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Advanced Control Room Evaluation: General Approach and Rationale

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Advanced control rooms (ACRs) for future nuclear power plants (NPPs) 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 and general approach to the development of a human factors review guideline for ACRs. The factors influencing the guideline development are discussed, including the review environment, the types of advanced technologies being addressed, the human factors issues associated with advanced technology, and the current state-of-the-art of human factors guidelines for advanced human-system interfaces (HSIs). The proposed approach to ACR review would track the design and implementation process through the application of review guidelines reflecting four review modules: planning, design process analysis, human factors engineering review, and dynamic performance evaluation.

Advanced control room concepts are being developed in the nuclear industry as part of future reactor designs. The ACRs will utilize advanced 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 human-system interface 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; U.S. NRC, 1981), 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 approach to the evaluation of ACRs. The specification of an approach is the first step toward the development of an NRC Advanced Control Room Design Review Guideline (ACRDRG).

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 have been associated with advanced technology, and (4) the state-of-the-art of human factors guidelines for advanced HSIs.

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 NPPs operating in the U.S. consists of more than 100 plants, all based upon light water reactor (LWR) technology. Although the next generation of plants will reflect advances on this same technology base, the industry has developed designs based on different technologies, including: heavy water reactors, liquid metal reactors, and gas-cooled reactors. 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 NPP 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 human-system interfaces 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 (for examples, see Coblentz, 1988; Rasmussen, Duncan, & Leplat, 1987; and Wiener & Nagel, 1989; Woods et al., 1990). However, since the contributors to unreliability in an advanced control room are likely to be different from those which are present in conventional control rooms, they are less obvious and generally less well understood (O'Hara & Hall, 1990). 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 (see, for example, Pew, et al., 1983; and Moray and Huey, 1988). 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 (Pew et al., 1983) and for the commercial nuclear industry in particular (Moray and Huey, 1988).

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 (Edwards, 1977) and the emergence of new types of human and system errors had been identified (Wiener & Curry, 1980). 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 (Warm & Parasuraman, 1987), with difficulty maintaining adequate "situation awareness" (Kibble, 1988), 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 (Moray, 1986, Wickens & Kessel, 1981; Ephrath & Young, 1981) together with a failure on the part of the HSI and system designers to account for this shift.

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 is 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 (1988). 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 and data processing algorithms into higher-level 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 (Smith, 1988), and have not been tested and validated through many years of design application which provides valuable lessons learned. 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 (Karat, 1989; Woods et al., 1990). These characteristics of advanced technology guidelines can make the reviewers' job more difficult (Reaux & Williges, 1988).

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 provides a sufficient basis for review. Gould (1988) has indicated that due to the nature of advanced human-system interfaces (as discussed above), a good system cannot be designed by guidelines alone. A similar conclusion resulted from an effort to evaluate a computer-based system using only guidelines (Potter et al., 1990). 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 ACRDRG

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

- Since many human factors problems occur early in system design and the industry is proposing standardized conceptual designs, the ACRDRG should provide guidance for reviews to be performed throughout the design life cycle.
- The ACRDRG should be capable of addressing the wide diversity of reactor types, operator tasks, control room evolutions, and approaches to HSI.
- The ACRDRG 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 ACRDRG 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 ACRDR 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.

CURRENT STATUS

At present, advanced human factors technology guidelines efforts available from both within and outside the nuclear industry are being reviewed and incorporated into an ACRDR Guideline. Guidelines for all four review modules described above are being developed. In addition to a hard copy of the document, the guideline is being developed in an electronic format. The ACRDRG will be field tested with a group of potential users. The objective of the test will be to evaluate the scope and content of the guideline and the usability of the electronic version. In addition, the ACRDRG will then be evaluated in a peer review workshop. It is intended that the ACRDRG be a "living document" that may be readily updated as further advances are made in the state of the art of control room design.

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