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The strategic value of human factors engineering in control room modernization

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ABSTRACT

Control room modernization is one of the most challenging and complex upgrade projects that a nuclear power plant can undertake. It can have almost as big an impact on operations as, for example, turbine replacement. The challenges of migrating an analog control system to a distributed control system are already well known and a number of nuclear utilities have embarked upon various levels of effort to upgrade some of the systems in the control room. When planning for control room upgrades, plants have to deal with a multitude of engineering, operational, and regulatory impacts. This will inevitably include several human factors considerations, such as workstation ergonomics, viewing angles, lighting, seating, new interaction modalities, new communication requirements, and new concepts of operation. In helping nuclear power utilities to deal with these challenges, the United States Department of Energy researchers located at Idaho National Laboratory (INL) have developed research-based human factors design and evaluation methods to be used in the development of end-state concepts for modernized control rooms and to manage the various phases of the upgrade life cycle. The methodology includes interactive sessions with operators in INL's Human System Simulation Laboratory, three-dimensional modeling to visualize control board changes and operator-system interaction, and development of human-system prototypes to evaluate various aspects of proposed modifications. This methodology has been applied at a number of U.S. nuclear power plants where modernization projects are underway, including Exelon's Braidwood and Byron plants, and Arizona Public Service's Palo Verde plant. It was demonstrated that including this methodology in the plant's engineering process helps to ensure an integrated and cohesive outcome that is consistent with human factors engineering principles and provide substantial improvement in operator performance.

1. Introduction

The nuclear energy industry is currently undergoing one of the most challenging phases in its sixty-year history since electric power was first produced in 1951 at the Experimental Breeder Reactor I in Idaho. The oldest commercial plants in the United States (U.S.) reached their 40th anniversary in 2009. Most currently operating nuclear power plants are licensed to operate for sixty years, but many of them will reach the end of their licensed lifetime within the next twenty years. In the meantime, domestic demand for electrical energy is expected to steadily increase over the next 15 years (EIA, 2017). This means that if current operating nuclear power plants do not operate beyond 60 years, electrical energy from nuclear power will begin to decline, even with the expected addition of new nuclear generating capacity.

As part of a strategy to mitigate this anticipated shortfall, the U.S. Department of Energy (DOE) has launched the Light Water Reactor Sustainability (LWRS) research and development (R&D) program. This program aims to extend the operating lifetimes of current plants beyond 60 years and, where possible, make further improvements in their productivity. A large part of these improvements involves the introduction of new processes, materials and technologies, notably advanced instrumentation and control (I&C) systems. Upgrading I&C systems, including those in the main control room and local control stations, is part of the strategy to address the obsolescence and reliability issues of legacy analog systems. Part of the LWRS program is therefore focused on developing requirements for replacement of aging materials, systems, structures, and components and developing and demonstrating methods and technologies that would support safe and economical long-term operation of existing reactors. The various activities conducted under this program aim to demonstrate the feasibility and benefits of control room modernization to the commercial nuclear operators, suppliers, and industry support community.

Through multiple LWRS Control Room Modernization projects, Idaho National Laboratory (INL) has been collaborating with a number

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of U.S. utilities, such as Exelon, Arizona Public Service, and others, in the development of guidance to address the challenges associated with reliability and obsolescence, and specifically to demonstrate how application of human factors principles could exploit the capabilities inherent in digital systems, particularly distributed control systems (DCS) and modern human-system interface (HSI) technologies. These collaborative projects also aim to improve operator and plant performance, and to avoid the introduction of new human error traps in both routine and off-normal plant conditions.

The human factors research objectives under the LWRS program include topics as diverse as the role of the operator in new concepts of operation, function allocation, workload variations, computer-based procedures, alarm management, and development of human factors engineering (HFE) methods and tools specifically for control room modernization projects. Special attention is paid to the development and application of a coherent framework for integrating human factors principles into other engineering activities during a control room upgrade project.

2. The role of human factors in nuclear power plant upgrades

Ever since the accident at the Three Mile Island Unit 2 (TMI-2) (Backgrounder on the Three Mile Island Accident, 2009), there has been general agreement in the nuclear industry that human factors principles and requirements should be incorporated in the engineering process. The industry has recognized that a systematic, integrated process was needed to identify and track performance and safety issues to ensure a balanced development of both technical and human aspects of systems, throughout the life cycle of the system. The nuclear industry has subsequently adopted several pragmatic approaches to defense-in-depth, resulting from regulatory guidance documents like NUREG-0800 (*Standard Review Plan*) (NUREG-0800, 2011), NUREG-0711 (*Human Factors Engineering Program Review Model*) (NUREG-0711 Rev 2, 2004) and NUREG-0700 (*Human-System Design Review Guidelines*) (NUREG-0700 Rev 2, 2002). These guidelines emphasize the crucial role played by humans in supporting plant safety and providing defense-in-depth.

