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Light Water Reactor Sustainability Program

Developing a Human Factors Engineering Program Plan and End State Vision to Support Full Nuclear Power Plant Modernization

Jeffrey C. Joe, Lewis Hanes, and Casey Kovesdi

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EXECUTIVE SUMMARY

The Light Water Reactor Sustainability (LWRS) Program, which is sponsored by the United States (U.S.) Department of Energy (DOE), conducts research and development (R&D) to establish the technical bases to sustain U.S. nuclear assets. One area in the LWRS program is the Plant Modernization pathway, which includes human factors R&D, human factors engineering (HFE), and ergonomics. LWRS program researchers in this pathway conduct targeted R&D to address aging and reliability concerns with the legacy instrumentation and control (I&C) and related information systems in commercial nuclear power plants (NPPs).

One key activity for this pathway is to develop a strategy for full nuclear plant modernization, which previous LWRS plant modernization milestone reports have begun to describe. To further support this comprehensive plan and vision for full plant modernization, additional details need to be further developed. In particular, a core aspect of a strategy for full nuclear plant modernization is an HFE program plan and an end state vision for plant modernization that is well-integrated with both 1) a technically defensible approach to migrating the existing, mostly analog I&C infrastructure to a digital I&C infrastructure, and 2) a valid business case methodology to cost-justify the modernization activity.

Thus, the purpose of this LWRS R&D activity and milestone report is threefold. First, the report provides guidance for operating commercial NPPs to support their development and evaluation of an HFE program management plan (HFE PMP) and an end state vision for plant modernization. The report presents best practices and lessons learned related to HFE PMPs based on MCR modifications in which analog systems were replaced by digital I&C systems. Second, the report summarizes the rationale for full digital I&C integration, highlights a number of factors that are critical to consider, and describes how HFE should merge with full digital I&C integration. Finally, the report summarizes and integrates the economic factors that must be considered to cost-justify HFE involvement in plant modernization.

DISCLAIMER

This report is not meant to be comprehensive and does not provide complete guidance for preparing the overall human factors engineering program management plan (HFE PMP) and the end state vision. Rather, it provides lessons learned that should be considered and applied, when appropriate, as the HFE PMP is prepared. The descriptive information provided about end state visions should be helpful in preparing an end state vision. Other HFE design guidance documents (e.g., EPRI, 2015) and HFE review guides, such as NUREG-0711 (NRC, 2012), which intended to verify safe operation, are more comprehensive and should serve as the primary sources for HFE guidance in preparing the plant HFE PMP and end state vision. This report provides recent lessons learned that supplement guidance provided by these other sources.

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ACRONYMS

CAD	Computer Aided Design
CAP	Corrective Action Program
CAVE	Cave Automatic Virtual Environment
CCF	Common Cause Failure
COTS	Commercial-off-the-Shelf
DCRDR	Detailed Control Room Design Review
DCS	Digital Control System/Distributed Control System
DI&C	Digital Instrumentation and Controls
DOE	Department of Energy
EPRI	Electric Power Research Institute
HED	Human Engineering Discrepancy
HFE	Human Factors Engineering
HRA	Human Reliability Analysis
HSI	Human System Interface
HSSL	Human Systems Simulation Laboratory
I&C	Instrumentation and Controls
INL	Idaho National Laboratory
ISG	Interim Staff Guidance
ISV	Integrated System Validation
LAR	License Amendment Request
LWRS	Light Water Reactor Sustainability
MCR	Main Control Room
NEI	Nuclear Energy Institute
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
O&M	Operations and Maintenance Costs
OER	Operating Experience Review
PMP	Program Management Plan
PRA	Probabilistic Risk Assessment
R&D	Research and Development
SRP	Standard Review Plan
TCS	Turbine Control Systems

U.S.	United States
V&V	Verification and Validation
VR	Virtual Reality

Developing a Human Factors Engineering Program Plan and End State Vision to Support Full Nuclear Power Plant Modernization

1. INTRODUCTION AND OVERVIEW

In the United States (U.S.), commercial nuclear power plants (NPPs) generate approximately one-fifth of the affordable, abundant, and reliable baseload electricity that is essential to maintaining the nation's economy. Because other technologies that reduce reliance on fossil fuels and provide base load electricity cost-competitively at a national scale are still under development, many NPP owners and operators are evaluating the technical and economic issues with continuing to operate. The Light Water Reactor Sustainability (LWRS) Program, which is sponsored by the U.S. Department of Energy (DOE) Office of Nuclear Energy, conducts research and development (R&D) to establish the technical bases to sustain U.S. nuclear assets. One area in the LWRS program is the Plant Modernization pathway, which includes human factors R&D, human factors engineering (HFE), and ergonomics. LWRS program researchers in this pathway conduct targeted R&D to address aging and reliability concerns with the legacy instrumentation and control (I&C) and related information systems in commercial NPPs. The two primary goals of the Plant Modernization pathway are: (1) to ensure that legacy analog I&C systems are not life-limiting issues for the LWR fleet, and (2) to implement digital I&C technology in a manner that enables broad innovation and business improvement in the NPP operating model.

Within the Plant Modernization pathway, one key activity of this work is to develop a strategy for full nuclear plant modernization, which previous LWRS milestone reports (Thomas & Scarola, 2018) for this pathway have begun to describe. To further support this comprehensive plan and vision for full plant modernization, however, additional details need to be further developed. In particular, a core aspect of a strategy for full nuclear plant modernization is a well-developed and detailed HFE program plan and a clear end state vision for plant modernization that is well-integrated with both 1) a technically defensible approach to migrating the existing, mostly analog I&C infrastructure to a digital I&C infrastructure, and 2) a valid business case methodology to cost-justify the modernization activity (Figure 1).

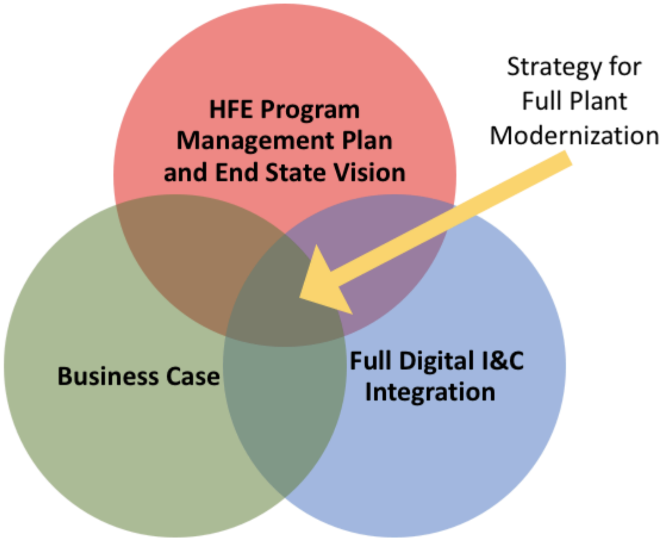

Figure 1. The integration of HFE to other key aspects of a strategy for full nuclear plant modernization

Thus, the purpose of this LWRS R&D activity and milestone report is threefold. First, the report provides guidance for operating commercial NPPs to support their development and evaluation of an HFE program management plan (HFE PMP) and an end state vision for plant modernization. The guidance is intended for use by NPPs planning to modernize main control rooms (MCRs) and associated facilities in which human performance and actions impact plant safety, and/or plant reliability, availability, power production, and economic and efficient operation. The report presents best practices and lessons learned related to HFE PMPs based on MCR modifications in which analog systems were replaced by digital I&C systems. Specifically, the HFE PMP content of this report includes lessons learned on control room modernization within the last five years.

Other sources include reports written by the Electric Power Research Institute (EPRI) (e.g., EPRI, 2015), provide detailed guidance for developing a complete HFE PMP and performing the many activities to implement the plan, including creating an end state vision (see Disclaimer in the frontmatter of this report). As such, guidance in this report is based on recent HFE activities performed in support of MCR digital I&C modernization projects at several operating plants, from HFE activities performed by LWRS program researchers located at Idaho National Laboratory (INL) in support of MCR upgrades, and supporting creation of end state visions for operating plants planning to modernize. In addition, information was obtained during discussions with several I&C and HFE experts who have been involved in digital system modernization activities, and from recent publications. Most of the guidance is based on recent plant modification projects involving I&C digital system modifications in which HFE was heavily involved.

Second, this report summarizes the rationale for full digital I&C integration, highlights a number of factors that are critical to consider, and describes how HFE merges with full digital I&C integration. Replacing the existing I&C infrastructure, which for many plants is mostly analog I&C combined with a handful of legacy digital I&C systems that are separately maintained and supported by different vendors is a challenging aspect of full plant modernization. Along with finding spare parts for all of these legacy systems, a concern about common cause failures (CCFs) in digital I&C systems has led plants to defer significant control room upgrades.

However, there are many benefits to full plant digital I&C integration with respect to costs and long-term aging and obsolescence, and when full plant digital I&C integration is done well, especially in conjunction with HFE best practices and principles, the concerns about CCFs can be effectively mitigated. This report describes an approach that can be taken that can provide all of the expected enhancements and eliminate the CCF concerns, and then describes how the inclusion of HFE considerations with this approach is essential to its success.

