# Human Factors and Modeling Methods in the Development of Control Room Modernization Concepts

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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 even have a bigger impact on operations than, 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 and operational impacts. This will inevitably include several human factors considerations, including physical ergonomics of workstations, viewing angles, lighting, seating, new communication requirements, and new concepts of operation. In helping nuclear power utilities to deal with these challenges, the Idaho National Laboratory (INL) has developed human factors design and evaluation methods to be used in the development of an end-state control room concept and to manage the various phases of the upgrade life cycle. This included interactive sessions with operators in INL's Human System Simulation Laboratory, and three-dimensional modeling to visualize control board changes. To make the various upgrade phases as concrete and as visible as possible, the end-state concept includes a set of visual representations of the control room before and after various upgrade phases to provide the context and a framework within which to consider the various options in the upgrade. This includes the various control systems, human-system interfaces to be replaced, and possible changes to operator workstations. This paper describes how this framework helps to ensure an integrated and cohesive outcome that is consistent with human factors engineering principles and also provide substantial improvement in operator performance. The paper further describes the application of this integrated approach in the strategic modernization program at a nuclear power plant where legacy systems are upgraded to advanced digital technologies through a systematic process that links human factors principles to the systems engineering process. This approach results in an integrated control room architecture beyond what is possible for individual subsystem upgrades alone.
*Key Words*: Control Room Modernization, Human Factors Engineering, 3-D modeling

## 1 INTRODUCTION

The development of a new generation of nuclear power plants is introducing new processes, materials and technologies, notably advanced instrumentation and control (I&C) systems. These new I&C systems inevitably lead to the design of more advanced control rooms using operator consoles with multiple digital displays for plant and process control and monitoring.

The U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program Control Room Modernization Pilot Project was initiated to develop the technologies, tools, and methodologies to implement and demonstrate the benefits of modern digital technologies in an operating nuclear power plant (NPP) main control room. The purpose of this project is to address the many legacy analog technology issues of reliability, obsolescence, as well as to enable improved operator and plant performance. This will also demonstrate the feasibility and benefits of control room modernization to the commercial nuclear operators, suppliers, and industry support community. This project is a major step in resolving legacy I&C issues that potentially impact long-term sustainability of the LWR fleet.

As part of the LWRS Control Room Modernization Project, Idaho National Laboratory (INL) is currently collaborating with Arizona Public Service Company's Palo Verde Nuclear Generating Station (PVNGS), as first-mover, in a first-of-a-kind Control Room Modernization project. The main purpose of this project is to assist PVNGS in addressing legacy analog technology issues of reliability and obsolescence, and specifically to demonstrate how such a design could exploit the capabilities inherent in

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digital systems, particularly distributed control systems (DCS). The project also aims to improve operator and plant performance, and to avoid the introduction of new human error traps in both routine and off-normal plant conditions.

Whereas previous efforts for control room modernization in the U.S. nuclear power plant fleet centered on partial system upgrades in the main control room, this project features a much more ambitious scope of upgrading multiple systems across the entire main control room.

Many of the planned system upgrades will be based upon a common digital distributed control system (DCS). This will help to standardize the operator interface, engineering requirements and related knowledge base, as well as system maintenance procedures, spare parts, and more. The DCS migration is expected to improve not only the reliability of systems, but also make overall control room operations more cost-effective by enabling operator control stations to serve more than one system, and also serve as back-ups to each other.

Most of the systems that are candidates for DCS migration have their operator controls and indicators on the main control boards in the main control room. Modification of these devices and their functions will have a direct impact on human factors considerations for the operators. The current migration strategy is to remove the legacy analog controls from the control boards wherever there are software equivalents within the DCS, with possible exceptions for redundancy purposes. This method will remove ambiguity in how a system is to be operated (soft or hard controls), and eliminate the cost of maintaining the analog devices for the remainder of the plant life.

The removal of analog devices from the control boards will provide the needed space on the boards to locate the new DCS operator interface (digital displays, touch screens, keyboards, mice, etc.). Care must be taken to avoid functional fragmentation of the vacated space on the boards by simply forcing displays into the vacated space where they would fit, as this might introduce new human factors challenges into the control room. The new DCS devices must be located in reasonable proximity to remaining analog devices that have to be referred to or operated in conjunction with the DCS functions. Where there is a substantial amount of vacated board space, there is also opportunity to mount large overview displays that can provide a much clearer picture of plant conditions and trends than the discrete analog devices.

