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HUMAN FACTORS DESIGN REVIEW GUIDELINES FOR ADVANCED NUCLEAR CONTROL ROOM TECHNOLOGIES

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ABSTRACT

Advanced control rooms (ACRs) for future nuclear power plants are being designed utilizing computer-based technologies. The U.S. Nuclear Regulatory Commission reviews the human engineering aspects of such control rooms to ensure that they are designed to good human factors engineering principles and that operator performance and reliability are appropriately supported in order to protect public health and safety. This paper describes the rationale, general approach, and initial development of an NRC Advanced Control Room Design Review Guideline.

INTRODUCTION

Advanced control room concepts are being developed in the commercial nuclear industry as part of future reactor designs. The ACRs will utilize advanced human-system interface (HSI) technologies that may have significant implications for plant safety in that they will affect the operator's overall role (function) in the system, the method of information presentation, the ways in which the operator interacts with the system, and the requirements on the operator to understand and supervise an increasingly complex system. The U.S. Nuclear Regulatory Commission (NRC) reviews the HSI aspects of control rooms to ensure that they are designed to good human factors engineering principles and that operator performance and reliability are appropriately supported in order to protect public health and safety. The principal guidance available to the NRC (NUREG-0700)[1], however, was developed more than ten years ago, well prior to these technological changes. Accordingly, the human factors guidance needs to be updated to serve as the basis for NRC review of these advanced designs. The purpose of this paper is to discuss the development of an NRC Advanced Control Room Design Review Guideline, hereafter referred to as the "Guideline."

ISSUES IMPACTING THE EVALUATION OF ADVANCED CONTROL ROOMS

In order to develop an approach to the evaluation of ACRs, it is necessary to consider: (1) the review environment for NRC ACR reviews, (2) the types of advanced technologies being developed for ACR HSIs, (3) the human factors issues that are associated with advanced technology, and (4) the state-of-the-art of human factors guidelines for advanced HSIs.

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Review Environment Issues

Standardization of Plant Designs: Control room reviews have traditionally been directed toward existing, operational facilities. However, the industry in the U.S. is moving toward the standardization of plant designs, and vendors are requesting NRC reviews of proposed control rooms prior to final design implementation. In order to reach a safety determination prior to design certification, the NRC staff has sought the authority to perform reviews of proposed designs at critical points during the design cycle.

Diversity of Plant Types: The current generation of commercial nuclear power plants (NPPs) operating in the U.S. numbers more than 100; all of those presently operating are based upon light water reactor (LWR) technology. Although the next generation of plants will reflect advances on this same technology base, the industry has also developed designs based on different technologies, including heavy water reactors, liquid metal reactors, and gas-cooled reactors. Some of these are proposed to be multiple units of smaller, modular reactors at the same site. Thus, the potential diversity of future reactors raises new issues relative to the design and operation of the reactors, and may result in different operator roles and tasks, different CRs, and different operator-control interfaces.

Continuum of Active to Passive Safety Systems: One important design initiative to improve safety and reliability has been the move from active safety features (based upon active components such as pumps) toward more "passive" safety features (based upon natural physical processes such as convection flow, radiation cooling, and gravity). The role of the operator during transients and accidents will change considerably with these proposed passive systems. Important issues include: how operators verify that these systems are ready during normal operation; how proper operation can be confirmed when the systems are utilized; what parameters should be monitored; and proper operator response when the passive systems do not function properly.

Advanced Nuclear Power Plant HSI Issues

Control Room Evolution: Three important trends are emerging in advanced HSI design concepts in the nuclear industry: increased automation, development of compact, computer-based workstations as the locus of control room operations, and development of intelligent operator aids. As these trends are implemented, they will result in a further diversification of CR types from conventional to hybrid to advanced to "intelligent" CRs.

