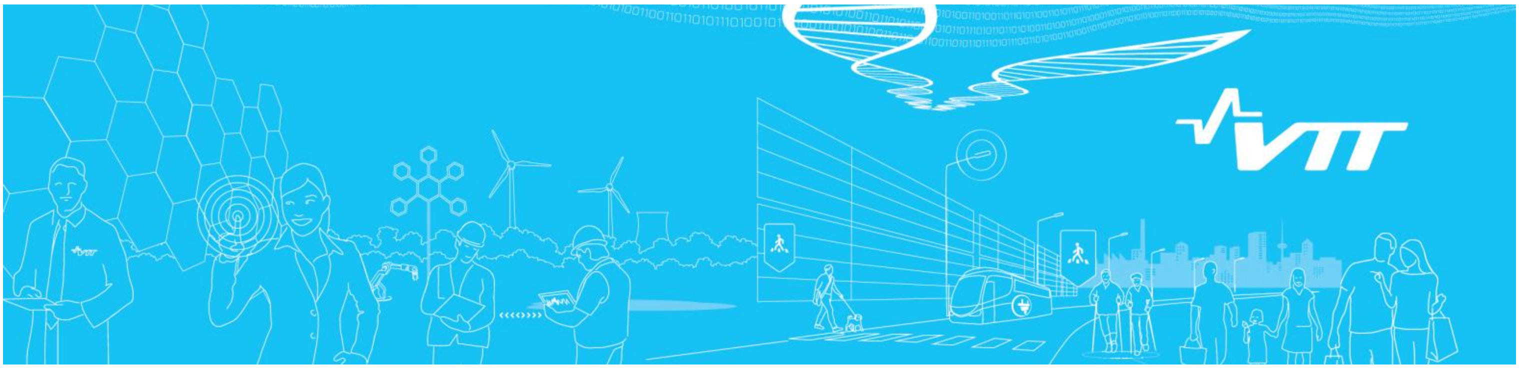


RESEARCH REPORT

VTT-R-00434-16

HRA of digital control rooms – Literature review

Authors: Markus Porthin, Marja Liinasuo, Terhi Kling

Confidentiality: Public

Report's title

HRA of digital control rooms: Literature review

Customer, contact person, address VYR	**Order reference** SAFIR 4/2015
Project name Probabilistic risk assessment method development and applications	**Project number/Short name** 101958/ PRAMEA
Author(s) Markus Porthin, Marja Liinasuo, Terhi Kling	**Pages** 20
Keywords Human Reliability Analysis, HRA	**Report identification code** VTT-R-00434-16

Summary

Digital human-system interfaces (HSIs) are becoming common in nuclear power plants (NPPs) through modernisations and new-builds. NPP control rooms with modern digital HSI are commonly referred to as advanced control rooms, and are characterised by integrated information systems, soft controls and computer-based procedures. Most of the HRA methods commonly used today do not properly account for the induced changes in the work of the operator.

This report reviews recent development related to HRA in NPPs using digital HSI. The use of digital HSI changes the working environment of the operator, induces new tasks and modifies the group dynamics and communication. This improves crew performance and reduces workload. Negative effects include declined primary task performance due to attention shift to interface management, and sub-optimal use of the HSI in high workload situations due to minimized capability to focus on interface management tasks.

Only two known HRA methods, HuRECA and MERMOS, are applicable to digital HSIs. In recent years there has also been some further methodological progress in the field mainly by Korean and Chinese researchers, including proposals for new performance shaping factors and typical error types when using soft controls.

HRA method development for digital HSI and advanced control rooms is currently an evolving research field. The need for method development has been recognised and some progress is under way. However, further work in the field is needed to properly take the new aspects introduced by digital HSI into account in HRA.

Confidentiality	Public

Espoo 8.2.2016

Written by	**Reviewed by**	**Accepted by**
Markus Porthin Senior Scientist	Ilkka Karanta Senior Scientist	Eila Lehmus Head of Research Area

VTT's contact address

VTT, P.O.Box 1000, 02044 VTT, Finland

Distribution (customer and VTT)

SAFIR reference group 2, VTT archives

The use of the name of VTT Technical Research Centre of Finland Ltd in advertising or publishing of a part of this report is only permissible with written authorisation from VTT Technical Research Centre of Finland Ltd.

List of abbreviations

ASEP	Accident Sequence Evaluation Program
CBDT	Cause-Based Decision Tree method
EDF	Electricité de France
EOP	Emergency operating procedure
HCR	Human Cognitive Reliability method
HEP	Human error probability
HFE	Human factors engineering (HFE can also stand for Human failure event, however this meaning of HFE is avoided in this document to avoid confusion)
HRA	Human reliability analysis
HSI	Human-system interface
HuRECA	Human Reliability Evaluator for Control Room Actions
I&C	Instrumentation and control
KAERI	Korea Atomic Energy Research Institute
K-HRA	Korean standard HRA
MCR	Main control room
MERMOS	Méthode d’Evaluation de la Réalisation des Missions Opérateurs pour la Sûreté
NPP	Nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PRA	Probabilistic risk assessment
PSF	Performance shaping factor
THERP	Technique for Human Error Rate Prediction
YVL	Ydinvoimalaitosohjeet (Finnish Regulatory Guides on nuclear safety)

Contents

1. Introduction

Human error probability is very context-sensitive; when circumstances change, there is a need for re-examination, and possibly revision, of existing human reliability analysis (HRA) methods and work practices. Thus, the modernisation of nuclear power plants (NPP), often in the form of digitalisation including control rooms, as well as new builds, call for the renewal of HRA methods. NPP control rooms with modern digital human-system interfaces (HSI) are commonly referred to as advanced control rooms, and are characterised by integrated information systems, soft controls and computer-based procedures. Most of the HRA methods commonly used today were developed before the introduction of advanced control rooms and digital HSI and thus do not properly account for the changes in the work of the operator induced by them.

This report reviews recent development related to HRA of NPPs using digital HSI, especially focussing on the work in the main control room (MCR) in post-initiator situations. Section 2 gives a broader overview on human reliability in digital environments in non-nuclear fields. The present situation, new studies and recommendations regarding HRA of advanced control rooms in NPPs is presented in Section 3. Section 4 describes present HRA methods from the digital HSI point of view and Section 5 goes through relevant recommendations and requirements. Finally, Section 6 concludes the report.

2. Human reliability in digital environments

Human reliability can be defined as the probability of successful performance of a mission (Evans, 1976). The concept of human reliability is closely related to the concept of humans prone to make errors. Thus, the approach implemented in the concept of human reliability is the high or at least relevant possibility of errors. The trend to perceive human error as the main cause of accidents in complex systems has been reinforced since the analyses of the Three Mile Island accident (e.g. Stojiljkovica et al., 2014). After that, it has been assumed (Stojiljkovica et al., 2014) that the share of human factors in industrial accidents is in the range of 70-90%, the remaining causes being technical failures.

One widely accepted definition describes human error as “any member of a set of human actions or activities that exceeds some limit of acceptability, i.e., an out of tolerance action (or failure to act) where the limits of performance are defined by the system” (Swain, 1989, p. 3). Accordingly, all human errors are regarded as such outputs of human behaviour that fall outside the tolerance scope of the system where a person operates. This conception is in accordance with the one prevailing in HRA.

