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ABSTRACT

Many nuclear power plants are modernizing with digital instrumentation and control systems and computer-based human-system interfaces (HSIs). The purpose of this paper is to summarize the human factors engineering (HFE) activities that can help to ensure that the design meets personnel needs. HFE activities should be integrated into the design process as a regular part of the engineering effort of a plant modification. The HFE activities will help ensure that human performance issues are addressed, that new technology supports task performance, and that the HSIs are designed in a manner that is compatible with human physiological, cognitive and social characteristics.

1. INTRODUCTION

Many nuclear power plants around the world are modernizing with new systems and equipment such as upgrading the instrumentation and control (I&C) system from analog to digital technology. Generally as part of these upgrades, control rooms are being modernized and computer-based human-system interfaces (HSI) are being introduced, such as software-based process controls, touch-screen interfaces, computerized procedures, and large-screen, overview displays.

Careful attention to the human factors engineering (HFE) aspects of design is essential in order to realize the full operational and safety benefits of modernization programs. This is consistent with a systems engineering approach to design (IEEE, 1999). In this paper we will discuss the HFE activities that are used to address the human factors aspects of design. Guidance for conducting these activities is being developed as part of the U.S. Department of Energy's Nuclear Energy Plant Optimization (NEPO) Program as a joint government-industry initiative. The industry contribution is being managed by the Electric Power Research Institute (EPRI).

2. OVERVIEW AND KEY PRINCIPLES

The main contributions of HFE are to help ensure that: (1) the role of personnel is well defined and their tasks are clearly specified; (2) the numbers of staff, their functions, and qualifications are adequate to fulfill the human role; and (3) the HSIs, procedures, and training meet task performance requirements and are designed to be consistent with human cognitive and physiological characteristics. Achieving these goals within a system engineering perspective requires incorporating user-centered design activities into the process. IEEE 1220-1998 states that "the design of the products and life cycle processes should consider the human as an element of the system in terms of operators, maintainers, manufacturing personnel, training personnel, etc. for the purpose of understanding the human/system integration issues and ensuring that the system products are producible, maintainable, and usable" (IEEE, 1999, p. 3-4). This concept has been promulgated in international standards and guidance documents for general product design (e.g., ISO 13407), general control room design (e.g., ISO 11064), and nuclear plant design (e.g., IEC 964 and NUREG-0711). Four key principles for addressing the human factors aspects of design are: integrate HFE into the design process; use a "top-down" hierarchical approach; apply HFE throughout the life cycle; and grade the HFE effort to focus on the areas of greatest significance.

For HFE to have the greatest impact, it should be fully integrated into the overall plant engineering process. This will help ensure timely and complete interaction with other engineering activities. Experience has shown that when HFE activities are performed independently from other engineering activities, their effectiveness is lessened.

The HFE aspects of the plant should be developed, designed, and evaluated on the basis of a systems analysis that uses a "top-down" approach. Top-down refers to an approach starting at the "top" of the hierarchy with the plant's high-level mission and goals. These are divided into the functions necessary to achieve the goals. Functions are allocated to human and system resources. Each function can be broken down into tasks. The tasks are analyzed to identify the alarms, displays, procedures, and controls that will be required for task performance. Task requirements reflect performance demands imposed by the detailed design of the plant. Tasks are arranged into meaningful jobs to be performed by plant personnel. The HSIs, procedures, and training are designed to best support personnel in performing their tasks. The detailed design (of the HSI, procedures, and training) is the "bottom" of the top-down process.

HFE should also be considered for the full plant life cycle; i.e., from concept planning through operations and ultimately decommissioning. HFE is sometimes thought to be a "usability" check of the final design. However, if user needs are to be considered during decisions such as how much automation to incorporate into the modification, HFE activities have to be performed early on. In fact, the thorough integration of personnel considerations at every step in the process can help ensure that good HSIs are developed.

Finally, HFE activities should be graded. This means that a process is in place to evaluate proposed changes and adjust the amount of HFE design and evaluation effort to the importance of the change. Such an approach enables the application of HFE to be directed to where it will have the most impact.

Figure 1 illustrates the key HFE activities that should be considered for any modernization program. Each is briefly summarized below.

