U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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# Human Factors Considerations with Respect to Emerging Technology in Nuclear Power Plants

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# Human Factors Considerations with Respect to Emerging Technology in Nuclear Power Plants

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# ABSTRACT

This Nuclear Regulatory Commission (NRC) sponsored study has identified human performance research that may be needed to support the review of a licensee's implementation of new technology in nuclear power plants. 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 organized into seven high-level HFE topic areas: Role of Personnel and Automation, Staffing and Training, Normal Operations Management, Disturbance and Emergency Management, Maintenance and Change Management, Plant Design and Construction, and HFE Methods and Tools. The research issues were then prioritized into four categories using a "Phenomena Identification and Ranking Table" methodology based on evaluations provided by 14 independent subject matter experts. The subject matter experts were knowledgeable in a variety of disciplines. Vendors, utilities, research organizations and regulators all participated. Twenty issues were categorized into the top priority category. This report contains a summary of the high-level topic areas and the issues in each. It also identifies the priority of each issue and the rationale for those in the top priority category. A companion Brookhaven National Laboratory (BNL) technical report provides additional details on the study methodology, issue analysis, and results. The information gathered in this project can serve as input to the development of a long-term strategy and plan for addressing human performance in these areas through regulatory research. Addressing human performance issues will provide the technical basis from which regulatory review guidance can be developed.

# FOREWORD

The increased use of automation and other technologies in existing, new and advanced nuclear power plant designs has the potential to introduce new Human Factors Engineering challenges. This research was begun to understand these challenges as well as to understand the priorities of stakeholders outside of the NRC.

Sixty-four potential human performance research issues associated with the introduction of emerging technologies in nuclear power plants were identified. These potential research issues are organized into seven high-level topic areas:

- roles of personnel and automation
- staffing and training
- normal operations management
- disturbance and emergency management
- maintenance and change management
- plant design and construction
- human factors engineering methods and tools

These seven topic areas are a novel classification scheme and work well as an organizational framework.

The research issues were prioritized using an evaluation method similar to a Phenomena and Identification Ranking Table (PIRT) evaluation. Each of the issues is briefly described in this report and its priority identified. The description of the highest priority items includes a human performance rationale that better describes the reason why each item is relevant. A companion Brookhaven National Laboratory technical report contains additional details regarding the classification and organization of the issues.

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# CONTENTS

# Figures



# Tables

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# ABBREVIATIONS

| | |
|---|---|
| ABWR | Advanced Boiling Water Reactor |
| AEOD | NRC Office for Analysis and Evaluation of Operational Data |
| ANSI | American National Standards Institute |
| AP600 | Advanced Plant 600 |
| AP1000 | Advanced Plant 1000 |
| BNL | Brookhaven National Laboratory |
| CANDU | Canada Deuterium Uranium (reactor) |
| CBP | computer-based procedures |
| CDF | core damage frequency |
| COL | combined operating license |
| COSS | computerized operator support systems |
| EPR | Evolutionary Pressurized Water Reactor |
| EPRI | Electric Power Research Institute |
| ESBWR | Economic Simplified Boiling Water Reactor |
| HEP | human error probability |
| HFE | human factors engineering |
| HSI | human-system interface |
| IAEA | International Atomic Energy Agency |
| I&C | instrumentation and control |
| IEEE | Institute of Electrical and Electronic Engineers |
| LFR | Lead-cooled Fast Reactor |
| LWR | Light Water Reactor |
| MSR | Molten Salt Reactor |
| NASA | National Aeronautics and Space Administration |
| NPP | nuclear power plant |
| NRC | U.S. Nuclear Regulatory Commission |
| PBMR | Pebble Bed Modular Reactor |
| PIRT | Phenomena Identification and Ranking Table |
| PRA | probabilistic risk assessment |
| ROP | Reactor Oversight Process |
| SME | subject matter expert |
| SKI | Swedish Nuclear Power Inspectorate |

## **ABBREVIATIONS** (Cont'd.)

| | |
|---|---|
| TMI | Three Mile Island Nuclear Power Plant |
| U.S. | United States |
| VDU | video display unit |
| VR | virtual reality |

# 1 INTRODUCTION

## 1.1 Background

Over two decades have passed since a new commercial NPP has been built in the United States (U.S.). There is now a renewed interest in nuclear energy and there are plans in the U.S. to construct new plants within the next decade.

Currently operating commercial NPPs in the U.S. are considered Generation II plants. New designs available today are referred to as Generation III plants. The new generation of plants is different from Generation II plants in several important respects, including reactor design, instrumentation and control (I&C) systems, and human-system interfaces (HSIs). Each of these three aspects of a NPP is briefly discussed below. More detail will be presented in later sections of this report.

First, the Generation III designs currently being considered for near-term deployment in the U.S. are light water reactors (LWRs). They are improved from older LWRs and most rely on passive rather than active safety features. General Electric’s Economic Simplified Boiling Water Reactor (ESBWR) is an example of such as design. Designs for later deployment include non-light-water 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. Operators will also be required to monitor online refueling in one module, with other modules in normal operating states. At any time, another module could experience a transient. This is a concept of operations that is significantly different from today’s plants. 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 Generation III designs currently being considered.

Second, while Generation II plants employ predominantly analog I&C technology, the new NPPs will be designed using 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 (a control that modifies its behavior based on plant dynamics), 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 increased automation and new forms of 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 lead to concepts of operations and maintenance that are different from currently operating NPPs. Different training and qualifications will likely be required for the plant staff to maintain digital systems and to focus decision-making on monitoring and bypassing automatic systems rather than the active control that LWR operators now take. Higher-levels of knowledge and training will likely be needed to respond to situations when automatic systems fail.

In addition to the technological advances described above, another important HFE difference between current and new plants is the methods and tools used for their design and evaluation. HFE analyses such as function allocation and task analysis have become more integrated and computer-based tools to support them are available. Tools such as computer simulation and virtual reality are now commonplace.

The potential benefits of the new NPP technologies are compelling and should result in more efficient operations and maintenance. However, it is equally important to recognize that, 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 (O'Hara, 1994).

## 1.2 Human Performance and Plant Safety

Considering the analysis of NPP events, the International Atomic Energy Agency (IAEA) (1988) noted "One of the most important lessons of abnormal events, ranging from minor incidents to serious accidents, is that they have so often been the result of incorrect human actions" (p. 19).

NPP personnel play a vital role in the safe and efficient generation of electric power. Operators monitor and control plant systems and components to ensure their proper functioning. Test and maintenance personnel help ensure that plant equipment is functioning properly and restore components when malfunctions occur. Human actions that fail to achieve what should be done in a given situation can be important contributors to the risk associated with the operation of nuclear power plants. Investigations of the noteworthy NPP events, such as the Three Mile Island (TMI) and Chernobyl accidents, have identified significant contributors of human actions to those events (Kemeny, 1979; Rogovin & Frampton, 1980; IAEA, 1992).

In evaluating the causes of the TMI accident, Kemeny (1979) stated that "The most serious mindset is the preoccupation of everyone with the safety of equipment, resulting in the down-playing of the importance of the human element in nuclear power generation. We are tempted to say that while an enormous effort was expended to assure that safety-related equipment functioned as well as possible, and that there was backup equipment in depth, what the NRC and the industry have failed to recognize sufficiently is that the human beings who manage and operate the plants constitute an important safety system" (p. 10).

The Kemeny report also noted that training of TMI operators was deficient. Further, they commented that specific operating procedures were very confusing and could be read in such a way as to lead the operators to take the incorrect actions that they did.

There are many examples given in the report that indicate a lack of attention to the human factor in nuclear safety. The TMI control room was lacking in many ways. The control panel was huge, with hundreds of alarms, and there were key indicators placed in locations where the operators could not see them. There was little use of “modern” information technology within the control room. The control room was seriously deficient under accident conditions. Overall, little attention had been paid to the interaction between human beings and machines under the rapidly changing and confusing circumstances of an accident.

The Kemeny report concluded that while inappropriate operator action turned this incident into a serious accident, many factors contributed to the action of the operators, such as deficiencies in their training, lack of clarity in their operating procedures, failure of organizations to learn the proper lessons from previous incidents, and deficiencies in the design of the control room.

Studies of lesser known events and plant operating experience have reached a similar conclusion (see the NRC’s Office for Analysis and Evaluation of Operational Data (AEOD) Series of NUREG-1275 reports – multiple volumes).

The importance of human performance as a significant contributor to plant safety has been also identified in probabilistic risk assessment (PRA) studies. BNL has performed studies using actual commercial NPP PRAs over the last several years to determine the sensitivity of risk to human error and to develop insights relative to the results (Samanta, Higgins et al.,1989; Wong, Higgins et al.,1990). These studies also showed that operations-related actions have the greatest contribution to risk of all personnel actions.

Similar results were found in other risk studies as well (Gertman et al., 2001). Taken together, the risk studies show the importance of human actions:

- Human error is a significant contributor to CDF.
- If human performance degrades from that assumed in typical PRAs, risk increases notably.
- By improving human performance, licensees can reduce their overall CDF.
- A significant human contribution to risk is in failure to respond appropriately to accidents.
- Human performance is important to the mitigation of and recovery from failure conditions.

Thus, while these studies all establish the important link between human performance and plant risk, they do not identify the mechanisms by which human performance can be adversely affected.

Operators contribute to the plant's defense-in-depth approach to safety and serve a vital function in ensuring its safe operation. Operators can negatively impact safety by making errors. For instance, an error of omission occurs when personnel do not perform a safety-related action within the time required. An error of commission may occur because personnel have an incorrect understanding of conditions and take the wrong action. To understand how technology can impact plant safety, it is first necessary to understand how errors are caused and how technology impacts those error causing factors.

Many attempts were made over the past 20 years to identify the causes of error. The main conclusion is that few errors represent random events; instead, most human errors can be explained by cognitive mechanisms. This is also true when one considers the influence of safety culture and organizational factors on human performance. In addition to operations, maintenance and I&C personnel can have a significant impact on plant safety and risk. Therefore, when we consider the effects of the advanced technology used in new NPP designs, a framework is needed that relates technology with human performance.

Such a framework was developed when the NRC first began to focus research on advanced control room technology and developing guidance for its review (O'Hara, 1994). Since its first publication, the framework has been further developed and used as part of the technical basis in numerous research projects. The framework is briefly summarized in this section. The reader is referred to the reports listed in Table 1 for additional information.

The impact of operators on the plant's functions, systems, and components is mediated by a causal chain as illustrated in Figure 1. The point of human-system interaction occurs when operations personnel perform their tasks using the HSI provided. Operator tasks are supported by their physiological and cognitive processes. It is through the HSIs that operator actions impact plant systems and components and ultimately higher-level plant functions, including safety functions.

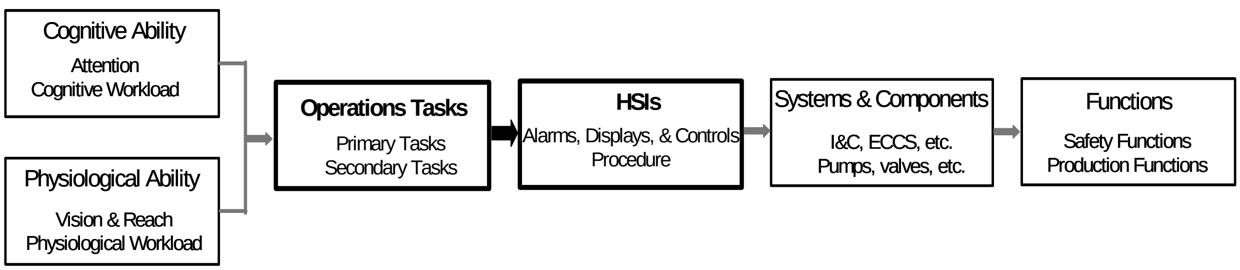


**Figure 1 Operator impact on plant safety**

In carrying out their roles and responsibilities, nuclear plant operators perform two types of tasks: primary tasks and secondary tasks. Primary tasks include activities such as monitoring plant parameters, following procedures, responding to alarms, starting pumps, and aligning valves. Secondary tasks are mainly "interface management tasks." Primary tasks have a number of common cognitive elements. These common elements are referred to as generic primary tasks. They are monitoring and detection, situation assessment, response planning, and response implementation. The relationship between these tasks is illustrated in Figure 2. Breakdowns in any of these generic primary tasks can lead to a human error.

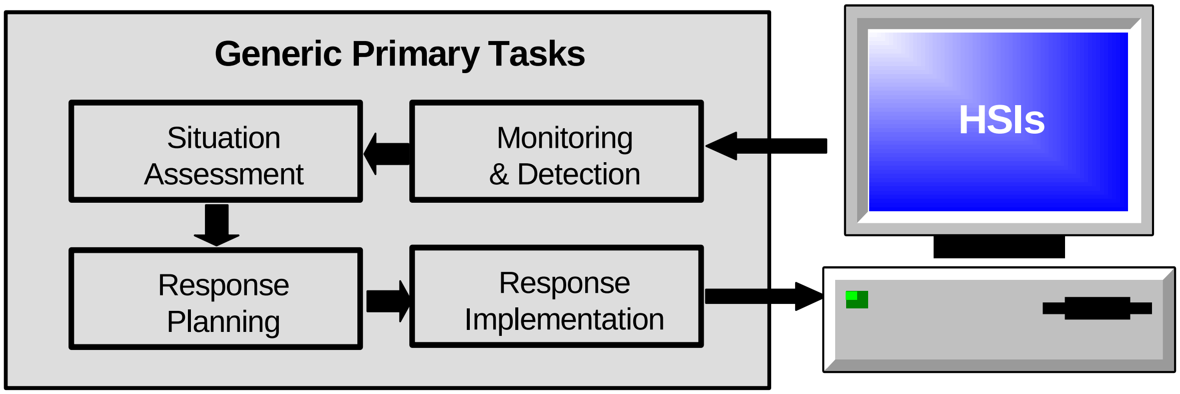


**Figure 2  Generic primary tasks performed by plant personnel**

*Monitoring and detection* refer to the activities involved in extracting information from the environment. Monitoring is checking the state of the plant to determine whether it is operating correctly, including checking parameters indicated on the control panels, monitoring parameters displayed on a computer screen, obtaining verbal reports from other personnel, and sending operators to areas of the plant to check on equipment. In a highly automated plant, much of what operators do involves monitoring. Detection is the operator's recognition that something has changed, e.g., a piece of equipment is not operating correctly.