Reason (1990a) has developed a model of human errors without assumptions on the environment. The central thesis is that the relatively limited number of error manifestations depends on the ways stored knowledge structures are selected and retrieved in response to current situational demands. Error is also connected to intention – the term ‘error’ can only be used in situations where planned actions fail. Error type depends on the stage when conceiving and carrying out an action sequence, involved in an error; the stages are planning, storage and execution. Planning refers to the identification of a goal and deciding on the means to reach it. Storage is needed as plans are not usually realised immediately. The execution phase covers the processes involved in implementing the stored plan. Reason presents two basic error types: slips (actions not performed as planned) and lapses (more covert, involve failure of memory, may only be apparent to the person who experiences them) where actions do not go as planned, and mistakes where that plan itself is not appropriate for achieving its desired objectives. Thus, slips and lapses are errors which result from a failure in the execution and/or storage of an action sequence whereas mistakes are deficiencies or failures in the judgemental and/or inferential process which is involved in the selection of an objective or in the selection of the means to achieve it. However, Reason has combined this model with another one, nowadays called as Swiss cheese model. According to that model (Reason, 1990b), failures are due to a combination of a large number of causal factors, each one necessary but not sufficient alone to produce the negative outcome. These causal factors are human errors which become realised one after another until the undesired situation happens.

On the other hand, since the mid-1990s it has also been stated that human error (or reliability) is not an appropriate approach in risk management. For instance, Rasmussen suggested in 1997 that task analysis focused on action sequences and occasional deviation in terms of human errors should be replaced by a model of behaviour shaping mechanisms in terms of work system constraints, boundaries of acceptable performance, and subjective criteria guiding adaptation to change. Accordingly, Hollnagel et al. (2006) coined the term ‘resilience engineering’, emphasising the importance in shifting from reactive to proactive measures to support safety. Still, the error-based approach is prevailing in the practises related to human reliability, such as in HRA.

From the “human error” point of view, it is not easy to identify the various types of human errors because human error types vary according to the characteristics of individuals and other factors, unique to the specific circumstance (e.g., Lee et al., 2011). One unifying factor in work environments is increased digitalization, changing the context influencing human performance. Even if digital technologies can be expected to improve usability, diminishing the possibility of human errors, the change from analogue to digital systems is challenging and the digital systems themselves can be regarded as a source of also new types of errors. Thus, in this report, the perspectives of human as the source of error and a more systemic viewpoint of errors as interactions of various and not only human factors are both used.

One perspective to risks related to digitalization is the nature of digital systems related to human capabilities and human nature as a whole. Hamelink (2006) deliberates that science and technology have made it possible to realize projects which are both destructive and large whereas the human mind seems rather ill-prepared for large-scale operations. Additionally, Hamelink suggests that as a result of technological development, an increasing number of tools and instruments are ill-understood by their human users. Advanced technology may exceed the knowledge and capabilities even of specialists. The usage of systems which decide for and instead of the human user encompass high risks as during failure, there is perhaps nobody to fix the problem or, furthermore, human users are not able to identify the existence of the failure. Hamelink (2006) states that increased technology may eventually imply the total loss of human autonomy to dependence upon more or less autonomous digital systems. In any case, with the increasing dependence upon advanced technology, human becomes more vulnerable to the malfunctioning of the technology. Furthermor, systemic flaws and deliberate misuse occur both separately and in combination with each other. This takes place, according to Hamelink (2006), in the level of human individual as well as in the level of society. When important social domains such as banking, telecommunications, air traffic or energy supply become dependent upon digital technology, society becomes vulnerable to the malfunctioning of the technological infrastructure. This raises the possibility of serious destabilization of these social systems and the underlying cause could be, among other possible causes, software failures and deliberate destruction of computer systems. Furthermore, Hamelink (2006) states that digital technology has enabled the provision of huge amount of information such as earthquake warning systems or medical life-support systems which offer interesting calculations but not certainty. Advanced information and communication technologies add human with volumes of information that are too much to process and order, thus leaving people uncertain as to what it means, what is relevant and what irrelevant. If digital systems are used in healthcare, making decisions affecting human life, the objective should, according to Hamelink (2006), be carefully considered, as the objective of patient well-being can lead to different outcome than, say, the one of level of productivity in health care system or mortality rate in the hospital. The intended or realised qualities of the system have moral and practical consequences. The digital healthcare system can increase dependence on the system or strengthen human autonomy; the system can increase patient vulnerability or may guarantee more patient integrity; and the system may or may not improve balance between uncertainty and security (Hamelink, 2006).

The considerations of Hamelink (2006) described above can be used in the contemplation of human dependability in digital environments. Human performance in digital environment is not dependable, because (i) human capability is not sufficient to deal with the masses of information provided by digital technology in an informed and dependable way; (ii) risks related to managing the malfunctioning of the digital systems resulting from systemic flaws or deliberate misuse are increased as humans lose their autonomy as individuals and in the level of society by depending too much on digital systems; (iii) humans are not capable of acting in a meaningful way and making correct decisions if the objectives and underlying principles of the digital technology assisting performance are not properly understood.

Bearman (2013) noted that introducing new technology to transport systems is not without risk; in such a complex environment as a train cab or train control room with hard to use interfaces, frequent false alarm and ambiguous information, drivers may and do make errors. As a whole, the key technology-related human factors issues, according to Bearman, are as follows:

- Inadequate operator understanding of the technology
- Sub-optimal physical design or location of the technology
- Sub-optimal information provision or feedback
- Distraction
- Attenuation to alarms
- Failing to act on an alarm
- Problems transitioning between different modes

Some of these issues are probably more specific in the transport technology as the work environment is radically changing, contrasting, say, control rooms and offices. As a whole, it has been stated, for instance, that digital instrumentation and control (I&C) systems lead to new human errors and error mechanisms, and the factors influencing human errors are organizational, situational and individual factors (Li et al., 2010). This type of approach seems appropriate when probing human reliability in digital environments.

To conclude, digitalization has been found to probably bear possibilities to specific human errors but the errors as such seem to be highly context dependent.

3. HRA of digital control rooms

3.1 Introduction and present situation

In the future, digital technology is expected to be more widely used in the MCRs of NPPs. It is believed that the introduction of digital I&C can lead to an overall improvement in operator performance and reduce workload in abnormal conditions. However some negative consequences will also arise due to faulty HSI design (Tian et al., 2014).

The use of digital control systems has been accompanied by challenges in probabilistic risk assessment (PRA) modelling because of several, unique features related to these newer systems. Among these is the fact that current human reliability models and data were developed before the digital systems and thus may need modification in order to properly assess the risk of NPP operation and to determine the risk of PRA applications, including being able to assess the impact of upgrading to digital controls (Julius et al., 2014).

This problem is further complicated by the dynamic nature of HRA. Even before the introduction of digital controls much has been written about developing and applying HRA methods in nuclear power PRA. Although we have 40 years of operating history for plants and nearly 30 years of analysis, HRA methods can produce significantly different results. These inconsistencies potentially affect the ability to develop insights and to make risk-informed decisions as part of PRA applications. In order to address these needs, the EPRI HRA Users Group was founded in the year 2000. Since 2000, the EPRI HRA Users Group has grown significantly to represent most of the USA power plants as well as vendors and international members (Julius et al., 2014).