Finally, the report summarizes and integrates the economic factors that must be considered to cost-justify HFE involvement in plant modernization. Previous cost-benefit analyses using an established and credible business case methodology (Thomas, Lawrie, Vlahapolis, & Hart, 2014; Adolfson, Thomas, & Joe, 2017) have been performed to cost-justify control room modernization and the inclusion of HFE in full plant modernization. For example, this methodology can be used to estimate the time saved in workload reductions using new digital technologies supported by full plant modernization. Other cost/benefits can be demonstrated with the methodology showing how integrating HFE into other plant modernization activities can lead to reductions in plant Corrective Action Program (CAP) costs, reduced outage time (Thomas, Lawrie, & Niedermuller, 2016), and reduced need for technical support.

The remainder of this report includes background on HFE, HFE PMP best practices and lessons learned, and a discussion on developing an end state vision. Finally, descriptions of full digital I&C integration and establishing a business case are then presented, followed by a conclusion and references.

2. HFE BACKGROUND

2.1 Importance of HFE During Modernization

NPP personnel play a vital role in the productive, efficient, and safe generation of electric power. Operators monitor and control the plant to ensure it is functioning properly and meeting safety and power production goals. Personnel performance and resulting plant performance are influenced by many aspects of plant design, including the level of automation and the human-system interfaces (HSIs) provided for operators to interact with the plant. The HSIs include alarms, displays, and controls that are located in the MCR and other control stations situated throughout the plant. HSIs are also located in support facilities such as the technical support center.

Many NPPs are modernizing plant I&C by replacing analog systems with digital systems that permit changes to interfaces used by control room operators, maintenance personnel, and others. There are many reasons for modernization, including:

- Addressing obsolescence and lack of spare parts for analog controls
- Meeting the need for equipment replacement due to high maintenance cost or lack of vendor support for existing equipment
- Implementing new functionality necessary for adding desirable capabilities (e.g., automation and display of integrated information)
- Improving plant performance, HSI functionality, and reliability by reducing human error and inefficient actions
- Enhancing operator performance and reliability by providing capabilities not available with analog systems (e.g., graphical representations of information on digital HSIs, and automating difficult operator manual control tasks)

These modifications can affect personnel in various ways. They can impact the role of personnel, the functions and tasks to be performed, and the way tasks are performed (i.e., affect concept of operations). As part of modernization, HSIs are becoming more computer-based, incorporating features such as graphic presentation of information, and providing additional information by navigating to other sources within the computer system.

The potential benefits of modernization are compelling and should result in more efficient operations and maintenance, leading to improved power plant availability and safety through the avoidance of transients, forced outages, equipment damage and unnecessary shutdowns. The potential benefits also include increased efficiency and power output as well as reduced operating costs.

New digital I&C systems provide the opportunity to give personnel information they did not have with conventional analog systems. Improved instrumentation and signal validation techniques can help ensure that the information is more accurate, precise, and reliable. In addition, data processing techniques and the flexibility of computer-based information presentation enable the display of information in ways that are much better suited to personnel tasks and information processing needs to achieve more efficient and cost-effective power production. Operators should realize improved situation awareness and reduced cognitive and physical workloads.

While plant modernization can improve personnel and plant performance, it is important to recognize that, if poorly designed and implemented, there is the potential to negatively impact performance, increase errors, and reduce human reliability resulting in a detrimental effect on safety and cost-effective power production. HFE knowledge is needed to be applied together with other stakeholder knowledge to ensure that the benefits of the new technology are realized and problems with its design and implementation are minimized.

2.2 MCR Modifications May Involve Stepwise Evolution

Modification projects may be considered as a stepwise evolution from a conventional analog MCR through a hybrid configuration, where the MCR is equipped with both analog and digital systems, and for some plants, eventually to a fully-digitalized control room. Some plants may decide that the final end state vision for the modification will be a hybrid MCR. One or more refueling cycles or other outages may be required to reach the final end state design for plants. Plants want to operate to the fullest extent possible, and try to implement modifications during refueling outages. It is possible that some plants will decide to install a fully-digitized control room during one outage.

Most of the digital system upgrades included in modifications will involve at a minimum new digital HSIs, alarm systems, probably soft controls, and some function and task automation. In addition, the modification end or intermediate state vision may involve changes to the physical design of the MCR. For example, controls at the boards currently require operators to stand to perform their tasks. This may be replaced with sit down consoles containing HSIs (e.g., workstations), which may result in more compact workplaces.

One or more intermediate end state visions may be created during a modernization project. A plant may determine that upgrades will occur in stages rather than just one outage during which all changes would be made. The plant could decide to create one end state vision that represents the final MCR design following completion of the modernization project. Or the plant could decide to prepare intermediate end state visions for each of the major upgrade stages.

For many plants, the better strategy may be to develop end state visions for each major upgrade stage. A reason is that a plant may need to change its upgrade plans. For example, the budget available for a modification may change, thereby impacting the digital systems and equipment that can be installed. New technologies may become available with capabilities that the plant decides are more desirable than provided by the original end state vision, or equipment planned for the modification may become unavailable.

2.3 Likely Increase in Number of Plant Modifications

For several reasons, it is possible that in the near future more plants will decide to modernize by using digital I&C systems. First, nearly all U. S. nuclear utilities have extended their reactor operating lifetimes to 60 years, and some are beginning to seek 80-year operating licenses. The need to upgrade plant analog I&C systems to digital is growing in importance because of analog parts aging, becoming obsolete, and no parts or replacements being available.

Second, the U.S. Nuclear Regulatory Commission (NRC) recently released a draft of an interim staff guidance (ISG) document (NRC, 2018) for public review that defines the licensing process used to support the review of License Amendment Requests (LARs) associated with safety-related digital instrumentation and control (DI&C) equipment modifications in operating plants. In a recent press release, the Nuclear Energy Institute (NEI) (NEI, 2018) noted that DI&C-ISG-06 (NRC, 2018), if approved, should simplify LAR submissions for digital systems that are part of safety-system upgrades. In the past, most modification efforts involving digital systems were performed under 10 CFR 50.59, which permits plants to implement digital systems for non-safety-related modifications without NRC prior approval. Some examples of non-safety systems upgraded include feedwater control systems, recirculation control systems, demineralizer control systems, and main turbine control systems. It has been expensive and time-consuming to obtain regulatory approval for digital systems to replace safety-related analog systems under the LAR process. Therefore, few LARs have been submitted for this kind of modernization. Submissions may increase if DI&C-ISG-06 (NRC, 2018) is approved because of the simpler LAR process.

The draft ISG discusses proposed use of the equipment including HFE considerations. For example, some DI&C equipment modifications may credit manual operator actions and require HFE considerations (e.g., HFE analyses and design processes). In these cases, an HFE safety evaluation should be performed in accordance with Standard Review Plan (SRP) Chapter 18 (NRC, 2016b), with close coordination within an I&C evaluation under SRP Chapter 7 (NRC, 2016a).

Third, there may be safety and economic benefits during the plant life cycle attributable to digital system upgrades. Each plant will need to determine if the benefits of the modification are greater than the costs incurred (e.g., regulatory licensing effort, systems and equipment cost, plant down-time with lost power generation attributable to the modification, and the addition of personnel added with digital skills including digital maintenance).

Fourth, digital I&C systems and HSIs are more flexible and easier to modify than with analog, so changes to these systems can be expected to be more frequent. Improvements may be possible as experience is gained in operation of the new systems. It is also likely that digital systems will become obsolete more quickly than the older analog systems, and so modifications (system replacements or updates) may be required more frequently.

2.4 Guidance for HFE Participation in Modernization Activities

The U.S. NRC Human Factors Engineering Program Review Model, NUREG-0711 Rev. 3, (NRC, 2012) has been used by some plants as a source of guidance for HFE involvement in plant MCR changes. NUREG-0711 is widely available; plant and HFE personnel are aware of its existence, and in many cases have applied it. If the modification requires a LAR and human performance is a factor in the modification, then the HFE part of the LAR will require review and evaluation by NRC HFE staff. The NRC staff will use NUREG-0711 as the basis for the review of the submittal. In addition, if a plant determines that the modification does not involve safety-related equipment or other changes affecting safety, the plant may perform the modification under 10 CFR 50.59. Records documenting the modification process must be maintained and may be reviewed by the NRC HFE staff, which will again apply NUREG-0711 as their HFE program review model.

A problem for a plant using NUREG-0711 is that it is intended to be used to review safety concerns. It is not intended to be a design guide, and does not consider the design process or plant availability, power production, and efficient operation. Other documents, such as those developed by INL (Boring, Ulrich, Joe, & Lew, 2015) and EPRI (EPRI, 2015), provide design guidance for modifications and address both safety and efficient operations and maintenance, leading to improved power plant availability.

3. HFE PROGRAM MANAGEMENT PLAN

The objective of an HFE PMP is to provide guidance to help ensure that a plant's modernization efforts impacting MCRs, related facilities, and HSIs satisfy regulatory requirements and expectations regarding HFE, and to ensure safe and reliable plant operation meeting human performance expectations as plant modifications are made over time.

An HFE PMP provides guidance for a plant to create an HFE design team with the responsibility, authority, placement within the organization, and composition to reasonably assure that the plant design meets the commitment to HFE guidelines. Further, an HFE PMP should guide the team to ensure that the HFE program is properly developed, executed, overseen, and documented. The HFE PMP describes the HFE activities (identified as elements in NUREG-0711) to ensure that HFE principles are applied to the design, development, and evaluation of HSIs, procedures, and training.

It is important during HFE PMP preparation to apply a graded approach. A graded approach determines which activities (elements), if any, can be omitted in the HFE PMP. For example, if there is no change in human reliability or risk associated with human actions, then the element in NUREG-0711 called the "Treatment of Important Human Actions," element can be omitted.

