Challenges for Human Reliability Analysis in New Nuclear Power Plant Designs

Andreas Bye[a], Jeffrey A. Julius[b], and Ronald Boring[c]
[a] IFE, OECD NEA Halden HTO Project, Halden, Norway, Andreas.Bye@ife.no
[b] Jensen Hughes, Seattle, USA, jjulius@jensenhughes.com
[c] Idaho National Laboratory, Idaho Falls, USA, ronald.boring@inl.gov

---

Abstract: Digital instrumentation and control systems are being added to operating nuclear power plants (NPPs) and included in the designs of the next generation of NPPs. Further, the newer advanced reactors are not only incorporating digital systems, but they are also increasing the amount of automation to improve plant safety and to decrease the reliance on human operators. In each of these cases, advancements in system design such as instrumentation, controls, automation, and data collection have significantly altered the human-machine interface. Human factors insights related to tasks, procedures, training, and allocation of functions help to improve safety and reliability. Operating experience with NPPs and other systems tells us that in addition to improvements, the design is not guaranteed to be free from errors. In order to evaluate the effectiveness of these improvements in the digital instrumentation and control systems, a human reliability analysis (HRA) as part of a risk assessment can provide insights into what is likely to go wrong and the consequences of errors. For the first generation of power plants in the USA, the risk assessment and HRA were developed after the plants were built and operating. In order to further improve the safety and reliability of new plants, an approach that combines these two disciplines during the design and pre-operational phase is recommended. This paper outlines the concept for this approach, discusses advantages and potential disadvantages of digital instrumentation, controls, automation, and data collection systems, and recommends a technology neutral approach to applying human factors and HRA techniques to improve NPP safety and reliability. A number of challenges in todays' human factors and HRA processes and methods are discussed, and also the way in which these challenges might change in future new designs.

---

1. INTRODUCTION

New nuclear power plants (NPPs) are being built, and existing power plants are being upgraded. The new control rooms are equipped with digital instrumentation and control (I&C), either as complement to existing analog back-up safety systems, or as a complete system for the new plants. These kinds of digital control rooms are in some ways operated similarly to the old analog control rooms, but in many ways, they change the way operators in the control rooms interact with the technology. This new technology also impacts the way the operating crew can and should work together. This again raises new challenges for the risk assessment of the new plants. Especially when analyzing the human contribution to safety, new digital I&C raises new challenges that must be taken into consideration.

1.1. Challenges Associated with Digital Control Rooms

There are many new challenges in modern control rooms, and in a literature review done for EDF Energy Generation Limited (ENGL), Wright and Bye [1] identified three main areas: Automation; implementation and navigation of advanced human-system interfaces (HSIs); and operating procedures. While each of these areas intends to promote overall system reliability and safety, these areas also can create potential challenges for operators. Potential higher degrees of automation have been discussed in a number of papers, and challenges such as reduced situation awareness (SA) [2,3], overreliance on automation [4] and automation transparency [5] are identified as central. Wright and Bye [1] states:

> *"Where conventional control rooms primarily utilize automation to assist with information gathering and execution type functions, newer digital systems may now incorporate automated functions for cognitive action stages such as information processing and decision making, which were previously undertaken by human operators. When coupled with the typical requirement for operators to provide manual back-up to a fully automated function, this issue becomes significant in terms of human reliability."*

Poorly implemented digital HSIs were pointed to early on as causing higher workload and increase in interface management tasks, which are secondary tasks in the monitoring of NPPs [6]. Another challenge is that degradation of instrumentation, should that happen, is a major challenge for operators in a control room [7]. This challenge may or may not be less in digital control rooms [8], although this depends on the implementation of the digital solutions.

Computerized procedures can be viewed as a combination of the two earlier challenges [9]. One may implement a varying degree of automation in the procedures, leaving more or less authority and practical control to the operators. Also, the way in which they are implemented makes their HSI important, to ensure a good interaction with the human operator.