The operation environment of MCRs in NPPs has changed with the adoption of new HSIs that are based on computer-based technologies. The MCRs that include these digital and computer technologies are called advanced MCRs. Among the many features of advanced MCRs soft controls is a particularly important feature because the operation action in NPP advanced MCRs is performed by soft control. Due to the difference of the interfaces between soft control and hardwired conventional type control, different human error probabilities and a new HRA framework should be considered in the HRA for advanced MCRs. Although there are many HRA methods to assess human reliabilities, these methods do not sufficiently consider the features of advanced MCRs such as soft control execution human errors (Jang et al., 2014).

3.2 Experiences, studies and new developments

Currently, NPPs in many countries are rapidly taking digital technology into use, and digital HSIs are being applied in their control rooms (Tian et al., 2014). The U.S. Nuclear Regulatory Commission (NRC) has made a study (Roth and O’Hara, 2001.) about digital and conventional HSIs which indicated that the new HSIs provide positive support for crew performance, reduced workload, and are well accepted by the crews. The study also found out that advanced HSI systems induce changes in crew structure and communication in a way that has potential implications for human performance and reliability.

A research by Brookhaven National Laboratory about Computer-Based Systems (O’Hara et al., 2002) found evidence of two forms of negative effects: (1) primary task (which refers to process monitoring and control) performance declines because operator attention is directed toward the interface management task, and (2) under high workload, operators minimize their performance of interface management tasks, thus failing to retrieve potentially important information for their primary tasks. Further, these effects were found to have potential negative effect on safety.

It has also been found out that in digital environments in NPP MCR’s, when using soft controls, typically six types of errors appear (Lee et al., 2011):

- Operation omission
- Wrong object
- Wrong operation
- Mode confusion
- Inadequate operation
- Delayed operation

Lee et al. (2011) stated that even if the error modes found were not much different from those of conventional controls, there are different causes for these soft control errors. For instance, a wrong object can be selected on both correct display and on a wrong one. Thus, even if human errors as such may be somewhat similar in digital and non-digital environments, the nature of digitalisation encompasses interface flexibility. The user interface in digital environments enables the redesign of these interfaces so that the possibility of human errors is diminished and their consequences are less fatal (by, for instance, prompting the user when an important decision is made via the user interface). This complies with the demands of proactive safety support.

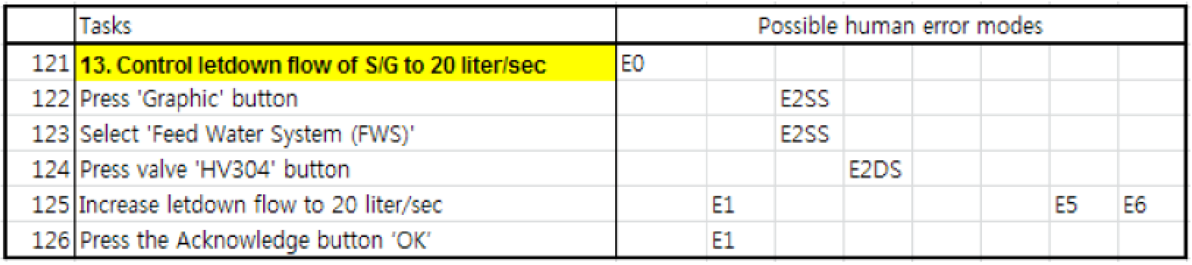
Just a few studies are conducted so far in the HRA domain to reflect operator performance under the digital HSIs. Most currently available human error data are collected in the operations of the current plants and simulators. The most widely used human error probabilities (HEPs) in HRA community are those in Technique for Human Error Rate Prediction (THERP) handbook (Swain and Guttmann, 1983), in which the data are collected 30 years ago without any information about the human performance dealing with the digital systems. It is necessary to study the characteristics of human performance in digital HSIs to get more information about when, where and how operators will fail and what is the risk contribution associated with these human actions (Tian et al., 2014).

Tian et al. (2014) have investigated operating plants (and those under construction) in China installed with fully digital I&C systems. Interviews were made with the simulator instructors, control room operators and designers of MCR about the control layout, computer interface, alarms, and procedures to understand the effects on operator performance. The objective of their study was to characterize the salient features of the digital HSIs, understand their effects on operator performance, identify specific performance shaping factors (PSFs) in HRA methods for the digital HSIs, and give a proposal to apply the specific PSFs in digital human factors engineering (HFE) and HSI design process. Their survey indicates that common characteristics exist in digital HSIs of different reactors using different digital I&C systems. The digital HSIs which satisfy the HFE principles in NUREG-0700, incorporate features such as soft controls, information display, computer-based procedures, computer-based alarms, touch-screen interfaces, sit-down computer workstations, and large-screen overview displays.

Jang et al. (2014) suggest a HRA method framework for evaluation of soft control execution human error in advanced MCRs. In order to develop the new framework for the HRA method, a soft control task analysis was performed to identify human error modes. From the results of the soft control task analysis, the possible human errors during the process were classified into eight types. Moreover, dependency among subtasks was considered by modifying the determination of levels of dependency in the THERP model. This modification is performed according to several causes of soft control human error pointed out in NUREG/CR-6635 that may be related to parameters for dependency level. In their model, a success path is considered to calculate soft control execution HEP with consideration of dependency between two subtasks. By deriving two examples of HEP equations for representative soft control unit tasks in consideration of secondary tasks, sequential behaviour, and dependency among subtasks, a HEP calculation equation is generalized. A database for inputs to the general HEP equation such as nominal HEPs and recovery failure probabilities is developed and applied to estimate HEPs. Finally, HEPs are estimated using the developed nominal HEPs by assuming three different cases of recovery failure probabilities.

Jang et al. (2014) analyse execution tasks in emergency operating procedures (EOP) to verify which human error modes may occur for each soft control task, as shown in Table 1. Due to sequential dependencies in unit task completion, failure or success of one subtask may affect failure or success of the next subtask if two subtasks are not mutually independent. After analysis of the feature of soft control, determination of the level of dependency for soft control is developed using a decision tree, as shown in Figure 1. The success probability of each subtask depends on the HEPs Ei (i = 0, 1, 2SS, 2DS, 3, 4, 5, 6) according to human error modes (example of classification in Table 1), and their recovery failure probabilities. Recovery failure probabilities according to human error modes are expressed as Ri. In other words, Ri equals the recovery failure probability of Ei. The probability that the operator succeeds in each subtask for a unit tasks is then expressed in Table 2.

Table 1. An example of a task including sub tasks (Jang et al., 2014).



