INL/RPT-22-70538
Revision 0

Light Water Reactor Sustainability Program

Demonstration and Evaluation of the Human-Technology Integration Guidance for Plant Modernization

December 2022

U.S. Department of Energy

Office of Nuclear Energy

INL/RPT-22-70538
Revision 0

Demonstration and Evaluation of the Human-Technology Integration Guidance for Plant Modernization

Zachary Spielman
Jeremy Mohon
Chloe Pedersen-San Miguel
Casey Kovesdi

December 2022

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy

SUMMARY

The significance of nuclear power in its role producing carbon-free electricity to the U.S. cannot be overstated. However, with changes in the energy market coupled with changes in incentives given to certain resources like solar and wind, the operating and maintenance costs for these sources have seen a significant reduction, which has consequently negatively impacted the economic viability of the existing U.S. nuclear power plant fleet.

Digital instrumentation and control (I&C) and control room modernization is a major critical work domain to reduce operating and maintenance costs. Existing nuclear power plants are commonly configured with mostly legacy analog I&C as well as isolated pockets of digital I&C (a plant process computer, digital recorders, etc.). One challenge with this analog I&C is that replacement parts are becoming prohibitively more expensive and difficult to obtain. Moreover, a significant challenge with the existing analog I&C is that the way in which plants are currently operated and maintained is no longer competitive with other electricity generating sources, like natural gas, where advanced digital I&C technologies are commonplace. This gap between the waynuclear power plants are operated compared to other electricity generating sources significantly challenges the economic viability of the nuclear industry.

Indeed, digital I&C systems can fundamentally change the way the plant is operated (i.e., the concept of operation). The introduction of digital I&C technologies offers a wealth of benefits to the nuclear industry. However, it is important to emphasize that, to realize these benefits, a careful understanding of how to integrate technology in a collaborative way that leverages the capabilities of people and technologies is necessary. Human-technology integration applies human factors engineering methods and tools to ensure the safe and reliable use of these technologies while ensuring that the inherent features of the technologies that provide economic value are not missed.

The scope of this work documents the demonstration of the recently developed human and technology integration methodology, as applied to developing a new vision and concept of operations for a major U.S. nuclear power plant fleet. This report focuses on the methodological aspects of developing a vision and concept of operations. This report shares the tools, activities, and lessons learned during a modernization currently underway for industry as a whole to consider when planning any significant digital modification and developing a new vision and concept of operations.

ACKNOWLEDGEMENTS

The authors would like to thank Harry Burke, Ray Herb, Liz Williford, and the entire Farley operations team at Southern Nuclear Corporation. Further, the team would like to thank Pareez Golub, Richard Paese, and John McCague of Sargent and Lundy who were closely involved in the planning and execution of this work. This report was made possible through funding by the United States Department of Energy Light Water Reactor Sustainability Program. Lastly, we would like to thank Alison Hahn and Bill Walsh of the Department of Energy, as well as Craig Primer and Bruce Hallbert of Idaho National Laboratory for championing this effort.

CONTENTS

SUMMARY iv

ACKNOWLEDGEMENTS v

ACRONYMS ix

1. INTRODUCTION 1

2. INTEGRATED DIGITAL ENVIRONMENT ROADMAP AND HUMAN-TECHNOLOGY INTEGRATION 6
    - 2.1 Strategic Planning 10
    - 2.2 Initial Modernization Scoping Activities 10
        - 2.2.1 Establish Project Charter and Develop Division of Responsibility 10
        - 2.2.2 Collect Initial Operating Experience 10
        - 2.2.3 Develop the Vision and New Concept of Operations 11
        - 2.2.4 Develop an Implementation Plan (HFE Program Plan) 11
    - 2.3 Design, Installation/Testing, and Project Closeout Activities 13

3. CASE STUDY 14
    - 3.1 Enabling Human Factors Tools 14
        - 3.1.1 Simulation Tools 14
        - 3.1.2 Three-Dimensional Modeling and Virtual Reality 15
        - 3.1.3 EPRI Endpoint Vision Worksheets 16
    - 3.2 Human Factors Activities Performed 17
        - 3.2.1 Collect Initial Operating Experience 17
        - 3.2.2 Develop the Vision and New Concept of Operations Methodology 22
    - 3.3 Use of Results 27
    - 3.4 Lessons Learned and Practical Guidance 28

4. CONCLUSIONS 32

5. REFERENCES 33

Appendix A Endpoint Vision Worksheets 36

Appendix B Concept of Operations Workshop Agenda 38

Appendix C Concept of Operations Report Table of Contents 41

FIGURES

Figure 1. Average capacity factor by electricity generating sources over the past decade. 1

Figure 2. LWRS Program Plant Modernization focus areas. 2

Figure 3. Key work domains that offer greatest opportunity for cost savings 3

Figure 4. Human-technology integration methodology 5

Figure 5. Systems engineering Vee Model. 6

Figure 6. Vee Model with the LWRS Program human-technology integration methodology overlaid. 7
Figure 7. Integrated Digital Environment Roadmap. 9
Figure 8. HFE grading considerations. 12
Figure 9. Crosswalk of the Human--Technology Integration Methodology with NUREG-0711. 13
Figure 10. Training simulator at Farley Nuclear Power Plant. 14
Figure 11. Use of the HSSL for the Static Concept of Operations Workshop. 15
Figure 12. Example use of 3D modeling to present a concept of the endpoint vision. 15
Figure 13. Example use of virtual reality to present a concept of the endpoint vision. 16
Figure 14. Operational Experience element of the Digital Environment Roadmap. 19
Figure 15. Develop concept of operations element of the Digital Environment Roadmap. 22
Figure 16. Image of 3D model workstation with displays and equipment. 24
Figure 17. Image of conceptual endpoint vision MCR 3D model. 25
Figure 18. Elements of an integrated team. 28
Figure 19. Technology Acceptance Model for nuclear power plant modernization (adapted from Kovesdi, 2021). 29
Figure 20. Advanced concept of operations pyramid (adapted from Thomas and Hunton 2019) 30
Figure 21. Grading HFE by complexity and risk. 31

TABLES

Table 1. Comparison of existing versus advanced MCR. 4
Table 2. Example of an endpoint vision worksheet. 19
Table 3. Uses of vision and concept of operations for subsequent HFE activities. 27
Table 4. Most useful aspects for operations in concept of operations workshop. 29

ACRONYMS

3D	three-dimensional
CWD	critical work domain
DA&A	data architecture and analytics
DEG	Digital Engineering Guide
DHM	digital human model
EPRI	Electric Power Research Institute
HFE	human factors engineering
HSI	human-system interface
HSSL	Human System Simulation Laboratory
HTI	human-technology integration
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
IEEE	Institute for Electrical and Electronics Engineers
INL	Idaho National Laboratory
ION	Integrated Operations for Nuclear
ISV	integrated system validation
LWRS	Light Water Reactor and Sustainability
MCR	main control room
NRC	Nuclear Regulatory Commission
O&M	operating and maintenance
OE	operating experience
R&D	research and development
U.S.	United States
V&V	verification and validation
VDU	video display unit

DEMONSTRATION AND EVALUATION OF THE HUMAN-TECHNOLOGY INTEGRATION GUIDANCE FOR PLANT MODERNIZATION

1. INTRODUCTION

The United States (U.S.) nuclear industry continues to provide safe, reliable, and carbon-free electricity. In fact, the capacity factor[a] for nuclear power has been notably greater than any other non-fossil fuel electricity generating source, as seen in Figure 1. Indeed, the significance of nuclear power in its role of producing continued carbon-free electricity to the U.S. cannot be overstated.

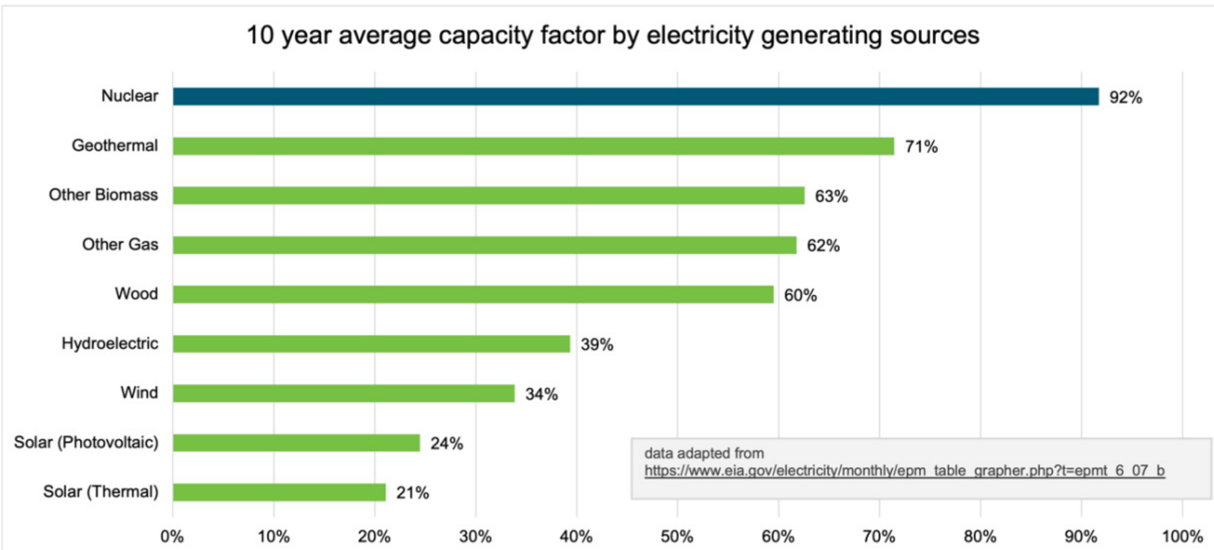


Figure 1. Average capacity factor by electricity generating sources over the past decade.

However, with changes in the energy market coupled with changes in incentives given to certain resources like solar and wind, the operating and maintenance (O&M) costs for these sources have seen a significant reduction, which has consequently negatively impacted the economic viability of the existing U.S. nuclear power plant fleet (Remer et al., 2021). The U.S. Department of Energy Light Water Reactor Sustainability (LWRS) Program Plant Modernization Pathway is conducting targeted research and development (R&D) to extend the life and improve the performance of the existing U.S. nuclear power plants by:

- Delivering a sustainable business model that enables the U.S. nuclear industry to remain cost competitive
- Developing technology modernization solutions that address aging and obsolescence challenges.

The U.S. LWRS Program addresses these objectives through four complementary primary research areas, which are shown in Figure 2.

[a] As described by the U.S. Energy Information Administration, "capacity factors describe how intensively a fleet of generators is run. A capacity factor near 100% means a fleet is operating nearly all of the time. It is the ratio of a fleet's actual generation to its maximum potential generation."

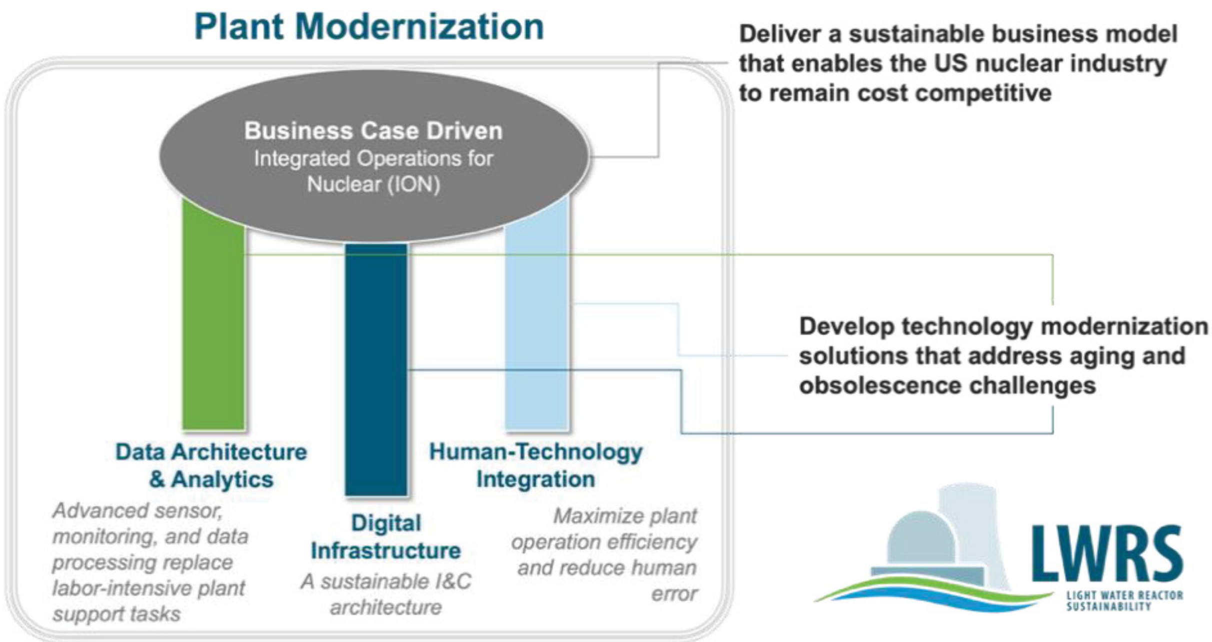


Figure 2. LWRS Program plant modernization focus areas.

At the top, the Integrated Operations for Nuclear (ION) effort is conducting R&D on delivering the sustainability business model (Remer et al., 2022). The three other research areas develop technology modernization solutions that follow the strategic business model from ION. Data architecture and analytics (DA&A) is developing advanced sensor, monitoring, and data processing capabilities for industry that replace currently labor-intensive tasks. Likewise, the digital infrastructure area provides a sustainable instrumentation and control (I&C) architecture that enables the advanced technologies from DA&A. Lastly, and the focus of this work, is human-technology integration (HTI). HTI performs human factors engineering (HFE) to ensure that advanced DA&A technologies are safe, reliable, and efficient to use. Indeed, these four research areas provide a cross-functional approach to enable the nuclear industry to continue electricity generation for decades to come.

Starting at the top, a key characteristic of ION is that it serves to determine a market-based price point for electricity generation and then focuses on identifying the organization capabilities, subcapabilities, work functions, and work reduction opportunities that can be transformed through a strategic use of technology. By changing the way in which people work, O&M costs can be reduced. This characteristic is coined people, technology, processes, and governance. The ION research team had recently identified focused work reduction opportunities that are at a sufficient technology readiness level and would support plant transformation within 3–5 years (i.e., defined as ION Generation I). The ION Generation I research identified several work reduction opportunities that could be grouped in ten critical work domains (CWDs). Figure 3 offers a mosaic graph of these ten CWDs, and the size of each CWD is indicative of the relative O&M savings from these areas.

