INL/RPT-23-71395
Revision 0

Light Water Reactor Sustainability Program

Demonstration of the Human and Technology Integration Guidance for the Design of Plant-Specific Advanced Automation and Data Visualization Techniques

March 2023

U.S. Department of Energy

Office of Nuclear Energy

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Demonstration of the Human and Technology Integration Guidance for the Design of Plant-Specific Advanced Automation and Data Visualization Techniques

Casey Kovesdi
Jeremy Mohon
Chloe Pedersen-San Miguel

March 2023

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

SUMMARY

Nuclear power continues to be a safe, reliable, and carbon-free electricity generating source for the United States, though the cost of operating and maintaining the current United States nuclear power plant fleet has become uncompetitive with other sources. This gap is attributed to the advent of new digital instrumentation and control technologies that other electricity generating industries are currently leveraging to streamline work and greatly reduce operating, maintenance, and support costs. Digital instrumentation and control systems and control room modernization offers significant opportunities to reduce operating and maintenance costs to ensure the continued operation of the existing United States light-water reactors.

These capabilities enable going beyond like-for-like replacement by offering new ways to transform current work processes through features like increased levels of automation, data analytics and visualization, and decision support. To ensure that the capabilities of the technology and people are being leveraged for safety and reliability, human and technology integration is an important consideration for any major digital main control room modification.

This report presents interim findings of two key collaborations with United States utilities currently planning and executing large-scale digital instrumentation and control modifications to their main control rooms. While these collaborations are ongoing, this report presents lessons learned in the demonstration of the human and technology integration methodology.

As this work continues, additional lessons learned will be developed. Collectively, this guidance provides industry with human and technology integration and human factors engineering guidance that reduces the technical, financial, and regulatory risk of upgrading the aging instrumentation and control systems to support extended plant life up to and beyond 60 years.

ACKNOWLEDGEMENTS

The authors would like to thank Constellation Energy Generation (Paul Krueger, Scott Schumacher, Mark Samselski, and the entire operations team), Southern Nuclear Corporation (Harry Burke, Ray Herb, Liz Williford, and the entire Farley operations team), and Sargent and Lundy (Pareez Galub, Richard Paese, and John McCague) in the continued collaboration that makes this research possible. The authors would also like to thank Paul Hunton and Jeffrey Joe of Idaho National Laboratory for ongoing technical support that made this work possible. 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 Jason Tokey of the Department of Energy, as well as Craig Primer and Bruce Hallbert of Idaho National Laboratory for championing this effort.

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ACRONYMS

3D	three-dimensional
CBP	computer-based procedure
CEG	Constellation Energy Generation
CV	conceptual verification
CWA	cognitive work analysis
CWD	critical work domain
D3	defense in depth
DCS	distributed control system
DEG	Digital Engineering Guide
DHM	digital human model
DOE	Department of Energy
EPRI	Electric Power Research Institute
FA&A	function analysis and allocation
FAT	factory acceptance test
FSAR	final safety analysis report
GONUKE	Guideline for Operational Nuclear Usability and Knowledge Elicitation
HED	human engineering discrepancy
HFE	human factors engineering
HSI	human-system interface
HSSL	Human System Simulation Laboratory
HTI	human and technology integration
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute for Electrical and Electronics Engineers
ION	integrated operations for nuclear
ISV	integrated system validation
LAR	license amendment request
LWRS	Light Water Reactor Sustainability
MCR	main control room
NRC	Nuclear Regulatory Commission
O&M	operating and maintenance
OE	operating experience

OER	operating experience review
OSD	operational sequence diagram
PRA	probabilistic risk analysis
PV	preliminary validation
R&D	research and development
RPS	reactor protection system
SER	safety evaluation report
SME	subject matter expert
SNC	Southern Nuclear Corporation
TAM	technology acceptance model
V&V	verification and validation
VDU	video display unit
U.S.	United States

DEMONSTRATION OF THE HUMAN AND TECHNOLOGY INTEGRATION GUIDANCE FOR THE DESIGN OF PLANT-SPECIFIC ADVANCED AUTOMATION AND DATA VISUALIZATION TECHNIQUES

1. INTRODUCTION

The nuclear power continues to be a safe, reliable, and carbon-free electricity generating source for the United States (U.S.), though the cost of operating and maintaining the current U.S. nuclear power plant fleet has become uncompetitive with other sources. This gap is attributed to the advent of new digital technologies that other electricity generating industries are currently leveraging to streamline work and greatly reduce operating, maintenance, and support costs. To address the gap, the U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program Plant Modernization Pathway is conducting targeted research and development (R&D) to keep the existing U.S. nuclear power plants economically viable and extend their lifespans by improving their performance through two complementary mission areas:

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

Integrated operations for nuclear (ION) is a driving LWRS Program plant modernization research area that focuses on delivering a sustainable business model to provide direction and focus for cross-functional R&D across the LWRS Program that focuses on developing technology modernization solutions. Recent ION research provides a target cost reduction needed in the next 3–5 years for the nuclear industry to remain cost competitive (i.e., described as ION Generation 1; Remer et al. 2022). This work has shown that a ~30% reduction in cost will be needed in operation, maintenance, and support functions to remain economically viable (Figure 1).

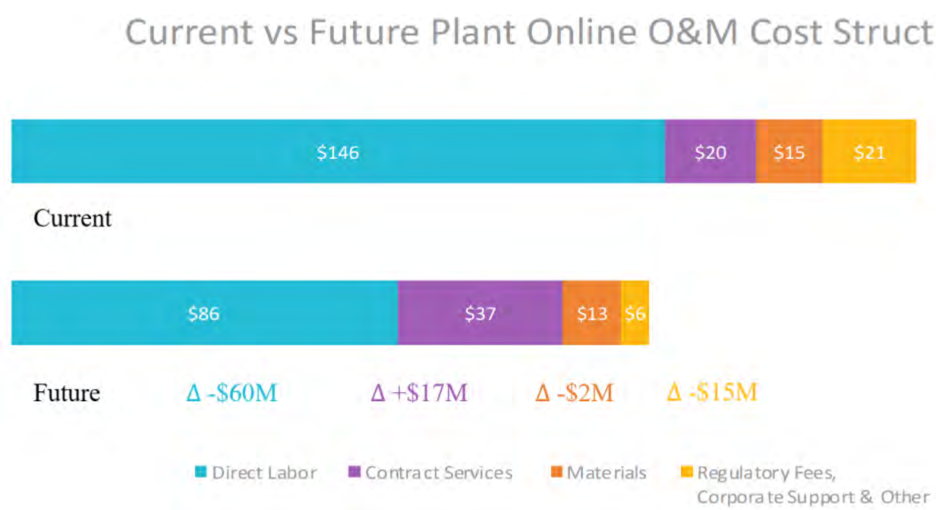


Figure 1. LWRS Program plant modernization focus areas (adapted from INL/RPT-22-68671).

The ION R&D has identified 10 critical work domains (CWDs) that should be the focus to meet the goal of a nearly one-third cost reduction. Figure 2 highlights these CWDs and offers a sense of magnitude in cost reduction based on the area size of each CWD.

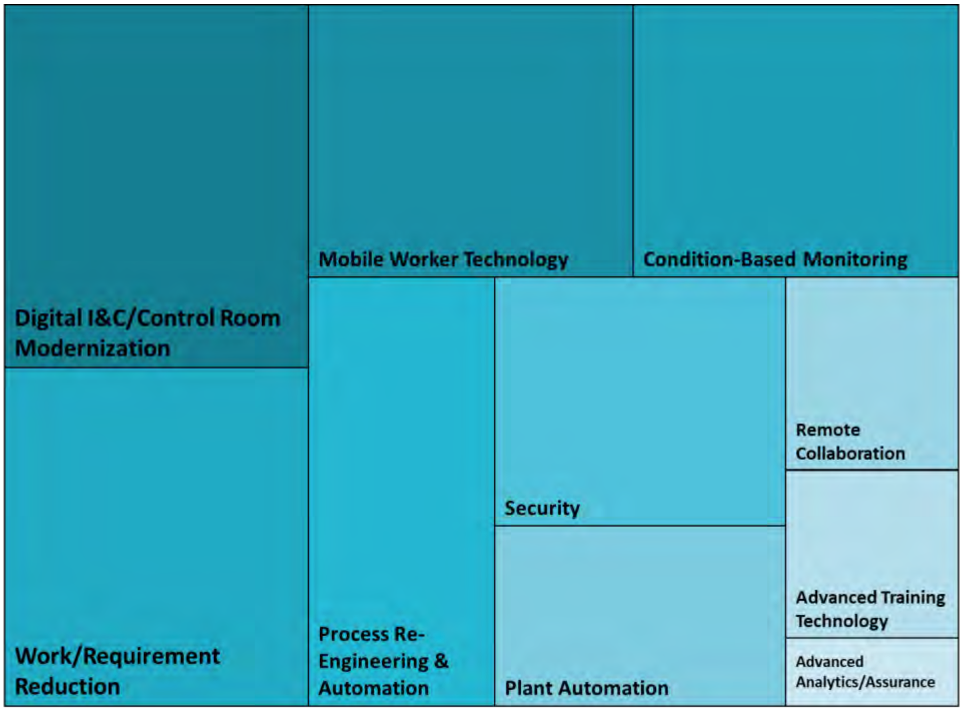


Figure 2. CWDs that offer the greatest opportunity for cost savings (adapted from INL/RPT-22-70538).

As seen in Figure 2, the digital instrumentation and control (I&C) and control room modernization CWD offers a significant opportunity for cost reduction. The current state of industry largely consists of hybrid main control rooms (MCRs) of mostly analog I&C with pockets of digital I&C. The integration of these components has been done reactively to the demands of obsolescence and replacement; this is often piecemeal in nature. This piecemeal approach favors "risk aversion" in terms of a path of least resistance, from a regulatory and licensing standpoint. That is, digital equipment often resembles its analog predecessor as a like-for-like replacement to minimize impacts to licensing and regulatory commitments given to the U.S. Nuclear Regulatory Commission (NRC). The result of this approach is often unfavorable for economic viability, in which the end-state is a digital resemblance of an earlier analog control room and the way in which work is done is nearly identical. No efficiencies are gained, and sometimes the technology can add a layer of unintended complexity, consequently negatively impacting efficiencies (e.g., such as with replacing paper-based procedures with a static digital version of it).

Indeed, there is a significant need to go beyond like-for-like replacement to critically examine current work processes and to integrate technology in a way that takes advantage of the capabilities of both people and technology. If done with both the human and technology in mind, digital I&C technology can offer a wealth of advantages. Some advantages cited by Remer and colleagues (2022) include:

- **Improved plant operations.** Increased efficiencies can be realized with advanced control automation, placing the control room operator at a supervisory level.
- **Reduced administrative burden and workload.** Digital technologies enable improved workflows and reduces the amount of manual administrative tasks. Workload may be reduced by removing secondary (i.e., administrative) tasks to allow operators to focus more on tasks important to safety or production.
- **Improved reliability.** Digital systems' high reliability can mitigate plant staff workarounds.
- **Reduced cognitive and task complexity.** A standardized non-safety and safety digital I&C system reduces the level of tacit knowledge required of operators (i.e., inside and outside the

MCR) to perform a given task through design convention standardization. This not only reduces errors and improves efficiency but may also reduce training requirements.

- **Improved crew decision-making and situation awareness.** Data visualization and advanced displays like task-based displays and large overview displays provide the right data and information to the right users for effective decision-making and overall situation awareness of the plant. Furthermore, advanced capabilities, such as prognostic systems, go a step further to provide recommendations from plant condition data to support situation assessment and response planning.

Enabling digital control room technologies that can be used to achieve these results are described next.

1.1 Enabling Digital Control Room Technologies

1.1.1 Digital Instrumentation and Control Platform

A digital I&C platform is a set of hardware and software components that provide the foundation for a digital I&C system. It includes the computer systems, software, and communications networks that are used to monitor and control the various systems and processes within a nuclear power plant. As discussed previously, digital I&C offers both a significant opportunity for cost reduction and a number of advantages for plant staff workload, decision-making, awareness, cognitive and task complexity, and improved reliability and operations. These improvements in control room functions are enabled by digital I&C in ways that are impossible with analog technology. However, existing plants largely rely on obsolete I&C technology, especially for safety systems. Non-safety I&C systems have more often utilized digital technology; however, these are often installed and implemented disjointedly and operate beyond their intended lifetimes. Supporting, maintaining, and troubleshooting such systems requires substantial effort that becomes continuously more difficult and costly with passing time.

Digital I&C systems include systems to support operations in case of an incident or power outage. These systems include safety-related heating, ventilation, and air conditioning controls, accident sequencers, and reactor protection systems (RPS) to ensure plant safety. Modern digital protection systems can self-perform health checks and can be continuously monitored or checked on demand. Additionally, digital I&C of non-safety systems that can host all non-safety I&C functionality in a nuclear plant are available and typically developed by non-nuclear vendors. By transitioning to a two-platform system (one safety platform and one non-safety platform), cost savings can be achieved through standardization across domains of equipment, software, implementation, and human factors engineering (HFE) implementation and development as well as lifecycle management consolidation to a minimum number of vendors and technologies (INL/RPT-22-68671).

1.1.2 Integrated Workstations

Integrated workstations leverage digital technology to enable safe and efficient plant control by integrating data and presenting meaningful information to support decision-making. As opposed to operators walking back and forth across the control room and manually collecting data, data can be gathered from a wide variety of sources, analyzed, modeled, and displayed at a singular centralized seated workstation. Relatedly, advanced sensors outside of the control room, integrated throughout the plant, could also be used to provide direct information to integrated workstations, reducing manual data collection and perhaps consequently reducing plant staffing levels. At integrated workstations, operators can be provided with task-relevant information, key plant safety and productivity parameters, and supporting information for ancillary tasks.

1.1.3 Large Overview Displays

Large overhead displays are computer monitors that present plant status and control information to personnel in the MCR. They are primarily located in the non-safety digital control system but can also be found in emergency response facilities and corporate maintenance and diagnostic centers. These displays can be configured by crew members to show alarms and information for emergency or accident conditions and can also be temporarily reassigned to other equipment in the control room during maintenance or replacement. This allows for efficient and effective interaction and coordination among the personnel.

1.1.4 Computer-Based Procedures

Computer-based procedures (CBP) are digital versions of detailed procedures that include an embedded process workflow (Oxstrand, Le Blanc, and Bly, 2016). They display the same information as paper-based procedures on computer screens and mobile devices and can also show the real-time or near-real-time plant status, as well as provide just-in-time training, diagrams, and photographs. CBPs are more resource-efficient in terms of creation, updates, revisions, and distribution than paper-based procedures. CBPs can also improve safety and efficiency by improving human interaction with procedures. Personnel performance can be improved by allowing for seamless transitions between procedures and providing situation-specific instructions based on plant data and previous logs.

CBPs offer various benefits, such as context-driven job aids, integrated human performance tools, and dynamic step presentation. The four main guidance documents available on the design of CBP systems are IEEE 1786 (2022), NUREG-0700, and EPRI 3002004310 (2015). However, much of the existing guidance is focused on control room procedures and may not address the challenges of implementing procedures in the field. The design guidance is often high level, leaving the designer to interpret how to implement it. The LWRS Program has conducted research to provide design guidance to both utilities and vendors. Design requirements, as well as examples of how to implement each requirement with illustrations and explanations of benefits, are outlined in INL/EXT-16-39808.

1.1.5 Control Automation

Control automation refers to a system's ability to carry out control tasks or actions that automatically manipulate equipment within the plant, for example, automatically inserting control rods when a reactor trip is detected. This type of automation, including process control automation and automated protective functions, is already in use in plants. However advanced digital systems provide for greater automation capabilities, improving efficiency and reliability while also reducing staffing and training.

1.2 Making Technology Work for People

To ensure that the capabilities of the technology and people are being leveraged for safety and reliability, human and technology integration (HTI) is an important consideration for any major digital I&C MCR modification. This report presents interim findings of two key collaborations with U.S. utilities currently planning and executing large-scale digital I&C modifications to their MCRs. The remainder of this report is broken down into three primary sections.

- Section 2 summarizes the HTI methodology developed by the LWRS Program.
- Section 3 summarizes key collaborations between two industry collaborators to which the HTI methodology has been demonstrated, including lessons learned.
- Section 4 gives conclusions and next steps.

2. APPLYING HUMAN AND TECHNOLOGY INTEGRATION TO LARGE-SCALE DIGITAL MODIFICATIONS

HTI, as described in this paper, is a research area under the LWRS Program Plant Modernization Pathway that uses HFE methods and tools to ensure the safe and reliable use of advanced technologies. HTI also focuses on applying technology in a way that makes a business impact, thereby reducing cost through reduced staffing needs, improved processes and decision-making, or reduced human error risk.

2.1 Goals of Human and Technology Integration

2.1.1 Ensure Safety and Reliability

The integration of humans and technology goals is to determine that new technologies are safe and reliable to use. The safety and reliability of integrating new digital I&C and HSIs into plants are evaluated by using structured analysis HFE methodologies to help verify and validate that the new control room modifications integrate successfully into the current MCR. The safety of new digital I&C and HSIs are reviewed and evaluated though the use of HFE methodologies to determine if the new upgrades reduce human error risk. NUREG-0711 is used throughout the upgrade lifecycle along with HFE methods to help ensure that safety issues are reduced or eliminated from the modifications.

The reliability of new digital I&C and HSIs are evaluated using HFE methods to help determine if safety-important human actions could lead to errors or safety concerns when using the new digital upgrades. NUREG-0711 and NUREG-0800 Chapter 18 are used to help review the reliability of the new upgrades to help ensure that human actions do not create increased error rates. Ensuring the safety and reliability of new digital upgrades helps to create a successful HTI.

2.1.2 Address Hybrid Issues and Considerations

Many plants are integrating new digital displays and controls into analog plants. Integrating new technology has several issues and considerations that must be evaluated prior to adding new technology into the plant. Sight lines to new displays, functional reach of controls, and legibility are evaluated using HFE to address issues and considerations. Three-dimensional (3D) modeling, using digital human models (DHMs), and NUREG-0700 (2002) guidelines are the HFE tools used to help address sight lines to new displays, functional reach, and legibility. 3D modeling is used to create visual representations of the plant to help identify new technology considerations. NUREG-0700 reviews are HFE guidelines used to address HFE considerations and issues such as the placement of new displays and controls in the plant.

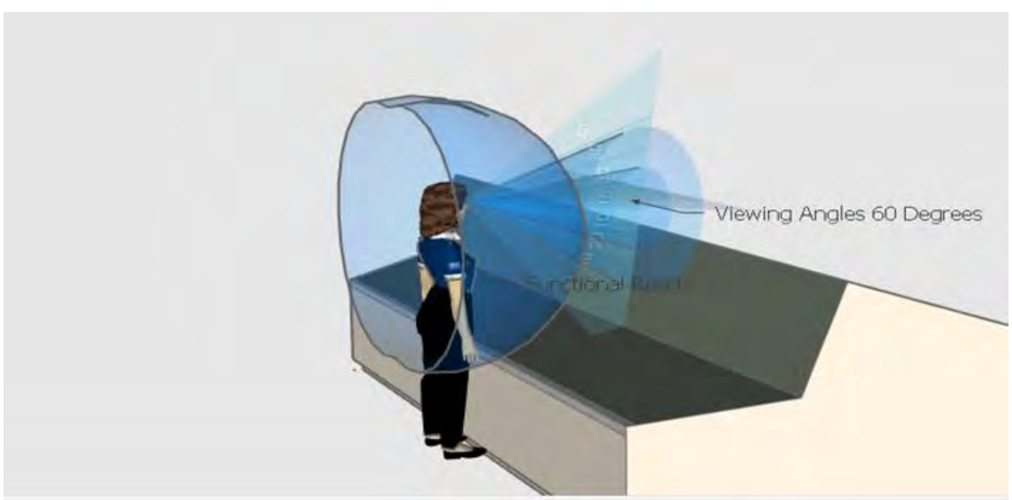


Figure 3. Example of DHM with functional reach and viewing angles (adapted from Mohon and Kovesdi 2022).

DHMs are used in 3D modeling to represent the largest to smallest height of personnel in the plant to help establish the proper positioning of new HSIs or control positions. Sight lines to new displays along with legibility are reviewed early in the design and implementation phases to establish the best placement for HSIs and controls. Figure 3 is an example of a 5th percentile female DHM used to review the functional reach and sight lines for new digital I&C and HSI placements. The blue half circle represents the functional reach area, and the blue cone represents the visual angles. Legacy plants have hybrid issues and considerations that must be addressed early in the design. One example is identifying the ideal placement for new HSI displays on legacy equipment, such as a standing workstation. The combination of 3D modeling and NUREG-0700 guidelines helps to prevent issues and considerations related to safety and reliability in plant operations when integrating new technology into the MCR.

2.1.3 Maximize Benefits of Technology and People

ION and HFE standards and guidance help maximize the benefits of integrating new technology into the plant, reduce O&M costs, and improve efficiencies in plant operations. HFE and ION are used to help support the plant beyond safety to support efficiencies in the plant, including reduced workload, increased situation awareness, and improving plant operations. Task analysis is one useful HFE method for evaluating current operational practices by evaluating the current tasks performed in the MCR and where improvements could be made to enhance efficiencies in the plant. Usability reviews are another HFE method used to support ION by reviewing the usability of new digital I&C and HSI upgrades to help determine if the proposed digital upgrades support efficient operations such as reduced workload and increased situational awareness of plant conditions. Combining HFE methods and ION help to identify ways to increase efficiency and reduce O&M costs. The next section will discuss the HTI process.

2.2 Human and Technology Integration Process

Over the past few years, the LWRS Program Plant Modernization Pathway HTI researchers have published three notable reports that provide recent guidance in this area:

- **INL/EXT-21-64320**, Development of an Assessment Methodology That Enables the Nuclear Industry to Evaluate Adoption of Advanced Automation (2021)
- **INL/RPT-22-68472**, Demonstration and Evaluation of the Human-Technology Integration Function Allocation Methodology (2022)
- **INL/RPT-22-70538**, Demonstration and Evaluation of the Human-Technology Integration Guidance for Plant Modernization (2022).

The primary approach taken by HTI can be summarized by Figure 4.

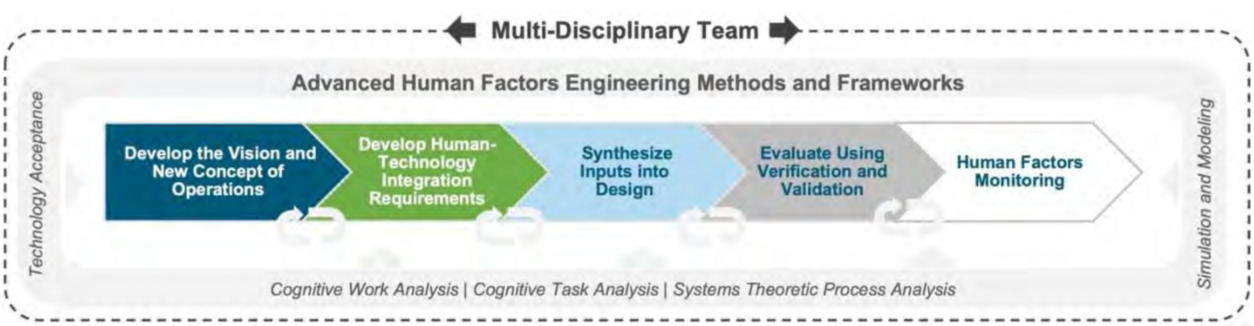


Figure 4. HTI methodology.

The HTI methodology developed by the LWRS Program is referenced in INL/EXT-21-64320 (2021). Elements of the methodology have been demonstrated with two major U.S. nuclear power plant utilities to support their large-scale digital modifications. This work is cited in INL/RPT-22-68472 and INL/RPT-22-

70538, respectively. The work between each utility is ongoing, and subsequent industry guidance in HTI is planned to continue, as described in this report.

The HTI methodology in Figure 4 has a few unique characteristics. First, it must be emphasized that the methodology builds on current industry standards and is intended to be used by industry in adopting advanced digital I&C technologies. The methodology therefore is complementary to existing industry endorsed HFE and systems engineering standards and guidelines including:

- U.S. NRC guidance:
  - **NUREG-0800 Chapter 18**, Standard Review Plan (SRP) for the Review of Safety Analysis Reports for Nuclear Power Plants: Human Factors Engineering, Revision 3 (2016)
  - **NUREG-0711**, Human Factors Engineering Review Model, Revision 3 (2012)
  - **NUREG-0700**, Human-System Interface Design Review Guidelines, Revisions 2 and 3 (2002; 2020)
  - **NUREG/CR-3331**, Methodology for Allocating Nuclear Power Plant Control Functions to Human or Automatic Control (1983)
- Electric Power Research Institute (EPRI) guidance:
  - **EPRI 3002011816**, Digital Engineering Guide (DEG): Decision Making Using Systems Engineering (2021)
  - **EPRI 3002004310**, Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification Guidelines for Planning, Specification, Design, Licensing, Implementation, Training, Operation, and Maintenance for Operating Plants and New Builds (2015)
  - **EPRI 3002018392**, HFAM - Human Factors Analysis Methodology for Digital Systems: A Risk-Informed Approach to Human Factors Engineering (2021)
- Institute for Electrical and Electronics Engineers (IEEE) guidance:
  - **IEEE 1023**, IEEE Recommended Practice for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations and Other Nuclear Facilities (2020)
  - **IEEE 845**, IEEE Guide for the Evaluation of Human-System Performance in Nuclear Power Generating Stations (1999)
  - **IEEE 2411**, IEEE Guide for Human Factors Engineering for the Validation of System Designs and Integrated Systems Operations at Nuclear Facilities (2021)
- International Atomic Energy Agency (IAEA) guidance:
  - **IAEA No. NR-T-2.12**, Human Factors Engineering Aspects of Instrumentation and Control System Design (2021)
- International Electrotechnical Commission (IEC) guidance:
  - **IEC 61839**, Nuclear Power Plants – Design of Control Rooms – Functional Analysis and Assignment (2000).