Within activities it may be possible to ignore select operator actions not impacted by the modification. Functions and tasks may not be part of the HFE study, if they are not involved or affected by the modification. For example, if only one digital HSI is to be installed for use with one analog system that is being replaced, then the graded approach would identify only those parts of the MCR affected by this modification for inclusion in the HFE effort. This might include change in level of automation with the new system, changed operator functions and tasks associated with the new HSI and system, the new HSI and other displays presenting system information that may need to be acted on, alarms associated with the new HSI or system, soft controls that may be provided with the new HSI, and changes in procedures and training. Other unaffected MCR functions and tasks would not be included in the HFE efforts. Additional guidance for application of a graded approach can be found in an EPRI HFE technical report (EPRI, 2015).

This report does not provide detailed information to support developing an HFE PMP. This is not the objective or in the scope of this report. Rather, the purpose is to demonstrate to NPP utility owners and operators that developing an HFE PMP is important, and adds value to the plant modernization activities they undertake. Other sources, such as in Sections 2.5.3.5 and 3.2.3 of an EPRI report (EPRI, 2015), provide guidance for developing an HFE PMP considering both safety and plant availability, power production, and economic operation issues. NUREG-0711 (NRC, 2012) in Section 2 also provides guidance in preparing an HFE plan although only providing guidance for safety reviews.

3.1 HFE PMP Best Practices and Lessons Learned

This section presents best practices and lessons learned for developing an HFE PMP. The best practices and lessons learned relate to preparation and level of detail of the HFE PMP, coordination with other stakeholders, and a few examples of studies conducted as components of an HFE PMP are performed.

Figure 2 is provided to help understand the context for the lessons learned. The figure shows how the 12 activities (elements) typically found in both HFE guidance documents concerned with safety and plant power production (e.g., EPRI, 2015) and safety (e.g., NRC, 2012) can be mapped onto the typical phases of a plant modification process (the top row of Figure 2). Some plants may use different terminology than shown in the figure, but the modification process and activities involved are similar.

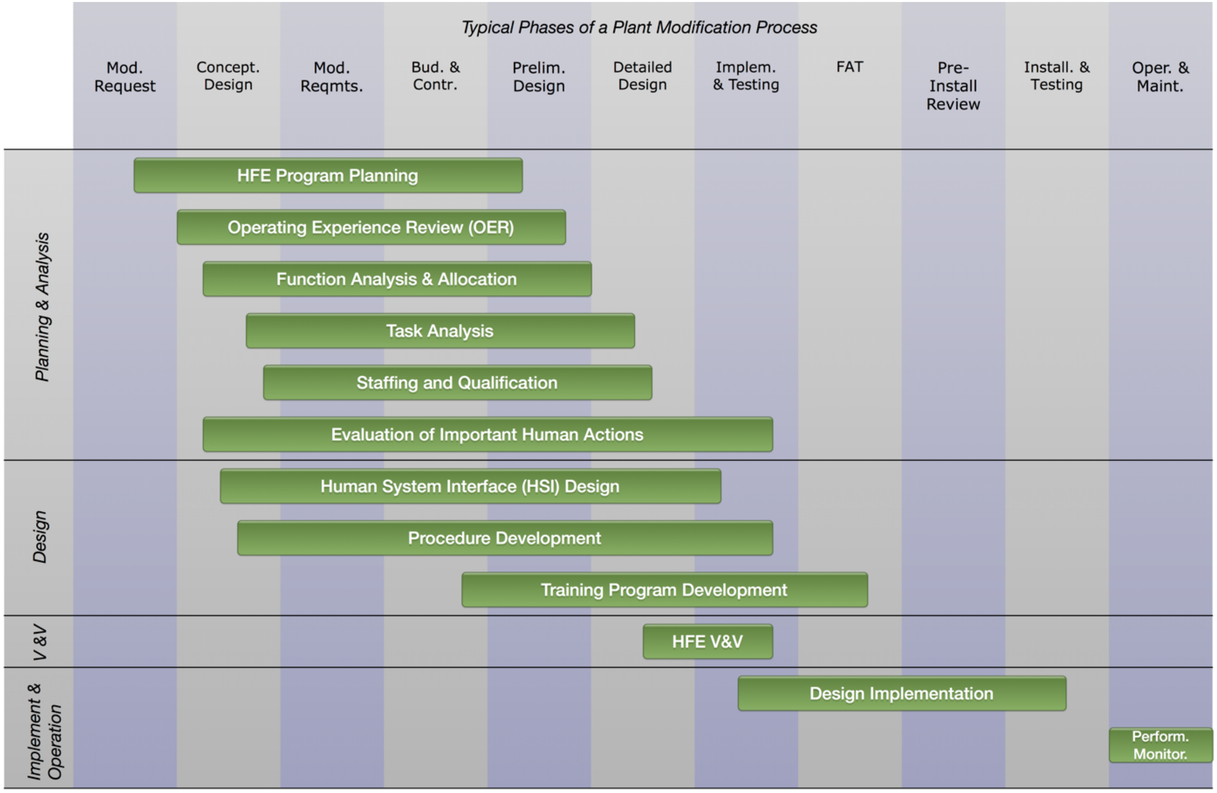

Figure 2. Example of how 12 HFE activities (elements) map onto the typical phases of a plant modification process

Although the columns for the modification process phases are all shown of equal width in Figure 2, this is not to imply they are of equal duration. The diagram is not intended to represent a timeline but simply the sequence of the phases and the overlap of HFE activities.

The point at which each HFE activity (element) starts and stops can vary depending on the modification. There likely will be some iterations as the modification process continues and detailed designs are developed and tested. Sometimes this can lead to changes to previously completed HFE activities. For example, if during testing and Verification and Validation (V&V) it is found that a particular task is more difficult and error-prone than originally anticipated, a decision may be made to automate that task, requiring a change to the initial function allocation, task analyses, procedures, training, etc.

HFE activities also may take advantage of information developed in previous phases of the modification. For example, although the Operating Experience Review (OER) may begin during the conceptual design phase (see Figure 2), this activity should take advantage of any OE that was identified earlier during the modification request phase.

3.2 HFE Should be Involved Early During the Modification Request Phase

Some plant organizations, such as the I&C group, may take the lead in the modification request phase to determine if a modification is needed, and if the decision is yes, prepare a proposal for a modification project (see Figure 2). Human factors engineers should participate during the modification request stage, if it is determined that HFE will be impacted by the modification. HFE should perform analyses and studies to provide information that may contribute to the modification request. This information may also be useful in later phases of the modernization process.

For example, HFE review of plant and similar plant OE at the beginning stage of the modernization process may show that human error with the system being considered for upgrade caused safety problems and/or outages resulting in lost revenue, or equipment damage requiring costly replacement. Human errors may have caused the turbine or reactor to trip, resulting in lost power production and other associated costs. Performing an OER early in the process may provide financial and other information to help justify the proposed modification.

At one plant, questions arose during the modification request phase (Figure 2) about the automation capabilities that should be provided by the new system. Operators from several plants that were expected to be modernized (all owned by one utility), plant and corporate I&C engineers, plant system engineers, a human factors engineer, and an engineer from a supplier familiar with new digital I&C systems being considered as a replacement, participated in a meeting lasting several days. This meeting was organized and conducted by the human factors engineer. The operators identified about 90 manual scenarios and associated tasks that were required by the system being considered for replacement. The operators discussed and prioritized these 90 tasks with regard to those most prone to human error, difficult to perform, and ones the operators preferred be automated, if possible. There was discussion by meeting attendees of the expected safety and plant availability benefits, if the requested automation capabilities were provided. The results of the meeting consisted of a prioritized list of current manual tasks that should be automated, if possible.

The information collected during this meeting and subsequent analyses provided input used to prepare the modification request and applied to system conceptual design, modification requirements and procurement specifications for the digital replacement system.

One lesson learned from the example described above is that HFE involvement early in the modernization process is desirable. Human factors engineers can help identify safety issues and economic benefits of the proposed modification based on an OER, as well as provide guidance in capabilities that should be included in the system recommended by operators and other stakeholders. This information could be included in procurement specifications and applied during subsequent phases of the modernization process.

In addition, active participation by human factors engineers could help make other stakeholders including management aware that HFE can provide valuable support to the modernization process.

3.3 Level of Detail in HFE PMP and its Application

An HFE PMP should be written at a general level when first created, and revised to be more plant-specific as information becomes available and the modernization project moves forward. The initial HFE PMP should be created during the preparation of the modification request (see Figure 2 and Section 3.2). The PMP may be needed to help justify HFE participation in the modernization project, and to obtain funding for the HFE activities.

A lesson learned at two plants is that two HFE PMP versions may need to be prepared. One version may need to be a summary of the HFE PMP to obtain management support for HFE participation and obtain funding (modification request or conceptual design in Figure 2). For example, a detailed HFE PMP was prepared for a plant involved in a LAR. HFE had not been part of the initial modification process, and the plant had not had expert HFE involvement since its Detailed Control Room Design Review (DCRDR) following the accident at the Three Mile Island plant. The detailed plan consisting of more than 10 pages was submitted to a senior plant manager for his approval of the HFE activities and the requested funding. He asked that a two-page summary be prepared for his review. This was done, and the plan and funding were approved.