In any complex system, the monitoring and detection tasks can easily be overwhelming due to the large number of individual functions, systems, components, and parameters involved. Therefore, support is generally provided for these activities in a NPP by an alarm system. The alarm system is one of the primary means by which abnormalities and failures come to the attention of plant personnel.

*Situation assessment* is the evaluation of current conditions to determine that they are acceptable or to determine the underlying causes of abnormalities when they occur. Operators actively try to construct a coherent, logical explanation to account for their observations. This cognitive activity involves two related concepts:  the situation model and the mental model. Operators develop and update a mental representation of the factors known, or hypothesized, to be affecting the plant's state at a given point in time. The mental representation resulting from situation assessment is referred to as a situation model, the person's understanding of the specific current situation. The situation model is constantly updated as new information is received. The term "situation awareness" is used to refer to the understanding that personnel have of the plant's current situation; i.e., their current situation model. The HSI provides alarms and displays that are used to obtain information in support of situation assessment. The HSI may provide additional support to situation assessment in the form of operator support systems.

To construct a situation model, operators use their general knowledge and understanding about the plant and how it operates to interpret the information they observe and understand its implications. Limitations in knowledge or in current information may result in incomplete or inaccurate situation models. The general knowledge governing the performance of highly experienced individuals is referred to as a mental model. It consists of the operator's internal representation of the physical and functional characteristics of the plant and its operation. The mental model is built up through formal education, training, and operational experience.

Situation assessment is critical to taking proper human action. This is noted in an IAEA report (1988) with respect to events involving incorrect human actions: "Frequently such events have occurred when plant personnel did not recognize the safety significance of their actions, when they violated procedures, when they were unaware of conditions of the plant, were misled by incomplete data or incorrect mindset, or did not fully understand the plant in their charge" (p. 19).

If operators have an accurate situation model, but mistakenly take a wrong action, they have a good chance of detecting it when the plant does not respond as expected. However, when an operator has a poor situation model, they may take many "wrong" actions because, while the actions are wrong for the plant state, they are correct for their current understanding of it.

*Response planning* refers to deciding upon a course of action to address the current situation. In general, response planning involves operators using their situation model to identify goal states and the transformations required to achieve them. The goal state may be varied, such as to identify the proper procedure, assess the status of back-up systems, or diagnose a problem. To achieve the goals, operators generate alternative response plans, evaluate them, and select the one most appropriate to the current situation model. Response planning can be as simple as selecting an alarm response, or it may involve developing a detailed plan when existing procedures have proved incomplete or ineffective.

In a NPP, response planning is usually aided by procedures. When available procedures are judged appropriate to the current situation, the need to generate a response plan in real-time may be largely eliminated. However, even with good procedures, some aspects of response planning will be undertaken. For example, operators still need to (1) identify goals based on their own situation assessment, (2) select the appropriate procedure(s), (3) evaluate whether the procedure-defined actions are sufficient to achieve those goals, and (4) adapt the procedure to the situation, if necessary.

*Response implementation* is performing the actions specified by response planning. These actions include selecting a control, providing control input, and monitoring the system and process response. There are a number of error types associated with controls, such as mode errors. Mode errors are a good example of a new error type associated with digital technology. A mode error occurs when operators take an action thinking the control system is in one mode when actually it is in another mode and the systems response to the action is not what the operator intended.

Performing these generic primary tasks well requires a moderate level of *workload*. If workload is too low, vigilance suffers and the ability of personnel to develop accurate situation assessment diminishes. As the demands of performing the task rise, greater workload is experienced. Ultimately, if workload gets high enough, the ability to perform the task is reduced.

To understand human performance, it is also important to consider the other class of tasks mentioned above - *secondary tasks*. To perform their primary tasks successfully, personnel must successfully perform secondary tasks or "interface management tasks." In a computer-based control room, secondary tasks include activities such as navigating or accessing information at workstations and arranging various pieces of information on the screen. 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. These tasks are called secondary because they are not directly associated with monitoring and controlling the plant.

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 (O'Hara & Brown, 2002). Thus, secondary tasks are important and need to be carefully addressed in design reviews.

The discussion above focuses on the primary and secondary tasks that operators perform. In actual plant operation, individual operators typically do not perform these tasks alone; *teamwork* is required. Tasks are accomplished by the coordinated activity of multi-person teams. Operators share information and perform their tasks in a coordinated fashion to maintain safe plant operation as well as to restore the plant to a safe state should a process disturbance arise. Crew members may perform a task cooperatively from one location, such as the main control room, while in other cases a control room operator may have to coordinate tasks with personnel in a remote location. Important HFE aspects of teamwork include having common and coordinated goals, maintaining shared situation awareness, engaging in open communication, and cooperative planning. Successful teams monitor each other's status, back each other up, actively identify errors, and question improper procedures.

As new technology has been introduced into control rooms and throughout nuclear power plants, there has been growing recognition that the design of technology needs to consider not only individual performance but also team performance. Relative to conventional control rooms, computer-based control rooms can impact teamwork in two ways: changes to the physical layout and characteristics of the workplace and changes to the functionality of the HSIs such that activities previously performed by a crew member are now performed by the HSI. Thus, new technology impacts teamwork; and it will be important to understand how this impact may change team performance and safety.

Thus the effect of human performance on plant safety can be understood by considering the effects of technology on the factors that support human performance in plant operations: primary tasks, secondary tasks, workload, and teamwork. To the extent that technology is implemented in a way that supports these factors, human performance and safety should be supported as well. To the extent that technology is implemented in a way that undermines or disrupts these factors, human performance will be negatively impacted and may lead to error. In the right circumstances, human errors have a negative impact on plant safety as was demonstrated in the analysis of operational experience and risk studies summarized above.

This framework for understanding human performance has been used in the development of review guidance for several aspects of advanced technology (see Table 1). The reader is referred to these documents for more detailed information.

**Table 1 Use of the human performance framework in NRC review guidance development**

| Cognitive Task | HFE Technology | Report | Reference |
|---|---|---|---|
| all primary tasks | general human-computer interaction | NUREG/CR-5908 | O'Hara, 1994 |
| monitoring and detection | advanced alarm systems | NUREG/CR-6105<br>NUREG/CR-6684 | O'Hara, Brown, Higgins, Stubler, l994; Brown, O'Hara & Higgins,2000 |
| monitoring and detection; situation assessment | Information systems/displays | NUREG/CR-6633 | O'Hara Higgins & Kramer, 2000 |
| monitoring and detection, situation assessment | group-view displays | BNL Report E2090-T4-4-4/95, Rev. 1 | Stubler & O'Hara, 1996a |
| response planning | computer-based procedure systems | NUREG/CR-6634 | O'Hara, Higgins, Stubler, & Kramer, 2000 |
| response implementation | soft controls | NUREG/CR-6635 | Stubler, O'Hara, & Kramer, 2000 |
| secondary tasks | navigation and interface management | NUREG/CR-6690 | O'Hara & Brown, 2002 |
| all primary tasks | maintenance of digital systems | NUREG/CR-6636 | Stubler, Higgins & Kramer, 2000 |

## 1.3 NRC Reviews of NPP HFE

The new Reactor Oversight Process (ROP) is based on a regulatory framework that describes how best to protect the public health and safety (NRC, 2000). This framework includes cornerstones to the three Strategic Performance Areas, (Reactor Safety, Radiation Safety and Safeguards) for NPPs that include Initiating Events, Mitigating Systems, Barrier Integrity, and Emergency Preparedness, Occupation Radiation Safety, Public Radiation Safety, and Physical Protection. In addition to the cornerstones, the reactor oversight program features three "cross-cutting" areas:

- Human performance
- Safety conscious work environment
- Problem identification and resolution

Thus there are human performance considerations in the ROP's cornerstones and the cross-cutting areas. This is consistent with the international view on the importance of human performance to plant safety. The IAEA identified "human factors" as an underlying technical principle that is essential to the successful application of safety technology for NPPs. The principle states:

> Personnel engaged in activities bearing on nuclear power plant safety are trained and qualified to perform their duties. The possibility of human error in nuclear power plant operation is taken into account by facilitating correct decisions by operators and inhibiting wrong decisions, and by providing means for detecting and correcting or compensating for error (p. 19, IAEA, 1988).

IAEA further states that "attention to human factors at the design stage ensures that plants are tolerant to human error" (p. 19, IAEA, 1988).

Knowledge about human performance comes from many scientific disciplines, including physiology, medicine, psychology, and sociology. "Human factors engineering" refers to the application of this knowledge to plant design and evaluation. The main contributions of HFE are to help ensure that:

- The role of personnel is well defined and their tasks are clearly specified.
- The numbers of staff, their functions, and qualifications are adequate to fulfill the human roles in the plant.
- The HSIs, procedures, and training meet task performance requirements and are designed to be consistent with human cognitive and physiological characteristics.

The NRC addresses human performance, in part, by conducting HFE safety reviews. The fundamentals of the approach are summarized below.

In accordance with 10 CFR 52, the NRC staff reviews the 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 Standard Review Plan (NUREG-0800) provides high-level guidance for the conduct of HFE reviews in Chapter 18, Human Factors Engineering (NRC, 2006). Detailed review criteria are contained in the Human Factors Engineering Program Review Model (NUREG-0711) (O'Hara et al., 2004). The approach is based on the concept that the HFE aspects of NPPs should be developed, designed, and evaluated on the basis of a structured systems analysis using accepted HFE principles at the same time other systems are being designed. The reviews address 12 elements of an HFE program: HFE program management, operating experience review, functional requirements analysis and function allocation, task analysis, staffing and qualifications, human reliability analysis, human-system interface design, procedure development, training program development, human factors verification and validation, design implementation, and human performance monitoring.

NUREG-0711 was originally developed to support the NRC's reviews of new NPP design certification applications. The review addressed both the design process (such as function and task analysis) and the HFE products of that process (such as the specification of personnel roles and responsibilities, HSIs, procedures, and training). This approach was developed for three reasons. First, the existing guidance at that time the initial design certification reviews were performed did not address the technological approaches used in the new NPP designs employing advanced technology. Second, the guidance was oriented toward the review of an existing control room, yet the design certification applications did not present completed design details (discussed further below). Third, NRC research on developing HFE guidance for advanced technology led to the conclusion that a review of the design process was a necessary addition to a review of the design product (O'Hara, 1994).

Using this guidance, the NRC has performed design certification reviews of several new plant designs, such as General Electric's Advanced Boiling Water Reactor (ABWR), Westinghouse's Advanced Plant 600 (AP600) and Advanced Plant 1000 (AP1000), and Combustion Engineering's System 80+. However, as noted above, since technology is continually advancing in the areas of HFE and I&C, details of the applicant's design in those areas was not completed before the NRC issued design certifications. These reviews focused mainly on HFE program plans. The design certification applications contain little design detail or information about the implementation and integration of the technologies impacting human performance. These aspects of the HFE program were deferred to the combined license (COL) applicant or holder.

Regulators will have to understand the safety implication of the new designs and their new technology, as well as the substantially different concepts of operations they may employ. As noted in Section 1.1, in addition to new technology, applicants will be designing their plants using new HFE methods and tools. These methods and tools are used to analyze, design, test and evaluate the HFE aspects of a plant such as the HSI. They are important because the criteria for the NRC HFE reviews of the design process are mostly technology neutral. However, the HFE review criteria are not neutral with respect to the HFE methods that are used as part of the design process. This will be increasingly important for new NPP reviews as we move to the future because of the diversity of reactor types, HSIs, and operational concepts will increase, especially for Generation IV plants.

## 1.4 Report Organization

This report is a summary of the high-level topic areas, their associated human performance research issues, and a brief discussion of the results. A companion BNL technical report provides the detailed methodology, issue analysis, and results (O'Hara et al. 2008).

The remainder of this report is organized as follows. Section 2 describes the study objectives and methodology. Section 3 presents the results for each of the high-level topic areas and their human performance issues. Section 3 also identifies the research priorities and the rationale for those ranked as the top priority. Section 4 summarizes the study and its conclusions. The report contains two appendices. The first Appendix provides a cross reference from the issues discussed in this report to the more detailed discussions in the companion BNL technical report. The second describes the NRC's HFE review guidance development methodology.

# 2 OBJECTIVES AND METHODOLOGY

The objective of this study is to identify potential human performance issues related to the role of personnel in new NPPs and the technological advances that will support that role. As used in this report, the phrase “research issue” or the term “issue” refers to:

- An aspect of new NPP development or evaluation for which available information suggests that human performance may be negatively impacted
- 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
- A technology or technique that will be used for new plant design or implementation for which there is little or no review guidance

Identifying potential human performance issues associated with new NPPs and new technology is a challenging task. At present, there are only a few Generation III NPPs in operation, such as the ABWR. Their operating experience is limited and not generally available in the literature. For NPPs that have yet to be designed and built, information concerning their operations or the design of their control rooms is limited at best (especially for reactor concepts of longer-term deployment, i.e., Generation IV designs).

Thus, our approach was to examine current industry developments and to make projections into the near- and longer-term future. This was done from four perspectives:

- Reactor design and technology
- Instrumentation and control technology
- Human-system integration technology
- Human factors engineering methods and tools

In order to more clearly relate individual issues to their importance from a human performance perspective and to better associate and integrate related issues, the issues were organized using a concept of operations framework. This framework is especially appropriate for plants in the early stages of design in order to identify design goals and expectations relative to human performance. A concept of operations covers all facets of personnel interaction with a complex system; therefore, it provides a good organizational framework within which to cluster and integrate a wide variety of issues.

Another reason for choosing concept of operations as an organizational framework is that it plays a significant role in the NRC's review of the human factors aspects of NPPs, as per NUREG-0711. To ensure that all of the important aspects of plant design and operations are identified, we developed a five-dimension model to characterize a plant’s concept of operations:

- Role of Personnel and Automation
- Staffing and Training
- Normal Operations Management
- Disturbance and Emergency Management
- Maintenance and Change Management

Each of these dimensions was used as a high-level topic under which the individual research issues are organized. Most of the issues were associated with one of these high-level topics; however, some were related to more than one. There were also several issues that did not clearly fall into any of these topics, these were grouped into two additional high-level topics:

- Plant Design and Construction
- HFE Methods and Tools

Thus, seven high-level topic areas were used to organize the research issues.

