Using participatory ergonomics to improve nuclear equipment design

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ABSTRACT

Inadequate human—system integration reduces safety, increases the overall complexity of the equipment, the time needed to perform tasks, the likelihood of human errors and complicates user training. Participatory ergonomics emphasizes the involvement of a multidisciplinary team to identify design goals, to actively participate in equipment development, to make decisions and to solve problems. The aims are to guarantee the participation of the multidisciplinary team in all phases of the design process; to improve operational reliability; and to design reliable and robust equipment, so that task demands can be compatible with human capabilities. This paper proposes a methodology for the design of nuclear equipment. The fluorometer is a device which measures an unknown amount of uranium. It is used in chemical analysis laboratories and nuclear research institutes. The approach of this paper is the application of participatory ergonomics principles, including a description of procedures and methods which are linked together to undertake the fluorometer design.

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1. Introduction

Human factors are a body of scientific factors about human characteristics, covering biomedical, psychological and psychosocial considerations, including principles and applications in the personnel selection, training, job performance aid tools and human performance evaluation (NUREG 0700, 2002). Human factors engineering (HFE) is the application of knowledge about human capabilities and limitations to plant, system and equipment design, in order to ensure that the plant, system design, human tasks and work environment are compatible with the sensory, perceptual, cognitive and physical attributes of the operators who operate, maintain, and support it (NUREG 0711, 2002). To achieve the goals of the human factors engineering program, within a system engineering perspective, it is imperative to promote the incorporation of user-related requirements into equipment design. Equipment design may consider the human being as an element of the system in terms of users and personnel training, with the purpose of understanding the issues of human—system integration and ensuring that the systems are maintainable and usable (IEEE 1220, 2005).

Ergonomics is the study of people at work. A working system involves people interacting with and/or a software, internal and external environment, processes and an organizational structure. Ergonomics tries to optimize a working system through considerations of technology, personnel, environmental variables and their interaction. The integration of ergonomics requirements into equipment design offers a lot of opportunities for improvement with regard to system effectiveness, efficiency, reliability and safety (Saleem, 1999). Participatory ergonomics is an approach that involves experts and workers actively engaged in system development and in the analysis of ergonomics problems. Participatory ergonomics involves end-users in planning, developing and implementing workplace changes (Imada, 1991). It emphasizes equipment development with a deep understanding of the activities performed by users, of their current work practices, of their needs and skills. An important concept is that the ease-of-use of the equipment can only be ensured if users are actively involved in all phases of the design lifecycle. The goal is to encourage and support workforce participation in the analysis, redesign and evaluation of their own tasks, workplaces and work practices by applying different methods and techniques (Dos Santos, Teixeira, Ferraz, & Carvalho, 2008). Wilson and Haines (1997) define participatory ergonomics as the involvement of people in the planning and control of a significant amount of their work activities, with sufficient knowledge and power to influence processes and outcomes in order to achieve desirable goals. Participatory ergonomics has been successfully applied in the industrial area, including...
manufacturing, aviation and construction (Robertson, 2000). The success rate of this approach is directly related to the strength of group involvement. It is important that the group realize the importance of participating in the process. It is important to recognize that the workers are experts at their jobs and that they can provide valuable insight into design problems.

The purpose of this paper is to present a methodology for the design of nuclear equipment. The fluorometer is a device which measures an unknown amount of uranium; it is used in chemical analysis laboratories and nuclear research institutes. The approach of this paper is the application of participatory ergonomics principles, including a description of procedures and methods which are linked together to undertake the fluorometer design.

2. Human factors and ergonomics in the nuclear area

According to NUREG 0711 (2002), the requirements for the integration of ergonomics and human factors issues in nuclear equipment design are related to the following elements: operational experience review, reference system analysis, functional requirement analysis, functions allocation, task analysis, human centered design, procedure development, training and verification/validation process. The approach emphasizes the use of human factors methods to collect human performance data for use in nuclear equipment development.

The operational experience review (OER) is performed to understand current work practices and operational problems in reference equipment that may be addressed in the new design. It includes both documented and undocumented sources, event reports and visits to relevant industrial plants, laboratories, research institutes and other facilities that use similar equipment.

The analysis of the reference system is used to discover salient features of the reference equipment that are similar to those in the equipment under development. The analysis obtains information about the operation of similar equipment and summarizes anticipated operations, situations or events that users will face with the new equipment.