1.2. Challenges Associated with New Designs and Small Modular Reactors (SMRs)

Obviously, there is less operating experience for new power plant designs that are proposed. Especially, the designs for microreactors and small modular reactors (SMRs) propose rather new concepts of operation and new roles for the operators, justified by more inherent safety features and also caused by the need to control several units from one control room without increasing the work force compared to the conventional plants. This means more units to control for one operating crew; however, the number of people surveying the total energy production is somewhat the same. Blackett et al. [10] outline a number of challenges in assessing human reliability in such First-of-a-Kind (FOAK) technologies. Blackett et al. propose simulator studies as a good alternative to operating experience in new designs. This would require that the studies are implemented in a way that is representative for the new solutions. The concrete challenges in SMRs are outlined in [11] and typical examples are multi-unit confusion and staffing strategies.

1.3. Challenges Associated with Safety Analysis

There are a number of aspects relevant for analyzing the safety in new designs. The first challenge is that the methods and scope of the Safety Analysis may or may not be the same as for the currently operating fleet of light-water reactors. Several of the new, advanced reactors consist of sufficiently different types of coolant, types of systems, and physics of operations that the Safety Analyses may be different. For example, in the United States, NEI 18-04 proposes a framework for incorporation of risk information for advanced reactors [12]. The NEI 18-04 framework is under discussion with the US Nuclear Regulatory Commission in conjunction with Part 53 (10 CFR Part 53, "Licensing and Regulation of Advanced Nuclear Reactors").

Incorporating digital systems into the currently operating fleet of light-water reactors will continue to rely on existing Safety Analysis requirements. One question associated with the current Safety Analysis is which HRA method to be applied, and for which type of assessment (e.g. a deterministic or a risk assessment) is it valid and can be used? Is the method valid for use with digital instrumentation and controls when it has been developed and used many years with analog controls? What type of scenarios and human action is it good for? What about the human reliability analyst knowledge? Is it applicable without operational experience for the new designs? Given these issues, how does the analyst treat these sources of uncertainty?

What is the nature of analyzing events in FOAK designs? For some solutions, there are few analytical and few operating or emergency procedures established, and few agreed upon standard scenarios that can be used as a basis. This gives the field some resemblance to other situations with much uncertainty, namely beyond design basis events. Also in these situations, there is more uncertainty than for the existing fleet, where we have nearly 50-years of operating experience. There may be guidelines developed, but decision making by the operating crew must be made with less support than in standard events supported by Emergency Operating Procedures (EOPs). Thus, similar analysis methods might be applied, and considerations need to be developed to understand the significance of these uncertainties such as leaning too much against adherence to procedures should not be used.

2. CHALLENGES ASSOCIATED WITH HRA

2.1. Understanding the Operating Challenges

In a situation without a full set of procedures to support decision making, a number of challenges occur for the HRA practitioner. Some of these are related to the qualitative analysis and are mostly independent of the quantification method that is used. In many new HRA methods the qualitative analysis is now part of the method itself, and the question is whether a method with built-in structure and guidance for qualitative analysis supports the kind of detailed analysis necessary.

The analyst needs to know what it is in the emergency scenario that makes things complicated and complex for the crew. This is necessary to understand what is happening and what kinds of mitigation actions are possible. In the “International HRA Empirical Study” [13], involving scenario analysis by multiple HRA teams, there were several examples where the analysis and the human error probability (HEP) were too optimistic, since the analysts did not manage to map complex scenarios realistically to actual operator performance. One example was a Steam Generator Tube Rupture (SGTR) scenario where there were no radiation indications in the secondary circuit [14]. The radiation indications were masked by a concurrent steamline break and failed radiation sensors in the secondary circuit. All the HRA teams who did not go into the specific procedure steps that the operators used when analyzing the situation failed to estimate the correct HEP. For example, one HRA team stated that the procedures were adequate since they were industry standard. However, they would need to dive into the way in which the actual procedure steps would lead the crew in the course of the scenario to understand that delays in entering the SGTR identification and isolation procedure were likely.