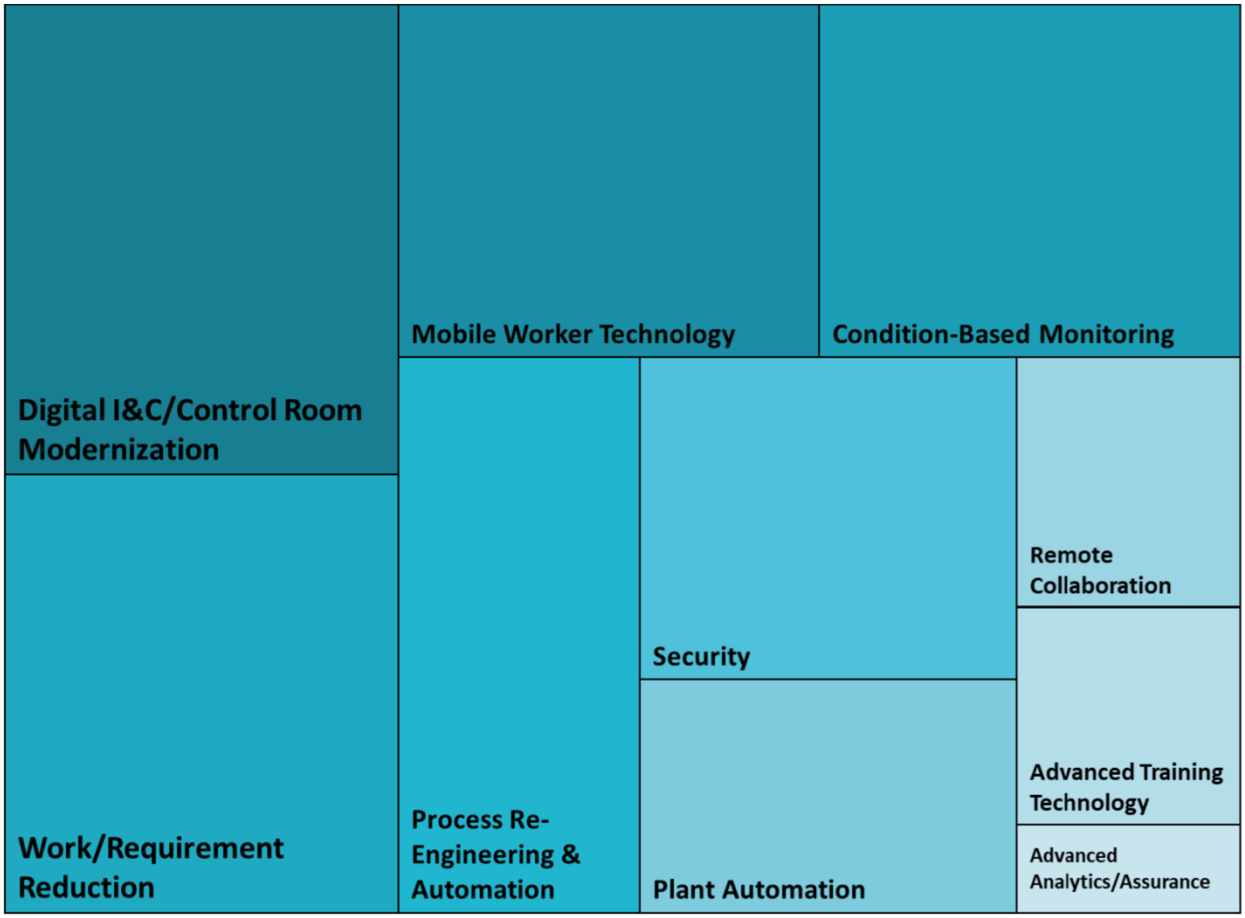


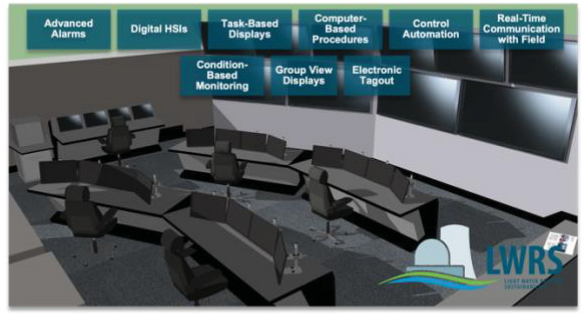
Figure 3. Key work domains that offer greatest opportunity for cost savings.

Digital I&C and control room modernization is a major CWD to reduce O&M costs. Existing nuclear power plants are commonly configured with mostly legacy analog I&C with isolated pockets of digital I&C (a plant process computer, digital recorders, etc.). One challenge with this analog I&C is that replacement parts are becoming more expensive and difficult to obtain. Moreover, a significant challenge with the existing analog I&C is that the way plants are currently operated and maintained is no longer competitive with other electricity generating sources, like natural gas, where advanced digital I&C technologies are commonplace. This gap between the way nuclear power plants are operated compared to other electricity generating sources significantly challenges the economic viability of the nuclear industry. The gap also negatively impacts attracting a new workforce who are far more comfortable with digital technology. Modernizing existing nuclear power plants with advanced digital I&C has several economic benefits, including:

- Improved testing and surveillance with digital technology that improves existing processes
- Reduced need for skill of the craft in the maintenance (i.e., diagnosing, troubleshooting, and maintenance) of I&C systems
- Improved plant operations resulting from improved handling of technical specifications, communication between the main control room (MCR) and field, and overall crew awareness
- Overall obsolescence management.

Digital I&C systems can fundamentally change the way the plant is operated (i.e., the concept of operation). Notable changes in the concept of operation are documented in Table 1.

Table 1. Comparison of existing versus advanced MCR.

Typical Existing MCR at a Nuclear Power Plant	Advanced MCR Concept
	
• Mostly standing work • Individual indications and controls throughout the MCR • Nonintegrated information from several sources • Many alarms, some being nuisances • Use of paper procedures • Low levels of automation requiring operators to perform more manual tasks • Requires high degrees of tacit knowledge (i.e., sometimes considered "tribal" knowledge) sometimes only carried by senior staff	• Going from standing to sitting at digital workstations • Using large overview human-system interface (HSI) displays for sensemaking as opposed to relying on the vast amounts of readily viewable analog indications • Using data visualization techniques and integration to support situation assessment, diagnosis, and response planning • Managing alarms differently because of new capabilities that filter and prioritize incoming alarms • Using computer-based procedures that offer new capabilities unseen in paper-based analogs • Using increased levels of automation to control the plant, which changes operation from tactical (i.e., at the boards) to more supervisory

The introduction of digital I&C technologies offers a wealth of benefits to the nuclear industry. However, it is important to emphasize that, to realize these benefits, a careful understanding of how to integrate technology to leverage the capabilities of people and technology is necessary. HTI applies HFE methods and tools to ensure the safe and reliable use of these technologies while ensuring that the inherent features of these technologies that provide economic value are not missed. HTI is best applied early in the modernization project lifecycle when developing requirements because it champions stakeholder needs (i.e., the voice of the operator) while ensuring state-of-the-art HFE design principles are accounted for in the design (Kovesdi et al., 2021). This differs from a viewpoint that considers HFE as an activity solely performed in verification and validation (V&V).

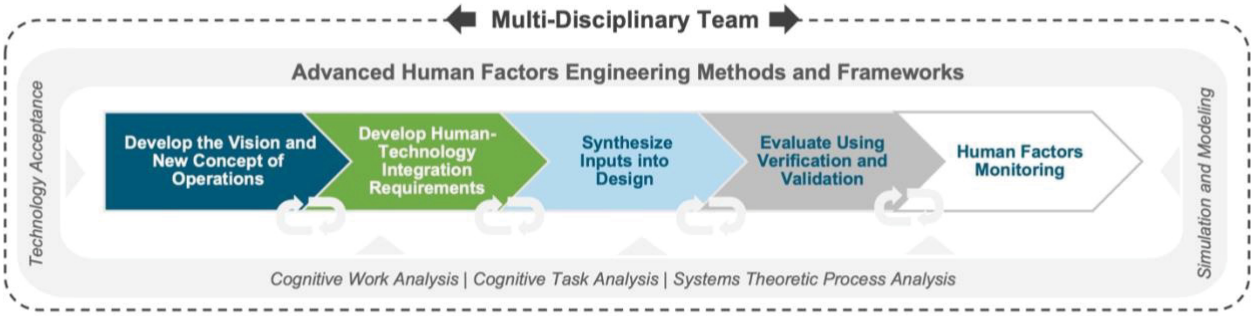


Figure 4. HTI methodology.

The HTI methodology can be characterized by five distinct phases (Figure 4). The methodology is described in detail in INL/EXT-21-64230. As described in this report, the HTI methodology contains the key characteristics that:

- *It Builds on Industry Best Practices.* The process builds on existing standards and guidance, including U.S. Nuclear Regulatory Commission (NRC) NUREG-0711, Electric Power Research Institute (EPRI) 3002011816, EPRI 3002004310, the International Atomic Energy Agency (IAEA) No. NR-T-2.12, and research from the LWRS Program
- *It Is Multidisciplinary.* The process emphasizes a need to include a multidisciplinary team throughout the lifecycle, including senior management, operations and training, I&C, HFE, licensing, vendor, and other parties
- *It Uses a Graded Approach.* The extent of HFE applied to the project is tailored based on several risk considerations, such as the safety and economic impact of the upgrade
- *It Addresses the Physical and Functional Changes.* The process addressed physical impacts on the way people work as well as function impacts associated with added levels of automation
- *It Emphasizes Early HFE Involvement.* The process focuses on supporting early HFE involvement to help define the vision so that the vision and concept of operations are developed with collaborative human and technology strategies
- *It Allows Iterative Feedback.* The process is intended to support iterative feedback throughout the lifecycle of the project.

A detailed methodology description goes beyond the scope of this report. Rather, the focus of this report is to document the demonstration of the methodology specific to the first phase: developing a vision and new concept of operations. This work was done in collaboration with a partnering utility who is undergoing significant digital modifications at multiple sites. The utility's goal is to strategically implement digital I&C technologies to enable standardization across the fleet while also being sensitive to existing plant conventions while avoiding human error traps. Specific results are purposefully omitted; a limited distribution report was developed following this guidance for the partnering utility. Rather, this report focuses on the methodological aspects of developing a vision and concept of operations and shares the tools, activities, and lessons learned for industry to consider when undergoing any significant digital modification. There are three primary sections to this report:

- Section 2 introduces the primary activities performed within the context of a common systems engineering framework
- Section 3 presents a case study of applying the HTI guidance to inform a new vision and concept of operations for a partnering utility

Section 4 provides conclusions and lessons learned.

2. INTEGRATED DIGITAL ENVIRONMENT ROADMAP AND HUMAN-TECHNOLOGY INTEGRATION

Large-scale digital modifications at nuclear power plants often follow a systems engineering approach. Systems engineering can be defined as:

> *An interdisciplinary collaborative approach to derive, evolve, and verify a life-cycle balanced system solution that satisfies customer expectations and meets public acceptability.* (Institute for Electrical and Electronics Engineers [IEEE] *Std 100, 2000)*

Within the nuclear industry, the EPRI Digital Engineering Guide (DEG) is a commonly referenced guidance document for practically applying systems engineering throughout the lifespan of any significant nuclear power plant digital modification (EPRI 3002011816, 2021). The EPRI DEG provides a multidisciplinary approach to completing digital modifications and includes detailed guidance for applying systems engineering and its associated subdisciplines, including:

- Procurement
- Obsolescence management
- Configuration management
- Testing
- Plant integration
- Cybersecurity
- Data communications
- HFE.

The systems engineering approach, including the DEG, follows the Vee model (Figure 5). The Vee model is a widely accepted model for technology development (Graessler, Hentze, & Bruckmann, 2018).

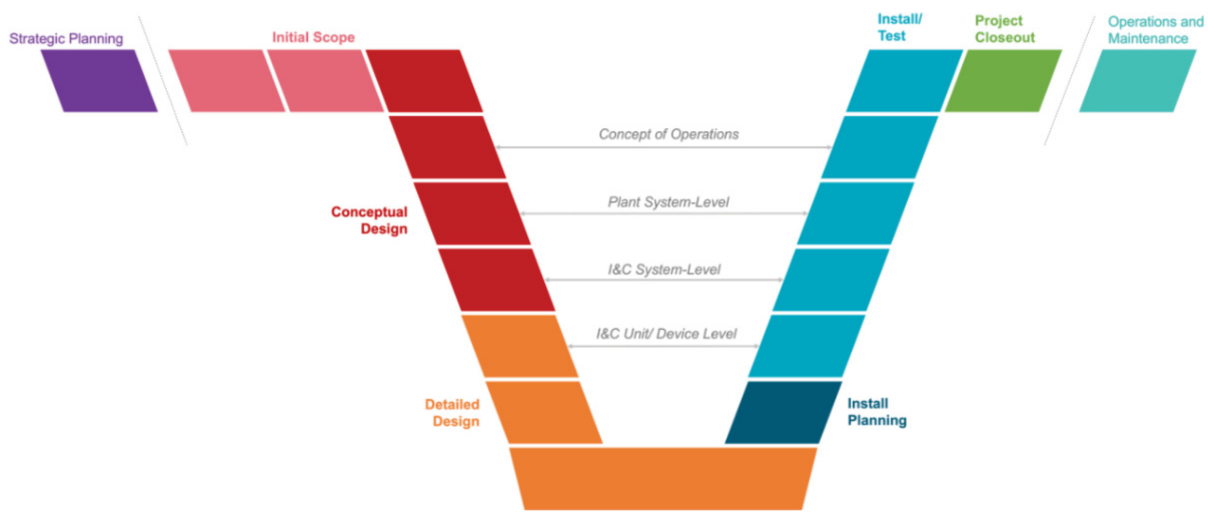


Figure 5. Systems engineering Vee model.

The Vee model has two notable characteristics to its shape. First, the x-axis (left to right) depicts the time to characterize key systems engineering phases across the project lifecycle. Second, the y-axis depicts the level of detail to which the system is defined and tested. That is, the beginning of the Vee model (top left) depicts that the system under development is scoped and designed at a high level. As the project matures, the system is further decomposed. The left side of the "V" indicates phases tied to requirements development and includes project scoping and design. The right side of the "V" indicates phases tied to system integration and includes V&V. The crosstie arrows that link design to testing are positioned across the different layers of the "V" curve. These crossties explicitly represent different levels of decomposition moving down the "V". The layers of the "V" towards the top comprise higher-level requirements and the layers of the "V" moving downwards contain more detailed requirements that are part of the higher-level requirements.

From a DEG perspective, an important characteristic of the Vee model early in the project lifecycle is determining where the impacts of the modification(s) are in terms of residing on the Vee model. That is, what level of abstraction on the Vee model do the elements of the planned modifiactions impact. Significant digital modifications may impact the entire concept of operations (e.g., refer to Table 1). On the other side of the spectrum, a small modification (e.g., replacing a paper chart recorder with a digital recorder) would be nearly like for like, and its focus would be at the device level of the "V" curve. The greater the change in terms of scope, complexity, and plant management concepts in its current state, the greater reason to focus higher on the Vee model.

In dealing with complexity, it should stand to reason that the vision of the system is often less concrete and oftentimes continuous iteration within the project is needed to add clarity. This is inherent to the Vee model, so as the system is matured and individual systems are developed, the progression up the right side of the "V" indicates greater levels of assurance through system integration and testing. At the highest level, the concept of operations is defined, and the requirements derived at this level inform subsequent plant systems, I&C systems, and devices. System integration then starts at the lowest level and progresses up the "V" curve. For HFE, the highest integrative testing as part of V&V is integrated system validation (ISV) and is described in detail in NUREG-0711 (2012).

The systems engineering framework and Vee model are also inherent to recently developed LWRS Program guidance for HTI documented in INL/EXT-21-64320 (Kovesdi et al., 2021). In fact, the HFE guidance described in INL/EXT-21-64320 is based on a systems engineering approach. The HTI methodology can be fit to the Vee model, as shown in Figure 6, where the HTI methodology is embedded within the "V".

