Research on HRA methods and application for digital human-system interfaces design

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ABSTRACT

Operators of nuclear power plant (NPP) play a vital role in the productive, efficient, and safe generation of electric power. More widespread use of digital technology is expected in the nuclear plants, especially main control rooms (MCR). Operators face a significant challenge in digital control rooms that will be produced at various stages of instrumentation and control modernization. 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 based on our research and other published research.

Human reliability analysis (HRA) is a technique to evaluate the reliability of the human actions, including those actions taken by the operators in the main control room. HRA can seek to evaluate the potential for, and mechanisms of, human error that may affect plant safety. Thus, it is an essential element in achieving the Human factors engineering (HFE) design goal of providing HSI that will minimize personnel errors, allow their detection, and provide recovery capability.

The paper discusses the findings of an investigation to operating and as-building plants in China installed with fully digital I&C systems. Interviews were made with the simulator instructors, control room operators, designers of Main Control Room (MCR) about the control layout, computer interface, alarms, and procedures to understand the effects on operator performance. Specific performance shaping factors (PSFs) for digital I&C control room are proposed to be considered in HRA methods. It is also suggested how to apply the specific PSFs in digital HFE/HSI design process.

Key Words: NPP, Human factors engineering, HFE, Human reliability analysis, HRA

1 INTRODUCTION

Nowadays more widespread use of digital technology exists in the operation and design nuclear power plants. Digital human-system interfaces (HSIs) are also introduced into NPPs. Advanced main control rooms (MCR) is substituted for conventional MCR as the vital parts of a nuclear power plant with which personnel interact in performing their functions and tasks. Operators face a significant challenge in digital control rooms. A study [1] about digital and conventional HSIs by NRC indicated that the new HSIs provided positive support for crew performance, reduced workload, and were well accepted by the crews. While another finding of the study is one of the more significant effects introduced by the advanced HSI systems was on crew structure and communication. These changes of crew structure and communication have potential implications for human performance and reliability. A research [2] by BNL about Computer-Based Systems 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. More researches have demonstrated that many uncertainties about human performance can be induced by the use of the digital HSIs.

To reduce the negative effect digital HSIs for human performance, good human performance goals should be satisfied. Some guidelines were submitted 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/CR-0711 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 MCR should be able to consider the possible effects of new HSIs on the operator performances. But few studies are conducted so far in the HRA domain to reflect the 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 THERP handbook (NUREG/CR-1278, 1983), in which the data are collected 20 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.

The objective of this paper is to characterize the salient features of the digital HSIs, understand the effects on operator performance, raise specific performance shaping factors (PSFs) in HRA methods for the digital HSIs, and give a proposal to apply the specific PSFs in digital HFE/HSI design process.

2 THE CHARACTERISTICS OF DIGITAL HSIS

Currently, nuclear power plants in many countries are rapidly developing digital technology and digital HSIs is being applied in their control rooms. A survey of operating and constructing digital nuclear power plants in China 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.

Table I summarizes the general characteristics of a well-designed HSIs.

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

2.1 Graphic-based Display System

Digital HSIs provide information of the process in form of readily and quickly understandable graphics-based display system on visual display units (VDUs) of workstations and on large screens. It annunciates incipient faults in the plant process and provides support for fast fault rectification.

Operators monitor the plant through screen-based displays selected from networks of hundreds or even thousands of display pages. Control of plant equipment is accomplished through soft controls that can be accessed through computer workstations.

The displays and sheets on the workstation are state-of-the-art graphic monitors using the windowing philosophy. The data are displayed in such a way that the operator can at a glance see the state of the data being displayed (e.g. back-up value, invalid value, operating state, etc.).

The display system supports each operator to choose the functions with which she/he is the most comfortable. The following are examples of the display formats available:

1. Overviews displays
2. Plant and Process displays,
3. Status displays,
4. Operator aid displays/sheets,
5. Dynamic logic and sequence Diagrams,
6. Trends, etc.

The display system follows the HFE principles of the display layout and organization in NUREG-0700.

2.2 Computer-based Alarm System

Digital HSIs contains computer-based alarm systems used to analyze, process, and reduce alarms. This requires HSI facilities to interface with alarms systems to sort alarms, view suppressed alarms, query alarm logic, modify set-points, and establish temporary alarms.

The alarm function allows fast recognition of importance in terms of necessary operator response. Classification of alarms allows for a fast recognition of their safety importance and alarm areas provide for grouping alarms according to their process system.

Alarms are indicated on the workstation screens in Alarm Sequence Display, Common Alarm Indication in the header of displays, and Operating displays, accompanied by an acoustic signal.

2.3 Computer-based Procedure System

In the operating plant investigated, operators still use paper procedures, but procedures in other constructing plants have been computerized in China.

Computer-based procedure systems provide access and display plant data referenced by procedure steps and resolve the logic of individual steps.

Computer-based procedures are likely to allow control actions are taken directly from the procedure display, or they may be semi-automated, with the operator authorizing the procedure’s embedded control functions to take actions.