	Tasks	Possible human error modes							
121	13. Control letdown flow of S/G to 20 liter/sec	E0							
122	Press 'Graphic' button			E2SS					
123	Select 'Feed Water System (FWS)'			E2SS					
124	Press valve 'HV304' button				E2DS				
125	Increase letdown flow to 20 liter/sec		E1					E5	E6
126	Press the Acknowledge button 'OK'		E1						

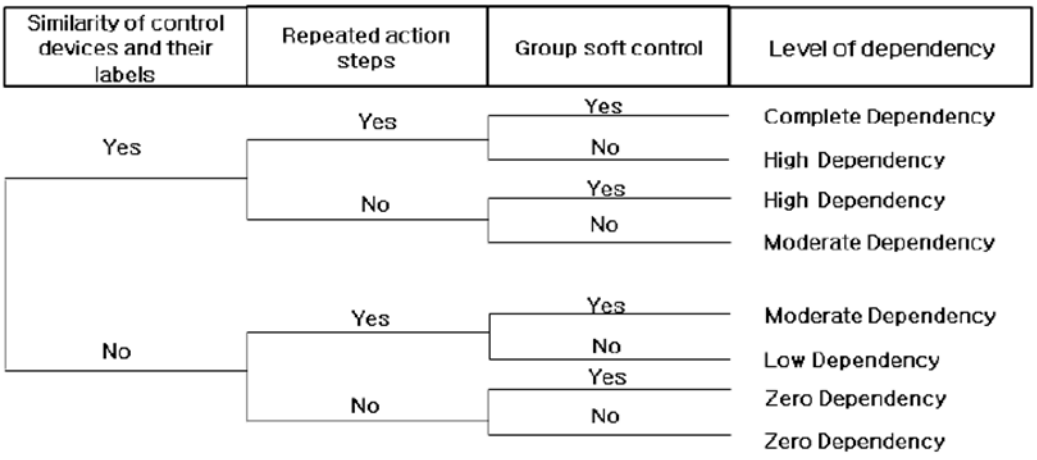
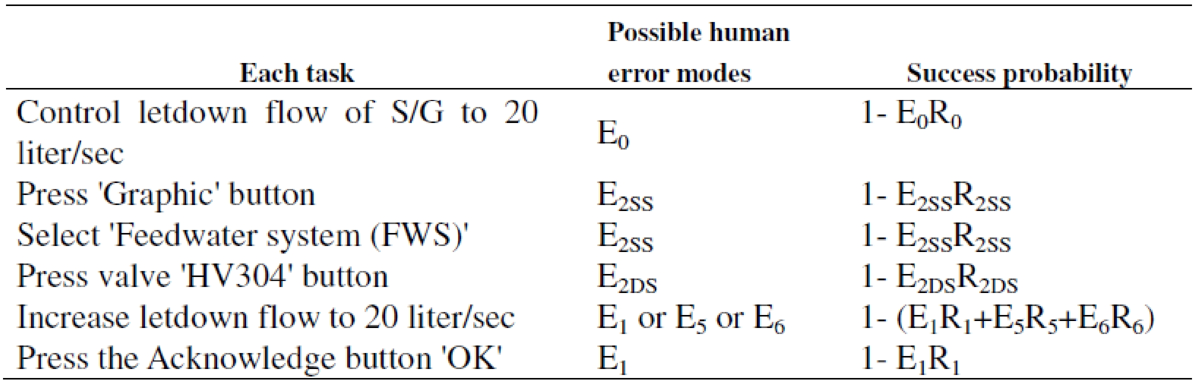


Figure 1. Decision tree for level of dependency (Jang et al., 2014).

Table 2. Success probability of each sub tasks for one unit task (Jang et al., 2014).



Each task	Possible human error modes	Success probability
Control letdown flow of S/G to 20 liter/sec	E_0	$1- E_0R_0$
Press 'Graphic' button	E_{2SS}	$1- E_{2SS}R_{2SS}$
Select 'Feedwater system (FWS)'	E_{2SS}	$1- E_{2SS}R_{2SS}$
Press valve 'HV304' button	E_{2DS}	$1- E_{2DS}R_{2DS}$
Increase letdown flow to 20 liter/sec	E_1 or E_5 or E_6	$1- (E_1R_1+E_5R_5+E_6R_6)$
Press the Acknowledge button 'OK'	E_1	$1- E_1R_1$

Liinasuo and Porthin (2015) analysed the information gathered from the validation of a MCR modernisation project. In the validation study performed by VTT, 801 human engineering discrepancies were identified. Liinasuo and Porthin revisited the whole set of discrepancies to judge their relevance from HRA point of view. 484 human error discrepancies were judged to potentially influence human reliability. They could be categorised into three main groups as shown in Table 3.

Table 3 Human engineering discrepancies from a MCR validation that were judged relevant for HRA (Liinasuo and Porthin, 2015).

Human engineering discrepancy category	Number of discrepancies
1. Display related issues	343
Unclear grouping on the display Display is ”full” Detail hard to perceive on the display The location of simultaneous tasks on separate displays Ambiguous notation on the display Deviation from logic on the display	59 10 18 1 156 99
2. Performance demands related issues	15
Parallel paths in procedure Loop in procedure The demand of moving from one location to another	5 1 9
3. Concept-level issues	126
The unfamiliarity of the safety user interface concept Scarcity of process information, related to the concept of safety user interface Lack of transparency of actions, related to the concept of accident management The unfamiliarity of concept of operations	47 17 2 41

Liinasuo and Porthin (2015) further judged that the commonly used decomposition of post-initiator operator actions into diagnosis and execution does not properly describe the work of the operator when using modern HSI. The computer system is doing most of the diagnosis automatically without the need of judgement by the operator. Instead they proposed the following task decomposition:

1. Detection of accident situation
2. Applying of procedure for accident identification in safety display
3. Selection of the accident-specific procedure display and control displays as defined in step 2
4. Execution of actions as defined in the accident specific procedures in a professional way

3.3 Guidelines, recommendations and conclusions

There are some guidelines to help operators and suppliers plan, specify, design, implement, operate, maintain, and train for the modernization of control rooms and other HSI in a way that takes advantage of digital system and HSI technologies, and addresses issues concerning digital HSIs, for example NUREG-0711 (NRC, 2012) among which HRA is one of the 12 elements.

HRA can be used as an evaluation tool to identify vulnerabilities to human error or human engineering deficiencies of the HSIs. HRA for the new MCRs should be able to consider the possible effects of new HSIs on operator performances (Tian et al., 2014). Table 4 summarizes the general characteristics of well-designed HSIs.