Secondly, the HTI guidance emphasizes both an early and iterative HFE involvement. While Figure 4 appears to show a linear process from left to right across each of the colored phases, the progression from one phase to the next may be iterative in which an earlier phase is revisited. Moreover, a utility may choose to start at a later phase with the intent of revisiting earlier phases later in the project lifecycle. Third, the methodology is intended to be highly cross-functional, requiring a multidisciplinary team from senior management, licensing, HFE, operations, training, and engineering to be integrally involved to ensure proper stakeholder input. Without a multidisciplinary team and close communication, project assumptions or requirements may be loosely defined, resulting in unnecessary rework. A fourth important point worth noting is that the methodology emphasizes a graded approach to help ensure the proper level of rigor is applied to the project. Risk, based on plant and personnel safety and economic impact, is one key factor that drives the grading. Likewise, the complexity, or extent of modernization, is another major factor. Grading the HFE ensures that the proper resources can be utilized to ensure safe and reliable use without overburdened scope, schedule, or budget. Finally, advanced techniques are leveraged, including simulation, modeling, and emerging HFE approaches like cognitive work analysis, system theoretic process analysis, and cognitive task analysis, as shown around the five phases of Figure 4. These methods are leveraged at key HFE activities to analyze the cognitive aspects of work performed by plant personnel such that it can be used in informing the requirements for the new digital technology being integrated.

The next subsections highlight important activities and attributes of the five phases shown in Figure 4. A detailed review of each is described in INL/EXT-21-64320 (2021). It is important to note that, while this report is specific to *design*, the phases described in INL/EXT-21-64320 all build on each other. Likewise, subsequent phases after design contain feedback loops into design. Therefore, the following sections summarize notable HFE activities that inform and bound the design synthesis phase.

2.2.1 Develop the Vision and New Concept of Operations

For any major digital modernization project, there is likely to be a target goal, budget, schedule, and set of unique constraints that bound the project. In terms of modernizing the MCR and associated I&C, likely goals are driven by a business case, which may be driven by obsolescence management (e.g., Hunton and England 2021) or improved operational efficiencies to reduce cost. These goals will need to be matched with the realities of a utility's budget, schedule, existing plant state, and conventions that must be accounted for in transitioning into a new state. Further, the available technology offered will further bound the reality of reaching this goal. This phase focuses on defining and realizing the goals of a major digital nuclear power plant modernization. Key elements of this phase are summarized below.

2.2.1.1 Defining the Vision

A *new state vision* (oftentimes referred to as *endpoint vision*) provides a clear and overarching trajectory of where the modernization efforts will ideally be in terms of the I&C architecture and HSIs design and functionality (i.e., refer to IAEA No. NR-T-2.12 2021). The vision is intended to communicate the planned state of the I&C and associated HSIs after the upgrade(s) is successfully completed. Its function is to guide engineering activities throughout the upgrade lifespan and should be driven on foundational principles, such as ensuring design consistency, system usability, and mitigating human error traps, while also addressing the business goals. As described in IAEA No. NR-T-2.12 (2021), the vision serves as an effective communication medium across different stakeholders to help identify user needs, identify and mitigate tradeoffs early, and share a common understanding of the project's trajectory throughout the project lifespan.

The vision has been effectively communicated through emerging HFE tools such as 3D modeling and simulation for early feedback (Mohon and Kovesdi 2022). The HTI methodology emphasizes the uses of these tools. An example of the use of 3D modeling of a new state vision can be seen in Figure 5, and an example of an equivalent representation of the vision in a glasstop simulator (i.e., the U.S. DOE LWRS Program Human System Simulation Laboratory [HSSL]) is shown in Figure 6. These figures were adapted from INL/RPT-22-70538 (2022); the use of 3D modeling and the HSSL served as enabling HFE tools for a major digital I&C modernization pilot project in collaboration with a U.S. utility.

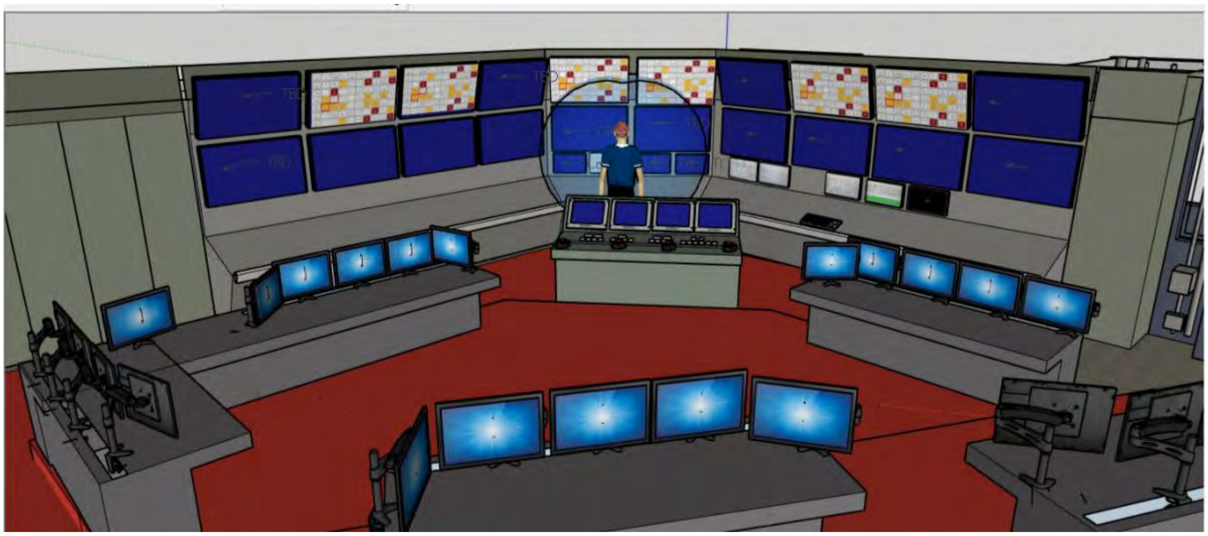


Figure 5. Example use of 3D modeling to present a concept of a new state vision.

Figure 6. Use of the HSSL to support new state vision development.

2.2.1.2 Developing a New Concept of Operation

Another important output of this phase is the *concept of operations*. The concept of operations describes the vision, goals, and expectations for the new system from the lens of the users (NUREG-0711 2012). For a major modification to an existing plant, it may be useful to understand what impacts the new digital technology will have on the way operators perform their work.

For example, an existing plant control room may require operators to perform work in a standing manner, walking to different indications and controls throughout the MCR. The operators may need to call out to auxiliary personnel to collect information that is not available in the MCR. The procedures may be paper based, and the level of automation may be lower, requiring operators to be more involved in direct manipulation of individual plant equipment. Contrarily, the new vision's concept of operation may be mostly seated, where the operators perform their tasks from an integrated set of HSIs. Information may be consolidated on digital displays and arranged functionally, as well as arranged for specific tasks for certain plant evolutions. The crew may share information via large overview displays to obtain a shared situation awareness of the plant. Procedures may be computerized, and advanced features may be considered, including embedding of key plant parameters, as well as linking to associated steps. The control system may provide increased levels of automation in which operators supervise the automation (e.g., setting a pressure band).

The HTI methodology leverages the use of endpoint vision worksheets, like those referenced in EPRI 3002004310 (2015) to help guide the description of key operational differences and impacts by common topics. An example template used is shown in Table 1.

Table 1. 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 operating experience (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

The work described in INL/RPT-22-70538 (2022) used these worksheets in combination with HFE guidance developed from the LWRS Program to guide the development of the new concept of operation and its impacts for a major U.S. utility. The intent of these worksheets was to help in understanding what the key HFE impacts are and focus and prioritize subsequent HFE activities in later engineering activities with the project.

It is important to emphasize that developing the vision and new concept of operation requires an iterative and multidisciplinary approach, involving stakeholders from operations, senior management, licensing, engineering, and HFE, among others. The development of the vision and new concept of operation documented in INL/RPT-22-70538 (2022) entailed a series of focused HFE activities with stakeholders from the previously mentioned domains. The activities entailed one plant visit (i.e., a kickoff meeting), one design workshop, and weekly virtual team meetings. The focus of these activities was primarily to:

- Establish the project goal.
- Develop a division of responsibility.
- Collect initial design input (i.e., OE via operating experience review [OER])
- Develop and converge on the vision and concept of operations such that engineering tradeoffs were identified early and HFE principles were accounted for.

2.2.1.3 Aligning the Vision and Concept of Operations with Digital Infrastructure

The I&C architecture is instrumental in realizing the new vision and concept of operations. From an I&C standpoint, detailed guidance can be found in INL/EXT-21-64580 (2021). This report describes the LWRS Program Digital Infrastructure Migration Framework and is based around developing a digital infrastructure such as shown in Figure 7. The digital infrastructure in this figure is simplified in nature and is adapted from the Purdue Enterprise Reference Architecture that has been in use since the 1990s. The Purdue Model Network is also cross-referenced to the NRC cybersecurity levels. Both mappings are presented on the left side of the figure. Details of each level can be obtained from Section 2.1 of INL/EXT-21-64580 (2021). However, it is worth pointing out here that, as the Purdue Network Levels decrease and NRC cybersecurity levels increase, the level of quality assurance requirements becomes greater to maximize safety, reliability, and availability. To this end, it should be understood that the most plant critical systems (i.e., safety-related I&C) reside at the bottom of Figure 7, indicating the lowest Purdue Network level and highest NRC cybersecurity level. Primary MCR I&C systems specific to plant operation reside between Purdue Network Levels 0–3. Capabilities such as drones, wireless sensors, and other mobile technologies that can be leveraged for maintenance and support functions reside on the corporate network at Purdue Network Level 4. The advantage of this architecture is to ensure extending the operating lifetime of existing light-water reactors to 80+ years while minimizing economic and technical burden throughout the entire plant lifespan.

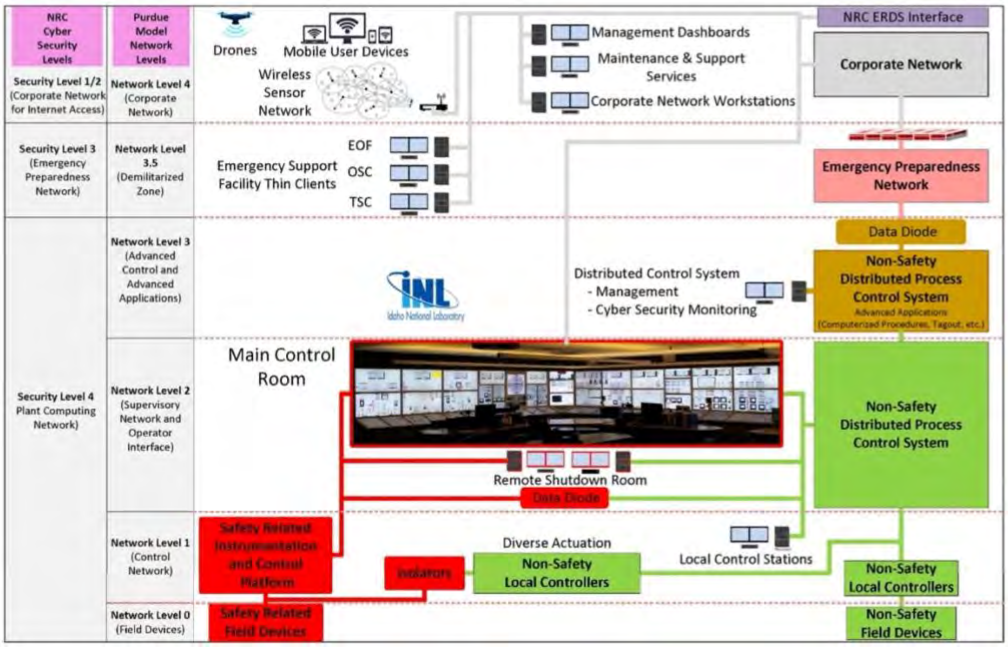


Figure 7. Simplified digital infrastructure (adapted from INL/EXT-21-64580).

2.2.1.4 Developing a Migration Strategy

Another important element in this phase is developing a *migration strategy*. The migration strategy describes the steps that will be completed to achieve the new vision and concept of operations (EPRI 3002004310 [2015]). For example, a common approach for U.S. utilities in modernizing is to do so in a stepwise manner. Utilities may leverage planned outages to install a subset of the vision at different points in time to maximize plant availability (avoiding excessive downtime) and allow existing plant staff to become familiar with the new digital technology with minimized impacts to training.

Identifying the systems being upgraded and their associated indications and controls is an important step from the migration phase. Mapping where these indications controls are in relation to the physical layout of the control room can be useful in the HFE analysis of each phase. Likewise, understanding how operators will use the upgraded equipment in combination with existing analog indications and controls can better define the scope and extent of HFE needed at each phase. Finally, depending on the systems involved at each upgrade phase, there may be licensing impacts. Safety-related equipment such as the RPS or emergency safety feature actuation systems are directly tied to reactor core integrity and the control of radioactive fission products to the environment (Hunton & England, 2019). Upgrading these systems may entail a license amendment request (LAR) whereas non-safety equipment may follow the 10 Code of Federal Regulation 50.59 process (Joe, Hanes, and Kovesdi 2018).

In recent work with a U.S. utility, the HTI researchers supported developing a migration strategy by reviewing each phase and providing HFE considerations to be evaluated at each phase. While the migration strategy was largely driven by the scope and schedule from the utility, operations and HFE had an integral role in identifying potential challenges with certain hybrid configurations by utilizing the 3D modeling and simulation capabilities. The team used the 3D models to evaluate impacts to the placement of visual display units (VDUs), presenting HSI displays in interim states to come to a preferred sequence of modifications that minimized rework (i.e., uninstalling equipment installed in recent upgrade phases) and did not introduce any new human error traps. The results were documented in a table, such as the template shown in Table 2.

Table 2. Template for recording human factors impacts by migration strategy.

Phase	Systems Impacted	Modernization Path	Summary of HSI Changes	Human Factors Impacts
Upgrade Phase Sequence	Enter system(s) impacted by phase	LAR or 10 Code of Federal Regulation 50.59	Summary of HSI changes	Identify HFE considerations

2.2.1.5 Developing a Human Factors Engineering Program Plan

The HFE Program Plan provides guidance to ensure that the modernization project ensures safety and reliability while also satisfying applicable regulatory requirements and expectations concerning HFE (Joe, Hanes, and Kovesdi 2018). The HFE Program Plan is one of the 12 elements in U.S. NRC guidance NUREG-0711 (2012). Key characteristics of the HFE Program Plan, as described by NUREG-0711, include:

- The HFE Program Plan goals and scope
- The team composition
- The HFE processes, procedures, and elements (Figure 8)
- HFE issue tracking.

These topics are further described in NUREG-0711 (2012), under Section 2.

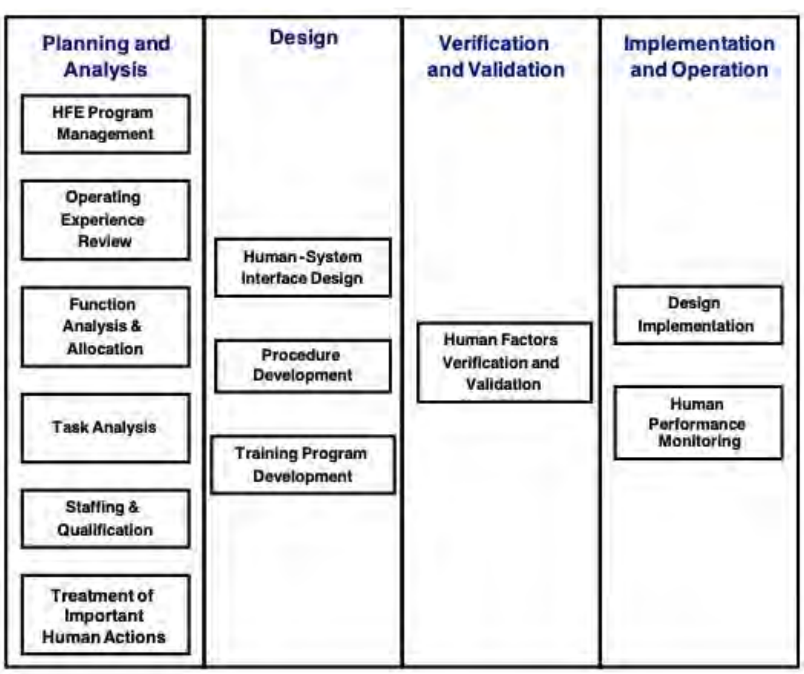


Figure 8. NUREG-0711 12 elements (adapted from NUREG-0711 2012).

It is also important to note that the HFE scope may be variable in terms of the level of effort and rigor needed across different migration phases of the project lifecycle. Thus, applying a graded approach to HFE, as defined by the HFE Program Plan, is pertinent to ensure that HFE is appropriately scaled so that the upgrade can stand alone from an operational readiness standpoint and can effectively integrate into a project's schedule and budget. The HFE Program Plan should therefore describe how HFE is applied via a graded approach to the project lifecycle at different migration phases. Commonly, grading is done by comparing the level of risk to plant safety, personnel safety, and economic impact in terms of defining the level of HFE effort needed. Further, the degree of complexity to which the digital upgrades affect the current concept of operations can further tailor the grading based on risk.

Together, both risk and complexity can be characterized as shown in Figure 9. HFE grading is defined by three levels set from risk and complexity. When risk and complexity is high, such as with a large-scale digital upgrade to a safety-related I&C system, the level of HFE effort would deem the project as "high." A like-for-like upgrade on a non-safety system may be low risk, and a low complexity deemed the project as "low." The result between the two would suggest applying different levels of rigor to the HFE involved.

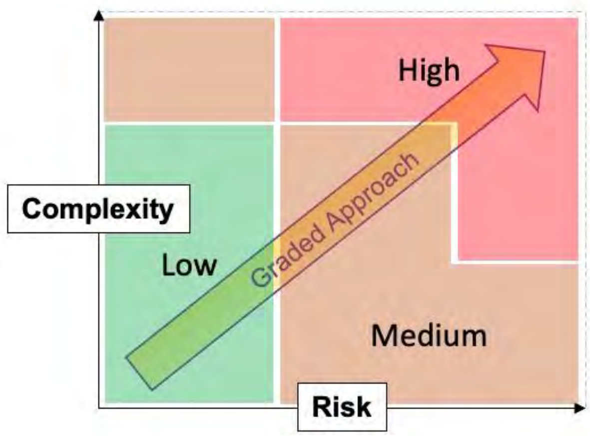
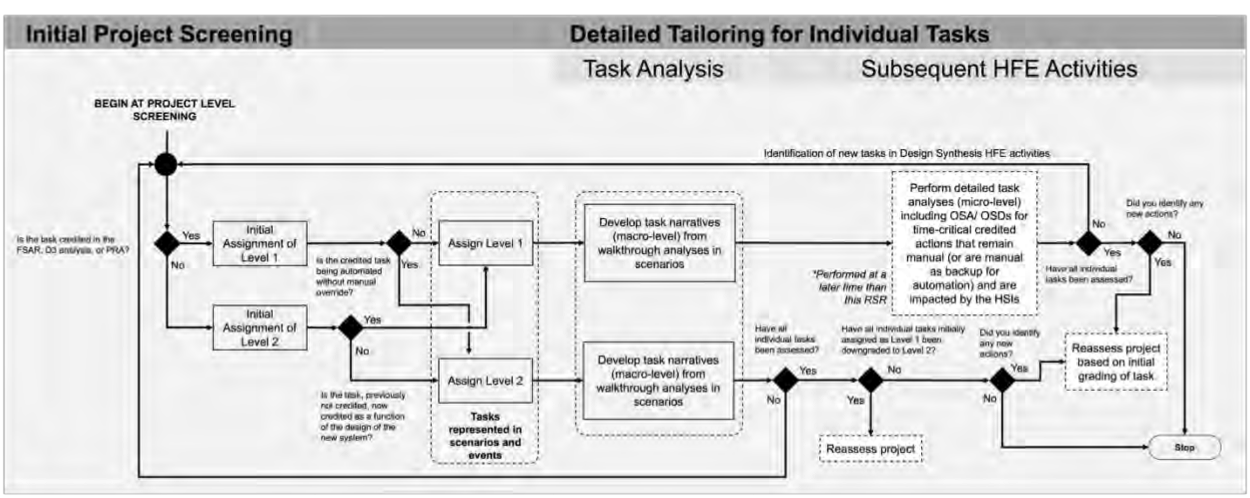


Figure 9. Grading HFE by complexity and risk (adapted from INL/RPT-22-70538).

It is also important to note that, while initial project grading (herein referring to a specific modification phase) may be assigned at a particular level, additional *tailoring* of specific elements may be needed to effectively integrate HFE into the project. This is seen in Figure 10.



Note. Tasks not impacted by the upgrade were noted as a Level 3 (little to no impact) and were not considered for subsequent HFE analysis.

Figure 10. Tailoring HFE by task risk level (adapted from INL/RPT-22-68472).

Where a project may be graded at "high" based on a screening of impacted tasks that are credited as part of the licensing basis, an additional tailoring of impacted tasks that are not credited may be considered to help focus HFE resources on the safety-related tasks. Figure 10 shows a process for tailoring HFE efforts to focus on the safety-related tasks (noted as Level 1 tasks) by determining if the tasks are in deterministic or probabilistic risk analyses for the plant. In terms of the level of HFE effort involved, the tailoring allows for detailed task analysis and performance-based tests on the Level 1 tasks and more generalized HFE methods (e.g., walkthrough analysis) for tasks not important to plant safety. In terms where there may be hundreds of tasks impacted, such tailoring can significantly support effective HFE integration.

An important consideration for utilities when developing an HFE Program Plan will be to decide how the upgrades (including updates to procedures and training) will be effectively designed, tested, verified, and validated (i.e., as indicated by the subsequent phases of the HTI methodology). Hunton and England (2019) provide guidance for distributed control system (DCS) integration. In this report, the authors describe the need for an additional simulator (beyond the training simulator) and selecting an I&C vendor who offers the seamless incorporation of the new plant control system into the simulator. Indeed, the use of simulation and modeling is a critical enabling capability of the HTI methodology. Simulator testbeds, such as the HSSL (refer back to Figure 6), can be useful in testing and evaluating proposed upgrades. As a utility planning for large-scale upgrades, having something like the HSSL (or a subset of glasstop simulator bays) can serve useful in strategically integrating HFE and operations input early and iteratively into the design process.

Another important consideration is to ensure that the HFE Program Plan accounts for close integration between the activities required of the I&C vendor and HFE activities within the Program Plan (EPRI 3002004310 2015). Coordination between major development milestones and specific HFE activities should be done to ensure that the output from such activities can be useful to the project. Ensuring that a *style guide* is developed or adapted can support a foundation in translating the HFE findings and requirements into the design of new HSIs. The HSI style guide will ensure consistency across the project while ensuring that HFE guidance and operational input is incorporated. It also provides a way to synthesize these inputs into a design that is achievable by the vendor's capabilities and conventions, when there is close coordination. The HSI style guide is a critical artifact to design synthesis, described later in Section 2.2.3. However, it is at the HFE Program Plan where the consideration of the style should be made. This includes adapting an existing HSI style guide or developing an entirely new one. In the former case, existing design conventions can be readily leveraged but will need to be adapted into the new HSIs. For example, there may be main control design conventions for the labeling of components with the existing indications and controls that pose challenges when put into the new digital format (e.g., such as with taking up too much space). In any case, identifying any existing style guide at this phase is critical to identifying these tradeoffs early and accounting for them when costs are less.

2.2.2 Develop Human-Technology Integration Requirements

HTI requirements translate the functional, information, and task requirements of the new state and concept of operations into requirements that drive the design of the new HSIs, impacted procedures, and training. In essence, this phase is a primary input into design synthesis. There are three primary HFE activities in this phase: function analysis and allocation, task analysis, and integration of risk analyses (i.e., treatment of important human actions). These activities are shown in Figure 11 and are described next.

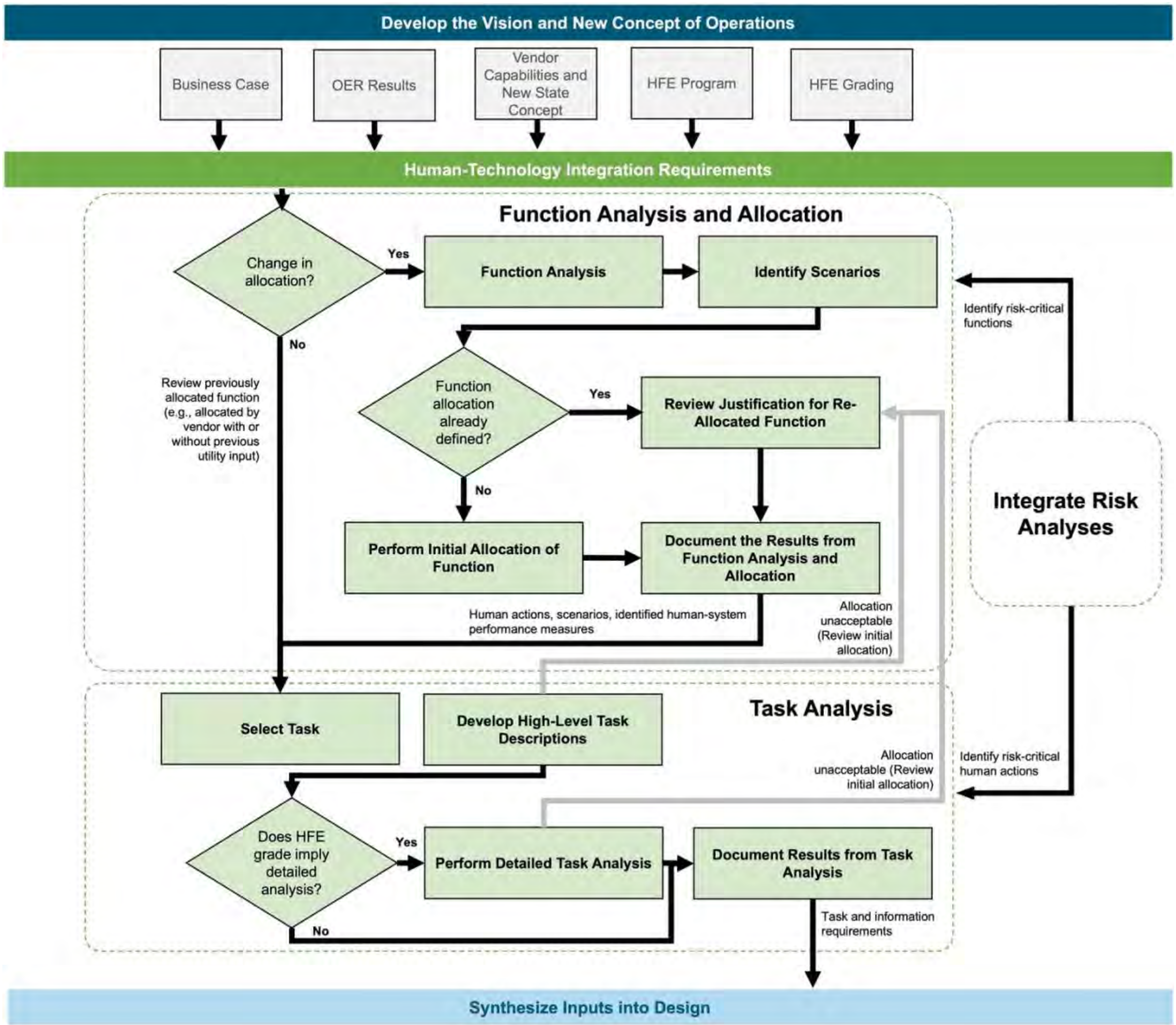


Figure 11. HTI requirements (adapted from INL/EXT-21-64320).