Another example of the need for a summary of the HFE PMP occurred at a plant that was at the modification request phase (see Figure 2). The senior manager responsible for approving HFE participation in and funding of this effort requested that a Power Point summary of the plan be presented to him, his staff, and other stakeholders in a 45-minute meeting with at least 20 minutes reserved for discussions. The presentation consisted of a summary of a detailed HFE PMP that had been prepared. As with the first example described above, the plan and funding were approved.

A detailed HFE PMP needs to be prepared in addition to a summary. The detailed plan identifies the activities that need to be performed and how to perform them, to the level of detail possible at that stage of the modernization process.

The summary or detailed plan should be used during discussions with other stakeholders (e.g., I&C, operations and operators, systems engineers) regarding the HFE role and activities during the modification process. The plan used for the discussions should be based on the appropriate level of detail for the discussion. At one plant, the detailed plan was used as the basis for discussions with the responsible engineer for the Engineering Changes for equipment requiring extensive operator actions. The summary plan was used at the same plant for discussions with the plant probabilistic risk assessment (PRA)/ human reliability analysis (HRA) expert regarding risk of human actions associated with the modification.

3.4 Reuse of Previous HFE PMP and Other HFE Documents

Another best practice is to research whether any HFE PMPs and other useful documents are available from a previous modification at the plant or from a similar plant owned by the same utility. For example, an HFE PMP may have been prepared for a previous modification at the plant. At that time, it may have been decided to limit the scope of the upgrade. The plan was only concerned with the original modification and did not consider additional modifications. The previous plan and other information should be reviewed and modified as applicable to support preparation of the HFE PMP for the current modification.

Other documents may also be available that will help with preparing the HFE PMP or performing some of the HFE activities identified in the plan. For example, one plant had a document entitled, "*Human Factors Design Conventions for the Control Room Specification and Criteria*." This document was prepared following the DCRDR, and included a style guide section that provided guidance for symbols, colors, nomenclature, etc., for use with the analog instruments still on the current control board. The planned I&C digital system modification may result in a hybrid control room containing some of these same analog instruments. The information in this "old" document proved to be useful in preparing a revised style guide containing guidance for the analog instruments remaining on the hybrid control board following the modification.

The lesson learned is that it is important to identify available documents to help prepare the HFE PMP. This may speed up preparing the new plan, and possibly provide guidance that might be difficult to recreate (e.g., style guide guidance for analog instruments remaining on hybrid control board).

3.5 HFE Should be Involved During the Conceptual Design Phase

Another best practice in developing an HFE PMP is to have HFE involvement early in the design phase of the upgrade. Early HFE participation in several digital I&C modification projects has proven beneficial in supporting initial HSI design decisions and possibly eliminating or reducing costly changes in design later in the modification process.

For example, in one project the human factors engineers organized and conducted a study to help determine the number of HSIs needed and their location on the control board with the new digital system that was expected to be acquired and installed. The study consisted of several parts, and participants included operators, I&C engineers, and HFE. Study participants identified a location on the control board where one or more HSI (the number had not been determined at that time) could be located. A wooden and photographic mockup of that part of the control board where the HSI(s) likely would be placed was constructed (Figure 3). Cutouts were made in the mockups, and two HSIs were mounted so that only their display surfaces could be seen. Demanding events and operator tasks with the new digital system were identified by the operators and I&C engineers.

Figure 3. Photograph of mockup used to evaluate number and location of HSIs

Static display screens were created for the tasks. Operators and the human factors engineer relied on a limited style guide, existing plant control board conventions, HFE display design guidelines, and operator preferences to design display screens for the events and tasks that had been selected. An operator could page through the display screens using a control, as required by the task. The operator could not change the content or activate anything on a given screen.

Procedures were developed for the events involving the operator tasks. Tests were performed during which operators walked through the scenario following the procedures and operating a control to change screens, as required by the event. Several HFE observers evaluated the use of the displays during the walkthroughs. Operators were interviewed regarding their observations and asked for their recommendations. The results of this study included a finding that two HSIs should be provided, and the HSIs should be mounted very near each other.

The results of the study, the preliminary style guide, and the displays used in the testing were provided for use in the procurement specification. Also, the same information was provided for use in subsequent phases of the modification process. Although further HFE studies and plant technical requirements resulted in some changes in the final control board and other designs, this initial work provided a solid foundation for the final design.

3.6 Conflicts Between HFE and Other Stakeholder Recommendations

It is common during the modification process that conflicts develop between HFE recommendations and the recommendations of other stakeholders. Resolving these conflicts is sometimes difficult. Some lessons learned on methods to help resolve these differences are presented below. Examples are used to identify a few of the conflicts found during completed digital system modernization projects, and how they were resolved.

3.6.1 Location of HSIs on control board

It was determined through task analysis that two HSIs were needed for operators to perform required tasks with a new digital control system. Human factors engineers and operators identified the preferred location on the existing control board where the HSIs should be located by performing static walkthroughs with mockup HSIs placed at various locations on the board and considering HFE guidelines. It was also recommended that the HSI display surfaces be mounted flush with the existing control board.

The stakeholder responsible for the control board (i.e., an architect-engineer) recommended a different location, and that the HSIs be mounted on the front surface of the control board rather than flush. His argument was that the recommended HFE placement and flush mounting would require cutting holes in the control board and moving structural supports and wiring cables behind the control board. The required changes in support behind the board and the cuts in the control board would result in the need for seismic requalification of the control board. This would be expensive and time consuming, and lengthen the modernization schedule.

HFE used operator walkthroughs and found that the HSI locations recommended by the control board stakeholder would require extra operator movement patterns to perform the important system tasks, and visibility problems would result because an operator working at one HSI would find it difficult to obtain information needed on the other HSI. These concerns, HFE guidelines, and strong operator opinions resulted in the person responsible for this part of the modification directing the control board stakeholder to investigate other options for the HSIs that would satisfy the HFE location recommendation.

The control board stakeholder subsequently searched for and found thin HSIs and mounting brackets that could be mounted on the surface of the control board eliminating the need for changing support and wiring behind the board and cutting holes in the board. Dimensions of the HSI were obtained and HFE prepared cardboard mockups of the HSIs. These mockups were pasted on the control board. It was found that the mockups extended several inches in front of the control board. Operators performed static walkthroughs with the mockups. It was found that when an operator was performing tasks on one side of an HSI mockup he could not see displays located on the other side of the mockup. Operators said this design was unacceptable, and HFE guidelines said all of the needed information should be viewable. The control board stakeholder was asked to search again for an even thinner mounting bracket and HSI. He was able to identify a bracket-HSI unit that was very thin and did not interfere with operator performance of tasks or viewability.

The lesson learned from this example is for human factors engineers not to accept what appear to be reasonable arguments for not accepting an HFE recommendation. Operator opinions and performance in walkthroughs, along with HFE guidelines were sufficient evidence in this case to require the control board stakeholder to investigate alternative methods to satisfy the HFE recommendation. Although the final solution did not satisfy the recommendation completely (to recess the HSIs), the thin mounting was found acceptable. Importantly, it was possible to locate the two HSIs in the recommended locations.

3.6.2 Automation of difficult operator tasks

In one modernization project involving the replacement of an analog Turbine Control System (TCS) with a digital system, a challenging manual operator task during turbine roll up was identified. The operators reported synching the turbine to the grid was difficult with the analog TCS and recommended the task be automated with the digital system. The operators were aware that the TCS being installed at their plant was capable of providing automated grid synching, but the modernization plan at their plant did not include automated synching. The reason for the exclusion was that the sensors and communication capabilities necessary to permit automated turbine synching to the grid were not available or included in the modernization project, and it would be difficult and expensive to provide automation of this task during that particular modernization cycle.

During detailed design (Figure 2) operators performed automated turbine roll up with manual grid synching using a dynamic simulator that had an accurate representation of turbine roll up and synching to the grid. Human factors engineers observed the scenario as the manual synching task was performed, and noted this although this task was difficult to perform, no human errors were observed, and the task was performed in a timely manner. Operators commented that they could perform the task, but it was one of the hardest tasks associated with operating the analog TCS.

A human factors engineer conducted an OER to identify incidents in which this task was not performed correctly causing a turbine trip or other undesirable outcome; no event was found. The operators were interviewed, and it was determined that they had never experienced any human errors or other problems in performing this task. Discussion with HRA personnel did not show human error in this task resulting in any change in safety risk. Even though operators preferred this task be automated, human factors engineers could not find other evidence to make automation of this task an HFE recommendation. As a result, the recommendation was to include this automation task in a future modernization project.

The lesson learned from this example is that HFE should identify and conduct evaluations of all applicable sources to determine recommendations. Even though strong operator preferences are very important sometimes it is necessary to examine other sources to determine if safety, economic issues, and HFE guidelines justify a recommendation. In this example, the answer was “No” except for the recommendation to include automation of synching the turbine to the grid task in a future modification.

3.7 Challenges in the Use of Commercial Off-the-Shelf Equipment and Systems

Major system modifications using a Digital Control System (DCS), for example, will involve use of commercial of-the-shelf (COTS) hardware and software products that may be limited regarding how much customization can be done from a practical standpoint, considering cost and schedule. Unless the customization is simple, it is likely that it will be expensive and time consuming to make these changes, and may not be supported by the COTS vendor when they update the hardware and software components of their product.

The plant may decide to obtain an estimate from the vendor of the cost and delay in delivery for making the requested changes to COTS system or equipment. Of course, the plant may also request a proposal from another vendor whose COTS system and equipment provides more, or all of the capabilities desired.