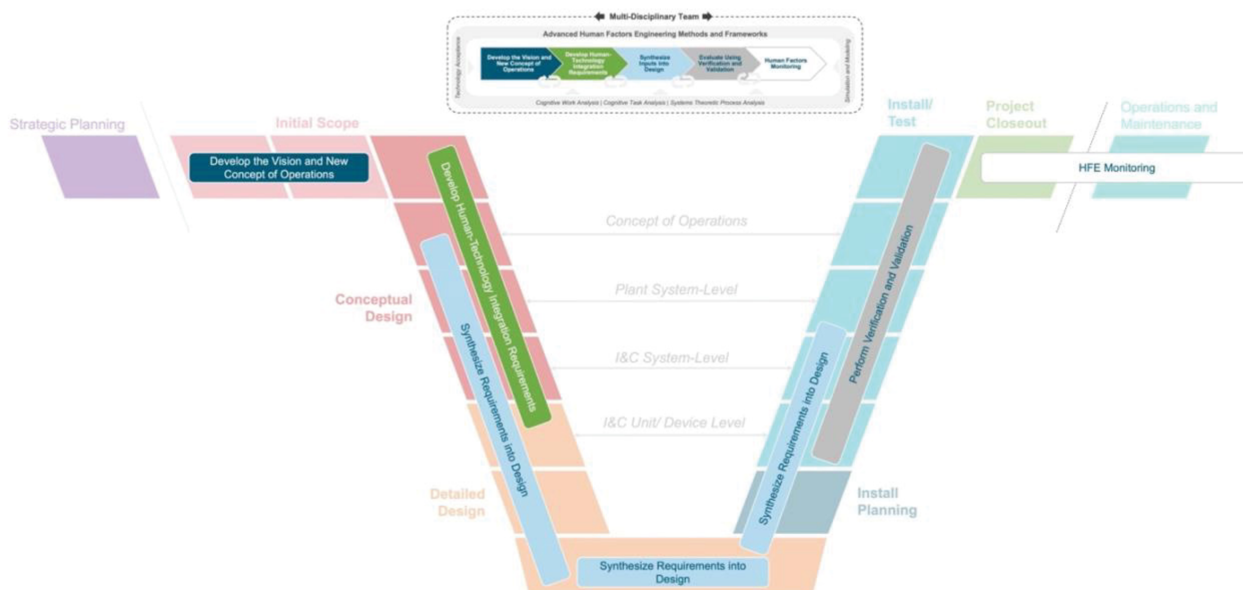


Figure 6. Vee model with the LWRS Program HTI methodology overlaid.

Developing the new vision and concept of operations (i.e., the first HTI phase shown in teal) is ideally done during the initial project scoping within the larger systems engineering Vee model. By ensuring that

HTI and HFE are integrated early within scoping, high-level requirements can be developed that account for stakeholder needs (e.g., operators), business needs (i.e., cost justifications), and HFE design principles. While it may be assumed that the vision and concept of operations may be further defined as the project matures, having a high-level vision that drives requirements in such a way can provide clarity to the design to ensure safety, reliability, and overall consistency across the digital modification project and for future digital modification projects.

Detailed HTI requirements are then developed from the vision and concept of operations. These requirements will define the use of digital human-system interfaces (HSIs), automation, alarms, and procedures. The requirements will become more detailed, specifying the functional requirements of these digital technologies and will subsequently inform design of the technologies. V&V of these technologies are then performed throughout the lifecycle and culminate at ISV. Iteration between requirements development, design, and early V&V is typical, before leading into ISV. The specific HTI and HFE activities performed throughout the systems engineering lifecycle can be further characterized in Figure 7, herein defined as the Integrated Digital Environment Roadmap. The figure shows key activities performed by different LWRS Program research areas, including ION, digital infrastructure, HTI, and DA&A. The systems engineering phases, as described in the DEG, are shown as the gray columns. For purposes of this work, only the HTI element is emphasized in the figure.

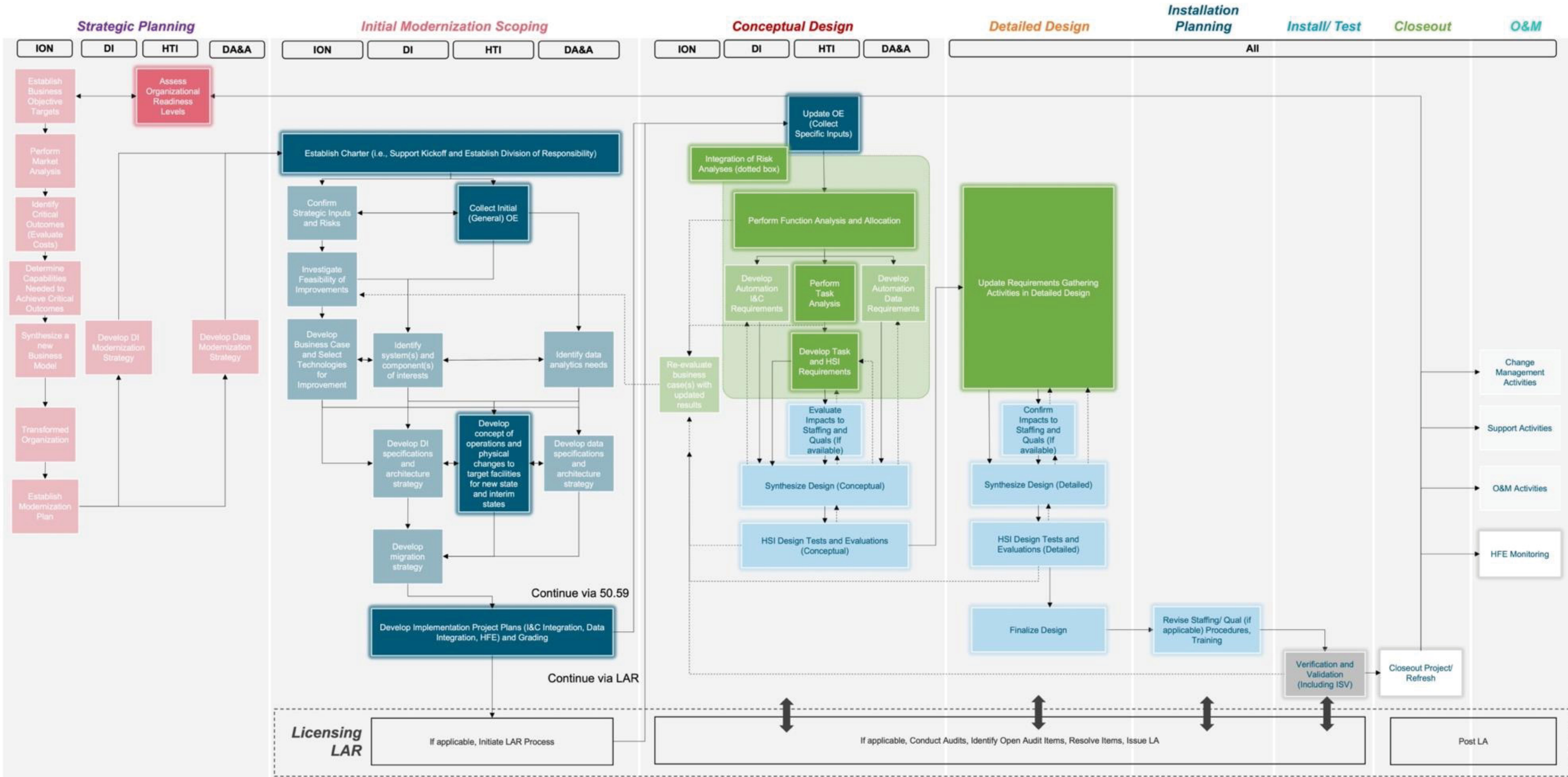


Figure 7. Integrated Digital Environment Roadmap.

The following subsections summarize the HTI activities highlighted in the Integrated Digital Environment Roadmap (Figure 7). Each of the systems engineering lifecycle phases, as defined in the DEG, are portrayed as the subsections describing the HTI activities.

2.1 Strategic Planning

The strategic planning phase is the only phase not described in the DEG (EPRI 3002011816, 2021). That is, this phase is performed before the initiation of a major digital modification and focuses on identifying opportunities across the plant to modernize, following the business needs. HTI's role in this phase is to provide input into assessing the organization's readiness for change. This activity is new and is currently being defined, following research that is outside the scope of this work.

2.2 Initial Modernization Scoping Activities

Initial modernization scoping refers to the identification of systems and components to be upgraded within the bounds of the project (EPRI 3002011816, 2021). This phase involves establishing a clear business case for the modifications and identifying the extent of the modernization (e.g., determining if digital modifications will be narrow or far-reaching, such as impacting the concept of operations), as well as determining the schedule on which the planned upgrades are to be implemented. Stakeholder needs and design tradeoffs are also identified and prioritized in this phase.

HTI and HFE are especially important at this phase to collect stakeholder needs, identify existing design issues (i.e., operating experience [OE]), and ensure that the design incorporates HFE design principles. All three of these inputs are pertinent in the identification and prioritization of requirements that will drive conceptual and detailed design. There are notable HTI activities performed under scoping. Initial activities broadly include establishing a charter, collecting initial OE, and developing a vision and new concept of operation. These activities will subsequently inform implementation planning, otherwise described as developing an HFE program plan (NUREG-0711, 2012), and are summarized next.

2.2.1 Establish Project Charter and Develop Division of Responsibility

The project charter identifies the utility and plant leadership responsible for initiating plant modernization activities that support the vision (EPRI 3002018428, 2020). The modernization effort objectives and a division of responsibility are generally defined in this phase, which specify the project scope and boundaries, the scheduling of each modification phase, as well as a list and description of each team member's role. Stakeholders are also identified and include plant personnel from senior management, licensing, engineering, operations, vendor(s), HFE, and other support organizations.

2.2.2 Collect Initial Operating Experience

Collecting initial OE offers one of the first opportunities to collect stakeholder feedback and design input for the modernization scope. The scope of OE here spans input from the utility and vendor if the vendor has been selected. Design input from operations should identify:

- Troublesome, problematic, and challenging tasks performed with the existing equipment
- Known HFE deficiencies with existing equipment
- Preferences for MCR enhancements, including alarms, digital HSIs, compact workstations, and automation.

Additionally, it can be helpful to observe operators performing tasks in the existing MCR to collect contextual data that will be critical to ensure established site conventions are accounted for in the requirements and design. It may also be helpful to collect OE related to vendor-specific conventions if a select technology or vendor has been identified. This input can inform what is technically feasible. The collection of OE provides input into many of the subsequent HTI activities, including developing the vision and concept of operations, described next.

2.2.3 Develop the Vision and New Concept of Operations

There are two critical outputs of this activity, including the development of a new vision[b] and new concept of operations. The new vision characterizes a succinct description of the ideal trajectory for a large-scale modernization project in terms of the proposed I&C architecture and use of HSIs (i.e., see IAEA No. TR-T-2.1, 2021). The vision describes the physical changes to the control centers in terms of the proposed architecture and interfaces by which plant personnel will operate, maintain, and support the plant (Kovesdi et al., 2021). It is written at a high level and is overarching regarding its consideration of different project stakeholder needs, encompassing a broad range of considerations from operations, training, maintenance, engineering, human factors, and licensing (EPRI 3002004310, 2015).

Complementary to the vision, the concept of operations describes the vision in terms of how it will be followed in performing its mission and functions; it also identifies and defines the plant personnel's roles (IAEA No. TR-T-2.1, 2021). Put differently, the concept of operations:

> *…defines the goals and expectations for the new system from the perspective of users and other stakeholders and defines the high- level considerations to address as the detailed design evolves*. (adapted from NUREG-0711, 2012)

The concept of operations is a high-level definition of many considerations relating to how personnel are expected to operate the plant. The intention is to promote reactor safety, plant reliability, and excellence in operations. Definitions can include information such as crew size and composition; how to operate under different plant conditions, roles, and responsibilities; and how the crew is coordinated and supervised (EPRI 3002004310, 2015).

The concept of operations may influence a site's conduct of operations, depending on the extent of the modifications, particularly if there are impacts to procedures, training, staffing, and qualifications. The conduct of operations exists to ensure high-quality plant safety and performance. A detailed review of the conduct of operations can be referenced in U.S. NRC Standard Review Plan NUREG-0800 Chapter 13, *Conduct of Operations* (1999).

To control room operators, this means not making any errors that risk personnel or plant safety. It also means operations can manage all plant situations in a timely, safe, and accurate manner. The organizational conduct of operations defines the high-level expectations and is useful when defining the performance goals of proper HTI. However, operators are uniquely aware of the actions, responsibilities, and plant responses that make them successful in meeting the expectations of the conduct of operations. Therefore, their input in the HTI process is paramount to successfully creating a control room environment that can harmoniously assist the operating crew and meet the organizational demands of the formal conduct of operations.

Collecting stakeholder needs and operational input is typically iterative in nature (Kovesdi et al., 2021). Focused activities include design workshops, technology demonstrations, and focused human factors studies can be used to collect this input, as well as evaluate certain design tradeoffs and build a technical basis for key design decisions. The vision and new concept of operations will serve as key inputs to many subsequent project activities, including developing a migration strategy, developing implementation plans, and performing conceptual and detailed design activities, such as function analysis and allocation.

2.2.4 Develop an Implementation Plan (Human Factors Engineering Program Plan)

Project implementation plans refer to the development of an HFE program plan and subsequent HFE project plans. The HFE program plan ensures that the modifications meet the regulatory, project, and stakeholder requirements as well as expectations concerning HFE. The HFE program describes how HFE

---

[b] Common terms for the new vision include new state vision, end state vision, and endpoint vision. These terms all refer to the same concept.

activities will be managed and executed across the project lifecycle and is one of the 12 elements described in NUREG-0711 (2012) and should include the program's goals and scope, HFE team and qualifications, processes and procedures for execution, issue tracking, and application of the remaining 11 HFE elements. Important considerations in developing an HFE program, as referenced by Kovesdi and colleagues (2021) and Joe and colleagues (2018), include:

- Ensuring that a graded approach is considered for planning and executing HFE activities, such as those described in NUREG-0711, including grading the level of HFE involvement and documentation
- Early and iterative involvement of HFE with operations, training, and other project team members
- Use of enabling tools, such as simulators, modeling tools, and user-centered design approaches.

It is important to note that the migration strategy in achieving the new vision and concept of operations is often performed as a phased approach, rather than a single large modification (EPRI 3002011816, 2021). The implementation of each phase can thus be planned around specific plant activities, like outages, and can ensure a smoother transition from the existing to new state. With this, certain migration phases may be more involved than others whether involving greater transitional steps from before and after or based on the type of systems impacted (e.g., safety-related versus non-safety). Figure 8 illustrates a common grading approach. The level of HFE involvement for a specific migration phase is determined first by primary risk factors associated with plant safety, personnel safety, and economic risk. Secondary factors are then accounted for to adjust the grading based on complexity, which considers the number of impacted systems and functions, the number of impacted HSIs and tasks, and the degree of change regarding the concept of operations, such as from added levels of automation.

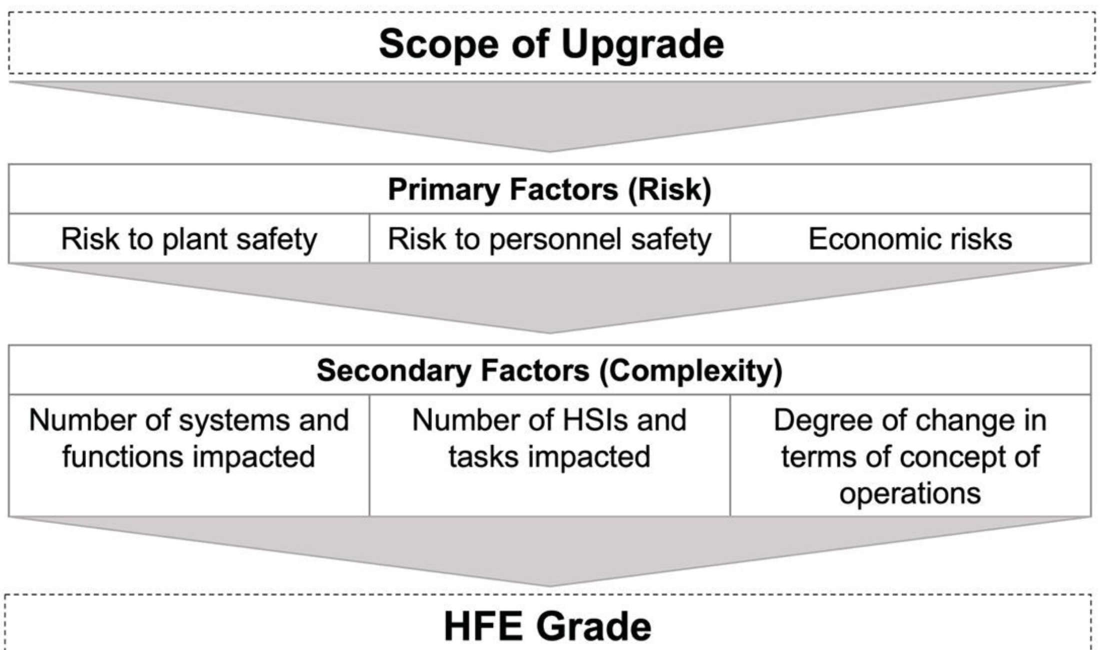


Figure 8. HFE grading considerations.