The issues where evaluated and prioritized using a Phenomena Identification and Ranking Table (PIRT) methodology. In this application, the phenomena are the issues identified in Section 3.1. The objective was to prioritize the human factors issues to identify those of greater importance with respect to regulatory activities.

Fourteen independent subject matter experts (SMEs) participated in the exercise. The SMEs had knowledge of human factors, I&C, plant operations, and HFE and PRA analysis methods. The SMEs represented a cross section of the industry and included regulators, vendors, utility personnel, and researchers. All SMEs were knowledgeable of the nuclear industry although several work in other industrial domains.

The procedures to evaluate the issues are described next followed by a discussion of the method used to prioritize them.

<u>Issue Evaluation Procedures</u>

Based on pilot testing of the methodology, the following issues were screened out of the SME evaluations based on consistently low ratings:

- Monitoring of Plant Personnel
- Change in HSI Demands and Training Requirements
- Rapid Learning Curve in Early Stages of Plant Operation
- Personnel Acceptance of Technology
- Biometrics, Fitness for Duty, and Security
- Portable Computers and HSIs
- Larger Number of Systems

The SMEs evaluated the issues in two phases. In Phase 1, each SME was sent:

- A draft of this NUREG/CR
- A draft of the BNL technical report (O'Hara et al., 2008) providing a detailed discussion of the issues
- An evaluation form that contained instructions and rating dimensions

The SMEs evaluated the issues according to the instructions and returned the completed forms to the project staff. The responses were then evaluated and the results compiled.

In Phase 2, a meeting of the SMEs was held. All but three of the SMEs were able to attend. The overall purpose of the meeting was to discuss those issues for which agreement was low so that SMEs could provide their rationale and basis for their ratings. They were given the opportunity to modify their ratings or any of the issues based on these discussions.

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 the following high-level topic areas:

- Role of Personnel and Automation
- Staffing and Training
- Normal Operations Management
- Disturbance and Emergency Management
- Maintenance and Change Management
- Plant Design and Construction

Human performance issues were evaluated on two primary dimensions: safety significance and immediacy (how soon an issue needs to be addressed).

*Safety Significance*

Each issue was evaluated in terms of its *potential* to compromise plant safety. 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 then evaluated on the following three-point scale:

1. High likelihood of safety significance - An answer of “yes” to any of the questions listed above led to a rating of “1.”

2. Probably safety significant - If no “yes” responses were given to any of the above questions and at least one was answered “probably,” a rating of “2” was given. A “2” could also be given if the issue represented a significant departure from the status quo and an impact on safety was suspected.

3. Low likelihood of safety significance - A rating of “3” was provided if the answer to all of the above questions was “unlikely.”

In addition to the safety rating, SMEs were asked to provide a brief description of the basis for their evaluation.

*Immediacy*

This evaluation dimension identified how soon an issue needs to be addressed. This dimension was evaluated using the following two-point scale:

1. Near-term – Guidance is needed for licensing activities within the next five years.
2. Longer-term – Guidance is not needed for licensing activities within the next five years.

HFE Methods and Tools issues were also evaluated on two primary dimensions: importance to regulatory effectiveness and immediacy.

The second group was the high-level topic area of HFE Methods and Tools. Since this group consisted of methods rather than aspects of NPP design or operations, it had to be evaluated somewhat differently.

*Importance to Regulatory Effectiveness Evaluation*

Each issue was evaluated in terms of its likely importance to effective regulatory review. Human factors methods and tools that are applied to the design and evaluation of nuclear power plants are constantly evolving as newer approaches are developed. The designers of new plants are already utilizing these methods and tools which will result in changes to the types of analyses and data that are included in submittals made by applicants. Since HFE reviews conducted in accordance with Chapter 18 of the SRP (NRC, 2007) 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. This dimension was evaluated using the following three-point scale:

1. High importance
2. Moderate importance
3. Low Importance

*Immediacy*

The methods and tools issues were evaluated for immediacy using the same two-point scale used for the human performance issues.

<u>Issue Prioritization</u>

The 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 and regulatory effectiveness significance dimensions (rated on a three-point scale), the average of all SME ratings was calculated for each issue. For the purposes of assigning a "summary rating" for each issue, the following criteria were used:

1. An average of 1.5 or less was assigned a summary rating of "1."
2. An average between 1.5 and 2.0 was assigned a summary rating of "2."
3. An average of greater than 2.0 was assigned a summary rating of "3."

Issues were assigned a summary rating for the immediacy dimension (rated on a two-point scale) based on which response was most frequent (1 or 2). 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 3 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 seven issues screened out of the evaluation were assigned to Priority Group 4.

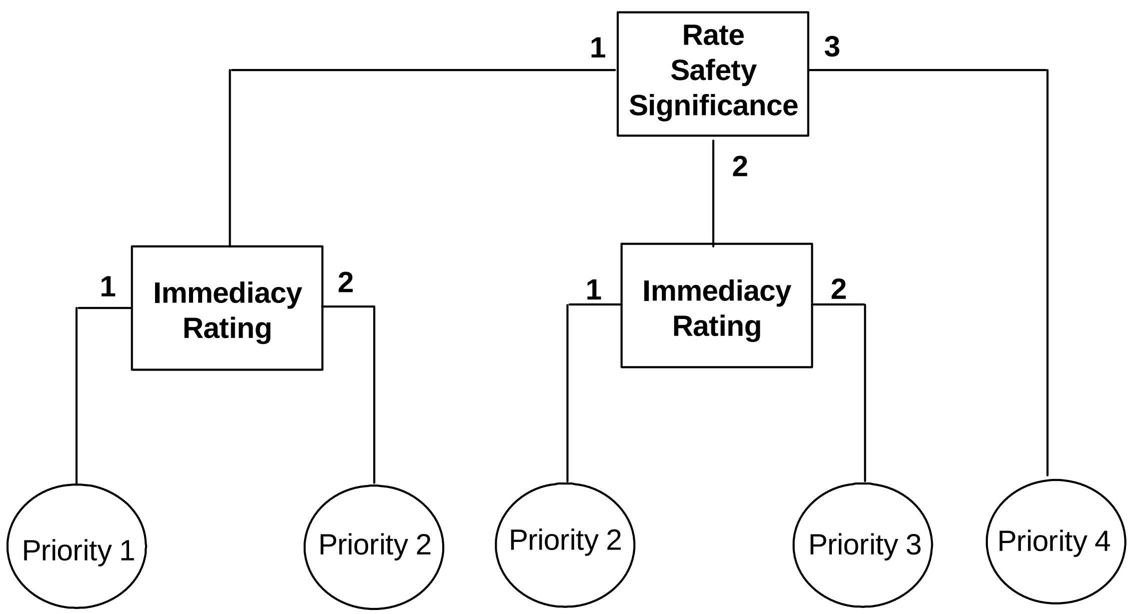


**Figure 3 Issue prioritization based on ratings of safety significance and immediacy**

# 3 RESULTS

## 3.1 Topic Areas and Human Performance Research Issue Summary

Many detailed issues related to potential human factors and human performance research needs to support a review of the implementation of new technology in nuclear power plants were identified. These issues were organized into seven high-level topic areas. In this section, each of these topics is described. In some cases, subtopics are defined for clusters of issues related to a common subtopic. Each of the individual issues that make up the topic are shown (in ***bold italics***). Appendix A to this report provides references to detailed issue descriptions in the BNL Technical Report (O'Hara et al., 2008). Some issues pertain to more than one topic, so the pertinence of the issue is discussed in each topic.

Appendix B to this report describes the NRC's general HFE review guidance development methodology than can be used to address these research issues.

### 3.1.1 Role of Personnel and Automation

The Role of Personnel and Automation topic addresses the relative roles and responsibilities of personnel and plant automation and the relationship between the two. Table 2 provides a listing of the individual issues identified within this topic. The table also identifies the reactor types for which each issue applies as well as the issue's priority ranking (per the methodology described in Section 2).

***Level of Automation*** is the broadest issue that captures the essence of the topic. A main goal for future NPPs is more economic operations by reducing staff and using advanced digital I&C technology. Hence, the overall level of automation in new NPPs can be expected to be much higher than in today's plants. A more significant change is the way automation may be implemented. Historically, processes were either manually controlled or fully autonomous. However, advances in digital technology offer the possibility to provide new and more flexible types of automation that involve personnel interaction at varying levels. Increasingly, intermediate levels of automation are being implemented in order to help crews maintain better awareness of the automatic actions and to be more informed when disturbances in the automation arise. Thus, operators may play a variety of roles in the control and management of automated systems.

One example of these new approaches to automation is "breakpoint automation." Using this approach, a task such as plant start up, is divided into a discrete sequence of steps. Operators authorize the automation to begin a step and monitor its progress. Once completed, the automation stops (a breakpoint) so operators can determine whether it is acceptable to proceed to the next step in the sequence. Thus, the task is shared between operators and automation. The ABWR uses this approach for plant start up.

Another example is "dynamic allocation." Functions and tasks are flexibly performed by automation or operators based on the current operational situation. Thus, for example, automation may assume control over lower priority tasks when the operators' level of workload increases to a point where it would be difficult to perform all their current work. This approach can ensure that operators are able to maintain their attention on high priority tasks because their workload levels remain within acceptable limits. Two considerations include defining what the specific levels of automation will be and the means for managing the dynamic changes in allocation. For example, the allocation may be specified by the operator, by the automation (based on predefined conditions), or jointly by the operator and the automation.

Another way automation is changing is its application beyond process control tasks to tasks that have been typically performed by operators, e.g., analysis of off-normal conditions, situation assessment, and response planning. Such applications of automation include intelligent agents, computerized operator support systems, and computer-based procedures. The implications for human performance are summarized below.

***Intelligent Agents*** are computer functions that perform information processing tasks for operators in a semi-autonomous or fully-autonomous manner. They are adaptive to changing plant conditions and can be independent from personnel. Intelligent agents will provide significant support for on-line monitoring, fault detection, situation assessment, diagnosis, and response planning through the use of advanced sensing and computational technology. The potential benefits of intelligent agents must be weighed against operator burdens associated with supervising these agents, and any potential problems that may result from their inappropriate application.

***Computerized Operator Support Systems*** (COSSs) can use predictive models and fast-time simulations to provide plant personnel with much better decision support than previously was possible. However, human performance issues have been identified that have limited the effectiveness of current COSSs. These include: poor integration with personnel task performance, complexity of COSS information processing, lack of transparency of the COSS decision process, inadequate explanatory information to address personnel verification needs, and absence of communication facilities that permit personnel to query the system and obtain confidence in the conclusions that have been drawn. To design effective COSSs and integrate them into plant work practices and procedures, these issues must be resolved.

***Computer-based Procedures*** (CBPs) offer many potential advantages over hard-copy procedures, e.g., support for procedure maintenance, configuration management, and procedure use. As sensor input and control capabilities are made available to computerized systems, it becomes feasible for CBPs to incorporate greatly expanded monitoring and control functionality. This raises a number of questions with respect to human performance.

First, use of CBPs may be hindered by some of the same factors as other computer-mediated interactions. For example, computer presentation may force a *narrow field of view*, which may limit the operators' ability to flip forward and back through the procedure, or to consult multiple procedures at the same time. Because only a portion of the procedure can be observed at one time, operators may lose a sense of where they are in relation to the total set of active procedures. The available display space may be inadequate to support simultaneous viewing of multiple procedures and associated plant data. The sheer burden of interface management in navigating and retrieving many displays can interfere with the operators' ability to obtain an overview of the plant's situation.

Second, while computerization of procedures may provide opportunities for new and different approaches to the structure of procedure content, the impact of such changes on procedure use will be an important consideration. At the same time, techniques that evolved for paper presentation may not be appropriate in a computer presentation. For example, it is not clear whether flowchart procedure presentations are acceptable in computer media where the limited screen view and need for scrolling may make them less effective. With respect to text presentations, too little information presented at each procedure step can cause operators to lose a sense of where they are, while too much detail may be a distraction. Further, reading text from VDUs for a long period of time is visually fatiguing.

If plant information is accessed by the CBP, the operator may not feel the need to look at other sources of information and may miss important indications that are not present in the CBP; the use of CBPs may therefore affect an operators' awareness of the state of the process. For example, operators may uncritically accept the CBP's assessment of the plant's condition. The nature of CBP use itself may diminish the chances that errors in the selection of a course of action or the execution of step logic will be detected.

Furthermore, to the extent that plant indications are available to the CBP, the personnel role in procedure use may be altered. This raises human performance questions. For example, should CBPs only automate data gathering and lower-level activities, or should they also automatically evaluate procedure-step decisions? The analysis of procedure step logic (i.e., the comparison of actual parameter values to the reference value identified in procedures using the logical relationships described in the step) is an important capability of CBP systems. However, when the step logic or the actual data analysis required for evaluating the step logic is incomplete, both the procedure and the operator may incorrectly assess the situation. A related issue concerns how to guard against this situation and how to specify when the evaluation of step logic should be left to the operator's judgment. Thus, the question arises as to how much of a procedure's function should be automated to ensure that personnel can independently assess the results.

In the control room, the operating crew is a team in which the members must share information and coordinate their tasks to satisfy specific goals or mission requirements. Team performance requires a common understanding of the status of the system and an understanding of each other's actions and intentions; CBPs have the potential to limit this knowledge. For example, it may not be necessary for the user of a CBP that integrates display and control capabilities to request information from or give control orders to other crew members. This can lessen the collective awareness of the state of the process and eliminate an important means of detecting when a procedure is not accomplishing the appropriate operational goal.

Finally, it is necessary to consider the implication for human performance of CBP failure in complex situations. Ensuring the transfer from CBPs to backups (e.g., paper procedures) has been identified as an important consideration in the design of CBPs, especially those used in emergency conditions. As the scope and functionality of CBPs increase in the future, the ability to cope with loss or degradation of CBP capabilities becomes a greater concern. Transitioning from a CBP to a paper procedure may be easily accomplished when the procedural context is simple, such as when operators are in the first few steps of a procedure. The transition from a computerized system to a backup may be quite complex if operators are deep into the procedures, when multiple procedures are open, or when the CBP is monitoring many conditional steps. How operators will manage failures in such complex situations is unknown. Operators' familiarity with paper-based procedures will also be an issue. In future plants, crews may train principally with the CBP system, and thus be at a greater disadvantage in the event of a CBP failure.