3. HFE ACTIVITIES

Operating Experience Review (OER)

With a good understanding of operating experience, changes made to personnel tasks and HSIs can be accomplished with a thorough understanding of the strengths and weaknesses of the design and the new technology that will be used once the modification is complete. Thus, the main purposes of conducting an OER are to understand (1) current work practices so the potential impact of planned changes can be assessed, (2) operational problems and issues in current designs that may be addressed in the modernization program, and (3) relevant industry experience with candidate technological approaches to system and HSI technology.

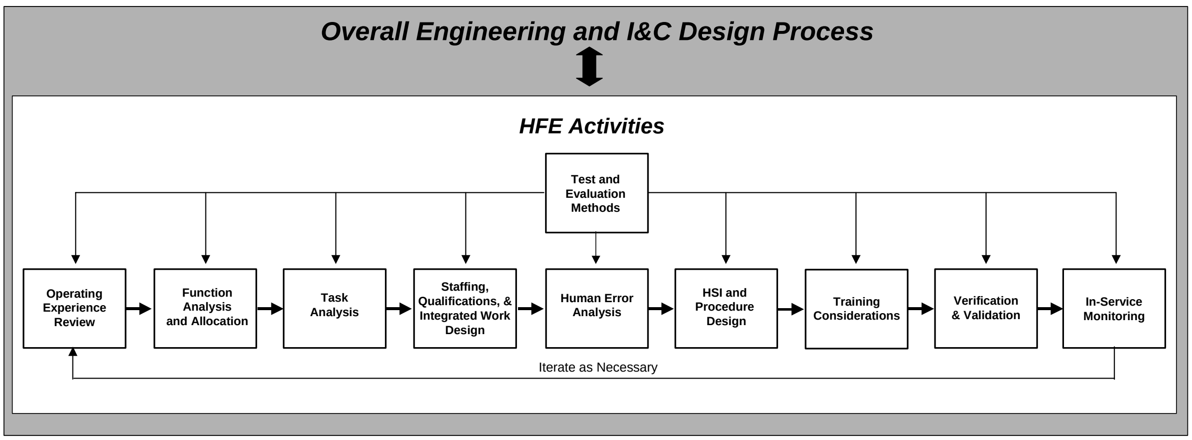

Fig. 1 Human factors design activities.

An overview of the OER methodology is shown in Figure 2. After identifying the functions, tasks, and HSIs that will be impacted by the modification, both plant specific and industry experience is sought. A variety of data sources can be used, including: available documentation; interviews; talkthroughs and walkthroughs with personnel; and interactions with other facilities and organizations.

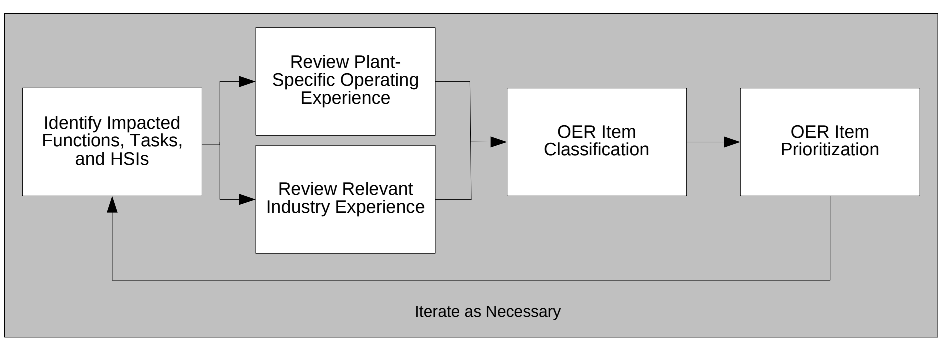

Fig. 2 Overview of operating experience review.

The next step is to classify OER items. Since OER information is useful only if it is available to the members of the design team who can make use of the information, it is desirable to classify the information according to design topics for which it is relevant. Finally, items are prioritized based on their importance.

Two things are emphasized as part of the OER methodology that are not typically addressed. First, the methodology emphasizes the identification of positive as well as negative experiences. Second, the methodology emphasizes the identification of collateral effects. These are tasks that might be impacted by a modification that are not directly part of the modification. They include: (1) *unintended consequences* - tasks that are inadvertently hampered by changes that are made; and (2) *targets of opportunity* - opportunities to positively impact tasks not directly involved in the modifications but which share resources with modified tasks.

Function Analysis and Allocation

The term function allocation as used here simply refers to the allocation of responsibility for conducting an activity to plant personnel, to automatic systems, or to some combination of the two. The allocation is made on the basis of a function analysis to determine what is required to perform the function. Using the results of the function analysis, responsibility is allocated in a way that best ensures overall accomplishment of the function. With respect to modernization programs, the main focus is on how functions are changed rather than the creation of new functions.

