IDENTIFICATION AND EVALUATION OF HUMAN FACTORS ISSUES ASSOCIATED WITH EMERGING NUCLEAR PLANT TECHNOLOGY

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This study has identified human performance research issues associated with the implementation of new technology in nuclear power plants (NPPs). To identify the research issues, current industry developments and trends were evaluated in the areas of reactor technology, instrumentation and control technology, human-system integration technology, and human factors engineering (HFE) methods and tools. The issues were prioritized into four categories based on evaluations provided by 14 independent subject matter experts representing vendors, utilities, research organizations and regulators. Twenty issues were categorized into the top priority category. The study also identifies the priority of each issue and the rationale for those in the top priority category. The top priority issues were then organized into research program areas of: New Concepts of Operation using Multi-agent Teams, Human-system Interface Design, Complexity Issues in Advanced Systems, Operating Experience of New and Modernized Plants, and HFE Methods and Tools. The results can serve as input to the development of a long-term strategy and plan for addressing human performance in these areas to support the safe operation of new NPPs.

KEYWORDS : Human Performance, Human Factors Engineering, Ergonomics, Control Rooms, Plant Operations, Design Methods

1. INTRODUCTION

Over two decades have passed since a new commercial nuclear power plant (NPP) has been built in the United States (U.S.). There is now a renewed interest in nuclear energy and there are plans to construct new plants within the next decade. The new plant designs, such as the Economic Simplified Boiling Water Reactor (ESBWR), AP1000, Economic Pressurized Reactor (EPR), are different from the plants currently operating in the U.S. in several important respects, including reactor design, instrumentation and control (I&C) systems, and human-system interfaces (HSIs).

First, the new designs currently being considered for near-term deployment in the U.S. are predominantly light water reactors (LWRs). They are improved from older LWRs and include passive safety features. Designs for possible future deployment include non-LWR designs, such as the Pebble Bed Modular Reactor (PBMR). PBMR operators may be expected to concurrently control multiple modules, which could be in different operating states, from a common control room. Looking longer-term, the U.S. is participating in an international effort to identify and develop new reactor technologies for use decades from now. These "Generation IV" plants are likely to be significantly different from the new plant designs currently being considered.

Second, while currently operating plants employ predominantly analog I&C technology, the new NPPs use digital I&C technology. Digital I&C systems are expected to provide functions and capabilities that are vital for plant safety. The I&C system monitors the plant processes and various barriers that prevent release of radioactive material to the public. Together with plant personnel, the I&C system is the "central nervous system" of the plant. It senses basic parameters, monitors performance, integrates information, and makes adjustments to plant operations as necessary. It also responds to failures and events. New digital systems perform sophisticated equipment condition monitoring and contain diagnostic and prognostic functions. They also provide the capability to implement control algorithms that are more advanced than have been used in plants to date, e.g., techniques for optimal control, nonlinear control methods, fuzzy logic, neural networks, adaptive control, and state-based control schemes. Application of these advanced techniques will lead to more intricate control of plant systems and processes and greater complexity. Digital I&C systems also provide the capability for new approaches to automation that make greater use of interactions between personnel and automatic functions. These innovations provide the basis to operate more closely to performance margins.

The third key difference between current and new plant designs is their HSIs. The HSIs in most of the plants currently operating in the U.S. use hardwired controls (e.g., switches, knobs, and handles) and displays (e.g., alarm tiles, gauges, linear scales, and indicator lights). They are arranged on control boards and operators walk the boards to accomplish their tasks using paper procedures. New NPPs are designed with computer-based HSIs organized into sit-down workstations. Personnel 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. Procedures are likely to be computer-based and control actions may be 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.

Taken together, the advances in reactor design, I&C technology, and HSIs will provide the technological infrastructure to develop concepts of operations and maintenance that are different from currently operating NPPs.

The potential benefits of these new technologies are compelling and should result in more efficient operations and maintenance. However, if poorly designed and implemented, there is the potential to negatively impact performance, increase errors, and reduce human reliability resulting in a detrimental effect on safety [1].

The U.S. Nuclear Regulatory Commission (NRC) staff reviews the human factors engineering (HFE) programs of applicants for construction permits, operating licenses, standard design certifications, and combined operating licenses. The purpose of these reviews is to help ensure safety by verifying that acceptable HFE practices and guidelines are incorporated into an applicant's HFE program. This helps to ensure that personnel performance and reliability are appropriately supported.