Other ways automation is expanding is through its application to: (1) maintenance and testing activities, including fault detection and diagnosis, automatic reconfiguration of systems, and automated work order generation for required manual interventions; (2) engineering and administrative functions; and (3) HSI (human-system interface) management, e.g., operators may be offered specific displays that are automatically retrieved based upon predefined plant conditions.

***Monitoring of Plant Personnel*** is a functional capability linked with increased automation. This includes monitoring, recording, and analyzing operator actions and providing “comments” under predefined circumstances such as when the operator makes a potential input error or monitoring physiological parameters in order to detect conditions such as fatigue.

Although there are potential benefits to be obtained from these increases in automation, there is also a range of human performance issues that can arise as well, especially when automation is poorly designed and implemented. Some of these issues include: developing a mental model (understanding) of how the plant works is more difficult because automation makes operations more complex, situation awareness and alertness are lowered, complacency can arise from confidence in automation (resulting in failure to properly monitor its performance), excessive workload can be created when there is a need to transition from monitoring automation to taking over manual control when the automation fails, and skills in performing automated tasks are degraded due to lack of use.

The safety consequences of such issues are a significant consideration when evaluating the increased and more diverse automation anticipated in new plants.

***Reduced Staffing*** is a final issue related to increases in automation. New designs are likely to rely on staffing approaches that are significantly different from those for current plants and include reductions in the numbers of personnel needed to manage the plant. As with any changes in staffing, the safety consequences will have to be evaluated.

**Table 2 Detailed issues associated with the role of personnel and automation topic**

| Detailed Issue | Reactor Type | Priority |
|---|---|---|
| Level of Automation | All | 1 |
| Intelligent Agents | All | 2 |
| Computer-based Procedures | All | 1 |
| Computerized Operator Support Systems | All | 2 |
| Monitoring of Plant Personnel | All | 4 |
| Reduced Staffing | All | 3 |

### 3.1.2 Staffing and Training

The Staffing and Training topic addresses approaches to staffing the plant and the training needed to ensure that personnel are adequately prepared to perform their roles and responsibilities. Table 3 provides a listing of the individual issues identified within this topic. The issues in this topic were further organized into two subtopics: Approaches to Staffing and Training Implications.

**Approaches to Staffing**

Most plants today have a large number of on-site personnel organized into functional groups including operations, maintenance, engineering, administration, and security. With the possible exception of modular plant designs such as the PBMR, most of the designs being considered for near-term deployment in the U.S. do not involve fundamentally different plant staffing concepts. However, because plant staffing and training are very costly aspects of plant operations, staffing will be an area of focus in new plants being designed for future deployment (in support of the Generation IV plant design goal of more economic operation). ***Functional Staffing Models*** is an issue related to staffing approaches that significantly deviate from current approaches. The functions that have to be addressed by the staffing model include: operations, maintenance, engineering, administration, and security.

To illustrate one such alternative model, the functions can be decentralized. In this model, a reactor or multiple reactor modules are 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. Thus, for example, emergencies may be handled by highly trained crisis management teams. Because these teams handle emergencies, their level of expertise would be superior to what could be attained when a single crew is responsible for both normal and emergency operations (today's model). Due to the low probability of emergencies, the teams are available to handle many sites, a role that will be supported by increased plant standardization. ***Reduced Staffing*** can result from such an approach, an issue that was discussed above.

***Crew Member Roles and Responsibilities*** have to be specified once a staffing model for a new NPP is identified. Aspects of this issue include whether a given crew member is responsible for particular modular units, for specific systems across modules, or for certain operating states, evolutions, or transients. Identifying and evaluating these roles and responsibilities is an important issue.

The staffing level and model chosen are very significant design decisions that drive many other aspects of the plant design, such as levels of automation (as discussed above), HSI design, and personnel training. Selection of the staffing approach that best meets the goals for the plant will require tools such as modeling techniques and simulation facilities. The safety impacts of such approaches have to be carefully evaluated.

**Training Implications**

***Training and Qualifications*** will necessarily change as technological trends, both near- and long-term, lead to changes in the organization of crews and crew member responsibilities. For example, effective use of some new display designs (function-based displays arranged in a hierarchy) may require greater emphasis in training on thinking about the plant in functional rather than physical terms. This poses near- and long-term issues. In the near term, there is the issue of how the transition to new ways of representing and using information will be accomplished. In the longer term, the issue is whether the selection criteria for plant personnel might have to be modified to include different types of cognitive characteristics. Training approaches may also change to provide for distributed training, embedded training, and virtual reality.

In today's plants, detailed operation of the HSI is often learned on the job. This is because the HSIs themselves, such as gauges, J-handles, and push buttons, are relatively simple devices with limited flexibility. In computer-based control rooms, greater emphasis on training may have to be devoted to how HSIs are used because of their added flexibility and complexity. Personnel will need to know about how data is processed, how system modes affect user inputs, and the strategies needed to manage the interface (e.g., information access, navigation, and workstation configuration). It will be important that HSI features, functions, and use be an integral part of personnel training. ***Change in HSI Demands and Training Requirements*** is an important issue to address in training.

***Rapid Learning Curve in Early Stages of Plant Operation*** is another issue. Utilities have been slow to implement new technologies and no new plants have been built in the U.S. for many years. Thus, the U.S. nuclear industry has not had the opportunity to gain much experience with the newer technologies as they have evolved over time. New plants in the U.S. will present a revolutionary change in I&C and HSI technology. It should be expected that there will be an accelerated learning curve that must be accommodated in the early years of operation.

***Personnel Acceptance of Technology*** is associated with significant changes. When new technology is initially introduced, some crew members are reluctant to accept it. In plants that have modernized, this has led some personnel to retire or request new assignments. Even when accepted, it can be expected that during this period of familiarization, the potential for errors is increased, both due to a lack of understanding for how the new HSIs should be used and negative transfer of training, i.e., when behavior associated with the old HSIs makes it more difficult to learn to use the new HSIs. Operators of new plants are likely to be faced with a change from the HSIs in their previous plant to those of a new plant. Thus, issues associated with negative impacts on safety due to learning curve effects need to be addressed. Training will be an important tool in addressing these impacts.

**Table 3 Detailed issues associated with the staffing and training topic**

| Detailed Issue | Reactor Type | Priority |
|---|---|---|
| **Approaches to Staffing Subtopic** | | |
| Functional Staffing Models | Gen IV | 3 |
| Reduced Staffing | Potentially All | 3 |
| Crew Member Roles and Responsibilities | All | 3 |
| **Training Implications Subtopic** | | |
| Training and Qualifications | All | 1 |
| Change in HSI Demands and Training Requirements | All | 4 |
| Rapid Learning Curve in Early Stages of Plant Operation | Gen IV & Passive Plants | 4 |
| Personnel Acceptance of Technology | All | 4 |

Note: See Section 1.1 for discussion of Gen III and Gen IV plants.

### 3.1.3 Normal Operations Management

The Normal Operations Management topic addresses issues related to how the plant will be operated by personnel to follow its normal evolutions, such as start up, low- and full-power operations, and shutdown. Table 4 provides a listing of the individual issues identified within this topic. The issues were further organized into five subtopics:

- General Knowledge Limitations
- Specific Changes to Operations

- Advances in HSI Technology
- Organizational Factors
- Complexity

**<u>General Knowledge Limitations</u>**

The ***Availability of Operating Experience of Generation III Reactors*** issue emphasized the need to obtain operating experience from Generation III plant designs (e.g., ABWRs in Japan and the N4 in France) and the lessons learned that can be derived from it. Operating experience should be obtained from vendors, utilities, and regulatory authorities. This information is very important to the identification of needed future research and as an input to the development of safety review guidance.

One of the lessons learned from plant modernization programs is that the full impact of technology changes is often not anticipated. This stems in part from limitations in our knowledge about the effects of technology on human performance. ***Unanticipated Impact of Technology*** is a significant issue given the significant technology changes anticipated in future plants, a better understanding of the impact of technology is needed, as are methods to identify technology impacts.

***Understanding How HSIs are Really Used*** is another limitation in our knowledge. Plant personnel sometimes do not use HSIs in the manner that designers expect them to be used. This often results when HSIs are not well suited to operator tasks or when operators are experiencing high workload. An important aspect of performing safety reviews will be to establish a realistic view of HSI usage and a recognition that the designer's vision may not fully characterize the human performance issues that may be encountered.

**<u>Specific Changes to Operations</u>**

Several issues were identified related to operational aspects of new NPP designs that are different from the current LWRs. One issue is ***Modular Plants***. Modular plant design, such as the Gas Turbine-Modular High Temperature Reactor and the PBMR, consist of a number of small reactors that may share common infrastructure and resources and are operated from a common control room. The issues associated with modular plant monitoring and control and their safety implications need to be better understood.

***Different Reactivity Effects*** is another issue confronting personnel in new reactors. For example, in the Lead-cooled Fast Reactor (LFR) design, the presence of lead in the core area may result in reactivity effects that are different from light water reactors. The LFR will have little neutron thermalization and lower Doppler effects. Also, the temperature coefficient of reactivity will be less negative and the neutron lifetime shorter. These all tend to increase the speed of dynamics related to core power and transient operations. Operators' control of reactor power and safety are dependent on their understanding of these reactivity effects.

***Increased Power Operations*** is a feature of some new reactors designs. They will have more and/or larger equipment and may operate closer to threshold limits. These types of designs could place higher demands on operators to ensure that equipment performs properly and that parameters are maintained within their specified limits.

***Continuous Fueling*** is part of the operation of some new reactors. Although this may share some features with on-line refueling as in Canada Deuterium Uranium (CANDU) designs, it is a new and less familiar concept. The need to manage this concurrent activity while the plant is operating will have to be taken into account in the plant's concept of operations; and, therefore, in its approach to staffing, function allocation, task design, etc.

***Physical Protection, Security, and Safety*** improvements are key goals for new NPP designs, especially with respect to acts of terrorism. An issue arises regarding concerns for ensuring that the added protection does not negatively impact safety, reliability, and plant or equipment availability.

***Biometrics, Fitness for Duty, and Security*** is another application of technology. Continued advances in the area of biometrics will permit the assessment of fitness for duty to be approached from a more functional perspective; e.g., measurement of relevant physiological and cognitive indicators can be compared to baseline criteria to indicate whether personnel are fit to perform their tasks. Biometrics may also play a role in meeting the goals for security in new plants by allowing the identities and movements of personnel within the plants to be monitored and documented. Selection of appropriate parameters and the methods used to monitor them will have to be made, in part, based on human factors considerations.

## Advances in HSI Technology

Just as the technology for reactor design and I&C systems is advancing in new plants, so are the HSIs that personnel will use to perform their tasks. We placed HSI-related issues in the Normal Operations topic; however, most of these same HSIs are applicable to Disturbance and Emergency Management as well. This subtopic is made up of 15 individual detailed issues.

***Interfaces to Automation*** refers to designing displays needed by operators to monitor and interact with new automatic systems. This will be challenging because there is currently little guidance available to support their design or review.

***Sensors and Condition Monitoring*** provide new approaches to plant monitoring. In plants today, there are a relatively small number of discrete sensors. When the operator suspects a problem or has an indication of a failure in the instrumentation, it is relatively straightforward to troubleshoot or diagnose the problem. Trends in sensors and measurement system technologies such as sensor proliferation, use of smart sensors, and sensor "data fusion," are likely to lead to a significant increase in the data that are available to operators. The individual pieces of lower-level data will be integrated and processed into hierarchal layers. This will ultimately lead to highly processed information at the top of the hierarchy that is presented to the plant personnel. Human performance issues associated with these new capabilities include determining the level of understanding of this functionality that will be needed by personnel to properly interpret and interact with condition monitoring systems, how they will be able to judge the quality of the information provided, and how they will deal with failures in these more complex systems.

***Digital Communication Networks*** are used extensively in digital I&C systems to collect data from sensors, transmit control signals to plant equipment, provide intercommunication among processors involved in monitoring, control and protection, and communicate with HSIs. These systems will have human performance implications, such as the potential difficulty in maintaining situation awareness regarding the condition of the complex communication networks and the quality and timeliness of the information being received.

***Alarm System Design*** is an important consideration in determining alarm effectiveness. Alarm system effectiveness continues to be an issue in today's plants. An example is the flooding of alarms received when a major transient occurs. In plants using digital I&C systems, the number of alarms is expected to increase significantly resulting in even more alarms. Strategies for managing the large number of alarms will be an important design consideration and the impact of the solutions on personnel performance will have to be assessed.

***Information Systems Design*** will address how the HSI will bring together process data, configuration data, engineering and maintenance information, information from intelligent agents, plant performance and economic data, data from multiple units/modules, and video and audio data. There is already a tendency for information overload in today's plants, and it may be a greater issue in new NPPs. Human performance issues arise with respect to methods of interacting with this information, shared responsibility (between human and machine) for analyzing and interpreting data, and the potential for users to get lost in the information.

***Display Design*** becomes a significant issue because digital systems provide the potential for very significant advances in the display of information that were not possible with analog equipment. However, there are no established techniques for identifying and designing these advanced displays. Guidance will be needed to review these techniques and the displays they produce to ensure operational safety.

***Control Design*** is evolving toward screen-based operations. Operator control actions will be increasingly mediated by computer systems. These soft controls differ from those typically found on traditional control boards and they are evolving rapidly toward highly flexible and functional controls. However, designers do not have the benefit of accumulated experience about the type of soft control implementation that is best for the different types of control actions operators must take and the types of errors that may occur in their use.

***Advanced Controls*** provide the capability to implement more sophisticated algorithms than have been used in plants to date, such as matrix techniques for optimal control, nonlinear control, fuzzy logic, adaptive control, neural networks, expert systems, state-based control, and schemes that combine multiple control methods in a multi-mode or hierarchical system. These techniques will lead to more integrated control of plant systems and processes (versus separate, non-interacting control loops). Human performance issues include: an increase in control complexity, the need for operators to have sufficient understanding of the control schemes to be able to monitor their performance, and how to react to control failures.

***Computerized Operator Support Systems*** were introduced in Section 3.1.1. Although first generation COSSs have been around for some time, the digital I&C infrastructure in new plants will provide a basis on which second-generation systems can be developed.

***Computer-based Procedures*** and ***Computation and Simulation*** (including the ability to run models and simulations faster than real time and the use of risk models to support decision-making) are examples of COSSs. Human performance issues have been identified including: poor integration with personnel tasks, complexity of information processing, lack of transparency of the COSS decision process, inadequate explanatory information and communication facilities to permit personnel to query the system. To design effective COSSs and successfully integrate them into work practices and procedures, it will be necessary to address these issues.

