems typically consist of the hardware (equipment, structure, and components), software, and the human aspects working in a symbiotic relationship to ensure the overall effectiveness of the system. PSAs can facilitate a systematic evaluation of the intricate interplay between human actions, initiating events, hardware, and software in the plant systems. By quantifying metrics like core damage frequency, PSAs allow designers to enhance defense-in-depth by focusing on high safety significance areas and guide the prioritization of safety improvements in NPPs.

For advanced reactors employing novel technologies “detailed human reliability analyses are needed to understand how changes in operator roles affect human error probabilities” (Dan & Romney, 2023). According to a workshop report by the OECD Nuclear Energy Agency (OECD-NEA, 2002), the treatment of issues like software failures, digital system modeling, and cyber-security vulnerabilities must be addressed as part of safety analysis of advanced nuclear reactors. By integrating these considerations using advanced, risk-informed PSA techniques from the design phase, a compelling safety case can be built for advanced reactor concepts (OECD-NEA, 2002) (Dan & Romney, 2023). Moreso, a keen eye should be kept on upholding stringent safety principles as the nuclear industry pursues the next generation of reactors.

Considerable progress has been made in recent years regarding the development of new advanced reactors. However, little has been discussed (in public by vendors) about the related safety analysis including HRA. The new advanced plants promise several novel characteristics including more inherent passive safety features, modular designs, co-generation applications, and more automation. Thus, it is expected that there would be significant difference in how the new advanced plants would be operated. The human role will be different in a highly automated plant in which the claim is that there will be fewer safety related actions by humans. The prediction is that the human role will be characterized by more monitoring and less procedure execution and thus much less hands-on actions.

This paper aims to bring to the fore an updated knowledge based on literature about how humans are likely to work in the new advanced reactors being proposed or designed. The issues raised also pertain to some newly deployed advanced reactors. The necessary changes to HRA methods and their implementation are highlighted.

While the previous definition of HRA still holds true, the qualitative analysis needed as a part of HRA must not be undermined. The discussion in this paper remains conscious of the very important qualitative analysis behind any quantitative analysis in HRA.

2. HUMAN FACTORS CONSIDERATIONS IN ADVANCED REACTOR DESIGNS

The nuclear energy industry is undergoing a transformative shift with the development of advanced reactor technologies. The innovative designs aim to enhance safety, improve efficiency, and address the challenges faced by traditional NPPs.

2.1. Advanced Reactor Designs

Advanced reactors encompass a diverse range of technologies, including advanced water-cooled reactors, gas-cooled reactors, liquid metal-cooled reactors, and molten salt reactors, each with unique features and capabilities that set them apart from traditional nuclear power plants. Many incorporate passive safety systems that rely on natural phenomena to potentially reduce the risk of human error. Most Small Modular Reactors (SMRs) and micro-reactors are designed for modular construction and transportation, enabling faster deployment and potential cost savings. Some of the advanced reactor types can operate at significantly higher temperatures, making them suitable for industrial applications like hydrogen production, district heating, and desalination. Additionally, some designs can more efficiently utilize nuclear fuel and potentially reduce the amount of long-lived radioactive waste generated. Table 1 gives a summary of the major advanced reactor types, characteristics, and status at the time of writing this paper.