3 HRA CONSIDERATIONS AND PERFORMANCE SHAPPING FACTORS IN DIGITAL MCR

Fig. 1 reveals the interrelation of HSIs’ characteristics and Human Response Model, and improvement of HRA application is focus on alarms, displays and procedures.

3.1 Discussion of the HRA Methods

HRA is performed as of NPP PSA to produce probability estimates for human error events (HEPs). In determining HEPs, most HRA methods account for the contextual aspects that contribute to human failure through the acknowledgment of plant conditions and performance-shaping factors (PSFs) potentially present during a task execution. The process used in most HRA methods to estimate an HEP for a task of interest is to first, estimate the base HEP (referred to as a nominal or conditional probability by some methods); second, to define the set of PSFs that affect that task; and third, to identify the significance (i.e. the size of the effect) of each PSF and to combine the effects of these PSFs to modify the base HEP for that task. Such a procedure is employed in many conventional HRA methods, e.g. THERP, ASEP, HCR, CREAM, HEART, CAHR and SPAR-H.

Most conventional HRA methods provided analysis data acquired by operating the current plants and simulators. It means that those methods do not pay attentions to the influence of digital HSIs. As a result, conventional HRA methods have limitations in considering the possibility of operators' unsafe actions due to digital HSIs and integrating with HFE activities in digital HSIs design.

To incorporate the interdependency of digital I&C systems and human operators, we believe that the current HRA methods should be modified and more applicable quantitative models for the human error assessment in digital HSIs, are necessary.

3.2 PSFs

As study results, new PSFs are recommended to improve in conventional HRA methods. The new PSFs are the three following:

PSF_D - used to evaluate display systems;

PSF_A - used to evaluate alarm systems;

PSF_P - used to evaluate computer-based procedures systems.

According to the principles in table II, new PSFs can be quantified and applied to evaluate HEP in digital HSIs.

Table I. General characteristics of well-designed HSIs and the relevant Human Response Model

<table>
<tr><th colspan="2">General Characteristics of a Well-Designed HSI</th><th rowspan="2">Human Response Model</th></tr>
<tr><th>Characteristics</th><th>Description</th></tr>
<tr><td>• Accurately represents the plant</td><td>To be consistent with and supports a user’s understanding and awareness of the system, its status, and the relationship between individual system elements</td><td rowspan="13">• 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</td></tr>
<tr><td>• Meets user expectations</td><td>To accord with HFE principles and fully enhance the work efficiency</td></tr>
<tr><td>• Supports situation awareness and crew task performance</td><td>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</td></tr>
<tr><td>• Minimizes secondary tasks and distractions</td><td>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</td></tr>
<tr><td>• Balances workload</td><td>Optimize function allocation between human and machine to maximum enhance the human-machine efficiency</td></tr>
<tr><td>• Is compatible with users’ cognitive and physical characteristics</td><td>To accommodate human physiological and cognitive characteristics and limitations such as visual/auditory perception and anthropometrics and biomechanics</td></tr>
<tr><td>• Provides tolerance to error</td><td>To minimize the occurrence of user errors and provides a way for users to detect and correct errors when they do occur</td></tr>
<tr><td>• Provides simplicity</td><td>Simplest design to meet the task requirements and potentially distracting features such as excessive decorative detail or nonfunctional icons should be avoided</td></tr>
<tr><td>• Provides standardization and consistency</td><td>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</td></tr>
<tr><td>• Provides timeliness</td><td>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</td></tr>
<tr><td>• Provides openness and feedback</td><td>Help users easily understand and track the plant process</td></tr>
<tr><td>• Provides guidance and support</td><td>Provide an effective “help” function on line or off line to help users understand and interact with the HSI</td></tr>
<tr><td>• Provides appropriate HSI flexibility</td><td>Computer-based HSIs can be tailored to better meet the demands of the user’s ongoing tasks and to accommodate personal preferences</td></tr>
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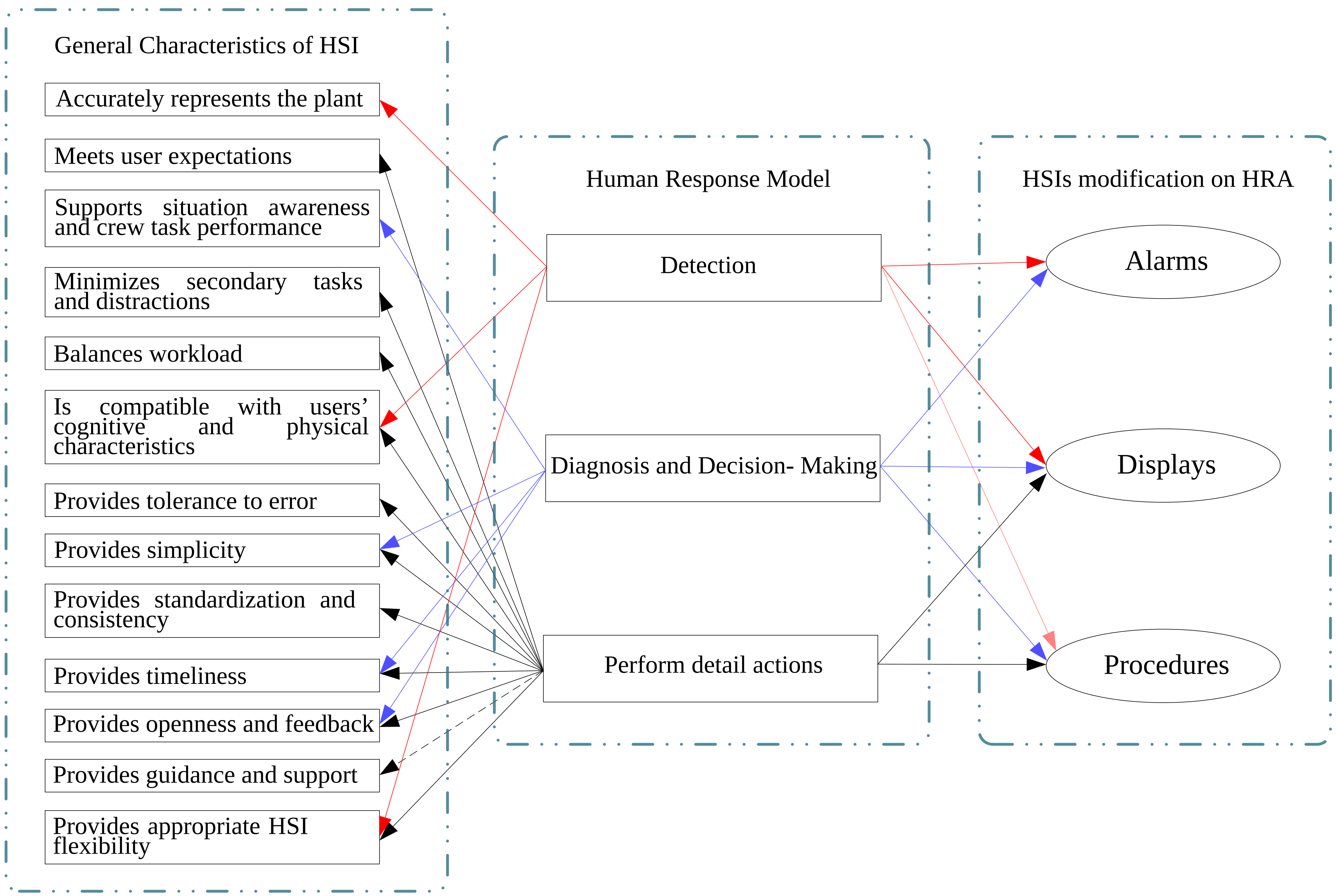

