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Light Water Reactor Sustainability Program

Development of an Assessment Methodology That Enables the Nuclear Industry to Evaluate Adoption of Advanced Automation

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Development of an Assessment Methodology That Enables the Nuclear Industry to Evaluate Adoption of Advanced Automation

Casey Kovesdi
Zachary Spielman
Rachael Hill
Jeremy Mohon
Tina Miyake
Chloe Pederson

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SUMMARY

Nuclear power has a crucial role in providing safe, reliable, and economical carbon-free electricity for today and the future. For continued operation, many of the existing United States nuclear power plants will begin the subsequent license renewal process for extending their operating license periods. As plants extend their expected operating lifetimes, there is a significant opportunity to modernize. These plants have a much stronger business case with these extended mission periods to modernize and significantly enhance their economic viability in current and future energy markets by implementing digital technologies that support innovation, efficiency gains, and business-model transformation.

Ensuring continued safety and reliability is crucial. Transformative digital technologies—including automation—that fundamentally change the concept of operation for the nuclear power plant operating models requires a critical focus on the human-technology integration element. Further, the nuclear industry has historically been reluctant to modernize due to a risk-adverse culture and lack of clarity for a transformative new-state vision. Common barriers include the perceived value and return on investment of digital technology; the perceived risk associated with licensing, regulatory, and cybersecurity; and insufficient guidance for performing digital modifications to power generation systems.

This work presents a methodology to address these barriers and support the industry in adopting advanced automation and digital technology through developing a transformative vision and implementation strategy that will address the human-technology integration element. This research leverages previous Light Water Reactor Sustainability (LWRS) Program and industry results. It draws specifically on previous LWRS Program research in the areas of advanced alarm systems, computer-based procedures, model-informed decision support, and advanced human-system interface displays (e.g., overviews and task-based). The modernization methodology can be used to guide transformative thinking when integrating a set of vendor-specific capabilities to support a new concept of operations and a utility's end-state vision.

The results of this research are organized into six major sections:

- Section 1 introduces the need for supporting large-scale digital modifications that will renew the technology base for extended operating life beyond 60 years.
- Section 2 describes the challenges that the nuclear industry is enduring with modernizing.
- Section 3 summarizes the primary standards and guidance.
- Section 4 presents earlier work from the LWRS Program regarding the development of a transformative conceptual design for an advanced control room of a hybrid plants.
- Section 5 presents a methodology that is designed to address the challenges in the industry today in achieving a transformative new-state vision and concept of operations.
- Conclusions and next steps of this research are provided in Section 6.

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ACRONYMS

AAM	Automation Acceptance Model
ACC	Adaptive Cruise Control
ACTA	applied cognitive task analysis
ADAPT	Analytics-Decision Support Advanced Procedure Tool
AH	abstraction hierarchy
CAT	contextual activity template
CBP	computer-based procedure
ConTA	contrdeg ol task analysis
COTS	commercial-off-the-shelf
CTA	control task analysis
CWA	cognitive work analysis
DEG	Digital Engineering Guide
DOE	Department of Energy
DRAM	Digital Reliability Analysis Methodology
EID	Ecological Interface Design
EPRI	Electric Power Research Institute
FA&A	function, analysis, and allocation
GOMS	Goals, Operators, Methods, and Selection Rules
HA	human action
HAC	Human-Automation Collaboration
HAZCADS	Hazards and Consequences Analysis for Digital Systems
HED	human engineering discrepancy
HFE	human factors engineering
HRL	human readiness level
HSI	human-system interface
HSSL	Human System Simulation Laboratory
HTA	Hierarchical Task Analysis
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
ICAP	Integrated Operations Capability Analysis Platform
INL	Idaho National Laboratory
IO	integrated operations
ION	Integrated Operations for Nuclear

ISV	Integrated Systems Validation
LAR	License Amendment Request
LOA	level of automation
LWRS	Light Water Reactor Sustainability Program
MCR	main control room
NGT	nominal group technique
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
O&M	operations and maintenance
OE	operating experience
OER	operating experience review
OSD	operational sequence diagram
PEOU	perceived ease of use
PRA	probabilistic risk assessment
PTPG	people, technology, processes, and governance
PU	perceived usefulness
R&D	research and development
ROI	return on investment
SA	situation awareness
SE	systems engineering
SOCA	social organization and cooperation analysis
SRK	skills, rules, and knowledge
STAMP	System-Theoretic Accident Model and Processes
STPA	System Theoretic Process Analysis
StrA	strategies analysis
TAM	technology acceptance model
TAM-NPP-M	technology acceptance model for nuclear power plant modernization
TRL	technology readiness level
TTA	Tabular Task Analysis
UCA	unsafe control action
V&V	verification and validation
WCA	worker competencies analysis
WDA	work domain analysis

DEVELOPMENT OF AN ASSESSMENT METHODOLOGY THAT ENABLES THE NUCLEAR INDUSTRY TO EVALUATE ADOPTION OF ADVANCED AUTOMATION

1. INTRODUCTION

Nuclear power has a crucial role in providing safe, reliable, and economical carbon-free electricity for today and the future. For continued operation, many of the existing United States nuclear power plants (NPPs) will begin the subsequent license renewal process for extending their operating license periods beyond their initial licensing period. As plants extend their expected operating timelines, there is a significant opportunity to modernize. These plants have a much stronger business case with these extended mission times to modernize and significantly enhance their economic viability in current and future energy markets by implementing digital technologies that support innovation, efficiency gains, and business-model transformation. The U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program Plant Modernization Pathway is conducting targeted research and development (R&D) that supports modernization through two strategic goals:

- To develop transformative digital technologies for NPP modernization that renew the technology base for an extended operating life beyond 60 years
- To enable implementation of these technologies in a manner that results in broad innovation and business improvement in the nuclear plant operating model, thereby lowering operating costs.

The resulting R&D products enable the modernization of plant systems and processes and build a technology-centric business model that ultimately supports the U.S nuclear industry's economic viability and long-term sustainability. In this effort, ensuring safety and reliability is crucial. Transformative digital technologies that fundamentally change the concept of operation for the NPP operating model (e.g., control automation, new decision support capabilities, and advanced displays) require a critical focus on the human and technology integration element. For instance, understanding how technology can be effectively integrated such that cost reductions can be realized in a way that ensure the end users can perform their tasks and maintain situation awareness of the processes being supervised is critical. Further, the integration of technology should minimize workload, minimize administrative and training burden, present meaningful and usable information, and be compatible with the work domain at hand.

Working closely with the nuclear industry, this work presents a methodology to support the industry in adopting advanced automation and digital technology through developing a transformative vision and implementation strategy that will address the human and technology integration element. The objective of this methodology here is ultimately to improve operational performance and ensure safety and reliability with the integration of enabling digital solutions that achieve plant operating cost reductions to extend the operating life of the U.S. NPP fleet for at least 60 years. Specific human and technology integration considerations that the guidance in this work support include:

- minimizing training demands
- eliminating human error modes
- reducing operator workload
- supporting decision-making and situation awareness (SA)
- enabling automation transparency

– ensuring optimal automation usability and trust

– addressing emerging information requirements for emerging digital technology.

Figure 1 highlights the overarching goals of this work (dark blue - top); the digital solutions that support innovation, efficiency gains, and business-model transformation (green - middle); and the specific human and technology integration considerations addressed (light blue - bottom). A transformation of the NPP operating model is seen in the conceptual rendering of a main control room. Here, technology such as automation, decision support, advanced human-system interfaces (HSIs), and advanced monitoring and communications capabilities across the plant allow for better decision-making and organization situation awareness to improve safety, reliability, and operational performance, consequently keeping these plants economically competitive in current and future energy markets.