Table 1. Types, characteristics, and status of major advanced reactors

Type	Examples	Nuclear characteristics	Capacity	Status
Water-cooled	CAREM, VOYGR, BWRX-300, ACP100, RITM-200M	Coolant and moderators vary from light water to heavy water	Most are less than 300MW	LWR SMRs are considered the most promising options for deployment in the short-term; In construction or operation in Russia, China, and Argentina (NEA, 2024).
Gas-cooled	Gas-cooled Fast Reactors (GFRs), High-Temperature Gas Reactors (HTGRs)	Coolant is generally helium gas; no moderator is used in GFRs, but graphite is moderator in HTGRs.	0.5-2400 MWth (Hatala, 2019).	HTTR operates in Japan; a demonstration GFR plant to be designed by 2025 and then constructed in a collaboration among some European countries (Arostegui & Holt, 2019).
Liquid metal cooled	Sodium cooled fast Reactors (SFRs), Lead-cooled fast Reactors (LFRs),	Coolant is generally liquid sodium, molten lead, or lead-bismuth eutectic alloy; no moderator is used	Varies, 25MW-450MW; Can range up to 1,500MW (GenIV, 2024)	Multiple SFRs currently in operation worldwide, with others expected soon; Progress is being made in the development of LFRs as one demonstration plant (BEREST-OD-300) is being constructed in Russia (NEA, 2024).
Molten salt cooled	Energy well, LFTR, Thorizon One, IMSR	Coolant is generally molten fluoride salt; moderator varies.	Often less than 300MW; Terrestial Energy MSR is up to 600MW (WNA, 2024).	Has been under development for decades but not yet deployed.
Micro Reactors	eVinci, PWR-20, Jimmy SMR, Project Pele, Calogena	Coolant and moderator vary	2-20 MW (Harold & Maheras, 2021).	Currently under development; mostly in the United States, with potential for deployment within the next decade.

Many countries now refer to two basic types of SMRs: Reactors based on light water, and Gen-IV types of reactors, including high temperature gas, sodium, lead, and molten salt. The latter is sometimes referred to as Advanced Modular Reactors (AMRs). In general, the light water based SMRs are more based on proven technology and will have a shorter time window to deployment.

2.2. Common Human Factor Considerations for Advanced Reactors

Based on the literature review and analysis by the authors the most prevalent human factor considerations that may have the strongest impacts on HRA for advanced reactors are given below. Some of these considerations are not relevant for all the types of SMRs and AMRs. For example, some initiatives are promoting one-unit operation. Also, there is not necessarily a difference between light water SMRs and AMRs in what the HF considerations are, there may be similar HF challenges for a Gen-IV HTGR and for a light water SMR.

2.2.1. Multi-unit Controls

The concept of one operator or a crew of operators being responsible for multiple modules of a reactor can become widespread in the future. It is also anticipated that such multi-unit controls for advanced reactors could be done on-site or remotely. At least a quarter of the proposed SMRs are planned as multi-modules. Examples are Xe-100, NUWARD, and VOYGR (NEA, 2024).

2.2.2. Reduced Staff

One of the common trends in the proposals for advanced reactors is the reduction in the number of persons that would be dedicated to controlling the daily functions of the reactor. The proposals are often justified with the ability to automate most of the current tasks performed by operators, as well as a higher reliance on passive safety systems. Therefore, typical HRA task analysis would yield less results for human tasks. However, it is still a debate regarding the importance of the few tasks that the humans may have and how that will affect safety analysis. Another question is whether tasks related to continuation of operation, efficiency of the plant, and ease of start up operations, or purely economic consequences may in the end affect safety in a way that is not covered by the traditional safety analysis of the immediate safety actions.

2.2.3. Digital Control Rooms

In the last few decades many conventional plants have become fully or partly digitized. Most have focused on digitizing only the turbine side because of the safety implication and the difficulty of digitizing the primary side. Lessons have been learnt about how the partly digitized control rooms affect human performance. However, fully digitized control rooms are still a new concept that have only been implemented in recent new builds.

2.2.4. Highly Automated Controls and passive safety systems

Automation in nuclear power plants is not new and have been applied in a controlled way in several systems within conventional nuclear power plants. However, they have been mostly for activation of safety systems e.g., reactor protection systems (RPS) and emergency core cooling systems (ECCS). They have also been used for turbine control systems, fuel handling systems, and process control e.g., steam generator level control and feedwater control. The concern for automation in the advanced reactors is regarding the level of autonomy that the automated systems will have. The new advanced reactors may apply high level of automation for control functions. It is also a question whether higher levels of automation and passive safety systems will have completely different effects for the operators. In some cases, the operators may see them as a similar phenomenon.

