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Updating Human Factors Engineering Guidelines for Conducting Safety Reviews of Nuclear Power Plants

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Updating Human Factors Engineering Guidelines For Conducting Safety Reviews of Nuclear Power Plants

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The U.S. Nuclear Regulatory Commission (NRC) reviews the human factors engineering (HFE) programs of applicants for nuclear power plant construction permits, operating licenses, standard design certifications, and combined operating licenses. The purpose of these safety reviews is to help ensure that personnel performance and reliability are appropriately supported. Detailed design review procedures and guidance for the evaluations is provided in three key documents: the Standard Review Plan (NUREG-0800), the *HFE Program Review Model* (NUREG-0711), and the *Human-System Interface Design Review Guidelines* (NUREG-0700). These documents were last revised in 2007, 2004 and 2002, respectively. The NRC is committed to the periodic update and improvement of the guidance to ensure that it remains a state-of-the-art design evaluation tool. To this end, the NRC is updating its guidance to stay current with recent research on human performance, advances in HFE methods and tools, and new technology being employed in plant and control room design. This paper describes the role of HFE guidelines in the safety review process and the content of the key HFE guidelines used. Then we will present the methodology used to develop HFE guidance and update these documents, and describe the current status of the update program.

INTRODUCTION

Human factors engineering (HFE) standards and guidelines (S&Gs) documents play an important role in the design and evaluation of complex systems (Karwowski, 2006). S&Gs provide users with principles to help ensure that the physiological, cognitive, and social characteristics of personnel are accommodated in system development. They also support standardization and consistency of human-system interface (HSI) characteristics and functionality.

Many HFE S&Gs are developed by professional organizations such as the Human Factors and Ergonomics Society (HFES) and the Institute of Electrical and Electronics Engineers (IEEE) using a consensus process. In fact, Dul et al. (2004) identified 174 international HFE standards from the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) alone. Consensus S&Gs are periodically updated to keep current with new research and technological developments. Government organizations also develop HFE S&Gs. The Department of Defense's HFE Technical Advisory Group (DoD, 2004) listed over 30 U.S. government HFE standards. Like consensus documents, government S&Gs are periodically updated. Ahlstrom et al. (2010) discussed the status of three key government standards that are being updated: DoD's *Design Criteria Standard: Human Engineering* (MIL-STD-1472), the Federal Aviation Administration's (FAA) - *Human Factors Design Standard*, and National Aeronautics and Space Administration's (NASA) *Space Flight Human System Standard* (NASA-STD-3001, formerly 3000).

The purpose of this paper is to describe the update of government guidelines used by the U.S. Nuclear Regulatory Commission (NRC) to perform safety reviews of the HFE aspects of new nuclear power plant (NPP) designs. With the U.S. planning for the construction of the next generation of plants and the existing plants modernizing their control rooms, it is essential that the NRC have review guidance that is up-to-date with state-of-the art HFE methods and HSI technology.

We will first describe the role of HFE guidelines in the safety review process and the content of the key HFE guidelines used. Then we will present the methodology used to develop HFE guidance and update these documents, and describe the current status of the update program.

USE OF HFE GUIDANCE IN NRC SAFETY REVIEWS

The NRC staff reviews the HFE programs of applicants for NPP construction permits, operating licenses, standard design certifications, and combined operating licenses. The purpose of these safety reviews is to help ensure that personnel performance and reliability are appropriately supported. The review methodology is based on a systems engineering approach (e.g., IEEE, 2005) and embodies two key principles to addressing the human factors aspects of design: a "top-down" methodology and "life-cycle" considerations. "Top-down" refers to an approach to HFE that starts at the "top," i.e., with the plant's high-level mission and goals. These are divided into the functions necessary to achieve the goals which are then allocated to human and system resources. Functions are broken down into tasks and analyzed to identify the HSIs (e.g., alarms, displays, and controls) that will be needed to support operator performance. Tasks are arranged into work activities to be performed by individual crewmembers and teams. The detailed design of the HSI, procedures, and training represents the "bottom" of the top-down process. HFE should be addressed over the plant life-cycle, e.g., concept planning through operations.

The NRC's safety review was developed to track the design process with these key principles in mind. The methodology examines the applicant's HFE design development process as well as its products, e.g., the main control room. Three primary guidance documents are used. Chapter 18, Human Factors Engineering, of the *Standard Review Plan* (NUREG-0800, Revision 2) provides high-level guidance for the conduct of HFE reviews (NRC, 2007). Detailed review criteria for evaluating an HFE program are

contained in the *HFE Program Review Model* (NUREG-0711 Revision 2) (O'Hara et al., 2004). NUREG-0711 consists of twelve review elements. Each element is divided into four sections: Background, Objective, Applicant Submittals, and Review Criteria. A brief description of each element follows.