Since this broad scope of system modification will inevitably affect how operators perform their jobs, it was necessary to define an approach that will integrate human factors requirements into the systems engineering process. This approach included the development of end-state vision of the modified control room based upon a combination of human factors principles and technical requirements. The end-state vision provides the context and a framework that will guide all possible options in the upgrade of the various control systems to be replaced, such that they result in an integrated outcome that is consistent with human factors engineering principles and provides substantial improvement in operator performance. Since the introduction of new technology in the control room will not achieve these gains when it is done piecemeal or partially, the end-state vision allows the plant to focus on creating integrated displays and control systems beyond what is possible for subsystem upgrades alone. The goal of the control room modernization project with PVNGS is therefore to help the plant achieve these improvements as can only be realized from the emergence of multiple systems on an integrated control platform.

## 2 HUMAN FACTORS REQUIREMENTS FOR CONTROL ROOM UPGRADES

Control room modifications, however small, will affect operator as well as system performance. This means that a number of regulatory requirements as well as industry standards must be considered. The scope of the PVNGS control room upgrade is significant enough to warrant a thorough review off all relevant guidelines and standards. Guidance from ISO 11064 Part 3 (*Ergonomic Design of Control Centers – Control Room Layout*), Part 4 *(Layout and Dimensions of Workstations*) and Part 6 (*Environmental Requirements for Control Centers*) [1] was considered, but the review guidance in NUREG-0700 Rev 2

("Human-System Interface Review Guidelines") [2] was found to be the most appropriate to identify design improvement opportunities, while also conforming to industry best practice. Chapter 11 and 12 include criteria for consoles and panels, specifically how human-system interfaces (HSIs) are integrated to provide an area where plant personnel can perform their tasks.

Specific design principles for the PVNGS end-state concept, such as how the proposed revised control board layouts and new HSIs would successfully addresses the criteria, were derived from the criteria for human factors and ergonomics considerations. These included criteria for the design of workstation features such as control-display integration and layout, labeling, and ergonomics, for example, console height, viewing angles, and reach. It also included criteria for the overall layout of the workstations and other equipment such as group-view displays within the workplace, and environmental characteristics including temperature, ventilation, illumination, and noise.

These criteria were applied during a workshop to review the end-state concept. The results were used to revise the concept. Further human factors evaluations and operator studies were then conducted to determine the suitability of the design to improve operator performance and provide substantial operational efficiencies.

## 3 MIGRATION STRATEGY

In order to migrate existing nuclear control rooms toward digital interfaces, a large modernization effort must be undertaken. A migration strategy for a project of this magnitude needs to define the specific steps that will be taken to modernize the control room in step with the various stages of I&C modifications, with the ultimate goal of reaching the defined end-state vision. This includes changes in functionality such as automation, changes in procedures and training, and physical changes to the human-system interfaces (HSIs). The technical phases of the migration plan have already been laid out in the plant's systems engineering process (SEP), but it is important to integrate the human factors engineering process into the SEP. This will ensure that the upgrade program is driven not only by the I&C part of the upgrade, but will also allow the prioritization and ordering of both technical and human-centered changes to be made at each step in the upgrade process. It will also ensure some flexibility in how the HSI upgrades are scheduled. For example, operational and human factors considerations may lead to a different ordering or prioritization of the changes.

Whether or not the modification of existing control rooms will affect the plant's licensing basis (in terms of the provisions of 10 CFR 50.59), the human factors engineering program has to adhere to the expectations described in NUREG-0711 ("Human Factors Engineering Program Review Model") [3].

The early recognition by all stakeholders of the value of following regulatory guidance, in conjunction with other guidance like the EPRI Human Factors Guide [4], also helped the early identification of human performance issues and opportunities for performance enhancement. This benefited the initial gathering of information, which directly supported the conceptualization of the end-state vision, as described below.