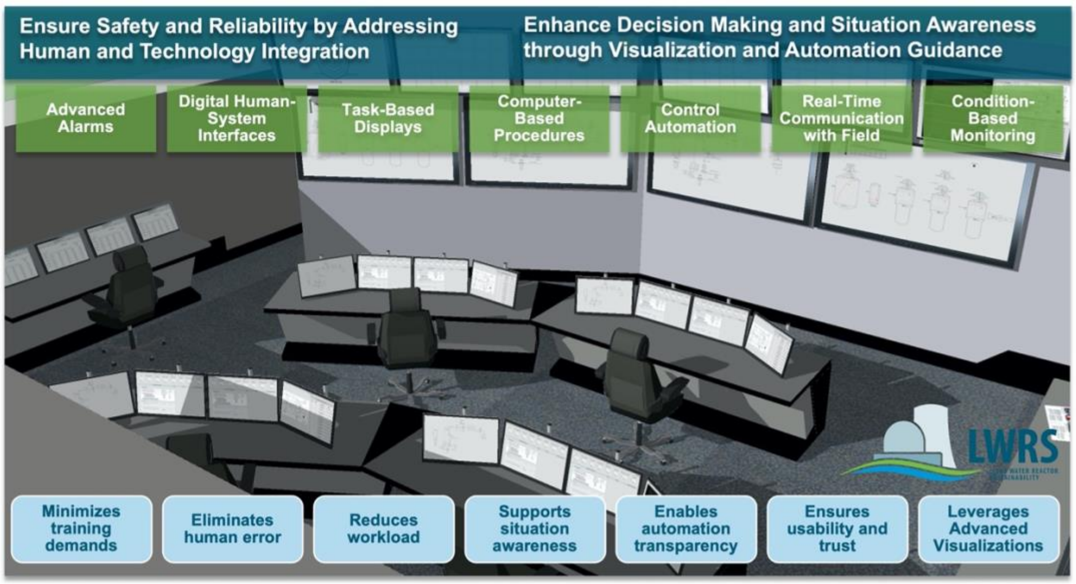


Figure 1. Concept advanced new state that address human and technology integration challenges.

This research leverages previous LWRS Program and industry results. It draws specifically on previous LWRS Program research in the areas of advanced alarm systems, computer-based procedures, model-informed decision support, and advanced HSI displays (e.g., overviews and task-based). Researchers evaluated the integration of these capabilities into an advanced control room concept. They developed a modernization methodology that supports the safe, reliable adoption of advanced automation and ultimately leads to a transformative yet achievable end state. The modernization methodology can be used to guide transformative thinking when integrating a set of vendor-specific capabilities to support a new concept of operations and a utility's end-state vision. The results of this research are organized into five major sections:

– Section 2 describes the challenges that the nuclear industry is enduring with modernizing.

– Section 3 summarizes the primary standards and guidance supporting digital modifications.

– Section 4 presents earlier work from the LWRS Program regarding the development of a transformative conceptual design for an advanced control room of a hybrid NPP.

– Drawing on earlier sections, Section 5 presents a methodology that is designed to address the challenges in the industry today in achieving a transformative new-state vision and concept of operations.

– Conclusions and next steps of this research are provided in Section 6.

2. A NEED TO TRANSFORM THE NPP OPERATING MODEL

One of the greatest challenges faced by the U.S. nuclear industry is looking beyond like-for-like instrumentation and control (I&C) technologies to develop an integrative strategy that leverages technology to reduce operating costs by changing the way work is done. A notable barrier has been the lack of a clear and strategic new-state vision that is transformative yet achievable, that either eliminates labor-intensive activities altogether or significantly improves their efficiencies while minimizing technical and regulatory risk (Lybeck, Thomas, and Primer 2020). For instance, in a U.S. DOE-sponsored nuclear innovation workshop held in June of 2019 (Kovesdi et al. 2019), industry leaders commented that the industry needs both a short-term and long-term roadmap in reaching a transformative new-state vision. The roadmap for a new-state vision must also fundamentally look at new ways in which work is performed at the plant by holistically considering the impact of change to the people, processes, technology, and governance in place (Thomas et al. 2020). The new-state vision must enable the industry to transition from a labor-centric to a technology-centric operating model where existing work practices and associated requirements are critically examined by their fundamental purpose in serving the plant; understanding the implications of why certain plant functions exist is pertinent in removing unneeded processes and using technology that can drastically enhance plant efficiencies where there are opportunities.

Without a license renewal, much of the existing U.S. NPP fleet is approaching the end of their licensed operating lifespan (Joe and Remer 2019). These plants' existing infrastructures have been largely left unchanged, comprised of mostly analog technology that requires a labor-centric approach to operate, maintain, and support these plants (Center 2020). Historically, the nuclear industry has been reluctant to modernize due to a risk-adverse culture and lack of clarity for a transformative new-state vision (Joe and Remer 2019; Thomas et al. 2020). Common contributors to these barriers include (1) the perceived value and return on investment (ROI) of digital technology, (2) the perceived risk associated with licensing, regulatory, and cybersecurity, and (3) insufficient guidance for performing digital modifications to power generation systems (i.e., as opposed to safety systems).

2.1 (Barrier 1) Perceived Value and Return on Investment of Digital Technology

One challenge for utilities has been developing a clear business case regarding the actual cost reductions seen with advanced technology (Thomas and Hunton 2019). Without a specific business case that justifies the ROI when implementing advanced technology, the value of a new technology cannot be fully realized. Hence, the added costs associated with implementation compounds with any misalignment of perceived value or ROI related to the potential benefits that the technology has on the plant and overall organization.

2.2 (Barrier 2) Perceived Risk: Licensing, Regulatory, and Cybersecurity

Perceived risk associated with licensing and regulatory considerations pose another challenge to modernizing. The U.S. nuclear industry has two primary paths for regulatory acceptance of digital upgrades: the License Amendment Request (LAR) and the 10 Code of Federal Regulation (CFR) 50.59 process (Electric Power Research Institute [EPRI] 3002004310 2015). While a detailed description of the distinction between these two paths is beyond the scope of this work, it is important to note that the latter process bounds any modification to the existing plant's design and licensing basis (hence, not requiring an LAR). While modifications made to non-safety systems of the plant may follow 10 CFR 50.59, major plant changes with an added scope for modifications made to safety systems would require an LAR.

There have been challenges from a licensing and regulatory standpoint in both paths. The U.S. nuclear industry's perception of performing upgrades via LAR has generally been less desirable in part due to the perceived project risks that result in unforeseen cost and schedule creep (EPRI 3002011816 2018). Likewise, utilities who follow the 10 CFR 50.59 path are often faced with their own challenges such as with responding to the associated screening and evaluation questions that require specific expertise like in human factors engineering (HFE).

There are also perceived risks associated with cybersecurity for digital upgrades. Digital technology can enable the distribution of data from non-safety and safety systems across the plant, which can create new capabilities that support overall plant-wide decision-making. However, a pitfall of this very advantage is the added risk of cyberthreats (Thomas et al. 2020). While cybersecurity is a known barrier in the industry and there are ongoing efforts to minimize the risks, an important consideration pertains to understanding the impact of perceived cybersecurity risk on technology acceptance.