2.3 Design, Installation, Testing, and Project Closeout Activities

The HTI activities that occur in design (i.e., conceptual design and detailed design) entail the project-specific HFE activities described in the HFE program plan and follow a graded approach. These activities can be broadly characterized by the planning, analysis, and design activities described in NUREG-0711 (2012), leading into V&V. Figure 9 shows a crosswalk of the HTI activities described in INL/EXT-21-64320 to NUREG-0711; this crosswalk is also reflected in the Integrated Digital Roadmap, a common systems engineering lifecycle, previously shown in Figure 7 under conceptual and detailed design.

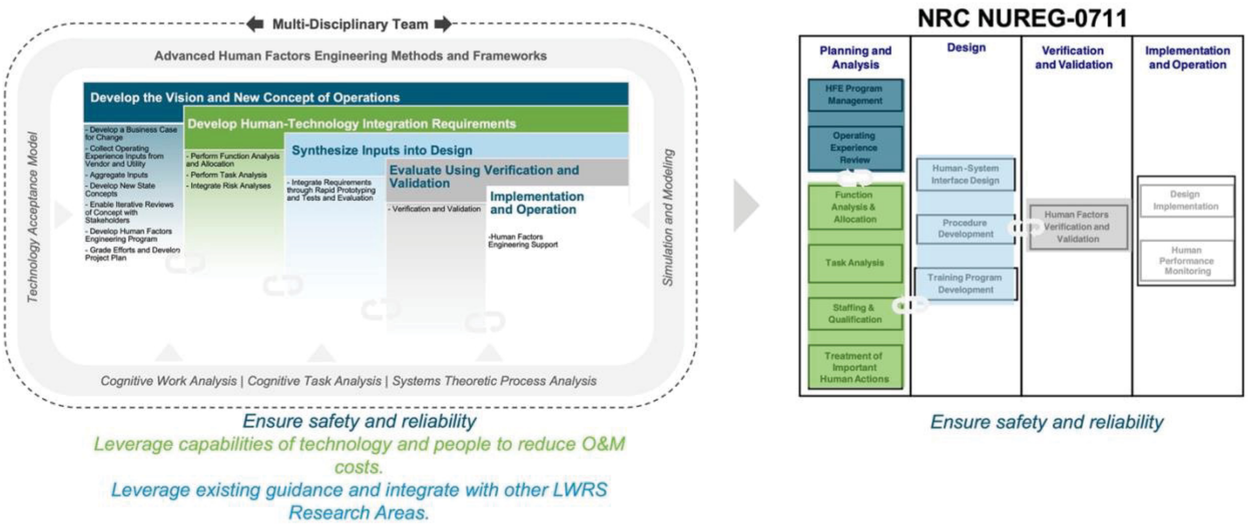


Figure 9. Crosswalk of the HTI methodology with NUREG-0711.

A detailed description of these HFE design activities is beyond the scope of this report. The reader may obtain a detailed understanding of these activities from:

- NUREG-0711 (2012) Sections 3–10
- EPRI 3002004310 (2015) Sections 3.3–3.10
- EPRI 3002011816 (2021) Sections 6.2–6.4
- IAEA No. TR-T-2.1 (2021) Sections 3–6
- IEEE Std 1023 (2020) Clauses 6.2–6.5
- INL/EXT-21-64320 (2021) Section 5.2–5.3
- INL/RPT-22-68472 (2022).

The resulting HSIs that come out of conceptual and detailed design are verified and validated through design verification, task-support verification, and ISV in transitioning to installation and testing. Figure 9 characterizes HFE V&V as the gray regions, which is also reflected in Figure 7. Detailed guidance on HFE V&V is reflected in:

- NUREG-0711 (2012) Section 11
- EPRI 3002004310 (2015) Sections 3.11
- EPRI 3002011816 (2021) Sections 6.4–6.6
- IAEA No. TR-T-2.1 (2021) Section 7
- IEEE Std 1023 (2020) Clause 6.5

- INL/EXT-21-64320 (2021) Section 5.4

A successful project after V&V activities will entail HFE monitoring that will continuously collect OE on the newly implemented I&C and HSIs. This OE will serve as subsequent input for later migration phases.

3. CASE STUDY

3.1 Enabling Human Factors Tools

The enabling human factors tools are used as part of the HFE activities to enable operators to understand planned changes and modifications in the MCR and provide feedback on the concepts to engineering and design teams. Exposing operators to different human factors tools allows operators to experience new ideas and concepts for the MCR that will help with maintaining situation awareness of operating conditions in the plant.

3.1.1 Simulation Tools

3.1.1.1 Site Training Simulator

The partnering facility has two simulators used to present the as-is state of the MCR, as well as their initial digital upgrades. Using a simulator that duplicates the control room environment to pilot control room upgrades gives operations personnel the opportunity to familiarize themselves with the digital I&C before the technology is installed. The training simulator enables the collection of early OE on existing operational conventions and feedback on the newly available digital I&C by allowing the design team to observe operators and collect feedback.

Figure 10. Training simulator at Farley Nuclear Power Plant.

3.1.1.2 Human System Simulation Laboratory

The Human System Simulation Laboratory (HSSL) is a full-scale, reconfigurable simulator that can be used to visualize the current MCR and proposed modifications (Figure 11).

Figure 11. Use of the HSSL for the Static Concept of Operations Workshop.

The HSSL is comprised of a full-scale reconfigurable virtual nuclear power plant control room simulator. Each of the 13 utilized bays hosts three 55” touchscreen flat panel video display units (VDUs). These bays are configurable to approximate the MCR layout, presenting both the existing MCR and endpoint vision. This enabled visiting operators and other stakeholders to easily envision design changes and impacts on operations while engaging in scenario walkthroughs.

3.1.2 Three-Dimensional Modeling and Virtual Reality

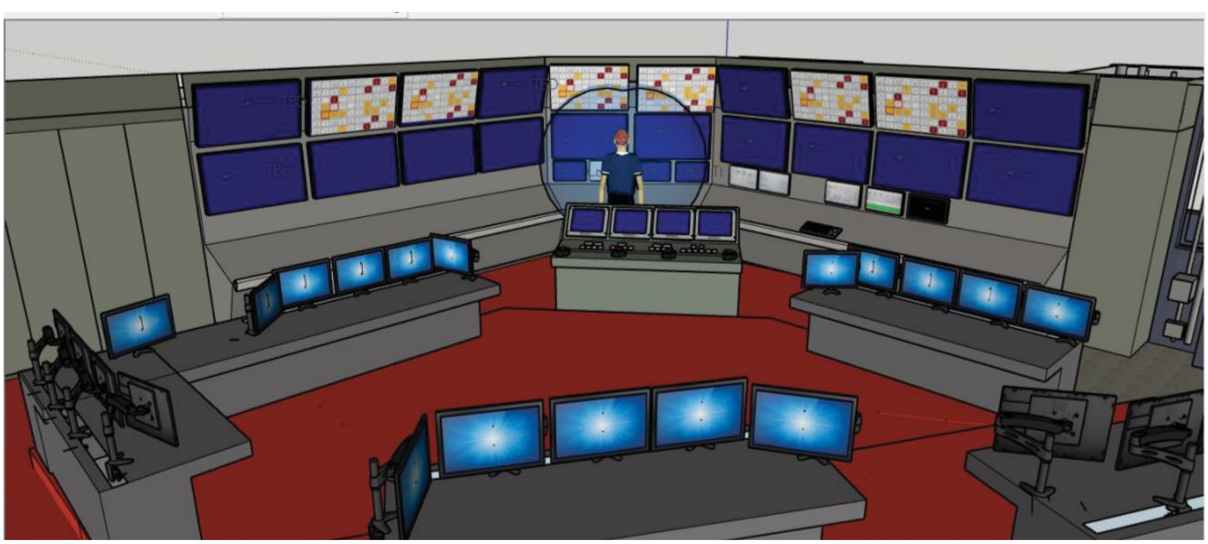


Figure 12. Example use of three-dimensional (3D) modeling to present a concept of the endpoint vision.

3D models are useful tools to visualize changes made from the current state to the new endpoint vision of the MCR. The 3D models help enable effective communication and visualizations with stakeholders, engineering, and design teams to show how new states in the MCR will look (Mohon & Kovesdi, 2022).

The models also support early and formal human factors MCR evaluations by applying human factors guidance, such as NUREG-0700 and other guidelines, directly into the 3D model. For instance, an early evaluation of the 3D models can be used to review changes, such as the placement of new HSI displays or changes to equipment or furniture. Digital human models (DHMs) are then added to the MCR model to identify anthropometric considerations, such as sight lines, legibility, and the functional reach of proposed modifications from the seated and standing workstations. In addition, 3D models may support OE review and function analysis and allocation when performing knowledge elicitation activities. This may be achieved by using the 3D model to provide visualizations to operations and stakeholders during workshops or meetings. The Trimble Sketchup tool allows images and other documentation to be imported into the software to develop the 3D models. Images and documents were provided by engineering and design teams to create visualizations in the 3D models of the equipment, instrumentation, and operational areas in the MCR. 3D models are reviewable by engineering and design teams prior to presenting the models to operations personnel for review.

The 3D models can be further utilized in virtual reality (VR). A VR immersion of the 3D model endpoint vision can be developed and presented at the Center for Advanced Energy Studies Visualization Laboratory (Figure 13).

Figure 13. Example use of VR to present a concept of the endpoint vision.

To be implemented in the VR environment, the endpoint 3D model is converted using Unity to create an MCR VR representation. This immersive environment allows operations personnel to see the endpoint vision in first person. A VR headset creates a realistic MCR visualization for operations personnel. VR can populate displays with anthropometrically and perceptually accurate information to provide a sense of legibility and visibility of information on the screens.

3.1.3 Electric Power Research Institute Endpoint Vision Worksheets

As described in EPRI 3002004310 (2015), the worksheets should be considered living documents subject to change as new problems and opportunities are identified and lessons are learned or as plant goals and priorities change. By capturing the original basis for the endpoint concept, changes proposed further down the line can be considered in light of the original intent. The worksheet includes columns of information sorted into the existing concept of operations, expected changes, and HFE impacts and considerations. Topics discussed and evaluated included those under normal and abnormal operations. These worksheets allowed Idaho National Laboratory (INL) personnel to identify relevant HFE impacts and considerations by topic related to changes in the endpoint vision. See Appendix A for the templates used in this work.

3.2 Human Factors Activities Performed

The enabling tools described in Section 3.1 all served to capture different aspects of OE from nuclear power plant operators. Applying diverse methods helped direct conversation towards functional topics and environments that provided different visual and environmental cues to operators. All this was done to gain a comprehensive understanding of the impact the planned control room modifications will have on how work is performed in the control room.

It is from this information that the HTI requirements can be developed. The perspectives and experiences can be processed through existing conduct of operations and HFE principles to identify control room design elements that require revision or focused consideration. The following sections detail this method and how information was collected from operators, tracked using a living concept of operations document, and used to create a more complete modernized control room vision and concept of operations.

3.2.1 Collect Initial Operating Experience

Operators have a unique understanding of how their plant operates. They understand both the organization expectations around plant operations (i.e., conduct of operations) and how to best achieve those expectations in the control room given the plant's operating characteristics (i.e., OE). As experienced during this effort, operator engagement began once an endpoint vision was first developed. The endpoint vision served as a high-level example of the modernization goals and a foundation to begin discussion regarding how current operations will be impacted and the potential of future operational conduct. As such, the endpoint vision for the utility control room and transitioning phases is still in the conceptual phase of development.

The initial scoping phase is the most flexible phase, as the design realization is less restricted by the potential project constraints; human factors considerations and operator feedback has the greatest opportunity for impact to drive the requirements of the vision and new concept of operations. Therefore, the effort to gather operational feedback at this point sought to inform multiple perspectives that support the development of HTI requirements to reveal the implications the current design concepts have on control room operations. The digital modernization framework referenced earlier contains a stage for initial modernization scoping. At this stage, the first HTI-specific activity was collecting operator experience to use as inputs to inform efforts in all other swim lanes from the Integrated Digital Environment Roadmap (refer to Figure 7) that include:

- Confirming strategic inputs and risks
- Investigating improvement feasibility
- Identifying system(s) and components of interest
- Identifying data analytics needs.

The modernization effort of our partnering utility is planned in a multiphase implementation plan toward a fully modernized control room. Therefore, not only is the final endpoint vision important to analyze from an operational perspective, but the migration strategy in achieving the vision at each interim phase must also remain operable and support the operator capability to adhere to the plant's conduct of operations, expectations, and responsibilities. For instance, most nuclear power plant MCRs require plant manipulations to take place "at the boards" from a standing position. Modern control rooms, such as the Westinghouse AP1000 pressurized-water reactor MCR or small modular reactor NuScale power MCR, have a seated approach to operation. The two advanced plant examples do not have to maintain operations during interim phases that may mix seated and standing methods of operation. However, legacy plants planning to digitalize their plants and control rooms must consider how each phase will be operated and managed after implementation and before complete modernization.

Operators have in-depth familiarity with what systems and processes are difficult to operate. They also understand the information and control requirements for important or time-sensitive processes that require peak operator performance. Therefore, their experience can help strategically guide and outline the systems and components that, if transitioned as a group, would help maintain operational expectations. Also, within these systems, there may be opportunities not yet acknowledged for providing improved data analytics or integrated information to support faster information processing and response selection in operators. Working back from operational needs influences the business case and development of the digital infrastructure required during each phase.

The early delineation of systems and components that should transition together develops a clearer picture of the feasibility of each phased implementation. Budget, timelines, and physical modification considerations are all impacted by the information provided by operators regarding transitioning systems to modern control applications. Also, when faced with more stringent feasibility constraints, the OE information gathered provides the project team with a greater capability to support operators through displays, ergonomics, or information integration to bridge the constraints in a manner consistent with the conduct of operations.

All the OE gathered to this point informs the tangential steps in developing the initial modernization scope that funnels to the next major action in HTI efforts, developing a new concept of operations and confirming the physical changes to target facilities for the final and interim states. Nuclear power plants have an expectation of excellence in operation that is defined in their conduct of operations. A full-scale modernization effort will impact an operator's ability to meet those expectations. To manage these impacts, HFE teams develop a concept of operations to track and identify how modernization efforts may positively or negatively affect plant performance, where positive impacts are sought and potential negative impacts are identified and removed or mitigated to the extent possible. This ensures that the modernization efforts are least disruptive to operations during the transitioning phases and that the endpoint is an improvement over the current control room capabilities.

It may be useful to think of two different concept of operations documents. One represents how the control room will be staffed and operated once the endpoint vision has been reviewed and tentatively established. The end-state concept of operations acts as the goal to deliberately move towards. It can inform tradeoff decisions, help guide the transitional phases, and prepare training and operations for working in the future control room. The second is a living document tied to the more fluid transitional phases, encompassing the migration strategy at each phase in achieving the vision. The role of the latter concept of operations through the transitional phases is tracking human factors considerations and constraints that require further review and analyses before work begins on the next phase. Understanding how these two documents are used throughout the Digital Integration Roadmap shapes how the information is collected and recorded.