HFE Program Management - The review objective is to verify that the applicant has an HFE design team with the responsibility, authority, placement within the organization, and composition to provide reasonable assurance that the design commitment to HFE is met. Also, the team should be guided by a plan to verify that the HFE program is properly developed, executed, overseen, and documented.

Operating Experience Review - The review objective is to verify that the applicant has identified and analyzed HFE-related problems and issues in previous designs that are similar to the current design under review. In this way, negative features associated with predecessor designs may be avoided in the current one while retaining positive features.

Functional Requirements Analysis and Function Allocation - The review objective is to verify that the applicant has defined the plant's safety functional requirements and that the function allocations take advantage of human strengths and avoid allocating functions that would be negatively affected by human limitations. This defines the operator's role and the levels of automation.

Task Analysis - The review objective is to verify that the applicant's analysis identifies task requirements.

Staffing and Qualifications - The review objective is to verify that the applicant has systematically analyzed the requirements for the number and their qualifications.

Human Reliability Analysis - The review objective is to verify that (1) the applicant has addressed human-error mechanisms in the design of the HFE aspects of the plant to minimize the likelihood of personnel error, and verify that errors are detected and recovered from; and (2) the HRA is integrated with the HFE program.

Human-System Interface Design - The review objective is to evaluate the process by which HSI design requirements are developed and HSI designs are identified and refined. The review should verify that the applicant has appropriately translated functional and task requirements to the detailed design of alarms, displays, controls, and other HSI aspects.

Procedure Development - The review objective is to verify that HFE guidance is applied, with all other design requirements, to develop procedures that are technically accurate, comprehensive, explicit, easy to use, and validated.

Training Program Development - The review objective is to verify that the applicant's approach to personnel training incorporates the elements of a systems approach that (1) evaluates the knowledge and skill-requirements of personnel, (2) coordinates the development of the training program with the other elements of the HFE design process, and (3) implements the training effectively in a manner consistent with human factors principles and practices.

Human Factors Verification and Validation (V&V) - This aspect of the review involves three evaluations, the review objectives are to verify that the applicant has performed:

- HSI Task Support Verification - an evaluation to verify that the HSI supports personnel task requirements as defined by task analyses.
- HFE Design Verification - an evaluation to verify that the HSI is designed to accommodate human capabilities and limitations as reflected in HFE guidelines such as those provided in NUREG-0700 (described below).
- Integrated System Validation - an evaluation using performance-based tests to determine whether an integrated system design (i.e., hardware, software, and personnel elements) meets performance requirements and acceptably supports safe operation of the plant.

Design Implementation - The review objective is to verify that the as-built design conforms to the verified and validated design that resulted from the HFE design process.

Human Performance Monitoring - The review objective is to verify that the applicant has prepared a human performance monitoring strategy for ensuring that no safety degradations occur over time.

The third document is the *Human System Interface Design Review Guidelines* (NUREG-0700, Revision 2) (O'Hara et. al, 2002). It is used to review the detailed control room design and that of other HSIs in the plant. Its guidance addresses the physical and functional characteristics of HSIs. The HSI topics addressed are identified in Figure 1.

Part I Basic HSI Elements
1 Information Display
2 User-Interface Interaction and Management
3 Controls

Part II HSI Systems
4 Alarm System
5 Safety Function and Parameter Monitoring System
6 Group-View Display System
7 Soft Control System
8 Computer-Based Procedure System
9 Computerized Operator Support System
10 Communication System

Part III Workstations and Workplaces
11 Workstation Design
12 Workplace Design

Part IV HSI Support - Maintaining Digital Systems

Figure 1 Organizational structure of NUREG-0700

Each of the section contains guidelines use for review. An example is given in Figure 2. Each guideline is formatted as follows:

- Guideline Number –Each guideline has a unique number that indicates its section/subsection location, followed by a dash, and then its serial number.
- Guideline Title – Each guideline has a unique, descriptive title.
- Review Criterion – Each guideline contains a statement of an HSI characteristic with which the reviewer evaluates the HSI's acceptability.
- Additional Information – Additional information is provided that may address clarifications, examples, exceptions, and details about measurements, figures, or

tables. This information is intended to assist the reviewer in the interpreting or applying the guideline.
- Source - The report number of the guideline's source document(s) is shown in superscript.