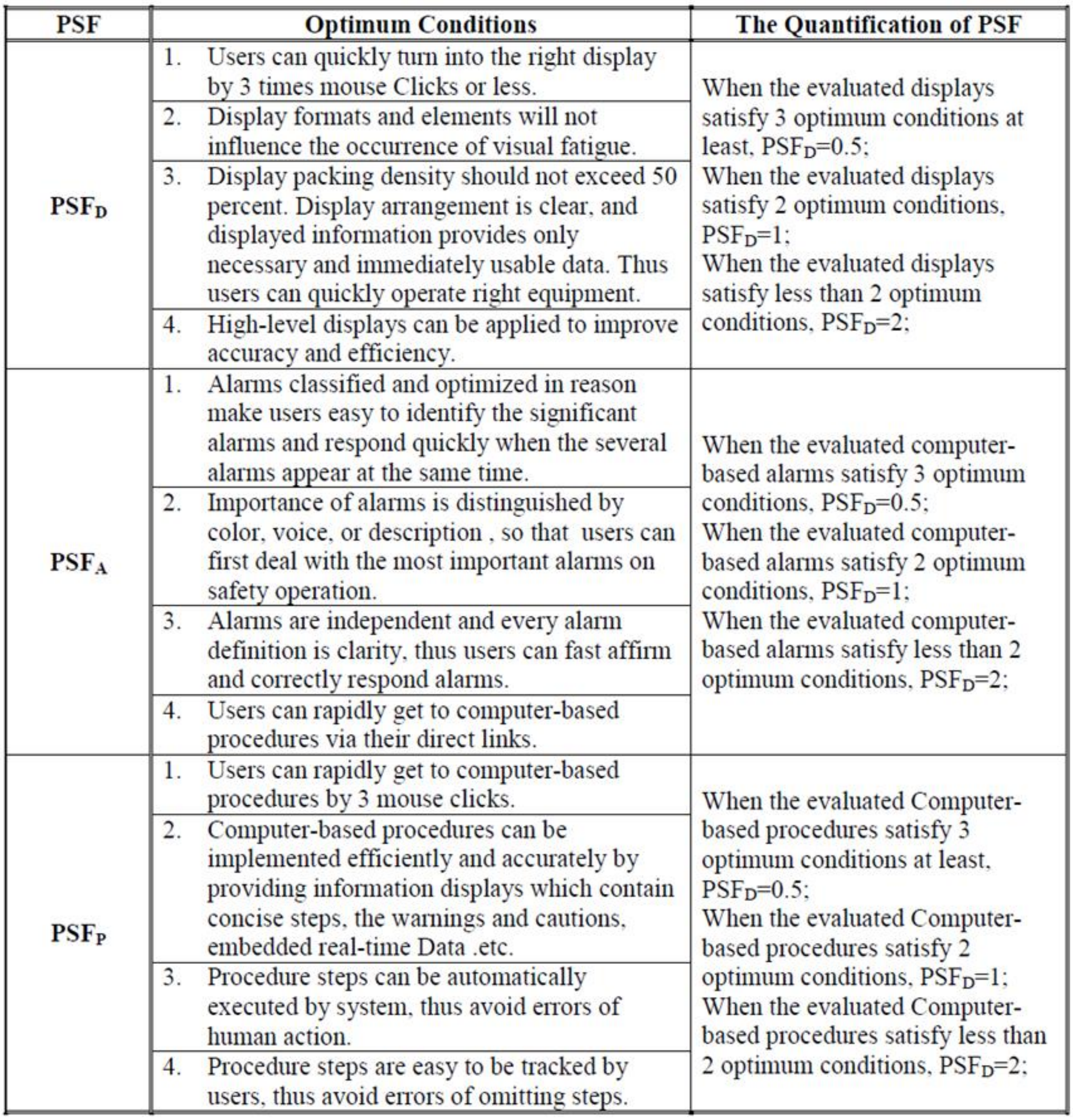
Table 4. General Characteristics of a well-Designed HSI (Tian et al., 2014).

General Characteristics of a Well-Designed HSI		Human Response Model
Characteristics	**Description**	
Accurately represents the plant	To be consistent with and supports a user's understanding and awareness of the system, its status, and the relationship between individual system elements	Detection to realize an abnormal scenario occur based on alert or unpredicted information display Diagnosis and decision- making using computerized HSIs, in support of computerized procedures, to make the diagnosis detection to ascertain the actual plant scenarios and the necessary response for next step Perform detail actions to perform certain measurements or series actions to eliminate system fault or alleviate the sequent of abnormal scenario to ensure the plant safety
Meets user expectations	To accord with HFE principles and fully enhance the work efficiency	
Supports situation awareness and crew task performance	Fully support users to accomplish their primary tasks of monitoring, situation assessment, response planning and response execution by providing alerts, information, procedural guidance, and controls when and where they are needed	
Minimizes secondary tasks and distractions	Users should not need to shift attention from their primary tasks to the interface. Therefore, the need for users to perform secondary tasks such as window manipulation, display selection, and navigation should be minimized as much as possible	
Balances workload	Optimize function allocation between human and machine to maximum enhance the human-machine efficiency	
Is compatible with users' cognitive and physical characteristics	To accommodate human physiological and cognitive characteristics and limitations such as visual/auditory perception and anthropometrics and biomechanics	
Provides tolerance to error	To minimize the occurrence of user errors and provides a way for users to detect and correct errors when they do occur	
Provides simplicity	Simplest design to meet the task requirements and potentially distracting features such as excessive decorative detail or non-functional icons should be avoided	
Provides standardization and consistency	Standardization and consistency make the HSI predictable and predictability lowers the workload associated with using the interface, leaving more attention for doing the primary tasks	
Provides timeliness	To ensure that tasks can be performed within the time required and this requires consideration of the user's capabilities and system-related time constraints	
Provides openness and feedback	Help users easily understand and track the plant process	
Provides guidance and support	Provide an effective "help" function on line or off line to help users understand and interact with the HSI	
Provides appropriate HSI flexibility	Computer-based HSIs can be tailored to better meet the demands of the user's ongoing tasks and to accommodate personal preferences	

To evaluate the impact of the digital HSIs on human performance and plant safety, Tian et al. (2014) describe the characteristics of the digital HSIs from graphic-based information display system, computer-based alarm system, and computer-based procedure system, which are necessary when operators implement required tasks.

The digital HSIs applied in NPPs offer potential for improved operator performance, but if they are not appropriately applied, they may introduce new burdens for the operator. Existing HRA methods are usually limited to evaluate the influence of digital HSIs on operator performance, and are difficult to give out advisable suggestion tending to the improvement of digital HSIs. Tian et al. (2014) propose specific PSFs for digital I&C control rooms to be considered in HRA methods (Table 5). They also suggest a way to apply the specific PSFs in digital HFE/HSI design process.

Table 5. PSF:s for digital HSI proposed by Tian et al. (2014).[D=Display, A=Alarms, P=Procedures)



PSF	Optimum Conditions	The Quantification of PSF
PSF_D	1. Users can quickly turn into the right display by 3 times mouse Clicks or less.	When the evaluated displays satisfy 3 optimum conditions at least, PSF_D=0.5; When the evaluated displays satisfy 2 optimum conditions, PSF_D=1; When the evaluated displays satisfy less than 2 optimum conditions, PSF_D=2;
	2. Display formats and elements will not influence the occurrence of visual fatigue.	
	3. Display packing density should not exceed 50 percent. Display arrangement is clear, and displayed information provides only necessary and immediately usable data. Thus users can quickly operate right equipment.	
	4. High-level displays can be applied to improve accuracy and efficiency.	
PSF_A	1. Alarms classified and optimized in reason make users easy to identify the significant alarms and respond quickly when the several alarms appear at the same time.	When the evaluated computer-based alarms satisfy 3 optimum conditions, PSF_D=0.5; When the evaluated computer-based alarms satisfy 2 optimum conditions, PSF_D=1; When the evaluated computer-based alarms satisfy less than 2 optimum conditions, PSF_D=2;
	2. Importance of alarms is distinguished by color, voice, or description , so that users can first deal with the most important alarms on safety operation.	
	3. Alarms are independent and every alarm definition is clarity, thus users can fast affirm and correctly respond alarms.	
	4. Users can rapidly get to computer-based procedures via their direct links.	
PSF_P	1. Users can rapidly get to computer-based procedures by 3 mouse clicks.	When the evaluated Computer-based procedures satisfy 3 optimum conditions at least, PSF_D=0.5; When the evaluated Computer-based procedures satisfy 2 optimum conditions, PSF_D=1; When the evaluated Computer-based procedures satisfy less than 2 optimum conditions, PSF_D=2;
	2. Computer-based procedures can be implemented efficiently and accurately by providing information displays which contain concise steps, the warnings and cautions, embedded real-time Data .etc.	
	3. Procedure steps can be automatically executed by system, thus avoid errors of human action.	
	4. Procedure steps are easy to be tracked by users, thus avoid errors of omitting steps.	