Functional analysis identifies the functions that must be performed to satisfy the goals and objectives of the equipment mission. It aims to identify the process, the control functions and their functional interrelationships.

Functions allocation is the process of assigning responsibility for the accomplishment of functions to human or to automatic systems or to a combination of the two. The allocation is done to determine what is required to perform the functions. Using the results of the functional analysis, responsibility is allocated in a way to ensure overall accomplishment of the functions.

Task analysis is what the organization assigns to the person with a purpose (Hollnagel, 2006). Task analysis produces a summary of actions as they have been carried out by the user. It describes the task steps, the actions to be performed — such as valve/pump operations — and the persons who performed the actions (Vicent & Burns, 1996).

Human centered design emphasizes the use of ergonomics methods to collect human performance data, so that the allocation of user needs in all phases of equipment design can be guaranteed. Human centered design should start at the earliest stage of the project and be repeated iteratively until the system meets the requirements. Technology should be comprehended from the point of view of providing tools for human activity analysis. It takes a dynamic evaluation of human performance to verify the appropriateness of this technology in the intended use (Axtell, 1997). According to Jou et al. (2009), the evaluation process of human—system interaction is one of the most critical factors. Neumann, Ekman, and Winkel (2009) emphasize the need of companies to develop the capability to conduct design in a way that makes ergonomics considerations a regular element of work routine. Software designers should be aware of the importance of designing their products so as to guarantee a good level of satisfaction concerning their use (Liljegren, 2006).

Ergonomics methods are being increasingly utilized in improving the ergonomic aspects of workplaces. The advantages of ergonomics methods have been discussed in order to optimize human—system interaction, to improve safety in the operation of complex systems and to reduce the likelihood of human error (Dos Santos, Grecco, Mol, & Carvalho, 2009). It is of particular interest that the use of ergonomics methods be extended to nuclear equipment design. Recent studies are being examined in order to determine what effective ergonomics methods can be used in the design or redesign of nuclear equipment.

3. The methodology used in the fluorometer design

According to Robertson (2000), user participation in system design is referred to as participatory ergonomics. It can take place at organizational, process or product level. This paper deals with the use of participatory ergonomics to improve the design of nuclear equipment at product level. The principal purpose of this methodology is to describe how the multidisciplinary team actively participates in equipment design, defining the design process, bringing together different information sources, representations, perspectives and fundamental principles. It also presents procedures, tools and ergonomics methods to undertake the fluorometer design. The methodology includes the following items: profile of the multidisciplinary team, definition of a work process for the team, assignment of tasks and choice of ergonomics methods and tools, as shown in Fig. 1.

![Fig. 1. The participatory ergonomics.](image-url)
3.1. Profile of the multidisciplinary team

Step one refers to the profile of the multidisciplinary team. The team included one human factors expert, two design engineers, one electronic technician, two industrial designers and two end-users.

3.2. Definition of the work process of the multidisciplinary team

This phase consisted of the description of the work process and the presentation of roles, commitment dates and the activity timeline. In meetings, the team discussed the problem the fluorometer was meant to overcome; defined what the equipment was intended to measure; and outlined the design goals.

3.3. Assignment of tasks to members of the multidisciplinary team

The tasks and responsibilities were assigned to each team member according to their technical capabilities. The human factors expert served as the leader of the team. This member was required to coordinate the overall discussion with users, engineers and industrial designers, manage conflicts relative to users’ preferences and carry out the methodology implementation. The design engineers and the electronic technician were responsible for hardware and software development. The initial sketches of mechanical design were developed by the industrial designers, what emphasizes the need to integrates ergonomics requirements into this development. Users provided information to team members in response to questions related to their work activities, needs, work practices and the operation of similar equipment.

3.4. Choice of ergonomics methods and tools

The information mentioned in the previous item resulted from the collective integration of data obtained in meetings attended by the multidisciplinary team. It was necessary to conduct a verification and validation process. Ergonomics methods were used to provide a way for the multidisciplinary team to use their expertise to analyze a job, design new equipment, collect human performance data and address ergonomics issues in the fluorometer development. The methods and tools were selected based on what kind of information they provide, on what kind of information the designers could use and on what ergonomics methods could generate more high-quality descriptive and predictive databases.

4. Results

During the definition of the multidisciplinary team’s work process, all the necessary activities for the identification of equipment mission were carried out; and the restrictions of equipment performance and safety aspects were discussed. The fluorometer would measure an unknown amount of uranium and the hardware and software design would be based on the uranium fluorescence when submitted to ultraviolet radiation.