## 4 DEVELOPING A CONTROL ROOM END-STATE CONCEPT

There are many challenges and potential benefits associated with rapidly evolving current technologies, and each must be evaluated to determine its merits. This requires all role players to be well informed about new control room design concepts, I&C systems, and HSI technologies in order to improve and further the planning efforts for the modernization process. To ensure that the end-state concept is "future-proofed", it must accommodate projected needs of the plant for operation 10 or 20 years later by incorporating resilient and cutting edge technology. The design should be flexible in order to accommodate further upgrades with future technological advancements that emerge during the modernization process. This flexibility should be incorporated into the end-state concept by framing the design in functional terms rather than concrete technological solutions based on existing available technologies. In addition to reviewing new technologies during the modernization process, any lessons learned should be incorporated into the process directly so that these solutions can be realized in the final product. For example, it is known that modern HSI technology has a much shorter life cycle than the existing analog devices, many of which have been in use for thirty years or more. This implies that the migration and upgrade process should also include a plan to handle manufacturers' planned obsolescence strategies, for example by retiring and replacing selected devices at predetermined intervals.

The ideal end-state concept would then be a unified control room system, including all HSIs, that harmonizes all control room functions, while also providing adequate redundancy across the distributed control system architecture. By incorporating appropriate new technology, new functionality, such as various levels of automation, can be provided. Well-integrated technology will ensure greater maintainability due to shared hardware and software across different systems. The unified HSIs will employ a common architecture based upon a hierarchy of high- to low-level information displays that offer operators greater plant situation awareness, while also reducing workload.

To ensure that all these perspectives are addressed in the development and evaluation of the PVNGS end-state concept, a combination of three methodologies was used:

### 4.1 Design Workshops in the Human System Simulator Laboratory (HSSL)

A design workshop on modernization options for the PVNGS control room was conducted in the INL Human System Simulation Laboratory (HSSL) to review proposed control room end-state concepts with the INL human factors team and the PVNGS engineering and operations representatives.

The HSSL is INL's reconfigurable testbed for operator-in-the-loop studies on control room modernization. The facility is used to host a variety of full-scope nuclear power plant simulators on a number of large touch screens that allow the representation of existing analog I&C as well as rapid development and testing of digital control technology on the virtual control panels.

The first phase of the evaluation used static representations of the existing as well as modernized control boards were displayed in the HSSL. These representations were used in a walk-through of plant operating procedures by the Palo Verde operations and engineering representatives, to determine whether the proposed control board modifications were optimally arranged and compliant with human factors principles. Westinghouse also provided input on requirements for their control system upgrades with respect to the control board arrangements.

For the second phase of the evaluation, the Palo Verde plant simulator was used in the HSSL in conjunction with new HSI prototypes to provide a functionally accurate tool for dynamic evaluation of the blend of new digital and legacy analog devices on the control boards. This also allowed the identification of additional opportunities for enhancing the end-state concept.

**Figure 1: Reviewing the existing control board layout in the HSSL**

## 4.2 3-D Modeling

Dimensionally accurate three-dimensional (3-D) models of the control room were developed, both for the current state and various phases of the planned upgrade. These models were used for desktop reviews of the current control room layout as well as the various phases of the end-state concept. The models were also incorporated into the HSSL to provide, a static representation of the current control room. This static version was developed by displaying photographs of the control boards (based on the Training Simulator) on the glass top panels. These images were arranged in the same order as in the actual control room to represent all the control boards necessary to review the systems targeted for upgrade. The combination of the static and dynamic simulations allowed the evaluation of human factors principles, as well as certain functional and physical constraints.