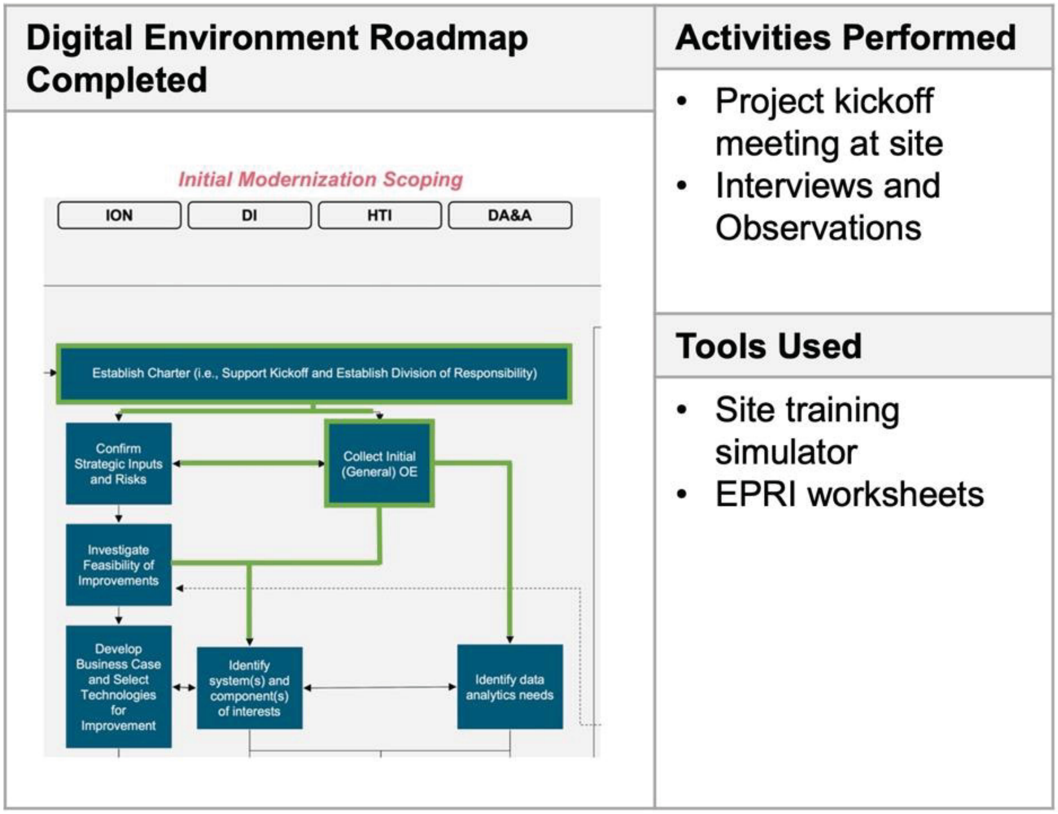


Figure 14. OE element of the Digital Environment Roadmap.

The tools described in Section 3.1 all offer different advantages towards eliciting operating knowledge during OE gathering activities. The approach taken here broadly involved familiarizing operators with the endpoint vision and anticipated control room technologies that make up the modern control room concept. Knowledge elicitation was focused on concept of operation categories based on the EPRI endpoint vision worksheets provided in EPRI reports 1010042 (2005) and 3002004310 (2015). The worksheets provide a holistic accounting of the activities performed in a control room during both normal and abnormal operations. To better track HF impacts and future considerations, an additional column to the left was added for tracking human factors impacts (Table 2). See Appendix A for details.

Table 2. Example of an endpoint vision worksheet.

Normal Operations			
Topic	**Existing Control Room**	**Endpoint Vision**	**Human Factors Impacts**
Monitor the plant process, systems, and equipment, including performance monitoring	Captures how operations currently manage the topic column based on the formal conduct of operations and OE	Captures the technology and changes the endpoint vision has that may impact how current operations manage the topic column	Captures the specific expected impacts on operations based on the endpoint vision column content that has been or will be addressed

To date, two primary activities collected operations input. The first activity took place at the plant undergoing modernization wherein their training simulator had received some updated displays and controls and operators were interacting with the simulated upgrade for the first time. A second activity occurred at INL's HSSL wherein the plant control room was statically displayed on the digital display bays (refer to Figure 11). 3D models and VR of the current and future control room were displayed on a separate large visual display (refer to Figure 12 and Figure 13), and the concept of operations worksheets were visible to a crew of four operators among other stakeholders involved in the modernization effort. The time in between the two activities was spent iteratively applying lessons learned during the initial activity to be reviewed and vetted by the operations crew present at the second activity. Together, a concept of operations was developed for tracking design justifications, feasibility, needs, and improvements to the endpoint vision.

3.2.1.1 Project Kickoff Meeting

The self-titled "kickoff" meeting took place at the partnering plant's control room simulator. This simulator is being used as the prototype for each modernization phase. It allows operations the opportunity to familiarize themselves with control room updates during training exercises and provide feedback on the configuration. Attending this kickoff allowed the project team to observe operator reactions to digital upgrades, such as digital system displays, digital controls, and navigating displays located on the control boards.

Notes were collected documenting operator feedback and reactions surrounding upgrades. Key topics of discussion included the expected MCR changes, alarms, concept of operations, communications, data logging, displays, hybrid states, maintenance and testing, procedures, shift turnover, situation awareness, and soft controls. In addition to acquiring general input for HFE analyses, this early OE data prompted considerations and investigations of potential features, capabilities, displays, and opportunities for automation.

This meeting also afforded the project team an opportunity to familiarize themselves with the control room environment, layout, and operations. Once operators had run through their training exercises, the project team was able to talk with them. During these discussions, the project team referenced the endpoint vision worksheets to get operator input on all the activities performed in the control room and how the initial upgrade either supported those activities or required further improvement. These discussions also conveyed some of the nuanced or cultural interpretations and actions operators employ to achieve the expectations conveyed in the company's formal conduct of operations. Establishing this clarity between end users and the project team supported more effective future communication and understanding of user needs and expectations for future control room capabilities.

3.2.1.2 Interim Development

Using the information gathered from the meeting hosted by the partnering facility, the project team began the concept of operations document. The team used the EPRI worksheets (see Appendix A for details) and the three right-most columns were populated with their associated information. The kickoff meeting, along with associated site materials (e.g., existing conduct of operations and final safety analysis report), provided content and clarification regarding the existing control room conduct of operations for each category (column one of the worksheets). Column one established a baseline to evaluate the impact on the current conduct of operations with the use of the proposed capabilities envisioned in the endpoint vision. Having the baseline also highlighted particularly important disruptions (e.g., human factors concerns as well as engineering challenges such as those associated with room constraints) that needed further deliberation. These disruptions became priority topics in follow-up meetings when operations personnel were brought in again for their experience and perspective.

During this time, the 3D control room models were developed, detailed, and discussed to ensure their accuracy based on current expectations of future phases. Early identification of physical constraints to control room layout, communication of staffing responsibilities, and location of operation , as well as spacing, legibility, sightlines, and ergonomic evaluations has greater accuracy and impact due to the accuracy of current 3D modeling capabilities. Identifying physical hurdles early on allows the project team to deliberate on alternate plans if some installation features are not feasible. These alternate plans and physical impacts are tracked in the concept of operations document as well.

The project team identified further knowledge gaps and prioritized HFE challenges that required more in-depth operator input. Tracked in the concept of operations document, these gaps and challenges established the purpose for the following in-person meeting hosted at INL in the HSSL. The activities and tools used in the follow-on activity were selected to inform the knowledge gaps and overcome the priority challenges.

3.2.1.3 Concept of Operations Workshop

The concept of operations workshop hosted in the HSSL at INL was designed to address numerous goals to elicit rich information from operators (see Appendix B for the agenda followed). Both the current MCR design and most recent endpoint vision were evaluated by operators during the workshop. To frame operators for what was expected of them, this workshop devoted time for operators to become familiar with the HSSL digital reconstruction of their current control room. Operators familiarized themselves with the static simulation by performing some talk- and walkthrough scenarios. These scenarios were selected based on what potential scenario candidates may be used during later stages in V&V activities. The operators performing this talk- and walkthrough activity served both as a baseline and a familiarization activity.

Operators were then shown advanced control room concepts that include plant and system overview displays (Braseth & Øritsland, 2013), computerized operator support systems (Boring et. al., 2015) advanced digital procedure solutions, computerized procedure systems, and the Analytics-Decision Support Advanced Procedure Tool (Kovesdi et. al., 2020). The intent was to introduce what advanced concepts for control room operations can do to support operations beyond digital like-for-like replacements and how MCR operations may transform as a result. Introducing them to advanced concepts was intended to prime operators to consider all possibilities, as later discussions involve reviewing the HFE impacts to their conduct of operations.

Operators also had exposure to a conceptual replication of their MCR endpoint vision configured both using the HSSL bays and a 3D model displayed within the laboratory for easy reference during the activities taking place in the laboratory. The 3D model could be manipulated in real time to both offer different control room views but also make changes reflecting operator questions and input. The flexibility and variety of interactions this activity offered helped immerse operators in a potential future environment, allowing them to explore and understand what is intended for their control room design.

Operators were invited to visit Center for Advanced Energy Studies to view a virtual representation of the MCR endpoint vision using VR. There, visualization researchers equipped the project team (i.e., especially operators) with head-mounted VR equipment to allow them to explore the endpoint concept physically and visually, being fully immersed in an accurate virtual representation of the physical space (refer to Figure 12). This activity demonstrated a different experience from the HSSL by providing operators with a clearer sense of the sightlines they may experience while seated at different workstations. Operators during the virtual immersion were able to walk around the control room and sit at the different sit-down workstation locations. The endpoint virtual immersion let operations personnel experience the new MCR state and helped to identify if there are anthropometric considerations present, such as sightline interferences, that could impact daily operations for maintaining a safe and effective state of plant operations. Several operators were able to experience the virtual environment and provide feedback on the location of displays, functional reach, and sightlines views of the new modifications. Their experience and feedback helped the project team develop questions for further discussions around the endpoint vision during the workshop for further operator needs and requirements in the MCR.

During the workshop, the EPRI endpoint vision worksheets were used to collect stakeholder feedback from an operations perspective. The worksheets provided in the EPRI guidance were intended to help organize thinking while developing the vision, providing a structure for defining the endpoint concept, as well as to document goals and objectives. The worksheets were displayed on a large monitor in conjunction with the walkthroughs. Using these worksheets, operations personnel were asked a series of questions by the project team about the endpoint vision design, using the EPRI worksheets, to verify the design and identify potential human factors issues.

3.2.2 Develop the Vision and New Concept of Operations Methodology

It is expected that nuclear power plants are operated at the highest regard for safety and secondly, efficiency. Utilities often define their expectations for maintaining these basic tenants in the conduct of operations, which is carried out by operators and other personnel alike. MCR operators in nuclear power plants are the most experienced personnel at maintaining these tenants and adhering to the conduct of operations. That is why their input is important when their control room environment is about to be transformed. While the basic operating tenants are unlikely to change, the method to achieve them is likely impacted. Therefore, a new control room must be designed to support operator adherence to these tenants. As part of ensuring the transformed operation center continues to support safe and efficient operations, both the endpoint vision and new concept of operations must be developed and iterated as required.

The endpoint vision referred to the physical arrangement of the control room. This included *how* and *where* information is displayed or accessed, *where* operational control takes place, and the *ergonomic* considerations for operation personnel. The endpoint vision was developed first as a concept then was shaped by constraints of the physical control room, including characteristics such as structural feasibility, accessibility, and available usable space in the current control room. It was also designed based on the needs of and expected use by the operators. These operator requirements were tracked and reviewed using the concept of operations document.

The concept of operations document framed the actions and responsibilities of control room operators. This effort used the endpoint vision worksheets to record expected impacts to the control room environment, the needs of the operators, and how the endpoint vision will meet those needs and alleviate previous operational bottlenecks or difficulties. The concept of operations was developed using inputs collected from different stakeholders, including operations, licensing, engineering, and HFE (Figure 15). Having input from these diverse stakeholders ensured the completeness of the information in the concept of operations, such as by capturing specific engineering tradeoffs only identifiable by representative subject matter experts in those technical domains.

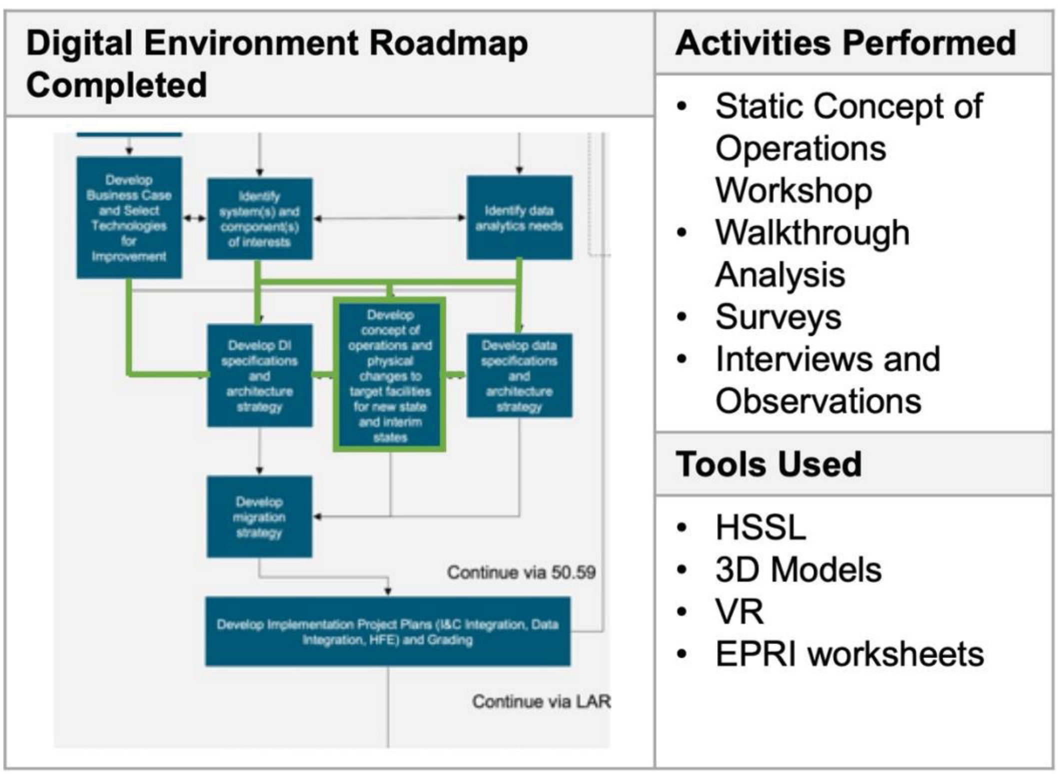


Figure 15. Develop concept of operations element of the Digital Environment Roadmap.

3.2.2.1 Developing the Modern Control Room Vision

3D models are useful tools to create visualizations of proposed MCR changes and modifications to share with stakeholders, operations, engineering, and design teams. 3D models are made to create visual representations of a scaled MCR that approximates the size and shape of the MCR. In addition, 3D models can be used for HFE activities, such as an evaluation and discussion of planned changes and modification in the control room with project stakeholders to determine the accuracy of the model and impacts to MCR operations.