2.2.2.1 Function Analysis and Allocation

Function analysis and allocation (FA&A)[a] contains two HFE activities. First, *function analysis* (or functional requirements analysis) identifies the functions that must be performed by the plant systems to ensure safety and generate power (NUREG-0711, 2012). Functions that are identified are then decomposed into more detailed functions in terms of the specific plant systems that accomplish the high-level functions. This decomposition typically enables an *assignment* of specific functions to automation, people, or a shared distribution of work between the two. The assignment of functions in this context is known as *function allocation*. The role of HFE in this context is twofold. First, it is important to ensure that the functions to be carried out are clearly defined. Secondly, these defined functions should be allocated to people (manual), automation (automatic), or a combination (shared) based on the capabilities of the technology and people. This activity is meant to address these points and is done through four steps, as shown in Figure 11.

An important distinction with existing light-water reactors to be modernized is that the higher-level functions are likely to remain the same. However, the way in which these functions are managed by

[a] Sometimes referred to as **functional requirements analysis and function allocation**.

technology is where there are differences. This is visualized in Figure 12, which illustrates where in the functional decomposition hierarchy digital upgrades will likely impact the plant.

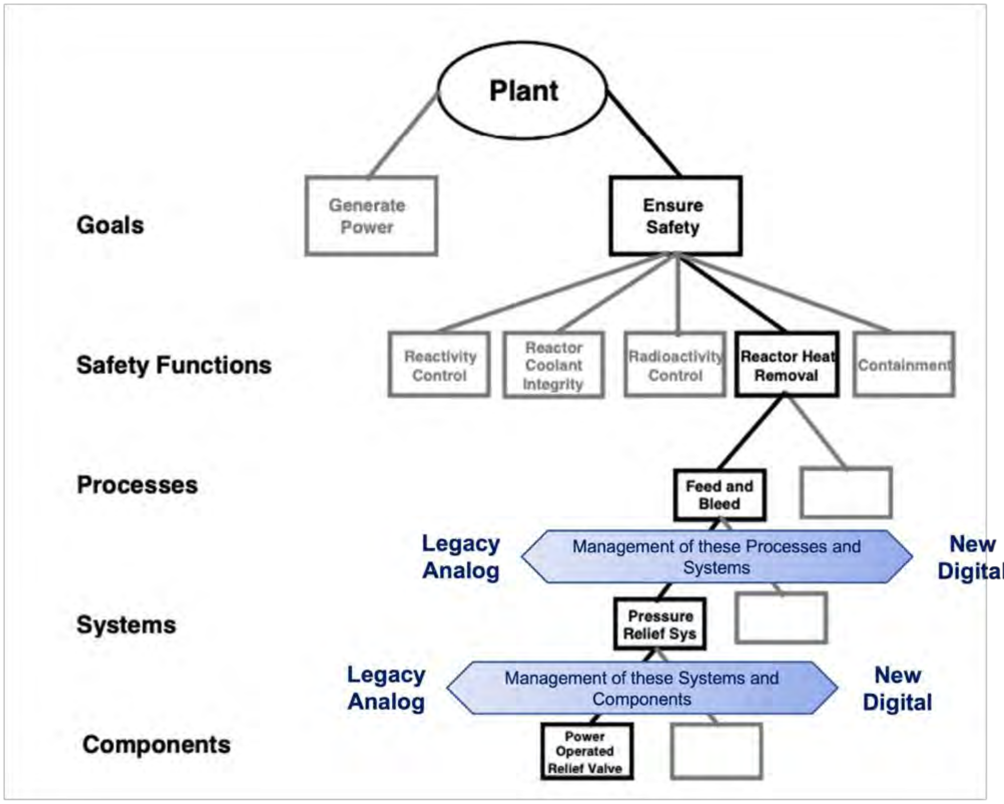


Figure 12. Vertical slide through a plant's functional hierarchy for ensuring safety (adapted and enhanced from NUREG-0711 2012).

From an HFE standpoint, the important questions for function analysis are around what are the impacted functions, what are the safety significance of the systems impacted, and how are these functions changing from their current state? To no surprise, the outputs of the new vision and concept of operations (i.e., as associated tools like the endpoint vision worksheets) serve as useful inputs into function analysis and allocation. This input can be used to further elaborate how specific tasks are impacted, given the identified impacted functions and associated systems. Of these tasks, it can be determined which of them are safety significant.

Task analysis and integration of risk analysis described later can address these considerations. Moreover, the guidance described in INL/EXT-21-64320 illustrates additional HFE steps in function analysis and allocation that can support a responsible assignment of functions by accounting for the capabilities of people and technology. Further, Section 3 of INL/RPT-22-68472 (2022) describes additional approaches to support function allocation. In any case, a scenario-based approach is given in which HFE methods like walkthroughs and talkthroughs can be applied early to inform function allocation. The use of simulation and modeling tools can be especially helpful in communicating preliminary designs and functions to operators, even before a detailed design is realized. Feedback at this phase can inform task analysis and later HFE activities, moving into design and verification and validation (V&V). A demonstration of function analysis and allocation, as described in INL/EXT-21-64320, in industry can be found in INL/RPT-22-68472 (2022).

2.2.2.2 Task Analysis

Functions that are allocated to people are further analyzed via task analysis to define information requirements and task considerations necessary for safe, reliable, and efficient use. Within the HFE community, task analysis is widely known. A detailed discussion of the methods is given by Kirwan and Ainsworth (1993) or Stanton and colleagues (2017). Task analysis as applied to nuclear power can be found in NUREG-0711 (2012) Section 5, EPRI 3002018392 Section 3.5 (2021), EPRI 3002004310 Section 3.5 (2015), or IEEE 1023 (2020). Further, INL/RPT-22-68472 (2022) describes the demonstration of task analysis following function analysis and allocation.

A salient point is that task analysis can be performed at various levels of detail, which corresponds to the graded approach. As described in INL/RPT-22-68472, task analyses can be categorized by considering both macro- and microlevel task considerations (Figure 13).

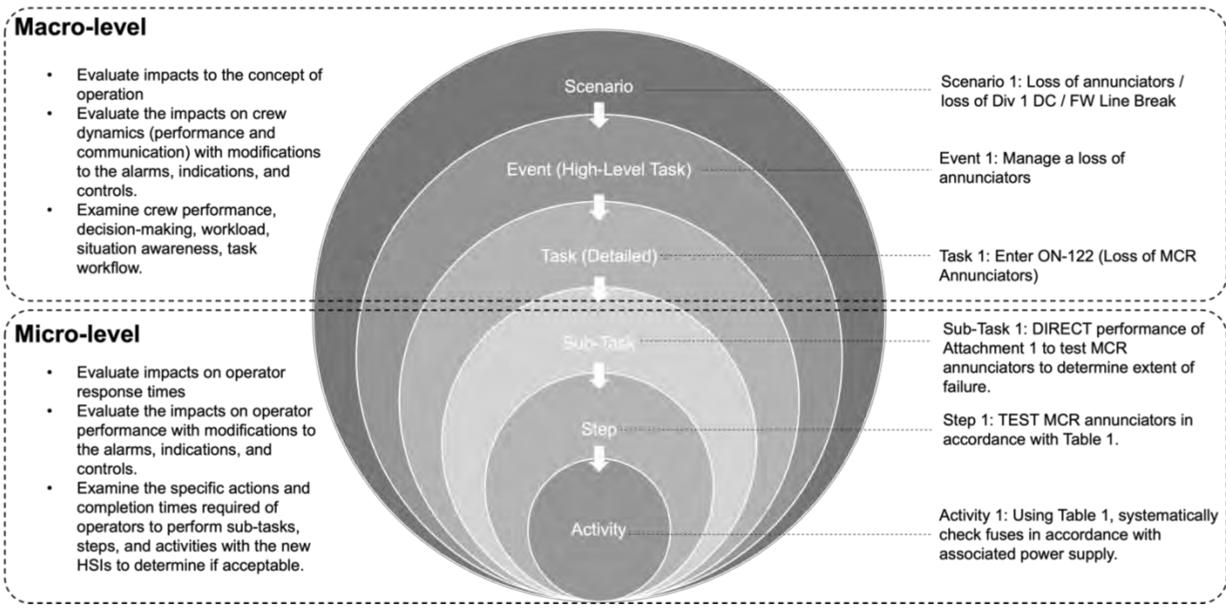


Figure 13. Decomposition of tasks for performing task analysis (adapted from INL/RPT-22-68472).

Impacted tasks that are not critical to safety may only be analyzed at a macrolevel. That is, such tasks may be of concern from a holistic crew performance perspective, regarding how the crew will perform their tasks using the new HSIs and modified procedures. Generalized design feedback can be captured by understanding how the HSIs supported these tasks using scenarios. Safety-related tasks can be further analyzed at a microlevel. This topic is key to this report and is discussed in detail in Section 3.1.2.9.

2.2.2.3 Integration of Risk Analysis

The primary objective in this activity is to identify the impacted important human actions and consider them in other HFE activities to ensure safe and reliable operation. This activity corresponds directly to NUREG-0711 Section 7 (2012); it drives the grading and tailoring of all HFE activities that comprise the HFE Program Plan. Both deterministic and probabilistic risk analyses are considered. As demonstrated in INL/RPT-22-68472 (2022), a project-level graded approach followed by further tailoring of tasks through specific mapping of the impacted tasks identified via deterministic risk analysis results (i.e., as reported in the plant final safety analysis report [FSAR] and diversity and defense in depth [D3] analysis) and probabilistic risk analysis (PRA) results follow. The net result identifies a set of impacted safety-important tasks (i.e., called Level 1), which are central to subsequent design and V&V efforts. The integration of risk analyses also supports identifying human-system performance requirements necessary for safe operation, later touched on in Section 3.1.2.9.

2.2.3 Synthesize Inputs into Design

The design synthesis translates the inputs previously collected from developing the new vision and concept of operations (Section 2.2.1) and human-technology integration requirements (Section 2.2.2) into HSIs that will be used by plant personnel. Figure 14, adapted from INL/EXT-21-64320 (2021), highlights the intersection of four main inputs that drive HSI design.

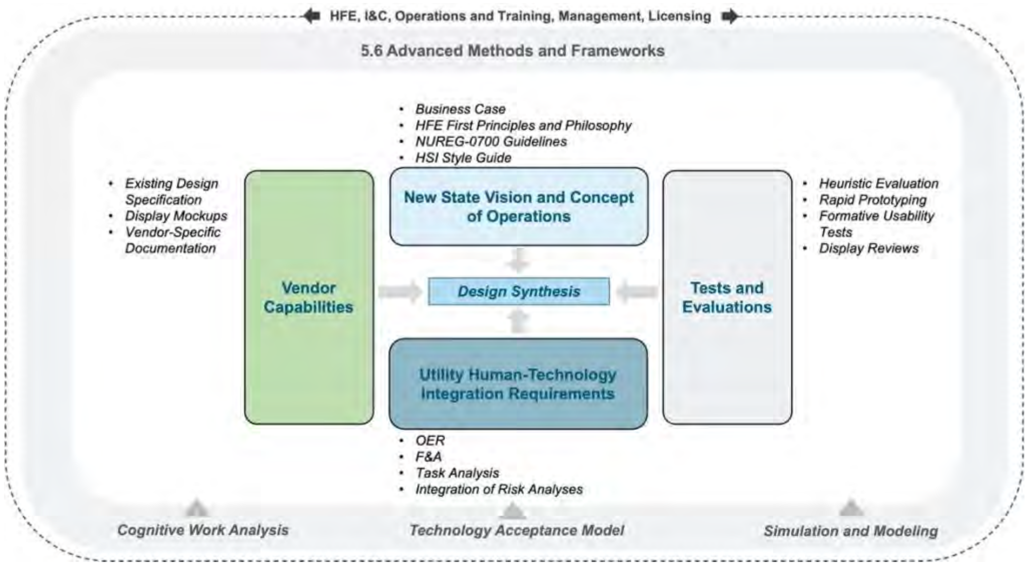


Figure 14. Inputs and activities for synthesizing inputs into design (adapted from INL/EXT-21-64320 [2021]).

They include considering vendor capabilities, the new vision and concept of operations, and the human-technology integration requirements (i.e., information requirements and task considerations), as well as results coming from tests and evaluations. A key design output is the suite of HSIs that will be used by the staff. With this, the development and use of an HSI style guide is important to ensure that HSIs conform to HFE guidelines and principles. These inputs and output are described in the next subsections.

2.2.3.1 Human-System Interface Design Inputs

Aligning to Vendor Capabilities

The features and functions that are native to the selected vendor should be accounted for to ensure minimum unnecessary impacts to cost (Hunton & England, 2019). This is both true for safety and non-safety I&C systems. From a safety system standpoint, the need to consider the capabilities inherent to its design is paramount, especially if the applicant pursues the recently revised *Digital Instrumentation and Control Interim Staff Guidance* (DI&C-ISG-06) *Licensing Process*, Revision 2 (2018) Alternative Review Process. The DI&C-ISG-06 Alternate Review Process is streamlined by omitting Phase 2 (Application, Review, and Audit Continued Review) from the Standard Review Process. A key characteristic of the Alternate Review Process is that a LAR submitted to the NRC can be approved by the NRC before a factory acceptance test (FAT); this differs from that Standard Review Process where approval was given after FAT (Figure 15).

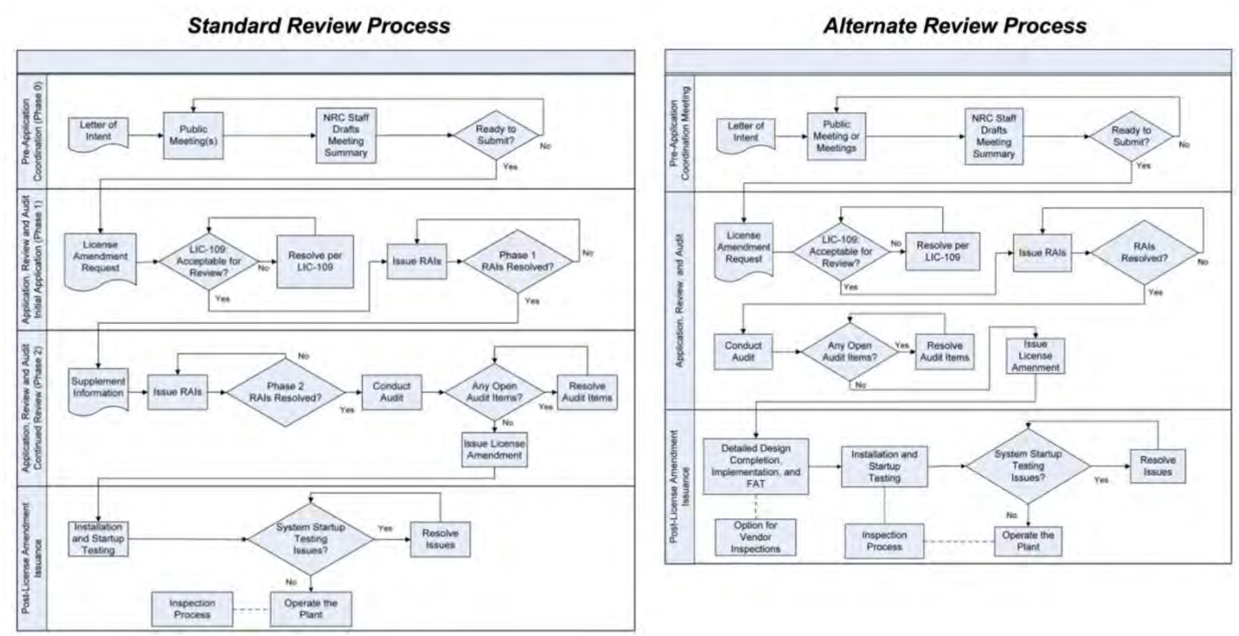


Figure 15. Comparison of the Standard Review and Alternate Review Processes

(from DI&C-ISG-06, 2018).

The primary advantage of the DI&C-ISG-06 Alternate Review Process is a reduced schedule to obtain LAR and NRC technical approval. However, to follow the DI&C-ISG-06 Alternate Review Process, it is necessary to leverage the safety I&C system that has already received a generic safety evaluation report (SER). Thus, minimizing any customization of the features and functions must be considered.

For non-safety I&C DCSs, there are also key advantages to considering the vendor capabilities inherent to the platform. That is, by leveraging the native vendor capabilities, total DCS cost of ownership can be minimized by avoiding additional resources needed for custom development, as well as ensuring software refreshes by the vendor seamlessly integrate into the DCS (i.e., as oftentimes customized code is not accounted for). From an HFE standpoint, it is necessary to provide guidance in configuring the vendor's native features and functions to support specific operational needs. This is accomplished through applying HFE design principles and performing iterative tests and evaluation. Moreover, these activities greatly benefit a multidisciplinary team involving operations, training, engineering, HFE, licensing, and the vendor. Indeed, while previously designed solutions from a vendor can serve as a design starting point, the design must be vetted by operations and carefully account for the utility conventions and existing licensing commitments, as appropriate. Thus, the need for *synthesizing* the vendor capabilities with previous inputs and perform tests and evaluations with operations is highly important.

Inputs from the Vision, Concept of Operations, and Human-Technology Integration Requirements

It should come as no surprise that findings from previous HFE activities, as related to design, should be considered as inputs. Starting with the vision and concept of operation, the HSIs being designed should support the way in which the crew will perform their tasks with the new system. That is, the intent in which the HSIs will be used by the crew will inform the HSI attributes being developed during conceptual and detailed design steps. For example, large overview displays identified in a new state vision will present information at different viewing distance requirements than HSIs at a workstation. These large displays may not be intended for control in their typical use and therefore designing for soft controls will not be central to their requirements. By this same token, new findings and engineering tradeoffs may be uncovered during design that further inform the vision and concept of operation. This may be seen with the placement of a VDU for HSIs for which seismic requirements are later discovered to necessitate an alternative location for the VDU. Such a coupling between the design, vision, and concept of operations development should be expected. OER is another important HFE activity completed early in the HTI methodology. The OE collected during OER that is pertinent to HSI design should be revisited to ensure that human error traps with the current plant design are avoided and that OE collected on related technology can be used to avoid any known usability issues.

Inputs coming from human-technology requirements (i.e., enveloping function analysis and allocation, task analysis, and risk analysis integration) entail the identification of automation requirements, information requirements, and task considerations. For automated functions, it is important to address design considerations with monitoring and supervising the automation. Considerations related to automation transparency and designing for situation awareness are central HFE topics in this regard. For impacted manual actions, design considerations relating to ensuring that operators can effectively perform their tasks safely and efficiently is important. Information formatting, navigation demands, and soft control designs are all relevant. Finally, specific focus on the important-to-safety human actions must be made. For these actions, ensuring that the designs do not negatively impact the human-system performance and workload is critical. Establishing performance acceptance criteria is important, as described next, for testing and evaluating during V&V.

Tests and Evaluations: Guideline for Operational Nuclear Usability and Knowledge Elicitation

Tests and evaluations for human factors V&V are used to determine that the HFE design conforms to HFE principles and enables personnel to successfully perform tasks and operations to ensure plant and operations goals are safely met. The Guideline for Operational Nuclear Usability and Knowledge Elicitation (GONUKE) is an evaluation method used for control room modernization efforts (Boring, Ulrich, and Lew 2015) to help verify and validate HFE principles and designs are included to help ensure plant safety. GONUKE uses three evaluation methods to help to establish the success of a design: expert review, user testing, and knowledge elicitation (Boring, Ulrich, and Lew 2015). Expert reviews are used to evaluate a system against a standard set of criteria by subject matter experts (SMEs). User testing evaluations test the user or operator system use to evaluate how usable the current and new systems are for task performance. Knowledge elicitation is used to capture insights from operators when using current and future systems. Using these evaluation types early on helps to ensure that human factors principles and guidance are applied to the design to help shape the new system.

Formative and summative evaluation phases are used in NUREG-0711 Section 8.4.6; however, they are sometimes used later in the design or when the design is completed. Formative evaluations are reviewed during the design, and summative evaluations are completed after the design is complete. This has some disadvantages, such as having no room for error, requiring additional participants to achieve statistical significance, or having decreased time for expert review of standards and criteria (Boring, Ulrich, and Lew 2015). The GONUKE method combines the formative and summative evaluation phases with expert review, user testing, and knowledge elicitation to better support the control room modernization process. Figure 16 provides an example of how the GONUKE process is used to evaluate new designs from planning to the post-completion stages.

Evaluation Phase

Evaluation Type	**Pre-Formative** *(Planning and Analysis[1])*	**Formative** *(Design[1])*	**Summative** *(Verification and Validation[1])*	**Post-Summative** *(Implementation and Operation[1])*
Expert Review *(Verification)*	[1] Design Requirements Review	[2] Heuristic Evaluation	[3] System Validation	[4] Requalification against New Standards
User Study *(Validation)*	[5] Baseline Evaluation	[6] Usability Testing	[7] Integrated System Validation	[8] Operator Training
Knowledge Elicitation *(Epistemiation)*	[9] Cognitive Walkthrough (Task Analysis)	[10] Operator Feedback on Design	[11] Operator Feedback on Performance	[12] Operator Experience Reviews

[1]Corresponding Phases in NUREG-0711.

Figure 16. GONUKE process (adapted from Boring, Ulrich, and Lew 2015).

The evaluation types and phases shown in Figure 16 are not all required as part of the GONUKE method. Validation from user studies provides more direct conclusive results; however, verification from expert reviews and knowledge elicitation helps to provide additional evidence to support the design (Boring, Ulrich, and Lew 2015). Major control room modernization upgrades would benefit from the use of the entire GONUKE method to help provide sufficient documentation and reviews to better align with the NUREG-0711 evaluation. This helps to ensure that the design has been fully evaluated throughout the entire design lifecycle.

A simplified version of the GONUKE method is also available for non-critical safety system designs, as shown in Figure 17 (Boring, Ulrich, and Lew 2015). This version of the GONUKE method is helpful to ensure good design principles were applied and evaluated. User testing and expert reviews evaluations can help to ensure that the design will function for its intended purpose.

Evaluation Phase

Evaluation Type	**Formative**	**Summative**
Expert Review (Verification)	Heuristic Evaluation	Design Verification
User Testing (Validation)	Usability Testing	Integrated System Validation

Figure 17. Simplified GONUKE process (adapted from Boring, Ulrich, and Lew 2015).

2.2.3.2 Design Synthesis Outputs and Human-System Interface Style Guide

Key outputs of design synthesis include a complete set of HSIs that can be safely, reliably, and efficiently used. Complementary to the HSIs, the *style guide* should be a developed output of design synthesis. The HSI style guide provides the set of rules that guide HSI design to ensure consistency across displays and to ensure that HFE principles and operational input are applied (EPRI 3002004310 2015). The style guide is especially important in HSI designs in development and future displays that may be part of subsequent modernization phases. The style guide is used in HSI design, serves as a key resource in V&V during HFE design verification, and should provide instructions for its use and address the:

- Organization and presentation of information on individual display pages to be presented on physical VDUs
- Organization and navigation between display pages
- Design of display fonts and symbols
- Use of color coding and labeling
- Design of touch panels to provide for operator input of decisions if this type of HSI is desired.

The process through which the HSI style guide is developed can be seen in Figure 18.

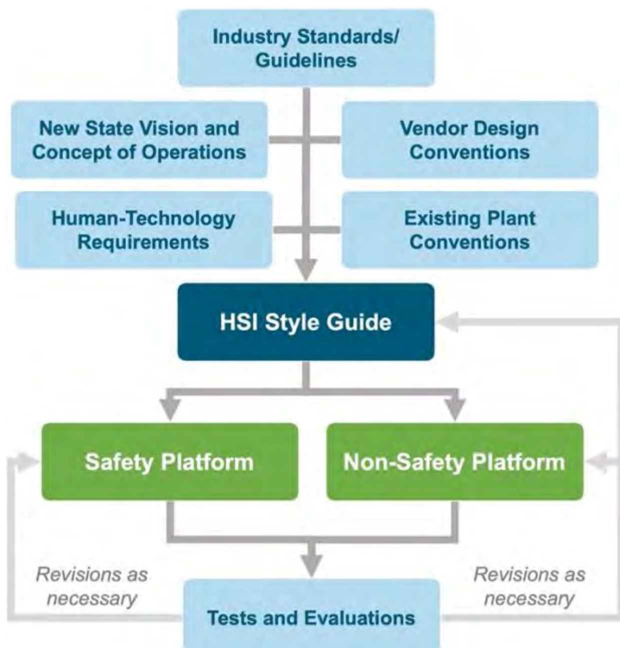


Figure 18. HSI style guide development process.

At the top of Figure 18, the inputs include industry standards and guidelines, such as the NRC *Human-System Interface Design Review Guidelines* (NUREG-0700 2020), the results from the vision and concept of operations, the results from human-technology requirements, vendor design conventions, and existing plant conventions. These inputs provide the technical bases for specific guidance in the style guide. The style guide may be written at a higher level than design specifications for individual I&C platforms. In such a case, the style guide provides a harmonized set of guidelines that apply to the platforms to be installed (e.g., a safety and non-safety platform). The style guide would thus provide guidance with sound HFE basis like the size of buttons on a touch screen. At the general level, the style guide may suggest that buttons be no smaller than 0.6 inches per NUREG-0700 guidance (2020). The specific hardware in place for the specific platforms would then translate this guideline to be specific to the design attributes at hand (e.g., no smaller than 60 pixels). During design synthesis, tests and evaluations (i.e., sometimes called formative usability tests or design tests) are completed to identify design issues or address tradeoffs before transitioning into V&V. The results of these tests should inform the style guide further, as indicated by the feedback loop in Figure 18.

A final point worth mentioning is that the HSIs designed in this phase must integrate as a system with the site's training program and procedures. Changes to HSIs may impact the procedures and training to which identifying the scope and extent of these changes is pertinent. In fact, performing usability tests with the proposed new HSIs in combination with draft update procedures can be extremely beneficial for procedure refinement. In essence, both HSIs and procedures must be integrated in a way that are usable and complete for the operator to safely, effectively, and efficiently perform the task.