The NRC's Standard Review Plan (NUREG-0800) provides high-level guidance for the conduct of HFE reviews in Chapter 18, Human Factors Engineering [2]. Detailed review criteria are contained in the HFE Program Review Model (NUREG-0711) [3] and in the HSI Design Review Guideline (NUREG-0700) [4]. To perform safety reviews of new plants, regulatory personnel will have to understand the safety implication of the new designs and their new technology. In addition to new technology, applicants will be designing their plants using new HFE methods and tools and these are also evaluated as part of the review process. Thus, to help ensure its HFE regulations and review guidance are up-to-date, the NRC is conducting research to (1) identify potential human performance issues related to the introduction of these new, emerging technologies in NPPs and the methods used to develop them; and (2) prioritize the issues to determine their regulatory importance [5,6]. Once important issues are identified, the result can be used to inform the NRC's research planning to develop HFE review guidance to support new reactor reviews. This paper describes the results of the issue identification and prioritization effort.

2. METHODOLOGY

2.1 Issue Identification

The term "issue," as used in this paper, refers to: (1) an aspect of new NPP development or evaluation for which available information suggests that human performance may be negatively impacted; (2) an aspect of new reactor development or design for which it is suspected that human performance may be impacted, but additional research and/or analysis is needed to better understand and quantify that impact; and (3) a technology or technique that will be used for new plant design or implementation for which there is little or no review guidance. Our approach to issue identification was to examine current industry developments and to make projections into the near- and longer-term future. This was done by considering developments and trends in reactor design, I&C technology, HSI technology, and HFE methods and tools. With respect to the latter, the HFE methods and tools that are applied to NPP design and evaluation are constantly evolving. Since NRC HFE reviews evaluate the design processes used, these developments have implications for the review criteria needed as well as the methods used by the staff to conduct reviews.

A variety of different data sources were used, including existing technical literature, contacts with relevant organizations, relevant industry workshops, and site visits to control room simulators reflecting the latest technology. Each is briefly described below.

Technical literature was a main source of information and included reports from organizations such as the U.S. NRC, U.S. Department of Energy, and the Halden Reactor Project. Conference reports and journal articles were reviewed as well. The second source of information was obtained from organizations involved with new reactors. Twenty-one organizations from 11 countries and two international organizations were contacted to obtain pertinent information. They reflected a cross section of the nuclear industry including vendors, utilities, regulators, research laboratories, and universities. Another source of information came from several international workshops addressing the HFE aspects of new reactors. An example was the Workshop on Instrumentation, Controls and Human-machine Interface Technology [7]. Finally, site visits were made to control room development simulators reflecting the latest technology, e.g., the FITNESS (Functional Integrated Treatments for Novative Ecological Support System) simulator developed by Electricity de

France (EdF) and located in Septen, France.

A total of sixty-four issues meeting the criteria above were identified. These issues are listed in Table 1. The issues were evaluated and prioritized to identify those of greater importance with respect to regulatory considerations.

2.2 Issue Evaluation and Prioritization

An issue evaluation and prioritization was performed by 14 independent subject matter experts (SMEs). The SMEs possessed expertise in HFE, I&C, plant design, operations, and risk/safety assessment. The SMEs represented a cross section of the industry and included regulators, vendors, utility personnel, and researchers. The procedures to evaluate the issues are described next followed by a discussion of the method used to prioritize them.

2.2.1 Issue Evaluation Procedures

The SMEs evaluated the issues in two phases. In Phase 1, each SME was sent: a document describing the issues and the issue identification methodology. In addition, they were given an evaluation form that contained instructions and rating dimensions. For the purposes of evaluation, the issues were divided into two groups. The first group was referred to as the human performance issues and included all of the issues except those related to HFE methods and tools. Methods and tools had to be evaluated differently than the technology-oriented issues.