For the analysts to understand the operating difficulties for the crews, one tool is central, and that is task analysis (TA). However, the challenge is to decide how deep a task analysis should go in an HRA. In Mosleh and Ekanem’s work on the new HRA method Phoenix, they have some concrete advice on this [15, p. 304]:

> *“There are no hard and fast rules on where to stop task parsing. However, we are providing some guidelines on which the analyst could base his or her decision. The level of task decomposition required for task analysis can be based on: (a) the level of detail required in the PRA model, (b) the resources available for modeling and conducting the analysis, (c) the HRA requirements and purpose of the analysis, (d) the amount and type of information available, and (e) the success criteria for achieving the safety function.”*

Point e) above is of particular interest. The critical actions for the operators are linked to the safety functions. For an operating plant, specific steps in the procedures fulfil the safety functions. By analyzing the safety functions together with the details of the procedures, the analyst can understand the way in which difficulties for operators may reveal themselves. What then with a new design for which detailed procedures are not available? This resembles the situation with beyond design basis events (BDBEs) in operating plants. These are situations not fully covered by procedures and as such have the same challenges. Several scenario progressions might be likely and should be analyzed. As Blackett et al. [10] point out, several experiments have been performed in the Halden Human-Machine Laboratory that might provide useful information to these kinds of situations, since these experiments often combine initiating events, which make the choice of the correct procedure difficult for the operating crew, and sometimes also not achievable by strictly adhering to the procedures. These simulated scenarios are in practice BDBEs, even though they operate in the EOP space.

This also relates to the way the TA is used in HRA methods. Does the HRA method require a detailed "operator event tree"? This may lead to other challenges, such as the way in which the quantification is done. Is it done for every analyzed task? Can all those HEPs be summed up without getting an unrealistically high HEP?

A related issue is the method used in the qualitative analysis when crews are interviewed, in order to reveal the difficulties and details of the complexity for the crews. Most methods use expert elicitation in some way; however there may be a large variance in the guidance and also in the required or recommended ways to do this. Some data collection routines would ask experts (instructors or operators) whether they would be able to solve challenges. However, it is important to find out how they solve the challenges, and whether they really are able to. Thus, a detailed walk-through/talk-through is often necessary. In the "U.S. HRA Empirical study" [16] some human reliability analysts asked experts (they were instructors and senior reactor operators) about their opinion only, and it turned out that this was not enough for some of the time critical actions. The scenario was a time critical one, and only the analysts who performed a detailed walk-through with the experts managed to reveal that the available time was not sufficient in order to manage the required actions in time.

In addition to the above, this question of understanding the situation for the operators is also linked to the method itself, e.g., the granularity of the performing shaping factors (PSFs) in the method. If the method has guidance that forces the analyst to dive into details, e.g., in order to decide the applicable multiplier for a PSF in the given situation, that will drive better results. This might be done by extensive examples in the guidance and good descriptions of anchor points. On the contrary, a method may give the analyst the opportunity to do a shallow analysis if the guidance is weak. The ability of a method to zoom in on what the factors mean in operational terms is important in order to give feedback with concrete advice to designers.

2.2. Analyzing Scenarios without Procedures

In an early phase of new designs, procedures for accident situations may not be developed. As noted, most HRAs rely heavily on the procedures in order to model human tasks. Early HRA methods focus on so called errors of omission (EOO), and typically analyze the way in which operators may fail by omitting the appropriate procedure steps. However, if procedures are not yet available, this will not be possible. As mentioned above, this situation is similar to the situation in BDBEs, since in those situations the existing procedures might not fit.

Probabilistic risk assessment (PRA) and HRA are normally based on modelling event sequences, even though extensive use of fault trees instead of event trees may give another impression. Scenarios form a central part of PRA and HRA. A relevant argument for sticking to a scenario-based modelling of post-initiating event actions is that after an initiating event has occurred, a plant, whether new or old, will have designed safety functions in order to handle the event. One may then model the failure of functions and actions implemented by the safety systems in the plant. These safety functions will typically be of sequential nature and thus be possible to model in a scenario or event tree. If you need to cool the core, you have a certain number of systems at your disposal, and a possible timing for when they can and should be taken into use. This can also be input to the design of the procedures later on.

A similar concern in early design phases is if HSIs or other parts of the control room are not available. These can similarly be anticipated based on the basic design of the plant and its safety systems or basic thermo-hydraulic qualities. Some lessons learned can be drawn from old plants as well. A case in point is that in work on training for the unexpected, Skjerve and Holmgren [17] pointed to the need for improving training of the basic knowledge of the physical properties and behavior of the plant instead of more scenario-based and procedure-based training in severe accident situations where the procedures do not necessarily fit. This argument will also be valid for an HRA of a new design which is not finished.