2.2.4 Evaluate Using Verification and Validation

Per NUREG-0711 (2012), the objective of V&V is to:

> …comprehensively determine that the HFE design conforms to HFE design principles and that it enables plant personnel to successfully perform their tasks to assure plant safety and operational goals. (page 73)

There are four V&V activities involved: sampling of operational conditions, design verification, integrated system validation (ISV), and human engineering discrepancy (HED) resolution (Figure 19).

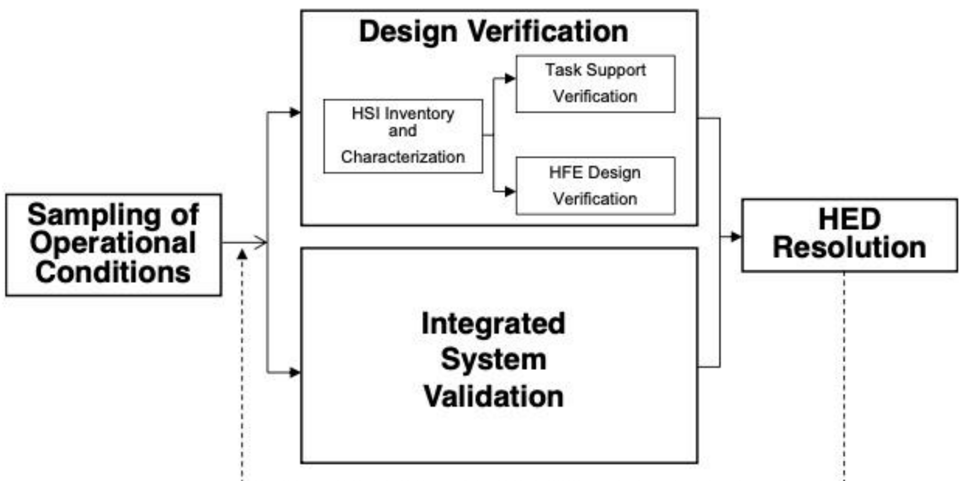


Figure 19. Overview of V&V activities (adapted from NUREG-0711, 2012).

Design verification and ISV serve as the primary reviews. The role of design verification is twofold. First, it is done to verify that the HSIs support the task requirements defined in previous HFE activities, such as in human-technology requirements (i.e., this is noted as task support verification). Second, it is done to verify that the HSIs are designed to accommodate peoples' capabilities and limitations; the application of a style guide and associated guidance like NUREG-0700 is used in this part. The role of ISV is to determine whether hardware, software, and people integrated as a system meet the performance requirements and support safe operation. ISV utilizes empirical-based approaches, such as performance-based tests.

Design verification and ISV rely on sampling operational conditions as a way of pragmatically addressing a large-scale modification where a complete analysis is impossible due to the sheer number of HSIs, involved tasks, etc. These activities also produce HEDs if performance criteria are not met. Thus, the final activity, HED resolution, evaluates any identified HED to provide reasonable assurance that it has been assessed and resolved.

The reader is referred to NUREG-0711 Section 11 for details on V&V. However, it is worth mentioning several key points in this report. First, the use of a scenario-based approach early in the HTI methodology, such as during function analysis and allocation, may support the sampling of operational conditions during V&V. For example, the scenarios identified during OER and applied in function analysis and allocation may be relevant for tasks performed in V&V. An advantage of collecting task data earlier in the process can help provide greater confidence towards V&V that pertinent design issues have been identified and addressed. Scenarios may evolve as well, when the project matures and there's a clearer understanding of the scope and impacts of the upgrades on personnel tasks. In this case, scenario sampling early can be a starting point in further refining scenario sampling at V&V.

Another important characteristic to differentiate is the intent of tests and evaluations at the design phase and V&V activities described in Section 11 of NUREG-0711. Complementary guidance in distinguishing these two sorts of evaluations is summarized in IEEE 2411 Annex B (2021). The key distinction as described by this standard is that design testing (i.e., otherwise referred to as tests and evaluation in NUREG-0711) is used by the design team to make design decisions. In the usability engineering literature, these sorts of evaluations are defined as *formative* in nature (Nielsen 1994). They serve many purposes but common motives for applying them include identifying design issues for correction or comparing two or more design options. The design may be of varying fidelity, and the questions at hand can be diverse. The HTI methodology emphasizes testing early even when designs are not fully mature in order to answer broad design questions that can further narrow down and focus the design throughout the project's lifecycle (INL/EXT-21-64320 2021).

V&V, on the other hand, assesses whether an aspect of the design meets its intended purpose. Design questions during design may be open ended in nature whereas V&V uses established acceptance criteria to determine whether the integrated system meets its purpose. There are differing degrees of formality between the two. Design tests may be done *by the design team* whereas V&V requires a degree of *independence* between the evaluators and designers to minimize bias (i.e., especially at ISV). Shortcomings with the I&C or HSI design during the *design phase* are treated as design issues and resolutions to these issues are developed by the team for refinement. Conversely, V&V identifies shortcomings as HEDs (deficiencies) and resolutions are typically not proposed directly; rather, the HEDs are provided to an independent design team for disposition. Documentation is more formal during V&V in which formal requirements and acceptance criteria are clearly defined. Configuration control becomes more important during V&V to closely match the design in question to the requirements that drive the acceptance criteria for the performance-based tests (IEEE 2411 2021).

2.2.5 Human Factors Monitoring

HFE is still involved during and after installation (NUREG-0711 2012; INL/EXT-21-64320 2021; IEEE 1023 2020). At this point, HEDs that require correction should have been resolved and modifications should be reflected accordingly in the procedures and training program. Human factors considerations that could not be directly addressed during ISV (e.g., temperature, humidity, or other environmental factors) should be considered at this phase to ensure that there are no negative interactions between the work environment, modifications, and plant staff. It is worth emphasizing that, by implementing HFE *early* such as when developing the vision and ensuring HFE is involved *throughout* the project lifecycle with a multidisciplinary team, potential HFE issues at this stage should be minimal. A primary benefit of the HTI methodology is to ensure safe and reliable operation by accounting for the capabilities of people and technology, which is done so early to drive requirements and resolve design issues when costs are less (i.e., like during conceptual design).

2.3 Applying Human and Technology Integration Within the Systems Engineering Framework

Human and technology integration is most useful when it is applied as part of a holistic, multidisciplinary approach (Kovesdi et al. 2021). One such complementary framework that provides an effective way to deploy HTI in a holistic manner is *systems engineering*. Systems engineering is described in International Organization for Standardization/IEC/IEEE 15288 (2015) as:

> …an interdisciplinary approach governing the total technical and managerial effort required to transform a set of stakeholder needs, expectations, and constraints into a solution and to support that solution throughout its life

Its use goes beyond nuclear power plant modernization and has recently gained interest in the industry as an approach to support large-scale digital modernization. Notably, EPRI developed the Digital Engineering Guide (DEG) to support large-scale digital modernization efforts, which is based on systems engineering (i.e., see EPRI 3002011816 2021). The DEG is industry endorsed, such as by being directed through the Nuclear Energy Institute Mandatory Efficiency Bulletin 17-06, "Implement Standard Design Change Process." The Nuclear Energy Institute bulletin establishes a standard industry design change process (i.e., IP-ENG-001) and corresponding supplemental guidance in NISP-EN-04; this guidance declares that the DEG should be used for design changes for digital equipment.

Important DEG attributes are that it:

- Focuses on meeting stakeholder needs with acceptable risk.
- Meets requirements with opposing constraints.
- Follows a multidisciplinary approach that does not allow any one single discipline to govern the solution.
- Focuses on minimizing development and lifecycle costs through following a holistic and integrative approach.

The DEG uses the Vee model approach to systems engineering, such as the model shown in Figure 20. The colors on Figure 20 represent distinct phases that are described in the DEG from EPRI 3002011816 (2021). These phases are indicative of a common facility change process model.

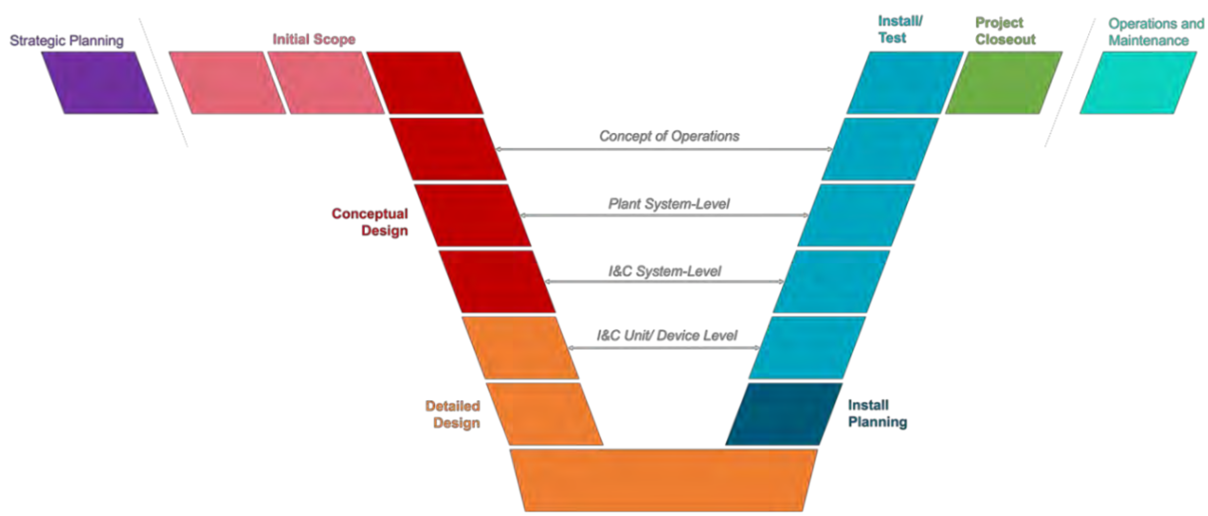


Figure 20. Systems engineering Vee model (adapted from INL/RPT-22-70538 2022).

The Vee model represents the system lifecycle, beginning with scoping and ending with project closeout, operations, and maintenance. The Vee model gets its shape to illustrate the decomposition of the system from high-level requirements to detailed requirements. V&V is performed at corresponding levels of detail, which creates the Vee model's shape. The Vee model allows a system to be further defined as the project matures. That is, early in the project, the vision and its requirements may be less detailed, and more assumptions are made about the system's attributes. As the project becomes more mature and understood, the requirements become incrementally more detailed. The nature of V&V allows for more focused tests earlier on and more integrated tests later, as the system becomes more mature. The nature of the Vee models closely aligns with the HTI methodology, such that it can be overlaid, as seen from Figure 21.

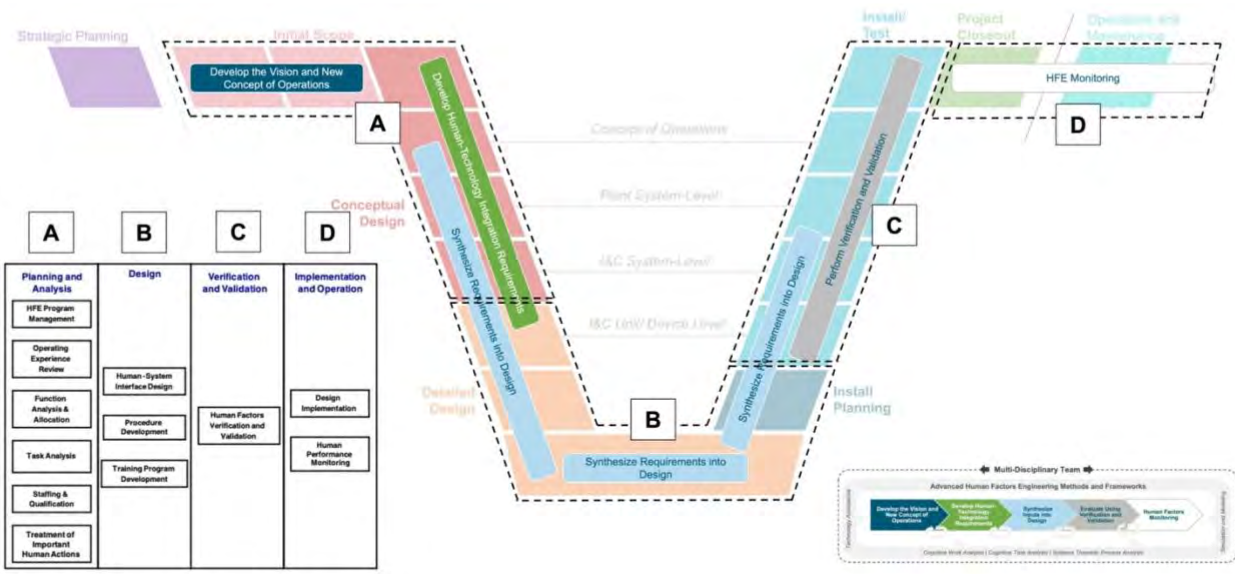


Figure 21. Vee model with the LWRS Program HTI methodology and NUREG-0711 overlaid.

The phases from the HTI methodology summarized in Section 2.2 and detailed in INL/EXT-21-64320 (2021) are applied at different phases of the systems engineering Vee model, as used in the DEG. Further, the four general activities outlined in NUREG-0711 (2012) are overlaid onto the Vee model, as indicated with A–D. This mapping provides context in how the specific HTI activities and related NUREG-0711 elements correspond to the broader systems engineering lifecycle and the DEG (EPRI 3002011816 2021). This correspondence is important as it highlights where specific HTI and NUREG-0711 HFE activities apply within the systems engineering lifecycle. As such, HFE activities can be more effectively planned and executed along with other interrelated engineering activities to ensure safe and reliable use while addressing potential design tradeoffs early in the project when design changes are more cost effective.

An even more detailed view of the specific HTI and NUREG-0711 activities as seen within the systems engineering lifecycle is shown in Figure 22, herein referred to as the Integrated Digital Environment roadmap. The specific DEG phases are shown as columns. Within each systems engineering phase, key activities from each of the LWRS Program research areas are shown in their corresponding swim lanes. The HTI swim lane is emphasized by being bolded. This figure is meant to show how specific HFE activities, as described in INL/EXT-21-64320, can be integrated throughout a project, following a systems engineering approach such as described in the DEG. It should be emphasized, however, that these activities shown in Figure 22 are generalized in that specific project needs and constraints may necessitate adjustment. In fact, key collaborations described later in Section 3 have adjusted these activities to support specific project needs.

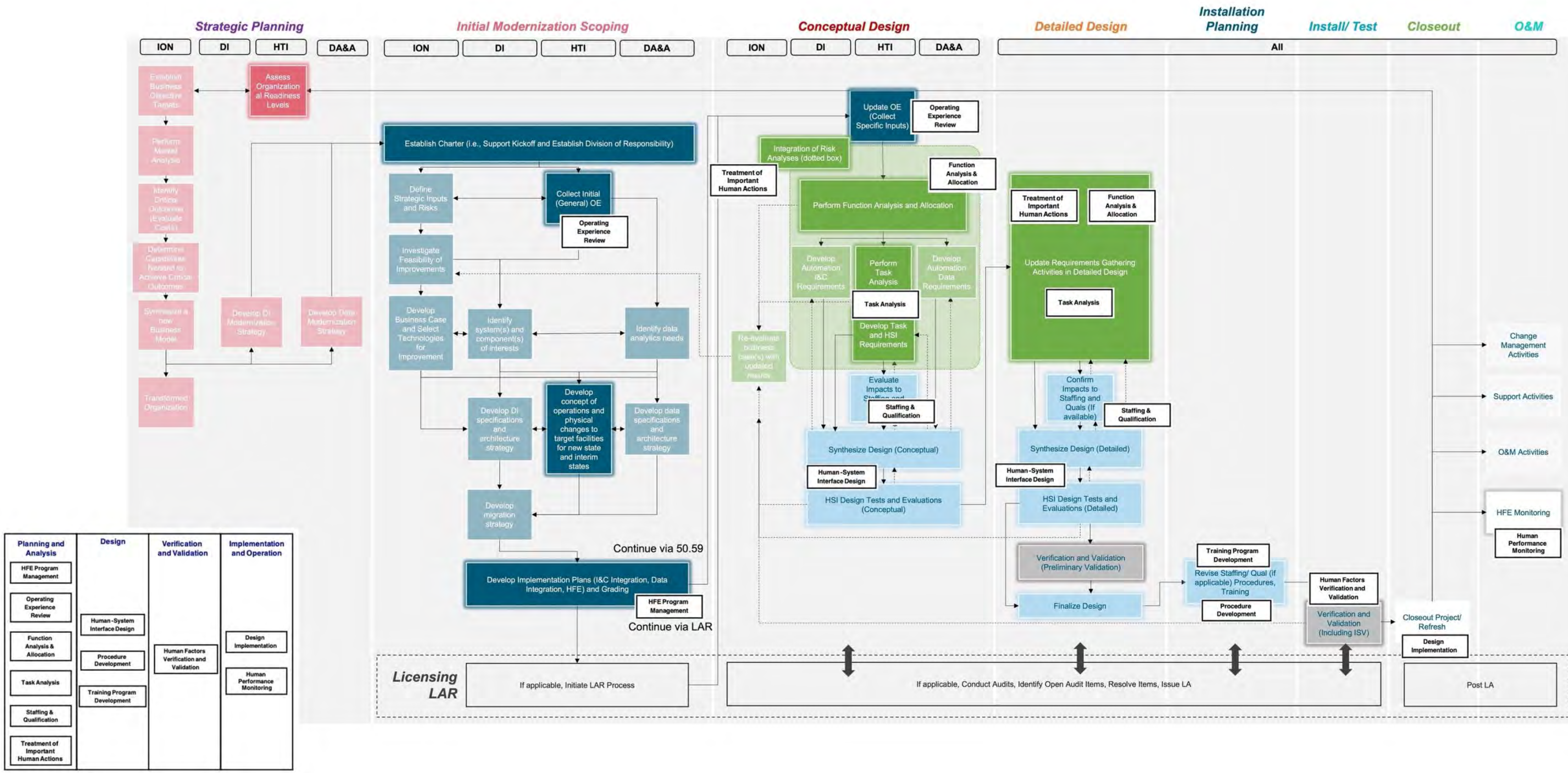


Figure 22. Integrated Digital Environment roadmap.

2.4 Enabling Human and Technology Integration Tools

2.4.1 Three-Dimensional Modeling

The use of 3D models in combination with DHMs are used to support effective team decision-making and are effective enabling HTI tools. 3D models are used to make changes based on design, engineering, and operations feedback. The 3D models present design changes to the MCR to help align stakeholders and provide visualizations of the proposed design. The 3D models can be further leveraged to evaluate HFE issues and considerations, such as those in NUREG-0700, using DHMs. 3D models are then used to apply HFE guidelines and recommendations to make iterative changes and come to a rapid consensus on the placement and location of safety and non-safety HSIs and controls. Stakeholder (i.e., engineering, design teams, and operators) feedback can then be collected in a combination of a series of workshops and virtual meetings. HFE guidelines and recommendations are then applied to the feedback to verify the acceptability of proposed changes to the MCR to help enable the successful integration of new technology into the MCR.

2.4.2 Simulators

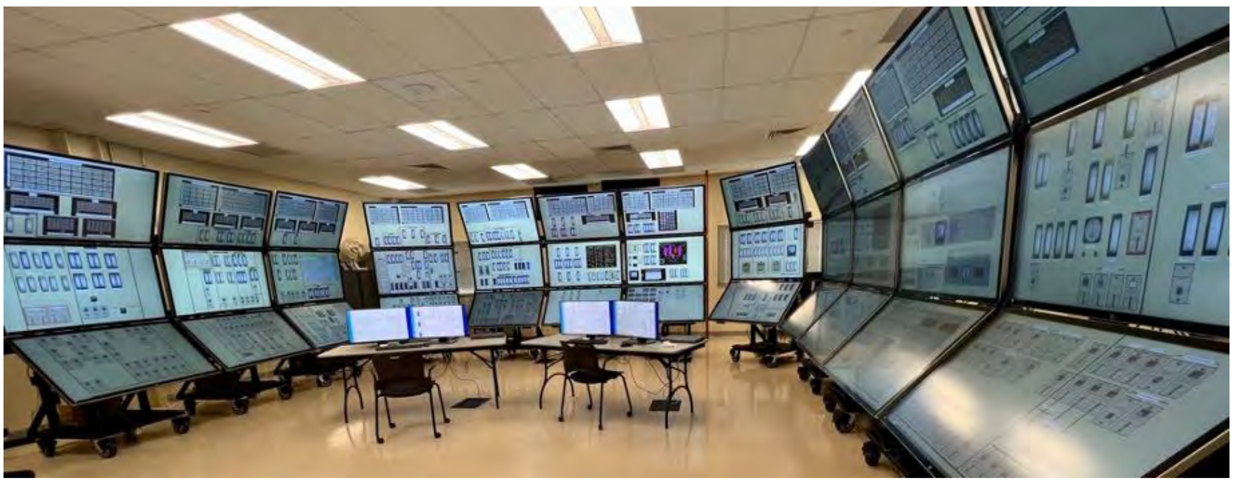


Figure 23. Picture of the HSSL (adapted from Mohon and Kovesdi 2022).

Simulators are useful enabling human factors and technology integration tools that can be used to present the current and future MCR state in the nuclear power plant. Current controls and as well as initial digital I&C upgrades and HSIs can be integrated into the simulator to evaluate how the new upgrades function and operate in the MCR. Using a simulator that duplicates the MCR to pilot new control room upgrades gives operations personnel the opportunity to familiarize themselves with the digital I&C and HSIs before the technology is installed. Simulators enable the collection of early OE on existing operational conventions and provide the opportunity for additional feedback on the newly available digital I&C by allowing the design team to observe operators and collect feedback. Early collection of OE feedback helps to identify safety and reliability issues early in the proposed design process. Demonstrations of HTI using simulators and 3D modeling is discussed in the next section.

3. DEMONSTRATIONS OF THE HUMAN AND TECHNOLOGY INTEGRATION METHODOLOGY IN INDUSTRY

This section shares two important collaborations with industry where the HTI methodology has been demonstrated to support major digital upgrades for U.S. nuclear power plants. Details of the specific approaches used in these efforts are summarized next.

3.1 Collaboration 1: Applying Human and Technology Integration to a First-of-a-Kind Major Safety-Related Digital Upgrade

3.1.1 Background

Most of the existing light-water reactors in the United States are relying on original technology for their I&C safety systems. While these systems are safe and reliable, they are expensive to maintain, and parts are difficult to obtain (Hunton et al. 2021). Industry acknowledges that the current I&C safety systems are becoming obsolete and recognize the opportunity to modernize these systems with advanced digital I&C technology. Constellation Energy Generation (CEG) in collaboration with the U.S. DOE LWRS Program is engaged in a first-of-a-kind safety-related I&C system upgrade to demonstrate the viability of executing a major digital modification to a nuclear power plant I&C safety system. This pilot project is developing a roadmap for performing a large digital transformation of an existing light-water reactor in the United States. The pilot project is forward looking by developing a roadmap that not only supports the digital I&C upgrades but also provides an I&C architecture that can be expanded into developing an advanced concept of operations (Figure 24).

Figure 24. Advanced concept of operations model (adapted from Hunton et al. 2021).

The scope of this project, as described by Hunton and colleagues (2021), entails implementing safety and non-safety I&C into a boiling-water reactor. The safety-related I&C include migrating the RPS, emergency core cooling system, and nuclear steam supply shutdown system functions onto a single safety-related digital I&C system. A portion of non-safety-related functions and safety-related diverse actuation system functions will be integrated onto the DCS.

The pilot project is following the EPRI DEG as a systems engineering framework to perform these upgrades (EPRI 3002011816 2021). The specific phases of this project have been modified from the original DEG to support this work. Key phases therefore include Phase 0 (Initial Scoping), Phase 1 (Conceptual Design), Phase 2 (Detailed Design), and Phase 3 (Implementation). This mapping is shown in the top portions of Figure 25 in dark gray, which shows how these project-specific phases correspond to the original DEG phases. The activities illustrated in Phase 0 of Figure 25 occurring before development of the HFE Program Plan are captured by Hunton and colleagues (2021). The subsections below describe the subsequent HTI activities leading into conceptual verification (CV) at Phase 2 (detailed design). These activities correspond to the Planning and Analysis phase of NUREG-0711 (2012). Lessons learned are described later in Section 3.1.3.4.

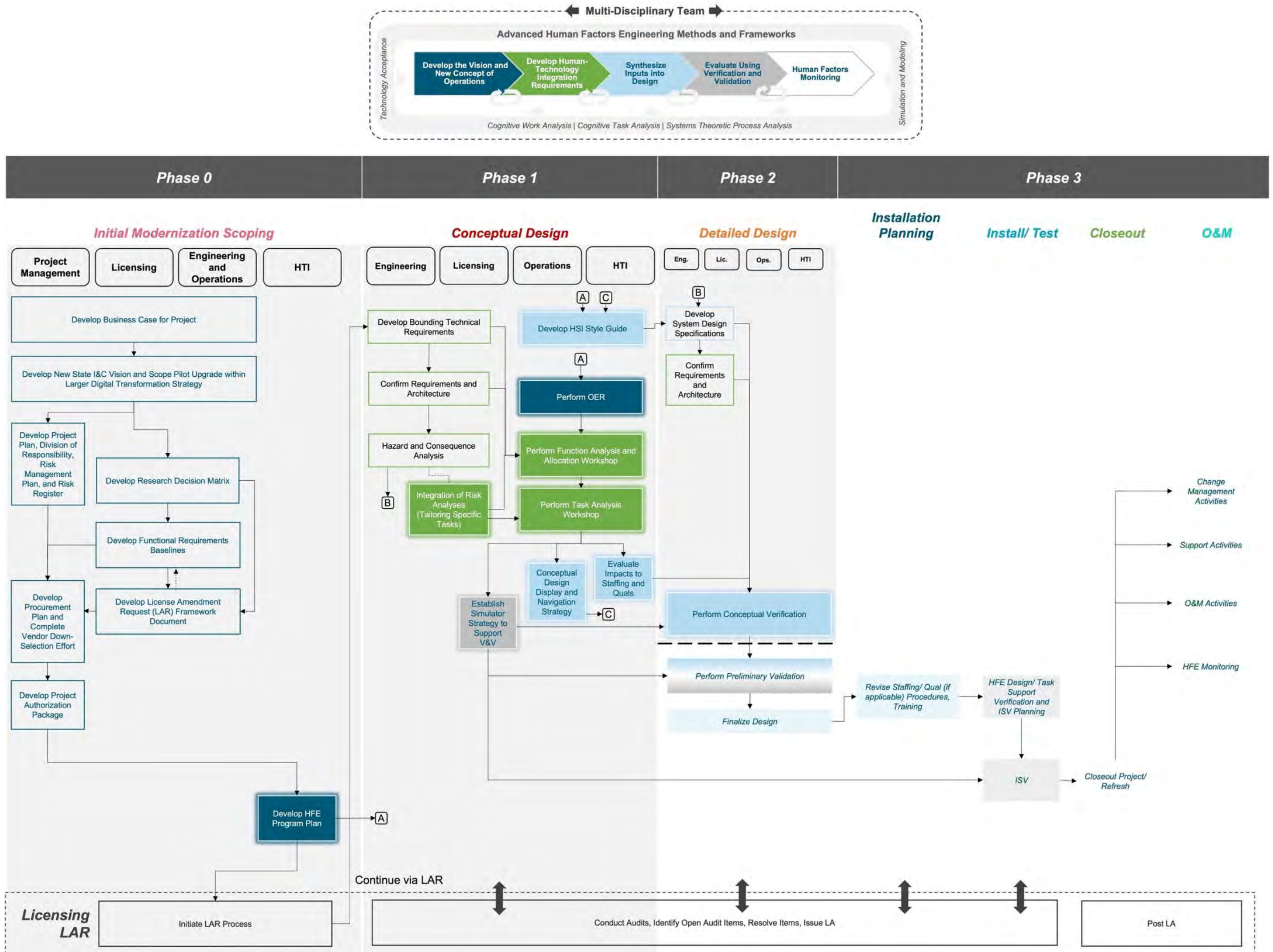


Figure 25. HTI activities demonstrated in Collaboration 1.