Several 3D models were created prior to the operator workshop based on feedback from engineering and design teams for proposed modifications for the endpoint vision. The primary method for gathering feedback for the 3D models was presenting and sharing models via virtual platforms with engineering and design teams. Several Microsoft Teams meetings were used to review changes to the model and apply feedback to create new model iterations. Another method used for gathering feedback was sharing screenshots of the models for review and directly sharing 3D model Sketchup files. The 3D endpoint vision model was reviewed in-person with operation personnel during a workshop to gain additional feedback from operations on anthropometric considerations, such as sight, legibility, and functional reach. The following sections discuss the inputs, process, and outputs for developing the 3D models.

Inputs

Operators, who have extensive experience operating the plant, were able to provide early feedback into their vision for the future endpoint MCR during meetings during the initial kickoff meeting. Feedback was collected from operators during interviews, discussions, and walkthroughs of different plant scenarios. Operators discussed the need for additional workstations, hard controls for certain safety actions, and other requirements to maintain safe and effective plant operations. EPRI worksheets (EPRI 3002004310, 2015) were also used to collect feedback from operations on how they would like the future MCR to function in the endpoint vision. Feedback from operators was provided to the engineering and design team to aid in 3D model development on operations needs for maintaining situational awareness of plant conditions in the MCR.

The initial 3D model was developing using an AutoCAD file that was developed from laser scans of the MCR to accurately measure the control room, equipment, instrumentation, and controls. The laser scans and AutoCAD file were developed by a partnering engineering firm that was part of the project team. The AutoCAD files were shared with the human factors engineers to add visual details and images recreating the current MCR's equipment, controls, and workstations. Photo editing software (i.e., Adobe Photoshop and GIMP photo editor software) was used to combine image files together for use in the 3D model. The combined image files were used to represent the current location of display, instrumentation, controls, and indications on the standup workstations to provide a photorealistic representation of the control boards.

Other objects and equipment, such as monitors, keyboards, computer mice, and other equipment, were then imported into the model from the Sketchup 3D model library to represent current displays and equipment available at operations sit-down workstations. The project team evaluated the developed model from Sketchup with the AutoCAD file and laser scans to confirm display and equipment measurements. Monitors sizes were approximated from measurements taken from the 3D laser scan of the MCR and included in the model to represent operator sit-down workstations (Figure 16).

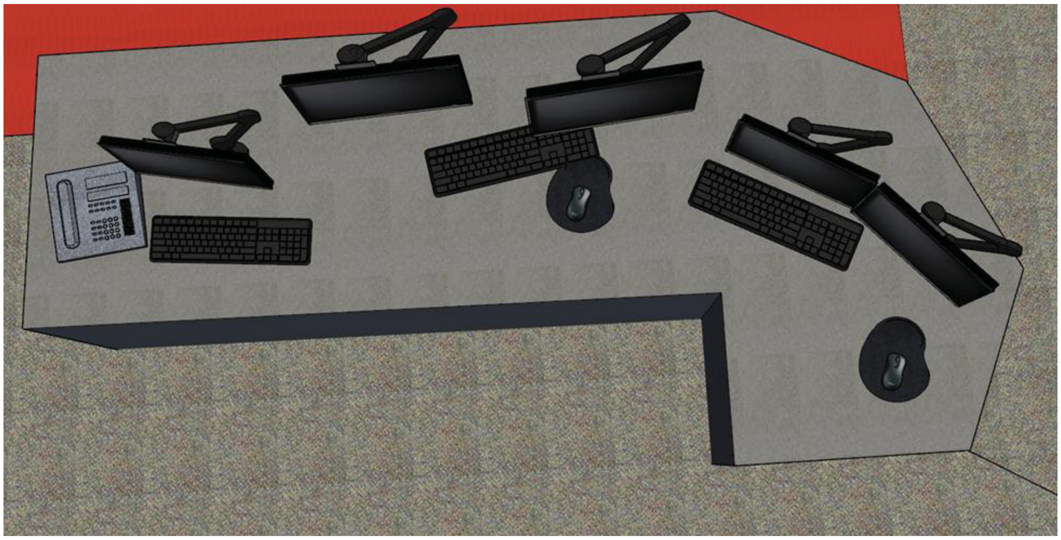


Figure 16. Image of 3D model workstation with displays and equipment.

Measurements were compared between the initial laser scan AutoCAD model and the Sketchup 3D model to check for accuracy between the files. Less than 0.2 inches were found between the different model showing that the Sketchup 3D model provides an accurate representation of the MCR. This allowed the HFE team to provide accurate visualizations of the MCR to stakeholders to review for accuracy.

Process

Once the initial 3D model was completed, human factors engineers from the project team were able to use Trimble Sketchup software to perform an HFE review for anthropometric considerations using guidance in NUREG-0700 (NRC, 2002). The NUREG-0700 (NRC, 2002) review is used to evaluate the control room to identify if potential HFE issues are present when making changes or modifications to the MCR. A Trimble Sketchup software extension called Ergo CGM Loader was used to create DHM representations of 5th percentile females and 95th percentile males to develop accommodations for approximately 90% of operators in the MCR by evaluating the smallest to largest anthropometric measurements in the endpoint vision design.

The DHMs were used as part of HFE activities to evaluate if new equipment or modifications would block operator sight lines when viewing information from the proposed VDUs on the control boards or in other locations. Functional reach was also evaluated with DHMs to determine if planned upgrades were within reach of the operators. Information legibility was also evaluated to determine adequate font sizes for operators to read the information from workstations and from a distance. Multiple 3D models, including the current layout, planned upgrades, and endpoint vision were developed and evaluated, using NUREG-0700 guidance, to provide visualizations and design recommendations for the endpoint vision and future states of the MCR.

It is worth noting that the development of the endpoint vision 3D models required several iterations. Several 3D model versions were created prior to the operator workshop based on project team discussions. A converged model was created based on project team consensus during these discussions.

Outputs

3D models of the current, planned modifications and endpoint vision were displayed to operators during a workshop activity to gain additional feedback on anthropometric considerations, such as sightlines, legibility, and functional reach. Operators verified that the 3D models were accurate and provided feedback on the endpoint vision for potential display modifications and locations to assist them with maintaining situation awareness of plant conditions. Figure 17 provides an example of a conceptual rendering of an endpoint vision analogous to what was used in these discussions with operators.

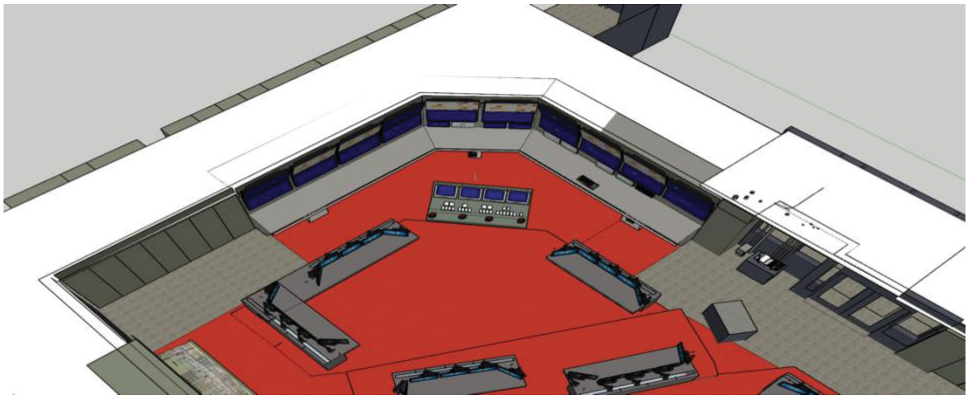


Figure 17. Image of conceptual endpoint vision MCR 3D model.

Prior to the workshop, changes to the MCR sit-down workstations were not discussed; however, operators provided feedback on the sit-down workstations that would help them maintain safe and effective plant operations. Modifications, based on operator feedback, were made to the endpoint 3D model sit-down workstations regarding safety display locations and adding in new sit-down workstations. These modifications were evaluated using NUREG-0700 (2002) to identify anthropometric considerations and if human factors issues would occur when adding in new sit-down workstations, such as obstructed sightlines of the new displays. To verify that information presented on what are currently the control boards is viewable without obstruction, the shortest DHM, the 5th percentile female, was used to evaluate sightlines from a seated position at the new workstations. The findings were shared with the project team to present the completed endpoint 3D model.

3.2.2.2 Develop New Concept of Operation

The development of a new concept of operations was done in tandem with the development of the new vision. The concept of operations describes the vision in terms of the plant personnel's roles in operations to promote safety, reliability, and excellence. This could include crew size and composition, coordination and supervision, roles and responsibilities, and operation under different plant conditions (EPRI 3002004310, 2015). Modernization efforts will impact operations, and each potential impact must be examined and mitigated to the extent possible to ensure the least disruption to operations during transition phases and at completion.

Inputs

HFE principles (e.g., EPRI 3002004310, IAEA No. TR-T-2.1, NUREG-0711) were used to ensure the interim phases and endpoint concept of operations support operators. HFE guidance is crucial to evaluating the proposed changes. HFE impacts under normal and abnormal operations and at each phase of modernization were carefully considered when developing the new concept of operations.

Operator experience regarding current and expected changes to the concept of operations is crucial in developing the new concept of operations. Operators have the most in-depth understanding of systems and processes, and their experience and knowledge regarding concept of operations were collected alongside the data collection pertaining to the new vision, using much of the same methods. Operators provided early feedback during the initial kickoff meeting as well as during the concept of operations workshop hosted at INL. Feedback was collected during interviews, discussions, and walkthrough analyses of plant scenarios. Endpoint vision worksheets originally provided in the EPRI reports 3002004310 (2015) and 1010042 (2005) were also used to collect feedback from operators.

Documentation of the plant's existing conduct of operations was used to identify the current roles and responsibilities of the operators, including the explicit duties of the operator at the controls, procedures throughout shift turnovers, and detailed responses to alarms. The current conduct of operations was used throughout the development of the new vision and new concept of operations to identify operator actions affected and evaluate human factors impacts throughout modernization phases and in the end state.

Process

In between the kickoff meeting and INL-hosted workshop, stakeholders met biweekly to continue the discussion and development of the MCR design and concept of operations. During these meetings, among other things, there was discussion of and sharing of documents pertaining to the existing concept of operations, including:

- Plant operation and monitoring during normal operation
- Plant operation and monitoring during transients and accident conditions
- Management of alarms under all plant conditions
- Coordination of all plant operators
- Enforcement of proper fulfilment of operating and administrative routines
- Authorization, supervision, and performance of maintenance operations.

From this, a description of the current concept of operations as well as the goals and expectations for the new state from the perspectives of stakeholders was developed. This described personnel roles, responsibilities and qualifications, operational impacts, HSI impacts, and failure management of the new instrumentations and control systems. This was reviewed by stakeholders, and feedback was integrated prior to the INL HSSL static workshop, where more OE was collected.

Throughout the workshop hosted in the HSSL at INL, current MCR design and endpoint visions were evaluated by operators using digital reconstruction of the current and future control rooms. Talk- and walkthrough scenarios were performed, and notes were collected on operator feedback. Advanced concepts were also presented to operators, to promote a consideration of how these advanced concepts might transform a modernized MCR design and operations. Throughout scenario-based walkthroughs and discussions, the 3D model could easily be displayed within the HSSL for reference and manipulation based on discussion and operator feedback. Operator and stakeholder feedback was documented throughout the workshop, using recordings, notetaking, and EPRI worksheets.

The EPRI worksheets were used to help organize thinking while developing the new vision and concept of operations, provide structure for defining the endpoint concept, and document goals and objectives. The worksheets include columns of information sorted into the existing concept of operations, expected changes, and HFE impacts and considerations. During the meeting at INL's HSSL, wherein models of current and future plant control rooms were displayed on the digital display bays, the concept of operations worksheets were visible to a crew of four operators and other stakeholders involved in the modernization effort, and each section of the worksheets was discussed and populated with feedback. These worksheets allowed INL personnel to identify relevant HFE impacts and considerations by topic related to changes in the endpoint concept of operations.

Outputs

The new concept of operations report served to define the goals and expectations for the new system. The report consisted of sections describing (see Appendix C for a table of content in the report):

- *Personnel roles, responsibilities, and qualifications.* This includes what personnel will be impacted by MCR changes and how staffing, workload, important human actions, communication, training, and procedure usage will be impacted.

- *Operational impacts*. Impacts such as how the plant will be managed by personnel during normal, abnormal, and emergency conditions.
- *The new HSIs, automation, and new control room features*. These features will support personnel in maintaining situation awareness and perform tasks.
- *Failure management of digital I&C and new HSIs*. This new concept of operations will serve as an important input in future HFE activities, which is described in the following section.

3.3 Use of Results

The primary products coming out of the HTI activities described in Section 3.2 comprised a 3D model of the MCR endpoint vision and a concept of operations documents. As previously discussed, the 3D model enabled the HFE team to perform anthropometric and ergonomic evaluations using NUREG-0700 in combination with DHMs on proposed layouts to evaluate the acceptability of the modifications from an HFE standpoint. The models were shared with the larger engineering team to evaluate other potential design considerations and tradeoffs, such as with accounting for seismic, cabling, and room constraints. It is expected that the 3D model will be considered a "living resource" and will be updated through subsequent planned HFE project activities.

The concept of operations document described the functional aspects of the proposed endpoint vision and explicitly documented the key differences in operational philosophies with using major HSIs, such as board indications, alarms, controls, as well as procedures. Its primary use will be informing fleetwide requirements for the utility's strategic modernization strategy. As such, the document will be used to inform procurement, system development, as well as focus and prioritize V&V efforts that will be part of individual design packages. An itemization of the likely uses of the results from this effort to subsequent HFE activities is presented in Table 3.

Table 3. Uses of vision and concept of operations for subsequent HFE activities.

DEG Phases	Subsequent HFE Activity	Use of the Vision and New Concept of Operations
Initial Scoping	Addressing considerations and tradeoffs that are fundamental to the vision	The vision and concept of operations identified potential design tradeoffs with the number of HSIs to use on the main control boards, as well as safety console placement. Impacts from transitioning from standing to seated were identified as part of focusing an early HFE study. The results can inform display design, HSI placement, automation, and the migration strategy. The results can also be used as a cross reference for other utility plant sites to ensure fleetwide consistency and document important differences, such as those inherent to the plant's design (e.g., being a pressurized- or boiling-water reactor).
	Developing an implementation plan	Grading individual design packages can be informed by the scope of the vision and identified migration strategy.
Conceptual and Detailed Design	Detailed OE review	Initial OE serve as a starting point for project-specific OE.
	Function analysis and allocation	Identified troublesome functions from initial OE can serve as input.
	Task analysis	Impacted tasks from impacted functions can serve as input.
	Risk analysis	Impacts to risk-important human actions can be integrated into risk analysis to provide a grading for HFE involvement across the project. Phases with significant impacts to plant safety and operational use will include greater HFE involvement.
	HSI design	The operational philosophy of the concept of operations and vision can inform the HSI style guide to drive the design of the HSIs across the fleet.

DEG Phases	Subsequent HFE Activity	Use of the Vision and New Concept of Operations
	Procedures	Impacts to procedures resulting from the HSI redesign and use of computer-based procedures can serve as input.
	Training	Impacts to training described in the concept of operations can serve as input. For instance, changes in automation and use of new MCR technologies, such as computer-based procedures, will be identified at specific migration phases and subsequently inform training impacts.
	Staffing	Staffing levels can be examined from the resulting vision and new concept of operation.
V&V	V&V	Specific scenarios, use cases, and impacted functions and tasks identified in early initial scoping activities can serve as inputs into V&V at specific migration phases.