Human performance issues were evaluated on two dimensions: safety significance and immediacy (how soon an issue needs to be addressed). The safety considerations given to the SME were derived from a safety significance evaluation methodology developed in prior research [8]. The methodology was developed based on the criteria contained in 10 CFR 50.59 [9] for the review of plant modifications. The SMEs were asked to consider whether:

- The issue increases the probability of occurrence of an accident
- The issue increases the consequences of an accident
- The issue increases the probability of occurrence of a malfunction of equipment important to safety
- The issue increases the consequences of a malfunction of equipment important to safety
- The issue creates the possibility of an accident of a different type than any evaluated previously in the industry
- The issue creates the possibility of a malfunction of equipment important to safety when the malfunction is of a different type than any evaluated previously in the industry
- The issue reduces the margin of safety

Safety was evaluated on the following three-point scale. An answer of "yes" to any of the questions listed above resulted in a rating of "1" indicating a high likelihood of safety significance. If there weren't any "yes" responses to the above questions and at least one was answered "probably," a rating of "2" was given indicating the issue was probably safety significant. A "2" could also be given if the issue represented a significant departure from the status quo and an impact on safety was suspected. Finally a rating of "3" was given if the answer to all of the above questions was "unlikely" indicating a low likelihood of safety significance. In addition to the safety rating, SMEs were asked to provide a brief description of the basis for their evaluation.

Each issue in the HFE methods and tools group was evaluated in terms of its likely importance to effective regulatory review. This dimension was evaluated using the following three-point scale: "1" for high importance, "2" for moderate importance, and "3" for low importance.

SME's evaluated all the issues on immediacy. This evaluation dimension identified how soon an issue needs to be addressed. This dimension was evaluated using the following two-point scale: "1" for near-term (guidance is needed for licensing activities within the next five years) and "2" for longer-term (guidance is not needed for licensing activities within the next five years).

Following their Phase 1 evaluations, each SME returned the completed forms to the project staff. The ratings were evaluated to identify areas of low agreement. In Phase 2, a meeting of the SMEs was held to discuss those issues for which agreement was low. The issues were discussed and SMEs were encouraged to provide the rationale and basis for their ratings. The SMEs were given the opportunity to modify and finalize their ratings based on these discussions.

2.2.2 Issue Prioritization

The final SME ratings were used to determine each issue's priority. This was accomplished in two steps. First, a "summary rating" for each evaluation dimension was calculated. With respect to safety significance and regulatory effectiveness dimensions (both rated on a three-point scale), the average of all SME ratings was calculated for each issue. The following criteria were used. An average of 1.5 or less was assigned a summary

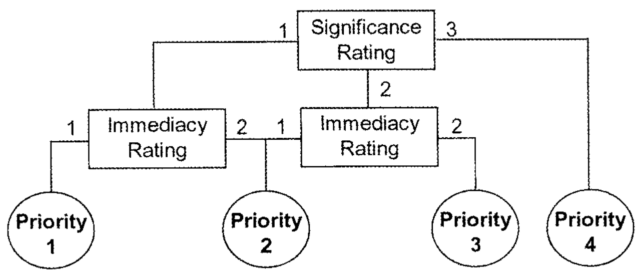

Fig. 1. Issue Prioritization Based on Ratings of Safety Significance and Immediacy

Table 1. Issues in Each of the Four Priority Categories with Safety Significance/Regulatory Effectiveness (S/E) and Immediacy (IM) Ratings

Priority	Issue	S/E	IM
1 (N=20)	Level of Automation	1	1
	Operations Under Conditions of Degraded I&C	1	1
	Design and Evaluation of Digital Systems and Software	1	1
	Operating Experience and Lessons Learned	1	1
	Validation of Integrated Systems	1	1
	Performance-based Methods	1	1
	Information System Design	1	1
	Computer-based Procedures	1	1
	Interfaces to Automation	1	1
	Modeling and Measurement of Effective Team Performance	1	1
	Design Process for Higher-level Interfaces	1	1
	Control Design	1	1
	Alarm System Design	1	1
	Evaluating the Effects of Advanced Systems	1	1
	Training and Qualifications	1	1
	HRA Methods for Advanced Systems	1	1
	Methods for Early Consideration of HFE in Plant Design	1	1
	Sensors and Condition Monitoring	1	1
	Interface Management Design	1	1
	Increase in Complexity and Opacity	1	1
2 (N=17)	Guidance for the Review of Intelligent HSIs	1	2
	Safety Culture	1	2
	Intelligent Agents	2	1
	Managing Design and Construction Errors	2	1
	Unanticipated Impact of Technology	2	1
	Display Design	2	1
	HSI Design Deficiencies	2	1
	Development of New Task Analysis Methods	2	1
	Computerized Operator Support Systems	2	1
	Physical Protection, Security, and Safety	2	1
	Availability of Operating Experience of Gen III Reactors	2	1
	Change in the Concept of Maintenance	2	1
	Digital Communication Networks	2	1
	Participatory Ergonomics	2	1
	Computation and Simulation	2	1
	Diagnostics and Prognostics	2	1
	Understanding How HSIs are Really Used	2	1
3 (N=17)	Reduced Staffing	2	2
	Managing Human Error In Operations And Maintenance	2	2
	Ease of Making System Modifications	2	2