The multidisciplinary team decided to use the standards NUREG 0711 (2002) and ISO 13407 (1999) as references. The standard ISO 13407 (1999) provides guidance on the incorporation of user needs in the design lifecycle. It is characterized by the clear understanding of the context of equipment use; by the specification of the user and of organizational requirements; by the definition of task requirements and by an appropriate allocation of functions between users and technology. In this step, the fluorometer lifecycle was defined as: basic design, detailed design, implementation phase, test phase and integrated evaluation. Basic design included functional analysis, functions allocation, task analysis, user analysis, working environment analysis and analysis of electronic design options. Detailed design featured the development of equipment hardware, software logic and mechanical design (connectors, mechanical box). It led to the functional design of the equipment. During the implementation phase, the logical structure designed in the previous phase was turned into a specific programming language, promoting the integration between hardware and mechanical design, and the conversion of this integration into the physical equipment. The test phase consisted of laboratory tests aimed at evaluating discrepancies between design characteristics and requirements of human factors guidelines; and at identifying design features that might negatively impact user performance. In the integrated evaluation, the equipment built was submitted to validation tests to ensure that it complied with the requirements. This phase demanded that users be participants and perform real tasks with the equipment in the working environment.

In two meetings, the multidisciplinary team decided which activities should be allocated in each phase of the design lifecycle. The approach is shown in Fig. 2. Level 1 concerns the lifecycle phases of the fluorometer. Level 2 concerns the activities used to guarantee the fulfillment of ergonomics and human factors requirements in each phase of the design process.

4.1. Analysis of the reference equipment

It was used to discover salient features of the reference equipment that were similar to those in the equipment under development. Information about the operation of similar equipment and anticipated operations were obtained. The reference equipment is shown in Fig. 3. It is an analog device that measures only solid samples of uranium.

4.2. Functions analysis, functions allocation and task analysis

In this step, the data obtained from previous phases were used to identify the sequence of functions that should be performed by the equipment, to allocate functions to the equipment, to users or to some combination of the two. Functions were identified and described as top levels being expanded into lower levels containing more detailed information.

4.3. Analysis of the equipment operational context

The aim of this analysis was the characterization of the working environment, of the users and their needs. The working environment is the physical environment where the equipment is expected to be used. All the aspects characterizing the working environment have to be carefully taken into consideration since they can have a strong impact on the definition of operational requirements. The characterization of the user population includes a basic set of common features and a set of properties that determines a workers class. It is necessary to analyze the workers class, taking into consideration a set of characteristic such as age, education background and professional background. It is necessary to elicit user needs and expectations regarding the equipment, its operation modes and interaction features.

4.4. Hardware, software and mechanical design

In this step, the fluorometer design was detailed. The multidisciplinary team determined a strategy for implementing the detailed design, considering the data obtained in the previous steps and focusing on the implementation of activities according to the knowledge and skills of each team member.
4.5. Integration and prototype tests

In the final stage there was the integration of electronic and mechanical design; the equipment was built and validation tests were performed to ensure that it complied with the requirements. This section is a validation process. It demands that users be participants, performing real tasks with the equipment in the working environment. The goal was to validate the equipment design; to identify usability problems that might negatively impact user performance; and to determine the needs of operating procedures.

4.6. Use of ergonomics methods

The ergonomics methods were used to collect the performance data of the users, the performance data of the equipment and information related to the end-users. The final objective was to allocate ergonomics issues in the fluorometer development. The methods were selected based on what data they provided and on the information needed. The multidisciplinary team chose the ergonomics methods for each phase of the fluorometer lifecycle (Fig. 2, level 3). The tasks and responsibilities were assigned to team members according to their technical capabilities.

The multidisciplinary team performed the analysis of the reference equipment and the characterization of the working environment and the end-users. The analysis was based on three visits to the chemical analysis laboratory. The analysis of the reference equipment was performed by means of interviews and talk-through with the users. Users provided information to the multidisciplinary team in response to questions, as they performed simulated tasks. The analysis was used to obtain information about points in the interaction where the equipment design did not complement user goals. To supplement and better focus on the information needs, questions such as the following were answered by the users: Why did you do that?; How did you do it?; What were the preconditions for doing that?; What information did you consult for doing that?; What were the results of doing that?.