2.2.5. Computer-based Procedures

Computer-based procedures (CBP) have come to stay, so it is a predictable feature of new advanced reactors. They bring so much additional capabilities to main control room (MCR) operator functions that they have become widely accepted. Some of the advantages they bring include automated place-keeping, embedded soft controls, integration (sometimes with links) with relevant plant indications [IEEE, 2022], guided flow map from step to step, included pop-up functions that force acknowledgement of warnings before moving along in the procedure, and many more. The advanced reactors may include new functions for the CBP.

2.2.6. Monitoring Role

With the higher level of automation comes more restriction of the operator role to monitoring only. It is one of the major claims of the new advanced reactor vendors that the systems will be mostly autonomous, requiring little or no human intervention, thereby limiting the operator to supervisory functions, and 'minimizing' the potential human errors. However, typically, operators want to 'operate' a plant and avoid idling. Frustration can be the result, and it is possible that the potential for category-B human errors may be increased.

2.2.7. Individual Operation

As the new advanced plants promise to be simpler to operate, there is a chance that the staffing plans might include one operator being responsible for each reactor (module) or multiple reactors rather than the full complement of a crew working as a team. This will influence HRA especially in the way analyst treat peer-checking and recovery.

2.2.8. Communication Style

The communication strategy in the generation III+ plants which use computerized procedures is already different from those that use paper-based procedures. As observed by (Hildebrandt & McDonald, 2020), there is a lot less (approx. 42%) three-way communication going on among the crew in plants that use computerized procedures. This is because the 'reader-doer' style of going through the procedure no longer holds, as the operator does both reading and acting on the CBPs from his/her desktop. The operator also does place-keeping and can access the procedure step logics. In most of such plants, the Shift Supervisor can do peer-checking via a mirrored function of the CBP and those process pages with operator mouse clicks. Thus, effectively performing some of the supervisory functions without communication. This trend is expected to continue in the new advanced reactors. The communication style is also expected to move to a more digitized format (Boring, 2023) i.e., communication between the MCR and the local operators moves from simply audio calls to digital calls (audio and video) and text in shared computer programs as handover notes between operating crews or for other purposes.

3. POTENTIAL CHANGE NEEDS OF HRA FOR SAFETY ASSESSMENTS

3.1. Merger of HRA and Human Factors Engineering

The HRA and human factors engineering practices already have a lot of overlap. Merging and applying principles from both fields can prove beneficial to save time, effort, and allow more accurate analysis. An example of how this can be done is shown in (Taylor, 2017). This has a framework including preliminary task and error analysis, HF engineering program (design), human reliability analysis (fault analysis), safety case operations chapter, and HF verification and validation. Some inputs in the framework include concept design, operating procedures, operating experience reports, task observation, and HAZOP. Some of the results of the framework include HF recommendations, updated HF issues register, updated HF supporting references, and a closed-out HF issues register. Moreso, technology should not be assessed alone and "previous HAMMLAB (Halden Man-Machine Laboratory) studies have shown that it is the combination of the new technology and how it is used by the crew that defines the overall performance of the system" (Bye, 2023). This has implications for both the human factors engineering validation and the predictive analysis from HRA.

3.2. Incorporating Advances in Cognitive Psychology and Human Factors Research

To maintain relevance, continuous improvement in HRA methods or development of new methods is necessary. Rasmussen (Rasmussen, 1985) noted that the integration of cognitive models into HRA improved the assessment of human error probability by considering the psychological feasibility of improvements in work safety. In addition, the use of cognitive psychology in HRA has highlighted the importance of understanding the complex processes of human cognition, including attention, perception, memory, language, and decision-making. Such developments have been supported by extensive literature reviews, like the one conducted by the U.S. Nuclear Regulatory Commission, which synthesized human cognition research into a technical basis for HRA (Whaley, et al., 2016). This was used as the basis when NRC created a generic HRA approach in IDHEAS-G (Xing, et al., 2021), and on that, a specific HRA method (Xing, et al., 2022). Although a lot of HRA methods already exist, the current 'nuclear renaissance' is an opportunity to infuse recent advances in our understanding of human cognition, decision making, and behavior into our HRA approach.