3.1.2 Human and Technology Integration Activities Demonstrated

Researchers from the LWRS Program have demonstrated HTI guidance to support Planning and Analysis activities described in NUREG-0711 (2012). The completed activities are summarized next and are illustrated in Figure 25; they also follow pertinent HFE activities described in the DEG (2021).

3.1.2.1 Human Factors Engineering Program Plan

The HFE Program Plan was developed by LWRS Program researchers and is being used by CEG in executing HFE activities in support of the safety-related pilot project. The breadth of the HFE Program Plan covers the application of the HSIs in the MCR and local HSIs impacted by the upgrades. The intent of the HFE Program Plan is to not only support these current upgrades within the scope of the pilot project but also to support future upgrades, such as by following a graded approach to applying HFE activities. The HFE Program Plan enables a scalable approach to applying HFE for future projects based on its risk to safety and production and complexity of the upgrade (i.e., refer to Figure 9).

The HFE Program Plan is comprised around the primary HFE activities described in NUREG-0711 (2012), as seen previously in Figure 8, and is also compatible with guidance given in IEEE 1023 (2020). This included addressing the review criteria for each of NUREG-0711's 12 elements across the four phases (refer to Figure 8). The grading described in the HFE Program Plan enables dispositioning certain elements or activities in NUREG-0711 as deemed appropriate and practical. Likewise, alternative activities that meet the intent of the activity in NUREG-0711 can be applied with justification.

The significance of the HFE Program Plan thus ensures that the set of HFE activities scoped across the modernization effort is complete, within reason for the scope of the upgrade, and address the criteria used by the U.S. NRC to assess the acceptability of an applicant's submittal regarding the safety of plant operation. Figure 26 illustrates the primary sections of the HFE Program Plan as they correspond to the HTI methodology. The activities that are italicized represent complementary activities that are not directly described in NUREG-0711 (2012). Rather, they are intended to support the NUREG-0711 activities comprised in Figure 8, when appropriate and practical for the project.

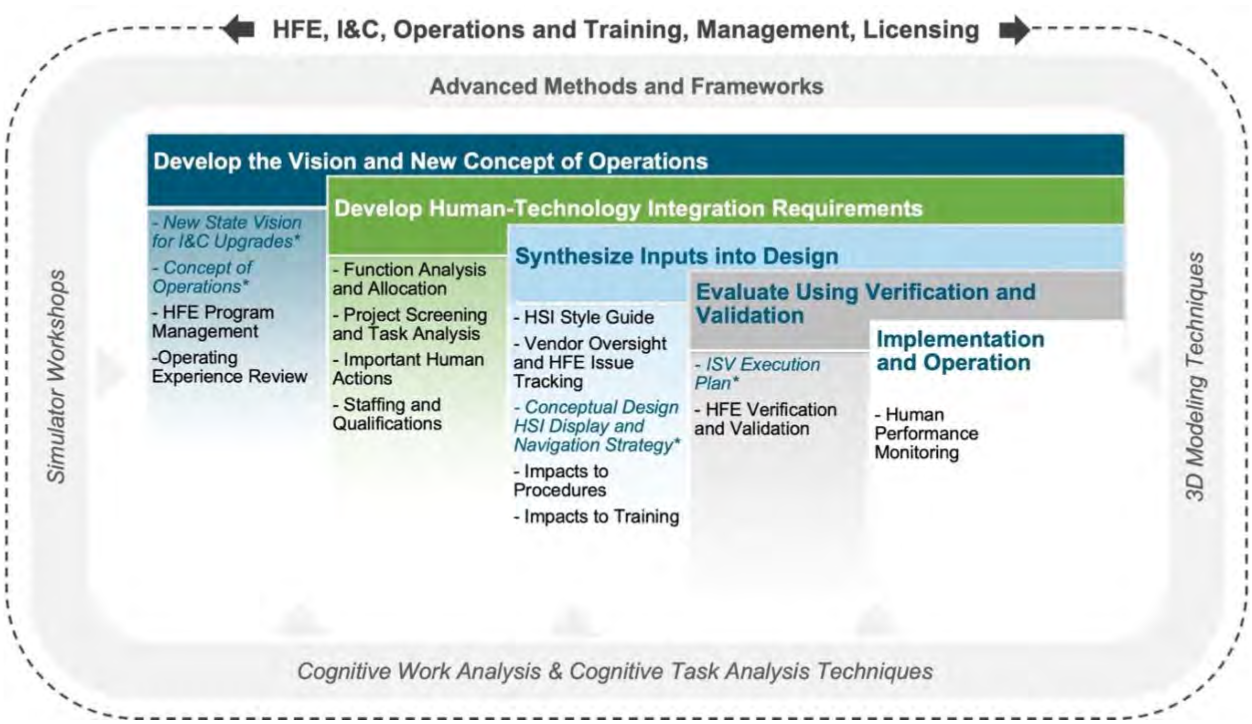


Figure 26. HTI activities described in the HFE Program Plan.

3.1.2.2 Operating Experience Review

The OER methodology applied was based on NUREG-0711, Rev. 3 review criteria, guidance in EPRI 3002004310 (2015), and the process and results criteria from prior OE studies with several other utilities.

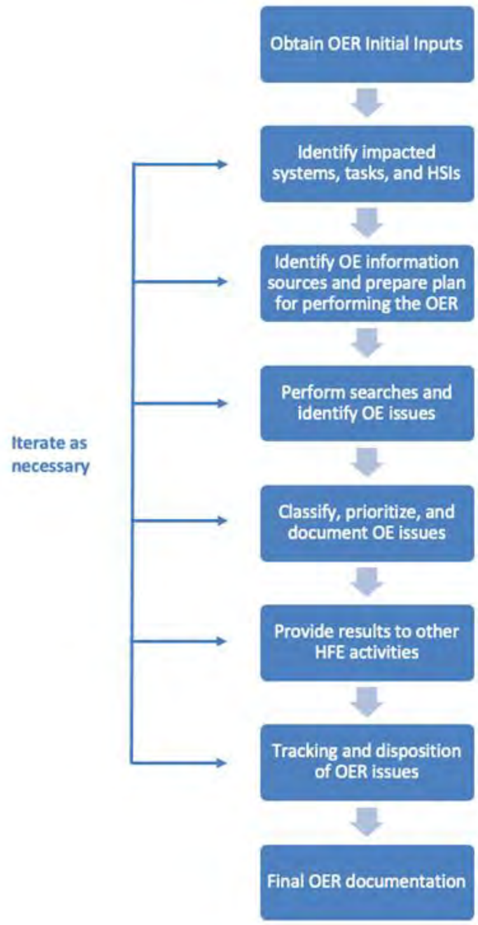


Figure 27. OER methodology.

The OER methodology shown in Figure 27 was applied by HTI researchers to collect detailed OE related to existing and potential human performance issues impacting the proposed safety-related I&C upgrade design as may impact future CEG control room operation. The OER result summary report contained pertinent HFE OE information obtained from:

- The site condition report database
- OE from previous U.S. safety-related I&C upgrades
- Keyword searches of the Institute of Nuclear Plant Operations consolidated event database
- Reviews of recognized industry HFE issues
- Keyword searches of the NRC Licensee Event Reports database.

Issues identified by control room personnel were also captured through a survey and a face-to face OER workshop held on August 31, 2021 in the plant training and simulation facility. This workshop facilitated the identification of potential issues and elsewhere within the site. Operations SMEs from CEG developed scenarios for each impacted function and task impacted by the safety-related I&C upgrade. Each scenario grouped the impacted tasks together in a contextually appropriate way. For instance, tasks are rarely performed in isolation. In many cases, the functions and tasks to be performed are part of a broader plant event. Using scenarios, the analysis of impacted functions and tasks account for different operational contexts that are important when understanding how any given function or task affects related tasks.

This workshop supplemented the other OE information gathered as described in the bullets directly above with information gathered from several group discussions with control room operators, engineers, instructors, and other staff.

The objectives of this effort were to acquire OE information specific or relevant to nuclear power plant I&C and associated control room modernization, preliminarily evaluate it regarding potential impact on design and operational considerations, and make it available for subsequent HFE analysis, design, and V&V elements for the CEG upgrade being pursued. HFE-related safety and availability events, issues, and information on past operational performance at the plant were examined, along with similar input from other U.S. nuclear power plants.

The results of this work support follow-on HFE analyses focused on control room modernization, as well as on current and future design decision-making on the part of CEG. Existing and potential human-system performance issues identified early in the design process through an OER can be formally tracked and addressed, thereby becoming significantly less likely to be overlooked in the overall systems engineering process. The relationship between HFE elements and OER item classification is shown in Table 3.

Table 3. OER item classification.

HFE Element	OER Item Classification
FA&A	Basis for initial requirements
	Basis for initial allocation
	Identification of need for modification
Task analysis, treatment of important human actions, staffing, and qualifications	Important human actions and errors
	Problematic operations and tasks
	Instances of staffing shortfalls
HSIs, procedures, and training development	Trade study evaluations
	Potential design issues
	Potential design solutions
V&V	Tasks to be evaluated
	Event and scenario selection
	Performance measure selection
	Issue resolution verification

Each OER item was prioritized as shown in Figure 28, which is derived and captured in a table in the OER. A graded approach was used to prioritize each item. Relevance to the new system was the first criterion, where OE irrelevant to the new system would be graded as low relevance. If the OE was relevant to the new system, but was only an I&C issue, it was recorded in a separate appendix for record keeping purposes but was no longer processed through the HFE graded approach procedure. For OE items that were human factors related or both I&C and human factors related, they were coded as a globally or specifically relevant issue to the planned upgrades. The final criterion in the graded approach was whether the OE item was linked to safety and production goals. If yes, the OE item was graded as highly relevant. If no, the OE item was graded as moderately relevant.

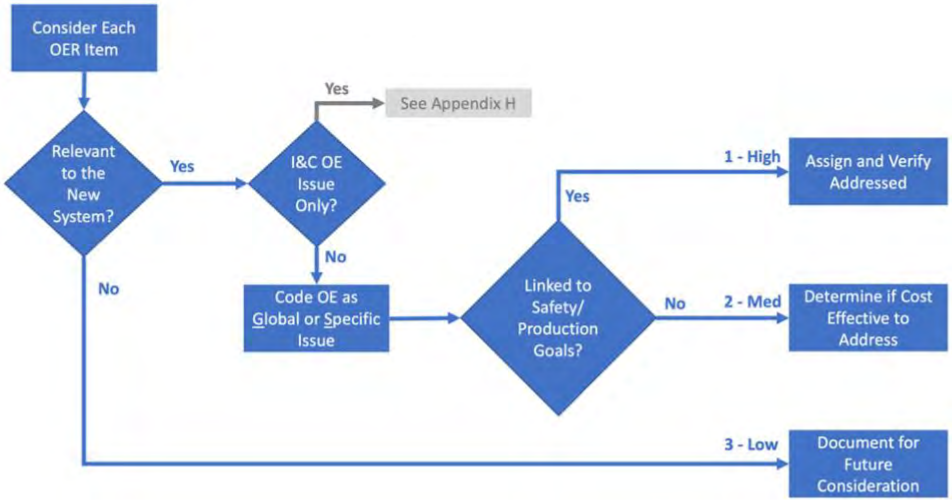


Figure 28. OER item prioritization method.

The OER results were applied to activities associated with the FA&A and task analysis elements of the HFE Program Plan. OE issues identified in the current report also impact subsequent HFE elements, such as the treatment of important human actions, HSI design, and V&V. OE results may also need to be considered when performing other elements, such as procedure and training program development. The OER report does not attempt to resolve the OE issues that it identifies nor is any control room design or operational guidance provided. Each OE item should be assigned to the one or more HFE teams responsible for the element to which the item applies for resolution and disposition.

3.1.2.3 Develop HSI Style Guide

The HSI style guide was developed to provide specific guidance to design new and modified HSIs for this effort. The style guide ensures consistency in the form, function, and operation of the HSIs across the MCR to the extent possible and that state-of-the-art HFE design principles are considered in the design of safety and non-safety HSIs. The style guide covers pertinent topics, including the formatting of information on display pages, the information architecture and navigation between those display pages, the design of display fonts and symbols, use of color and labeling, and the design of the soft controls for touch interaction.

The resources used in initially developing the style guide included synthesizing inputs from the new state vision and concept of operations, existing plant conventions, and selected vendor standard features and functions, as well as industry standards and guidelines, such as in NUREG-0700 (2002). This is illustrated in Figure 29.

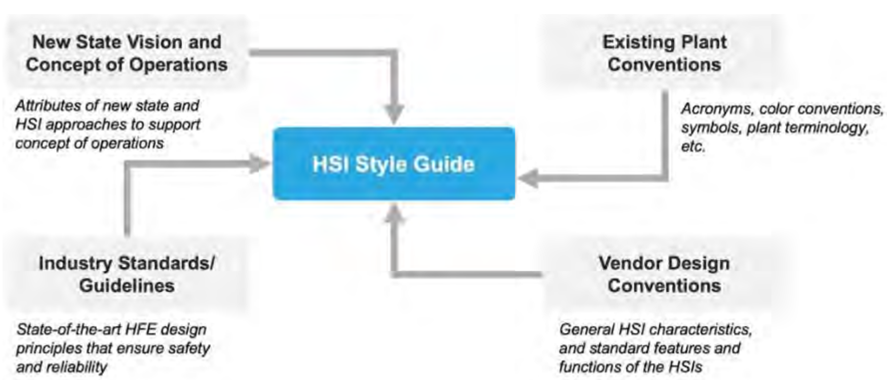


Figure 29. Inputs into developing the style guide.

The style guide was also informed through conceptual design HFE activities, such as the task analysis workshop. For instance, where there were identified tradeoffs between vendor conventions and existing plant conventions, the task analysis workshop provided additional context into an optimal design path to support the information and task requirements. This feedback was incorporated into the style guide as a revision to support detailed design efforts.

3.1.2.4 Perform Function Analysis and Allocation Workshop

FA&A aims to identify and allocate responsibilities for new and changed control functions in a plant, to improve safety and availability while accounting for the strengths and limitations of both human operators and automation. The function analysis sets the objectives, performance requirements, and constraints for the HSI design and defines the role of personnel and automation. The allocation of functions between manual, automated, and shared control will improve safety and performance by reducing human errors and inappropriate actions. By allocating functions and utilizing the functional capabilities of the modernized safety platform and non-safety platform, human errors can be reduced, improving system safety and economic performance.

Inputs to the function analysis included the project scope through preliminary design documents, an understanding of the "New State," I&C vendor capabilities, the operator experience review, the initial understanding of the MCR concept of operations, and the prioritized tasks impacted by the upgrade based on difficulty, importance, and frequency. Scenarios were identified, using impacted tasks as a guide. Of the number of events, scenarios, and procedures in which operator tasks were expected to change, the ones with the largest positive and negative impacts on operator and system performance were selected. Additionally, scenarios were selected that provided the greatest opportunities for human error, changes from manual to shared or automatic functions, significant changes in operator roles and responsibilities, increased workload, reduced action times, and the greatest opportunities for improved safety and economic performance.

The FA&A workshop was performed at the plant training simulator with qualified MCR crew. HTI researchers and site simulator personnel ran scenarios, and HTI researchers documented observations in real time, capturing operator inputs through surveys and interviews after each scenario and at a wrap-up session. Observations, operational difficulties, key decisions, and the impacts of modifications in each scenario were discussed. The findings from the FA&A workshop were used as input into task analysis.

3.1.2.5 Perform Task Analysis Workshop

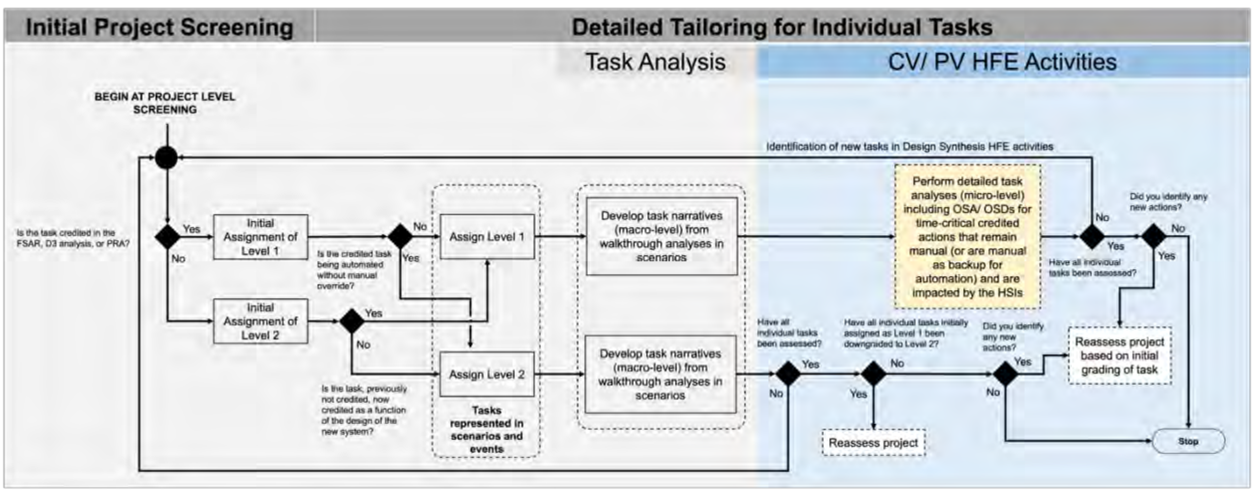
Task analysis examined the functions assigned to plant personnel to achieve a successful performance and identifies the specific tasks, as well as the information, control, and task support required to complete those tasks. The results of the task analysis activity played a crucial role in designing the HSIs, modifying procedures, and the training provided to the plant personnel.

The task analysis technique started with macrolevel considerations to understand the impact on the concept of operations, crew dynamics with modifications to alarms, indications, and controls, and crew performance, decision-making, workload, situation awareness, and task workflow. As the design progressed, the task analysis was iterated upon to understand the impacts on microlevel HFE considerations, such as the impacts on response times, performance with modifications, and the specific actions and completion times of subtasks and activities with new HSIs. This top-down approach to task analysis involved developing scenarios with events that were logically grouped to accomplish a goal. This allowed for a natural evaluation of tasks and the influence of other tasks being performed in succession or in parallel. The task requirements played a major role in designing the HSIs, procedures, and training provided to plant personnel. The results of the task analysis were used in subsequent analyses, such as staffing, error analysis, HSI and procedure design, training, and V&V. The methodology for performing task analysis followed the guidelines of INL/EXT-21-64320 (2021), EPRI, 3002004310 (2015), and NUREG-0711 (2012).

The main task analysis method used was a series of walkthroughs from nine scenarios in the HSSL simulator testbed. The walkthroughs were performed by two operators from the site with the help of human and technology researchers, a training SME from the site, and other key stakeholders. The HSSL was set up to represent the current and new HSIs, and the walkthroughs were facilitated by presenting tasks to the operators and having them perform tasks within the defined events and scenarios. Verbal and observational data were collected during the walkthroughs and a semi-structured set of questions was asked in post-scenario discussions. After the walkthroughs, a static display review was completed to focus on the HSIs, and the operators provided design feedback on these HSIs, based on their operational experience.

3.1.2.6 Integration of Risk Analyses: Tailoring Specific Tasks

The important human action element is a key focus of the HFE efforts for this project. To identify important human actions, there was an initial screening to determine the extent of potential HFE impacts. Changes that included impacted operator HSIs and other potentially impacted operator tasks were considered. This screening process was based on guidance given in NUREG-0800, Chapter 18, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition – Human Factors Engineering," and EPRI HFE guidance (2015) and is depicted in Figure 30.



Note. Tasks not impacted by the upgrade were noted as a Level 3 (little to no impact) and were not considered for subsequent HFE analysis.

Figure 30. Tailoring process to support addressing impacted important human actions.

Credited tasks were identified using key documentation from the utility, including the FSAR, the D3 analysis (which identifies portions of the safety system architecture susceptible to common cause failure), and the PRA. Credited tasks not being automated without manual override were assigned Level 1 or as having high potential nuclear safety and economic risks. Previously uncredited tasks now credited as a function of the design of the new system were also deemed Level 1. Credited tasks being automated without manual override were assigned Level 2 or having medium potential nuclear safety and economic risks. Previously uncredited tasks that remained uncredited were also deemed Level 2.

3.1.2.7 Evaluate Impacts to Staffing and Qualifications

Impacts to staffing and qualification requirements at the site were evaluated based on the results from previous HFE activities performed during the conceptual design. This included the results coming from OER, FA&A, and task analysis. These results indicated that there were no fundamental impacts to staffing and qualification requirements in the MCR. Therefore, no changes to required staffing levels or basic qualifications were within scope of this effort.

3.1.2.8 Establish a Simulator Strategy to Support Verification and Validation

The project identified a series of planning and execution activities leading into ISV. These activities are illustrated in Figure 25, coming out of the "Establishing a Simulator Strategy to Support V&V" activity. They included:

- **Conceptual Verification.** Building on the results from task analysis, the conceptual HSI displays developed during conceptual design would be refined through a series of iterative tabletop design reviews (hosted virtually) using operational knowledge and HFE guidance from the style guide and associated guidelines like NUREG-0700 (2002). In addition, procedure modifications would be made, and coordinated with the HSIs, to enable task support verification. The combined prototyped HSIs and modified procedures would then be evaluated in combination with virtual reviews and a CV workshop. This workshop would present the HSIs in limited fidelity (i.e., static in nature but with navigation) to enable scenario-based walkthroughs. Specifically, the impacted important human actions would be further evaluated to ensure that they can be reliably completed within the time available. Section 3.1.2.9 describes the execution and CV.
- **Preliminary Validation.** Building on the CV results, the preliminary validation workshop confirms that the impacted important human actions can be reliably performed within the acceptance criteria defined in CV. Here, the HSIs are dynamic in nature and connected to the Limerick simulator. While the HSIs are functional, they are presented on glasstop simulator bays and their layout is faithfully represented (i.e., though not exact). These HSIs will be used in conjunction with the modified procedures to allow the licensed operators to perform their tasks in a realistic manner. Section 3.1.3.1 describes preliminary validation in more detail.
- **Integrated System Validation.** Finally, final modifications to the HSIs or procedures coming out of preliminary validation will be used for ISV. This input will be provided to the vendor to develop the HSIs to be integrated into an MCR simulator of sufficient fidelity for ISV. A detailed ISV test plan will be developed, reviewed, and accepted prior to executing ISV.

3.1.2.9 Perform Conceptual Verification

CV was performed as part of the HSI design in transitioning into V&V (i.e., this is illustrated in Figure 25) to verify that the HSIs being developed for the safety-related project, along with the associated procedure changes, were progressing towards subsequent V&V activities, including preliminary validation and ISV. Specifically, the CV served as an extension of FA&A and task analysis activities to evaluate the identified impacted important human actions (i.e., tasks determined as being Level 1 by CEG as shown previously from Figure 30). Within this context, CV bounded the types and number of safety and non-safety HSI displays necessary for operators to perform these Level 1 manual actions and impacted tasks; it also identified necessary procedure changes to enable the use of these HSI displays. Further, key CV objectives were to:

- Identify the existing overall time available to complete each Level 1 manual action.
- Establish an estimated time to perform these actions using the new HSIs and procedures.
- Document the sequence of actions required to navigate the HSIs in performing these actions, using temporal operational sequence diagrams (OSDs).

To support these primary objectives, CV leveraged guidance from NUREG-0800, Ch. 18, Attachment A on "Guidance for Evaluating Credited Manual Operator Actions – Phase 1 Analysis" (2016). Additionally, because CV served as a transition point from design into V&V, design feedback concerning the HSIs and procedures were captured and dispositioned.

To minimize bias, there were independent teams with distinct roles. The *design team* created the HSI design concepts to produce design inputs. The design team applied design principles from the HSI style guide in the creation of these concepts. The design team was also responsible for identifying and proposing procedural changes to enable plant operation. Next, the *HFE team* ensured that the project established and executed the HFE activities described in the HFE Program Plan. Primarily for CV, this entailed executing technical HFE data collection activities, such as collecting operator response times, observations, and verbal feedback in the walkthroughs. The third team was the *validation team*, qualified and licensed operators that represent the ultimate end users for the HSIs and procedures. Their knowledge and experience were critical in the project design and V&V process. Finally, the *simulator team* worked towards integrating the plant simulator model with the prototype HSIs. They also were responsible for running the scenario during the walkthroughs, setting up initial conditions and triggering specific faults from the simulator workstation to enable the validation team to perform their tasks during CV.

CV was performed following a scenario-based approach; these scenarios were built off the results from FA&A and task analysis and refined to envelop the Level 1 tasks identified to support the workshop objectives. The scenario-based approach enabled an evaluation of the operator's ability to perform these actions in representative context to their application. As such, the scenarios enabled evaluating whether other tasks would have impacted the operators' abilities in accurately and reliably completing these Level 1 manual actions. For each scenario, a temporal OSD was developed for each Level 1 manual action (see the example OSD in Figure 31).