2.3. Orthogonality in Performance Shaping Factors

Many HRA methods strive to enable assessment of the error-driving context for the operators in such a way that one risk-contributing factor is only accounted for once. If a phenomenon contributing to risk is double counted, the error probability will be too conservative. Many PSF-based HRA methods try to avoid this by defining the PSFs to be orthogonal. However, this is not easy to accomplish. For example, a non-optimal HSI may be accounted for in a factor called complexity. Or, non-optimal procedures can be mitigated by good training, as training can be a remedy for most non-optimal designs in the control room. It may be extremely difficult to define all PSFs to be orthogonal, since the definitions of the various factors will be dependent on many details in various dynamic situations and scenarios. Additionally, some PSFs have contextually sensitive definition, meaning even when orthogonality is achieved, PSFs may still fail to be orthogonal for all situations. Thus, this must eventually be up to the analyst, and the analyst must be aware of these issues, make sure and document that s/he counts each performance phenomenon only once in the analysis at hand.

In human factors engineering (HFE), this is maybe not a critical point. If an HRA method is used predictively in an early design phase and the results are fed back into HFE, it could actually be an advantage if a weak design point was addressed from two different angles, originating from the analysis of two different PSFs. The problem only arises when doing quantification (also in the design). If double counting is done, one may address the wrong error reduction issues since they are incorrectly given too high risk importance, potentially resulting in fixing the wrong problem first.

2.4. Error Taxonomies for Digital I&C in Modern Control Rooms

A set of new challenges arise in new computerized control rooms, as pointed out above, especially within the areas of automation, HSIs, and operating procedures. The question is whether existing HRA methods that were made for old analog control rooms can be applied to the new ones. This is very much linked to the question whether the old method covers the error mechanisms in the new control rooms. Are there new error mechanisms related to higher degrees of automation, modern HSIs and computerized procedures?

In a study for ENGL, Wright and Bye [1] studied the applicability of HRA methods for modern control systems, and questioned whether a new error taxonomy is needed for new digital I&C. For some error taxonomies used in some existing methods, the conclusion was that there are a few things that need to be included to cover computerized procedure systems and higher degrees of automation. However, if the general error taxonomy used in the HRA method is based on cognitive mechanisms, it will also cover digital I&C. For example, the error taxonomy as used in the new HRA method IDHEAS-ECA [18] is based on cognitive failure modes (CFMs), and these are the same regardless whether the external context for the operators is created by digital or analog control rooms.

One emerging challenge to digital control rooms is the opportunity for cyber attacks, which introduce a new modality of faults to the plant. Cyber attacks are malicious attempts to sabotage cyberphysical systems, and they can result in misaligned performance by operators, especially when the attacks involve spoofing of required indicators or denial of service to required controls. The types of human errors that result from deliberate obfuscation of critical information or barriers to operator completing actions are not currently well understood in HRA [19] but may represent the need to reevaluate taxonomies to account for operational challenges due to external cyber events.

2.5. Crew Roles and Teamwork

New digital I&C may introduce challenges in itself. However, more importantly is how the technology is used by the operator and the crew, and how it leads to and accompanies changes in crew roles and teamwork. Bye [20] discusses this based on a series of experiments in the simulator laboratory at the Halden Project and the main message is that "*New technology, unless underlying a fully autonomous system, cannot be evaluated stand-alone".* The reason is that the interplay between the technology and the use of the technology, e.g., computerized procedures and the way in which they are used, is too entangled to analyze each part separately.

The crew roles and teamwork are also related directly to the recovery and dependency issues in HRA, regardless of the technology used. For example, recovery may be credited in a safety analysis if good work practices are in place, such as the use of a second checker, or the degree of independence of a shift technical advisor (STA). Routines for briefing and decision making meetings are also important for recovery as well as for dependency assessments [20].

Crew roles, teamwork and work practices can be trained. Thus, these aspects of nuclear safety are very relevant for operating nuclear power plants. Also for HRA practitioners, it is important to get an overview of the training of these aspects and how they are interlinked with the technology used in the control room. Only then it is possible to know the impact of the training on human performance and hence human reliability. Also, knowing the way in which this is trained will enable the HRA practitioner to know the interaction with other factors, such as complexity, in order to count a risk phenomenon only once and avoid double counting.