Priority	Issue	S/E	IM
	New Hazards	2	2
	Crew Member Roles and Responsibilities	2	2
	Human Performance Models	2	2
	Continuous Fueling	2	2
	Modular Plants	2	2
	Different Reactivity Effects	2	2
	Advanced Controls	2	2
	Simplified Maintenance Practices	2	2
	Changing Testbeds	2	2
	Post-core-melt Mitigation	2	2
	Increased Power Operations	2	2
	Development of New Function Allocation Methods	2	2
	Rapidly Changing HSI Technology	2	2
	Functional Staffing Models	2	2
4 (N=10)	Computer-supported Collaboration	3	2
	Knowledge Gap between Licensee Organization and Supplier	3	2
	Development/Application of Knowledge Engineering Techniques	3	2
	Collection/Analysis/Use of Real-time Human Performance Data	3	2
	Passive Safety Systems	3	2
	More Frequent Changes Due to Obsolescence	3	2
	Quantitative Human Performance Criteria	3	2
	Rapid Prototyping	3	2
	Vendor Diversity and Its Impact on Operational Philosophy	3	2
	Modular Construction	3	2

rating of "1." An average between 1.5 and 2.0 was assigned a summary rating of "2." An average of greater than 2.0 was assigned a summary rating of "3." For the immediacy dimension (rated on a two-point scale) the summary rating was most frequent response. In the case of ties (i.e., 7 each), a summary rating of "2" was assigned.

In the second step, the ratings were combined using the logic shown in Figure 1 to place each issue in one of four priority levels. Priority 1 issues are the most important and Priority 4 issues are the least important. The issues in each of the four priority categories are listed in Table 1.

The Priority 1 issues are briefly described in the next section. Descriptions of the Priority 2 through 4 issues can be obtained elsewhere [6].

3. TOP PRIORITY ISSUES AND RESEARCH PROGRAM AREAS

Many of the individual issues are related to one another. Therefore, in this section we have organized individual research issues into five broad research program areas:

- New Concepts of Operation using Multi-agent Teams (COP)
- HSI Design (HSI)
- Complexity Issues in Advanced Systems (CI)
- Operating Experience of New and Modernized Plants (OE)
- HFE Methods and Tools (M&T)

The issues associated with each program area are shown in Table 2. In this section the research program areas are described.

3.1 New Concepts of Operation using Multi-Agent Teams

The issues in this research program area are shown in Table 3. These issues address the changing role of personnel and automation in advanced systems and its impact on concepts of operations (CONOPS). A major impact on CONOPS will come from advances in automation,

Table 2. Integration of Priority 1 Issues into Research Program Areas

	Research Program Areas*				
Issue	COP	HSI	CI	OE	M&T
Level of Automation	V				
Operations Under Conditions of Degraded I&C		V			
Design and Evaluation of Digital Systems and Software					V
Operating Experience and Lessons Learned				V	
Validation of Integrated Systems					V
Performance-based Methods					V
Information System Design		V			
Computer-based Procedures		V			
Interfaces to Automation		V			
Modeling and Measurement of Effective Team Performance	V				
Design Process for Higher-level Interfaces					V
Control Design		V			
Alarm System Design		V			
Evaluating the Effects of Advanced Systems					V
Training and Qualifications	V				
HRA Methods for Advanced Systems					V
Methods for Early Consideration of HFE in Plant Design					V
Sensors and Condition Monitoring	V				
Interface Management Design		V			
Increase in Complexity and Opacity			V		

*Research Program Topic abbreviations are defined in the paper.