While it is increasingly recognized in most industries that the human must be considered a central part of system development, it is not as readily recognized that human factors issues vary widely according to the type of system being modified, its function, its location, and its users. Particularly, experience in modernization projects over the past few years has shown that it is ineffective and risky to address human issues as an afterthought. The risks associated with poor human factors can best be avoided by starting human factors activities as early as possible in the modification process and continuing them throughout the project. Good management and coordination between engineering disciplines is needed to address human factors comprehensively and consistently.

Regulatory guidelines as well as national and international standards (including supplementary guidelines and standards developed by organizations such as the Institute for Electrical and Electronics Engineering (IEEE), the American National Standards Institute (ANSI), the International Electrotechnical Commission (IEC), the International Atomic Energy Agency (IAEA) and many others) are all aimed at promoting nuclear safety, conservative design, quality assurance, administrative controls and rigorous HFE programs. Especially the adoption of guidelines for HFE programs suggests that the nuclear power industry recognizes that the ever-increasing complexity of automation and information technology significantly impacts human performance.

As a result of the adoption of these guidelines, there is now growing evidence that long-term improvements in nuclear power plant (NPP) safety stem from human factors solutions, especially in systems that require human involvement, or that may impact the life and work of humans in any way. Further, both regulators and engineers know that such solutions are more likely established through consistent, long-term support for the application of human factors principles in the planning, analysis, design, development, verification, validation, and implementation of such systems.

Unfortunately, in practice many nuclear engineering organizations still find it very difficult to achieve this ideal; as a result, human-system interface issues are often not addressed until late in the development cycle, even after the configuration of a particular system has been set. There still appears to be a lot of fragmentation and lack of consistency in the application of human factors knowledge. This is probably not surprising, because these organizations are already experiencing challenges due to changes in design, materials, and construction techniques that have changed dramatically since the construction of Tennessee Valley Authority's Watts Bar plant, the newest reactors in the U.S., started in 1973.

From past operating experience, the DOE has recognized that the nuclear energy industry not only needs a systems approach to HFE, it also needs to institutionalize the application of human factors principles within the organization. As a result, a significant part of the DOE's LWRS program is now focused on the human in the system, not only for new reactor projects, but also for modernization projects that are already underway. While systems engineers intuitively understand that the human operator and maintainer are part of the system under development, they are not expected to have the expertise or information needed to link human capabilities with the capabilities of the hardware and software.

INL's role in these projects has been to ensure that human considerations are integrated into all phases of system design, development, operation, and maintenance (Hugo, 2013), (Hugo and Farris, 2016). This is a systems approach to human factors integration that provides the human performance information necessary for engineering design and development processes before the project starts. It also ensures human factors verification and validation of systems and operations throughout the project life cycle to identify problems and help engineers define cost-effective solutions to achieve human and system performance enhancements.

2.1. Human factors requirements for control room upgrades

Control rooms in light-water reactor plants typically consist of a set of control boards arranged in a U-shaped layout to accommodate the thousands of discrete controls, instruments, indicators, and alarm annunciators required by analog control technologies. The complexity and sheer number of legacy devices in the control room pose a formidable challenge not only to operators, but also to maintenance staff. These challenges are overcome only through familiarity and intense training. One of the most critical challenges, however, is dealing with increasing reliability and obsolescence issues presented by legacy control systems. They are expensive to maintain and even more expensive to replace when parts can no longer be obtained. Today, superior control and automation system technology is available for NPP control rooms. Such modern technology is already widely used in conventional power plants and the process industry in general, where the new digital control room technologies have demonstrated benefits in operator performance, operational cost, and plant maintainability.

In addition to the general human factors principles for systems engineering, there are specific design principles for upgrading and modifying control rooms and human-system interfaces (HSIs). These principles deal with how revised control board layouts and new HSIs would successfully address human factors and regulatory criteria. Specific human factors and ergonomics considerations and risks associated with control room design and modernization are described in well-established guidelines and international standards, as mentioned before. These guidelines emphasize how the risks associated with poor human factors can be avoided by starting human factors activities as early as possible in the design process and continuing them throughout the project.

Building on the extensive human factors body of knowledge, a

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