Improved Human Cognitive Reliability (HCR) and THERP methods are applied to HRA in several NPP design projects in China. More uncertainties about human performance can be induced by the wide use of the digital techniques, which lack of enough practical experiences. The improvement of HRA methods cannot evaluate all the change of human performance in digital HSIs. More real and reasonable HRA models are expected in future. (Tian et al., 2014).

According to Boring (2014) a central goal for phasing in newer technologies is to ensure that a new system is at least as reliable as the system it is replacing. In terms of HRA, the goal is to ensure that operator performance using the newer technology is at least as reliable as performance using the older technology. Such a comparison may be made by estimating the HEPs of various human activities, including human failure events.

HRA development is ongoing. Recent work in progress by the NRC to develop a cognitive framework for HRA builds heavily on the Cause-Based Decision Tree (CBDT) method without specifically addressing new applications (Whaley et al., 2012). Boring (2014) addresses the need for HRA for digital HSIs as follows:

1. Conduct a systematic operating experience review of human errors in interacting with digital HSIs as documented by non-nuclear industries with significant digital HSI experience,

2. Identify human failure events specific to NPP control room operations using digital HSIs,

3. Establish those PSFs that are unique to digital HSIs—these PSFs will need not simply be identified; the empirical basis for quantification needs to be established,

4. Perform a validation study using a research simulator on the effects of digital HSIs on reactor operator performance, and

5. Develop guidance for including and quantifying these human failure events in the HRA and PRA.

Each of these areas for research is discussed separately in the paper.

4. Present HRA methods from the digital point of view

Most of the existing HRA methods do not address the new aspects introduced by digital HSI, as confirmed e.g. by the OECD WGRISK/WHGOF Task Group on Establishing Desirable Attributes of HRA Techniques for Nuclear Safety in 2015 (OECD, 2015). For example, THERP, one of the most known and used HRA methods in NPP context, originating in human reliability studies performed in the early 1950s on the reliability of military systems and components, states that *"some of the display and control concepts being considered for future plants are so new that insufficient information exists to develop quantitative indices of human performance"*. The THERP documentation further states that *"the Handbook does not provide estimated HEPs related to the use of new display and control technology that is computer-based"*. In 2008, the WGRISK task on HRA Data and Recommended Actions to Support the Collection and Exchange of HRA Data stated that HEPs applicable to conventional interfaces from sources such as the THERP Handbook often continue to be used for digital HSIs, but the failure modes specific to computer-based HSIs have generally not been addressed (OECD, 2008).

The papers of Julius et al. (2014) and Boring (2014) address issues and insights related to applying current HRA techniques to the PSA of digital control systems. As noted throughout the papers, no existing HRA method adequately addresses digital HSIs. Current HRA methods and data can be used to assess HEPs while additional research and operating experience develops new data and insights. However, PSA of plants with digital control systems should conduct a range of uncertainty and sensitivity evaluations in order to assess the potential impact of changes to operator failure rate data or new failure modes. For example, by varying the amount of recovery credit and varying the assessed level of dependence between operator actions.

Hickling and Bowie (2013) examined the validity and applicability of the HRA methods THERP, ASEP (Accident Sequence Evaluation Program) and SPAR-H (Standard Plant Analysis Risk HRA) to modern control room environments with digital HSI. They compared the estimates by these methods to HEPs from empirical studies in simulator environments with digital HSI. They found that the examined methods in most cases deliver overly optimistic HEP assessments compared to the empirical data. They suspect that THERP may have always been optimistic, or that digital HSI-based tasks are less reliable than tasks on discrete interfaces. Hickling and Bowie further emphasize that a HSI that increases the performance of the operator may lead to either increased or decreased HEP. Thus the commonly made assumption that increased performance decreases the HEP does not hold. They suggest that in the future less emphasis will have to be placed upon the existing HRA methods that synthesise error probabilities and far more emphasis on carefully designed observational studies that test proposed digital HSI design in simulated tasks.

WGRISK/WGHOF (OECD, 2015) identified two HRA methods applicable for assessing human reliability in advanced control rooms, namely Méthode d'Evaluation de la Réalisation des Missions Opérateurs pour la Sûreté (MERMOS) (Bieber et al., 1998; Bilrando and Pesme, 2002; Desmares and Cara, 2000) and Human Reliability Evaluator for Control Room Actions (HuRECA) (Kim, 2012; Kim et al., 2011).

MERMOS was initially developed by Electricité de France (EDF) to support PSAs for the new generation of reactor plants that used computers extensively in the MCRs, including computer-based EOPs. MERMOS considers human actions as the result of the whole operational system with multiple interactions between the components (the crew, the organisation, the EOPs and the HSI) and the process (OECD, 2015). Due to the flexible and generic approach of the method, it can be applied to realistic failure events seen in accidents and scenarios as accident sequences progress. It also can take organisational issues into account. However, applying MERMOS requires extensive resources and high level of expertise. Moreover, while being applicable to advanced control rooms, it does not explicitly deal with digital issues.

HuRECA is an HRA method developed by Korea Atomic Energy Research Institute (KAERI) in 2007-2012. It models human actions in using computer-based procedures in the post-accident phase of operations. HuRECA estimates error probabilities for the diagnostic and execution phases of operator actions. It is built upon the Korean standard HRA (K-HRA) (Jung et al., 2005), which is a Korean extension of THERP and ASEP, and uses PSFs that account for computer-based design features such as computer-based procedures and soft controls. According to WGRISK/WGHOF (OECD, 2015), HuRECA has not yet been applied in practice.

5. Recommendations and requirements related to HRA of advanced control rooms

5.1 Finnish Regulatory Guides on nuclear safety (YVL)

Section A.7 of the Finnish Regulatory Guides on nuclear safety (YVL) (see http://plus.edilex.fi/stuklex) covers PRA and risk management of a NPP. The section sets requirements on the scope, contents, documentation and usage of PRA. The Guide requires, among other things, that the Level 1 PRA shall present a human reliability analysis. The Level 2 PRA shall present reliability analysis of the systems intended for severe accident management taking into account the conditions prevailing during an accident and also human action. The Guide also requires that human errors shall be analysed as initiating events and that the licensee shall maintain a database of human errors. The YVL Guide does not specify any explicit requirements concerning the HRA of advanced control rooms.