2.3 (Barrier 3) Insufficient Guidance for Digital Modifications to Power Generation Systems

A final barrier that has been identified by industry[1] is that much of the guidance available in support of digital modifications have been focused on safety systems and that there has been little focus on adequate guidance for power generation systems within the public domain. As such, it is unclear whether the current guidance will support substantial modifications to power generation systems. For example, much of the guidance described next focuses on identifying critical actions that are important to safety. Functional decompositions are well-known from the safety side of the plant, but there is no formal functional decomposition of the plant for the power generation side in the public domain. While the methods applied to safety systems can likely be leveraged to support guidance for power generation, the implementation of these key activities is difficult to attain for the industry at large.

3. RELEVANT STANDARDS AND GUIDANCE

Notable standards and guidance documents that are important to developing a new-state vision are characterized as being either systems-level or domain-specific guidance. Systems-level guidance that provides best practices in systems engineering (SE) are first summarized. Next, domain-specific guidance in HFE is summarized, which focuses on the sociotechnical factors in developing a new-state vision.

3.1 Systems-Level Guidance

SE is interdisciplinary in nature and focuses on both technical and managerial aspects of developing, integrating, and managing a system throughout its lifespan. SE provides a holistic view of the problem space by accounting for multiple technical perspectives (EPRI 3002011816 2018). SE also focuses on providing a solution that is grounded in the needs of the stakeholders. Requirements are generated, prioritized, and tracked so that the solution is purposely built and managed throughout its life. These qualities of SE make it valuable to the application of developing a new-state vision for NPPs, particularly when significant changes must be made to not only the underlying technology but also the overarching operating philosophy (i.e., concept of operations) of these plants. Notable standards and guidance documents specific to SE are summarized next.

3.1.1 ISO/IEC/IEEE 15288: Systems and Software Engineering - System Lifecycle Processes

ISO/ IEC/IEEE 15288 provides a common SE framework for describing the lifecycle of developed systems (ISO/IEC/IEEE 15288 2015). This standard describes key activities to perform throughout the lifecycle of a system, grouped by four central categories: agreement processes, organizational processes, management processes, and technical processes. Collectively, ISO/IEC/IEEE 15288 is one of the core standards that provides a technical basis for the development of nuclear-specific SE guidance documents.

[1] In collaboration with Dominion Energy, a primary challenge for the industry has been related to incomplete guidance on performing digital modifications for power generation systems.

3.1.2 ISO/IEC/IEEE 15289: Systems and Software Engineering - Content of Lifecycle Information Items (Documentation)

International Standard ISO/IEC/IEEE 15289 provides requirements for users of common SE approaches like ISO/IEC/IEEE 15288 in developing and revising the documentation that is part of the development, integration, and management of systems (ISO/IEC/IEEE 15289 2017). Like ISO/IEC/IEEE 15288, the standard provides a technical basis in nuclear-specific SE guidance documents, focusing on the aspects of required documentation across the system lifecycle.

3.1.3 EPRI 3002011816: Digital Engineering Guide

The EPRI Digital Engineering Guide (DEG) (EPRI 3002011816 2018) provides nuclear-specific guidance in applying SE to support the installation of new and modified I&C technologies for NPPs. EPRI 3002011816, also known as the DEG, was developed by integrating and adapting the relevant guidance from ISO/IEC/IEEE 15288 and ISO/IEC/IEEE 15289 to the specific SE considerations of NPP modernization. The DEG adds to other guidance by including a risk-informed grading approach to support an adequate and efficient completion of key engineering activities at NPPs. Moreover, specific guidance across relevant technical domains (e.g., HFE, I&C, and cybersecurity) is provided and described within the context of the specific SE phases. That is, for each individual technical domain within the SE umbrella, the DEG provides guidance on the associated activities performed at specific phases of the system lifecycle, including initial scoping, conceptual design, detailed design, planning, installation and testing, closeout, and operations and maintenance (O&M). Figure 2 summarizes the key technical domain covered. The figure shows two import characteristics. First, a graded approach is taken when applying DEG guidance to a project. The grading ensures that the right level of rigor is applied to the activities, based on applicability, technology configurability, and consequence of error. Second, the SE box intersects all technical domains. Key SE activities require an interdisciplinary approach and the guidance in the DEG highlight where relevant domains are required for effective decision-making.

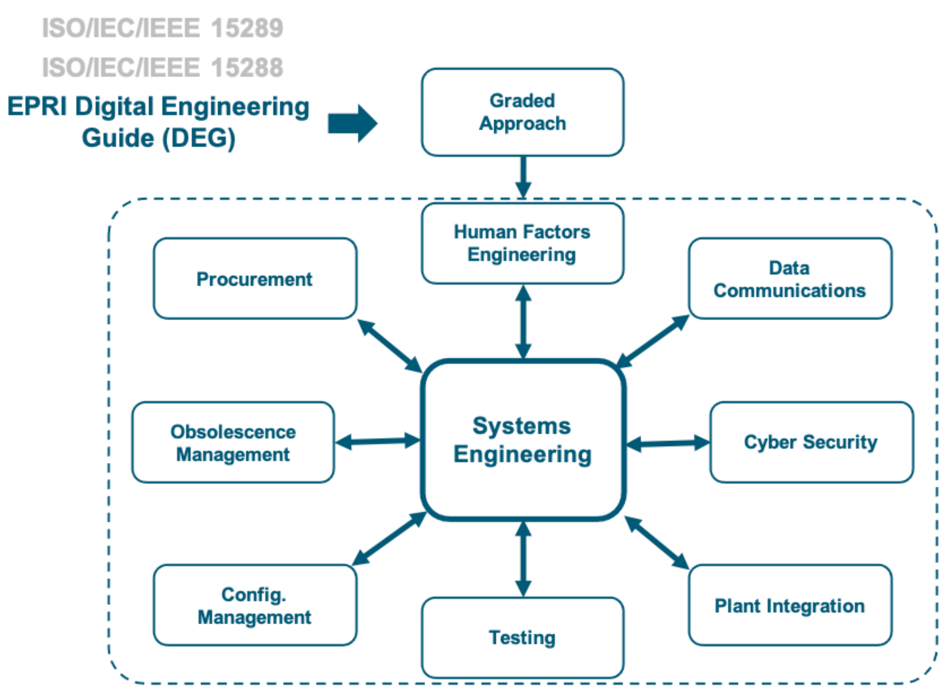


Figure 2. Primary domains covered in the DEG (EPRI 3002011816 2018).

With developing a new-state vision, the activities described across domains for initial scoping are particularly relevant in characterizing the problems that the new state intends to resolve, by identifying the systems of interest and stakeholder needs, as well as creating a migration strategy. The DEG highlights the importance of HFE within SE early in the initial scoping phase to address potential impacts that the envisioned technology may have on task requirements for operations and maintenance activities.

3.2 Human Factors Guidance

Within SE, HFE is a key domain in addressing the sociotechnical considerations of developing a transformative new-state vision. By applying scientific knowledge on human performance and its implications on system design, HFE provides technical bases to important design decisions presented at different points throughout the NPP modernization process (EPRI 3002004310 2015; Kovesdi et al. 2019). Early HFE involvement can guide the configuration of enabling technologies and capabilities that are necessary in making significant changes to the concept of operations. HFE focuses on understanding the implications of the new technology on its impact to staffing levels and roles, business goals and changes to the work domain, changes in information and task requirements, and changes in procedure design and training programs. The nuclear industry has several HFE design and process standards and guidelines available to support NPP modernization. These standards and guidelines described next are important inputs into the new-state vision definition methodology.