Table 3. Priority Issues Related to New Concepts of Operation using Multi-agent Teams

Issue	Description
Level of Automation	Since automation helps to define the role of the personnel and can be applied to essentially any task, it can affect performance of any of the generic primary tasks. Its most significant impact is on situation assessment, especially when automated activities are not clearly visible to operators.
Modeling and Measurement of Effective Team Performance	While teamwork is essential to effective human performance and plant safety, it is generally a neglected aspect of test and evaluation. Understanding teamwork and how to measure it is even more important with the advent of expected staffing reductions and increased application of automation. Team performance is particularly important in the distributed control environment.
Training and Qualifications	The activities involved with training and qualifications development provide the foundation for personnel to perform their new roles in advanced plant designs and for understanding the new I&C and HSI technology. Thus, training and qualifications development will have broad effects on primary tasks and team performance.
Sensors and Condition Monitoring	The availability of new sensors and condition monitoring capabilities will have a direct impact on monitoring, detection, and situation assessment. The complementary concerns of information overload (due to the proliferation of sensors) and potential masking of raw data due to data integration were identified as important aspects of this issue.

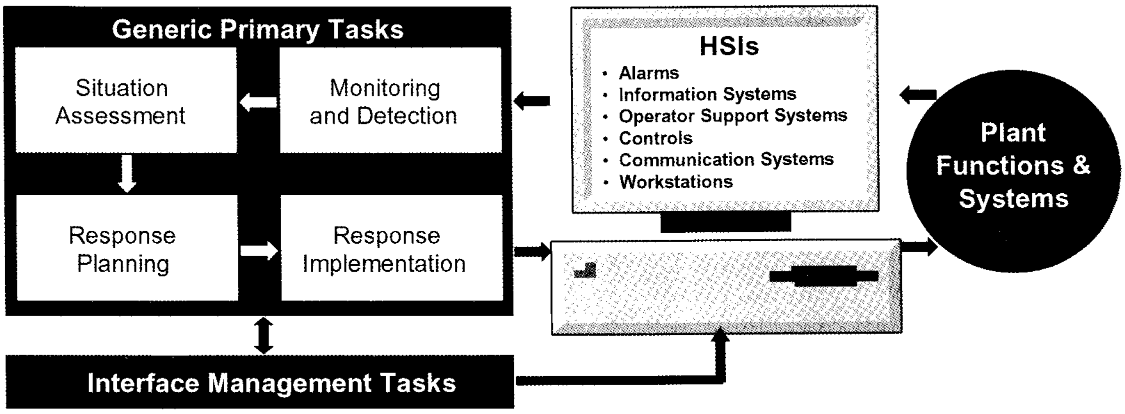

Fig. 2. Operator Tasks

particularly in automation's role as a team member. The operation of a nuclear power plant depends on the coordinated activity of multi-person teams to monitor and control plant systems. The new technology available offers increases in the automation of all aspects of plant operations. To understand the extent of automation's impact we need to consider the tasks that operators perform.

Nuclear plant operators perform two types of tasks: primary tasks and interface management tasks. Primary tasks include activities such as monitoring plant parameters, following procedures, responding to alarms, starting pumps, and aligning valves. Primary tasks have a number of common cognitive elements referred to as generic primary tasks. They are monitoring and detection, situation assessment, response planning, and response implementation (see Figure 2). Breakdowns in any of these generic primary tasks can lead to a human error. To perform their primary tasks, personnel must successfully perform "interface management tasks." In a computer-based control room, these tasks include activities such as navigating the information system, accessing information, and arranging information on monitors. In part, these tasks are necessitated by the fact that operators view only a small amount of information at any one time through the workstation displays. Therefore, they must perform interface management tasks to retrieve and arrange the information. The distinction between primary and secondary tasks is important because of the ways they can interact. For example, secondary tasks create workload and may divert attention away from primary tasks and make them difficult to perform [12]. Thus, secondary tasks are important and need to be carefully addressed.

Automation can be applied to all of these tasks, e.g., alarm systems automate monitoring and detection, computerized operator support systems automate aspects of situation assessment, computer-based procedures automate aspects of response planning, and high-level controls and process automation provide automatic response implementation. In modern digital systems, operators and automation share in the performance of these tasks. In some systems, the level of automation can be changed dynamically in response to operator workload or situational factors. Thus, increasingly, nuclear plants are monitored and controlled by teams consisting of human and machine agents.