3.4 Lessons Learned and Practical Guidance

Lessons learned from this demonstration are summarized broadly as the following five themes:

Lesson 1. An integrated team is critical in developing the vision and concept of operations

An integrated team is pertinent to the development of the vision and new concept of operations. The team composition should include key stakeholders, such as operations, engineering, vendors, and HFE. Figure 18 illustrates how intersecting key disciplines support the effective development of the new vision and concept of operations. That is, industry needs (dark blue), driven by business goals, operational requirements, and engineering and licensing considerations, must be accounted for to ensure that there is a clear value proposition, that the modifications align with operational needs, and that the modifications can be practically implemented with accounting for existing engineering and licensing considerations. Vendor input (green) must also be accounted for as early as practical to ensure that the industry needs can be achieved with the selected vendor offerings. If a vendor has not been selected, the industry needs should then drive the selection of a vendor. Finally, HFE principles (light blue) must be integrated early in the process to ensure that the requirements being developed, that offerings of the vendor do not introduce any human error traps, and that state-of-the-art HFE principles are implemented.

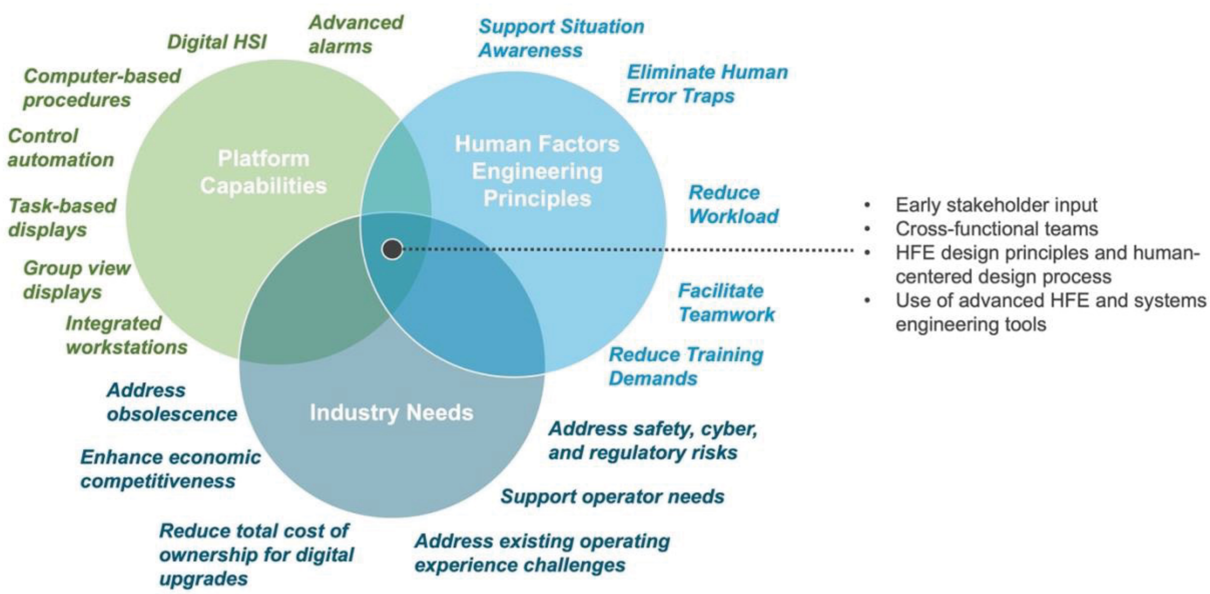


Figure 18. Elements of an integrated team.

This work demonstrated the use of an integrated team throughout the course of this project. For instance, key stakeholders from operations, engineering, licensing, and HFE were involved throughout the course of planned activities, including the kickoff meeting, iterative team meetings, and concept of operations workshop. The implications of this allowed the team to develop an endpoint vision and resolve tradeoffs with proposed design characteristics effectively and efficiently.

Lesson 2. Using demonstrations, prototypes, and workshops enable effective feedback from stakeholders

An important aspect to developing a new vision and concept of operations that goes beyond like-for-like replacement is stakeholder "buy-in." Operations, who will be the end users of the new digital systems, must accept the new technology to successfully implement it. A useful model of stakeholder "buy-in" is the Technology Acceptance Model (TAM; Davis, Bagozzi, and Warshaw, 1989). The underlying basis of TAM is that perceived usefulness and perceived ease of use contribute to technology acceptance, which results in technology adoption. There have been many extensions of TAM, one of which entails its use for nuclear power plant modernization, as shown in Figure 19 (Kovesdi, 2021).

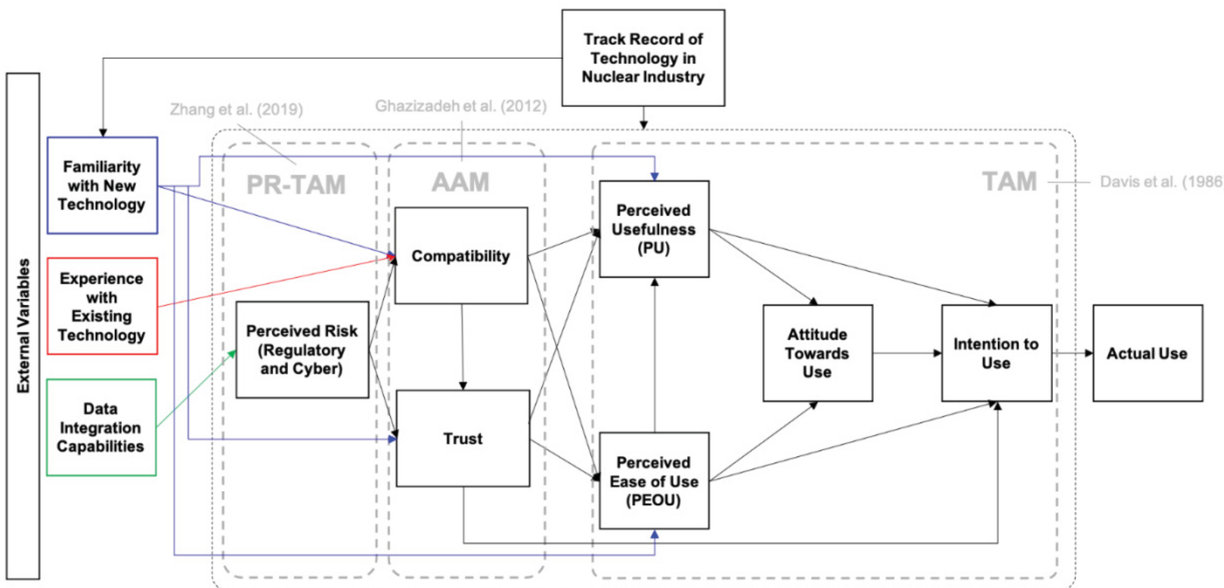


Figure 19. TAM for nuclear power plant modernization (adapted from Kovesdi, 2021).

Important elements of this TAM extension as it relates to the buy-in of advanced MCR capabilities entails the *familiarity with a new technology* (blue) and *experience with existing technology* (red). That is, the familiarity with a new technology, for better or worse, can influence one's trust and perceived task compatibility of that technology. One's experience with an existing technology also influences these attributes of trust and task compatibility. The use of demonstrations, rapid prototypes, and design workshops essentially provide exposure to these advanced concepts to support gaining familiarity with a new technology. Moreover, embedding operations throughout the design process further supports familiarity. To no surprise, a feedback questionnaire delivered to operations that asked about what tools were most useful suggested that these advanced tools were particularly useful in gaining exposure (Table 4).

Table 4. Most useful aspects for operations in concept of operations workshop.

Use of Advanced Tools	Use of an Integrated Team	Other
78% (7 of 9)	44% (4 of 9)	11% (1 of 9)

Table 4 shows that seven of nine operations members at the concept of operations workshops explicitly commented on the advanced HFE tools (i.e., use of HSSL, VR, modeling, and walkthroughs with the new concepts) being most useful. The rationale for these responses were characterized as allowing the team to gain more experience with the new endpoint concepts and to "see" these concepts through immersive tools like VR and the HSSL. Thus, a key recommendation is to apply these advanced HFE methods early, such as in developing the vision to align expectations with the new technologies, gain familiarity, and ensure stakeholder "buy-in."

Lesson 3. A top-down approach for defining the concept of operations is needed

A top-down approach to defining the vision and concept of operations is beneficial, particularly in helping the project focus its resources on actionable recommendations that have widespread impacts. Referring back to the Vee model (Figure 5) in Section 2 of this report, a salient feature is that higher-level requirements are typically developed first and later decomposed as the project matures. This effort followed a top-down approach, particularly in starting with defining key impacts in the way operations will perform their job functions in different conditions (e.g., in normal and abnormal conditions) using the capabilities featured in the envisioned endpoint vision. Notable topic areas included how teamwork, communication, situation awareness, workload, and command and control (i.e., referring to the way in which the crew perform their duties) would be impacted. For instance, the HFE input provided broad recommendations concerning the suitability of the workplace and workstations envisioned in the new vision. The project team was able to utilize 3D modeling and DHMs to evaluate workplace and workstation considerations like the viewability of VDUs and accessibility of remaining controls in the MCR.

The concept of operations document described the impacts of the vision on broad job functions across different plant conditions and was developed using tools like the EPRI endpoint vision worksheets. The concept of operations paralleled previous guidance provided by Thomas and Hunton (2019). That is, Figure 14 is adapted from Thomas and Hunton (2019), which shows that transformational change (i.e., going beyond like for like) begins at the top of the pyramid.

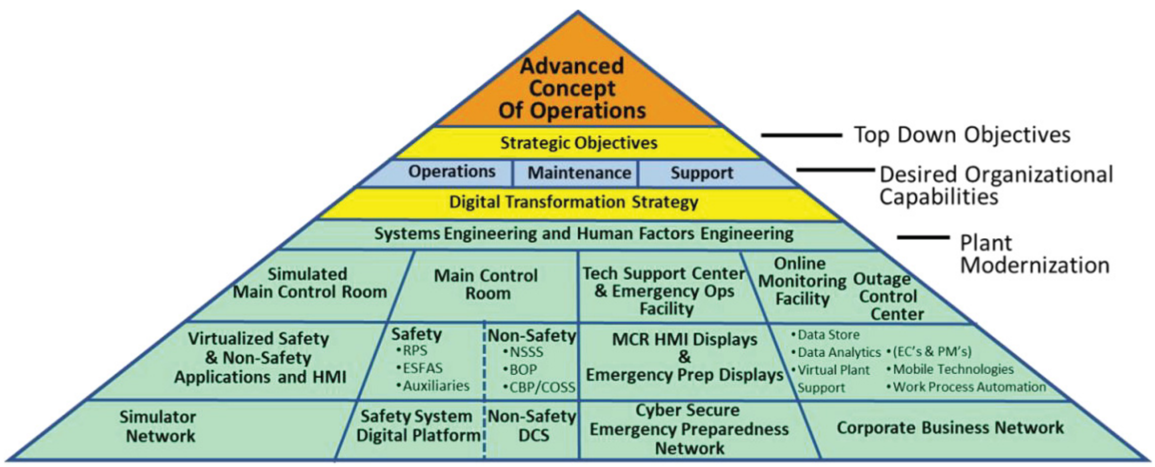


Figure 20. Advanced concept of operations pyramid (adapted from Thomas and Hunton 2019).

The focus must be on developing requirements for the concept of operations in terms of how it will fundamentally impact the enterprise. The requirements developed at this high (i.e., mission) level then drive the identification and selection of digital technology that fit within this mission. Thomas and Hunton (2019) further elaborate on characteristics that are inherent to a digital transformation:

- *Implementing a minimum set of foundational digital platforms to eliminate disparate, obsolete, and legacy I&C equipment and the costs associated with them*

- *Systematically consolidating the functionality of disparate, obsolete equipment to these platforms, moving beyond the like-for-like replacement model*
- *Exploiting these platforms to perform higher order functions, such as control automation, plant monitoring, surveillances, system health monitoring, and problem diagnosis, thereby greatly reducing workload across the plant organization*
- *Establishing a lifecycle support strategy for the foundational platforms so that technology investments are planned, executed, maintained, and refreshed in a continuous and deliberate manner.*

The concept of operation document and resulting endpoint vision were developed at a level to broadly consider these characteristics described in Thomas and Hunton (2019). For example, the EPRI worksheets were used to describe how operations perform certain job functions in the existing state, how they will perform job functions in the proposed vision, and what the HFE implications were. The vision characteristics were informed in combination with I&C best practices from Thomas and Hunton (2019). For example, using a minimum set of foundational digital platforms and leveraging these platform higher ordered functions were considered in this work. The results were also synthesized with HFE best practices, and important human factors implications were documented by cross walking the existing concept of operations to the new. As the project evolves, we envision that the implications documented at this high level will serve as a basis for focusing subsequent activities for each specific design package.

Lesson 4. A risk-based approach is critical for guiding and prioritizing subsequent human and technology integration activities

The development of a new vision and concept of operations to inform the requirements for the new I&C systems that enable a digital transformation should be closely tied to risk analyses to support a graded approach to HFE. For instance, a stepwise approach to modernization is often applied to reduce project and economic risk where subsets of scope that are part of the endpoint vision are executed in separate design packages. The subsets of scope (i.e., phases) may be of varying complexity and include different plant systems that are of varying levels of safety and economic criticality (Figure 21).

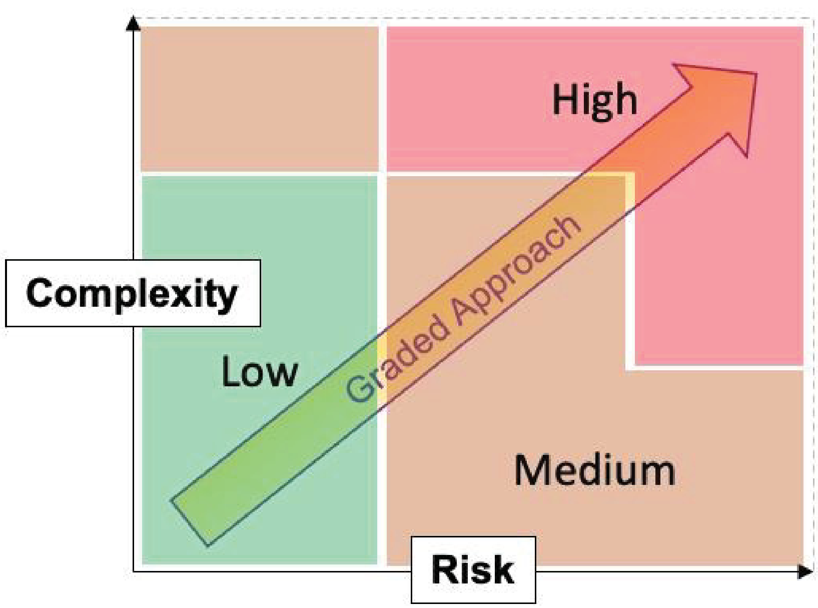


Figure 21. Grading HFE by complexity and risk.

Phases that are of less complexity and less risk may require less HFE involvement than others. Guidance in performing HFE grading is described in EPRI 3002004310 (2015) and is based on NRC guidance in NUREG-1764 (2007). It is important to clearly identify the impacted systems and components and have a delineation of how they are reflected in the migration strategy. The scope and risk profile of the phases reflected in the migration strategy then drive the level of HFE involvement necessary during design, V&V, and installation to ensure safe and reliable operation at a practical level with the proposed digital modifications. Thus, basic questions to ask are:

Related to risk:

- What credited actions from deterministic risk analyses (e.g., diversity and defense-in-depth or final safety analysis report) and probabilistic risk analyses are impacted at a given phase?
- How are these credited actions impacted?
- Are they fundamentally changing through uses of increased levels of automation?

Related to scope and complexity:

- For a given phase, what is the modification scope?
- How are operations impacted with the new technology?
- Are operators placed in a different (e.g., supervisory) role with the new technology?
- Are operators fundamentally changing the way in which they perform their tasks (e.g., transitioning from standing to seated)?