Diversity of Human-System Interface Technologies: Related to CR evolution is the wide range of technological approaches to HSIs in computer-based CRs. In part, this is due to the tremendous flexibility offered by software-driven interfaces to provide for alternative data processing, display and control.

Advanced Technology and Human Performance Issues

While the use of advanced technology is generally considered to enhance system performance, computer-based operator interfaces also have the potential to negatively impact human performance, spawn new types of human errors, and reduce human reliability.[2,3,4,5] However, since the contributors to unreliability in an advanced control room are likely to be different from those which are present in conventional CRs, they are less obvious and generally less well understood.[6] Some of the factors contributing to the problems of integrating human operators and advanced systems are reviewed below.

General State of Knowledge: Despite the rapidly increasing utilization of advanced HSI technology in complex, high-reliability systems such as NPPs and civilian aircraft, there is broad consensus that the knowledge-base for understanding the effects of this technology on human performance and system safety is in need of further research.[7,8] The operating environment associated with advanced systems is very different from that of a conventional control room. Cognitive and human information processing issues are emerging as more significant than the physical and ergonomic considerations which dominated the design of conventional HSIs. While these issues have been recognized for a long time, their full implications for human performance and system safety have only recently begun to be addressed in research, and there is not a long history of operational experience upon which to draw. The National Academy of Sciences, for example, has identified areas such as automation, supervisory control, and human-computer interface as high priority research areas for the human factors community in general and for the commercial nuclear industry in particular.[7,8]

Allocation of Function and Automation: Many human factors problems originate early in the design process. Historically, functions were allocated to automated systems based largely on the capability of available technology to reliably and safely execute the function, rather than on the human operator's ability to perform as part of the overall system. This was true even though the human factors problems associated with automation had been known for some time[9] and the emergence of new types of human and system errors had been identified.[10] Increases in automation have been associated with a shift from physical to cognitive workload, with a loss of operator vigilance and a concomitant increase in vigilance-associated human errors,[11] with difficulty maintaining adequate "situation awareness,"[12] and with loss of skills to perform the task in the event of automated system failure. In part, many of these issues may be the result of a shift in the operator's role from that of an active, in-the-loop controller to an out-of-the-loop supervisor and monitor, together with a failure on the part of the HSI and system designers to account for this shift.[13,14,15]

Cognitive Task Analysis and Advanced HSI Design: Computer-based HSI design requires, to a far greater extent than traditional control room designs, the specification of cognitive requirements and processing resources that the operator must utilize in task performance; i.e., cognitive task analysis. That information is needed for proper evaluation of the interface. Four aspects of HSI are primarily responsible for this requirement. First, information is typically presented in "predigested" form; i.e., raw data parameters are processed and integrated into a higher level of information, thus potentially obscuring their meaning. Second, the operator typically has much more information available which, if not properly organized and presented, can be overwhelming. Third, information is typically resident in a "virtual" work station, rather than in dedicated spatial locations spread out across control stations. Information is located somewhere in a computer system which provides only a glimpse of its contents (through a display device) at any one time. A poorly designed interface can make location of information and navigation through data difficult. Fourth, the flexibility of software-driven interfaces can increase the workload associated with managing the interface.

Skills, Training, and Operator Selection: NPP operations have always demanded a high level of skill and readiness on the part of the operating staff. These demands will increase, however, because of the need for operators to understand and evaluate the performance of advanced systems, to know their limitations, and to be ready to assume manual control where appropriate. There is a somewhat paradoxical relationship between these requirements and the day-to-day tasks that operators must perform, which, in a highly-automated plant, are predominantly monitoring functions. Thus, there is a risk that these carefully selected and highly trained operators may be required to perform a routinely boring and monotonous job.