**Figure 2: Existing PVNGS Control Room**

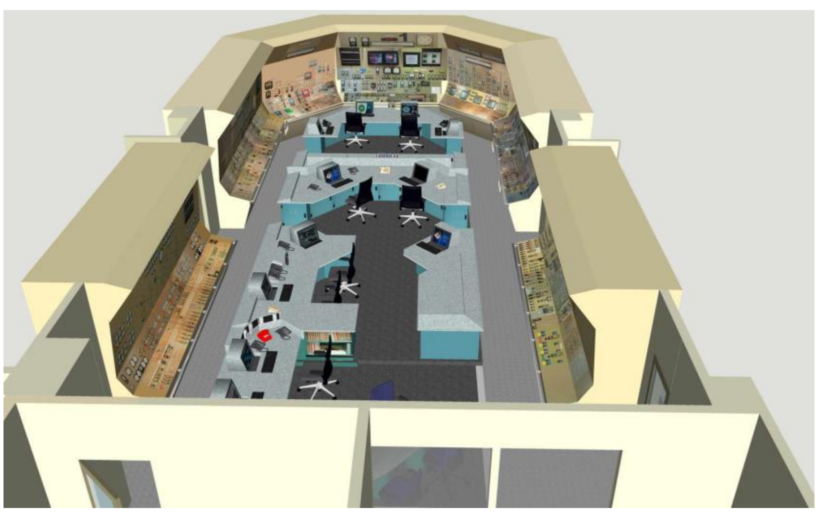

**Figure 3: 3-D Model of the existing PVNGS Control Room**

**Figure 4: 3-D Model of End-State Concept**

### 4.3 Virtual Reality

The 3-D models were converted into a version that could be viewed immersively in INL's Computer-Assisted Virtual Environment (CAVE) to improve understanding of the spatial aspects of the control room. One model represented the current control room and the other one represents the upgraded boards described above.

**Figure 5: Viewing the 3-D model in the CAVE**

Viewing of these virtual models by the project team members formed part of the design workshop and comments and suggestions were captured for refinement of the concept design where necessary.

## 5 END-STATE CONCEPT IMPLEMENTATION

The implementation of the end-state concept at PVNGS is a complex process that spans several upgrade phases over a number of years. The migration strategy described before includes a large number of important inputs and considerations for the analysis and development of the end-state concept and the migration strategy. The key implementation steps are as follows:

1. Gather inputs that will be needed to develop the migration plan, including the initial modernization strategy and information about potential technologies.

2. Apply human factors engineering guidelines or principles that should be followed in the analysis of potential end-state options and in the planning and implementing of the migration. This process is adapted from the review criteria in NUREG-0711 [3] and also EPRI Reports 3002004310 [4] and 1010042 [5], which cover the entire life cycle of a control room modernization project. Each of the phases of the PVNGS project will follow a graded approach that adds the appropriate level of human factors effort to the systems engineering process.
3. Follow a graded approach in the application of human factors principles during each phase. This graded approach is described in detail in the Human Factors Engineering Program Plan (HFEPP) for PVNGS. It will be applied to all modifications to determine whether they have potential HFE impact. This involves a screening method to identify changes that are likely to have a high, medium or low impact on operator or system performance. Changes that do not modify HSIs but could have other potential impacts on operator tasks are also included (e.g., system changes that reduce the amount of time available for an operator to perform a task).
4. Plan and evaluate the HSI transitions, in accordance with the HFEPP, over the various upgrade phases to allow sufficient time for training and updating of procedures to ensure that operators and other users become familiar with the changes and comfortable with the new technologies being introduced, and to minimize the likelihood of human error. This phase may include the development of conceptual layouts, updated 3-D models, prototypes, and physical mockups as needed.
5. Ensure the effectiveness of hybrid HSIs produced at each stopping point – at each step, the modifications must result in an HSI that is acceptable for operation until the next step is taken, even though this may involve interim, “less than optimal” designs and hybrid configurations.
6. Develop and evaluate conceptual designs of the individual HSI changes to be made during migration.
7. Evaluate costs and minimizing project risks.
8. Perform licensing evaluations and minimizing licensing risk.
9. Develop and implement the final migration strategy.

# 6 DISCUSSION

The ultimate vision for a modernized PVNGS control room is to have largely computer-based I&C systems that allow operators to monitor and control the plant from workstations with computer-based HSIs that integrate alarms, soft controls, and information displays. Applying HFE principles and methods in the design, verification and validation of the control room and associated HSIs is important to ensure that the modification will meet the applicable regulatory requirements and will provide a high level of operator performance and plant reliability. Implementation of new I&C and HSI technologies should not be left to chance, as this can have a negative impact on system as well as human performance. The guidance developed during this project will ensure that human factors considerations, in combination with engineering requirements, will help shape or even drive the modernization. In this way the upgrade to newer technologies will make positive improvements in both human and system performance. Understanding what is possible with modern HSIs is necessary in order to determine how to take advantage of them.