***Interface Management Design*** is an important consideration in large information systems. As was discussed in Section 1.2, the primary tasks performed by operators are process monitoring and control. To perform these tasks, operators must perform interface management tasks such as retrieving information and configuring workstation displays. These tasks have been found to divert attention away from the primary tasks potentially resulting in performance decrements and errors. The burden associated with the performance of interface management tasks has been linked to the design of HSI features associated with them, such as the means provided to navigate the display system. As NPP HSIs become more computer-based, it will be important to more precisely define the effect on performance of different interface management design approaches. If interface management tasks create sufficient burden, plant safety may be compromised.

***Portable Computers and HSIs*** are increasingly used, enabling personnel to bring HSIs where they are needed in the plant. However, the information and control design is significantly impacted by the size constraints imposed by portability. Maintaining performance and safety while using these devices will have to be demonstrated.

***Computer-supported Collaboration*** refers to the use of advanced information systems to supply information within the organization that is needed by different groups to perform work in the most efficient, safe manner. It also refers to the use of technology to support crew communication and coordination. Potential concerns related to this technology include: (1) the means by which knowledge and information can be generated and distributed among work groups; (2) the means by which work can be conducted and coordinated within a plant complex (possibly involving multiple plant modules); and (3) the principles for use of computer support tools to enable broad group communication and coordination.

***HSI Design Deficiencies*** continue to be found with new technology. Appropriate HFE processes have to be applied to ensure that designs meet personnel task requirements, performance demands, and are well designed from the standpoint of human cognitive and physical characteristics. NRC review criteria will have to keep pace with advances that are made in HSI designs.

**<u>Complexity</u>**

An ***Increase in Complexity and Opacity*** is often associated with the HFE aspects of the plant even though new NPP designers are seeking greater simplicity. The ***Larger Number of Systems*** of many new NPP designs contributes to the complexity of some new plant designs. ***Intelligent Agents*** (as discussed earlier) can also add to the apparent complexity of a design. Other features include increases in sensing capabilities, information processing support, automation, and software mediated interfaces. Although all of these features are potentially beneficial, they add to the complexity of the design and can make it difficult for operators to maintain situation awareness. This complexity can also limit the ability of operators to understand the appropriate uses and limitations of such systems. In this sense, the behavior of these systems can seem opaque or less visible to operators.

A more general aspect of this issue is that little is known about precisely what factors make a plant, system(s), HSI, scenario, task, or operation complex to plant personnel. If complexity were better understood, then a measure of complexity could be developed that can be used as part of a safety evaluation.

## <u>Organizational Factors</u>

Several issues were identified that relate to organizational factors. Different approaches to designing and operating NPPs have evolved in different parts of the world with respect to reliance on automation and organization of control room crews. When a plant designed in one location is used by plant staff in another location, the plant staff may have fundamentally different ideas about how a plant should be operated than is reflected in the plant design. ***Vendor Diversity and Its Impact on Operational Philosophy*** needs to be studied for its possible safety implications.

***Safety Culture*** is another issue. There has been a recent industry trend toward large energy corporations that acquire many diverse plants. An issue that arises is how safety culture is transmitted to personnel at the individual units, and determining the impact on safety culture of combining units with different original cultures under a single large operating entity. Longer-term, issues may arise defining safety culture in the context of radically different concepts of operation and approaches to staffing. For example, one alternative concept of operations for future plants is to have minimal onsite staff to handle routine operations and offsite disturbance management crews that respond to emergencies as needed. The impact on safety culture of distributed functional organizations is presently unknown.

***Managing Human Error in Operations and Maintenance*** addresses the fact that designs may incorporate error tolerance features to minimize human errors and the consequences of any errors that occur. Safety reviews will have to specifically address error tolerant design activities and features as well as the organizational elements of licensee programs to minimize human error. This will require the development of comprehensive approaches to error tolerance. For new designs with no operating experience, it will be especially important to have a good risk analysis, to define risk-important human actions, and then to address those actions in all aspects of the design.

**Table 4 Detailed issues associated with the normal operations topic**

| Detailed Issue | Reactor Type | Priority |
|---|---|---|
| **General Knowledge Limitations Subtopic** | | |
| Availability of Operating Experience of Gen III Reactors | Gen III | 2 |
| Unanticipated Impact of Technology | All | 2 |
| Understanding How HSIs are Really Used | All | 2 |
| **Specific Changes to Operations Subtopic** | | |
| Modular Plants | Modular | 3 |
| Different Reactivity Effects | LFR | 3 |
| Increased Power Operations | All | 3 |
| Continuous Fueling | PBMR | 3 |
| Physical Protection, Security, and Safety | All | 2 |
| Biometrics, Fitness for Duty, and Security | All | 4 |
| **Advances in HSIs Technology Subtopic** | | |
| Interfaces to Automation | All | 1 |
| Sensors and Condition Monitoring | All | 1 |
| Digital Communication Networks | All | 2 |
| Alarm System Design | All | 1 |
| Information System Design | All | 1 |
| Display Design | All | 2 |
| Control Design | All | 1 |
| Advanced Controls | All | 2 |
| Computerized Operator Support Systems | All | 2 |
| Computer-based Procedures | All | 1 |
| Computation and Simulation | All | 2 |
| Interface Management Design | All | 1 |
| Portable Computers and HSIs | All | 4 |
| Computer-supported Collaboration | All | 4 |
| HSI Design Deficiencies | All | 2 |
| **Complexity Subtopic** | | |
| Increase in Complexity and Opacity | All | 1 |
| Larger Number of Systems | MSR* | 4 |
| Intelligent Agents | All | 2 |
| **Organizational Factors Subtopic** | | |
| Vendor Diversity and Its Impact on Operational Philosophy | Gen III | 4 |
| Safety Culture | All | 2 |
| Managing Human Error In Operations And Maintenance | All | 3 |

*MSR - Molten Salt Reactor

### 3.1.4 Disturbance and Emergency Management

The Disturbance and Emergency Management topic addresses issues related to how plant design addresses risks and how abnormal events are handled. Table 5 provides a listing of the individual issues identified within this topic.

***New Hazards*** characterize many new reactor designs. These new hazards include hydrogen, liquid sodium, liquid fuel, liquid metal, graphite in the core, and supercritical water. Some new designs also use much higher temperatures/pressures than LWRs. Graphite cores are flammable and could create radiologically hazardous fumes. The new hazards have to be understood and addressed in safety systems that are used to monitor and mitigate the hazard.

Operators will have to understand these hazards, monitor them, and have procedures to mitigate them if automatic systems are either unavailable or fail. Safety review of how the new hazards are managed, including their impact on personnel actions, will be needed.

***Passive Safety Systems*** that support emergency management are included in many new NPP designs. Because they depend on physical processes, they are not as amenable to routine testing as active systems. Operators may not know from actual operational experience how to verify their proper automatic initiation and operation when they are called upon to perform in a real event, e.g., the flow rates and temperatures may be much lower. The human performance aspects of monitoring and verification of passive system success will need to be defined along with any operator actions necessary to initiate back-up systems should they fail to operate as designed.

***Post-core-melt Mitigation*** is a new aspect of some plant designs. An example is the Evolutionary (or European) Pressurized Water Reactor (EPR) strategy to avoid the need for emergency evacuation outside the immediate vicinity of the plant. This is accomplished by designing advanced mitigating systems for managing a damaged core. Some of these systems are passive, but others are active and rely on operator monitoring and actions. Operator actions at this stage of a severe accident may raise new human performance issues.

***Diagnostics and Prognostics*** will aid personnel during emergencies. Diagnostics refer to techniques for identifying and determining the causes of faults in the plant systems or processes. Prognostics refer to estimating the rate of physical degradation and the remaining useful life of equipment, predicting time to failure, and applying this information to more effectively manage a facility's assets and to schedule maintenance on an as-needed basis. Accuracy and reliability of diagnostics and prognostics are significant issues for human performance, as are their impact on operational strategies. Plant operators and maintenance personnel are currently trained to work with procedures, and the procedures are for the most part deterministic. In future plants with extensive diagnostic and prognostic capabilities, operators will be faced with results that come with uncertainties, predictions, and recommended actions, and risk assessments that are inherently probabilistic. This will need to be addressed in training, qualification and licensing.

***Operations Under Conditions of Degraded I&C*** will have to be managed by plant personnel. This situation may be caused by a variety of events, such as instrument failure, computer failures (hardware and software), seismic events, fire and smoke damage, internal flooding, and loss of electrical power. These events may cause a range of failures from individual control room instruments to more significant degradations such as the loss of all displays. Some of the human performance considerations in dealing with operations under degraded conditions include:

- *Detection of digital system failure* - The degradation modes and failures in digital systems can be more difficult to detect, especially in the case where there is not a complete failure.
- *Transition to back-up systems* - Digital systems provide a great deal of support to crews in terms of information access, analysis, and presentation that is not available from conventional technology. However, when digital systems fail, crews may have to transition to hardwired controls and displays and paper procedures. There may also be training implications for using digital and conventional systems together and for the transition between them.

- *Teamwork* - Digital systems have a significant impact on the nature of crew members' tasks and their interactions with each other. This may become significant as new generations of operators, trained mainly on digital system operations, have to cope with degraded conditions that impact teamwork.

***Managing Human Error in Operations and Maintenance*** was discussed in Section 3.1.3 but is also applicable to disturbance and emergency management, where the impact of human errors on plant risk may be more directly apparent. ***HSI Design Deficiencies*** correction is one aspect of managing errors.

**Table 5 Detailed issues associated with the disturbance and emergency management topic**

| Detailed Issue | Reactor Type | Priority |
|---|---|---|
| New Hazards | Gen IV | 3 |
| Passive Safety Systems | All except ABWR | 4 |
| Post-core-melt Mitigation | EPR | 3 |
| Diagnostics and Prognostics | All | 2 |
| Operations Under Conditions of Degraded I&C | All | 1 |
| HSI Design Deficiencies | All | 2 |
| Managing Human Error in Operations and Maintenance | All | 3 |

### 3.1.5 Maintenance and Change Management

The Maintenance and Change Management topic addresses concepts for system maintenance, installing upgrades, and configuration management. Table 6 provides a listing of the individual issues identified within this topic. The issues in this topic are further organized into two subtopics: Rapid Pace of Technology Change and Impact on Maintenance Practices.

**Rapid Pace of Technology Change**

***More Frequent Changes Due to Obsolescence*** are anticipated since digital I&C systems and computer-based HSIs develop at a rapid pace. These become obsolete much faster than equipment typically found in current plants, leading to the need to make changes to ensure that the installed equipment can continue to be maintained and that adequate vendor support will be available. Also, enhancements will be made available from the vendors as their product lines and associated functional capabilities evolve. These changes will impact operations, maintenance and training. Also, the level of involvement of plant personnel in the changes will be an issue; e.g., the trend toward automatic or semi-automatic updates of commercial software will need to be considered carefully before it is implemented in nuclear plants.

***Ease of Making System Modifications*** is a related issue. Conventional hardwired I&C and HSI systems are relatively difficult to modify. Making changes is very expensive and often requires modifications to field cabling and/or replacement of equipment to obtain new or different functionality. However, digital I&C systems provide much more flexibility and are easier to modify. Enhancing functionality or adding new functions may be accomplished via a workstation without any physical change to equipment. Advanced I&C systems may incorporate capability for knowledge capture and machine learning, or adaptive control methods that automatically make adjustments to control schemes based on experience gained in operation. The capability for easy change and the opacity of that change have the potential to impact both safety and security.

**Impact on Maintenance Practices**

***Change in the Concept of Maintenance*** is one of the most notable impacts of digital I&C systems that have more extensive self-diagnostics and self-correction capabilities. Some important aspects of this change include the following:

- *Unique features of digital I&C* - Digital systems have features and capabilities that pose challenges for maintenance activities, such as the rapid evolution of digital technology.
- *Workstation-based maintenance* - Troubleshooting and maintenance will be done through dialog with the system at a workstation, possibly with software agents acting as automated assistants. Further, operations and maintenance personnel will work cooperatively when performing maintenance, collaborating via the computer. Operator awareness of maintenance activities when maintenance personnel are working with the systems via workstations is an important concern.
- *Merging of maintenance and operations functions* - With the advent of more complex automation and information systems, on-site personnel who are charged with operating the plant also will increasingly need to act as the first line of defense when faults are detected or failures occur in the I&C systems. With digital systems, the distinction between I&C maintenance and operations tends to become blurred in the early stages of fault response.

***Simplified Maintenance Practices*** is another issue. Generation IV plant vendors are likely to submit designs that are easily maintainable to ensure quick and inexpensive repairs when needed. This may result in maintenance being more quickly performed by operations personnel without the checks and balances done by maintenance departments. This may also impact the knowledge, skills, and abilities required of operations staff and increase their workload. The changes in maintenance practices that may result will have to be evaluated to determine that they do not negatively impact plant safety.

***Portable Computers and HSIs*** will be increasingly employed and supported by new technology. The issues associated with portable computers and HSIs were discussed in Section 3.1.3.

***Managing Human Error in Operations and Maintenance*** was discussed in Sections 3.1.3 and 3.1.4. Human errors will have to be minimized to reduce equipment failures that lead to unplanned outages and added repair costs.

**Table 6 Detailed issues associated with the maintenance and change management topic**

| Detailed Issue | Reactor Type | Priority |
|---|---|---|
| **Rapid Pace of Technology Subtopic** | | |
| More Frequent Changes Due to Obsolescence | All | 4 |
| Ease of Making System Modifications | All | 3 |
| **Impact on Maintenance Practices Subtopic** | | |
| Change in the Concept of Maintenance | All | 2 |
| Simplified Maintenance Practices | All | 3 |
| Portable Computers and HSIs | All | 4 |
| Managing Human Error in Operations and Maintenance | All | 3 |

### 3.1.6 Plant Design and Construction

This topic pertains to the HFE aspects of general plant design and construction. Table 7 provides a listing of the individual issues.