5.2 NUREG-1792 Good Practices for Implementing HRA

The NUREG-1792 Good Practices for Implementing HRA (NRC, 2005) are of a generic nature and not tied to any specific methods or tools. It is not intended to constitute a standard, but rather a reference guide to support the implementation of Regulatory Guide 1.200 for determining the technical adequacy of PSA for Risk-Informed Activities in the USA. The report does not explicitly address advanced control rooms. However, it provides a set of good practices of general nature for post-initiators regarding identifying of post-initiator human actions, modelling of specific human failure events corresponding to the human actions, quantifying of the corresponding HEPs for the specific human failure events and adding recovery actions to the PRA. The Guide lists several post-initiator PSFs to be considered for both control room and local (ex-control room) actions:

- Applicability and suitability of training and experience
- Suitability of relevant procedures and administrative controls
- Availability and clarity of instrumentation (cues to take actions as well as confirm expected plant response)
- Time available and time required to complete the action, including the impact of concurrent and competing activities
- Complexity of required diagnosis and response. In addition to the usual aspects of complexity, special sequencing, organization, and coordination can also be contributors to complexity.
- Workload, time pressure, stress
- Team/crew dynamics and crew characteristics (degree of independence among individuals, operator attitudes/biases/rules, use of status checks, approach for implementing procedures, (e.g., aggressive vs. slow and methodical)). Note: Observation of simulator exercises and discussions with operating crews and trainers are particularly important to obtaining this type of information. Weaknesses and strengths in organizational attitudes and rules as well as in administrative guidance may bear on aspects of crew behaviour and should be considered.
- Available staffing and resources
- Ergonomic quality of HSI
- Environment in which the action needs to be performed
- Accessibility and operability of equipment to be manipulated
- The need for special tools (keys, ladders, hoses, clothing such as to enter a radiation area)
- Communications (strategy and coordination) as well as whether one can be easily heard
- Special fitness needs Consideration of “realistic” accident sequence diversions and deviations (e.g., extraneous alarms, failed instruments, outside discussions, sequence evolution not exactly like that trained on). Note: This item is essentially addressing aleatory factors that could have important effects on performance. While analysts may choose to explicitly address these factors only when a more detailed investigation of the scenario is warranted or when they are explicitly part of the question being asked, it should be recognized that in some cases they could have strong effects. If they are not addressed explicitly in the analysis, it is suggested that their potential impacts be considered in assessing the HEP values.

5.3 NUREG-0700 Human-System Interface Design Review Guidelines

NUREG-0700 Human-System Interface Design Review Guidelines (NRC, 2002) specifies design guidelines for HSI elements and systems. It has been developed to support NRC staff in reviewing the HFE aspects of NPPs in accordance with the Standard Review Plan

(NUREG-0800). The guidelines can be used to review the design of HSIs and review a design-specific HFE guidelines document or style guide. The HFE guidelines are organized into four basic parts. Part I contains guidelines for the basic HSI elements: information display, user-interface interaction and management, and controls. These elements are used as building blocks to develop HSI systems to serve specific functions. Part II contains the guidelines for reviewing seven systems: alarm system, safety function and parameter monitoring system, group-view display system, soft control system, computer-based procedure system, computerized operator support system, and communication system. Part III provides guidelines for the review of workstations and workplaces. Part IV provides guidelines for the review of HSI support, i.e., maintaining digital systems.

The guidelines present detailed desirable characteristics for modern computerized HSI in form of review criteria, additional information and sources for the guidelines. The review criteria are not requirements, as discrepant characteristics may also be judged acceptable during the review process.

Appendix B of the document contains additional guidelines on important considerations in the design of information displays, user interface interaction and management, and computer-based procedure systems. Regarding the user interface interaction and management design process, the review guidelines state that *“HRA should be performed when the introduction of HSI technologies are likely to change interface management demands associated with risk-important tasks to determine the potential impact on reliability. The scope of these HRAs should address personnel actions resulting from the HSI technologies and their interactions with the rest of the plant.”* The guidelines state further that consideration should be given to the effects that changes in the HSI may have on the existing plant HRA, including:

- Whether the original HRA assumptions are valid for the upgraded design
- Whether the human errors analysed in the existing HRA are still relevant to the upgrade
- Whether the probability of errors by plant personnel may change
- Whether new errors not modelled by the existing HRA and PRA may be introduced
- Whether the consequences of errors established in the existing HRA may change.

Regarding the computer-based procedure system design process, the review guidelines state that:

- Any effects on performance caused by computerization of procedures should be analysed for their implications for those human actions modelled in a PRA.
- The analysis should consider the effects on human reliability of loss of computer-based procedures and transfer to paper-based procedures.

5.4 NUREG-0711 Human Factors Engineering Program Review Model

NUREG-0711 Human Factors Engineering Program Review Model (NRC, 2012) is used by the NRC to review the HFE programs of applicants for construction permits, operating licenses, standard design certifications, combined operating licenses, and license amendments in USA. Also internationally it is the main reference document followed in plant modernisation and new-built projects in the nuclear sector. The purpose of NRC’s reviews is to verify that the HFE aspects of the plant are developed, designed, and evaluated via a structured analysis founded on acceptable HFE principles.

NUREG-0711 clearly states that HRA should form part of the HFE process: “A HRA evaluates the potential for, and mechanisms of human error that might affect plant safety. Thus, it is an essential feature in assuring the HFE program goal of generating a design to minimise personnel errors, support their detection, and ensure recovery capability” (p. 43). According to the document, HRA and PRA should begin early in the design process in order to identify human actions most important to safety, which should be given greater attention in the system design and HFE process. The HRA should also be updated iteratively as the design progresses to ensure that actual important human actions are captured and considered. At the very least, the initial PRA/HRA, and the set of important human actions, should be finalized when the design of the plant and HSI are complete.

NUREG-0711 states that, for important human actions, the HSI design should minimize the probability that errors will occur, and maximize the probability that any error made will be detected. Important human actions should also be considered in the procedure development.

6. Conclusions

Digital HSIs in NPP control rooms are becoming common through modernisations and new-builds. Where paper-based procedures, hard-wired indicators and LCD displays and hard-wired analogue controls form the HSI in conventional analogue control rooms, in advanced digitalised control rooms they are replaced by computer-based procedures, integrated information systems and soft controls. This impacts the work of the operators in several ways: the working environment changes, new tasks emerge and the group dynamics and communication are modified. Introduction of digital HSI is believed to have positive effect on crew performance, reduce the workload of operators and is well accepted by the crews (Roth and O’Hara, 2001) in a way that has potential implications for human performance and reliability. Evidence of two forms of negative effects has also been found: (1) primary task performance, i.e. process monitoring and control, declines because operator attention is directed toward the interface management task, and (2) under high workload, operators minimize their performance of interface management tasks, thus failing to retrieve potentially important information for their primary tasks. Some studies also suggest that digital HSI-based tasks are inherently less reliable than tasks on discrete interfaces. The NCR guidelines NUREG-0700 and NUREG-0711 recognise that HRA should form part of the HFE/HSI design process and that existing plant HRAs should be reviewed when new HSI technologies are introduced to ensure that their effects to human reliability and plant safety are accounted for.

Traditional HRA methods cannot properly address the new aspects introduced by digital HSI. While their shortcomings in modelling the operator performance in advanced control rooms have been recognised (e.g. (OECD, 2008)), the development of new methods, or updating of old ones, has only started during recent years. One of the most mature developments in this area is the Korean HuRECA method, which extends the K-HRA (the Korean application of THERP and ASEP) method with digital HSI aspects. Still, up to 2015 it has not been applied in practice. In addition to HuRECA, the methodological progress during recent years has been performed mainly by Korean and Chinese researchers, including proposals for new PSFs and typical error types when using soft controls. Also the EPRI user group recognises the new methodologic HRA challenges introduced by the use of digital HSI, but so far the updates to EPRI HRA Calculator have been very minor.