Potential human performance problems may be associated with a control room employing a mixture of older, analog equipment and more modern, digital equipment and systems. These issues may impact regulatory and licensing activities, updating of procedures, and the development or modification of training programs. Many of these issues are not new, as existing plants have dealt with a mix of analog and digital technologies for some time. For example, in many plants the operators currently work with a combination of analog and digital or computer-driven displays for monitoring plant variables, including Safety Parameter Display Systems (SPDS) and Post-Accident Monitoring Systems (PAMS). The end-state vision will introduce many more such devices, including several flat panel displays, touch screens, and large overview displays. This means that the human-system interaction modalities will change from predominantly manipulation of hard-wired switches and buttons on the control boards, to predominantly interacting with computer-controlled systems by means of keyboard, touch screen, and mouse actions.

A number of typical issues may arise from a combination of old analog equipment and moderns HSIs. The following table summarizes the potential changes in HSI design concepts and how the challenges posed by the changes could be resolved in the modernized control room:

**Table 1: Human Factors Considerations for Control Room Modernization**

| Concept | Potential resolution in modernized control room |
|---|---|
| *Hybrid HSI considerations* | |
| Inconsistencies in design or operation | Extensive modeling and simulation work to identify human factors issues, coupled with an HSI Style Guide used in development of HSIs, will help to ensure that inconsistencies are eliminated. Prototypes and scenarios in the HSSL will also allow operators to become familiar with the new HSIs. |
| Inconsistencies in operator workload | Although the DCS might make more information available to operators, care must be taken to design displays based upon an analysis of operator tasks and a rational allocation of functions to the operator, to the automation system, or a combination of the two. Integrated system validation and performance measurements will be conducted in the HSSL to verify operator workload will be better, or at least the same as before the modification. |
| Inconsistencies in interaction mode | It is inevitable that migration of analog controls to digital soft controls will introduce different modes of interaction. These changes will be addressed through training. However, where analog devices are replaced by digital equivalents displayed on a DCS screen, the mode of interaction should be similar. For example, where the manipulation of an analog device required a clockwise rotation to actuate a function, the actuation of the same function on the digital equivalent must also be performed clockwise, either with a mouse or by touching an object on a touch screen. Exceptions to this must be carefully analyzed. For example, where a single press of an analog pushbutton was required to actuate a function, the digital equivalent might require a touch action plus a confirmation action. |
| Duplicated controls | In a hybrid configuration, some analog controls might be duplicated on the DCS displays for redundancy purposes. In this case procedures must be very clear about the use of the specific control under specific circumstances. |
| Duplicated indications | As with controls, some analog indications might be duplicated in the DCS either for redundancy purposes, or because of a delay in removing the analog device. In this case procedures must be very clear about the use of the specific indication under specific circumstances. |
| Deactivated controls and indicators | Some control devices and indicators may remain on the control boards, due to structural difficulties in removing them from the boards. Such devices will be clearly marked with a suitable label or other method. In addition, procedures and training will be updated to reflect this change. |

| Concept | Potential resolution in modernized control room |
|---|---|
| Difference in level of automation | It is inevitable that migration of control functions to the DCS will introduce a different level of automation. In general, the operator will still be in total control of important functions, but the need for low level control and monitoring of detail functions will be reduced. This might be the case where previous sequential manual actions are combined into an automated sequence. Such sequences will usually be started by the operator, with indications of the progress of the sequence. Provision will be made for operators to intervene in the execution of such functions where it is safe to do so. (It should be noted that a multi-level automation scheme as described in NUREG-0711 might not be feasible until all plant control functions have been fully integrated in the DCS). |
| Difference in failure mode | Control systems for non-safety equipment may also contribute to safety and should be properly designed, operated and maintained. Where their failure can raise the demand rate on the safety related system, and hence increase the overall probability of failure of the safety related system to perform its safety function, the failure rates and failure modes of the non-safety systems should have been considered in the design, and they should be independent and separate from the safety related system.<br>In all cases provision must be made for the operator to take actions necessary to restore the system to a safe condition. Exceptional care must be taken in the human factors design of, for example, alarm systems, procedures, and training. Where such arrangements are monitored and reviewed, a very low probability of failure may be achievable. Any supporting hardware or software, such as alarm systems, would also need the requisite integrity level. |
| Inconsistencies in procedure | No inconsistencies will be allowed at any stage of the modification process. However, exceptions might occur when it is necessary to maintain procedures for both analog and digital systems while control boards are being modified. These inconsistencies will be carefully documented and included in operator training. |
| *New HSI considerations* | |
| Levels of HSI modernization | The migration of controls and indicators from the control boards to DCS displays are determined primarily by the technical and functional requirements of the relevant system. This process involves three levels of upgrade:<br>*Equipment replacement* - individual devices on the control board are replaced with digital equivalents, without any significant change in functionality. This will usually achieve some level of device standardization, which will simplify maintenance.<br>*Architecture update* - the migration of control functions to the DCS is implemented to improve the reliability of monitoring and control systems. This provides additional flexibility and functionality, and achieves further standardization through use of common platforms. The architecture update includes the improvement of the HSI configuration and arrangement of the interfaces on the control board as well as on the displays. This will reduce the complexity of conventional control board layouts with many discrete controls, indicators and annunciators spread out along panels. Instead, the modernized control room consolidates many functions in a few displays on the control |