2.6. The Need for Data

The effects of new digital I&C and new crew roles and teamwork need more data and knowledge. There are a number of unexplored issues regarding the details of the challenges mentioned above. Simulated laboratory studies may explore most of these issues before final solutions are implemented in real plants. A recent review led by Electric Power Research Institute (EPRI), for example, explored the applicability of using HFE studies on digital control rooms as a source of data to inform HRA for digital systems [21]. Additionally, recent led by Idaho National Laboratory have explored the ability to use microworld simulators to collect HRA data [22]. The idea is to use a simplified simulator that is easy enough to use non-professional operators like students [23]. The question of how much results from less experienced operators can be generalized for HRA purposes is currently being explored [24].

2.7. New Challenges Beyond Post-Initiating Event Actions

Using postulated accident scenarios makes sense for assessing human actions that occur after initiating events (e.g., post-initiating events). These kinds of human actions are defined as Type C human actions in PRA [25]. Type A human failure events are the ones that are performed during routine test and maintenance that may lead to latent (unrevealed) failures of systems or components due to misalignment or miscalibration. Type B events are operator actions that lead to initiating events [25]. Digital systems such as instrumentation, controls, computer-based procedures, and automation introduce opportunities for new types of Type A and Type B events. Because digital systems provide additional flexibility in the configuration of the systems, this also introduces new challenges in the identification of Type A and Type B actions that may be risk significant.

Methods for identifying and handling Type A and B events are underexplored. What type of methods are needed when digital systems are introduced? Currently, maintenance activities are typically modeled regarding the availability of the system (or train of a system) so they go into the fault tree supporting event tree quantification. However, maintenance activities from isolation, to maintenance, to restoration, to post-maintenance test can also be modeled in which digital systems with soft controls and indications complement or replace hard systems. Such evaluation of the Type A events could be used in a more direct way as input to system models in the PRA, and as inputs to PSFs of potentially impacted Type C events in the HRA.

3. INTEGRATION OF HUMAN FACTORS ENGINEERING AND HRA

3.1. Quantification of HRA to Complement HFE

For existing plants with a history of sustained operations, a detailed HRA can be performed based on detailed insights and information about the already built plant, regardless of whether they have an analog or digital I&C and control room. Such a detailed assessment including an error reduction strategy is then used in the risk-informed strategy of the plants in order to prioritize which items to fix first.

An argument for applying a quantification methodology over conventional HFE approaches is that it forces the analysis down to an extent of detail that enables quantification. It is thus not so easy to do a shallow analysis. If outliers or unrealistic HEPs are revealed, the analysts must typically revisit the analysis and document and justify details supporting the quantitative findings. This might be a problem in early phases of the design as input to HFE, since not all details are in place yet. However, what one may do is document detailed assumptions and also analyze different cases with different assumptions, in order to make practical safety cases on which design choices can be made. This can be of high importance to the final design, especially when it comes to important choices about the level of automation and the function allocation between the humans and the digital I&C. It may even be the most important analysis in the current era of ever-increasing possibilities in advanced technical systems resulting in higher degrees of automation.

3.2. Integrating HFE and HRA during Plant Modifications

For existing plants that are modifying the plant such as to add digital I&C, a combination of HFE and HRA can be performed to ensure that the benefits of each type of analysis are realized. EPRI has developed, and is in the process of applying, an approach called Hazards and Consequence Analysis for Digital Systems (HAZCADS) that uses HRA insights to complement HFE [26]. HAZCADS combines elements of Systems-Theoretic Process Analysis (STPA) with fault tree analysis to identify risks in digital systems.

3.3. Integrating HRA with HFE during Design

For new plants that are developing a whole new set of safety systems that include I&C, and computer-based procedures, a combination of HFE and HRA similar to the HAZCADS approach can be performed to ensure that risk-significant cases or scenarios (typically beyond design basis events) are identified along with the associated operator actions. Then, the HRA and HFE analyses can be used for error reduction and/or risk mitigation, including the evaluation of uncertainties.