Stakeholders (e.g., I&C engineering) may determine COTS equipment with certain capabilities should be purchased for the modification. Even though the COTS products may not satisfy some HFE concerns, the cost, availability, compatibility with other existing or planned plant equipment and systems, etc., may be compelling reasons to obtain this COTS system. In this case, HFE would need to provide strong evidence that the COTS system is not acceptable.

A lesson learned is that HFE should help evaluate supplier proposals for COTS products, and help determine if HFE guidelines or operator performance may be adversely affected by the COTS product design or operation. If potential problems are identified, they should be brought to the attention of involved stakeholders, and the problems resolved. One action that HFE could take is to perform an OER to determine if other plants have experienced serious human errors caused by COTS system design or operation. In addition, simulator walkthroughs could be used to help determine if human errors would be likely with the COTS design and operation.

3.8 Multi-Stage Evaluation and Testing, Verification and Validation

It is desirable to perform tests and evaluations throughout the modernization process rather than primarily relying on extensive evaluation during the V&V activity (element) such as at Integrated System Validation (ISV). ISV 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 supports the plant's safe operation and power generation goals.

A problem with waiting to very near the completion of the modification process is that HFE Human Engineering Discrepancies (HEDs) may be difficult and expensive to correct at that time. For example, if it is determined during ISV that a task designed to be performed automatically is found to require manual operator actions, this may impact significant parts of the modification design. In this example, the HSI may need to be revised, the software providing automation may need to be changed, procedures and training may need revisions, etc. It would be much better to identify the HED when performing the task analysis or designing the HSI (Figure 2). Testing using a dynamic simulator with simulation software representing the new system during HSI design would likely identify the problem with automation of this task. This HED would therefore be resolved at that time, and the cost and schedule delay should be less than if this problem were discovered during ISV.

Another example might be the location of HSIs on the control board. Mockups and static or dynamic simulations were used in several plants during preliminary and detailed design (Figure 2) to help determine the number and location of HSIs on the control board. Operator preferences, analysis of operator movements as tasks were performed, HFE guidelines regarding visibility and reach limits, location of HSI controls, etc., were applied to determine recommended HSI control board placements. Problems were identified and resolved regarding HSI placement. In the ISVs performed in the last few years by LWRS program researchers, no placement HEDs have been noted.

Another example involved evaluation of the design of display content shown on the HSIs. The concern was design of symbols, use of colors, display element organization, density of elements shown on display screen, nomenclature, etc. A contractor responsible for developing the HSI display content participated in the HSI design activity and interacted with operators, human factors engineers, and a person from the I&C vendor providing the DCS. The style guide prepared by the HFE team was provided. The contractor, who had a good understanding of the HSI display design requirements, created sample displays. A challenge was that he needed to use the default DCS library established by the vendor to support display designs.

Operators, human factors engineers, and the contractor reviewed each design in detail first during preliminary design, and then the revised designs during detailed design analyses (e.g., HSI design activity shown in Figure 2). HFE guidelines, the style guide, operator recommendations, and the DCS library were applied to finalize the display designs. The evaluation process described in this example may be considered as early HFE design verification. HFE design verification is part of V&V. The final HSI display designs were used during the system ISV. The process described in this example was applied at three plants. No significant HEDs were identified related to display design during the three ISVs.

Testing and evaluations were performed throughout the modification process at the three plants. Problems were identified during these tests and evaluations and resolved before moving on to subsequent phases. The result was that almost no significant HEDs were identified during ISV. Figure 4 shows one HSI graphic developed during this project.

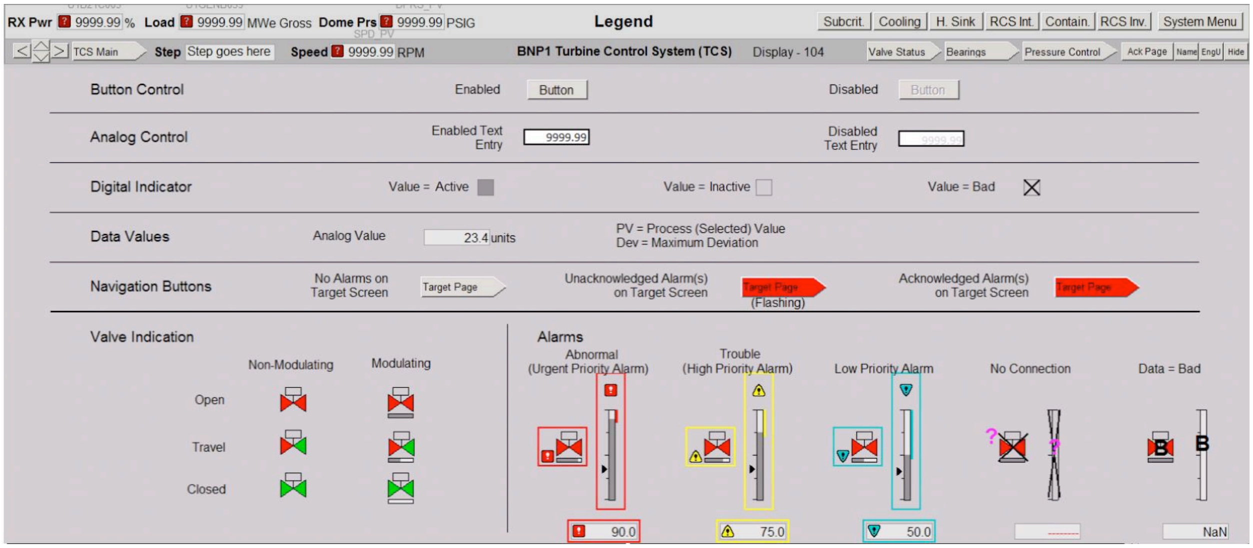

Figure 4. One display screen graphic developed following the process described in the example

The HFE lesson learned is that testing and evaluation of the design, operation, and other factors should be performed as part of performing each HFE activity (element). The HED identified can be corrected following the tests and evaluations, and the impact on other parts of the modification process minimized. An alternative is to delay most of the testing and evaluation to the ISV. The problem with this approach is that it may be expensive to correct the HEDs, and there may be a schedule delay. Rework and redesign should be less with the approach described in this example. This approach may be called multi-stage testing and evaluation or something similar.

3.9 Importance of Simulation to Support HFE Efforts

Recent digital system modernization projects have used simulation to provide information that has been vital to HFE work during the modernization process. The simulation tools have helped develop quantitative and qualitative evidence used to help justify HFE recommendations.

There are numerous technologies used to provide simulation capabilities. These technologies include partial (e.g., part-task) and full-scale control board and workstation mockups, plant training simulators, glass-top and other simulators, personal computers, rapid display prototyping software, etc. The technologies provide static and dynamic simulation capabilities, depending on their design.

The simulation technologies are used to support many HFE studies, such as evaluating proposed and alternative designs and design layouts, supporting task analyses (e.g., manual versus automated), measuring operator performance, identifying human errors and confusion, assessing operator situation awareness and cognitive and physical workload, supporting ISV evaluations, etc. Examples of the use of some simulation technologies are presented in lessons learned Sections 3.5, 3.5.2, 3.6.1, and 3.8.

Simulation is not always required to support HFE in developing a recommendation. Sometimes HFE guidelines provide an incontrovertible basis for a recommendation. For example, HFE guidelines are available regarding the acceptable height placement of HSIs requiring operator use of a control device on a control board. The guidelines provide maximum and minimum heights to permit acceptable operator reach. If the HSIs can be located in the acceptable height range, then there likely will be no controversy about placement and no simulation is required. If a stakeholder, however, has a compelling reason that one HSI should be located higher than provided by the HFE guideline, then a mockup may be required and walkthroughs with operators performed to help resolve the placement issue.

The selection of available simulation devices is evolving. Several years ago, mockups such as shown in Figure 3 were constructed early in the modernization process to help answer control board layout and other questions. Although these mockups worked well to support HFE studies, they may be somewhat expensive and take time to construct. There may be available today alternative devices to consider. A mockup, however, may be the best solution to support some HFE studies.

A training simulator may be needed for certain HFE evaluations. At many plants, however, access to a training simulator is limited due to high usage. An example of use of a training simulator for a limited HFE study follows. Figure 5 shows a photograph of paper representations of analog instrument displays expected to be used as part of the modification. These paper representations were pasted on a training simulator control board. Operators walked through scenarios with paper prototypes of the new equipment and instruments. Operators could request that the paper displays be moved if they believed a different arrangement would result in better performance. HFE guidelines applicable to layout were applied also. Two HFE observers evaluated the operator movement patterns and their comments during the scenario walkthroughs, and operators were asked for their display layout recommendations at the completion of each scenario trial. The results provided the basis for the control board layout. Other simulation devices could have been used, but they were not available at this plant.

Figure 5. Photograph of paper representations of proposed display locations pasted on training simulator

Other simulation devices are available that would facilitate performing many HFE studies. For example, if the plant has access to a glass-top simulator (see Figure 6 below), one bay of a glass-top simulator or equivalent showing only part of a control board, or an engineering simulator, then it becomes possible to readily present different control board arrangements. Also, it should be possible to move HSIs or other displays to other locations on the board quickly and easily, and redesign displays with rapid prototyping software. If the simulation device contained appropriate software (e.g., training simulator software) it might be possible to provide operators with dynamic simulation, if required by the HFE study.

A glass-top simulator (Figure 6) is a tool for performing static and dynamic simulations and may be used whenever appropriate during the modification process. Glass-top simulators have been used successfully at three plants in supporting tests and evaluations involving task analysis, HSI design and ISV. The tests and evaluations were performed in support of digital I&C system modernization projects.