Advanced HSI Guidelines Issues

Hardware vs. Software Interface Review Guideline: In an advanced CR, the physical layout of the display devices and computer input devices may be less important than the design of the human-software interface; i.e., the information management system and the methods with which information is displayed to the operator. This information can be displayed in a complex network of thousands of computer displays and flexible, operator-defined display formats. The difficulty of developing guidelines for human-software interfaces when compared with human-hardware interfaces has been elaborated by Smith.[16] Perhaps most significant to the evaluation of human-software interfaces is that the most important design features are often hidden to the reviewer and transparent to the operator, while important hardware design features are usually readily observable. For example, the observable display may be an end product of data integration providing higher-level, more abstract displays in contrast to the "single sensor/single display" characteristic of conventional CRs. As a result, while hardware guidelines tend to be relatively clear and specific, software guidelines tend to be stated in more general language.

Status of Existing Human Factors Guidelines for Advanced Technology: Advanced CRs are based upon relatively new technology which is rapidly changing. Relative to the guidelines available in NUREG-0700, the guidelines available for advanced technology have a considerably weaker research base, and have not been tested and validated through many years of design application which provides valuable lessons learned.[16] Thus, the human factors guidelines available for the review of advanced CR technology are less firm and, as indicated above, are typically stated in more general terms (pending further specification through research and design experience). Further, the cognitive task requirements, critical to human software interface design, are typically less familiar to designers and reviewers.[17,5] These characteristics of advanced technology guidelines can make the reviewers' job more difficult.[18]

Suitability of Human Factors Engineering (HFE) Guidelines for Evaluation: Another issue related to the maturity of advanced technology guidelines is whether evaluations based only on conformance to HFE guidelines provide a sufficient basis for review. Gould has indicated that due to the nature of advanced human-system interfaces (as discussed above), a good system cannot be designed by guidelines alone.[19] A similar conclusion resulted from an effort to evaluate a computer-based system using only guidelines.[20] Evaluations need to be broader and, in terms of final design must include dynamic, real-time testing under simulated or actual operating conditions.

IMPLICATIONS FOR THE GUIDELINE

The factors and issues discussed above have implications for the development of an NRC Guideline. These implications are summarized below.

- Since many human factors problems originate early in system design and industry is proposing standardized conceptual designs, the Guideline should provide guidance for reviews to be performed throughout the design life cycle.

- The Guideline should be capable of addressing the wide diversity of reactor types, operator tasks, CR evolutions, and approaches to HSI.

- The Guideline should incorporate the state-of-the-art knowledge as available, but will have to be capable of modification and revision as technology develops, knowledge increases, and experience is gained.

- The Guideline will have to focus strongly on the cognitive and information processing aspects of the interface and on the human-software interface.

- Available human factors guidelines for advanced HSI technology are relatively general and not as well tested in comparison to guidelines for conventional technology. Consequently, discrepancies are more difficult to detect, and more burden is placed on the skills of the reviewer.

- A comparison of a final design against HFE guidelines is insufficient to ensure a safe, acceptable design. Dynamic evaluation of the integrated HSI system will be required.

PROPOSED APPROACH OF THE GUIDELINE

The factors and issues identified above have led to the development of a top-down approach to the review of ACRs. Guidelines should be developed in two general broad areas and each is further divided into two subareas, resulting in four review modules. When used in total, the review process should permit the tracking of the design from initial conception through final design implementation.

Design Process Review Guidelines

The "design process" guidelines can be used by the NRC staff or other reviewers to evaluate design proposals prior to final design in terms of currently accepted human factors engineering practices. Design process review guidelines are divided into two general modules: planning and analysis. Each can be divided into a number of design review elements and each of these into a number of review/acceptance criteria. Planning refers to elements such as the organization of the human factors team and its role in the design process, the human factors program plan, and the specification of high level design goals and objectives. Analysis refers to elements such as the system analysis, function analysis, task analysis, technology assessments, allocation of function, specification of performance requirements, trade-off studies, development of design-specific guidelines, and tests/evaluations at the system/function or part-task level (and the use of human factors design and evaluation tools).