3.3 Application of HRA methods for higher levels of automation and passive safety systems

One of the prominent changes in new advanced reactors is the introduction of passive safety systems and higher levels of automation. What will be the most important characteristics of HRA methods, new or old, that can be used for these applications? Even in highly automated systems the operator will have a role to play. As described in other places in this paper, the prediction is that this role will be more that of a monitoring role, not as action oriented as earlier. Is the human in the future going to be monitoring the automation system and perform control actions when automation does not work?

Independent of the exact detail of the operator task, one must be able to analyze the task to such a detail that it is relevant for the actual collaboration between the operator and the automatic system. As underlined in (Bye, et al., 2022), understanding the operating challenges is key to HRA. This will be even more important in the future with more automation, since many assumptions will be put on the table claiming that human actions are not important.

Are there certain types of HRA methods that will be better suited for analysis of human-automation collaboration than others? To understand this collaboration, the whole system should be treated as a Joint Cognitive System (Hollnagel & Woods, 2005)). To do that, the analysis should be based on a good understanding of the human role. This can be done if the HRA method is based on a proper model of human cognition. Most HRA methods are based in some way on such models. However, some are more systematic than others. A good example is the IDHEAS-ECA (Xing, et al., 2022) which uses a set of macro-cognitive functions as basis for detailing tasks and PSFs on these and then to quantify human error probabilities. These kinds of methods may be able to describe the relation between the humans and the automation in such a way and detail that the outcome can be quantified. The reason for this claim is that the human is put in the center of the analysis, not the automation or the technical assumptions. See a more detailed discussion on this in (Bye, (2024, in press).

3.4. Defining Useful HRA Data while Delineating Re-usable and Specialized Data Points

Many new methods are based on data. The SACADA database (Chang, et al., 2014) is a good example of a database that is based on training data and used for feeding IDHEAS-ECA with data. For any such link, it is important that the data is valid for the dimensions that they are used for in the HRA method. That is, the generalizability of the data is key, and that can be achieved by ensuring that the data is characterized by the same dimensions as the needed input to the HRA method. Old data will probably in some way be relevant for new plants. The big question is whether the data describes the same tasks. If the tasks are similar in the new plant as in the old one where the data comes from, it is a good chance that they are relevant. However, the way in which they are used is important and should be scrutinized, so data and methods are not wrongly applied.

3.5. Consideration of Potential HFEs in Maintenance Activities and New Job Demands

Maintenance activities have always been within the scope of HRA, but such activities will become even more important for advanced reactors. The advanced reactors will likely depend on the passive systems that must come into function when needed. However, as is typical with any system, it would inevitably need maintenance (in one form or the other). The maintenance activities for the passive systems and related Systems, structures, and components (SCCs) become safety significant. Thus, the passive system job demands in advanced reactors would need to be given due attention by HRA analyst.

Another important thing is maintenance that might leave latent errors in the system, which then are handled by automatic systems. As catastrophically seen in the Boeing Max8 accidents (Seyer & Londner, 2020), the automation algorithm worked well but the input was flawed due to an erroneous instrument. This created an output from the automatic system that caused a disaster. This might be the biggest challenge with more automation: The system is given wrong input that was not assumed by the designer of the automation system. The possibility for an operator who is monitoring the automation to detect such flaws and to do something about it will be key. HRA methods need to be able to analyze this. Thus, the importance of pre-initiators will be more important. This is a challenge since the nature of such tasks are more open and not so confined as post-initiator mitigation tasks (category-C human actions). The category-C human actions are confined by the Emergency Operating Procedures, but above all by the safety systems at hand. Thus, new developments of new HRA methods for pre-initiators (category-B errors) is needed.