This type of simulator provides a unique capability to simulate in a realistic fashion the current control board configuration and operation, as well as new control board configurations that will result from planned modifications. The simulator can run plant-specific dynamic models that provide realistic behaviors during test scenarios. The simulation capability and control board design flexibility permit asking and evaluating "what-if" questions. For example, how would the operator's tasks change if a task were performed automatically compared to being performed manually? I&C engineers, for example, and operators may have competing suggestions for displays to be provided to the operators during this operation. The glass-top simulation and display capability can permit these types of design alternatives to be simulated and evaluated with a realistic representation of the control board, allowing comparisons of human performance and operator opinions with the different displays. Some plants are acquiring glass-top simulators, similar to the one in the human systems simulation laboratory (HSSL) at INL shown in Figure 6, to support HFE R&D, engineering, and other studies, and support operator training and testing.

Figure 6. Photograph of glass-top simulator located in the HSSL at INL

The HSSL glass-top simulator does not provide an exact representation of any plant's physical control board dimensions or layout (e.g., angles between control boards may differ, and the position of the Senior Reactor Operator and other workstations away from the control boards are not always dimensionally correct with respect to the reference MCR). As a result, operator viewing and reach distances are somewhat different than in the plant. Therefore, HFE studies concerned with viewing, reach distances, etc., should be performed using the plant training simulator or a dimensionally correct mockup.

Some plants, if they acquire glass-top or similar simulators, may replicate the control board and control room configuration, especially if they plan to use the simulator for training purposes.

The HFE lesson learned regarding simulation is that it is a powerful tool that needs to be applied throughout the modernization process. It is important to select the simulation device that best meets the needs of the HFE study. Consideration should be given to whether static or dynamic simulation is needed for the HFE study, or if simulation is even required.

Simulation technology is advancing rapidly, so HFE personnel should maintain awareness of new simulation capabilities that become available, and select the most cost-effective method that meets the simulation needs for a given HFE study.

4. END STATE VISION DEVELOPMENT

This section provides a description of end state visions, and tools that may be used to help create graphical representations of MCR end state vision designs.

4.1 Description of End State Vision and Concept of Operations

An end state vision describes an expectation for the MCR at the completion of the modernization process. Preparation of an end state vision should apply a graded approach, and only include those features involved in the modification. An exception may be made when it is desirable to show how other parts of the MCR relate to the modification.

The end state vision should include descriptions of digital I&C systems and equipment that the modernization process will introduce into the MCR. The concept of operations following completion of the modernization process also needs to be included. Concept of operations refers to the way the control room operating crew is organized, and monitors and controls the plant under normal, abnormal, and emergency conditions, including situations in which failures have degraded the I&C systems or the HSIs.

The end state vision should also define the physical MCR following the modernization process, if physical changes are planned. Examples of some of the physical features that may be altered in the modernization process and should be incorporated in the end state vision include:

- Workstations—replace existing stand at the control boards where operators stand to perform their tasks with sit down work stations each containing HSIs
- Overview/wall display—provide large wall display for viewing by all operators and others in the MCR
- MCR lighting—change lighting to minimize glare on new HSIs or for other reasons
- MCR redesign—provide new arrangement of work stations, book storage, control room personnel, etc., in the current or new MCR to accommodate sit down work stations or other changes

The end state vision should be created in close coordination with other stakeholders involved in the modernization process (e.g., I&C engineering, operations, and operators) to the extent possible. For example, I&C engineering is expected to identify analog systems it proposes to replace with digital systems. Operators can identify features they recommend be included (e.g., manual task performance that they recommend be automated). It is important that the I&C end state vision and the HFE end state vision be closely coordinated for modifications involving digital I&C systems.

Concept of operations may vary widely between plants. For example, one plant may develop a concept of operations for a digital I&C upgrade that minimizes changes to the greatest extent possible. It may decide not to automate any manual task that does require automation even if that is a capability in the new I&C digital system. Also, presentations on the new HSIs required by the upgrade may be designed to resemble and operate like the current analog instruments. A justification for this concept of operations could be to minimize plant engineering, HFE, and contractor costs and time, and costs and time to rewrite procedures and retrain operators.

Of course, it is also possible that a change in concept of operations is not needed for simple modifications. For example, replacing analog with digital recorders with no change in recorder locations would not require preparation of a concept of operations.

In contrast, the concept of operations at another plant may be to apply the new digital I&C system technology capabilities to the maximum extent possible. For example, HFE personnel, I&C, operators, and other stakeholders will be heavily involved, as the overarching design philosophy will be to: a) automate as many manually performed operator tasks as possible, b) provide HSIs that integrate information and soft controls, and c) arrange the HSIs and other displays on the control board to support operator viewability, facilitate operator communication and, their access to needed information. Justification for this concept of operations may be to take advantage of the capabilities of the new technology to reduce human errors and inappropriate actions resulting in undesirable plant conditions. Improved human performance and resulting better plant performance should result in fewer safety problems, equipment damage, and loss of power production.

4.2 Visualization to Present End State Visions

4.2.1 Tools to Support Creation of End State Vision Visualizations

Text may be used to describe end state visions, but usually would only be used for very simple modifications. This section contains descriptions of several tools that may be used to create visual representations of end state visions. The tool selected depends on several factors (e.g., the complexity of the control room modernization design, the need for and intended use of the end state vision, the need for the vision to be dynamic and support interaction, availability of tool to create the vision, and the availability of resources [expertise and budget] to apply the tool). Several tools for creating end state visions are described below.

4.2.1.1 Paper sketches and drawings and artist's renderings

Paper sketches and drawings of end state visions are quick to create and inexpensive. Several alternative designs can be created, and operators and others can evaluate and make recommendations. Artist's renditions typically would be of higher fidelity, but cost more to create.

This method is static and does not support dynamic interaction, but can be applied at the beginning of the process of creating an end state vision. Also, it may be a good method to use if a plant does not have technology tools readily available.

4.2.1.2 Rapid prototyping using personal computer

Rapid prototyping is a software-based tool located on a personal computer. This tool permits relatively rapid creation of part or all of an end state vision. It is usually used for lower fidelity representations.

This tool permits rapid changes to elements of the original vision based on operator and other stakeholder recommendations, although using the tool to make changes requires some skill. Operators and others can view the current design and make recommendations for changes that in many cases can be quickly made. This tool has been found to be most applicable in the early stages of the modernization process.

4.2.1.3 Physical mockup

A physical mockup of the end state vision may be constructed. Wood, foam core, and instrument and HSI photographs are examples of materials used to construct mockups. Figure 3 shows a photograph of a mockup used in an HFE study of HSIs on a control board. Figure 3 also shows how I&C components can be included in a mockup.

Mockups may be constructed of movable modules or parts (e.g., workstations, consoles, HSIs). Mockups may be used for dynamic scenario walkthroughs, although the HSIs and controls may be static. For example, a walkthrough may be performed with operators to aid in developing an end state vision for a new control room providing seated work stations. Operators and other stakeholders could recommend layout changes, and modules (in this example each workstation) could be moved to accommodate the recommendations.

Another example would be to construct a control board mockup and paste HSI representations on the board. This mockup would be used to help identify HSI locations in the end state vision. Operators could perform scenario walkthroughs with static HSIs, and operators and other stakeholders could provide recommendation for changes in HSI locations. Walkthrough could be repeated until the operators and other stakeholders were satisfied with placement.

4.2.1.4 Training simulator

A training simulator could be a tool to support defining an end state vision. The last example in Section 4.2.1.3 describes a process that could be used with a training simulator. The only difference is that no mockup would need to be constructed. This could reduce the time and cost to build a mockup. Section 3.9 and Figure 5 illustrate how a training simulator could be used to define the end state vision for a control board design.

4.2.1.5 Virtual reality

Virtual reality (VR) is a tool that has been applied in at least three plants to support evaluation of end state visions (EPRI, 2005; EPRI, 2010; Hugo, 2016). VR technology is rapidly developing, and the tool is becoming more affordable and easier to use. VR supports some of the same kinds of evaluations possible with control room and partial control room mockups (Section 4.2.1.3) in that it provides three-dimensional views and the capability to simulate moving through the end state vision representation.

The VR model may be presented on a personal computer and projected on a screen for group viewing, if wanted. EPRI has called this 2.5-D VR (EPRI 2005; EPRI, 2010). Perspective techniques are used to create the illusion of 3-D on a 2-D surface. The viewer may use a keyboard and mouse to show an avatar moving through the virtual model of the end state vision. Different views are possible (e.g., as viewed from an operator seated or standing, from above, and from different locations in the control room). The viewer is not required to wear shutter glasses or a headset to view the 2.5-D rendition.

The VR model may also be presented on a projection screen in which the viewer stands and moves in front of the screen and is provided a hand control that permits the viewer to simulate moving through the model (EPRI, 2005). The viewer wears shutter glasses to provide a realistic appearing 3-D image. The views available are similar in many ways to those provided by 2.5-D. The ability to move around the screen, use the hand-held device to move about in the image, and the realistic 3-D views are features not available with 2.5-D viewing.

A third way to view and interact with images is to wear a head mounted devices containing shutter glasses. The fourth method is total immersion in a Cave Automatic Virtual Environment (CAVE). A CAVE is an immersive VR environment where projectors are directed to the walls of a room-sized cube. A CAVE has been used in at least two HFE studies of end state visions (EPRI, 2005; Hugo, 2016). The viewers wear shutter glasses, and either are tracked or hold a device that permits them to move throughout the virtual image.