The advances in automation and multi-agent teams set the stage for significant changes in CONOPS. The CONOPS for NPPs has changed very little over the first half-century of commercial nuclear power generation. While the CONOPS continuously improved over time, no major changes have occurred. And in all likelihood, little will significantly change with the current fleet of new reactors. However, the technology currently available provides the infrastructure to support changes in plant CONOPS that will help meet longer-term goals of more economical, efficient, and safe operations. Examples of potential changes include operation of a plant by a single operator and operation of multi-modular reactors by a single crew. Looking longer term, improved automation and condition monitoring can set the stage for functional decentralization, e.g., a plant is staffed with a very small number of on-site personnel, possibly limited to technicians who oversee the highly automated operation and occasionally perform minor operations and maintenance tasks. Responsibilities for other functions are handled by off-site specialists who either come to the site when needed (such as for maintenance) or perform their tasks remotely, e.g., emergencies may be handled by highly trained crisis management teams.

Research is needed to support the effective integration of all agents and avoidance of many of the negative effects on human performance of poorly designed automation, such as loss of vigilance, low workload, complacency, and poor operator situation awareness. A better understanding of these issues is needed to define new CONOPS and the multi-agent teams that will work together to ensure efficient and safe operations. Aspects of human-machine teams that will be addressed include:

- defining the relative roles of human and automatic resources in static and dynamic situations
- identifying the requirements for monitoring and communication between team members including human-human and human-automation interactions
- identifying principles of smooth transition of work between human and automation agents
- identifying the training and qualification implications to support new CONOPS

3.2 Human-System Interface Design

The issues in this research program area are shown in Table 4. To perform their tasks, operators obtain information and take actions through the HSI. The characteristics and functions of HSIs have evolved very rapidly and as can be seen from Table 4, the changing nature of nearly all the HSI resources has been identified as high-priority issues.

Some of the general trends in HSI evolution are that:

- information is generally presented at hierarchical levels, e.g., plant overview information at the top and detailed system and component information at the bottom
- a great deal of decision support is provided, e.g., alarm reduction processing to make the number of important alarms manageable, and computer-based procedures

Table 4. Priority Issues Related to Human-system Interface Design

Issue	Description
Alarm System Design	Since alarm systems monitor the plant and often are the initial means by which plant disturbances are brought to the operator's attention, its design directly affects monitoring, detection, and situation assessment. One specific concern identified is the potential exacerbation of the alarm 'overload' problem resulting from the additional alarms associated with digital systems. The challenges and difficulties of effective alarm system design are highlighted by the fact that human performance issues related to alarm system design persist in the nuclear industry and in many other industries despite efforts to address them.
Information System Design	Information is at the core of human performance and is the primary determinant of monitoring, detection, and situation assessment. Poor information systems design will significantly impair these cognitive functions. Related considerations are information overload and the extent to which secondary task "costs" are incurred while accessing information.
Control Design	Operators directly impact the plant through the actions they take at the controls, thus, their design directly impacts response implementation tasks. Advanced controls (such as controlling plant processes, systems, and components through screen-based controls) will also affect the secondary task demands associated with accessing and manipulating them.
Interfaces to Automation	As the levels of automation in new plants are varied, the HSI design for interacting at the different levels of automation is a significant aspect of new plant design that is quite different from current designs. HSIs serve to help operators maintain awareness of the automation and monitor its effects. In addition, the HSIs will provide the means for an operator to direct automation and interact with it.
Computer-based Procedures	Since NPP personnel actions are largely governed by procedures, their design directly affects response-planning tasks. As procedure functions are increasingly automated, many of the human performance issues associated with automation pertain to them as well. Other HFE concerns associated with computer-based procedures use are usability, navigation, and error detection.
Interface Management Design	The design of the interface management features of the HSI has a direct impact on operator workload. Performing interface management tasks requires operators to divert attention and effort away from their primary tasks, thus, the primary task may be negatively impacted.
Operations Under Conditions of Degraded I&C	Since the I&C system is the primary means by which personnel obtain information about the plant, its degradation will have a significant impact on the operator's ability to monitor the plant, detect disturbances, assess the plant situation, and implement their responses. While major I&C failures are likely to be recognized by personnel, more subtle degradations may be overlooked which could lead to incorrect assessments of the plant condition. Another consideration is the need to use backup HSIs in the event of I&C failure.

that support information retrieval and action step analysis

- HSI functions are integrated. Alarm information is presented in information displays and these displays are presented in computerized procedures. Controls can be accessed from procedures and information displays. In a sense, the boundaries between different HSI resources are disappearing
- control, as noted above is increasingly automated

These trends are made manageable by a great deal of software processing of information.