3.2.1 NUREG-0700: Human-System Interface Design Review Guidelines

The U.S. Nuclear Regulatory Commission (NRC) Human-System Interface Design Review Guidelines (NUREG-0700 2020) provides a comprehensive list of detailed design guidelines to support NRC staff reviews of HFE aspects of NPPs in accordance with U.S. NRC NUREG-0800 Chapter 18 (Standard Review Plan - Human Factors Engineering) (NUREG-0800 2012). This detailed guidance can also be used by utilities in design activities at conceptual and detailed design stages, such as when developing a HSI style guide. NUREG-0700 (2020) has recently been updated to Revision 3 that notably accounts for emerging technologies like digital HSIs, overview displays (i.e., group-view displays), automation (i.e., displays for automation, computerized operator support systems, and adaptive automation), and computer-based procedures for main control rooms. There are 14 total sections divided into four parts. A summary of the content in NUREG-0700 is highlighted below in Figure 3.

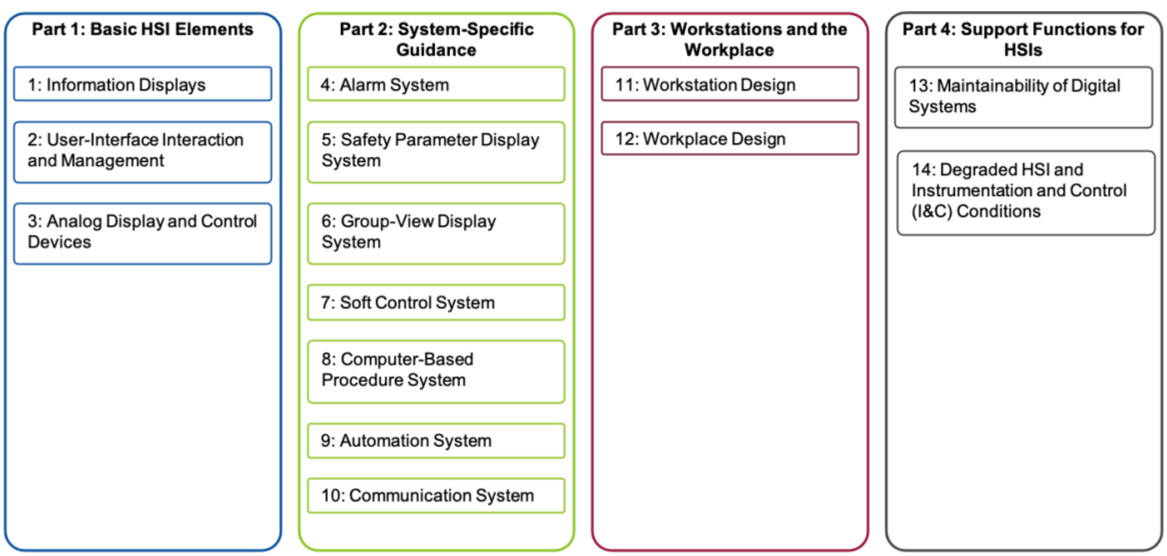


Figure 3. Primary sections of U.S. NRC NUREG-0700 Revision 3 (2020).

Basic HSI design elements are included in Part 1; design guidance for information displays, user-interface interaction and management, and analog display and control devices are comprised in this part. Regardless of system type, Part 1 guidance can apply universally where applicable. For example, guidance for recommended font size can be universally applied to HSI design regardless of its specific application use. The technical basis is specifically the legibility considerations for people. Part 2 entails specific guidance for six types of digital systems: the alarm system, the safety parameter display system, the group-view display system, the soft control system, the computer-based procedure system, automation system (i.e., including control and decision automation), and the communication system. Part 3 is specific to workstation and workplace designs, which focuses primarily on the anthropometric considerations of the environment. Finally, Part 4 pertains to design guidance for maintaining digital systems, as well as managing degradations in I&C and HSIs. Collectively, there are over 2,000 guidelines across these sections and parts.

3.2.2 NUREG-0711: HFE Program Review Model

The U.S. NRC HFE Program Review Model (NUREG-0711 2012) provides detailed process guidance to support the NRC staff in their reviews of HFE programs for the applications of construction permits, operating licenses, standard design certifications, combined operating licensing, and license amendments. NUREG-0711 is applicable for HFE of new NPPs, existing NPPs that are undergoing major modifications (e.g., to the main control room), and modifications that impact risk-important human actions (HAs). NUREG-0711 is structured around four general phases: planning and analysis, design, verification and validation (V&V), and implementation and operation. These phases map to the phases described in common SE frameworks like the DEG (EPRI 3002011816 2018). Twelve HFE activities are described in NUREG-0711 around these four phases (Figure 4).

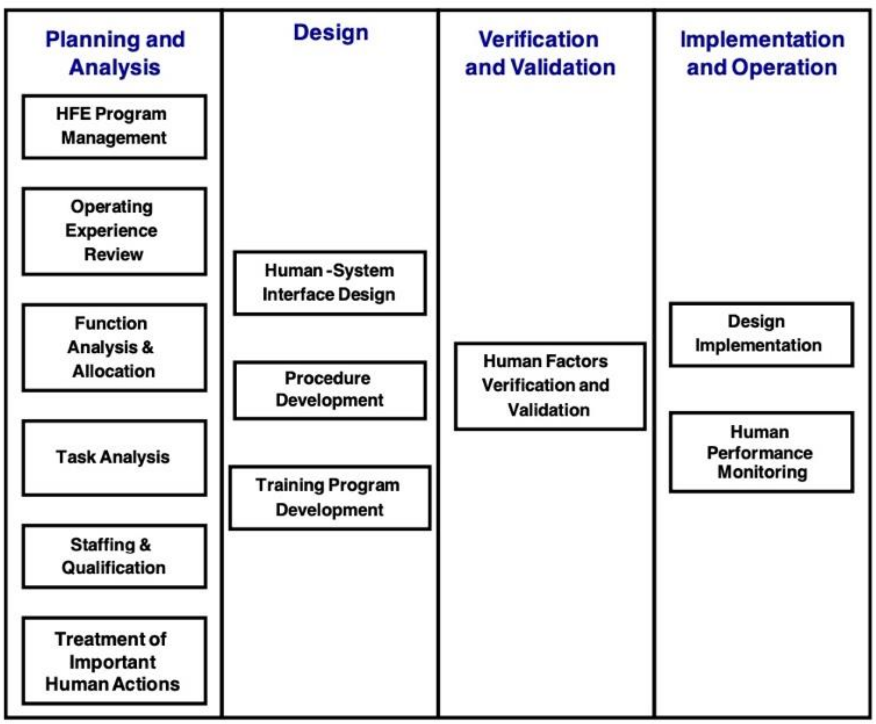


Figure 4. HFE phases and elements in NUREG-0711 (2012).

Within planning and analysis, NUREG-0711 provides review guidance on HFE program management; operating experience review (OER); function, analysis, and allocation (FA&A); task analysis; staffing and qualification; and the treatment of important HAs. Within the design phase, key HFE activities include HSI design, procedure development, and training program development. In V&V, guidance is provided around performing activities including HFE design and task support verification as well as integrated system validation. Finally, NUREG-0711 includes specific review guidance on the HFE aspects in implementation and operations related to design implementation and human performance monitoring. While the guidance in NUREG-0711 is intended to support regulatory review, it has been used to support utilities in performing modifications. To this end, there are notable utility-focused guidance that align with NUREG-0711, such as EPRI 3002004310, described next.