| Concept | Potential resolution in modernized control room |
|---|---|
| | boards, as well as at seated workstations with well-designed information displays, soft controls, and alarm information.<br>*Integration and automation* - I&C systems are integrated functionally to achieve specific performance improvements. Additional automation is implemented in the control systems and HSI. This will simplify certain operator tasks, such as stopping and starting control sequences, instead of having to perform discrete, low-level control actions. When an advanced alarm system and computer-based procedures are approved and implemented, it will introduce a further improvement in general situation awareness and operators' ability to rapidly and effectively respond to changing conditions. |
| Selection of HSI technologies | HSI technologies (large displays, touch screens, keyboards, mice, etc.) will be chosen, not only for their technical characteristics, but also for the human factors considerations associated with the intended task (monitoring, control, diagnosis), the ergonomic requirements (locations, reach, interaction, resolution, ambient lighting, etc.). Limiting the number of selected devices is recommended for maintenance purposes. Care must be taken to ensure that all selected devices perform exactly the same under all operational and environmental conditions. |
| Control board changes and location of HSIs | While the amount of board space that is typically vacated by removing analog devices in a DCS implementation might be sufficient to locate DCS control displays, the vacated board space becomes very fragmented, which is not conducive to optimized design from a human factors perspective. Wherever possible it will be attempted to move and relocate some devices that are not involved in the upgrades in order to improve the new design of the boards for ease of use by operators and conformance to human factors principles. |
| Negative transfer of training | Migrating from analog HSIs to digital controls and indicators will introduce inconsistencies in layout, appearance and interaction mode. This may cause negative transfer of training from the old removed devices to the new HSIs. For example, operators may consciously or unconsciously try to perform the same action on the new HSI, where such action might be inappropriate, or even cause unwanted results. Negative transfer could also appear in the form of subjective prejudices, resulting in operator performance being negatively impacted, simply because, for example, they need to search for an indicator or control or try to perform a function in the way they used to. These issues should be identified and addressed early during design and training. The incidence of negative transfer could also be reduced by involving operators at all phases of the modification. |
| *Workstation design considerations* | |
| Design of seated operator workstations | As described earlier, the removal of analog devices (controls or indicators) from the control boards involves one of the following options:<br>1. Replacing that device with a digital equivalent on the same the board,<br>2. Replacing the analog device with a soft control or indicator on a new DCS display,<br>3. Integrating the functionality of that device in another DCS function and representing that functionality in the corresponding HSI on the same control board, |

| Concept | Potential resolution in modernized control room |
|---|---|
| | 4. Integrating the functionality of that device in a DCS display on new workstations for reactor operators (ROs) and senior reactor operator (SRO). This might duplicate the HSI on the control board (option 3) during the early stages of the control room modernization.<br><br>In the case of option 4, many design considerations arise:<br>1. The retention and modification, or complete replacement of the existing RO and SRO desks. For new desks, the exact configuration and location will need detailed analysis and design of technical, physical, functional, and ergonomic requirements.<br>2. The minimum number and size of displays required on the RO/SRO desk must be determined through careful analysis to avoid the "keyhole effect". This happens when too few displays and too much navigation to reach required information restrict the operator to only a very limited view of the plant state at any time. (According to EPRI Report 3002004310, at least four displays per operator are needed for a full-featured operator workstation – the applicability of this constraint is subject to review and verification).<br>3. The need for, and the design and location of large overview displays. This includes consideration of mounting requirements to satisfy seismic qualification requirements, monitor size, viewing angles, lighting, glare, and many more. |