The objective of this analysis is to specify the roles and responsibilities of plant personnel in the performance of plant functions and tasks (F/Ts), and how F/Ts may be changed as a result of the modification. The methodology (1) evaluates F/Ts that may be impacted by the modifications; (2) evaluates the suitability of full automation, partial automation, and manual F/T performance; and (3) identifies the design consequences.

The general methodology is illustrated in Figure 3. For each impacted function, the first consideration is whether an allocation is mandatory; e.g., required by regulatory requirements. For those that are not mandatory, it must be determined whether the F/T is automatic or not. If it is automatic, an evaluation should be performed as to whether there is some need for human involvement. There are typically three reasons for human involvement in an otherwise automatic task, as shown in the shaded box in Figure 3. If none of these reasons exists, then full automation is suggested. If some human involvement is warranted, then some activities needed to perform the F/T should be redesigned to address the concern and a partial automation solution may be best.

If the change in allocation involves a manual action, then it should be evaluated to see if there are any F/T requirements and characteristics that raise concerns over the suitability of the task for personnel (see the shaded box in Figure 3). Automation should be considered for any F/Ts having these requirements and characteristics. It must next be determined whether it is technically feasible to automate the task, and if so, whether it is cost effective. If automation is a possibility, then the desirability of maintaining some level of human involvement should be evaluated (as was discussed above).

There may be other cases where it is not possible to automate. In this case, F/T redesign should be considered; i.e., alternative means to accomplish the F/T that can eliminate or reduce the undesirable F/T requirements and characteristics. If efforts to redesign the F/T are successful, then manual performance may be acceptable. If the F/T requirements and characteristics cannot be redesigned and automation is not possible, then enhanced task support may be used.

This analysis leads to four possible outcomes: Full F/T automation, partial F/T automation, manual F/T performance, and manual F/T performance with task support.

Task Analysis

Task analysis is the analysis of functions that have been assigned to plant personnel in order to specify the requirements for successful task performance. The tasks personnel perform are a primary consideration in designing the HSI, procedures, and training that are provided to plant personnel.

The method developed for this project combines features of several approaches to task analysis and is intended to be sufficient for most task analysis needs in plant modernization programs. The first task analysis activity is to select tasks to analyze. Once accomplished, tasks need to be described and then the requirements for performance identified. Task descriptions provide information about the task, such as its purpose, its relationship to other tasks (e.g., performed in sequence or in parallel), the time it takes, etc. Task requirements are the resources that must be available to perform the task, e.g., the information and controls required. Finally, in addition to task requirements, personnel may require specific knowledge, skills, and abilities (KSAs) in order to perform the task. KSAs are identified as well.