Design Implementation Review Guidelines

Design implementation review guidelines can also be divided into two modules: human factors engineering review and dynamic evaluation (full-mission, dynamic, real-time, system performance evaluation). Human factors engineering review of the HSI refers to the evaluation of control room interfaces according to currently accepted human factors design guidelines. Dynamic evaluation assures that the final design actually meets all design performance goals as an integrated operational whole. Guidelines are needed for this aspect of the review to assure that an assessment of human performance-related design goals and objectives using human performance variables is clearly incorporated into the test design and that the test plan is adequate from a human factors perspective.

GUIDELINE DEVELOPMENT METHODOLOGY

The Guideline development effort is composed of a primary "Guideline Development" task and three related support tasks: Electronic Document Development, Test and Evaluation, and New Guideline Development. The first draft of the Guideline will be generated across four revisions of the document. The individual guidelines will be developed across two separate subtasks. Revision 0 contains the human factors engineering guidelines. In the next subtask, the guidelines for design process and dynamic evaluation will be developed (Revision 1). Further revisions of the Guideline occur following testing (Revision 2) and peer review (Revision 3). At the present time Revision 0 has been completed. Its development is briefly described below. (A similar process is being used to develop the guidelines for Revision 1.)

Guideline Development

The effort began with an identification of human factors guideline documents for advanced HSIs. Through a review of the human factors literature and contact with organizations which sponsor such research, approximately 50 guideline efforts were identified. The next step was to select those documents that would serve as the "primary sources" for the initial set of guidelines to be incorporated in the NRC Guideline. A high priority was given to establishing the validity of the guidelines; i.e., assuring that they were based upon empirical research and/or accepted human engineering practice. Validity was defined in terms of two aspects of document development. "Internal" validity was evaluated by the degree to which the individual guidelines within a document were based upon empirical research and an audit trail to the research was maintained.

"External" validity was evaluated as a function of the degree to which the guidelines were subjected to independent peer review. The peer review process was considered a good method of screening guidelines for conformance to accepted human engineering practices. In general, documents which had both internal and external validity were considered primary source documents to serve as a basis for Revision 0.

Revision 0 is organized according to a structure similar to that of documents that focus heavily on HCI, but modified to accommodate HSI trends in advanced control rooms. The seven major sections of the draft document include: Information Display, Operator Input and Control, Alarms, Operator Aids, Inter-Personnel Communication, Information Protection, and Workstation Design. The individual guidelines in the primary source documents were sorted into the various sections of the organizational structure. The guidelines were edited to combine similar guidelines and to transform the material into a standardized format. Where compound guidelines were encountered (several guidelines in a single statement) an effort was made to break them into logical units and represent the units as separate guidelines. Conflict resolution between guidelines was handled on a case-by-case basis.

Electronic Document Development

The Guideline is being developed in electronic as well as hardcopy form to facilitate guideline access and review, editing, compilation of individual guidelines for a specific review, and incorporation of new guidelines as they become available. Availability of the Guideline on a portable computer will also facilitate in-the-field reviews. In order to identify the guideline requirements, an analysis was performed of the inspection task and the variety of ways the document would be used. These requirements were organized into four categories: general usability requirements, inspection task requirements, electronic document functionality requirements, and general hardware requirements to support prototype development of the system. Based on the initial pass at requirements analysis, an Apple Macintosh computer and HyperCard software were selected for prototyping and testing.

Each guideline in the database is represented by seven primary fields: Guideline number, title, statement of the guideline, comment, assessment methods, source (link to primary source document), and classification (primary or secondary). Other user assistance fields are also available, e.g., to provide location (in the document) information and a notepad for users to append comments related to specific guidelines. The prototype user interface (see Figure 1) provides for many document functions such as instant table of contents (TOC) access, context index, glossary, and placemarkers. Users can automatically go to desired sections by clicking on the TOC or index entry. Guideline evaluation, evaluation summary and reporting functions are also available.