Throughout the design workshops consideration was given to the human factors principles that would affect the modification of the control boards, or how operator performance might be affected by certain design decisions. It was found that these effects might arise from, for example, the physical mounting of large overview displays, touch panels and other devices, or from the design of the DCS displays. It might also arise from environmental conditions in the workplace, for example, the additional heat load created by a large number of additional displays and its effect on air conditioning requirements, and also new illumination requirements due to the need to prevent glare and reflections on the displays.

One of the important changes envisaged for a more advanced control room is the change from an environment designed primarily for standing operations, to one that allows more tasks to be performed sitting down at the reactor operator and senior reactor operator workstations. In fact, this is one of the advantages of the DCS migration: control and monitoring functions are effectively available wherever a connected workstation can be located. Such a configuration will make it possible to monitor operations on the large overview display from that seated position. However, this can only be confirmed through more detailed human factors assessments.

Ergonomic studies in other industrial environments have shown that standing-only work is unnecessarily strenuous for the duration of an eight-hour shift, and even worse for a twelve-hour shift, as is the practice in most U.S. control rooms where operators perform the majority of their tasks at the control boards. Because we now understand more about biomechanics, today's ergonomic standards are based upon more realistic assessments of how operators actually work at consoles. The latest ergonomic studies show that seated work is conducive to focus and concentration, but that periodic physical movement is important for alertness and situation awareness [6]. For this reason specific attention must be paid to the design of such workstations when they are upgraded.

While no change to the physical configuration of the control room has been included in the modernization strategy, significant functional, ergonomic and operator performance benefits might be offered by the implementation of advanced automation and HSI technologies.

## 7 CONCLUSIONS

Modern digital HSI technology has the potential to offer substantial benefits in improved operator performance and improved capabilities in managing the plant configuration, operational transitions, and plant events. However, these benefits cannot be assured without a well-designed end-state vision for the control room. This end-state vision must provide appropriate guidance to ensure that the future operating environment is technically sound from an engineering and human factors perspective.

Defining an end-state concept or vision for the desired control room and its associated HSIs will ensure that the final configuration meets all requirements and expectations for improved operator performance and operational efficiency. It will also ensure that the changes are accomplished in an orderly and efficient manner, and also conform to all relevant regulatory guidance for human factors and nuclear safety.

The three methodologies with accompanying tools described here were proven highly effective to design and validate options for progressing from knowledge of the scope of I&C upgrades to a coherent end-state concept for a modernized control room.

It was also shown that, in combination with an HFEPP, a well-designed end-state concept should serve as guidance to conduct advanced human factors studies to measure and verify the actual effects of new control room features on operator performance and plant operational effectiveness. It should also support the development of a business case framework to help describe and quantify the benefits of control room modernization.

The design reviews that formed part of the development of the end-state concept helped to confirm that all modifications must conform as far as practicable to human factors principles. This includes physical ergonomics (readability, viewing angles, reachability of new displays, and general operator comfort) as well as cognitive ergonomics (mental models, visual salience, visual complexity, information complexity and functional complexity). It also includes adhering to the basic principles of grouping, proximity, labeling, and association, i.e., keeping related components together.

An important result of the workshops was that the 3-D models could be used in conjunction with the PVNGS plant simulator in the HSSL. This allowed various types of visualization techniques to provide a greater understanding of the end-state concept. In particular, the three-dimensional visualizations allowed operators and engineers to determine the suitability of the design. Overall it proved to be a very useful tool to help participants orient themselves in the virtual control room and also to identify some ergonomic challenges that would not be apparent when viewing individual images of control boards. In addition, the use of anthropometrically correct operator mannequins in the 3-D models were useful to verify the range of human attributes (e.g., height, eye sight, reach, peripheral vision, etc.) that are important in validating the suitability of the operating environment to support effective and safe human performance. The expert assessments using 3-D models, coupled with empirical results from separate operator studies in the HSSL, have provided verification of the effectiveness of particular layout options.

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