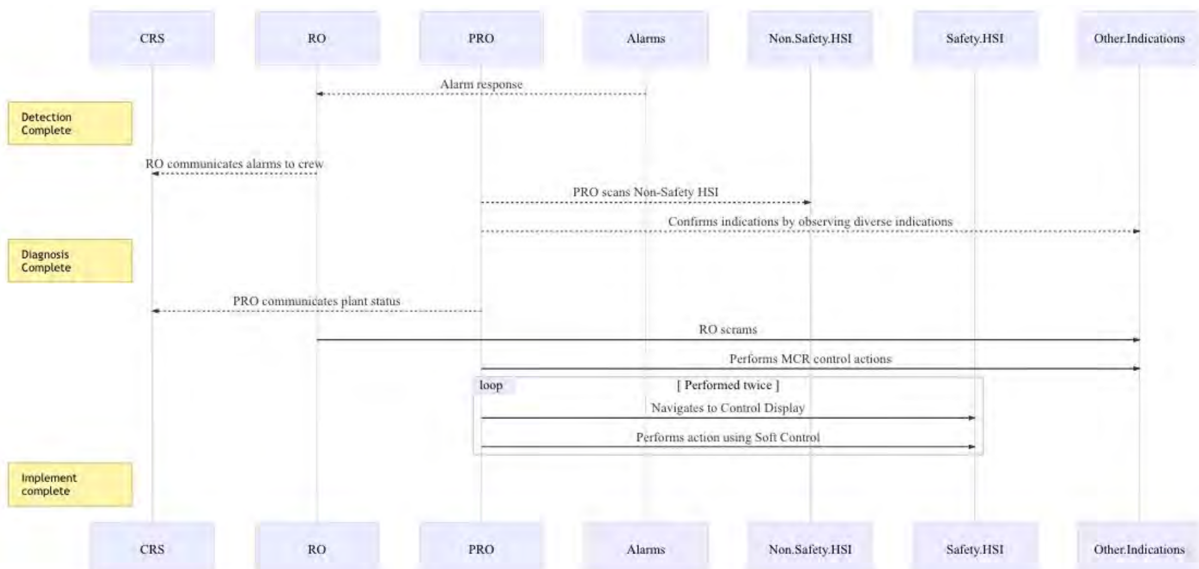


Figure 31. Example OSD.

The temporal OSD presented the sequence of interactions between the crew and associated indications and controls for each Level 1 action. The task elements, as indicated by the horizontal axis, was generalized by each member of the crew and the alarms, indications, and controls available to them. These alarms, indications, and controls were broadly characterized by whether they stemmed from the non-safety HSIs, safety HSIs, or elsewhere in the MCR. Further, the sequence of activities were presented from top to bottom, from the action onset to completion. These sequences were grouped into *detection*, *diagnosis*, and *implementation* activities, which corresponds to the primary perceptual, cognitive, and physical activities required of the operators as characterized in NUREG-1852 (2007). With this, the OSDs were used to enable human factors engineers to construct timelines for analysis in ensuring that these actions can be reliably performed within the time available to perform these actions. The timeline analysis followed guidance in NUREG-1852 (Figure 32), which was adapted to be appropriate for evaluating the stie-specific acceptance criteria.

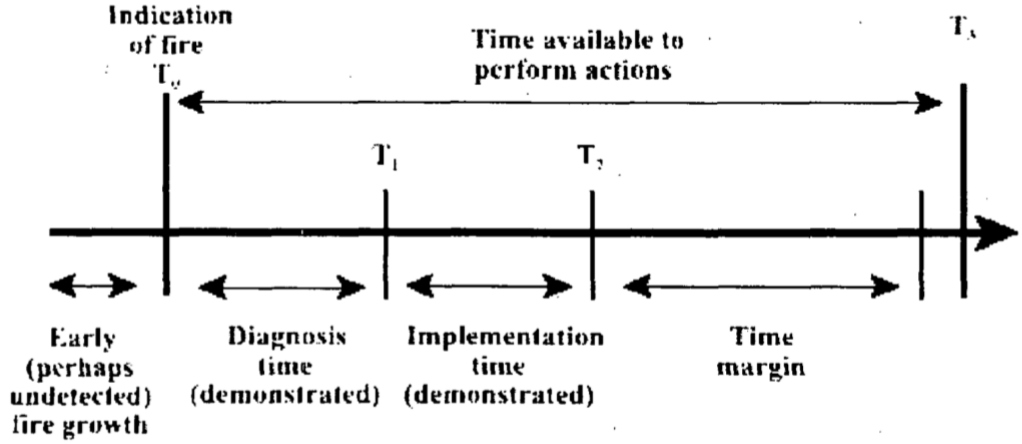


Figure 32. Timeline guidance for evaluating manual operator actions (adapted from NUREG-1852 2007).

The associated scenarios and prototype HSIs used for CV built off the results from FA&A and task analysis, and the HSIs followed design guidance specified by the style guide. These prototypes were presented in a part-task simulator at Idaho National Laboratory, in conjunction with associated modified procedures, where the level of prototype fidelity was static in nature but with the capability for navigation for the safety and non-safety displays (Figure 33).

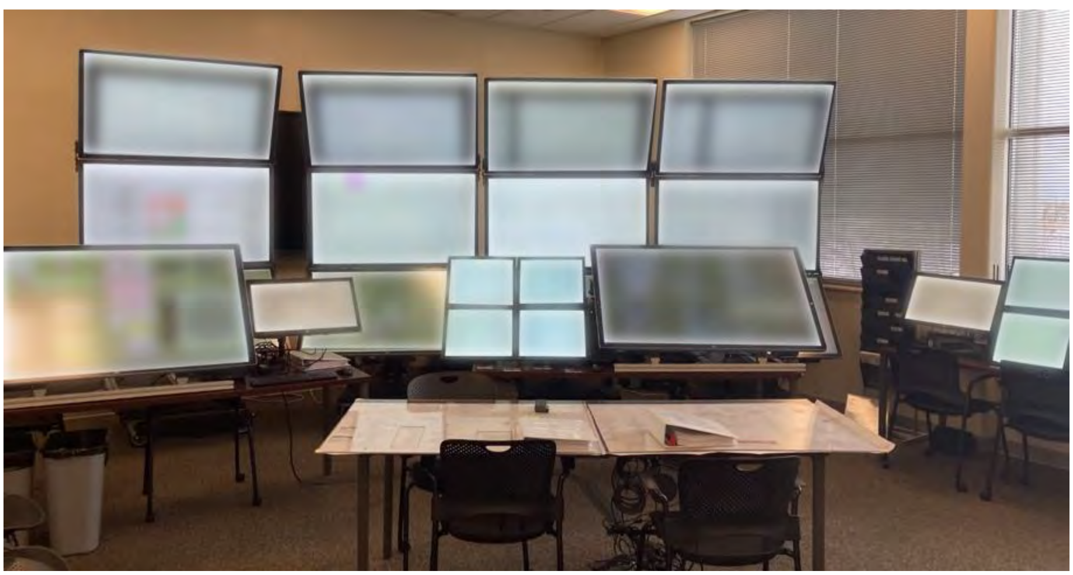


Figure 33. Part-task simulator testbed used for CV.

The operators performed walkthroughs of each scenario and used a think-aloud technique in which they verbalized their intended actions, as well as provided design feedback for the HSIs and procedures. During the scenario walkthroughs, HTI researchers collected observational data and feedback from the operators. Further, the OSDs were used in tracking the performance of each Level 1 manual action using a custom software tool that recorded timing data (Figure 34). The tool presented each OSD for a given scenario and allowed the researcher to add timestamps when observing the completion of detection, diagnosis, and implementation activities. Notes could be captured in a text field for observations related to the OSD.

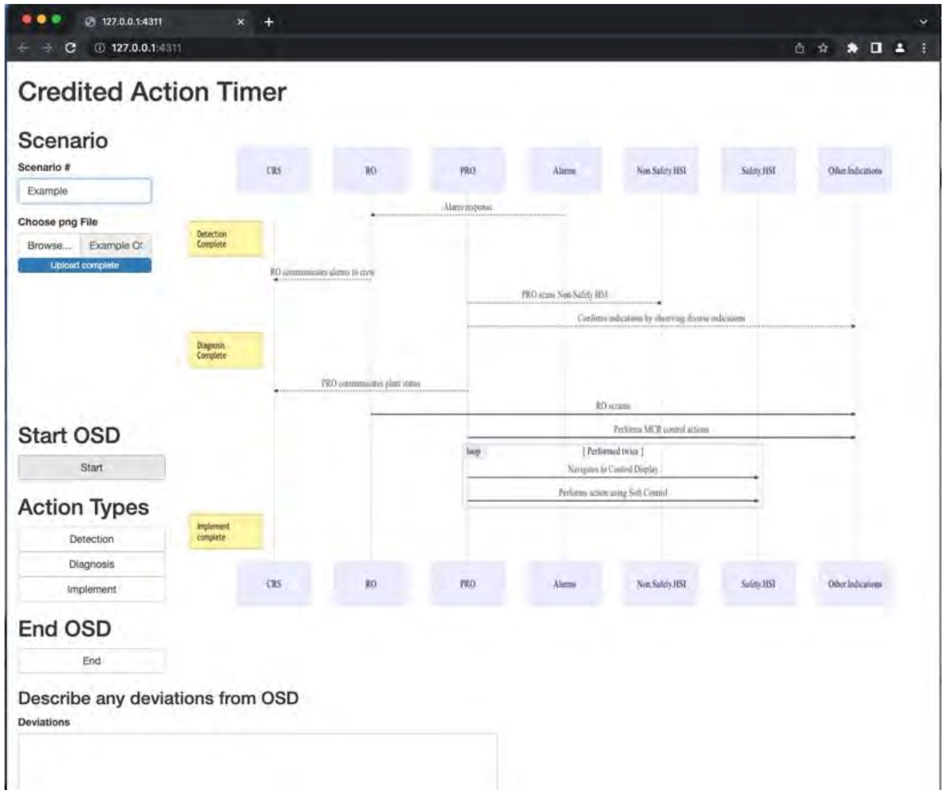


Figure 34. Custom timeline analysis tool.

The results from the timeline analysis tool enabled the researchers to develop timelines to evaluate whether the time to perform these actions could be completed within the time available. This is seen in the generic timeline in Figure 35, with T_2 being less than T_3, indicating a time margin.

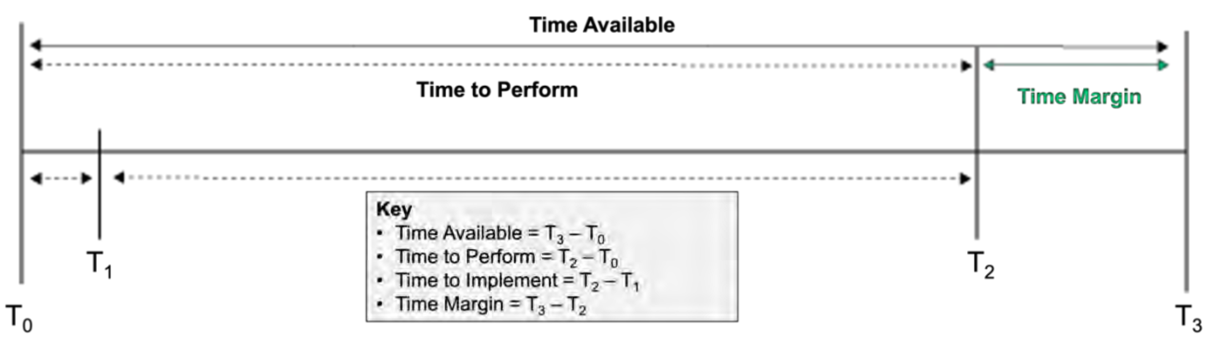


Figure 35. Generic timeline analysis.

Other criteria in the analysis included determining whether the new HSIs did not negatively impact the time to implement the Level 1 action (i.e., shown by comparing observed T_2 to the time to implement with the existing indications and controls per plant documentation, as the gray horizontal bar). Further, it was determined that the types of Level 1 actions were categorized as being one of two key *types*. Some of these actions were self-revealing in nature, where the diagnosis was accomplished from direct indication of the event. In this context, these types of actions (referred to as Type 1 events) were inambiguous in nature. From an HFE standpoint, such actions were performed using rule-based decision-making characteristics (Wickens et al. 2004). A useful framework used to conceptualize these actions were decision ladders from the cognitive work analysis (CWA) framework (Stanton et al. 2017; Stanton et al. 2013; Figure 36).

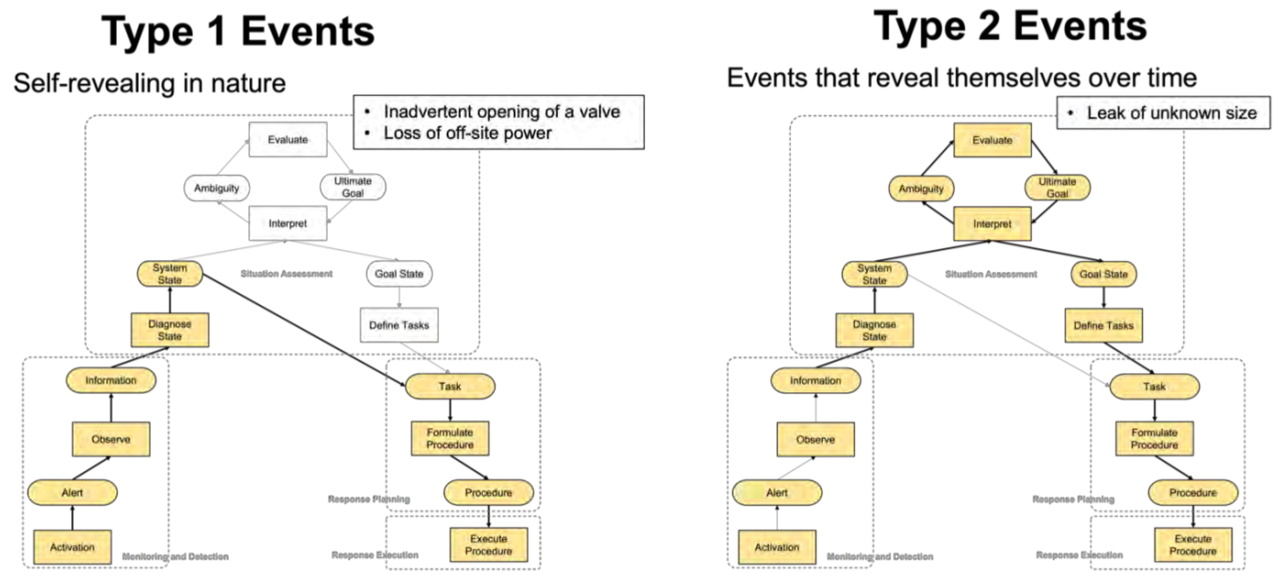


Figure 36. Types of manual actions as characterized by decision ladders from cognitive work analysis.

As seen in Figure 36, these Type 1 events do not require knowledge-based decision-making that demands overcoming degrees of ambiguity, assessing multiple goals, and determining a course of action based on assessing and prioritizing these goals. An example of a Level 1 event is a task addressing the inadvertent opening of a valve or a loss of offsite power in which the event is salient, and the course of action is not ambiguous. On the other hand, there were some Level 1 tasks that revealed themselves over time, such as determining the size of a leak and taking the appropriate course of action. These Type 2 events required sifting through ambiguity and performing knowledge-based decision-making. For these Type 2 events, the time to diagnose could be considerably variable based on plant conditions. As such, an additional criterion was applied to these that required the time to perform these actions to be less than or equal to the time margin available. This would allow for a factor of two of time available to time to perform, which was based on guidance in NUREG-1852 (2007).

Finally, HFE observations were used to determine whether the time to diagnose was not being negatively impacted by the new HSIs or procedures. The framework applied to supporting HFE judgment can be seen in Figure 37. Observations and comments were qualitatively analyzed followed by thematic analysis (i.e., see INL/EXT-20-58538 [2020] for details of thematic analysis) using generalized themes to categorize the findings as being in at least one of four categories: HSI design, procedure design, training and experience, or simulator artifact.

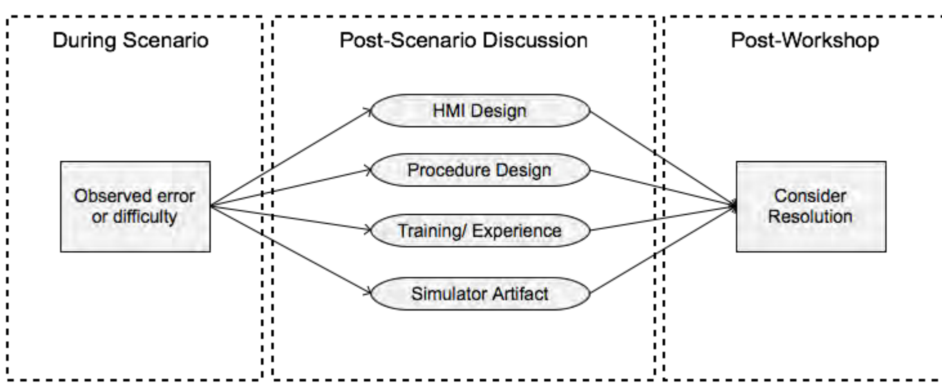


Figure 37. Contributors to observed difficulties or errors.

The CV results identified several design improvements for the HSIs and procedures and established the time available to perform the identified impacted Level 1 manual actions. CV also established the estimated time to perform these actions using the results from the scenario walkthroughs; sequence of actions using OSDs were developed for each action to understand the sequence of actions using available alarms, indications, and controls. Consequentially, the CV results established a time margin between the time available and estimated time to perform each action; this time margin provided evidence that the HSIs and procedures can enable the operators to safely and reliably complete these tasks within the time available. While these results were preliminary in nature, it provided reasonable confidence that the project was converging towards a successful path in preparation for later V&V activities. These results served as input into the planning of subsequent V&V activities described next.

3.1.3 Future Activities

3.1.3.1 Preliminary Validation

Preliminary validation (PV) will be performance-based tests, as defined in NUREG-0711 (2012) and leveraging concepts from NUREG-0800 Chapter 18 Attachment A Phase 2 (2016), performed to:

- Confirm that the time to perform the impacted manual actions can be performed within the established acceptance criteria, as assessed by a multidisciplinary team.
- Evaluate the new HSIs and modified procedures in other important evolutions (i.e., using scenarios that incorporate a broader sequence of impacted tasks) to:
    - Assess the acceptability of these interfaces.
    - Ensure that the operators can safely and reliably operate the plant using the alarms, controls, displays, and equipment that remain functional.

Thus, a primary goal of PV is to provide high confidence that the manual operator actions will be accomplished correctly, reliably, and within the time available, using the new HSIs and modified procedures. PV therefore leverages guidance from NUREG-0711 and NUREG-0800 Chapter 18 to show compliance with the site's existing requirements in NUREG-0737 Supplement 1.

PV will be facilitated through independent teams (i.e., as described in Section 3.1.2.9 and used as good engineering practice) and will build off the scenarios developed from CV by adding incremental fidelity through dynamic HSIs that integrate with the plant simulator model. The HSIs will present dynamic information from the simulator and enable dynamic navigation and control. Control actions that are not central to the upgrades (e.g., actions taken on legacy HSIs) will use a think-aloud protocol. In this case, a Wizard of Oz technique will be executed, facilitated by the simulator team, to approximate the plant behavior once the operators verbalize their intent. Leveraging guidance from NUREG-0800 Chapter 18 (2016) and IEEE 2411 (2021), *IEEE Guide for Human Factors Engineering for the Validation of System Designs and Integrated Systems Operations at Nuclear Facilities*, PV provides a multistage approach to V&V by providing an early PV (i.e., prior to completing ISV) of the upgrades to establish reasonable confidence that the system can be safely operated. The approach to PV is visualized in Figure 25 and more directly in Figure 38.

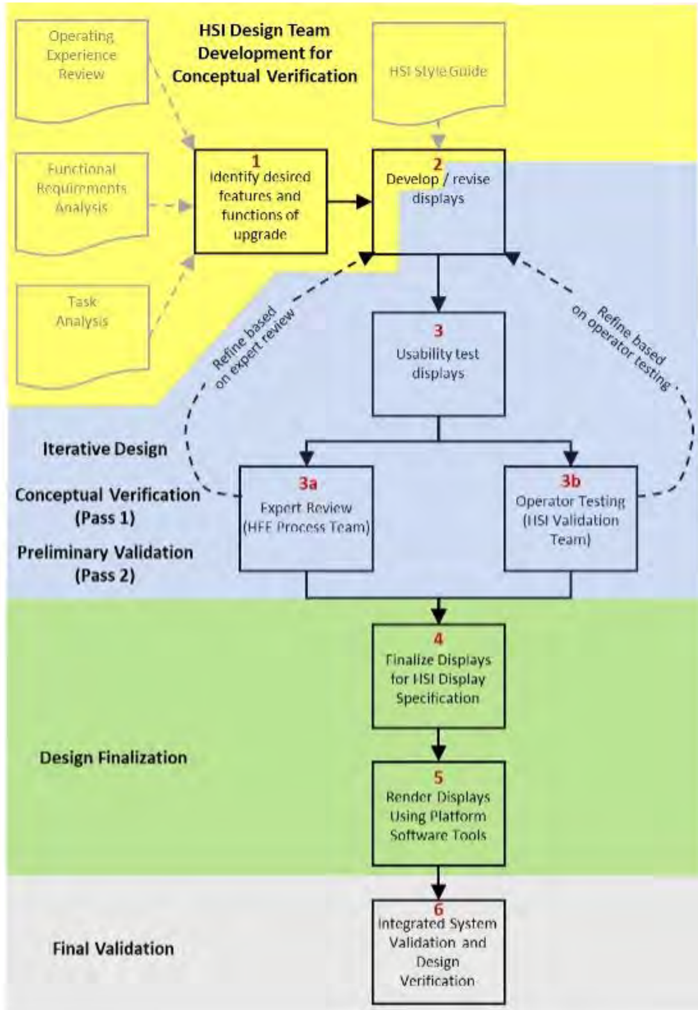


Figure 38. Flow diagram for developing new HSI displays (and procedure modifications).

Figure 38 shows PV as a second iteration to HSI design, following CV. PV's purpose is to build the safety case and reduce risk in the safety and reliability of the upgrades through a staged approach. It should be noted that the PV execution does not eliminate a need for ISV. As seen in Figure 38, the PV results should provide reasonable assurance that the HSIs and procedures can be safely and reliably used by the plant personnel and to prepare for finalizing these HSIs and procedures to execute ISV. The combined efforts should support the DI&C-ISG-06 Alternative Review Process by providing early staged results in building a safety case for these upgrades.

3.1.3.2 Design Finalization

The resulting outputs from PV will be used to finalize the design of the HSIs and procedures. There are several important aspects to finalizing the design, including:

- Translating HFE findings into design specification.
- Finalizing modifications to impacted procedures.
- Evaluation of impacts to training.
- HED tracking.
- ISV planning.

Translating HFE Findings into Design Specification

The features and functions demonstrated in the prototypes used for related HFE activities must be translated into specifications and resulting designs from the vendor. In this process, findings from previous HFE activities, including OER, FA&A, task analysis, CV, and PV, that pertain to the design elements of the HSIs must be carried over into the vendor-built HSIs. In this process, verification activities should be carried out, following guidance from NUREG-0711 (2012), including HSI inventory and characterization, HSI design verification, and HSI task support verification.

With this, findings related to the modification of existing hard controls and indications being relocated must be reviewed by HFE to ensure acceptable placement when accounting for anthropometric and ergonomic considerations.

Finalizing Modifications to Impacted Procedures

Leveraging the utility procedure program, procedures changes will be modified to support the tasks to be performed with the updated HSIs. Previous HFE findings related to procedures will be incorporated. Moreover, task support verification will be performed to also verify that the procedures (when used with the HSIs) provide accurate and complete information to support the operators in performing their tasks.

Evaluation of Impacts to Training

Training is important in ensuring that operators can safely and reliably operate the plant with the new HSIs and procedures. Training associated with this upgrade will be based on an analysis of job and task requirements impacted by the upgrade, as previously identified in earlier HFE activities. Changes to the training program will address personnel tasks impacted by the modifications. Objectives of the project-specific training effort entails:

- Systematically analyzing the jobs and tasks impacted
- Developing learning objectives based on desired performance
- Developing training based on these learning objectives
- Evaluating the trainees' knowledge, skills, and abilities in meeting these objectives
- Assessing and revising the training using feedback from trained personnel.

HED Tracking

HEDs will be formally tracked with a tracking system. This tracking system will provide a means to collect and track HEDs throughout the V&V process and will enable an HED analysis, selection of HEDs to correct, as well as development and evaluation of design solutions. Its use will be formally applied to support V&V efforts, including task support verification, HFE design verification, and ISV.

ISV Planning

ISV entails determining if the integrated design (HSIs, procedures, and training) meets the performance requirements. ISV also entails validating the role of the plant personnel; the adequacy of the alarms, indications, and controls; procedure changes; and training provided to operators to perform their tasks with the integrated system. To support ISV, a detailed ISV plan will be developed to ensure that all aspects of the project necessary to accomplish it are properly coordinated. The detailed ISV plan will require a cross-functional approach, including systems engineers, I&C engineers, plant operators, simulator experts, personnel training and simulator operations, procedures writers, vendor, HFE, and architect engineers. A detailed schedule for the ISV planning and execution will be developed. This schedule includes key considerations, including preparing an acceptable testbed (including preparing the HSIs, procedures, and training), selecting scenarios that adequately sample operational conditions, identifying and verifying performance measures and validation criteria, and selecting participants, among other considerations described in NUREG-0711 Section 11 (2012).

3.1.3.3 Integrated System Validation

ISV will be executed following the ISV test plan. This includes key steps including identifying operators who will support ISV as participants, developing familiarization training on the modifications (HSIs and procedures) prior to running ISV, verifying that the HSIs have been fully integrated into the testbed for ISV, and conducting a pilot ISV with operators who will not participate in the ISV. Any HEDs identified during ISV will be prioritized and determined to be dispositioned or corrected. Finally, the ISV process will be formally documented and will include the criteria in NUREG-0711 Section 11 (2012). Representative topics for the ISV report are outlined in Figure 39.

I. Objectives

II. Validation Team and Independence

III. Summary of Modifications

- **a. Impacted HSIs**
- **b. Impacted Procedures**

IV. Method

- **a. Scenarios and Operational Sampling**
- **b. Participants and Sample Size**
- **c. Testbed**
- **d. Test Design**
- **e. Protocol**
- **f. Measures**
  - **i. Human-System Performance Measures**
    - **1. Performance**
    - **2. Workload**
    - **3. Situation Awareness**
    - **4. Teamwork**
  - **ii. Methods for Identifying and Prioritizing HEDs**
- **g. Analysis and Acceptance Criteria**

V. Results

- **a. Performance**
- **b. HED Identification, Analysis, and Prioritization**

VI. Validation Conclusion

Figure 39. Representative ISV report content

3.1.3.4 Human Performance Monitoring

HTI will be carried out through the implementation and use of the upgrades in this project. This effort entails ensuring that all HEDs identified during V&V that require correction are addressed and closed out prior to installation. Further, the site human performance monitoring program will be used to ensure that the impacted HSIs, procedures, and training are maintained over time. Methods of collecting feedback during monitoring will be based on the site program and may include information collected through observations, interviews, or self-reported problem identification sheets (e.g., EPRI 3002004310 2015).