8.1.2-1 Overall Representation of an Automation System
The HSI should accurately represent automation and its plant interfaces. *Additional Information*: Providing a representation of the automation and the aspects of the plant with which it interfaces helps operators to link the actions of automation to its goals for the plant itself. For example, if automation is maintaining a level in a tank that has a leak, so long as automation can pump water in, the level is achieved and operators may not know there is a problem. When the level can no longer be maintained, operators need to quickly determine whether the failure is in the automation or the controlled system. Offering an overall representation of both automation and its plant interfaces helps operators assess this situation.[91017]

Figure 2 Example of a NUREG-0700 guideline

Using the HFE guidance, the reviewer makes a safety determination of the design's acceptability. The regulator and the public have the greatest confidence in a design that: (1) was developed by a qualified HFE design team with the requisite skills required, using an acceptable HFE program plan; (2) resulted from appropriate HFE studies and analyses that provide accurate and complete inputs to the design process and provide V&V assessment criteria; (3) designed using proven technology based on human performance and task requirements incorporating accepted HFE standards and guidelines; and (4) was evaluated using thorough V&V tests.

The HFE guidance has, and continues to be used, for the review of applicant submittals. Over time, however, new technologies evolve and new methods are developed and utilized to analyze, test, and evaluate the new control room designs. The NRC is committed to keeping its HFE review guidance up-to-date. NUREGs-0800, -0711, and -0700 were last updated in 2007, 2004 and 2002, respectively. Since the last revisions, the NRC has conducted research in many areas of HFE in order to provide a technical basis on which to update the review guidance (examples are provided below). In the next section we will describe the approach taken by the NRC to update its human factors evaluation guidance.

GUIDANCE DEVELOPMENT METHODOLOGY

Woods et al. (1992) observed that the value of good human factors guidelines "...lies in the degree to which the guidance can be said to constitute a useful synthesis of the state of knowledge in the field, and in the degree to which it assists in detecting and correcting flaws in the design of human-machine systems." When standards and guidelines meet this objective, they make an important contribution to human-system integration. We developed a guidance development methodology to do just that.

Before discussing the individual steps involved in our guidance development methodology, it's important to mention an attribute that serves as a fundamental tenet of our overarching approach. At the NRC, a high priority is placed on establishing the validity of the human factors guidelines that are used by our evaluators. A guideline's validity is defined along two dimensions: internal and external. *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 criteria or standards, while others are based on engineering judgment that the guidelines represent sound practices based on the information reviewed. Providing a link between guidance and its technical basis supports: (1) the evaluation of the technical merit of the guidance by others, (2) the informed application of the guidance since its basis is available to users, and (3) evaluation of deviations or exceptions to the guideline. *External validity* is the degree to which the guidance is 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. The specific methodology employed for developing the evaluation criteria utilized in our regulatory reviews consists of the following four steps: User Needs and Lessons Learned Analysis, Technical Basis and Guidance Development, Peer Review, and Guidance Integration and Document Publication. Each of these steps is briefly discussed below.

User Needs and Lessons Learned Analysis

Feedback from user groups is obtained to identify their guidance needs and to identify aspects of the guidance needing improvement. In addition to the NRC and its contractors, NUREGs-0711 and -0700 are used by regulatory agencies in other countries as well as by users in other industrial domains, e.g., the guidance has been used in the evaluation of a rocket test facility control room for NASA. Feedback is obtained from the NRC and other user organizations.

Technical Basis and Guidance Development

Guidance development involves a number of steps including: topic characterization, technical basis development, and guidance development and documentation. The first step in developing guidance for any topic, such as automation, is to develop a characterization of the subject matter 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 during safety reviews. Topic characterization is somewhat unique to the NRC's guidance development methodology and is not typically done in other S&G development efforts.

The next step in our guidance development process is to analyze information resources that address the topic. Existing HFE S&G documents are considered initially utilizing an

established process for evaluating the their technical merits from a regulator perspective (see O'Hara, Higgins, Xing & Fleger, 2010 for an example). Some organizations have developed S&G documents specific to NPPs, such as the standards developed by the IEEE Nuclear Power Engineering Committee (Fleger, 2010). While such documents provide a valuable starting place, there are usually many aspects of a topic that extend beyond the technology and human performance considerations addressed by existing S&Gs.

We next seek documents providing good analysis and syntheses of existing literature, such as handbooks or special book releases from journals that provide reviews of a specific area of interest. The *Handbook of Human Factors and Ergonomics* (Salvendy, 2006) is one such example. These documents are valuable in that they constitute a review of research and operational literature by knowledgeable experts. 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 new technology topics, 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. However, greater effort is needed to develop such information into design review guidance. Because individual studies have unique constraints that limit their generalizability (such as their unique participants, types of tasks performed, and types of equipment used), engineering judgment is required to generalize from the unique aspects of individual experiments and studies to actual applications in the workplace.