In addition, because HSIs, in conjunction with the I&C system, are the primary means by which personnel monitor and control the plant, degradation in either will have a significant impact on the operator's ability to monitor plant conditions, detect disturbances, assess the plant status, and take actions in response to unfolding conditions. Thus, research is needed to address the effects of degraded conditions on operator performance.

As the technology rapidly evolves, it is important that guidance for the review of the HSIs keeps pace. The need for this was recognized in the numerous issues identified in the area of HSI technology. Research is needed to develop guidance to support the review of new HSI technology, including (1) their features and functions, and (2) the implications of and response to I&C and HSI degradations and failures.

3.3 Complexity Issues in Advanced Systems

The issue associated with this research program area is shown in Table 5. While specifically identified as a single issue, complexity is one of the recurrent themes that cut across many of the issues identified. While the reactor designs, in some ways, are seeking greater simplicity, the HFE aspects of the plant are in many respects more complex than in today's plants. Increases in sensing capabilities, information processing support, intelligent agents, automation, and software mediated interfaces distance personnel from the plant itself. Complexity was also identified as an issue in a recent survey of I&C experience at several new advanced reactor sites [13]. Research in this area is needed to identify the underlying factors that make plant, systems, HSIs, scenarios, tasks, or operations complex to personnel.

An issue arising from increased complexity is the potential for unplanned, unanticipated events. The complexity makes it difficult to foresee and anticipate all types of failures events that can occur. When such events are identified, they can be analyzed in advance, procedures can be developed to manage them, and operators can be trained to handle them. When they are not identified, operators have to handle them in real time.

Research is needed to improve our understanding of how situation assessment can be supported in the face of complexity and the unplanned, unanticipated events that may result from it. Understanding and responding to such events involves many aspects of new plant design, including alarm systems, information systems, computer-based procedures and new decision aids that will support the identification and evaluation of novel conditions.

3.4 Operating Experience of New and Modernized Plants

The issue in this research program area is also shown in Table 5. While NPPs employing many aspects of the new plant technologies identified in this study have been operating for several years, very little operating experience information is available to the general HFE community. The same can be said for the many NPPs around the world that have undergone extensive modernization programs using many of the same technologies. This information is very important to the development of future research and as an input to the identification of regulatory approaches

Table 5. Priority Issues Related to Complexity and Operating Experience

Issue	Description
Increase in Complexity and Opacity	Computer-based HSIs are generally based on software that processes lower-level data into higher-level information. Such processing can make the HSI more complex to understand, much more than is the case with "one sensor - one display" approaches typically used in analog control rooms. This can impact situation awareness as it might not be clear to the operators how the information is being processed. Overall complexity can also make the identification and analysis of failure conditions more difficult.
Operating Experience and Lessons Learned	Operating experience provides an important basis for establishing the acceptability of new technology, as well as providing the basis for the development of industry guidance, good practices, and regulatory review guidance. Acquiring this experience and extracting its lessons should be a proactive activity. Better analysis may also be needed because human performance aspects of experience are too often missed.