3.2 Collaboration 2: Applying Human and Technology Integration to Support Developing a New Vision and Concept of Operations

3.2.1 Background

Southern Nuclear Corporation (SNC) is committed to sustaining the life of their existing nuclear fleet for continued carbon-free electricity production. A key objective in ensuring the sustained operation of these plants is to address obsolescence considerations with existing legacy equipment and reduce O&M cost through business-driven innovations and technology solutions. SNC is addressing these objectives through multiple strategic initiatives, including performing a large-scale digital modernization of their existing I&C infrastructure across multiple sites. This effort is set to develop a digital modernization strategy and define common requirements that provide consistency across each of the sites (Figure 40).

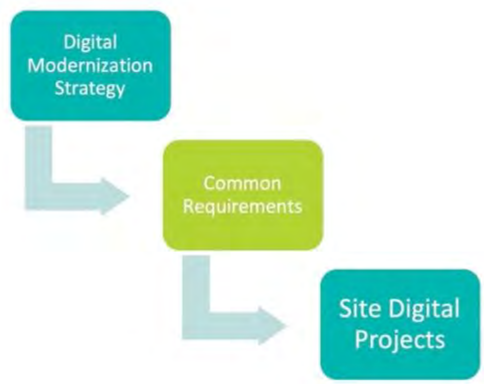


Figure 40. SNC fleet digital modernization implementation (adapted from Ray Herb's presentation at the 2022 LWRS Program Stakeholder's Meeting on August 17, 2022).

These sites are currently operating safely and reliably, but there is a business need to strategically modernize their fleet with digital technology to address obsolescence challenges and reduce O&M costs. SNC is considering the use of advanced digital technologies, such as those described in Section 1.1, to transform the way in which these plants are being operated, maintained, and supported. Such advanced capabilities will fundamentally change the way in which plant personnel perform certain work functions and associated tasks. For instance, digital I&C systems with increased levels of automation will put the control room operators into a more supervisor role than they once had. This shift in responsibility changes how they perform tasks in the control room and what is necessary for detecting, diagnosing, and responding to abnormal plant conditions.

The scope of this collaboration encompasses key HTI activities that comprise Initial Scoping, as seen in the DEG (2018). Specifically, the collaboration has supported SNC and associated collaborators (e.g., Sargent and Lundy) in this project in developing a new vision and concept of operation, being informed by early operator input (i.e., OE) and HFE guidance and methods. The efforts described in this collaboration have focused on a single site, but the continuing collaboration will expand across the fleet. The goals of this effort are to address the needs of end users in operations, maintenance, and engineering (i.e., stakeholder needs), ensure standardization across the fleet to reduce training costs, and consolidate support, as well as improve performance through modern technologies that leverage increased automation and plant data integration.

A recent report, INL/RPT-22-70538 (2022), documents earlier activities completed in this collaboration. Figure 41 highlights the extent of these activities covered through Initial Scoping, as well as continuing Initial Scoping activities that will be used to further define the vision and concept of operation. The following subsections summarize these HTI activities.

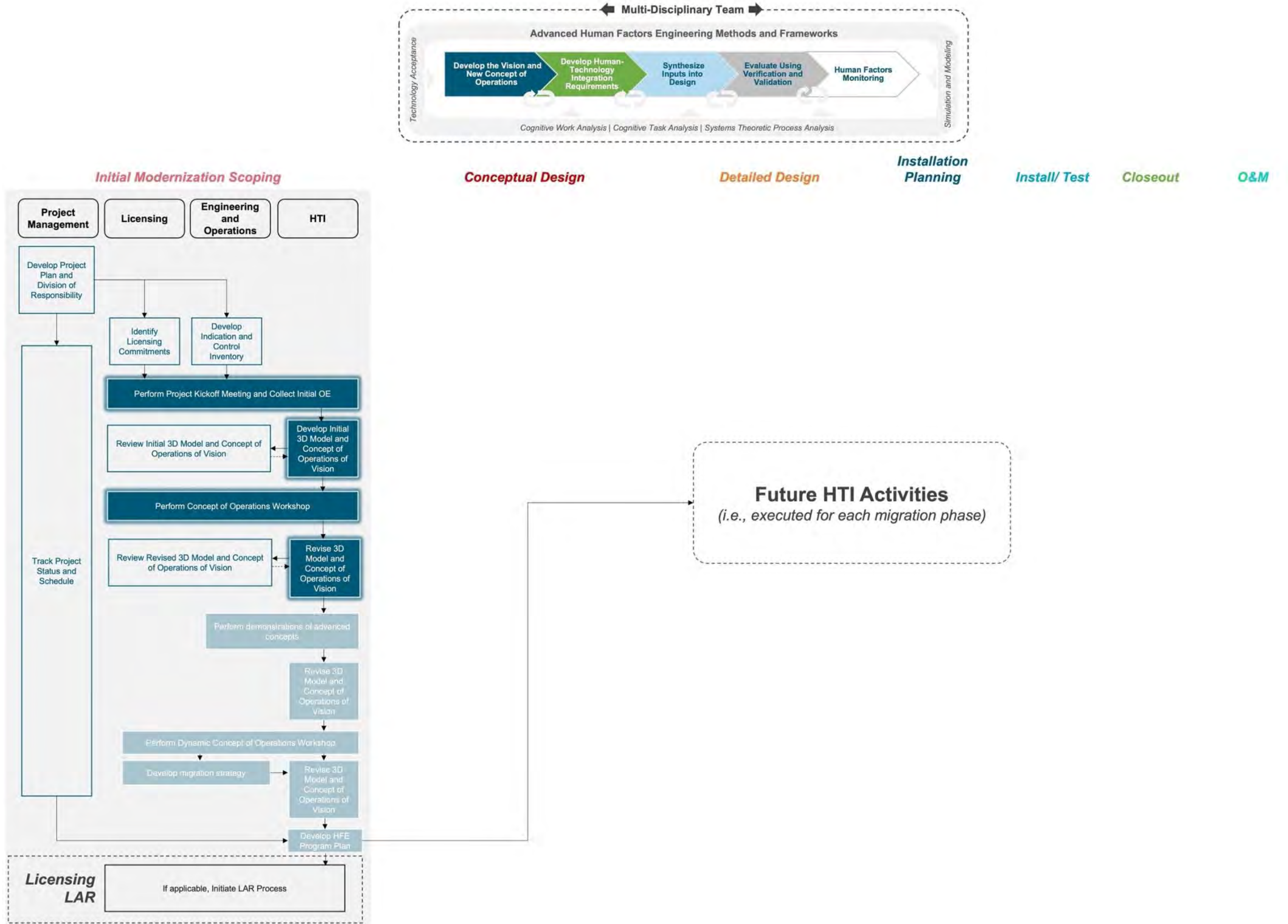


Figure 41. HTI activities demonstrated in Collaboration 2.

3.2.2 Human and Technology Integration Activities Demonstrated

3.2.2.1 Perform Project Kickoff Meeting and Collect Initial Operating Experience

The kickoff meeting was held at the site's training simulator; there, the simulator facility contained a simulator of the existing configuration and a simulator of the currently scoped digital modifications. During this meeting, operations personnel had the chance to get familiar with control room upgrades through training exercises and provide feedback on the configuration. The HTI researchers (HFE team) were present to observe how operators responded to digital upgrades, such as digital system displays, digital controls, and navigating displays located on the control boards. This meeting also gave the HFE team the chance to become familiar with the control room environment, layout, and operations. After the operators had run through training exercises, the HFE team had the opportunity to speak with them to collect initial OE, based on the use of the digital upgrades with the currently scoped digital modifications.

During these discussions, the endpoint vision worksheets from EPRI 3002004310 (2015) were used to gather operator input on activities performed in the control room and how the initial upgrade either supported those activities or required further improvement. Operators have a unique understanding of the plant's operation and are crucial in the conceptual phase of design, as their feedback informs multiple perspectives that support the development of HTI requirements to reveal the implications the current design concepts have on control room operations. These discussions also revealed the more nuanced or cultural interpretations and actions operators use to achieve expectations conveyed in the company's formal conduct of operations. Having this clarity between end users and HFE teams supports effective communication and understanding of user needs and expectations for future control room capabilities.

3.2.2.2 Develop Initial Three-Dimensional Model and Concept of Operations

Operators, who have extensive experience operating the plant, provided early feedback into their vision for the future endpoint MCR during the initial kickoff meeting with the plant. Feedback was collected from operators during interviews, discussions, and walkthroughs during an initial visit at the plant. Operators discussed additional needs and requirements, such as hard controls and new workstations to maintain safe and effective plant operations. Feedback from the operators was collected and provided to the engineering and design team to begin the 3D model development.

The initial 3D model was developed using a computer-aided design file that was created from laser scans of the MCR to accurately measure the entire MCR. Photo editing software was used to combine image files together to represent workstations and other equipment in the 3D model. The design team evaluated the 3D model to confirm MCR measurements and placements.

Once the initial 3D model was completed, an HFE review for anthropometric considerations using guidance in NUREG-0700 (2002) was completed. The NUREG-0700 review is used to apply HFE guidance and recommendations in the MCR. Ergonomic software was used to create DHM representations of 5th percentile females and 95th percentile males. The DHMs aid in developing accommodations for approximately 90% of the population by evaluating the smallest to largest anthropometric measurements in the 3D model.

The DHMs were used to evaluate if new equipment or modifications block operator sight lines when viewing information from the digital HSIs on the control boards or in other locations. Functional reach was evaluated with DHMs to ensure that the new digital upgrades are within functional reach of the operators. Legibility on HSI displays was evaluated to determine the adequate font sizes for operators to read the information at workstations from a distance. Multiple 3D model iterations were developed and evaluated, using NUREG-0700 guidance, to provide visualizations and design recommendations for the endpoint vision and future states.

3.2.2.3 Perform Concept of Operations Workshop

A static concept of operations workshop was held at Idaho National Laboratory's HSSL to gather more detailed feedback on the new vision and proposed concept of operation. The workshop began by familiarizing the operators with the digital reconstruction of their control room. Operators then explored advanced control room concepts, including Plant and System Overview Displays (Braseth & Øritsland 2013), Computerized Operator Support Systems (Boring et al. 2015), and an Advanced Data Analytics and Procedure Tool (Kovesdi et al. 2020), to understand the potential transformation of MCR operations. The intent was to introduce what advanced concepts for control room operations can mean beyond digital like-for-like replacements and how MCR operations may transform as a result. All this to help prime operators to consider all possibilities as later discussions begin to involve reviewing the HFE impacts to the plant's conduct of operations.

A 3D model of the new vision of the MCR was also displayed in the HSSL, which could be manipulated in real time, to give operators a glimpse of the future control room design. Operators were also taken to a visualization laboratory, where they experienced a virtual representation of the new vision through virtual reality equipment. The endpoint vision worksheets were then used to evaluate stakeholder feedback from an operations perspective. The worksheets included columns for existing concept of operations, expected changes, and HFE impacts and considerations (refer to Table 1). Topics discussed included normal and abnormal operations. These worksheets allowed INL personnel to identify relevant HFE impacts and considerations by topic related to changes in the vision.

The HFE team used feedback from the workshop to support informing the migration strategy. The team focused on identifying each phase of the implementation to be planned around specific plant events, such as outages, leading to a smoother transition from the current state to the new state. The team leveraged Table 2 as a tool to describe these migration phases and HFE impacts across each phase, documenting the results in the concept of operation report.

3.2.2.4 Revise Three-Dimensional Model and Concept of Operations

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 42 provides an example of a conceptual rendering of an analogous endpoint vision to what was used in these discussions with operators.

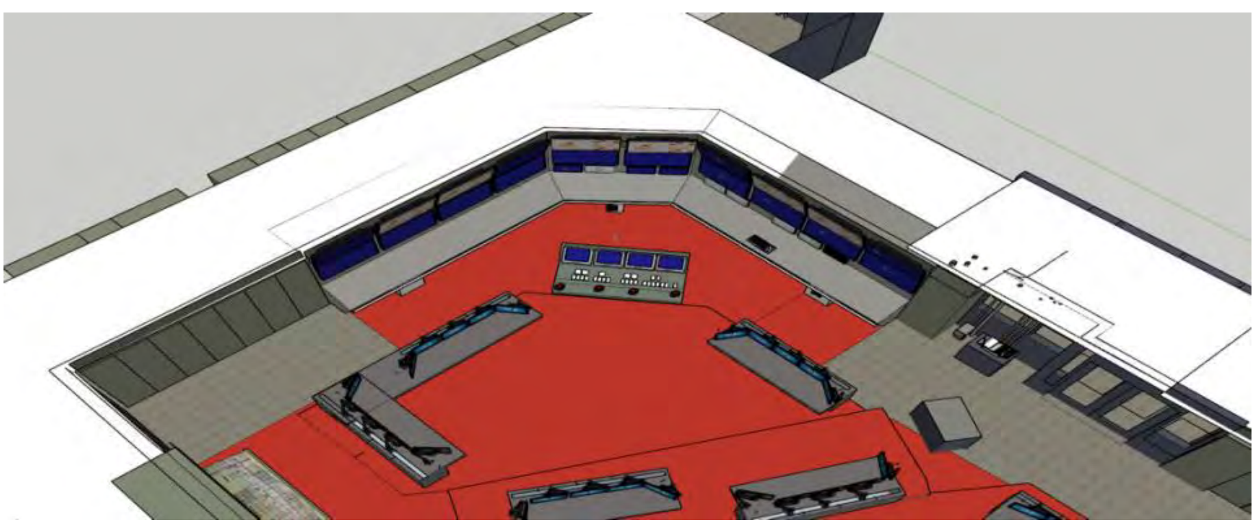


Figure 42. Conceptual model of an MCR endpoint vision.

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.

3.2.3 Future Activities

3.2.3.1 Perform Demonstrations of Advanced Concepts

Following the static concept of operations workshop, an advanced MCR concept demonstration workshop will be completed along with researchers from the Institute of Energy Technology. This demonstration workshop will allow operators from the site to perform walkthroughs with advanced MCR concepts in the HAMMLAB using the generic pressurized water reactor as the simulator model. For example, advanced display concepts, including the use of large-screen displays and operator work displays, will be demonstrated to support operators increased situation awareness (McDonald, Braseth, and Joe 2019).

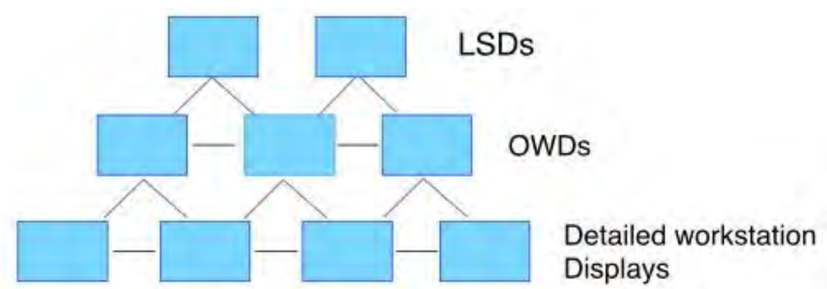


Figure 43. Advanced MCR Halden information hierarchy.

These demonstrations will allow operators to use advanced visualization technologies developed by the Institute of Energy Technology, including large-screen overviews, operator work displays, digital HSIs, and CBP in selected scenarios for design feedback (e.g., see preliminary example in Figure 44).

Figure 44. Preliminary advanced MCR concept using the Halden advanced control room layout.

The results of this workshop will inform the digital modernization strategy by serving as a technical basis for a fleetwide style guide and common fleet requirements. A driving framework for this workshop can be understood through the technology acceptance model (TAM; Kovesdi 2021). The TAM framework theorizes that technology adoption is driven by the intent to use or adopt (Davis, Bagozzi, and Warshaw 1989). The intent to adopt technology is further explained through internal variables, including the perceived usefulness and usability of a technology. These two variables can be further explained by the degree of compatibility of a technology to support a user's tasks and level of trust in the technology. External variables of interest for influencing compatibility and trust may entail the level of familiarity with a new technology. Using TAM as a framework for conceptualizing factors that influence technology adoption, it can be reasoned that early exposure to potential MCR concepts through interactive demonstrations can enable stakeholder "buy-in" and promote operations to champion the realization of these technologies in the new vision and concept of operations.

3.2.3.2 Perform Dynamic Concept of Operations Workshop

The purpose of the dynamic concept of operations workshop is to further inform the vision and concept of operations for SNC's fleetwide modernization. While the static concept of operations workshop provided static images of the HSIs in the HSSL to allow operators to provide high-level feedback on the placement and nature of HSIs, the dynamic concept of operation workshop will provide a set of HSIs that read live simulator values and have live navigation links to allow for design input related to the specific content and navigation strategy for the HSIs. This information will support the development of an HSI style guide and common requirements across the sites.

3.2.3.3 Develop Human Factors Engineering Program Plan

While this effort has not been explicitly scoped at the time of this report, it can be reasoned that a key HTI activity needed to enable the implementation of the planned upgrades across multiple phases and sites requires the adaption and development of an HFE Program Plan. Aspects covered in Section 3.1.2.1 are key HFE elements to be considered. As this work matures, specific activities scoped for the HFE Program Plan will be further defined. It is envisioned that these HTI activities will follow those described in NUREG-0711 (2012) and related HFE standards (e.g., EPRI 3002004310 and IEEE 1023), as well as INL/EXT-21-64320, across the developing human-technology integration requirements (Section 2.2.2), design synthesis (Section 2.2.3), V&V (Section 2.2.4), and HFE monitoring (Section 2.2.5) phases to the extent practical.

3.3 Lessons Learned and Recommendations

The following lessons learned are a culmination of findings in applying the HTI guidance described in INL/EXT-21-64320 (2021). These lessons learned have been derived from the demonstrations documented in INL/RPT-22-68472 (2022) and INL/RPT-22-70528 (2022). Additionally, an updated list has been added. The lessons learned are generally applied, as well as specifically applied, to each of the phases that have been demonstrated at the time of this report, including developing a vision and concept of operations, developing HTI requirements, and design synthesis. The intent is to provide a cohesive set of recommendations that can be holistically applied to future modernization efforts.

3.3.1 General Lessons

Lesson 1. An integrated team is critical throughout the HTI process.

An integrated team is pertinent throughout the project lifecycle. This includes including key stakeholders from operations, licensing, engineering, vendors, and HFE throughout each of the HTI phases.

For instance, when developing the vision and concept of operations described in Section 3.2, an integrated team was applied throughout the course of this project. 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. This allowed the team to develop an endpoint vision and resolve tradeoffs with proposed design characteristics effectively and efficiently.

An integrated team was also used in developing human-technology integration requirements and synthesizing these requirements into design, as described in Section 3.1. A cross-functional team significantly benefited this project in enabling the effective identification of scenarios, designing early concepts, identifying key considerations to address, as well as integrating prototype HSIs into the simulator.

Lesson 2. A risk-based approach is critical for guiding and prioritizing subsequent HTI activities.

The grading and tailoring of HTI activities should follow a risk-based approach. While this is particularly notable in the execution of primary HFE activities linked to NUREG-0711 (2012), the development of a new vision and concept of operations can also benefit from interlinking the level of risk proposed by each upgrade when informing a migration strategy. When the migration strategy is stepwise in nature (i.e., implemented in distinct phases), a risk-based approach can be applied to grade the level of HFE effort and tailor specific activities across phases. Phases that are notably impactful from a risk standpoint or are of a higher complexity (i.e., significantly impacting the concept of operations) ought to apply a greater level of HFE rigor.

It is therefore important to begin identifying any important human actions, as described in NUREG-0711 Section 7, that are being directly impacted by the upgrades for a determined migration phase. Impacted important human actions can be identified from deterministic (i.e., D3 analysis or FSAR) or from PRA. The graded approach would therefore determine the highest level of HFE rigor to the phases and tasks that envelop these actions. A secondary factor that should be considered includes the upgrade complexity. This may be defined by several factors including:

- The total extent of modernization, including number of HSIs impacted, number of tasks impacted, and associated plant systems impacted.
- The degree of change in concept of operation, including the degree of deviation from the way operators will be required to perform their tasks with the new system (e.g., seated versus standing), the degree of change in level of automation, or degree of change in the way the crew will coordinate as a team.

It is also worth noting that each migration phase (i.e., project) may be globally graded, but the specific tasks impacted can be tailored up or down depending on their association with plant safety, personnel safety, or economic risk. This was seen in Figure 30 where the project was graded a Level 1 but was later tailored to specifically address those tasks identified within the site's risk analyses or determined to be time sensitive. Because the scope of an upgrade can impact upwards of hundreds of tasks, and with scheduling and budgetary considerations of a project, the tailoring can help better focus the HTI activities to the most critical tasks impacted. Table 4 illustrates the types of HFE methods to address developing human-technology integration requirements, following a graded approach; these factors are based on guidance given in NUREG-1764 (2007) and EPRI 3002004310 (2015).

For instance, in Collaboration #1 (Section 3.1), the project was initially screened in as High (or Level 1). With secondary factors accounted for, the result of the project became Medium (or Level 2). The project was then tailored to review risk-important impacted tasks at a High (Level 1) grading. The end result enabled task analysis activities to be performed at a high level for all impacted tasks. However, the identified impacted risk-important tasks (i.e., those identified from the D3 analysis, FSAR, or PRA) would be analyzed further through detailed task analyses, namely through OSDs, and reviewed using CWA techniques like decision ladders. The highlights in Table 4 illustrate this.

Table 4. Graded approach for applying human-technology requirements gathering activities.

<table>
<tr><td colspan="5">HTI Requirements
FA&A, Task Analysis, Risk Analyses</td></tr>
<tr><td colspan="2" rowspan="2"></td><td colspan="3">Complexity
"Secondary Factors"
Number of HSIs impacted
Number of tasks impacted
Number of associated systems (functions) impacted
Degree of change in concept of operations
Impact on hypothesized levels of automation and information processing
Team dynamics</td></tr>
<tr><td>Low</td><td>Medium</td><td>High</td></tr>
<tr><td rowspan="3">Risk
"Primary Factors"
Risk analysis
Risk to personnel
Economic risk</td><td>Low</td><td>Level 3

Methods
Operator preference
Expert judgment</td><td>Level 3

Methods
Operator preference
Expert judgment</td><td>Level 2

Methods
FA&A methodology (where there are changes in function allocation) of the most troublesome use cases
High-level task analysis of the most troublesome impacted human actions</td></tr>
<tr><td>Medium</td><td>Level 2

Methods
FA&A methodology (where there are changes in function allocation) of the most troublesome use cases
High-level task analysis of the most troublesome impacted human actions</td><td>Level 2

Methods
FA&A methodology (where there are changes in function allocation) of the most troublesome use cases
High-level and detailed task analyses (walkthroughs, or hierarchical task analysis/ tabulated task analysis) of the most troublesome impacted human actions</td><td>Level 2

Methods
FA&A methodology (where there are changes in function allocation) of the most troublesome use cases
High-level and detailed task analyses (walkthroughs, or hierarchical task analysis/ tabulated task analysis) of the most troublesome impacted human actions</td></tr>
<tr><td>High</td><td>Level 2

Methods
FA&A methodology (where there are changes in function allocation) of the most troublesome use cases
High-level task analysis of the most troublesome impacted human actions</td><td>Level 1

Methods
FA&A methodology (where there are changes in function allocation) of all use cases
High-level and detailed task analyses (walkthroughs, or hierarchical task analysis/ tabulated task analysis) of all impacted human actions

Advanced Methods (Suggested)
Systems Theoretic Process Analysis</td><td>Level 1

Methods
FA&A methodology (where there are changes in function allocation) of all use cases
High-level and detailed task analyses (walkthroughs, or hierarchical task analysis/ tabulated task analysis) of all impacted human actions

Advanced Methods (Suggested)
Systems Theoretic Process Analysis
CWA and cognitive task analysis techniques</td></tr>
</table>

Lesson 3. A clear division of responsibility between parties is pertinent for effective collaboration and minimizing bias.

Having a division of responsibility is pertinent for two primary reasons. First, and the most explicit, having clearly delineated roles for specific stakeholders promotes good project management through minimizing ambiguity between task assignments and allows for effective communication between team members based on having clear responsibilities. A second benefit that is less explicit is that having clear roles and responsibilities can enable developing independent teams across the project. These independent teams can minimize bias in evaluative activities, such as when transitioning into V&V. With Collaboration #1, independent teams were developed to support specific project functions, including his and procedure design, simulator integration, HFE, licensing, and validation (Table 5). These teams had specific roles and responsibilities to reduce bias in the evaluation of the impacted HSIs and procedures.

Table 5. Independent cross-functional teams used for effective collaboration and minimization of bias.

Team Name	**Team Role(s)**	**Team Composition**
HSI Design and Procedure Modification Team	— To create the HSI design concepts to produce design inputs. — To then iterate and refine the design of the HSIs to conform to those inputs and established HFE principles. — To identify and propose procedural changes to enable plant operation with the new digital I&C.	Site engineering and operations personnel with significant knowledge of: — The legacy plant I&C and HSIs being upgraded. — Plant operations. — Use of existing operating procedures. Additionally, vendor staff who have significant understanding of the capabilities of the selected platforms.
HFE Process Team	— To ensure that the Project establishes and then executes the HFE activities described in the HFE Program Plan.	Staff with significant knowledge of HFE and experience applying HFE in main control room modernization.
HSI and Procedure Validation Team	— To evaluate whether the modified HSIs and procedures acceptably promote plant operation.	The ultimate 'end users' of the HSIs and procedures being developed. These include qualified and licensed operations personnel from the site.
Simulator Team	— To support integration of the simulator and HSI concepts to enable interactive capabilities in an immersive simulator environment. — To run the simulator during HFE activities and assess the ability of the operators to use the upgrades HSIs.	A combination of simulator engineering personnel and site simulator training personnel.

Lesson 4. Having access to a digital glasstop simulator is instrumental in collecting early feedback from stakeholders.

There is significant value in early prototyping and presenting the proposed concepts in a glasstop simulator. Both collaborations have leveraged the HSSL to collect stakeholder feedback and resolve design tradeoffs early in the process. The level of fidelity for prototypes presented on the glasstop may vary depending on the maturity of the project and specific goals.