3.6. Consideration of Organizational and Cultural Factors in HRA

Expanding HRA frameworks to incorporate organizational and cultural influences on human performance was suggested by (Reason, 1997). (ibid) argued that conducting organizational assessments to identify factors influencing human reliability is imperative. The new advanced reactors will potentially present significant changes to the concept of operations for nuclear power plants as we know it today. As described above about automation, such changes in the way of working and the roles of the crews may also lead to considerable changes in the safety relevance of such changes. The question is whether such organizational changes will have an impact on safety on the sharp-end, and how. It may be important to grasp the way in which such influences will affect safety.

3.7. Early Application of HRA in the Design Stages

Most of the current HRA methods were applied to as-built nuclear power plants but there is a strong argument that HRA should be done at the early stages of the design phases of nuclear power plants. This can be a good source of eliminating many potential human failure events in advanced reactors. For example, (Taylor, 2017) argues, “HRA can also assist with the assessment of different design options by providing a quantitative judgement of the human contribution to risk from the different designs. This information can support risk-informed decision making about which design option to go for.”

3.8. HRA Training and Competence Development

According to the International Atomic Energy Agency (IAEA, 2019), providing specialized training for analysts conducting HRA in the context of Advanced Reactor safety will foster interdisciplinary collaboration between nuclear engineers, psychologists, and human factors specialists. In a related perspective, Boring (Boring, 2023) discusses the ways to catch up and facilitate such training including the support of university education “to build a pipeline of human factors practitioners in nuclear energy”.

4. DISCUSSION

This paper has identified some characteristics of advanced reactors differentiating them from conventional reactors and thus posing new challenges for HRA. To apply human-centered and technology-neutral HRA methods effectively, analysts must first identify the cognitive functions and performance shaping factors (PSFs) relevant to the unique characteristics of advanced reactors. Section 2.2 of this paper outlines the specific features of advanced reactors that present challenges for HRA. A key aspect in determining whether an HRA method is suitable for advanced reactor applications is its ability to incorporate the appropriate cognitive types and PSFs to evaluate how these reactor characteristics impact human reliability. For instance, as discussed in Section 2.2.1, one such characteristic is multi-unit control, where operators must manage multiple reactor modules simultaneously. This scenario introduces the challenge of multi-tasking, where operators interact with several modules within the same timeframe. A human reliability concern in this context is the increased likelihood of memory recall errors during task switching—such as confusing which module is being interacted with. The effectiveness of an HRA method in addressing multi-unit control hinges on its capacity to account for the impacts of multi-tasking through corresponding PSFs and an adequate data foundation.

Interestingly, related to the specific example above was a recent report (Blackett et-al, 2023) that opined that unit confusion was rarely seen in an experimental facility that mimicked a six-module SMR control room. Even when found, they were easily dealt with, and future occurrence was reduced with measures to physically discriminate the modules. Although they were preliminary results, they provide early directions for HRA of the advanced reactors and what data may eventually confirm. Again, this shows the importance of the co-ordination of human factors and HRA efforts.

5. CONCLUSION AND FUTURE WORK

This paper has outlined recommendations for enhancing HRA in advanced reactor safety assessments. While not exhaustive, this work aims to stimulate further discussion and re-examination of the potentials of HRA methods. This also contributes to laying the groundwork for effectively addressing human reliability aspects in the safety analysis of advanced reactors. Providing evidence for the claims of no operator action may be a key role of future HRA. Thus, including the qualitative task analysis in future HRA will be as important as it is today.

The HRA activity in the Human-Technology-Organization (HTO) Project (2024-2026) will conduct stakeholder surveys to address key questions, including: Will PSA/PRA continue to rely on claims about operator actions as they do for conventional NPPs? Are there new human error modes unique to advanced reactor operations? Are there new scenario types exclusive to advanced reactor operations, such as those related to passive safety systems or human-automation interaction? The survey responses, including assumptions, will inform empirical studies within the Program.

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