Lesson 5. The vision and concept of operations should be treated as a living document

A final lesson learned from this work is that the vision and new concept of operations should be treated as a living document. Indeed, it is possible that the vision will be modified throughout the project lifespan either from generated lessons learned and OE from previous modifications, changes in market and economic factors, and changes in the technology readiness of emerging capabilities. In fact, it is possible that the endpoint vision may never be reached for any reason described. The vision should thus be treated as a living resource, and changes to the vision should be grounded in sound rationale, such as relating to business needs, operational requirements, and critical engineering requirements that necessitate a shift in direction. Moreover, specific phases that are part of the migration strategy must be properly human factored such that they can stand alone, from an operational and licensing standpoint. The work demonstrated and documented in this report considered the vision and concept of operations as a living document, being informed through added layers of knowledge gained through key activities like the kickoff meeting, iterative team meetings, and focused design workshops.

4. CONCLUSIONS

Nuclear power will continue to be a critical asset to the U.S. as safe, reliable, and carbon-free electricity. The U.S. Department of Energy LWRS Program Plant Modernization Pathway is ensuring the continued life of the existing light-water reactors in the U.S. through targeted R&D that delivers a sustainability business model and by developing technology modernization solutions. This R&D has identified specific work reduction opportunities and CWDs that are critical to reducing O&M costs within the next 3–5 years. Digital I&C and control room modernization, which goes beyond like-for-life replacement, is a major area for the continued operation of the existing U.S. plants. It is important that these large-scale digital modernization projects apply HTI early and throughout the project lifecycle.

The recently developed HTI guidance documented in INL/EXT-21-64320 has been demonstrated in recent activities (Figure 4).

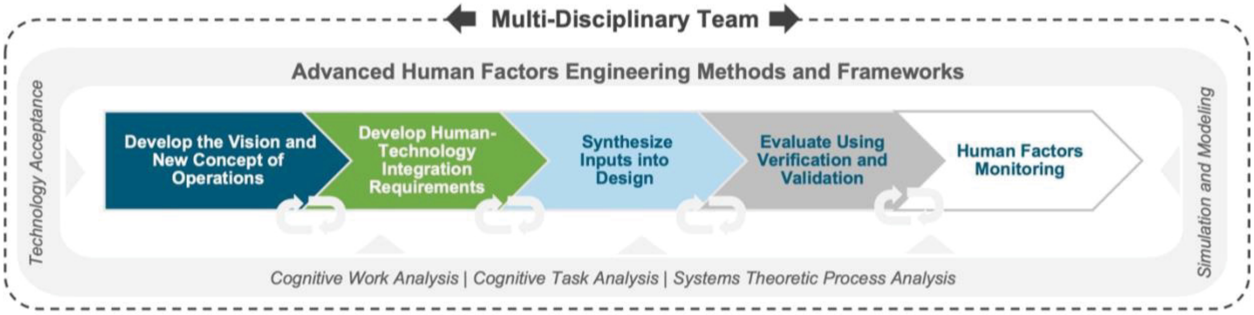


Figure 4 (repeated). HTI methodology.

For instance, in a separate pilot project, the second phase (i.e., developing HTI requirements, shown in green of Figure 4) has been demonstrated and documented in INL/RPT-22-68472. This report describes the demonstration of developing the vision and concept of operations (i.e., phase one) for a fleetwide modernization project (shown in dark blue of Figure 4). The results of this work will inform fleetwide requirements in developing a transformative vision and concept of operations.

As this work continues, we envision that the guidance from INL/EXT-21-64320 will be applied to support subsequent HFE activities including supporting early tradeoff studies of advanced MCR concepts, implementation plan development (e.g., developing an HFE program and HFE implementation plans), as well as HFE integration support for each modification through conceptual design, detailed design, and V&V. The results of this future work will be documented in lessons learned reports to provide comprehensive industry guidance in incorporating human and technology integration throughout the lifespan of large-scale digital modifications.

5. REFERENCES

Boring, R. L., Thomas, K. D., Ulrich, T. A., & Lew, R. T. (2015). Computerized operator support systems to aid decision making in nuclear power plants. Procedia Manufacturing, 3, 5261-5268.

Braseth, A. O., & Øritsland, T. A. (2013). Visualizing complex processes on large screen displays: Design principles based on the Information Rich Design concept. Displays, 34(3), 215-222.

Davis, F. D., R. P. Bagozzi, and P. R. Warshaw. 1989. “User Acceptance of Computer Technology: A Comparison of Two Theoretical Models.” Management Science 35(8): 982–1003. https://doi.org/10.1287/mnsc.35.8.982.

EPRI. 2005. “Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification.” EPRI 1010042, Electric Power Research Institute. https://www.epri.com/research/products/000000000001010042.

EPRI. 2015. “Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification.” EPRI 3002004310, Electric Power Research Institute. https://www.epri.com/research/products/000000003002004310.

EPRI. 2020. “Nuclear Power Plant Modernization—Strategy Development and Implementation Process.” EPRI 3002018428, Electric Power Research Institute. https://www.epri.com/research/products/000000003002020578.

EPRI. 2021. “Digital Engineering Guide: Decision Making Using Systems Engineering.” EPRI 3002011816, Electric Power Research Institute. https://www.epri.com/research/products/000000003002011816.

Graessler, I., Hentze, J., & Bruckmann, T. (2018). V-Models for Interdisciplinary Systems Engineering. In Proceedings of the DESIGN 2018 15th International Design Conference.

IAEA. 2021. “Human Factors Engineering Aspects of Instrumentation and Control System Design.” NRT2.12. International Atomic Energy Agency

IEEE. 2000. “Standard Dictionary of Electrical and Electronic Terms.” IEEE-100. Institute of Electrical and Electronics Engineers.

IEEE. 2020. “Recommended Practice for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations and Other Nuclear Facilities.” IEEE1023. Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/IEEESTD.2021.9361514.

Joe, J., L. Hanes, and C. Kovesdi. 2018. “Developing a Human Factors Engineering Program Plan and endpoint Vision to Support Full Nuclear Power Plant Modernization.” INL/EXT-18-51212, Idaho National Laboratory. https://doi.org/10.2172/1484690.

Kovesdi, C. (2021). Examining the Use of the Technology Acceptance Model for Adoption of Advanced Digital Technologies in Nuclear Power Plants. In International Conference on Applied Human Factors and Ergonomics (pp. 502-509). Springer, Cham.

Kovesdi, C., P. Hunton, J. Mohon, J. Joe, T. Miyake, and S. Whitmore. 2022. “Demonstration and Evaluation of the Human-Technology Integration Function Allocation Methodology.” INL/RPT2268472, Idaho National Laboratory.

Kovesdi, C., Spielman., Z., Hill, Li, R., Miyake, T., Mohon, J., and Le Blanc, K. 2020. “Demonstration and Evaluation of an Advanced Integrated Operations Concept for Hybrid Control Rooms,” INL/EXT-20-58538, Idaho National Laboratory.

Kovesdi, C., Z. Spielman, R. Hill, J. Mohon, T. Miyake, and C. Pedersen. 2021. “Development of an Assessment Methodology That Enables the Nuclear Industry to Evaluate Adoption of Advanced Automation.” INL/EXT2164320, Idaho National Laboratory.

Mohon, J. and Kovesdi, C. (2022). Demonstrating the Value of 3D Models to Support Large-Scale Digital Modifications at Nuclear Power Plants. In: Sofia Scataglini and Sudhakar Rajulu (eds) Digital Human Modeling and Applied Optimization. AHFE (2022) International Conference. AHFE Open Access, vol 46. AHFE International, USA. http://doi.org/10.54941/ahfe1001894

Remer, J., J. Hansen, C. Kovesdi, Z. Spielman, S. Lawrie, L. Martin, M. Dep, and B. Szews. 2022. “Integrated Operations for Nuclear Business Operation Model Analysis and Industry Validation” INL/RPT2268671, Idaho National Laboratory.

Remer, J., K. Thomas, S. Lawrie, K. Martin, and C. O'Brien. 2021. "Process for Significant Nuclear Work Function Innovation Based on Integrated Operations Concepts" INL/EXT2164134, Idaho National Laboratory.

Thomas, K. and P. Hunton. 2019." Nuclear Power Plant Modernization Strategy and Action Plan" INL/EXT-19-55852, Idaho National Laboratory

U.S. Nuclear Regulatory Commission. 1999. "Conduct of Operations." NUREG-0800, Standard Review Plan, U.S. Nuclear Regulatory Commission.

U.S. Nuclear Regulatory Commission. 2002. "Human-System Interface Design Review Guidelines." NUREG-0700, Rev. 2., U.S. Nuclear Regulatory Commission.

U.S. Nuclear Regulatory Commission. 2007. "Guidance for the Review of Changes to Human Actions." NUREG-0764, Rev. 1, U.S. Nuclear Regulatory Commission.

U.S. Nuclear Regulatory Commission. 2012. "Human Factors Engineering Program Review Model." NUREG-0711, Rev. 3, U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML1228/ML12285A131.pdf.

Appendix A
Endpoint Vision Worksheets

Normal Operations			
Topic	**Existing Control Room**	**Endpoint Vision**	**Human Factors Impacts**
Monitor the plant process and systems/equipment, including performance monitoring			
Perform or participate in maintenance & testing			
Equipment switching and tagging			
Take readings and log information			
Accomplish shift turnovers			
Startups and shutdowns			
Surveillance testing			

Abnormal Operations			
Topic	**Existing Control Room**	**Endpoint Vision**	**Human Factors Impacts**
Identify and respond to plant equipment failures and other situations requiring operator action			
Diagnose and troubleshoot problems with the plant process, systems and equipment			
Respond to plant transients and upsets Respond to accidents using emergency operating procedures Maintain situation awareness			
Handle compliance with tech spec conditions			
Monitor and control the plant under conditions of degraded or failed I&C/HSI			

Appendix B
Concept of Operations Workshop Agenda

Idaho National Laboratory

Southern Farley Nuclear Plant
Concept of Operations Workshop

August 29-31, 2022

Objectives:

- INL will host a workshop in collaboration with Southern and Sargent and Lundy to provide guidance on developing a new concept of operations that support their end state vision.
- Focused discussions of INL's key capabilities will be given as applied to Southern Farley around the topics of digital infrastructure, data architecture and analytics, human-technology integration, and integration operations for nuclear.
- The HSSL will be used to facilitate the following key activities:
    - The Farley current state MCR (( )) will be used as a baseline line to walk through identified scenarios with Farley operations.
    - Following each scenario walkthrough, static conceptual changes of the MCR for the endpoint vision will be presented in combination with the 3D model to confirm key changes. Interim states will also be shown to verify the correct indications and controls were removed at each phase.
    - Different advanced capabilities shown on a generic pressure water reactor will be demonstrated for advanced HSIs, alarms, computer-based procedures, and decision support systems to consider in the end state for Farley to aid in the walkthrough discussions.
    - These demonstrations will be used to facilitate discussion around how these capabilities can improve performance, situation awareness, while reducing workload and error.
- The results of this workshop will be used to inform implement planning for the upgrades in later activities.

Attire: Casual

Lunches and Breaks:

- Lunches will be determined during the morning of each day.
- Breaks will be provided as needed throughout the course of the workshop.

Revision Number 0

Date agenda revised: 08/10/2022

Page 1 of 5

Day 1: Monday, August 29, 2022

Location	Time	Activity	Role
Willow Creek Building (WCB)	07:30 – 08:00	Visitor Badging	
Engineering Research Office Building (EROB): Room 398	08:00 – 08:45	Welcome and Introductions	
	08:45 – 09:00	Workshop Objectives	
	09:00 – 09:45	Southern Nuclear Corporation (SNC) Farley Generating Station's Modernization Objectives	
	09:45 – 10:30	Sargent and Lundy (S&L) Collaboration with SNC and Modernization Overview	
	10:30 – 10:45	Break	
	10:45 – 11:15	Light Water Reactor Sustainability (LWRS) Program Plant Modernization Overview	
	11:15 – 12:00	Westinghouse Modernization Overview	
	12:00 – 13:00	Lunch	
Center for Advanced Energy Studies (CAES) - CAVE	13:00 – 14:30	Introduction and Overview of the End-State and New Concept of Operations	
EIL - HSSL	14:45 – 15:00[a]	1. Team Introductions to HSSL, Facility Overview, and Safety Brief 2. [a] Break-out discussion	
	15:00 – 16:30	Discussion of End-State and Impacts of New Concept of Operations At this time, Westinghouse will present demonstrations of key capabilities from their commercial systems available that reflect HFE principles shared by INL.	
	16:30 – 16:35	End of Day Debrief and Adjourn	

Day 2: Tuesday, August 30, 2022

Location	Time	Activity	Role
EIL: HSSL	08:00 – 08:45	Demonstration of Advanced Main Control Room Concepts INL will present an overview of interactive demonstrations, using the generic Pressurized Water Reactor (GPWR).	
	09:00 – 10:30	Walkthrough 1: Familiarization +	
	10:00 – 11:00	Walkthrough 2:	
	11:00 – 12:00	Walkthrough 3:	
	12:00 – 13:00	Lunch	
	13:00 – 13:30	Introduction to Flexible Plant Operation and Generation – H2 Generation with Nuclear by Richard Boardman	
Energy Systems Laboratory (ESL)	13:30 – 15:30	Energy Systems Laboratory Tour by Richard Boardman	
EIL: HSSL	15:30 – 17:00[b]	1. Team Follow-on Discussion of Flexible Plant Operation and Generation with Farley Operations at EIL: HSSL 2. [b] Break-out discussion for Liz Williford and Richard Boardman at ESL	
	17:00 – 17:15	End of Day Debrief and Adjourn	

Day 3: Wednesday, August 31, 2022

Location	Time	Activity	Role
EIL: HSSL	08:00 – 09:00	Walkthrough 4:	
	09:00 – 10:00	Walkthrough 5:	
	10:00 – 11:00	Walkthrough 6:	
	11:00 – 12:00	Walkthrough 7:	
	12:00 – 13:00	Lunch	
EIL: Conference Room 203	13:00 – 15:30	Closing Discussion and Next Steps — Based on walkthroughs, close discussion on significant MCR enhancements envisioned in endpoint — Close out any items not covered in previous activities. — Action items will be captured and distributed to the team. — Next steps will be discussed in terms of subsequent planning and collaboration opportunities	

[b] At this time, a breakout session will be provided for Liz Williford for detailed discussion with Richard Boardman in Flexible Plant Operation and Generation – H2 Generation with Nuclear.

Appendix C
Concept of Operations Report Table of Contents

This section describes the existing concept of operations for Farley. The concept of operations is described by the following categories:

PERSONNEL ROLES, RESPONSIBILITIES, AND QUALIFICATIONS

- Impacts to staffing levels, roles, and qualification

OPERATIONAL IMPACTS

- Normal operations
    - Monitor the plant process, systems, equipment, including performance monitoring
    - Perform or participate in maintenance and testing
    - Equipment switching and tagging
    - Take readings and log information
    - Accomplish shift turnovers
    - On-shift training
    - Startups and shutdowns
    - Surveillance testing
- Abnormal operations
    - Identify and respond to plant equipment failures and other situations requiring operator action
    - Diagnose and troubleshoot problems with the plant process, systems, and equipment
    - Respond to plant transients and upsets
    - Respond to accidents using emergency operating procedures
    - Maintain situation awareness
    - Handle compliance with technical specifications
    - Monitor and control the plant under conditions of degraded or failed I&C and HSI
    - Monitor and control the plant when the MCR must be evacuated

HSI IMPACTS

- Alarms
- Plant monitoring
- Command and control
- Use of automation
- Procedures

ANTICIPATED FAILURES OF THE NEW I&C SYSTEMS

- Degraded HSIs