Table 6. Priority Issues Related to HFE Methods and Tools

Issue	Description
Methods for Early Consideration of Human Factors in Plant Design	Human performance is an important aspect of plant safety and defense-in-depth. However, it is difficult to evaluate designs in the early conceptual stages for their compatibility with human performance. The availability of such methods may also support early identification of designs that might be more susceptible to human error than others.
Design Process for Higher-level Interfaces	The rapid pace of technology change has resulted in different approaches to HSI design and a wide variety of design solutions. However, the processes used to design them often are not as well defined as was the case for analog HSIs. Regulatory approaches to reviewing the bases for the new designs will be needed.
Human Reliability Analysis (HRA) Methods for Advanced Systems	While HRA and probabilistic risk (safety) assessment (PRA/PSA) are important design and regulatory tools, there are a number of deficiencies in current methods when HRA is conducted for new NPPs. Deficiencies that need to be addressed include: the lack of methods for dealing with passive systems, the need for better models and quantification, and the need for better human error databases.
Evaluating the Effects of Advanced Systems	The need to evaluate the effects of advanced systems on human performance, from both design and regulatory perspectives, is an important consideration. Reliable and valid evaluation approaches and criteria will be needed that can address the features and functions of advanced systems.
Performance-based Methods	Evaluation methods based on measured performance is an important component to achieving review methods that are neutral with respect to specific technologies that are used in design.
Validation of Integrated Systems	Integrated system validation is one specific case of the use of performance-based methods. Evaluating the integrated human-machine system to ensure it meets performance requirements is important to determining the safety of the design. While methods for validation are available, additional work is needed to improve those methods, especially in the area of acceptance criteria.
Design and Evaluation of Digital Systems and Software	Design of a digital system has the potential to affect any of the generic primary tasks in highly-computerized plants. Incomplete or inadequate design and evaluation methods may lead to a failure of the I&C system to achieve its mission. Since most of the tasks performed by plant personnel rely on data and information from the I&C system, a poorly designed system can undermine human performance.

to the safety review of new technology.

Research should address the collection of operating experience related to these plants in areas pertaining to HFE. While event reports provide some insight into operating experience, the number of reports and their scope is limited. They do not provide the depth of information needed to develop robust lessons learned. Thus, a proactive program is suggested where detailed and specific information is obtained pertaining to both positive and negative aspects of new technology. Once collected, the information will be evaluated to derive lessons learned that may be generally applicable to future new reactor designs. In addition to collecting much needed operating experience information, research should address the development of more structured methodologies for information collection, organization, and analysis.

3.5 HFE Methods and Tools

The issues in this research program area are shown in Table 6. As noted earlier, just as the technology for new reactors is changing, so are the methods and tools used to analyze, design, and evaluate the HFE aspects of NPPs. The broad range of methods and tools available is illustrated by the number of issues identified in this area (see Table 6). These advances are revolutionizing the ways in which the tasks of HFE professionals are accomplished. A recent study [10] of new and emerging HFE methods and tools identified seven major trends:

- Computer Applications for Performing Traditional Analyses
- Computer-aided Design
- Integration of HFE Methods and Tools
- Rapid Development Engineering

- Analysis of Cognitive Tasks
- Use of Virtual Environments and Visualizations
- Application of Human Performance Models

These changes will have to be addressed in the licensing reviews conducted by the regulatory authorities. In the U.S., reviewing an applicant's HFE methods and tools is an important aspect of a safety review. The documents reviewed and the SMEs who evaluated the issues consistently emphasized the importance of those issues associated with HFE methods and tools to the safety review process. Their importance was also emphasized in a recent study by the National Research Council [11]. The study identified the major reasons systems fail and, of the 15 reasons given, most have to do with various aspects of the design process and the methods and tools used by HFE practitioners.

Thus, research is needed to address advances in HFE methods and tools that will be used to analyze, design, and evaluate new reactor designs. The research should have at least two objectives. First, to develop review guidance and acceptance criteria to ensure that new methods and tools used by applicants are valid applications and that they are appropriately applied to NPP design. A second objective is to develop tools for use by regulatory authorities to support the review of the HFE aspects of NPP design, operations, and maintenance.

4. SUMMARY AND CONCLUSIONS

This study identified sixty-four human performance research issues related to the HFE aspects of the integration of new technology into NPPs. The issues were evaluated and 20 were identified as Priority 1 - the most significant category. The issues were then organized to combine related issues into research program topics.

The information obtained in this research project can support the development of a long-term strategy and plan for addressing human performance in these areas through research. In fact, the NRC currently has research underway addressing the first two priority 1 topics: Level of Automation and Operations Under Conditions of Degraded I&C. Continuing industry developments in the area of human performance will be monitored to identify new and emergent issues so that they can be integrated into the plan as appropriate.

In conclusion, new plants offer the potential for improvements in performance and safety. However, there are challenges ahead, especially as personnel and technology are integrated into final designs. Although these advances will pose challenges for vendors and licensees, they will present challenges to safety reviewers as well. Addressing these issues by the nuclear community at large will provide the technical basis from which regulatory review guidance and design guidance can be developed to meet these challenges.

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