3.2.3 EPRI 3002004310: Human Factors Guidance for Control Room and Digital HSI Design and Modification

EPRI published "Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification" (EPRI 3002004310 2015) in support of providing comprehensive guidance in performing HFE activities that support control room modifications and meet regulatory guidance and expectations. EPRI 3002004310 provides both process and design guidance for the utility to follow that supports performing major modifications, such as in the main control room. The guidance document offers guidance using a graded approach for each of the 12 elements described in NUREG-0711 and provides specific methods that can be done to satisfy the requirements at each grading. EPRI 3002004310 is referenced as a core resource for performing HFE where it applies in the larger SE framework described in the DEG (EPRI 3002011816 2018). Notably, EPRI 3002004310 provides guidance on developing an endpoint (i.e., herein referred to as the *new state*) vision. EPRI 3002004310 describes core activities that are important for defining the new state and provide usable worksheets that are foundational to this work.

3.2.4 IEEE 1023: Recommended Practice for the Application of HFE to Systems, Equipment, and Facilities of Nuclear Power Generating Station and Other Nuclear Facilities

The IEEE "Recommended Practice for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Station and Other Nuclear Facilities" (IEEE 1023 2020) is a consensus standard that provides recommended practices for applying HFE to NPP systems and equipment with significant HSIs. IEEE 1023 suggests that HFE is integral across the lifecycle of a system and is critical in the earliest phases. It outlines the basic considerations that HFE should address, including the tasks, work environment, equipment, personnel, and organization. The standard offers a process model akin to NUREG-0711's phased approach, which includes the application of HFE across planning, analysis, specification (design), testing and evaluation, and operations and maintenance. These phases also align with common SE frameworks. IEEE 1023 also provides planning and scoping tools for applying HFE in its annex. One such tool, the screening checklist, provides a way to determine if a proposed project requires little or extensive HFE involvement; this tool can be used to initiate HFE effort scoping by quickly determining the level of involvement based on the impact to the tasks, work environment, equipment, personnel, and organization. Finally, IEEE 1023 provides a normative list of references that are integral to its use. Some of these that are referenced in this report later include:

- IEEE 845 (2011), "IEEE Guide for the Evaluation of Human-System Performance in Nuclear Power Generating Stations."
- IEEE 1082 (2017), "IEEE Guide for Incorporating Human Action Reliability Analysis for Nuclear Power Generating Stations."

3.2.5 IAEA No. NR-T-2.12: Human Factors Engineering Aspects of Instrumentation and Control System Design

The International Atomic Energy Agency (IAEA)'s role is to accelerate and broaden the use of nuclear energy to "peace, health, and prosperity" across the world (2021). IAEA No. NR-T-2.12 provides HFE guidance to address proposed I&C systems, components, and replacement HSIs for new build and modifications to NPPs. The guidance broadly covers the general areas of a typical I&C project, including end point (new state) vision and planning, design basis, HFE analyses, HSI design, HFE in procurement, and HFE V&V, implementation, and operation. Importantly, IAEA No. NR-T-2.12 emphasizes a strong need for HFE to integrate within I&C early and throughout the lifecycle of the project, ranging from defining the vision, performing analyses and design, procuring commercial-off-the-shelf (COTS) technologies, and performing V&V, implementation, and monitoring activities. The guidance largely follows what is in NUREG-0711 but adds guidance around developing a new state and applying HFE in procurement processes. For defining the vision, the guidance suggests that both *HSI design concepts* and a *concept of operations* should be defined and include scoping information, such as having a:

- High-level statement of the objective
- Definition of key stakeholders
- Definition of key interfaces, such as equipment, staff, and team (i.e., division of responsibility)
- High-level definition of possible solutions and (if available) a procurement strategy.

Combined, the design concepts and concept of operations answers *where* the HSIs and components will reside, *which* are the known components in scope, *who* the intended users for each HSI are for, *when* will the HSIs be operated (i.e., determine plant states), *what* the main functions are, *how* the HSIs and components are expected to be used in the environment, and *why* specific decisions were made per technical bases.

3.3 Existing Human Factors and Related Guidance from the LWRS Program

The U.S. DOE LWRS Program Plant Modernization Pathway has developed numerous resources that provide technical guidance for the modernization of NPPs. The following documents are some of these resources previously published by the LWRS Program that are of relevance to this report.

3.3.1 INL/EXT-18-44798: Control Room Modernization End-State Design Philosophy

The purpose of this effort was to develop a general design philosophy to inform control room end-state modernization designs from a technical basis. Control room upgrades are rarely an all-or-nothing undertaking. While it may be viable for one nuclear utility in a regulated market to complete a full-scale digital upgrade, the cost, expertise, and time required for such an upgrade is significant. Consequently, nuclear utilities generally upgrade in phases (i.e. piecemeal approach). The intent of an end-state design philosophy is to determine what a plant should resemble upon completing modernization upgrades. After the end goal is established, phases are identified to divide the work into manageable portions.

Although there are significant challenges in undertaking control room modernization, there are also significant opportunities to enhance the efficiency and reliability by carefully designing the upgraded systems to support operators and to include advanced features, such as diagnostic support, advanced human-system interface designs, and decision support tools. This work provides design guidance on how to realize those opportunities by designing control room HSIs with these advanced capabilities in mind. Furthermore, this work sought to ensure that control room modernizations are undertaken with a sound understanding of the impacts to human operators and are designed based on state-of-the-art human factors principles.

This research was conducted in close collaboration with a utility partner, Palo Verde, undergoing a phased modernization approach. The first phase of the project was updating a local control room for the liquid radiological waste system (i.e., see INL/EXT-18-51107 2018), and additional phases will result in modernizing the majority of the main control room equipment. The purpose of this research was to provide an industry-wide approach and road map for effective modernization that not only addresses obsolescence but provides guidance for enhancing the economic viability of the existing fleet by improving efficiency and safety through an effective design of the control room, incorporating human factors principles across the entire design. The approach addresses human factors throughout the entire upgrade process by first identifying a realistic and desirable end-state concept for the control room layout, then identifying how to ensure consistency throughout the upgrade process with an overarching design philosophy, and finally by providing guidance on how to enhance the effectiveness of upgraded HSIs. This was done by considering the end state throughout the life of the phased upgrade project and incorporating an integrated approach to HSI design in each system upgrade, regardless of the individual components being upgraded. Previous work had defined an end-state vision for the control room layout, which identified which component would be removed in each phase of the upgrade and where new digital displays will be located on the control boards. This effort continued that work by defining how the information on the digital displays should be presented.

In summary, the purpose of this effort was to provide an initial description of an overarching design philosophy that could serve as high-level guidance for identifying the functional and design characteristics of human-system interfaces that are included as part of control room upgrades. This effort provided background on existing guidance, industry best practice, and focused research where it was available. LWRS Program researchers intended to document the design philosophy to provide a consistent approach to designing HSIs as part of control room modernization and update it as new findings emerged. INL/EXT-18-44798 (2018) provides the basis for subsequent R&D undergone by the LWRS Program described next.

3.3.2 INL/EXT-18-51107: Development and Evaluation of the Conceptual Design for a Liquid Radiological Waste System in an Advanced Hybrid Control Room

This work summarized R&D undergone in collaboration with Arizona Public Services (Palo Verde Nuclear Generating Station) to address human factors in the modernization of their radiological waste control room. Palo Verde Nuclear Generating Station planned to modernize their liquid radiological waste system through full digitalization, including removing all control boards associated with the liquid radiological waste system and associated controls, indicators, and alarm systems, and replacing them with modernized digital instrumentation and controls and displays. To be sure the new system either supported current operational performance or enhanced it, researchers carried out four planning and analysis activities: OER, function allocation analysis, task analysis, and HSI design using human factors design principles and design applications.