VR is a powerful tool for evaluating end state visions when it is appropriate to use. For example, it may be useful for evaluating major changes to the physical arrangement of a control room. On the other hand, it may not be very useful for evaluating HSI locations on a control board.

It is becoming easier, faster, and less expensive to create virtual models. For example, 3-D cameras are widely available. Many Computer Aided Design (CAD) systems produce 3-D models. VR systems providing 2.5-D use personal computers. Head mounted systems and virtual walls are available but somewhat expensive and require specialized knowledge to make them work properly. CAVE and similar systems are expensive and also require specialized knowledge to make them work properly. As such, a plant should decide if evaluation of an end state vision requires the use of a VR tool.

4.2.1.6 Glass-top or equivalent simulator

A glass-top simulator or other simulators with equivalent capabilities could be a useful tool for evaluating certain types of end state visions. It might be applicable to evaluating end state visions involving control board layouts and concept of operations.

Both static and possibly dynamic simulations could be performed to evaluate an end state vision. HSIs and other instruments could easily be relocated, HSI presentations could be changed, etc., based on viewer recommendations. If the plant model is provided in the simulator software, dynamic simulations involving operators walking through scenarios could be performed.

A concept of operations included in the end state vision might provide for manual performance of some operator tasks. Operators could walk through scenarios and evaluate manual versus automatic performance of these tasks. The results could provide a basis for revising, or leaving as is, the concept of operations and end state vision.

Glass-top and equivalent simulators are expensive. It is unlikely that such devices would be purchased and operated only to evaluate end state visions. However, as mentioned in Section 3.9, some plants are acquiring these simulators to support a variety of activities, and the INL HSSL has a glass-top simulator used for research purposes. If available, use of a glass top simulator may be a relatively inexpensive tool to support the development of end state visions.

4.3 HFE Observations Based on Helping Develop End State Visions

This section provides a few observations for developing and applying HFE end state visions to support a NPP MCR modernization process. The observations are based on (1) recent efforts at three plants to develop and apply end state visions as part of nuclear plant modernization planning (EPRI, 2005; EPRI, 2010; Hugo, 2016), and (2) review of LWRS, EPRI, and other publications on this topic.

It should also be noted in particular that Section 4.2.4 in an EPRI technical report (EPRI, 2015) provides additional detail in preparing an end state vision and a concept of operations.

4.3.1 Develop initial end state vision early in modernization process

The initial end state vision should be developed as early as possible during the modernization process. It should be prepared during the modification request and conceptual design (Figure 2) parts of planning, if possible, and should present a high-level vision of the MCR design and operation at the completion of the modernization process.

There may be one or more end state visions prepared near the beginning of the modernization process. For example, there may be one end estate vision representing the MCR after the first (and possibly only) modification phase. The plant may need to replace an analog system with a digital I&C system because of problems in finding replacement parts. The plant then may determine that the system will be retired in a few years and no further upgrades are planned.

A plant may adopt a phased approach to modernization, in which upgrades are made during subsequent refueling outages. It may decide it wants only a final end state vision showing the MCR configuration following the last modification process. Or the plant may plan to prepare an end state vision describing the MCR following the first modification phase, and then update it during planning for the second modification phase, and so on until the final end state vision is ready to be implemented.

Yet a third option for a plant would be to prepare an end state vision for each major modification stage so that it had a road map for the entire modernization effort. Each plant will need to decide how many end state visions it wants to prepare. It may be one of the choices described above, or a different choice altogether.

4.3.2 End state visions will need to be updated as modernization process progresses

An end state vision prepared early in the modification process needs to be expanded and updated as the process moves forward and additional information becomes available. For example, the initial end state vision may be that an analog TCS is going to be replaced by a digital TCS and associated HSIs. The HSIs will be located on one or several control panels located in the MCR. The exact positions for the HSIs have not been determined at the time the original vision was prepared. It was during the preliminary design (Figure 2) that location of the HSIs was determined. In this case, the end state vision should have been updated with this new information.

End state visions may need modified for several additional reasons. Therefore, the end state visions and associated plans may need to be flexible to allow for changes that can occur due to changes in plant conditions, budgets, priorities, and even the development of new technologies. In addition, experience gained and lessons learned in other related projects may be applied to later projects and their end state visions, as appropriate.

4.3.3 HFE needs to work with other stakeholders in developing end state visions

HFE will need to work with other stakeholders in helping develop an end state vision. For example, I&C and HFE will need to work together if the modernization project involves replacing an analog system with a digital one, and digital HSIs are included in the upgrade.

Another example involves changes to the operator workstations in the MCR. During planning it may be decided to redesign the MCR to provide operators with workstations where they sit rather than stand at control boards. Several stakeholder groups should be involved in creating the end state vision.

Operators should be involved in preparation of almost all end state visions. They will be the users of the results of the modification process, and their opinions and recommendations carry a great deal of weight at most plants.

4.3.4 HFE guidelines and studies may help define and refine end state vision

HFE guidelines may be applied and studies may need to be performed to support development of end state visions. Human factors engineers should identify and apply HFE guidelines as part of developing end state visions. For example, anthropometric (body size) and biometric (body movement) guidelines may be used to design workplaces to provide space for operators to move about in the redesigned control room. Also, HFE guidelines can be applied to help identify areas on a control board to locate HSIs and controls that are within reach of operators.

An HFE study may help create or refine an end state vision. In one study performed by EPRI (EPRI, 2005), a VR representation of the MCR end state vision was created. A plant planned a multi-stage (upgrade planned during several refueling outages) modernization project to replace the complete control room with digital and other systems and equipment. The first phase was to replace an existing operator desk with a new console that accommodated two operators and a supervisor. This crew would be able to use HSIs to access much of the plant information currently available in the control room, and soft controls for control inputs. It was planned in a subsequent outage to move more of the indicators and controls from the existing console to the new module. Further upgrades were planned to eliminate other consoles completely.

A virtual model was constructed to represent the control room as it currently existed and how it would appear following the first upgrade. This was not called an end state vision at the time of this study. Rather, it was identified as a plan for the first stage of the control room modification prepared during conceptual design.

The virtual model was used during HFE evaluations to obtain operator opinions and recommendations about the design, and location of control room elements. HFE viewing distance and reach guidelines were applied to determine if operators could see and reach displays and controls. Avatars were provided and used to determine if enough space was provided in the walkways between furniture in the control room. The HFE results were applied to modify the design, as required.

Similar work has been done more recently by LWRS program researchers. In two different collaborations with NPP utility partners, 3-D models of the respective MCRs were developed and avatars were used to perform assessments of the HSIs. One example of these analyses is shown in Figure 7 (from Joe, Kovesdi, Hugo, & Clefton, 2018). The analyses revealed that the physical placement of touch screen HSIs on the control boards was beyond the reach of some operators, and that other aspects of their design (e.g., font size) and placement (e.g., viewing angle) affected screen legibility because they were not designed in a manner that is consistent with HFE design recommendations, such as NUREG-0700 (NRC, 2002).

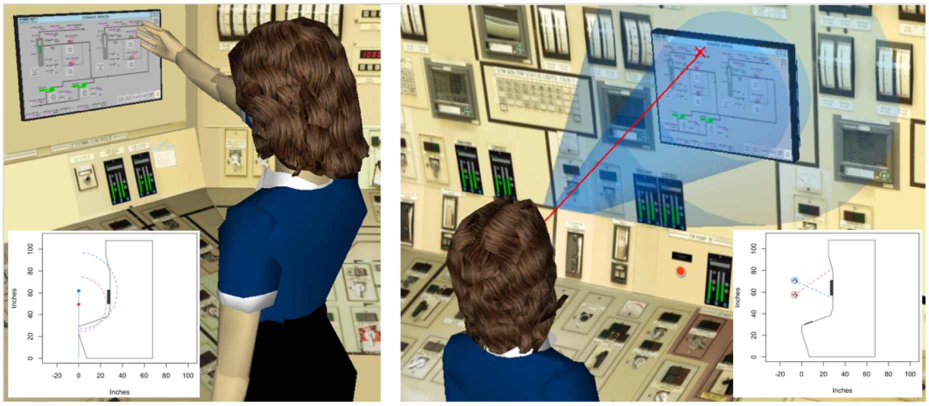

Figure 7. Ergonomic and HFE evaluations using 3-D modeling to identify and prevent the introduction of new human error traps when performing digital I&C upgrades

5. SUMMARY OF HFE BEST PRACTICES AND LESSONS LEARNED

This section provides a summary of the best practices and lessons learned regarding developing and evaluating an HFE PMP and an end state vision for control room modernization. The summary is not prioritized with regard to importance, but it is provided here before moving on to the remaining two key aspects of developing a strategy for full plant modernization.