Test and Evaluation

The prototype Guideline is being evaluated in a series of usability tests and peer review. The objective of the tests is to evaluate the electronic document with respect to its scope and content (i.e., its adequacy for the review

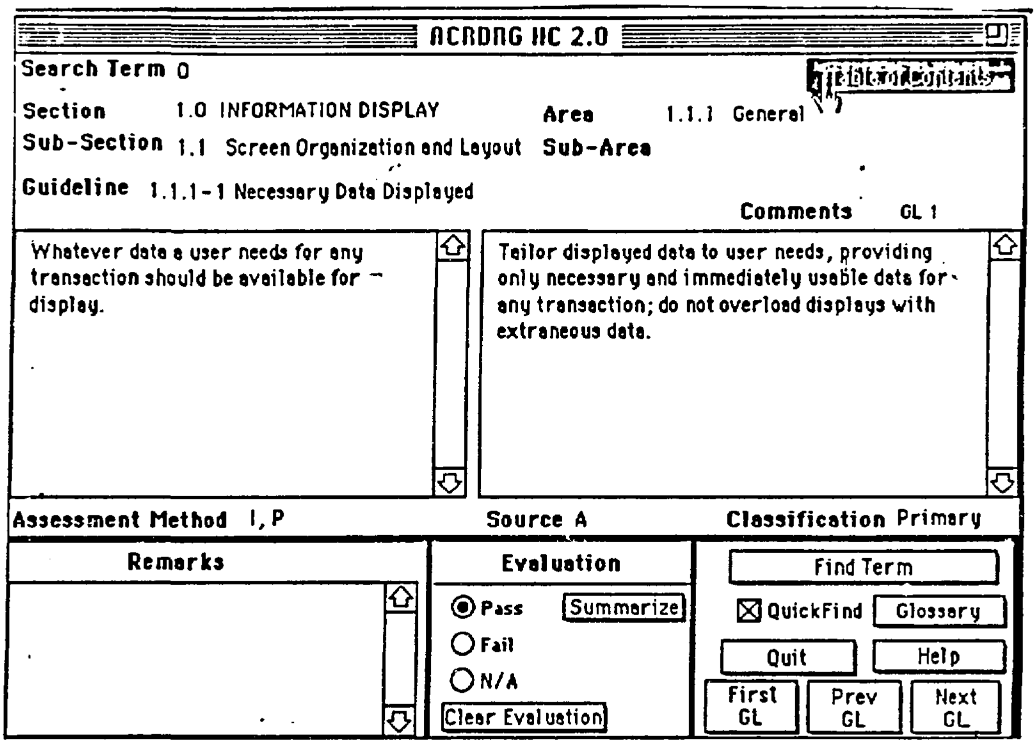

Figure 1. Prototype NRC Guideline User Interface

of advanced control room technology), and usability (i.e., guideline presentation, electronic document functionality, and user interface). Recommended modifications to the Guideline will result in Revision 2. Then the Guideline will be peer reviewed in a workshop format. Input from the peer review will be used to develop Revision 3, and this will comprise the complete first draft of the Guideline.

New Guideline Development

In part, the identification of areas where new guidelines are needed is accomplished by finding a mismatch between the scope of the Guidelines document and the individual guidelines obtained from the primary sources. The preliminary identification of areas needing further guideline development includes user interface requirements for: supervised automation, intelligent operator aids, interface management and navigation, virtual image displays, visual display hardware such as flat panel displays, screen design for graphic presentation of information, new input devices, and selected nuclear-specific applications.

FUTURE DEVELOPMENT

The approaches established to review, develop, and integrate additional information into the Guideline will be an ongoing task in order to ensure that the document always has the most up-to-date and valid human factors review guidance. Since the technology is rapidly changing and the nuclear industry's experience (as well as that of other application areas) will be increasing, the Guideline will need to remain a living document in order to meet NRC needs.

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