Researchers utilized access to domain experts (operators) to elicit knowledge of the system. Operators performed talk-through analyses and operational sequence diagrams (OSDs; see Section 5.2.2.3) to develop information and task requirements, as well as identify current pain points in the existing system to serve as design input for the new digital upgrades; HAs that were identified to be automated were evaluated in these activities. Later in HSI design, prototypes, tests, and evaluations were conducted (Section 5.3) to collect additional feedback that informed design requirements and addressed key tradeoff considerations, such as the application of color. The prototype design incorporated well-known human factors principles (such as those described in NUREG-0700 [2020] and INL/EXT-18-44798 [2018]). Guideline verification was also conducted using analytical tools that evaluated considerations such as legibility, readability, and usability. An ergonomic assessment was also performed on the workspace, resulting in various recommendations for placing and designing the new workstation. A three-dimensional (3D) model (Section 5.6.6.1) of the control room was created to depict the options available with in-depth descriptions of each. This work served as a major step towards performing digital modifications and served as one of the major inputs into developing an HFE design philosophy (Section 5.1.4.1).

3.3.3 INL/EXT-18-45149: Connecting LWRS Human Factors Engineering R&D to NUREG-0711 Elements and Modification Activities in Nuclear Power Plants

This report describes work done by LWRS Program researchers prior to May 2018 using HFE R&D, industry guidance, standards, and regulations (most notably, NUREG-0711 2012) to assist in the modernizing and modifying of NPP I&C systems. Following a brief overview of the history and purpose of HFE in nuclear, the identification of the HFE regulatory drivers [10 CFR 50.34(f)(2)(ii & iii) and 10 CFR 52.47(a)(8)], the majority of this report focuses on LWRS Program HFE activities and examples.

The NPP's main control room (MCR) is one focus area, including the modernization of I&C systems and the related modifications of human-system interfaces (Figure 5). Figure 5 showcases the need for a well-thought-out implementation plan to ensure that earlier installed improvements in the plant's design are not undone throughout the process. HFE activities, and the resulting technical reports, are also necessary for developing effective aging management programs. Technical reports are essential documentation of observations, findings, and deviations from recognized HFE standards or applicable regulations, including recommendations. These technical reports generally address three of the 12 HFE elements identified in NUREG-0711: HSI Design, Human Factors V&V, and Human Performance Monitoring. Additionally, NUREG-0711 results summary reports provide the basis for HFE technical reports provided to utilities, resulting in a documented technical basis for each recommendation. This report also outlines how HFE technical reports may be used by plants throughout the screening and evaluation process of 10 CFR 50.59, which the LWRS HFE staff contribute to by providing subject matter expertise throughout the process.

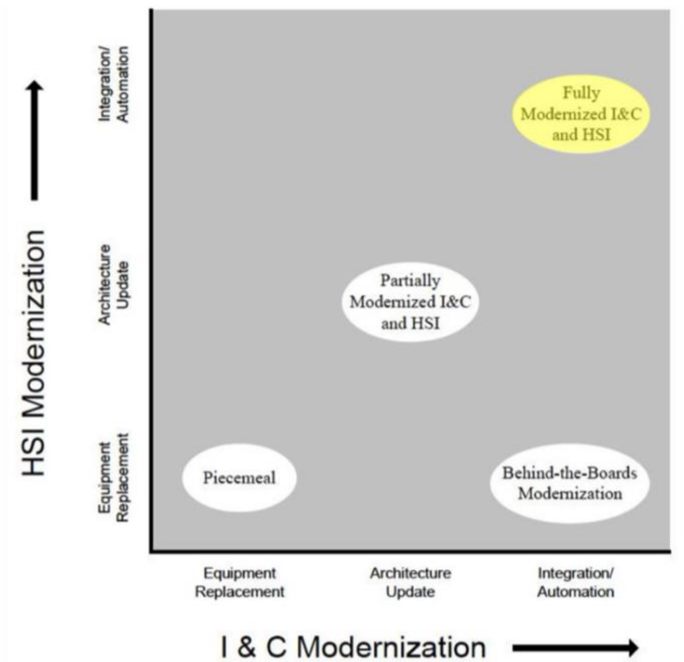


Figure 5. Control room modernization strategies (adapted and enhanced from INL/EXT-18-45149 2018).

The most in-depth example of HFE activities provided in this report is the work done with Exelon at the Byron and Braidwood plants, wherein researchers conducted studies of the modified control room HSI, identifying potential human engineering discrepancies (HEDs) and determining whether the HSI satisfied HFE guidelines and supported an improved operator performance. This resulted in several limited distributed result summary reports that identified scenarios in collaboration with operations and training, as well as documenting the results of human-system performance for operator-in-the-loop studies that collected completion times, workload, SA, and HSI usability. Additionally, work done with the Palo Verde Nuclear Generating Station, with Duke Energy at their Brunswick, Robinson, and Harris plants, and with Southern Nuclear Company to support the upgrades of their General Electric Mark II TCS to the Mark VI-e TCS for Vogtle Units 1 and 2. Overall, these examples serve to demonstrate how HFE activities done in collaboration with utilities to ensure modification and modernization are done in an effective and efficient manner, supporting NRC's safety mission to protect both people and the environment.

3.3.4 INL/EXT-18-51212: Developing a Human Factors Engineering Program Plan and End State Vision to Support Full Nuclear Power Plant Modernization

INL/EXT-18-51212 (2018) first provides guidance for the development and evaluation of an HFE program and an end-state vision for plant modernization, while also presenting best practices and lessons learned related to HFE programs. The HFE program is the key document for a modernization project. The objective of an HFE program is to help ensure that modernization efforts affecting MCRs, related facilities, and HSIs meet both regulatory requirements and HFE guidelines, ensuring safe operation and meeting human-system performance expectations as modifications are made. An HFE program should provide guidance to the design team such that the HFE program is properly developed, executed, and documented. A graded approach should be used in preparing an HFE program. Only systems or equipment that involve HAs and performance should be included, and previous HFE programs and other documents should be used to reduce the effort of preparing the HFE program, if possible. Section 2 of NUREG-0711 (2012) provides guidance in preparing an HFE plan; although, it is only in relation to reviewing safety concerns. Other documents, such as those developed by Idaho National Laboratory (INL) (Boring et al. 2015) and Sections 2.5.3.5 and 3.2.3 of EPRI 3002004310 (2015; Section 3.2.3), provide guidance for developing an HFE program considering both safety and plant availability, power production, and economic operation issues. An end state (herein referred to as *new state*) vision is included in the HFE program and describes an expectation for the control room at the completion of the modernization process. New-state visions may need to be flexible to allow for changes that can occur due to changes in plant conditions, budgets, priorities, and new technologies. Tools include paper sketches, rapid prototyping, physical mockups, training simulators, virtual reality, and glass-top simulators should be used to create visual representations of new-state visions.

Some best practices or lessons learned not already summarized include that HFE should be involved as early as possible in creating a new-state vision during the modernization process and that HFE should work closely with other stakeholders to develop a common or closely coordinated new-state vision. Vendors and suppliers should also be included in the development of the HFE program. Modification projects can be considered as a progressive evolution from analog systems through a hybrid configuration, and for some plants, eventually full-digital control rooms. Automation and HSI design/placement should also be considered. Evaluations and testing should be done throughout the modernization process, and simulation should be used to help develop qualitative and quantitative evidence to justify HFE recommendations.