Figure 1. Interrelation of HSIs' characteristics and the Human Response Model

Table II. The quantification principles of new PSFs

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.	

4 THE APPLICATION OF NEW PSFS

4.1 Improvement of HRA Methods

To simplify description, PSF_{HSI} ($PSF_{HSI}=PSF_D \times PSF_A \times PSF_P$) will be introduced to modify convention -al HRA methods such as HCR, THERP and SPAR-H.

For HCR model, analysts can affirm the coefficient of K_3 (a PSF related quality of operator/plant interface) by the value of PSF_{HSI}. When PSF_{HSI} is less than 1, the coefficient of K_3 is -0.22 (Excellent); when PSF_{HSI} is equal to 1, the coefficient of K_3 is 0 (Good); when PSF_{HSI} is greater than 1, the coefficient of K_3 is 0.44 (Fair);

For improvement of THERP, the BHEP should be modified by the PSF mentioned in THERP book and PSF_{HSI}.

For SPAR-H, PSF_{HSI} can be applied to affirm PSF level of ergonomics/HMI the same as HCR model.

4.2 Integration of HRA with Design

It is known that errors resulting from human factors deficiencies such as poor control room design, procedure, and training are an important contributing factor to NPP incidents and accidents. Therefore a good HFE in a NPP is an essential part to ensure public health and safety.

The HFE Program Review Model (NUREG-0711, 2004) consists of twelve review elements which provide detailed review criteria of HFE. HRA is required as one of 12th elements.

To integrate the HRA results with the HFE design of digital HSIs, the HRA should be conducted through a systematic process in identification of the performance shaping factors, task analyses, quantification method, and dependence analysis. The identified critical actions and risk important actions in HRA/PSA process should have enough detailed information to support HFE amendments through human system interface design, procedure development and training. After the HFE design review is completed, there is a need to re-evaluate and possibly re-quantify the HRA/PSA [3].

HRA methods improved by New PSFs are applied HFE activities of digital HSIs. It has much more pertinence and maneuverability to modify digital HSIs design.

5 CONCLUSIONS

The digital HSIs applied in NPPs offer potential for improved operator performance, however if not appropriately applied, they may introduce new burdens for the operator. Existing HRA methods are 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.

In this paper, new PSFs are introduced into conventional HRA methods and used for the evaluation of human performance in digital HSIs. The HCR and THERP improved 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 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.

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