Industry experience is another valuable source of information, including reports from regulators and surveys of plant personnel and designers. Operational experience can also be obtained from interviews, knowledge-elicitation sessions, and walk-through exercises. As with basic literature, the information gleaned from operating experience and lessons-learned reports needs to be critically analyzed and synthesized to develop review guidance. Finally, information can be obtained from experiments we perform as part of the guidance development effort. This has the advantage of focusing on the specific issues that need to be addressed. 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.

Once the characterization and technical basis are completed, guidelines are developed and assembled into a standard format (see Figure 2). The results are documented in technical reports describing the development methodology, the technical basis used, and the resulting guidelines.

Peer Review

The technical reports are reviewed by subject matter experts to evaluate their scope, comprehensiveness, technical content, technical basis, and usability. The peer review is performed by subject matter experts within the HFE field and the nuclear industry, as well as by organizations external to the NRC, e.g., the IEEE. The comments and recommendations received from these reviews are used to revise the guidance.

Guidance Integration and Document Publication

Once the technical reports are finalized, the criteria are integrated into the appropriate guidance documents: NUREG-0800, NUREG-0711, or NUREG-0700. In addition to the design review guidelines, the NUREGs also include references to the appropriate technical reports where additional information on the guidance can be obtained.

OVERVIEW OF NRC GUIDANCE UPDATES

NUREG-0711 will be updated in two phases. Revision 3 will be completed in 2011, and will provide updates for new research findings, e.g., concept of operations (O'Hara, Higgins, Brown & Fink, 2008), human performance models (O'Hara, 2009), automation (O'Hara & Higgins, 2010), and degraded instrumentation and control (I&C) (O'Hara, Gunther, & Martinez-Guridi 2010). In addition, modifications will be made to incorporate user feedback and lessons learned, and to clarify and consolidate existing content. Revision 4 will incorporate the results from current, ongoing research, namely in the areas of integrated system validation, cognitive task analysis, and analysis methods to identify risk-important I&C degradations. It is scheduled to be completed in 2013.

NUREG-0700 will be updated to incorporate the HSI considerations contained in the automation and degraded conditions documents cited above. We will also be updating old guidance and annexing or removing guidelines that are dated and no longer applicable. It is scheduled to be completed in 2013. Additional information on the research behind the technical basis that led to the updates of both NUREG-0711 and NUREG-0700 can be found in Fleger and O'Hara (2010).

Chapter 18 of NUREG-0800 will be updated to make it consistent with changes the other documents. It will be updated to address advances in the NRC's licensing procedures. The revision to Chapter 18 of the Standard Review Plan is presently scheduled for publication toward the end of 2013.

In addition to updating the content of the guidance, the usability of the documents will also be improved. The usability of HFE S&Gs has frequently been questioned (e.g., Ahlstrom, 2008), thus usability improvements are identified for the DoD, FAA, and NASA standards updates mentioned earlier. The same is true for our guidance. Usability improvements will be approached in two ways. First, we will develop a "primer' or handbook to provide tutorial and instructional material related to the HFE guidance topics, principally for the criteria referenced in NUREG-0711. Second, we will develop electronic tools to help users identify applicable guidance that's needed to conduct reviews and prepare safety evaluation reports. The electronic tools also will provide ready access to the technical basis reports.

DISCUSSION

Like other consensus and government S&Gs, the NRC is updating its HFE review guidance. The update will enable the guidance to stay current with recent research on human

performance, advances in HFE methods and tools, and new technology being employed in plant modernization efforts and in new control room designs. By focusing on guidance validity, the development of new guidance is accomplished using a method that strives to meet Wood's (1992) challenge to produce a "useful synthesis of the state of knowledge in the field." In addition, the updates will reflect user needs and lessons learned from guidance usage.

The updated guidance will facilitate the NRC's safety review of the HFE aspects of NPPs to ensure that they reflect state-of-the-art principles in order to meet the challenges of new and modernized plants. It should be acknowledged that even with up-to-date guidance, there are sometimes HFE methods or HSI technologies that are not specifically addressed by the guidance. The NRC's safety review methodology accommodates such innovations using a diversity of evaluation approaches (O'Hara & Higgins, 2004).

Our new guidance documents should also contribute to the broader community of HFE S&G users. In the past, criteria within our guidance documents have been incorporated into national NPP standards (e.g., IEEE, 1998), international control room design standards (e.g., ISO, 2000), as well as other government standards (e.g., FAA, 2003). We believe the new updates will similarly provide guidelines for topics of interest to HFE practitioners, such as HSIs for automaton, computer-based procedure systems, and soft-controls. While there are some unique aspects to NPP HFE guidance, most of the guidelines are generally applicable, or easily adapted, to other industrial systems.

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