This report also summarizes the rational for full-digital I&C integration. Digital I&C integration enables consolidation of multiple I&C functions into a single digital controller, effectively reducing O&M costs. Interconnectivity between multiple digital controllers allows for improved human-system integration through intelligent automation. This leads into the business case methodology for MCR modernization, and the report summarizes how digital I&C systems and other technologies can be employed to improve human performance, reduce errors, and reduce costs. Overall, this report provides guidance to develop an HFE program, including a valid and defensible methodology to establish the business case and cost justify plant modernization activity.

3.3.5 INL/EXT-18-51366: Developing a Strategy for Full Nuclear Plant Modernization

The INL/EXT-18-51366 (Joe, J., and C. Kovesdi. 2018) report largely focuses on the methods, techniques, and tools that can be used to help weigh decisions surrounding the cost of new digital technologies relative to the value or benefit they provide. The report identifies the most significant known barriers or challenges to modernization. These include cost to implement relative to the expected value and benefits, licensing and regulatory processes for digital upgrades, cybersecurity for digital upgrades, insufficient process and operational experience with digital upgrades, and a lack of an end-state vision. There are also additional concerns relating to cost, such as minimizing the number of days an NPP is not generating electricity, which places time constraints on I&C modernization tasks. Additionally, overcoming the inertia of status quo solutions can be difficult, as designing and developing new I&C systems is expensive. Therefore, if a system is available for one application, there is a tendency to market this solution to other applications that may or may not be suitable or ideal for the original system. Improving or modifying these systems can add significant costs, so there can be considerable inertia for maintaining the status quo. In addition to barriers and challenges, the report identified expected benefits to modernization, including reduced O&M costs, reducing in staffing levels, improved plant efficiency, potentially improved plant capacity, consistency among multiple NPP units, reduced outage time, and improved human-system performance.

To identify a digital technology's benefits and costs, assess the strength of each benefit and cost, and determine whether a potential digital technology presents value to the plant, we present tools adapted from the Design for Six Sigma methodology. However, the tools presented in this report are neither exhaustive nor prescribed. A potential set of alternative tools that can be used have been presented in previous LWRS Program reports (e.g., Thomas et al. 2014; Thomas, Lawrie, and Niedermuller 2016; Adolfson, Thomas, and Joe 2017) on the development of a business case methodology for plant modernization activities.

The report first identifies tools associated with identifying a digital technology's benefits and costs, and these are designed to map the benefits of a technology to a plant's requirements, identify areas for improvement in the existing infrastructure, and identify plant issues that can be mitigated through digital improvements. These tools include identifying and considering critical-to-CTx requirements, gap analysis, fishbone (Ishikawa) diagrams, as well as other methods such as interviews, focus groups, and surveys. After identifying costs and benefits, we present tools that can be used to help with prioritization and the weighing of importance, including the nominal group technique (NGT) and Pareto analysis. Finally, this report presents tools meant to aid in the decision-making process, including a force field analysis and the Pugh analysis (decision matrix). By identifying and describing these tools in detail, this report provides more guidance for developing a strategy for full NPP modification.

3.3.6 INL/EXT-20-57862: Development of an Advanced Integrated Operations Concept for Hybrid Control Room

The purpose of this effort was to develop an advanced integrated operations concept for hybrid control rooms that would drastically reduce operations and maintenance costs. The next section (Section 4) describes this concept, Analytics-Decision Support Advanced Procedure Tool (ADAPT), in detail whereas this section focuses on the context leading up to the development.

This research is a part of the LWRS Program Plant Modernization Pathway and is focused on developing a vision and roadmap for the nuclear industry that describes how enabling technology can be strategically implemented to promote business-driven innovation that reduces O&M costs and improves performance. This work fits within the LWRS Program Plant Modernization Pathway's mission through the development of an advanced yet realistic end-state control room concept that demonstrates how the strategic integration of advanced technology can greatly reduce cost. ADAPT utilizes commercial technologies to gather data from the field, control systems, and additional sensors for use in advanced analytics, modeling, and decision support capabilities that streamline O&M functions by transforming the way in which work is done. The selection of these technologies was guided by findings from previous LWRS research that indicated a high economic value with operating and maintaining the plant, which describes the overarching design philosophy, analyses used to inform the design, implementation approach, as well as detailed descriptions of the primary functions and display systems of ADAPT.

After a control room end-state design philosophy was established and tested, the development of the ADAPT concept provided an ample opportunity to strategize how an advanced operations concept might be integrated into a hybrid control room. The ADAPT effort leveraged all the previous design philosophy work (e.g., INL/EXT-18-44798 [2018] and INL/EXT-18-51107 [2018]) and applied state-of-the-art HFE design principles (e.g., NUREG-0700 [2020]) into a single concept utilizing the generic pressurized-water reactor simulator platform. The resulting product of this work entailed a conceptual design of an advanced control room concept, which is used as the technical and foundational basis to the work described here.

3.3.7 INL/EXT-20-59537: Analysis and Planning Framework for Nuclear Plant Transformation

This report focuses on how commercial nuclear power in the U.S has created safe, low cost, carbon-free electricity for decades but is now contending with lower cost electric generation sources (Thomas et al. 2020). The current nuclear business model that served well during its initial lifespan is now creating higher costs due to its reliance on a large skilled labor force. The nuclear power industry has responded to this challenge to modernize plant equipment but has not transformed the business model to fully exploit the capabilities of modern digital technology to help lower production costs and sustainable market viability. Integrated operations (IO), which is a system for integrating people, disciplines, organizations, and work processes by using new information and technologies to foster decision-making. One example of an industry that has implemented IO into its business model successfully is the North Sea oil and gas industry, which faced many of the same issues as the nuclear power industry in the 1990s with high operating costs and product competition. A new framework called Integrated Operations for Nuclear (ION; Section 5.6.1) is being developed in partnership with the LWRS Program and Xcel Energy. This report describes the key principles and methods of IO and how they can be applied to the development of the ION project.

IO has been adopted by several other industrial sectors, such as transportation, communication, mining, and other industries, and has become a discipline in and of itself. The IO concept is based on the availability of using new technology allowing for new work forms and a sharing of information in real time in person or electronically. Operational key concepts of IO that may be transferable to ION development are collaboration, staffing according to activity, campaign-based (block) maintenance and modifications, multi-skilled staff, offsite monitoring by equipment vendors, bring the problem to the experts, collaboration between operators and contractors. By identifying the operational key concepts that can be transferred to the ION effort, the IO method can be developed further to its full potential.

ION processes have been developed through collaboration with Xcel Energy and the LWRS program to create a business case to meet future operational objectives. The steps identified for developing the ION process are setting operational context, identifying capabilities, sub-layering capabilities, identifying work processes, identifying work enablers and work reduction opportunities, configuring capabilities, and ION-derived implementation documents. The capability stack model in Figure 6 was created to show how the PTPG requirements tie into the capability, sub-capability, and work processes to become a transformed operating model.