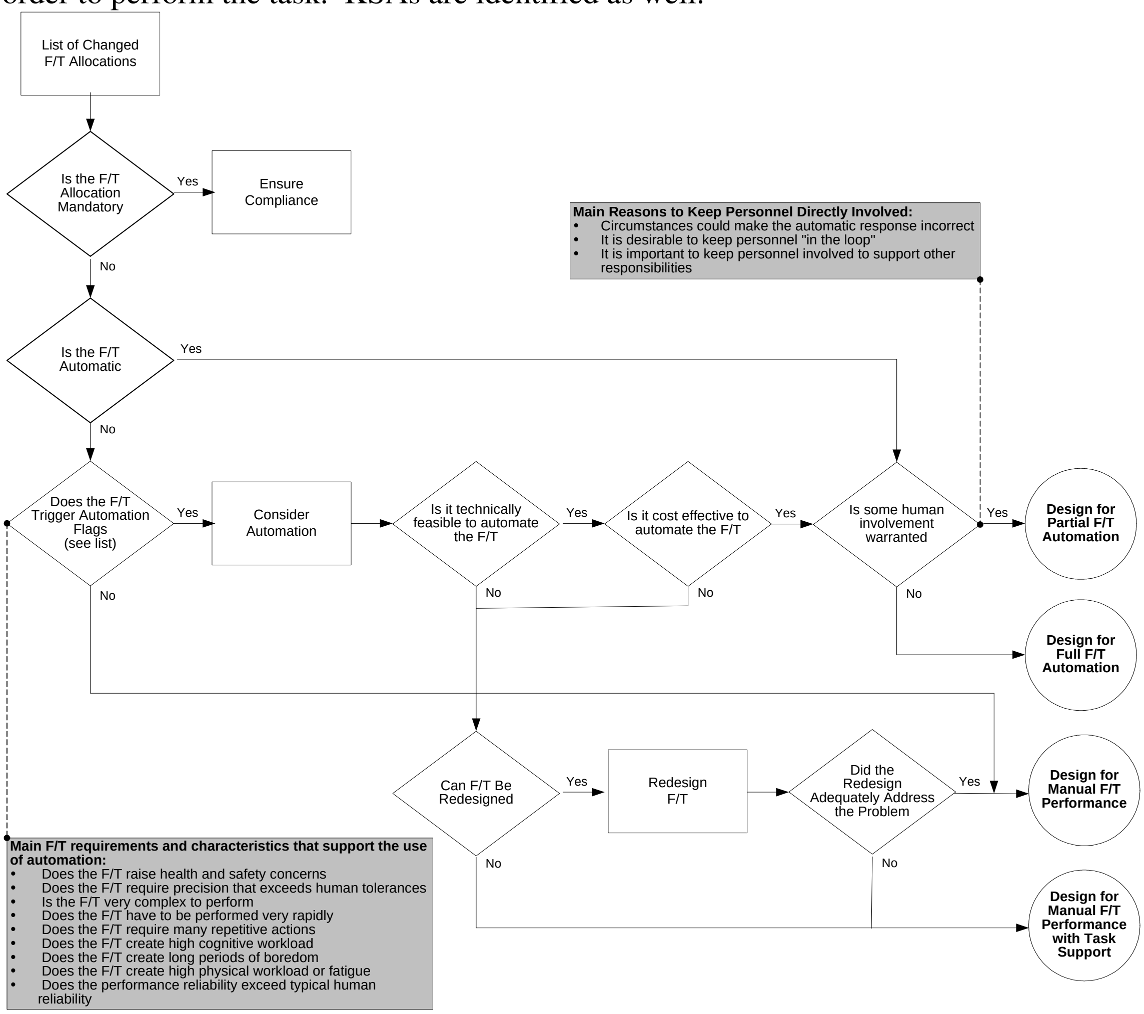

Fig. 3 Overview of function allocation.

Staffing, Qualifications, and Integrated Work Design

The purpose of this activity is to guide the assessment of the staffing levels and personnel qualifications associated with a modification. In particular, the analysis is intended to accomplish the following: (1) allocate new tasks to crewmembers, (2) evaluate whether shifts in task assignments should be made, (3) evaluate whether the new and modified tasks impact other personnel responsibilities when they are considered in an integrated fashion, and (4) evaluate whether plant changes drive new job qualifications. The methodology uses a combination of analysis and walkthrough techniques.

Human Error Analysis

The purpose of this activity is to evaluate the potential for human error in plant operation and maintenance and to define the circumstances surrounding an error specifically enough so that means for reducing the error can be identified. The analysis largely rests on qualitative methods. Analysis of potential human errors should be undertaken throughout the design process, since it can help prevent or minimize the likelihood of errors; i.e., an effort can be made to minimize critical errors through design of the HSIs, procedures, and training or through changes in plant automation. The design can also focus on making the system “error tolerant” by providing support for error detection and recovery in case errors do occur.

Human-System Interface and Procedure Design

The objective of this activity is to develop HSI and procedures that (1) reflect the plant's functional and physical design, (2) meet personnel task requirements, (3) exhibit the general characteristics of a well-designed HSI, and (4) are easy to use and learn. An overview of the methodology is illustrated in Figure 4.

The HSI design process begins with information developed in formulation of the endpoint definition and the HFE analyses that specify changes to human functions (automation), new and modified tasks and the requirements for their performance, and the expected allocation of work to various crewmembers. Using that input, a concept design(s) is (are) developed that reflect these inputs. Once a concept design is selected, the detailed design of the HSIs can be accomplished. The design is developed using the detailed HSI guidance that is provided in different parts of the document (see EPRI, 2003 for an interim version of the HSI guidelines). As with any modification, the new HSIs must be integrated into their locations (e.g., main control room or local control stations) along with existing equipment. Finally, procedures have to be developed and/or modified to reflect plant changes. At any point along the way, various types of tests and evaluations can be performed to collect needed information, obtain user feedback, resolve design options, or evaluate performance with the new HSIs.