A central goal for the HRA is to ensure that operator performance using the newer technology is at least as reliable as performance using the older technology. While the need for method development has been recognised and some progress is under way, further work in the field is needed to properly take the new aspects introduced by digital HSI into account in HRA. This includes e.g. reviewing of human errors in interacting with digital HSIs in non-nuclear industries, further exploring the human failure events using digital HSI, identifying and establishing empirical basis for quantification of PSFs suitable for digital HSI, validation studies using research simulators and development of guidance for including and quantifying these human failure events in the HRA and PRA (Boring, 2014).

References

Bearman, C. 2013 Key technology-related human factors issues. In C. Bearman, Naweed, A., Dorrian, J. (Eds.) Human factors in road and rail transport: Evaluation of ail technology: A practical human factors guide. Ashgate Publishing Ltd, pp. 9-22.

Bieber, C., P. Le Bot, E. Desmares, F. Cara and J.-L. Bonnet (1998). MERMOS: EDF's new advanced HRA method, Proceedings of the 4th International Conference on Probabilistic Safety Analysis and Management (PSAM4), 13-18 September 1998, New York, United States.

Blirando, C., Pesme, H. (2002). Guide Application de la méthode MERMOS d'évaluation probabiliste de la fiabilité humaine pour les EPS de référence, Note technique HT-54/02/020/A, EDF, France.

Boring, R. L. 2014. Human Reliability Analysis for Digital Human-Machine Interfaces: A Wish List for Future Research. PSAM12, Probabilistic Safety Assessment and Management Conference, 22−27 June 2014, Sheraton Waikiki, Honolulu, Hawaii, USA.

Desmares, E., Cara, F. (2000). MERMOS: justifications théoriques, HT-54/98/007/B, EDF, France.

Evans, R.A. 1976. Reliability optimization. In E.J. Henley and J.W. Lynn, Eds, Generic techniques in systems reliability assessment, Leyden, Netherlands: Noodhoff International Publishing, pp. 117-131.

Hamelink, C.J. 2006. Rethinking ICTs - ICTs on a Human Scale. European Journal of Communication, 21(3), pp. 389-396.

Hicking, E. M., Bowie, J. E. 2013. Applicability of human reliability assessment methods to human-computer interfaces. Cognition, Technology & Work, 15, 19-27.

Hollnagel, E., Woods, D.D., Leveson, N.G. 2006. Resilience engineering: Concepts and precepts. Aldershot, UK: Ashgate.

Jang, I., Kim, A.R., Jung, W., Seong, P.H. 2014. A Framework of Human Reliability Analysis Method Considering Soft Control in Digital Main Control Rooms. Proceedings of the Human Interface and the Management of Information thematic track (HIMI 2014), Part II, 16th International Conference on Human-Computer Interaction, HCII 2014, Heraklion, Greece. LNCS 8522, pp. 335–346.

Julius, J. A., Moieni, P., Grobbelaar, J., Kohlhepp, K. 2014. Next Generation Human Reliability Analysis – Addressing Future Needs Today for Digital Control Systems. PSAM12, Probabilistic Safety Assessment and Management Conference, 22−27 June 2014, Sheraton Waikiki, Honolulu, Hawaii, USA.

Jung, W. Kang, D. Kim, J. 2005. Development of a standard method for human reliability analysis (HRA) of nuclear power plants: level I PSA full power internal HRA, KAERI/TR-2961.

Kim, J. 2012. The HuRECA-based Human Reliability Analysis Procedure for Computer-based Control Room Actions. KAERI/TR-4385/2011.

Kim, J, Lee, S.j., Jang, S.C. 2011. HuRECA: Human Reliability Evaluator for Computer-based Control Room Actions. Transactions of the Korean Nuclear Society Autumn Meeting Gyeongju, Korea, October 27-28, 2011.

Lee, S.J., Kim, J., Jang, S-C. 2011. Human Error Mode Identification for NPP Main Control Room Operations Using Soft Controls. Journal of Nuclear Science and Technology 48(6), pp. 902-910.

Liinasuo, M., Porthin M. 2015. Updating Human Reliability Analysis - insights from Human Factors oriented control room validation. VTT Reseach report VTT-R-05278-14.

Li, P., Zhang, L., Chen, G., Dai, L. 2010. Study on Human Error Expanded Model and Context Influencing Human Reliability in Digital Control Systems. 2010 International Conference on E-Product and E-Entertainment, Henan 7-9 Nov 2010, doi 10.1109/ICEEE.2010.5660132

NRC, 2002. Human-System Interface Design Review Guidelines. NUREG-0700, Revision 2. U.S. Nuclear Regulatory Commission.

NRC, 2005. Good Practices for Implementing Human Reliability Analysis (HRA). NUREG-1792. U.S. Nuclear Regulatory Commission.

NRC, 2012. Human Factors Engineering Program Review Model. NUREG-0711, Revision 3. U.S. Nuclear Regulatory Commission.

OECD, 2008. HRA Data and Recommended Actions to Support the Collection and Exchange of HRA Data. OECD NEA CSNI WGRISK Report, NEA/CSNI/R(2008)9.

OECD, 2015. Establishing the Appropriate Attributes in Current Human Reliability Assessment Techniques for Nuclear Safety. OECD NEA CSNI WGRISK/WGHOF, NEA/CSNI/R(2015)1, March 2015.

O'Hara, J. M., Brown, W. S., Lewis, P. M. and Persensky, J. J. 2002. The Effects of Interface Management Tasks on Crew Performance and Safety in Complex, Computer-Based Systems: Overview and Main Findings (NUREG/CR-6690, BNL-NUREG-52656),Washington, DC.

Rasmussen, J. 1997. Risk management in a dynamic society: a modelling problem. Safety Science 27(2-3), 183-213.

Reason, J. 1990a. Human error. New York: Cambridge University Press.

Reason, J. 1990b. The Contribution of Latent Human Failures to the Breakdown of Complex Systems. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 327 (1241), 475–484.

Roth, E. and J. M. O'Hara, M. J. 2001. Integrating Digital and Conventional Human-System Interfaces: Lessons Learned from a Control Room Modernization Program (NUREG/CR-6749), Washington, DC.

Stojiljkovic, E. Glisovic, S., Grozdanovic, M. 2014. The Role of Human Error Analysis in Occupational and Environmental Risk Assessment: A Serbian Experience. Human and Ecological Risk Assessment: An International Journal 21(4), pp. 1081-1093.

Swain, A.D. 1989. Comparative evaluation methods for human reliability analysis. Report No. GRS-71. Gessellschaft für Reaktorsicherheit, Köln, Germany.

Swain, A. D., Guttmann, H. E., 1983. Handbook of Human-Reliability Analysis with Emphasis on Nuclear Power Plant Applications. U.S. Nuclear Regulatory Comission. NUREG/CR-1278.

Tian, X., Jian, X. & Liu, J. 2014. Research on HRA methods and application for digital human-system interfaces design. PSAM12, Probabilistic Safety Assessment and Management Conference, 22−27 June 2014, Sheraton Waikiki, Honolulu, Hawaii, USA.

Whaley, A.M., Xing, J., Boring, R.L., Hendrickson, S.M.L., Joe, J.C., and Le Blanc, K.L. 2012. Building a Psychological Foundation for Human Reliability Analysis, Draft NUREG-2114. Washington, DC: U.S. Nuclear Regulatory Commission.