4. CONCLUSION

In this paper we have pinpointed a set of challenges for future HRA for new designs including digital I&C and possibly higher levels of automation. HRA may be a very important tool as input to HFE in order to avoid non-analyzed technical solutions and automation levels that will put the operators and crews in difficult situations when the automation is outside its defined scope of design. In addition, empirical testing of new solutions is important. HRA can be a first analysis tool before solutions are tested in simulator environments. Additionally, HRA can be used to complement HFE for changes to existing designs and also for new designs of advanced reactors. These analytical approaches can help ensure the operator actions in the safety case are reliable, and that operator actions for beyond design basis and to address uncertainty are also reliable.

The challenges of HRA are not completely solved by current HRA tools. As highlighted in this paper, there are still many gaps, but adaptations of current methods and introduction of new methods are helping to ensure HRA adequately addresses design issues and ensures safe operations with new control technologies. These new challenges are bringing about a stronger convergence of HFE and HRA than in the past [26], and it is clear that both qualitative aspects of HRA to inform design and quantitative aspects of HRA to prioritize risk are needed to support new nuclear power plants.

Acknowledgements

Funding: This work was supported by the OECD Nuclear Energy Agency (NEA) Halden Human-Technology-Organization (HTO) Project. Thanks to the members of the Programme Review Group of the Halden HTO Project for review and constructive comments. Additional work was sponsored by Idaho National Laboratory (under Contract DE- AC07-05ID14517), an agency of the U.S. Government.

References

[1] A. Wright and A. Bye. "*Do Modern Control Rooms Pertain New Error Mechanisms?*", Proceedings of the 32nd European Safety and Reliability Conference, ESREL-2022, (in press, 2022).

[2] L. Onnasch, C.D. Wickens, H. Li, and D. Manzey, "*Human performance consequences of stages and levels of automation: An integrated meta-analysis.*" Human factors, 56(3), 476-488, (2014).

[3] C.J. Lin, T.C. Yenn, and C.W. Yang, "*Automation design in advanced control rooms of the modernized nuclear power plants*". Safety science, 48(1), 63-71, (2010).

[4] T.B. Sheridan, and R. Parasuraman, "*Human-automation interaction*". Reviews of human factors and ergonomics, 1(1), 89-129, (2005).

[5] G. Skraaning Jr, and G.A. Jamieson, "*Twenty years of HRP research on Human-Automation Interaction: Insights on Automation Transparency and Levels of Automation*". HPR-387. OECD Halden Reactor Project, (2017).

[6] O'Hara, J. M., Brown, W.S., Lewis, P.M., Persensky, J.J. (2002). Human-System Interface Design Review Guidelines. NUREG-0700 Rev. 2. US Nuclear Regulatory Commission, Washington, DC.

[7] Nystad, E., Kaarstad, M., McDonald, R. (2019). Crew Decision-making in Situations with Degraded Information. In Proceedings of ESREL 2019, Hannover.

[8] O'Hara J., Gunther, W. and Martinez-Guridi, G., (2010) The Effects of Degraded Digital Instrumentation and Control Systems on Human-system Interfaces and Operator Performance (BNL Tech Report No. 91047-2010). Upton, NY: Brookhaven National Laboratory.

[9] Boring, RL, and DI Gertman, "Considerations for the Treatment of Computerized Procedures in Human Reliability Analysis," 8th International Topical Meeting on Nuclear Power Plant Instrumentation, Control, and Human-Machine Interface Technologies (NPIC&HMIT), pp. 1476-1487 (2012).

[10] C. Blackett, M.H.R. Eitrheim and A. Bye, "*The Challenge of Assessing Human Performance and Human Reliability for First-of-a-Kind Technologies".* Probabilistic Safety Assessment and Management PSAM 16, June 26 – July 1, Honolulu, Hawaii, (*In press*, 2022).

[11] C. Blackett, M.H.R. Eitrheim, R. McDonald and M. Bloch, *"Human Performance in Operation of Small Modular Reactors"*, Probabilistic Safety Assessment and Management PSAM 16, June 26 – July 1, Honolulu, Hawaii, (*In press*, 2022).

[12] NEI technical report, (2019). *"Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development".* NEI 2019.