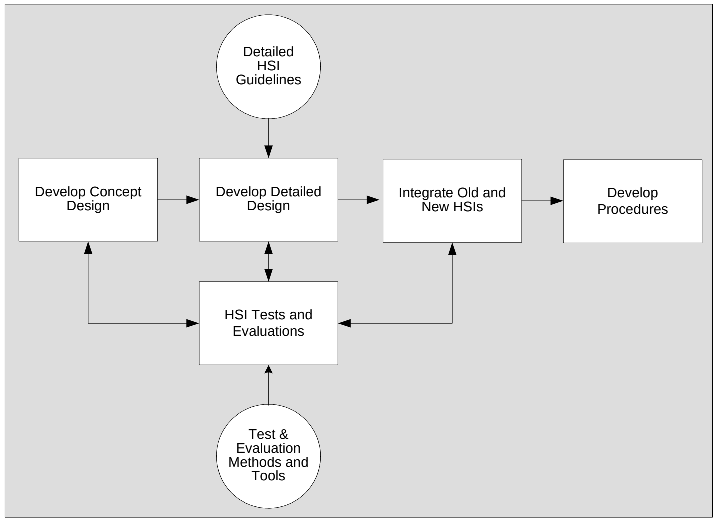

Fig. 4 HSI design process.

Training Considerations

New digital I&C and computer-based HSIs will impose new demands on training programs to address their operation and maintenance. In addition, the new systems may significantly alter the way tasks are performed and may result in new tasks for which training needs to be developed. Utilities have well-developed training programs that reflect a "Systems Approach to Training" (SAT). While this approach is well suited to training for plant changes, two unique aspects stemming from digital I&C modernization need to be considered: (1) new issues to be addressed, and (2) coordinating plant modifications, simulator modifications, and training needs.

With the shift from analog to digital technology, many new training issues arise. Some examples of issues for operations staff include: changes in crew roles, responsibilities, and teamwork; recognizing and handling failures; and managing the HSI. Some examples of issues for maintenance staff include: workstation operations, changes in configuration management requirements, and new maintenance testing.

One common lesson learned from many modernization programs is that the coordination of plant modifications, simulator modifications, and training needs is a significant challenge. Managing and scheduling changes to the simulator while supporting ongoing training and qualification of the operators on both the existing and modified designs is very difficult since most training facilities operate nearly around the clock as it is. This problem is more difficult when the changes extend over multiple outages and multiunit plants are involved. Several approaches for supporting the transition are provided. One approach, for example, is the use of alternative training aids, such as part-task simulations.

HFE Verification and Validation (V&V)

HFE V&V are conducted to ensure the HSI is well designed, easy to use, and meets performance requirements. This includes three evaluations:

- *HSI Task Support Verification* is an evaluation to verify that the HSI supports personnel task requirements as defined by task analyses

- *HFE Design Verification* is an evaluation to verify that the HSI is designed to accommodate human capabilities and limitations as reflected in HFE guidelines
- *Integrated System Validation* is 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 and economical operation of the plant

These evaluations identify potential design problems that should be assessed for importance and corrected if necessary.

In-Service Monitoring

A common lesson learned from plants that have completed major digital I&C and HSI modernization programs is that once the new systems are used on a "day-to-day" basis, additional issues will arise. Examples include an incorrect label on a process display, an HSI function that behaves differently on the simulator than in the control room, and a change in the way a task is performed creating unanticipated difficulties. Treating these types of issues in a formal program can help to systematically identify and address issues, rather than depending upon anecdotal information and ad hoc fixes.

Test and Evaluation Tools and Techniques

Tests and evaluations (T&E) are conducted throughout the design process for two general reasons. The first is to support system or equipment design. The design team may wish to resolve a tradeoff (for example, whether to use touch screen or mouse input), obtain design information (for example, determine the meaning of a set of icons), or to try out a new approach (for example, web-like monitoring and control of remote equipment). The second reason is to perform an evaluation, for example, to evaluate whether the design meets performance requirements. T&E methods range from activities as simple as interviewing operators about how they perform their tasks to measuring task performance and workload as part of full-mission simulator test scenarios.

4. DISCUSSION

With careful attention to the HFE aspects of design, the full operational and safety benefits of new I&C and HSI technology can be achieved. Human factors analyses provide a means to identify and address human performance issues and ensure that new technology supports task performance and that it is designed in a manner that is compatible with human physiological and cognitive characteristics.

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