One of the lessons learned from the current LWR fleet is that there were design errors that impacted different aspects of the plant. Many such errors were discovered and corrected at various points in the plant's life cycle: design, design verification, construction, pre-operational testing, startup testing, and during the several decades of plant operation. Some design errors are still being identified, many years after startup. Thus, ***Managing Design and Construction Errors*** will be an important consideration for new NPPs. Human errors can occur both in modular/factory construction and in the onsite field construction. If not found, they create potential safety problems for the newly operating plant. Research may be needed to address means to catalogue such human errors, identify root causes where possible, and develop NRC review guidelines with the intent of avoiding, detecting, and correcting these types of human errors in new NPP designs.

A particularly important aspect of the design for new plants is the reliance on software. Therefore, ***Design and Evaluation of Digital Systems and Software*** is an important issue.

New NPPs will employ digital I&C systems relying heavily on software for critical monitoring and control functions. Software and knowledge representation will also form the foundation for designing COSSs and intelligent agents. Some of the aspects of digital system design that are noteworthy include the following:

- *Increase in complexity* - The complexity of the I&C systems envisioned for new NPPs is much higher than for current plant designs and there is no practical limit to how complex software can be. A program can have a large number of execution paths, which, in combination with process states and human inputs, lead to a very large number of distinct system states. Software is also error sensitive. In typical engineering contexts, small errors have small effects; this is not so with software.
- *Common-mode failure* - The possibility of correlated failures in software can make it more likely that a fault occurs. It is typical for programmed "components" to be re-used; thereby, weakening the protection afforded by redundancy. Even when two software systems are developed independently, the similarity of industry design and testing approaches leaves them vulnerable to common mode failure.

- *Hardware-software interaction* - Although much of the research on safety-critical systems has focused specifically on software, problems that have been experienced with digital systems often relate to hardware-software interaction, digital system architecture or other design issues, and inappropriate applications of digital systems.
- *Design team skills* - Experience with critical digital systems to date has shown that the qualifications and experience of the design team are very significant factors; yet, most efforts to evaluate and manage digital system risks have been directed primarily toward the process.
- *Human error* - One of the biggest issues in software development is human error. Mistakes and oversights occur, but may only manifest themselves in interaction with the process or with other software components; i.e., the software errors often remain latent until a unique set of plant conditions occur and there are system failures or other performance problems. Given these limitations and the fact that new plants will be software based, human error in software development needs to be evaluated.
- *Defensive design techniques* - Defensive design techniques are very important in managing the risks of digital systems, such as making systems tolerant of design errors that may be present in software or digital system design. Their use in new plant designs will have to be evaluated.
- *Software quality assurance* - Software verification and validation techniques are still evolving and need to mature further before they are sufficiently robust to establish firm and objective criteria.

Together these aspects of I&C system development will directly impact the operators' ability to monitor and control the plant. Because 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 and make control tasks difficult to perform. Further, decision support systems built on poorly designed I&C systems have the potential to provide incorrect assessments that can lead operators to take unnecessary or incorrect action.

***Modular Construction*** has implications for plant personnel. In the past, plant personnel participated in the onsite construction, component-level testing of installed components, and preoperational testing of completed systems. This gave personnel a thorough knowledge of plant structures, systems, and components. Fabrication of plants at factories rather than the site may limit plant personnel knowledge of systems and components. The implications of this approach to safety are not known.

The ***Knowledge Gap Between Licensee Organization and Supplier*** in the areas of digital and computer technology in the beginning stages of I&C/HSI modernization programs has been a significant issue in many current plants. In addition to digital I&C and HSIs, however, utilities may have to deal with different reactor technology as well. An existing nuclear licensee may be familiar with LWR technology, so an adjustment will have to be made for dealing with a different technology, such as a modular, pebble bed design.

**Table 7 Detailed issues associated with the plant design and construction topic**

| Detailed Issue | Reactor Type | Priority |
|---|---|---|
| Managing Design and Construction Errors | All | 2 |
| Design and Evaluation of Digital Systems and Software | All | 1 |
| Modular Construction | Potentially All | 4 |
| Knowledge Gap between Licensee Organization and Supplier | Gen III | 4 |

### 3.1.7 HFE Methods and Tools

The topic of HFE methods and tools pertains to the way the HFE aspects of a plant are designed and evaluated; i.e., the resources used by HFE personnel, whether as part of vendor organizations, licensees, or NRC, to accomplish their roles and responsibilities. This topic is especially relevant to NUREG-0711, the NRC's guidance for reviewing the design and evaluation process. Table 8 provides a listing of the individual issues identified within this topic. The issues in this topic were further organized into three subtopics: Analysis Methods and Tools, Design Methods and Tools, and Test and Evaluation Methods and Tools.

**Analysis Methods and Tools**

Analysis methods and tools are used to develop information that is used as input to HFE design activities. ***Methods to Support the Early Consideration of Human Factors in Plant Design*** emphasizes the need for general approaches to this issue. Methods are needed for evaluating designs early in their development for compatibility with human performance. This type of method could then be used to compare designs before too much detailed design work is performed.

Although the development and use of operating experience is generally considered an important design activity, and is part of a NUREG-0711 review, standardized methods to support this activity are not available. Instead, operating experience use and review is guided by general qualitative approaches. ***Operating Experience and Lessons Learned*** methodologies are needed to ensure that appropriate information is collected, human performance insights are analyzed, and lessons learned are identified.

Generally accepted methodologies for the conduct of function analyses are lacking. Function analysis methods are used to analyze plant functional requirements and allocate those functions to automation, personnel, or a combination of the two. As was discussed in Section 3.1.1, this is a very important activity for new NPPs since the degree of plant automation is expected to increase and become more widely applied. The ***Development of New Function Allocation Methods*** for nuclear plant applications is an important issue.

Once personnel functions are allocated, task analysis is performed to identify the requirements for task performance. These requirements are used to design HSIs, procedures, and training programs. The development of task analysis methodologies is a rapidly developing area in human factors. Recent advances in work analysis, cognitive task analysis, and cognitive engineering are especially applicable to supervisory control tasks and are particularity well suited to analyzing the nature of expertise. However, there is a lack of guidance on the appropriate application of such methods. As these approaches are relatively new, their methodologies are not formalized yet. The ***Development of New Task Analysis Methods*** is needed as is guidance for their review.

***Human Reliability Analysis Methods for Advanced Systems*** are needed. HRA methods may not be applicable to new designs which incorporate increased automation, alternative concepts of operation, and intelligent interfaces. The conduct of HRA will be further hampered by the lack of databases upon which to estimate human error probabilities. Research to address this gap is needed.

***Development and Application of Knowledge Engineering Techniques,*** i.e., techniques for identifying and documenting the knowledge of subject matter experts, is another issue. When this knowledge is coupled with simulation and analysis tools, a powerful knowledge base is created upon which to improve operations and maintenance performance. This information can be applied to the development of more intelligent interfaces (such as intelligent alarm processing and analysis) and to intelligent agents that reflect the knowledge of experts. Efficient methods to obtain and store such knowledge in integrated databases are needed. In addition, review criteria are needed to evaluate HSIs developed using the knowledge elicited from experts.

## Design Methods and Tools

Design methods and tools are used to develop detailed designs of HSI, procedures, and training. ***Rapidly Changing HSI Technology*** is a one significant difference between digital and analog interfaces. To keep pace with the rapid technology changes, methods will continue to be developed to produce designs in far less time than has traditionally been the case. A potential concern relates to the completeness of the technical basis on which HSIs resulting from these methods are developed.

***Participatory Ergonomics*** refers to obtaining input from users early and often during a design project. Although this is an important development and fully consistent with NUREG-0711, an accepted view has yet to emerge as to what specific contribution users should make or how such input should be solicited. More explicit guidance is needed to address these issues for future design projects and regulatory reviews of them.

Design methods themselves are evolving at a fast pace. ***Rapid Prototyping*** is one aspect of this evolution. With rapid prototyping tools, designs quickly evolve through a number of iterations with system users to obtain feedback and make HSI modifications. The cycle is repeated until the design is completed. This is quite different from the more traditional approach of performing careful information requirements analysis, applying HFE guidelines, and conducting evaluations in a much less iterative manner. As a new approach, acceptable methods of rapid prototyping have yet to be developed and the methods of documenting the design basis of HSIs developed this way are not established. Similarly, review guidance for evaluating designs developed in this manner does not currently exist.

***Design Process for Higher-level Interfaces*** is another issue in this topic. While interfaces incorporating higher-level, functionally-oriented displays may be a promising advance, there are no well-defined processes for conducting the analyses needed to specify them. The ability of such interfaces to support the successful handling of unplanned-unanticipated events under actual operational conditions has not been clearly demonstrated.

**Test and Evaluation Methods and Tools**

Several issues addressing different aspects of the test and evaluation process were identified.

***Evaluating the Effects of Advanced Systems*** is a general area that needs to be addressed. Better knowledge of the effects of advanced systems provides a basis from which review and acceptance criteria can be developed. ***Guidance for the Review of Intelligent HSIs*** is one area of guidance that is particularly lacking. Based on current trends, it is likely that HSIs will continue to become more intelligent. The knowledge and reasoning bases of these systems will be diverse, e.g., application of knowledge engineering or use of formal analysis rules. At present, we do not have sufficient guidance to address the review of intelligent HSIs.

***Validation of Integrated Systems*** is an important review issue in NUREG-0711. Integrated system validation is especially important in the context of new NPPs, because the designs will be more complex and the HSIs will incorporate more functions than in conventional designs. More clearly defined methodological criteria are needed to review licensee validation submittals.

***Changing Testbeds*** is a key issue related to validation. HFE tests and evaluations often use testbeds, such as full-mission simulators. However, new technologies are being developed that provide flexible alternatives that can be used to support both design and evaluation activities. For example, virtual reality (VR) can be used as an alternative to physical mockups or simulators. An important question that needs to be addressed is the validation of VR models and the methodology for their use.

Another key consideration is performance measurement. In general, there is a trend towards ***Performance-Based Methods***, in contrast to design verification methods (such as evaluating a design using HFE guidelines). It will be necessary to establish NRC acceptance criteria and review procedures for independently assessing performance-based evaluations.

Another issue relates to ***Collection, Analysis, and Use of Real-Time Human Performance Data*** in the plant. Computer-mediation of human actions in future plants will allow the use of data logging capabilities that can be integrated into display, control, and communications interfaces to automatically gather and analyze human interaction data. This, in turn, will support the development of HFE tools that could be used to assess human performance and predict performance shortfalls. The effects of applying this technology to plant safety are largely unknown.

With respect to performance measurement, much of the focus is on the individual. However, in NPPs, personnel work as teams to accomplish their functions and tasks. Thus, ***Modeling and Measurement of Effective Team Performance*** is an important issue. Understanding team performance will be especially significant in future plants that may involve alternative concepts of operation, use of intelligent agents, and the application of technology to support teamwork, such as computer-supported cooperative work. Research is needed to identify what constitutes good and effective teamwork and how it is affected by technology. In addition, measures of effective team performance are needed that can be applied to system design and evaluation, including integrated system validation.

While the above issues relate to measuring actual human performance, whether individual or team, current trends suggest that obtaining “performance data” from other sources may be common in the future. ***Human Performance Models***, such as task network modeling and discrete event simulation, are being applied to design and evaluation projects. Operator availability is limited and the means to collect data can be expensive, such as using full-mission simulators. Models, therefore, can be an attractive alternative. As the sophistication of the models improves, their application will be extended to more complex design and evaluation situations. To be used in a regulatory review, whether by the NRC staff or as part of an applicant submittal, the validity of the modeling and its results will have to be assured.

In addition to human performance models, other alternatives to the collection of actual performance data are being developed. ***Quantitative Human Performance Criteria*** are being sought with the objective of characterizing plant design features that influence human performance in quantitative terms. These criteria would be used, for example, to compare various Generation IV plant options. The technical basis for such measures and their application will have safety implications.

**Table 8 Detailed issues associated with the HFE methods and tools topic**

| Detailed Issue | Reactor Type | Priority |
|---|---|---|
| **Analysis Methods and Tools Subtopic** | | |
| Methods to Support the Early Consideration of Human Factors in Plant Design | All | 1 |
| Operating Experience and Lessons Learned | All | 1 |
| Development of New Function Allocation Methods | All | 3 |
| Development of New Task Analysis Methods | All | 2 |
| HRA Methods for Advanced Systems | All | 1 |
| Development and Application of Knowledge Engineering Techniques | All | 4 |
| **Design Methods and Tools Subtopic** | | |
| Rapidly Changing HSI Technology | All | 3 |
| Participatory Ergonomics | All | 2 |
| Rapid Prototyping | All | 4 |
| Design Process for Higher-Level Interfaces | All | 1 |
| **Test and Evaluation Methods and Tools Subtopic** | | |
| Evaluating the Effects of Advanced Systems | All | 1 |
| Guidance for the Review of Intelligent HSIs | All | 2 |
| Validation of Integrated Systems | All | 1 |
| Changing Testbeds | All | 3 |
| Performance-Based Methods | All | 1 |
| Collection/Analysis/Use of Real-Time Human Performance Data | All | 4 |
| Modeling and Measurement of Effective Team Performance | All | 1 |
| Human Performance Models | All | 3 |
| Quantitative Human Performance Criteria | All | 4 |

## 3.2 Issue Evaluation and Prioritization

As per the methodology described in Section 2, the research issues were prioritized into four categories from most to least important. Each issue's priority was given in Tables 2 through 8. In this section, the issues are grouped by priority.

The number of issues in each of the categories was:

Priority 1: 20 issues
Priority 2: 17 issues
Priority 3: 17 issues
Priority 4: 10 issues

The issues in each of the four priority categories are listed below. Within each priority category, the issues are listed according to their average significance, with the most significant first.