[13] Forester, J., Dang, V.N., Bye, A., Lois, E., Massaiu, S., Broberg, H., Braarud, P.Ø., Boring, R., Männistö, I., Liao, H., Julius, J., Parry, G., Nelson, P. (2014). The International HRA Empirical Study – Final Report – Lessons Learned from Comparing HRA Methods Predictions to HAMMLAB Simulator Data. NUREG-2127, U.S. Nuclear Regulatory Commission, Washington D.C.

[14] Bye, A., Lois, E., Dang, V.N., Parry, G., Forester, J., Massaiu, S., Boring, R., Braarud, P.Ø., Broberg, H., Julius, J., Männistö, I., Nelson, P. (2010). The International HRA Empirical Study – Phase 2 Report – Results From Comparing HRA Methods Predictions to HAMMLAB Simulator Data on SGTR Scenarios. HWR-915; NUREG/IA-0216, Vol. 2, U.S. Nuclear Regulatory Commission, Washington D.C.

[15] Ekanem, N.J., Mosleh, A., Shen, S.H. (2016). Phoenix – A model-based Human Reliabiltiy Analysis methodology: Qualitative Analysis Procedure. Reliability Engineering and System Safety 145 (2016) 301-315.

[16] Forester, J., Liao, H., Dang, V.N., Bye, A.. Lois, E., Presley, M., Marble, J., Nowell, R., Broberg, H., Hildebrandt, M., Hallbert, B., Morgan, T. (2016). The U.S. HRA Empirical Study – Assessment of HRA Method Predictions against Operating Crew Performance on a U.S. Nuclear Power Plant Simulator. NUREG-2156, U.S. Nuclear Regulatory Commission, Washington D.C.

[17] A.B. Skjerve and L. Holmgren, "*Towards an Approach for Training Nuclear Power Plant Operators to Handle Unforeseen Events – Second Study".* HWR-1280, OECD Halden Reactor Project (2020).

[18] Xing, J., Y. J. Chang, and J. DeJesus, "Integrated Human Event Analysis System for Event and Condition Assessment (IDHEAS-ECA)," U.S. Nuclear Regulatory Commission, RIL-2020-02 (ADAMS Accession No. ML20016A481), Feb. 2020.

[19] Boring, RL, Ulrich, TA, Medema, HM, and R Lew, "Operator Resilience to Cyber Interdictions in Nuclear Power Plants," Proceedings of IEEE Resilience Week 2019, pp. 247-251 (2019).

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

[21] Presley, M, Boring, R, Ulrich, T, Medema, H, Mohon, J, Delvecchio, M, Massaiu, S, Bye, A, Park, J, Kim, Y, and J Julius, "A Taxonomy and Meta-Analysis for Combining Disparate Data to Understand the Effect of Digital Environments on Human Reliability," Proceedings of the 2021 International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2021), 2021, pp. 1033-1042.

[22] Park, J, Boring, RL, Ulrich, TA, Lew, R, Lee, S, Park, B, and J Kim, "A Framework to Collect Human Reliability Analysis Data for Nuclear Power Plants Using a Simplified Simulator and Student Operators," Reliability Engineering and System Safety, 221, 2022, Article 108326.

[23] Ulrich, TA, Lew, R, Werner, S, and RL Boring, "Rancor: A Gamified Microworld Nuclear Power Plant Simulation for Engineering Psychology Research and Process Control Applications, Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 61, No. 1, pp. 398-402). Sage CA: Los Angeles, CA: SAGE Publications, (2017).

[24] Park, J., Jang, I., Park, J., Boring, R.L., and T.A. Ulrich. "A Framework to Integrate HRA Data Obtained from Different Sources Based on the ComplexityScores of Proceduralized Tasks," Proceedings of the Probabilistic Safety Assessment and Management Conference (PSAM 16), in press.

[25] Wakefield, D J, Parry, G W, Hannaman, G W, and Spurgin, A J. SHARP1: A revised systematic human action reliability procedure. United States: Electric Power Research Institute. p., 1990. Web.

[26] Electric Power Research Institute, *HAZCADS: Hazards and Consequences Analaysis for Digital Systems, Revision 1*, EPRI TR-3002016698 (2021).

[27] Boring, R., and Bye, A., "Bridging Human Factors and Human Reliability Analysis," Proceedings of the 52nd Annual Meeting of the Human Factors and Ergonomics Society, pp. 733-737 (2008).