- HFE should be involved as early as possible in creating an end state vision during the modernization process (e.g., during the modification request or the conceptual design phase). A major reason is that HFE may be able to identify financial and safety information based on OE and operator reports to help justify the need for a modification or for some of the features that should be provided in the modification. In addition, early participation makes it more likely that HFE-desired features will be considered and possibly incorporated into the end state vision.
- HFE should work closely with other stakeholders to develop a common or closely coordinated end state vision. For example, I&C and HFE usually should work closely together. I&C may identify a need to replace analog with digital systems, and HFE can help identify features and capabilities that should be included in the I&C upgrade to improve safety and plant power production.
- The HFE PMP is the key guiding HFE document for a modernization project, and represents the comprehensive management and technical approach used to integrate HFE guidelines, data and principles into the overall design, development, and evaluation of an upgrade of an MCR. An end state vision is an activity typically identified in an HFE PMP.
- Modification projects may be considered as a progressive evolution from a conventional analog control room through a hybrid configuration equipped with both analog and digital systems, and for some plants, eventually to a fully-digitalized control room. Some plants may decide that the final end state vision for the modification will be a hybrid control room.
- A graded approach should be used in preparing an HFE PMP. Only systems and equipment being replaced that involve human actions and performance should be included in the HFE PMP. Previous HFE PMPs and other documents should be used to reduce the effort of preparing the current HFE PMP, if available.
- Many of the recent HFE studies in support of HFE modifications involving replacement of analog with digital I&C systems have involved automation and HSI design and placement. These are issues that should be emphasized in HFE PMPs.
- There are several best practices and lessons learned regarding HFE PMPs that are described in more detail in Sections 3 and 4.3. They should be applied if relevant, or at least considered.
- Vendors, or suppliers, should be part of the team early in the development of an HFE PMP. They know capabilities and limitations of the commercial hardware and software (COTS products) they represent.
- It is important to perform evaluations and testing throughout the modernization process rather than relying on an extensive evaluation as part of the verification and ISV activity. This may be called multi-stage evaluation and testing. A problem with waiting to very near the completion of the modification process is that HEDs may be difficult and expensive to correct at that time.
- Simulation is used extensively to provide information that has been vital to HFE work during the modernization process. The simulation tools have helped develop quantitative and qualitative evidence used to help justify HFE recommendations. There are numerous devices used to provide simulation capabilities, and the selection of a simulator depends on the simulation needs.

- An end state vision is one of the elements in an HFE PMP and describes an expectation for the control room at the completion of the modernization process. An end state vision includes a concept of operations that refers the way the control room operating crew is organized, and monitors and controls the plant under normal and abnormal conditions, including situations in which failures have degraded the I&C systems or the HSIs.
- End state visions and concept of operations may need to be flexible to allow for changes that can occur due to changes in plant conditions, budgets, priorities, and even new technologies.
- End state visions should use visualization techniques to facilitate user viewing of end state visions.
- Tools exist to create visual representations of end state visions. The tool selected depends on such factors as the complexity of the control room modernization design, the need for and intended use of the end state vision, the need for the vision to be dynamic and support interaction, availability of tool to create the vision, and the availability of resources (expertise and budget) to apply the tool.
- Tools include paper sketches, rapid prototyping, physical mockups, training simulators, VR, and glass-top simulators.

6. FULL DIGITAL I&C INTEGRATION

Full plant digital I&C integration offers many benefits to address known issues concerning operating costs and long-term aging and obsolescence with the existing U.S. NPP fleet. For instance, the inherent capabilities of digital technologies afford plant integration, interconnectivity, and standardization that can significantly reduce operations and maintenance (O&M) costs, as well as enhance plant performance and availability while maintaining or improving plant safety (i.e., see Thomas & Scarola, 2018 for details). To this end, digital I&C integration enables consolidation of multiple I&C functions into a single digital controller, effectively reducing O&M costs. Interconnectivity between multiple digital controllers allows for improved human-system integration through intelligent automation, reducing initial and O&M costs with hardwired connections. Further, standardization pertains to the implementation of a common digital platform that serves multiple control functions to improve engineering and maintenance efficiencies.

In light of these identified benefits of full-digital I&C integration, there are potential challenges that must be understood to ensure such integration does not present new failure modes. Namely, the issue of digital CCFs has been a challenge from a technical and regulatory perspective, which has led nuclear plant utilities to defer plant modernization altogether. While an in-depth description of digital CCFs goes beyond the scope of this document, it is important to understand that the same inherent benefits of digital integration can be sources of CCF if not properly designed. For example, a known CCF that would be attributed to a software defect may entail failure of a digital platform interconnected to multiple plant components (e.g., pumps and valves). See Thomas and Scarola (2018) for a detailed discussion of digital CCFs.

Nevertheless, a key aspect to the success of a full plant digital I&C integration is in having a modernization strategy put in place that addresses possible digital CCFs in a cost-effective manner. To this end, the basis of this strategy should be focused on meeting an end state vision to ensure that each phase is synergistic and minimizes unnecessary rework (Thomas, Scarola, Hernandez, & Lambdin, 2017). Furthermore, having an end-state generalized digital architecture in place is critical to the success of plant modernization. While some degree of customization may be necessary on a per-plant basis, the overall architecture of digital I&C systems remains fairly similar. By maintaining consistencies across the industry, development costs can be ultimately reduced through fewer customized implementations and reduced need for interface rework. A successful end-state architecture should be based on the plant's requirements that offset O&M costs. Further, establishing a business model is important to determine how the end-state (1) minimizes O&M costs and (2) enables collateral savings throughout the plant (e.g., reducing the need for additional platforms such as a plant process computer). Finally, it is important to develop a logical migration path for the plant that considers where the plant currently is, and how it can reach the final end-state vision. For example, utilities will take different migration paths for plant modernization, and if a step-wise or phased approach is chosen, any intermediate phases must comply with regulatory requirements.

7. BUSINESS CASE DEVELOPMENT

The decision to fund plant modernization activities often depends on demonstrating actual cost reductions that can be credited to budgets and thereby truly reduce O&M or capital costs. The business case methodology developed for plant modernization addresses the fact that the lack of a business case is often cited by utilities as a barrier to pursuing large-scale modernization activities.

The business case methodology for MCR modernization bases cost savings on the installation advanced digital I&C systems that improve human operator and overall system performance. One way this is achieved is by new control room technologies providing significantly better situational awareness for operators and control room supervisors than a traditional analog control room, which leads to a reduction in certain types of operator errors. For example, Adolfson, Thomas, and Joe (2017) pointed out that a digital I&C system coupled with an advanced alarm system can distinguish real plant events from sensor failures, alert the operators and transition them to the correct alarm response procedure, and then transition them to the correct procedure to mitigate the plant upset. Other advanced control room technologies automate functions that potentially reduce the need for extra operators to be on shift during times when there are elevated levels of activity occurring at the plant (e.g., coming out of outage, starting up the reactor, and synching the turbine to the grid). Some examples of the cost-saving technologies that can be employed in MCR include:

- Large overview displays
- Task-based operator displays
- Computer-based procedures
- Advanced alarm systems
- Computerized operator support systems

Each one of these technologies has the capability to improve human performance, reduce human errors, and therefore improve overall system performance, which Joe, Thomas, and Boring (2015) have argued is the ‘value chain’ by which cost reductions can be realized. Additionally, there are many work process technologies that allow field or auxiliary operators to conduct maintenance and surveillances with improved human factors and efficiency (e.g., automated work packages), and therefore operate with fewer staff.

The business case methodology shows labor savings can be harvested in terms of reduced overtime and through the redistribution of work. In short, it addresses the benefits of the technology instead of just the investment costs to the utility, but it goes further in that it provides the means to determine the maximum investment that will result in a positive return. For example, Thomas, Lawrie, and Niedermuller (2016) showed significant savings can be realized as reduced time to bring the plant back on line after completion of outages. Granted, the benefits are quantified to a rough order of magnitude, but these estimates nevertheless provide directional guidance to utilities considering full plant modernization.

Additionally, the most recent work on developing a strategy for full nuclear plant modernization has used this business case methodology to further cost-justify the merits of full digital I&C integration. The transition from a mostly analog legacy I&C system to a fully digital I&C system is technically challenging and controversial, and so it is well understood that it must be cost-justified with an established business case methodology.

8. CONCLUSION

The operating model of many U.S. NPPs is becoming less competitive in today's energy market, largely because it relies on outdated technologies and inefficient work processes. The objective of DOE's LWRS program is to support the long-term sustainability of U.S. commercial NPPs. LWRS program researchers conduct R&D that utilities should undertake to modernize technologies and improve processes, thereby providing the technical bases that help reduce the uncertainty and risk full plant modernization.

The research specifically described in this milestone report is part of a larger goal to collaborate with utilities to develop a strategy for full nuclear plant modernization that will enhance the safety and economic performance of plants. As such, the objective and scope of this milestone report was as follows. First, the report elaborated on the importance of HFE, having an HFE PMP, and developing an end state vision. The HFE PMP is the key guiding HFE document for a modernization project, and represents the comprehensive management and technical approach used to integrate HFE guidelines, data and principles into the overall design, development, and evaluation of an upgrade of an MCR. An end state vision is an activity typically identified in an HFE PMP. The report highlighted the importance of HFE PMPs by summarizing recent lessons learned from participating in I&C digital system modifications in which HFE was heavily involved, and by providing a description of end state visions.

The report then described how HFE needs to be integrated into a strategy for full nuclear plant modernization by further integrating HFE with 1) approaches to fully migrate legacy I&C systems that are mostly analog to a fully digital I&C architecture, and 2) with the methods used to cost-justify modernization activities. Clearly, it is important to establish a technically defensible approach to fully migrating existing, mostly analog infrastructure to a new digital architecture, and to have a valid and defensible methodology to establish the business case to cost justify the full plant modernization activity. What this report further demonstrated is how HFE needs to be integrated with these activities in order to have a complete strategy for full nuclear plant modernization, and provided insights how to do so. Future work in the LWRS plant modernization path with continue to work towards the grand unification of these diverse disciplines and activities.

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