*Priority 1 Issues*

- Level of Automation
- Operations Under Conditions of Degraded I&C
- Design and Evaluation of Digital Systems and Software
- Operating Experience and Lessons Learned
- Validation of Integrated Systems
- Performance-Based Methods
- Information System Design
- Computer-based Procedures
- Interfaces to Automation
- Modeling and Measurement of Effective Team Performance
- Design Process for Higher-Level Interfaces
- Control Design
- Alarm System Design
- Evaluating the Effects of Advanced Systems
- Training and Qualifications
- HRA Methods for Advanced Systems
- Methods to Support the Early Consideration of Human Factors in Plant Design
- Sensors and Condition Monitoring
- Interface Management Design
- Increase in Complexity and Opacity

*Priority 2 Issues*

- Guidance for the Review of Intelligent HSIs
- Safety Culture
- Intelligent Agents
- Managing Design and Construction Errors
- Unanticipated Impact of Technology
- Display Design
- HSI Design Deficiencies
- Development of New Task Analysis Methods
- Computerized Operator Support Systems
- Physical Protection, Security, and Safety
- Availability of Operating Experience of Gen III Reactors
- Change in the Concept of Maintenance
- Digital Communication Networks
- Participatory Ergonomics
- Computation and Simulation

- Diagnostics and Prognostics
- Understanding How HSIs are Really Used

*Priority 3 Issues*

- Reduced Staffing
- Managing Human Error In Operations And Maintenance
- Ease of Making System Modifications
- New Hazards
- Crew Member Roles and Responsibilities
- Human Performance Models
- Continuous Fueling
- Modular Plants
- Different Reactivity Effects
- Advanced Controls
- Simplified Maintenance Practices
- Changing Testbeds
- Post-core-melt Mitigation
- Increased Power Operations
- Development of New Function Allocation Methods
- Rapidly Changing HSI Technology
- Functional Staffing Models

*Priority 4 Issues*

- Computer-supported Collaboration
- Knowledge Gap between Licensee Organization and Supplier
- Development and Application of Knowledge Engineering Techniques
- Collection/Analysis/Use of Real-Time Human Performance Data
- Passive Safety Systems
- More Frequent Changes Due to Obsolescence
- Quantitative Human Performance Criteria
- Rapid Prototyping
- Vendor Diversity and Its Impact on Operational Philosophy
- Modular Construction

Based on information obtained from SMEs from their evaluation sheets and during the meeting discussions, the technical basis for classifying each Priority 1 issue is briefly discussed below. These bases are often closely tied to the issue discussions provided in Section 3.1. The basis discussions below are meant to illustrate the key aspects of each issue that led to a Priority 1 evaluation. In the issue discussions, links between related issues were often identified. These links are identified as well.

The issues are organized by the high-level topic area in which they belong. It is interesting to note that issues from all but one high-level topic area (Maintenance and Change Management) were represented in the Priority 1 group. The two areas in which most of the issues fell were Normal Operations Management, largely due to advanced HSI technology issues, and Methods and Tools.

**Role of Personnel and Automation**

*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. Level of Automation is closely coupled to the issues of “Interfaces to Automation” and “Computer-based Procedures” both of which are discussed below. It also is closely tied to the “Development of New Function Allocation Methods” since these methods are used to help determine what aspects of plant operations should be automated.

**Staffing and Training**

*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.

**Normal Operations Management**

This area was dominated by issues related to advanced HSI technology. In general, the issues are related to technologies that form the core HSIs used by personnel in the performance of their tasks.

*Interfaces to Automation* – As the levels of automation in new plants will be 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.

*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.

*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 many other industries despite efforts to address them.

*Information System Design* – Information is at the core of human performance and 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.

*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.

*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. The design of controls is related to the issue of “Operations Under Conditions of Degraded I&C” since the controls available to personnel may change depending on the type of degraded condition that may exist.

*Interface Management Design* – The design of the interface management features of the HSI have 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.

*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. Since training on these systems will be a key consideration, this issue is linked to the “Training and Qualifications” issue discussed above.

**Disturbance and Emergency Management**

*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, detection 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.

**Plant Design and Construction**

*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.

**HFE Methods and Tools**

*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 and better analysis may be needed because human performance aspects of experience are too often missed. Thus, this issue is directly tied to “Availability of Operating Experience of Generation III Reactors.”

*HRA Methods for Advanced Systems* – While HRA and PRA 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.

*Methods to Support the 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.

*Evaluating the Effects of Advanced Systems* – The need to evaluate the effects of advanced systems on human performance, both from 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. This is closely tied to “Performance-Based Methods” and “Validation of Integrated Systems,” discussed below.

*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.

*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.

# 4 SUMMARY AND CONCLUSIONS

This study identified sixty-four potential human performance research issues related to the HFE aspects of the integration of new technology into NPPs. The research issues were organized into seven high-level research topics. The issues were then evaluated and 20 were identified as Priority 1 – the most significant category. These topic areas and the related human performance considerations are potential research issues that could be used to develop guidance.

There are several recurrent themes that cut across many of the topics and issues identified. They are: complexity, roles of personnel and automation, management of human error, and the design and evaluation process. While each was identified as a topic or issue, their pervasiveness deserves mention.

The first recurrent theme is complexity. Although NPP designers are seeking greater simplicity, the HFE aspects of the plant are likely to be more complex than in today's plants. Increases in sensing capabilities, information processing support, intelligent agents, automation, and software mediated interfaces increase the “distance” between personnel and the physical plant. Although these technologies are potentially beneficial, they may sometimes add to complexity for the personnel operating and maintaining the plant.

A second theme is the role of personnel and automation. Many of the issues identified were related to increases in automation and reductions in staff. Increased automation cuts across many aspects of plant operations and maintenance from process control, to decision support, to HSI management, to routine tasks such as keeping logs. Decisions regarding staffing impact the requirements for automation, i.e., all other things being equal, fewer staff can lead to the need for greater automation.

Another theme is the management of human error. Although several specific human error issues were identified, many other issues contained aspects that involve human error. Because the safety implications of human error are well established, management of errors in plant design, software development, construction, maintenance, and operations will be a significant consideration for new designs. Methods to minimize human error, in all aspects of a plant’s lifecycle, will be important as will providing personnel with the means to detect and correct errors when they do occur. Designing to minimize and manage errors is part of a fault tolerant design strategy that should be a major focus as new NPPs are designed and built in the U.S.

A fourth theme is the importance of the design and evaluation process. Currently, NRC HFE reviews are process oriented, which is a positive step toward addressing new NPP issues. A process orientation enables acceptance criteria to be relatively technology neutral. This will be extremely important in new NPP reviews because the diversity of reactors, HSIs, and concepts of operation will expand significantly. Because analysis, design, and evaluation methods and tools are rapidly changing, modifications and improvements to the review methods and criteria are necessary.

The “Plant Design and Construction” topic is a relatively new consideration. With the rapid advance of technology, a more focused approach to this aspect of the design process, especially in minimizing human errors that impact aspects such as software design and plant construction, may be warranted.

Our results also have implications for the NRC’s current HFE-related regulations and design review guidance documents. There are at least three aspects of the current guidance that should be evaluated further:

- First, the wording of the regulations and guidance often reflects LWR technology. However, non-light water reactors are viable candidates for near-term deployment, as well as longer-term Generation IV designs. Thus, changes will be needed to address non-LWR designs.
- Second, the regulations and guidance reflect current concepts of operation used in today's plants. For example, the current definition of crew member roles and responsibilities reflect the staffing approaches used in older, less automated plants. Another example is that safety monitoring reflects current approaches and LWR technology, such as in the safety parameter display system requirements. Some new plants may employ new concepts of operation and implement new technologies that may not fit the current review criteria.
- Third, the HFE review process and its guidance may have to be modified to accommodate new design and evaluation approaches, such as the use of human performance modeling for HSI evaluation in place of data collected from actual operations crews. The current review guidance is based on a systems engineering process that itself is changing as new design and evaluation methods and tools become available.

The information obtained in this research can support the development of a long-term strategy and plan for addressing human performance in these areas through regulatory research (Appendix B to this report describes the NRC’s HFE review guidance development methodology than can be use to address these issues). 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 will 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 will provide the technical basis from which regulatory review guidance can be developed to meet these challenges.

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# Appendix A  Issue Description Cross Reference to BNL Technical Report

### Table A.1  Detailed issues associated with the role of personnel and automation topic

| Detailed Issue | Tech. Report Section |
|---|---|
| Level of Automation | 3.2.1 |
| Intelligent Agents | 3.3.3 |
| Computer-based Procedures | 3.3.3 |
| Computerized Operator Support Systems | 3.3.3 |
| Monitoring of Plant Personnel | 3.2.1 |
| Reduced Staffing | 3.1.3.2 |

### Table A.2  Detailed issues associated with the staffing and training topic

| Detailed Issue | Tech. Report Section |
|---|---|
| **Approaches to Staffing Subtopic** | |
| Functional Staffing Models | 3.3.1 |
| Reduced Staffing | 3.1.3.2 |
| Crew Member Roles and Responsibilities | 3.3.1 |
| **Training Implications Subtopic** | |
| Training and Qualifications | 3.3.1 |
| Change in HSI Demands and Training Requirements | 3.1.1.2 |
| Rapid Learning Curve in Early Stages of Plant Operation | 3.2.2 |
| Personnel Acceptance of Technology | 3.1.1.2 |

### Table A.3  Detailed Issues associated with the normal operations topic

| Detailed Issue | Tech. Report Section |
|---|---|
| **General Knowledge Limitations Subtopic** | |
| Availability of Operating Experience of Gen. III and III+ Reactors | 3.1.2.2 |
| Unanticipated Impact of Technology | 3.1.1.2 |
| Understanding How HSIs are Really Used | 3.1.1.2 |
| **Specific Changes to Operations Subtopic** | |
| Modular Plants | 3.1.2.2 & 3.1.3.4 |
| Different Reactivity Effects | 3.1.3.4 |
| Increased Power Operations | 3.1.2.2 |
| Continuous Fueling | 3.1.2.2 |
| Physical Protection, Security, and Safety | 3.1.3.2 |
| Biometrics, Fitness for Duty, and Security | 3.3.1 |
| **Advances in HSIs Technology Subtopic** | |
| Interfaces to Automation | 3.3.3 |
| Sensors and Condition Monitoring | 3.2.1 |
| Digital Communication Networks | 3.2.1 |
| Alarm System Design | 3.3.2 |
| Information System Design | 3.2.1 |
| Display Design | 3.3.2 |
| Control Design | 3.3.2 |
| Advanced Controls | 3.2.1 |
| Computerized Operator Support Systems | 3.3.3 |

**Table A.3 Detailed Issues associated with the normal operations topic** (Cont'd.)

| Detailed Issue | Tech. Report Section |
|---|---|
| Computer-based Procedures | **3.3.3** |
| Computation and Simulation | 3.2.1 |
| Interface Management Design | 3.3.2 |
| Portable Computers and HSIs | 3.3.2 |
| Computer-supported Collaboration | 3.2.1 |
| HSI Design Deficiencies | 3.1.1.2 |
| **Complexity Subtopic** | |
| Increase in Complexity and Opacity | 3.1.1.2 |
| Larger Number of Systems | 3.1.3.4 |
| Intelligent Agents | 3.3.3 |
| **Organizational Factors Subtopic** | |
| Vendor Diversity and Its Impact on Operational Philosophy | 3.3.1 |
| Safety Culture | 3.3.1 |
| Managing Human Error In Operations And Maintenance | 3.1.3.2 |

**Table A.4 Detailed issues associated with the disturbance and emergency management topic**

| Detailed Issue | Tech. Report Section |
|---|---|
| New Hazards | 3.1.2.2 (Graphite Cores) and 3.1.3.4 |
| Passive Safety Systems | 3.1.2.2 & 3.1.3.4 |
| Post-core-melt Mitigation | 3.1.2.2 |
| Diagnostics and Prognostics | 3.2.1 |
| Operations Under Conditions of Degraded I&C | 3.2.2 |
| HSI Design Deficiencies | 3.1.1.2 |
| Managing Human Error in Operations and Maintenance | 3.1.3.2 |

**Table A.5 Detailed issues associated with the maintenance and change management topic**

| Detailed Issue | Tech. Report Section |
|---|---|
| **Rapid Pace of Technology Subtopic** | |
| More Frequent Changes Due to Obsolescence | 3.2.2 |
| Ease of Making System Modifications | 3.2.2 |
| **Impact on Maintenance Practices Subtopic** | |
| Change in the Concept of Maintenance | 3.2.2 |
| Simplified Maintenance Practices | 3.1.3.2 |
| Portable Computers and HSIs | 3.3.2 |
| Managing Human Error in Operations and Maintenance | 3.1.3.2 |

**Table A.6 Detailed issues associated with the plant design and construction topic**

| Detailed Issue | Tech. Report Section |
|---|---|
| Managing Design and Construction Errors | 3.1.3.2 |
| Design and Evaluation of Digital Systems and Software | 3.2.2 |
| Modular Construction | 3.1.2.2 |
| Knowledge Gap between Licensee Organization and Supplier | 3.1.1.2 |

**Table A.7 Detailed issues associated with the HFE methods and tools topic**

| Detailed Issue | Tech. Report Section |
|---|---|
| **Analysis Methods and Tools Subtopic** | |
| Methods to Support the Early Consideration of Human Factors in Plant Design | 3.4.1 |
| Operating Experience and Lessons Learned | 3.4.1 |
| Development of New Function Allocation Methods | 3.4.1 |
| Development of New Task Analysis Methods | 3.4.1 |
| HRA Methods for Advanced Systems | 3.4.1 |
| Development and Application of Knowledge Engineering Techniques | 3.4.1 |
| **Design Methods and Tools Subtopic** | |
| Rapidly Changing HSI Technology | 3.4.2 |
| Participatory Ergonomics | 3.4.2 |
| Rapid Prototyping | 3.4.2 |
| Design Process for Higher-Level Interfaces | 3.4.1 |
| **Test and Evaluation Methods and Tools Subtopic** | |
| Evaluating the Effects of Advanced Systems | 3.4.1 |
| Guidance for the Review of Intelligent HSIs | 3.4.1 |
| Validation of Integrated Systems | 3.4.1 |
| Changing Testbeds | 3.4.2 |
| Performance-Based Methods | 3.4.2 |
| Collection/Analysis/Use of Real-Time Human Performance Data | 3.4.1 |
| Modeling and Measurement of Effective Team Performance | 3.4.1 |
| Human Performance Models | 3.4.2 |
| Quantitative Human Performance Criteria | 3.1.3.2 |

# Appendix B  NRC HFE Guidance Development Methodology

## B1 Background

As was noted in Section 1.2, the NRC HFE review guidance is contained in several NUREGs, such as NUREG-0800 (Chapter 18), NUREG-0711, and NUREG-0700. To keep the review guidance up-to-date with a state-of-the-art technical basis, a methodology was established for guidance development (see O'Hara, 1994). The methodology has now been used in many HFE guidance development efforts (see Table B.1).

**Table B.1 Guidance development technical reports using the NRC's HFE guidance development methodology**

NUREG/CR-5908: *Advanced Human System Interface Design Review Guideline* (O'Hara, 1994).

NUREG/CR-6105: *Human Factors Engineering Guidelines for the Review of Advanced Alarm Systems* (O'Hara, Brown, Higgins & Stubler, (1994).