There is great value in the use of a glasstop simulator while following an iterative design. Figure 45 shows the different types of simulator studies (i.e., workshops) that can be applied throughout a project's lifecycle. When developing a vision and concept of operations, the specific project scope may be still in the process of being defined but the new vision is conceptualized. A vendor may not even be selected at this point. Early feedback from stakeholders may be useful at this stage to better define the MCR attributes of the vision, such as how many VDUs are needed for large overviews, the location of workstations, or use of advanced capabilities like CBP. One or more workshops at this phase can add clarity to early design decisions.

As the modernization effort matures to specific projects for each migration phase, simulator studies become instrumental in supporting HFE activities, such as task analysis, design synthesis, and V&V. The scope of prototyping for these activities should reflect the scope of the modifications to be implemented by a selected vendor. The degree of fidelity should also become greater as the project progresses towards V&V. The outputs of these workshops that are part of the specific migration phase should be traceable throughout the project such that key HFE findings are incorporated and can be used as technical bases for key design decisions that drive the requirements and specifications for the HSIs.

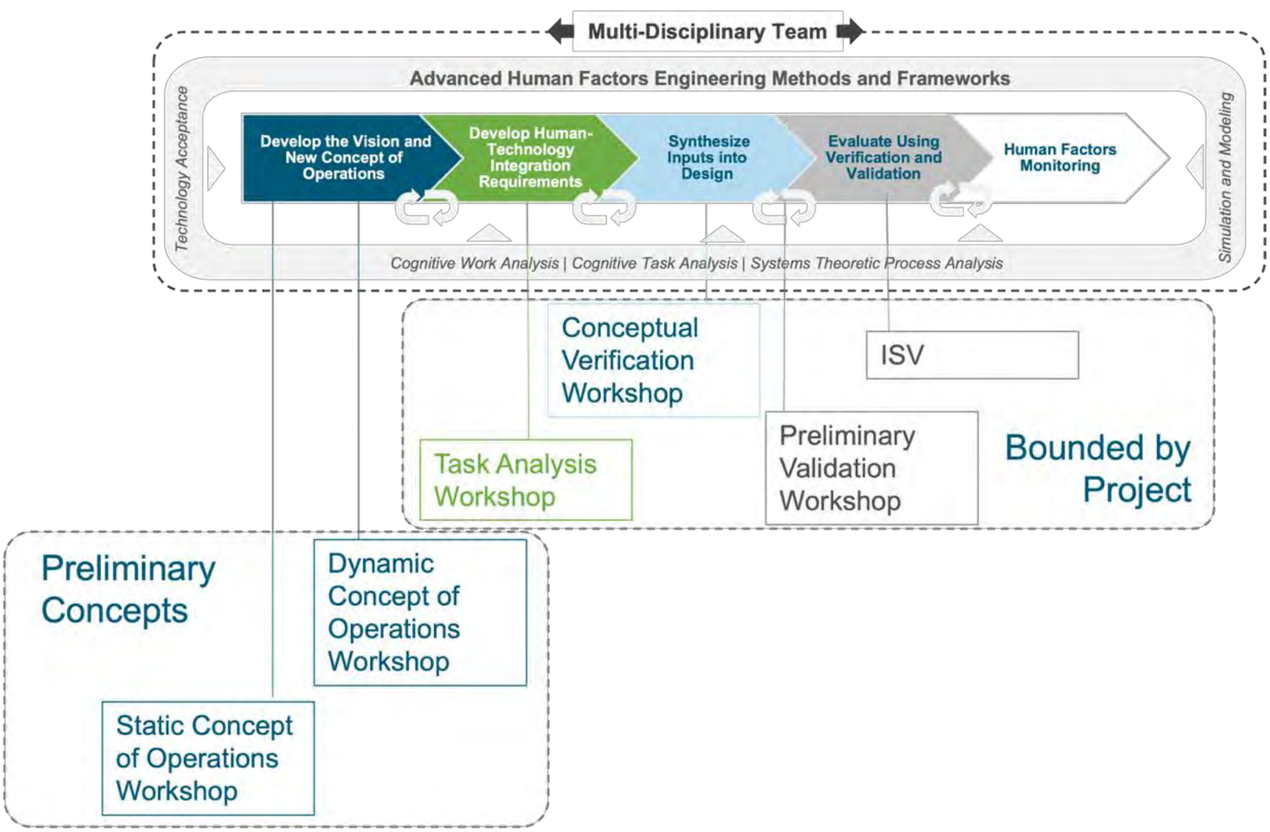


Figure 45. Types of simulator studies for each HTI phase.

Lesson 5. Advanced HFE frameworks like CWA can complement HTI activities.

CWA, when used as a complementary method to other HFE methods (e.g., operator-in-the-loop studies), can serve as a useful framework in evaluating the cognitive and decision processes required of the operators when performing the impacted tasks. CWA offers a suite of methods to evaluate system characteristics. The CWA methods include work domain analysis, control task analysis, strategies analysis, social organization and cooperation analysis, and worker competencies analysis. Each of the methods may be used depending on the need of CWA. The use of decision ladders under the control task analysis umbrella was notably useful in characterizing the cognitive characteristics of impacted tasks, described in Section 3.1. Notably the decision ladders were used to develop questions in understanding the cognitive characteristics of the impacted tasks during task analysis. They were also used in characterizing the impacted Level 1 manual actions into two types, based on their qualities of diagnosis. This was seen in Figure 36. The decisions ladders thus were applied as an explanatory framework to support developing human-system performance acceptance criteria for these actions for V&V efforts.

Lesson 6. Real-time 3D and digital human modeling can significantly improve design team decision-making.

The use of 3D modeling tools is complementary to the use of simulators (Lesson 4) to evaluate ergonomic and anthropometric design considerations related to digital upgrades. 3D modeling is particularly useful in addressing hybrid considerations, such as those described in Section 2.1.2. As described in INL/RPT-22-70528 (2022) and Section 3.2.2, 3D modeling and the use of DHMs have been valuable in the support of defining the new vision. Specifically, these capabilities allowed the cross-functional team to address design tradeoffs regarding the placement of specific VDUs and workstations to support operation's needs, seismic requirements, and HFE guidance, such as with NUREG-0700.

The use of 3D modeling and DHMs have also been significantly useful in addressing similar design tradeoffs across subsequent HTI phases, leading into design synthesis. For instance, with ongoing collaborations with CEG (Collaboration #1 in Section 3.1), these capabilities have continued to serve as a useful approach in addressing these tradeoffs, particularly as specific hardware components are selected. An important consideration with the use of 3D models in later staged HTI efforts is ensuring that there is some degree of traceability and configuration control for the development and revision of each iteration of models being developed. Having linear traceability to the design decisions made through each HFE iteration (e.g., from FA&A through design) provides assurance that the modifications are converging to finalization and that ergonomic and anthropometric considerations have been systematically made throughout the lifespan of the project.

3.3.2 Licensing

Lesson 7. The I&C-ISG-06 process places unique challenges in planning and executing HFE.

A notable licensing challenge, encountered in Collaboration #1 in Section 3.1, dealt with scheduling constraints of important HFE activities within the larger project. Notably, the time window available for executing HFE activities was limited because of a compressed timeline with following the DI&C-ISG-06 Alternate Review Process for LAR submittal and approval. The Alternate Review Process reduces schedule, licensing, technical, and project cost risks from an I&C perspective when using a safety platform with a generic SER. However, current HFE regulatory guidance (i.e., NUREG-0711) has maintained expectations to that of the Standard Review Process (i.e., see Section B.1.4, "Review Areas Outside the Scope of this Interim Staff Guidance" of DI&C-I&C-06, Revision 2).

Following the Standard Review Process and NUREG-0711, the expectation is to perform design verification and ISV at the time of FAT. However, following the Alternate Review Process, LAR submittal and approval can be accomplished before FAT. This discrepancy is seen in Figure 46. Here, a typical HTI schedule (e.g., see NUREG-0711 or INL/EXT-21-64320) is overlaid across the systems engineering phases, such as those described in the DEG (2021). The Standard Review Process shows approval after FAT (in orange). The Alternative Review Process is shown in red, where approval of a LAR can be accomplished before FAT. Here, HFE V&V is still completed at FAT.

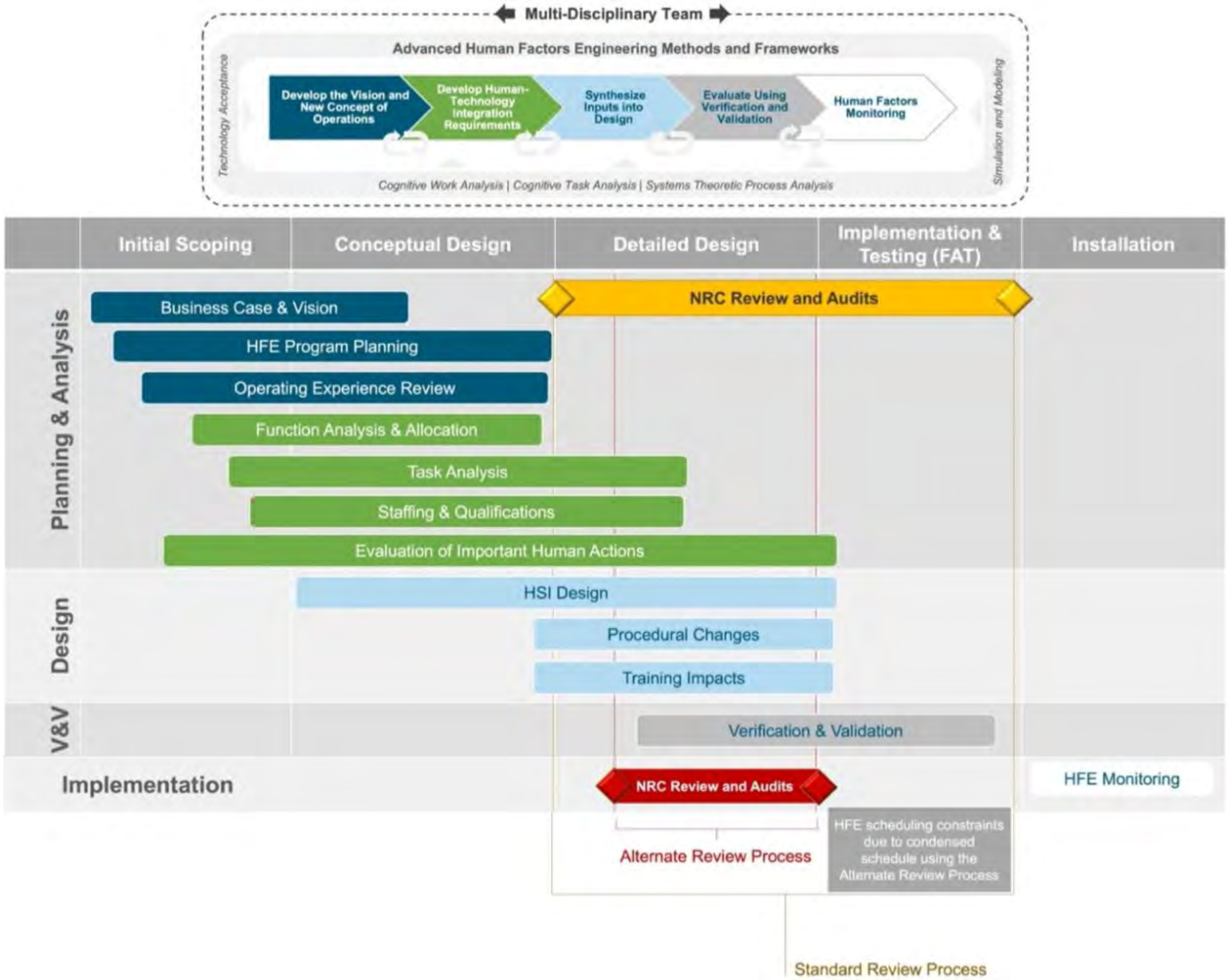


Figure 46. Typical HFE schedule overlaid with the Standard Review and Alternate Review Processes.

It should be noted that the NRC staff is aware of this and has been working with industry to find ways to address this NUREG-0711 process compression to support timely and complete LAR submittals and subsequent SER issuance, in following the Alternate Review Process. Notably, a recent paper was published at the Human Factors and Ergonomics Society 2022 annual conference (Vazquez, Green, and Desaulniers 2022). This work provided possible alternatives for licensees to provide HFE validation information necessary for demonstrating reasonable assurance for safety of the modifications. A multistage validation approach is proposed to support enabling the NRC to make a safety determination for a proposed design change prior to the completion of ISV testing.

3.3.3 Developing the Vision

Lesson 8. Using demonstrations, prototypes, and workshops enable effective feedback from stakeholders that drive technology acceptance.

Stakeholder "buy-in" (i.e., technology acceptance) is an important element to defining the vision and new concept of operations. The TAM provides a useful framework in understanding the drivers to stakeholder "buy-in." Key drivers include the perceived usefulness and perceived ease of use for a given technology to support their task needs (Davis, Bagozzi, and Warshaw 1989). Kovesdi (2021) conceptualized additional drivers that may influence technology acceptance within the nuclear industry. Considerations, including familiarity with a new technology and perceived level of trust and task compatibility (i.e., the degree to which the technology will support a user's task demands), are two salient factors in this adapted TAM framework that drive perceived usefulness and ease of use. To put into context, an increase in familiarity with a new MCR technology (e.g., computer-based procedure system or increased automation) will better align stakeholders (i.e., operators) in understanding how these new capabilities can improve their task needs. As a result, their degree of perceived usefulness and ease of use will be better aligned with what the capabilities offer to support "buy-in" and consequently acceptance. Using this TAM framework, a practical consideration is to enable stakeholders to become familiarized with the technology through early demonstrations and design workshops that provide hands-on experiences using these technologies in their day-to-day lives. The use of early technology demonstrations is being leveraged for Collaboration #2 (Section 3.2).

Lesson 9. The new vision and concept of operations should drive the planning and execution of subsequent HTI activities.

Related to Lesson 2, the development of the new vision and concept of operation should drive the planning and execution of subsequent HTI activities. Specifically, the extent to which the vision and new concept of operation differs from how the plant is currently operated, maintained, and supported should inform the grading of HFE activities described in the HFE Program Plan. This is reflected in grading criteria described in Section 2.2.1.5. The new state vision in Collaboration #1 drove the requirements for the safety and non-safety I&C scoped for the project. This consequently served as input into performing OER, FA&A, task analysis, and design synthesis activities. In Collaboration #2, HTI researchers developed a concept of operations document to describe the characteristics of the proposed new state. In this document, the team identified proposed migration phases in reaching the vision. The researchers were able to characterize, at a broad level, what specific systems would be impacted by each migration phase, whether these systems were safety significant, the extent of digital I&C and new HSIs being implemented at that specific phase, and the characteristics of the physical modifications made to the MCR to determine HFE considered that should be of focus. The team used the HFE impacts table shown earlier in this report in Table 2. The output of Table 2 was meant to serve as subsequent input for later HTI activities.

Lesson 10. The vision and concept of operations should be a living document.

The vision and concept of operation provides a target direction to support strategizing the migration of existing I&C to new digital I&C. While the vision and concept of operation should be realistic (i.e., capturing capabilities that can be reasonably implemented), it is likely that the vision may be updated for any combination of reasons:

- Lessons learned from prior engineering activities (i.e., whether I&C or HFE related).
- Advances in technology.
- Changes in project direction and budget.

As such, it is important to plan feedback loops from subsequent HTI activities to inform the vision and concept of operations as the design converges, like what is reflected in Figure 22. These feedback loops can be enabled throughout the completion of specific HFE activities, such as task analysis, or towards the end of a specific I&C migration phase.

3.3.4 Human-Technology Integration Requirements

Lesson 11. Applying a "baseline" evaluation of the existing state offers value in comparing human-system performance to the new state.

A baseline is an evaluation of operator or system performance at a given point in time (Boring and Joe 2015). Baseline evaluation of the existing configuration was used on several occasions with Collaboration #1. First, HTI researchers were able to visit the site's training simulator to perform operator-in-the-loop tests with the existing MCR configuration during FA&A. In doing so, the baseline measures of human-system performance, workload, situation awareness, and system usability were collected to inform ways in which the new digital system can improve performance. The results were leveraged to inform considerations for automation enhancements and characteristics of the new HSIs. Later, the researchers utilized presenting a combination of the new HSIs in tandem with the existing HSIs so that operators were able to talk through performing specific tasks, using the existing configuration as a comparative means to the new HSIs to better identify information requirements for the HSIs.

Lesson 12. Focus on knowledge elicitation via qualitative measures is pertinent to the success of addressing HTI requirements.

The purpose of developing HTI requirements is to translate the functional, information, and task requirements of the new state and concept of operations to serve as the technical bases of design and V&V (Kovesdi et al. 2021). Developing effective technical bases requires a clear rationale in which a requirement is important to plant safety or production. Methodologically, qualitative measures provides the best means for eliciting knowledge from SMEs in collecting this rationale. Qualitative data may comprise objective measures (i.e., via observational) or subjective measures (i.e., via interviews). There is merit in using both, and it is generally considered good HFE practice to implement a diverse set of measures (IEEE 845 1999). IEEE 845 (1999) provides detailed guidance for evaluating human-system performance related to systems, equipment, and facilities in nuclear power plants. Further Kovesdi and Joe (2018) describe an overview of common methods and measures for nuclear power plant modernization. Figure 47 is adapted from this work and shows the landscape of these common HFE methods and measures regarding the degree to which they are objective or subjective and qualitative or quantitative.

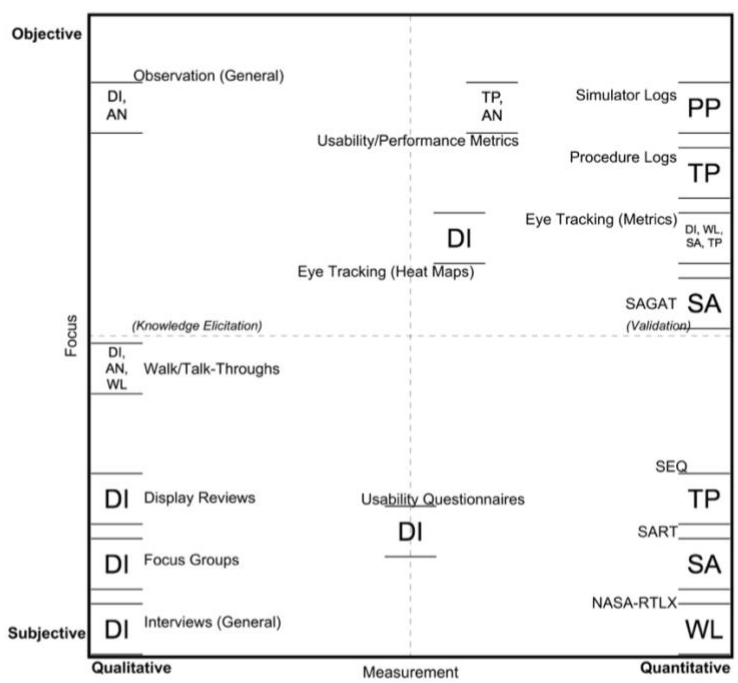


Figure 47. Landscape of HFE methods and measures (adapted from Kovesdi, Joe, and Boring 2018).

Both collaborations utilized qualitative measures to elicit knowledge from the operators, reflected in:

- Collaboration #1: OER (Section 3.1.2.2), FA&A (Section 3.1.2.4), task analysis (Section 3.1.2.5), and CV (Section 3.1.2.9)
- Collaboration #2: Initial OE (Section 3.2.2.1) and static concept of operations workshop (Section 3.2.2.3)

Both projects leveraged the use of walkthroughs and talkthroughs to observe operator behavior and collect their verbal feedback regarding the cognitive considerations when performing their tasks. These walkthroughs employed a "think-aloud protocol" to provide insights into the design of the new HSIs, workload considerations, and crew coordination considerations. The think-aloud protocol is a well-known technique in the HFE and usability engineering literature (e.g., Nielsen, 1994).

3.3.5 Design Synthesis

Lesson 13. Developing acceptance criteria that demonstrate the safe and effective use of the new HSIs early in design enables high confidence that the performance criteria will be met at ISV.

The goal of design tests and evaluation, such as those described in NUREG-0711 Section 8.4.6, is to support design decisions. These tests may utilize a combination of qualitative methods and measures (e.g., refer to the lefthand side of Figure 47) to identify design issues or collect design insights. Contrary to design tests, validation tests, in V&V, assess whether an aspect of the design or the integrated design meets its intended purpose (IEEE 2411, 2021). Validation tests use predefined criteria that determine the *acceptance* of whether an objective is met. While V&V requires the use of acceptance criteria to make a safety determination, developing acceptance criteria during late stages of design can provide early assurance that the new HSIs and procedures are converging to be usable going into V&V. NUREG-0711 provides different bases that can be used in developing acceptance criteria, and these include basing criteria on a:

- Requirement
- Benchmark
- Norm
- Expert judgment.

The former may be weighted as more technically sound. The criteria may be dispositive (pass or fail) or diagnostic in nature (IEEE 2411 2021). Developing acceptance criteria in design was a demonstration with Collaboration #1 in performing CV (Section 3.1.2.9). Here, the researchers leveraged NUREG-0800 Chapter 18 Attachment A guidance and developed acceptance criteria based the impacted action's time available to perform these action per licensing basis as a dispositive criterion (i.e., per licensing basis requirement). The utility further developed criteria based on existing performance data (i.e., per utility defined benchmark) as good engineering practice. The criteria in CV were conceptually evaluated in a walkthrough to collect estimates of performance in providing reasonable assurance of the design's usability prior to PV. While developed the acceptance criteria went beyond the intent of design testing, it provided an additional degree of confidence to ensure that the new HSIs and modified procedures can be effectively used to safely and reliably operate the plant.

Lesson 14. Vendor involvement is critical to ensure the proposed HSI solutions are reasonably achievable.

During CV (Section 3.1.2.9), it was critical to have the vendor participate in the workshop, especially when design feedback pertained to modifications to the new HSIs. The vendor was able to readily determine if proposed solutions identified during the walkthroughs could be reasonably achievable by using the standard HSI conventions for the given platform. In cases where there were limitations, the team was able to discuss alternative solutions that met operator needs and HFE guidance. The advantage of this process, as opposed to linear reviews, was significant savings in time and resources. This had a positive influence on addressing scheduling constraints, such as those described in Lesson 7.

Lesson 15. Design input should be prioritized to support timely implementation and preparation for V&V activities.

The CV (Section 3.1.2.9) workshop generated hundreds of design comments. In order to ensure that the most impactful of these comments would be effectively implemented in preparation for PV, a high-level prioritization was necessary to help focus on comments being most critical. The project screened design comments based on whether:

- They were needed for PV, ISV, or “wish list”
- The comment pertained to significantly impacted operator performance (e.g., unable to perform a manual action).

This basic screening process allows the design team to prioritize the comments into a manageable set in preparation for PV. The prioritization did not need to be overly complex. In fact, a more intricate scheme may have created unneeded burden.

4. CONCLUSION

Digital I&C and control room modernization offers a significant opportunity to reduce O&M cost to ensure the continued operation of the existing U.S. light-water reactors. There is a significant need to go beyond like-for-like replacement to critically examine current work processes and to integrate technology in a way the takes advantage of the capabilities of both people and the technology. To ensure that the capabilities of the technology and people are being leveraged for ensured safety and reliability, HTI is an important consideration for any major digital I&C MCR modification.

This report presents interim findings of two key collaborations with U.S. utilities planning and executing large-scale digital I&C modifications to their MCRs. While these collaborations are ongoing, this work presented lessons learned in the demonstration of the HTI methodology.

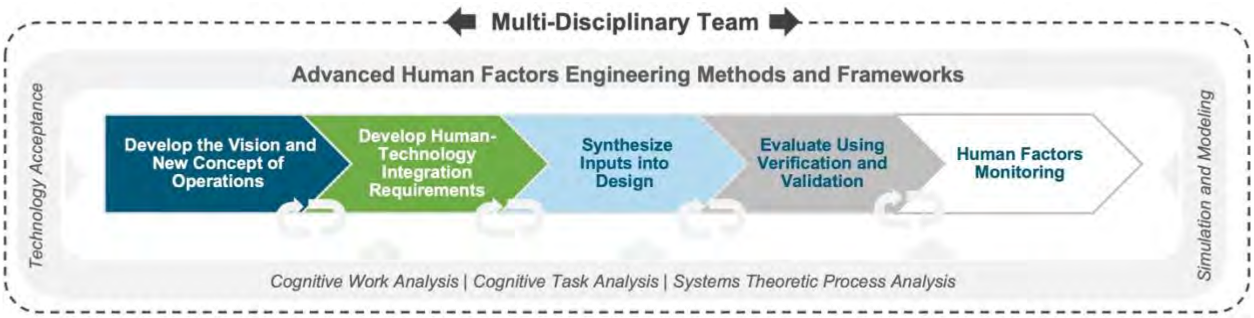


Figure 4 (reprint). HTI methodology.

A summary of lessons learned identified from this work can be summarized as:

General Lessons

- An integrated team is critical throughout the HTI process.
- A risk-based approach is critical for guiding and prioritizing subsequent HTI activities.
- A clear division of responsibility between parties is pertinent for effective collaboration and minimizing bias.
- Having access to a digital glasstop simulator is instrumental in collecting early feedback from stakeholders.
- Advanced HFE frameworks like CWA can complement HTI activities.
- Real-time 3D and digital human modeling can significantly improve design team decision-making.

Licensing

- The I&C-ISG-06 process places unique challenges in planning and executing HFE.

Developing the Vision

- Using demonstrations, prototypes, and workshops enable effective feedback from stakeholders that drive technology acceptance.
- The new vision and new concept of operations should drive the planning and execution of subsequent HTI activities.

- The vision and concept of operations should be a living document.

Human-Technology Integration Requirements

- Applying a "baseline" evaluation of the existing state offers value in comparing human-system performance to the new state.
- Focus on knowledge elicitation via qualitative measures is pertinent to the success of addressing HTI requirements.

Design

- Developing acceptance criteria that demonstrate the safe and effective use of the new HSIs early in design enables high confidence that the performance criteria will be met at ISV.
- Vendor involvement is critical to ensure the proposed HSI solutions are reasonably achievable.
- Design input should be prioritized to support timely implementation and preparation for V&V activities.

As this work continues, additional lessons learned will be developed. Specifically, lessons learned will be developed specific to V&V through the continued collaborations with CEG. Further, additional lessons learned will be developed in collaboration with SNC in subsequent HTI activities that will support developing a fleetwide migration strategy across multiple sites. Collectively, this guidance provides industry with HTI and HFE guidance that reduces the technical, financial, and regulatory risk of upgrading the aging I&C systems to support extended plant life up to and beyond 60 years.

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