The human factors expert, the design engineers and the two end-users carried out the functions analysis and functions allocations. The multidisciplinary team performed the verification
process of this item. Functional flow analysis was the technique used to identify the sequence of functions that had been chosen to be performed by the users and by the equipment automatic control system. After functional flow analysis and functions allocation, the design engineers developed a detailed description of the tasks to be performed by the users. The hierarchical task analysis included the identification of a set of nominal tasks for the user class, the assessment of task frequency and of the importance of each task.

The two engineers and the electronic technician were responsible for developing the equipment hardware and software. The operation of the fluorometer is based on uranium fluorescence when it is submitted to the incidence of ultraviolet radiation. Fluorescence is measured by an electronic optical system with optics filters, a photomultiplier tube and a current amplifier. Fig. 4 shows the photomultiplier tube with filters, a high voltage power supply to polarize the photomultiplier tube, a converter/amplifier current to voltage, a microcontroller, graphical display, a keyboard and a serial output (USB converter) to a personal computer. The logical structures of system functioning were turned into a specific programming language and into human—system interactions requirements. The equipment control and information processing are digital, with graphical touch-screen interfaces which make it possible to carry out calibration, data storage and information readings. The NUREG 0700 (2002) guideline provided detailed characteristics of the interfaces and panel, such as control organization, the way equipment features and functions are presented to users, the use of color and aesthetic design.

Industrial designers were responsible for the initial sketch of the physical design, mechanical design and details about the information to be presented in the equipment panel, given the need to integrate ergonomics requirements into this process. The multidisciplinary team chose the definitive mechanical design, which allows the analysis of solid and liquid uranium samples. The samples are placed in front of the device. The samples to be
analyzed, either liquid or solid, are replaced by means of a rotating shaft. Only one side at a time faces the photomultiplier, while the opposite side faces the opening space. In this position, the sample can be replaced or removed. If another sample is to be examined, it is necessary to rotate the button at the top of the rotating shaft until the desired sample is facing the photomultiplier. Acrylic fabric keeps the sample fixed and a door prevents the entrance of natural light. The solid sample is inserted into the circular area, using uranium pellets. The liquid sample is inserted into the rectangular cavity, using an acrylic tube. Fig. 5 shows the interior details of the equipment. Fig. 6 shows details of the insertion of solid and liquid samples.

The fluorometer prototype will be developed in the next phase. It is the result of the integration of hardware, software and mechanical design. In this step, the use of an integrated checklist will establish a review method to assure that the design has incorporated important ergonomics criteria, establishing a comparison with the desired human factors standards.

The prototype will be tested with potential users, using simulations at the laboratory, to determine if it really meets user needs. The validation of the fluorometer design will be an evaluation based on user performance and its users will perform the tasks under real conditions. The goals are to ensure that the fluorometer is operable within all requirements and that it supports safe operation, to identify usability problems that will negatively impact user performance and to identify the need of changes in operating procedures. The methods employed to meet these objectives include a user satisfaction questionnaire and evaluations on activity and usability. This phase will be initiated within three months.

5. Conclusions

After several incidents in the nuclear area, nuclear power plant regulators around the world have formulated recommendations to designers and owners related to the use of human factors and ergonomics in the design and modernization of control rooms and equipment. However, these processes are still predominantly driven by technology. The use of participatory ergonomics in the nuclear industry presents many opportunities for improvements with regard to system effectiveness, efficiency and safety.

In this paper, the overall results showed a positive and significant contribution of participatory ergonomics. This approach reflects the importance of having a group of professionals from diverse fields of knowledge and with different technical capabilities, who, together, provide decisions, take actions, work on the coordination, and promote communication among the members, assisting in the choice of ergonomics methods and definitions related to the design goals. The process of sharing information and the continuous process of verification and validation are essential to the allocation and integration of the data obtained into the design lifecycle. There are several ergonomics methods that should be used in participatory ergonomics. The choice of the best ergonomics method expresses the goal of providing a way for the multidisciplinary team to use their knowledge and experience in defining requirements for the incorporation of end-user needs in the design of nuclear equipment.

From a systemic point of view, the process must start at the earliest stage of the project, when the initial concept for the equipment is being formulated and must be repeated iteratively until all requirements are met. The requirements defined and established in early phases of equipment design represent the basis for the development of its structural model; they represent the functional model with a specific goal and the contextual model with a useful description of the context of use and of working environment. In our approach, additional factors are being considered to ensure a good match with user requirements, such as usability and tests based on user performance. Equipment design must fit the working and living patterns of users, allowing efficient and effective use and also addressing safety needs.

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