NUREG/CR-6684: *Advance Alarm Systems: Guidance Development and Technical Basis* (Brown, O'Hara & Higgins, 2000).

NUREG/CR-6633: *Advanced Information Systems: Technical Basis and Human Factors Review Guidance* (O'Hara, Higgins & Kramer, 2000).

NUREG/CR-6634: *Computer-based Procedure Systems:  Technical Basis and Human Factors Review Guidance* (O'Hara, Higgins, Stubler, & Kramer, 2000).

NUREG/CR-6635: *Soft Controls: Technical Basis and Human Factors Review Guidance* (Stubler, O'Hara, & Kramer, 2000).

NUREG/CR-6690: *the Effects of Interface Management Tasks on Crew Performance and Safety in Complex, Computer-based Systems*. (O'Hara & Brown, 2002).

NUREG/CR-6636:  *Maintenance of Digital Systems: Technical Basis and Human Factors Review Guidance* (Stubler, Higgins & Kramer, 2000).

NUREG/CR-6637: *Human-system Interface and Plant Modernization Process: Technical Basis and Human Factors Review Guidance* (Stubler, O'Hara, Higgins & Kramer, 2000).

NUREG/CR-6393: *Integrated System Validation: Methodology and Review Criteria* (O'Hara, Stubler, Brown & Higgins, 1997).

BNL Technical Report E6835-T5-1-6/01: *Update of NUREG-0700 Control Room and Work Place Environment Review Guidance* (Brown, 2001).

BNL Technical Report W6546-T6A-1-3/01: *Human-system Interface Management: Human Factors Review Guidance* (O'Hara & Brown, 2001).

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BNL Report E2090-T4-5-11/95: *Human-system Interface Design Process and Review Criteria* (Stubler & O'Hara, 1996b).

## B2 Methodology

Figure B.1 provides an overview of the guidance development methodology.

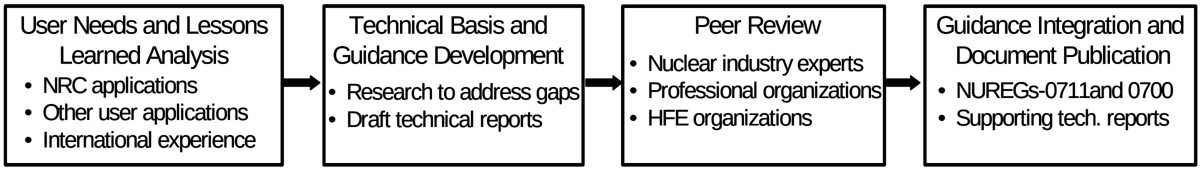


**Figure B.1 Major steps in NRC HFE guidance development**

The development of the method was guided by the following objectives:

- Establish a process that will result in valid, technically defensible, HFE guidance
- Establish a generalizable process that can be applied to any aspect of HSI technology for which guidance is needed
- Establish a process that optimally uses available resources, i.e., develops guidance in a cost-effective manner

A high priority is placed on establishing the validity of the guidelines. Validity is defined along two dimensions: internal and external validity. *Internal validity* is the degree to which the individual guidelines are linked to a clear, well founded, and traceable technical basis. The technical bases vary for individual HFE guidelines. Some guidelines may be based on technical conclusions from an analysis of empirical research, some on a consensus of existing standards, while others are based on engineering judgment that guidelines represent sound practices based on the information reviewed. Maintaining an audit trail from each guideline to its technical basis serves several purposes:

- Evaluation of the technical merit of the guideline by others
- A more informed application of the guideline since its basis is available to users
- Evaluation of deviations or exceptions to the guideline

*External validity* is the degree to which the guidelines are supported by independent peer review. Peer review is a good method of screening guidelines for conformance to generally accepted HFE practices and to industry-specific considerations, i.e., for ensuring that the guidelines are appropriate based on practical operational experience in actual systems.

For individual guidelines, these forms of validity can be inherited from the source documents that form their technical basis; such as when the HFE standards and guidance documents on which they were developed have good internal and external validity. However, when validity is not “inherited” from the source documents, it must be established as part of the guidance development process. The NRC HFE guidance development methodology was established to provide internal validity based on a documented technical basis and external validity based on test, evaluation, and peer review.

Each of the steps of the guidance development process is discussed in greater detail in the sections that follow.

User Needs and Lessons Learned Analysis

One step in identifying improvements to be made in the NRC HFE guidance is to obtain feedback from all these "user" groups to identify user needs and to identify areas needing improvement. This feedback is obtained using a variety of methods, including surveys and telephone conferences.

NUREG-0711 and NUREG-0700 are extensively used by the NRC. The NRC has used the guidance for performing advanced NPP design certification reviews (e.g., AP600, ABWR, and System 80+), review of technical reports submitted by vendors in advance of COL applications, reviews of licensee technical specification amendment requests, and the resolution of HFE issues as they arise in current operating plants.

The BNL authors have used the guidance for a wide variety of applications, such as the review of a NPP control room modernization in Sweden (O'Hara & Higgins, 2002), safety evaluation and control room modification in Spain (O'Hara & Higgins, 2001), safety evaluation of a rocket test facility control room for NASA, and numerous reviews of Department of Energy facilities.

The guidance is also used internationally by regulatory authorities, vendors, and utilities.

Feedback from these organizations provides important lessons learned in use of the guidance and information on the needs of the broader community of users.

Technical Basis and Guidance Development

Guidance development involves a number of steps including: topic characterization, technical basis development, and guidance development and documentation.

*Topic Characterization*

A topic is an HFE issue or group of issues for which design review guidance is being developed. The first step in developing guidance for any topic, such as computer-based procedures, is to develop a topic characterization in order to identify the areas for which review guidance is needed. To accomplish this, we review existing systems and identify the characteristics and functions along which the topic can be defined. The characterization is important because it provides a structure for developing and organizing the guidance. The characterization also provides a reviewer with a framework for requesting information from applicants and licensees during a review.

*Technical Basis Development*

The next step is to analyze information addressing the topic. This analysis provides the technical basis upon which guidance can be developed and justified. Figure B.2 illustrates the use of several sources of information in order of preference for guidance development. Proceeding down the flow chart, the technical basis sources changes in three ways. First, the sources of information near the top are already in or close to HFE guidance format. Toward the bottom, individual research studies must be synthesized and HFE guidelines abstracted. Second, the information at the top already possesses a degree of validity (as discussed earlier), while towards the bottom the validity of the guidance must completely be established during guidance development. Third, the use of the information for guidance development is generally more costly toward the bottom of the flow chart. Thus, the preference is to use sources higher in the figure.

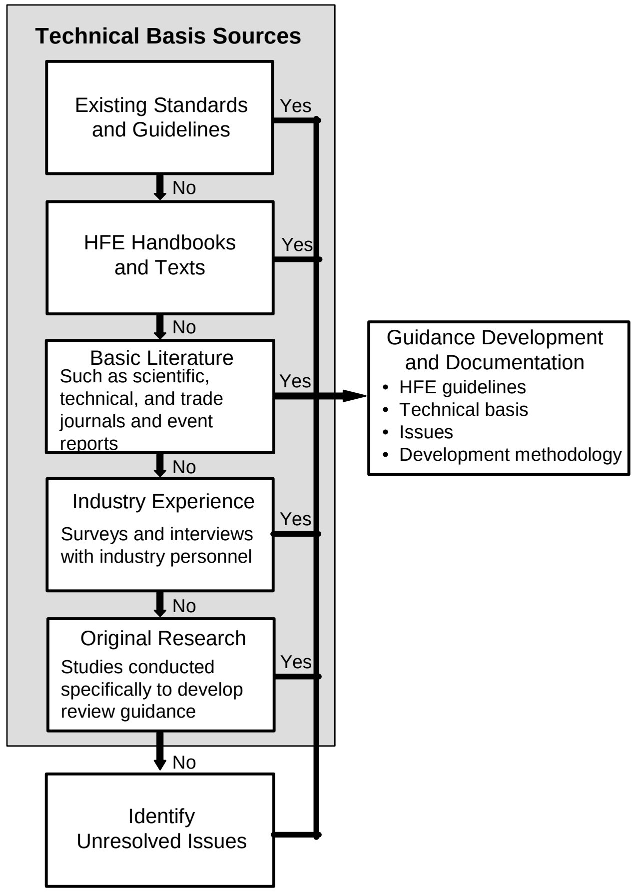


**Figure B.2 Technical basis and guidance development**

Existing HFE standards and guidance documents are considered first. The standards developed by the U.S. military and standards organizations such as the American National Standards Institute (ANSI) are examples of this type of information. The authors of such documents have developed HFE guidelines using the available research, operational experience, and their own knowledge/expertise. In addition, many existing standards and guidance documents have been peer reviewed. Thus, the documents have internal validity or external validity, or both. Since the information is already in guideline form, it is generally easier to use than information from other sources.

While such documents provide a valuable starting place, there may be many aspects of a topic that extend beyond the technology and human performance considerations addressed by these documents. Thus additional sources of information are utilized. We next seek documents providing good analysis and syntheses of existing literature, such as handbooks. Salvendy's Handbook of Human Factors and Ergonomics (Salvendy, 2006) is and example of this information source. These documents are valuable in that they constitute a review research and operational literature by knowledgeable experts. However, the information is usually not expressed in guidance form. Guidance needs to be developed from these documents, but the establishment of technical basis is usually expedited by the information provided in the handbook.

For topics reflecting new technology, the sources discussed above may not be sufficient to support guidance development. Basic literature is then reviewed. This literature consists of papers from research journals and technical conferences. Basic literature provides a theoretical basis for understanding human performance concerns related to complex human-machine systems. It also provides general theory for human-machine interaction relevant to user interface design, human error, and usability. Empirical studies of human-machine interaction reported in the literature address a broad range of technologies and user tasks. However, greater effort is needed to develop such information into design review guidance.

When guidance is based on basic literature, engineering judgment is required to generalize from the unique aspects of individual experiments and studies to actual applications in the workplace. This is because individual experiments have unique constraints that limit their generalizability (such as their unique participants, types of tasks performed, and types of equipment used). For example, laboratory experiments often do not involve tasks that are as complex as NPP operations. Most experiments do not examine tasks under the same performance shaping factors (such as rotating shifts, stress, and fatigue) that exist in a work environment. While information from research is a valuable part of guidance development, it cannot be blindly adopted. Thus, the results must be interpreted in the context of real-world tasks and systems, which involves judgment based on professional and operational experience. Some of the same issues of generalization exist for event reports as well.

Industry experience is a valuable source of information. It includes reports and surveys of plant personnel, including designers, plant personnel, and regulators. Operational experience can also be obtained from interviews, knowledge-elicitation sessions, and walk-through exercises using the actual HSI or a high-fidelity training simulator. Industry practices include design approaches that have evolved through experience. They are incorporated into the technical bases as practical examples of the design and evaluation strategies. This information can be more difficult and costly to obtain than basic literature. However, it may be more directly applicable to the NPP domain than basic literature. Like using basic literature, the information needs to be critically analyzed and synthesized to develop review guidance.

Finally, information for the technical basis is developed using original research. Original research has the advantage of focusing on the specific issues that need to be addressed in guidance development. However, because of the time and resources required to conduct original research, it is only used when important information is needed that cannot be obtained through other means.

Examples of studies conducted in the course of developing technical bases for NRC HFE guidance development include the following:

1. Evaluation of the effect of alarm system display, processing, and availability characteristics on disturbance management (O'Hara et al., 2000)
2. Evaluation of the effect of interface management tasks on primary task performance (O'Hara & Brown, 2002)
3. Evaluation of the introduction of computer-based procedures, advanced alarms, and interface management into an operating control room (Roth & O'Hara, 2002)

In the development of design review guidance all of these sources of information are used.

*Guidance Development and Documentation*

Once the steps above are completed, review guidelines are developed from the source materials and documented in a standard format. NUREG-0711 guidance uses a fairly simple number list format. NUREG-0700 guidelines have a more structured format. An example is presented in Figure B.3.

10.2.2-2 Automatic Monitoring of Plant Parameters and Equipment Status

The CBP should automatically provide accurate and valid information on the values of parameters and status of equipment, when they are available to the system.

ADDITIONAL INFORMATION: It should be clear to operators what specific information is used as the source of these actual values and states.

*Discussion*: Supporting cognitive functions, such as obtaining parameter values (monitoring) may reduce the demands on attentional resources and working memory and enable the operator to focus more on evaluating higher-level procedure goals. It may also help solve PBP issues. This capability was identified as being beneficial to the crew's reliability (Orvis and Spurgin, 1996; Pirus and Chambon, 1997; Niwa et al., 1996). Further, presenting plant parameters and status in procedure steps is a URD requirement (EPRI, 1993a). This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Cognitive Workload (see Appendix B).

**Figure B.3 HFE design review guideline format**

The guidelines are documented in a technical report, usually a NUREG/CR. The purpose of the technical report is to document the guidance development methodology, the technical basis used, and the guidelines that were developed.

Additional study reports are developed as necessary to provide the results of detailed tests, evaluations, and analyses that contributed to technical basis information. For example, the alarm guidance documented in Brown et al., (2000) references the alarm study (O'Hara et al., 2000) conducted in support of that effort.

Peer Review

The results of individual guidance development efforts are reviewed by subject matter experts. The first reviews are by personnel from the NRC with expertise in human factors engineering and engineering fields directly related to the topic. Once these review comments are resolved, the documents are ready for review by outside experts.

The reports are then reviewed by (1) industry human factors specialists such as the Institute of Electrical and Electronic Engineers (IEEE), Subcommittee 5 *Human Factors, Control Facilities, and Reliability*; and (2) HFE specialists outside the industry such as the Crew System Ergonomic Information Analysis Center. These reviews include evaluations of the topic characterizations and guidance. The reports are evaluated with respect to scope, comprehensiveness, technical content, technical basis (adequacy of its internal validity), and usability (i.e., presentation, functionality, procedures, tools, and user interface). The comments and recommendations received from these reviews were used to revise the guidance.

Guidance Integration and Document Publication

When the reviews are completed and comments resolved, the documents are ready for publication. The guidance is then integrated into NUREG-0711, NUREG-0700, or other applicable NRC design review document. These NUREGs provide only the information necessary for conducting HFE reviews. References to the appropriate technical reports describing the technical basis are provided.

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