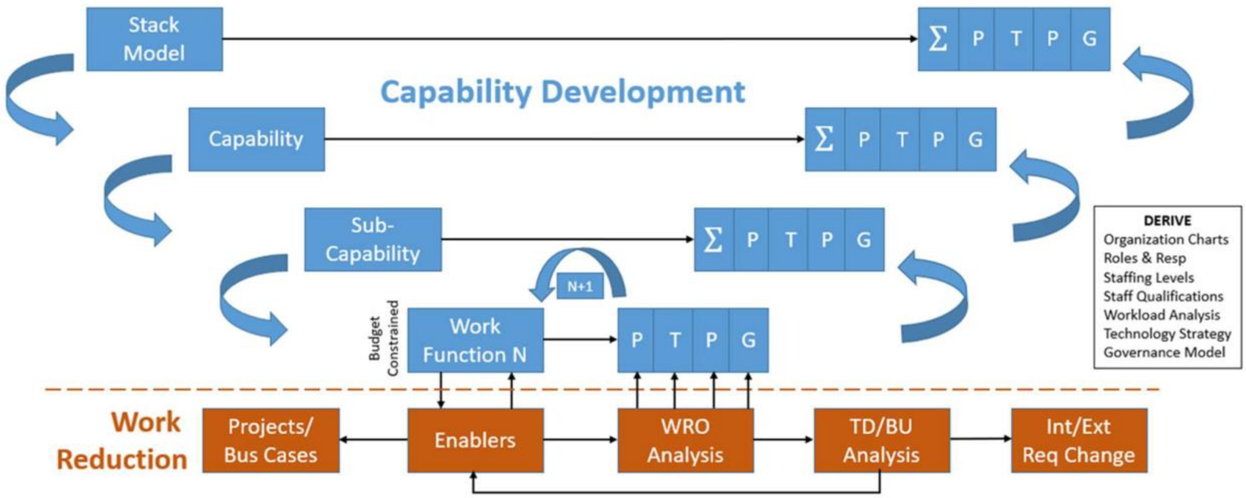


Figure 6. The capability stack model: combined IO and work reduction opportunities (adapted from Thomas et al. 2020).

Analysis tools have been created to support the development of the ION transformation model through computer-based applications. The Integrated Operations Capability Analysis Platform (ICAP) and Innovation Portal have been created to help develop the framework and processes for developing an ION business case for reducing O&M costs in Xcel Energy NPPs. ICAP uses information from the Capability Stack model and helps to develop and analyze NPP work functions and apply innovative concepts. The Innovation Portal is used as a repository for a wide range of information on innovative technologies that can be accessed on its own or applied to work reductions in the ICAP tool. Further research is being completed to fully evaluate IO and capability thinking to determine their applicability to the NPP industry. Sections 5.6.1.1 and 5.6.1.2 describe how ICAP and the Innovation Portal can be used in human-technology integration.

3.3.8 INL/EXT-20-57908: Addressing Human and Organizational Factors in Nuclear Industry Modernization: An Operationally Focused Approach to Process and Methodology

INL/EXT-20-57908 addresses NPP modernization by performing a digital transformation involving the design of an integrated set of systems that together enable a technology-centric operating plant (Dainoff et al. 2020). The model for this transformation is an advanced concept of operations to design the digital infrastructure of an NPP to enable a technology-centric operating model. The digital transformation process needs to involve technology considerations and systems engineering but should involve human and organizational expertise. Therefore, it is critical that there is harmonization among technological, organizational, and other enablers. An NPP modernization strategy action plan was developed to represent a “Technology-Centric Operating Model” as shown in Figure 7 (Thomas and Hunton 2019; Dainoff et al. 2020). This model is used to represent a utility company perception of their concepts of operations of the modernization process by representing a top-down and bottom-up process through mapping strategic objectives onto individual work functions. Utilities will be somewhere between the top and bottom of Figure 7 in their strategic approach during modernization activities.

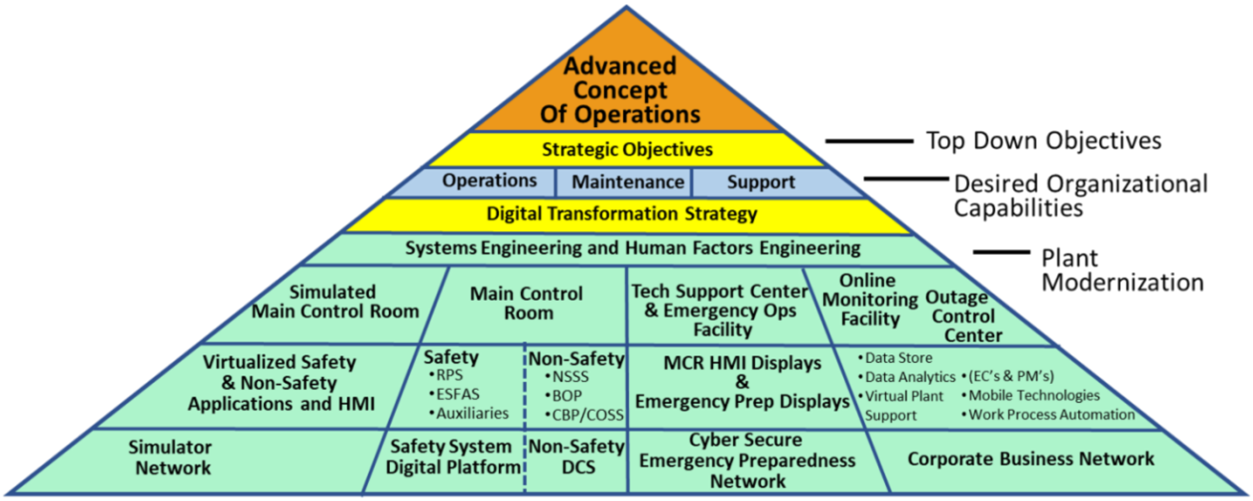


Figure 7. Technology-centric plant operations model (adapted from Thomas and Hunton 2019 in Dainoff et al. 2020).

Objectives of this report focus on the human and organizational issues required to achieve the necessary integration across multiple levels of system development and operation. We completed literature reviews on a broad area of sociotechnical systems, tools, and methods that are applicable to the NPP modernization (Dainoff et al. 2020). HFE guidance on use of Cognitive Work Analysis (CWA; Section 5.6.2), System-Theoretic Accident Model and Processes (STAMP), and System Theoretic Process Analysis (STPA; Section 5.6.4), among other sociotechnical and applied methodologies, have been provided to solve real world problems to facilitate and enable coordination. CWA provides a set of modeling tools and conceptual framework to provide a perspective that allows for the development of support tools that makes the underlying system structure and dynamics transparent and allows the operator to make rapid decisions to unforeseen events. STAMP is a system-theoretic-based accident causation model where the emphasis is changed from failure prevention to enforcing behavior. Another part of the STAMP method that is included in the overall framework is the STPA, which is a specific hazard analysis method to identify the safety constraints that must be in place to mitigate hazards.

Additional guidance on knowledge elicitation, knowledge representation, and cross-functional integration can be applied to a set of practical NPP problems. Use of the tools and methods are not meant to be used rigidly but are a means to practical solutions. Many of the methods and tools are meant to be used together to identify practical solutions. By using the methods and tools, a human and organizational framework can be applied to NPP modernization efforts.

3.3.9 INL/EXT-20-60264: Guidance on Including Social, Organizational, and Technical Influences in Nuclear Utility and Plant Modernization Plans

This report provides guidance on applying methods described in INL/EXT-20-57908 to address the sociotechnical issues for current and future modernization efforts (Hettinger et al. 2020). The methods include considerations of factors or staffing, job, and personnel requirements along with the development of enabling technical, management, and procedural support focused on an effective integration of people, technology, processes, and governance (PTPG). Guidance from this report focuses on an analysis of sociotechnical issues in NPP modernization relating to multidisciplinary cross-functional teams, presented in three stages:

– **Understand the Problem.** The first stage in a three-stage analysis for NPP modernization that should be completed is the development and documentation of a shared understanding of the project’s goals, constraints, timelines, and enabling sociotechnical assumptions to identify specific items for analysis.

- **Develop Analysis Approach.** The second stage focuses on the selection of specific procedures and methods to develop a logical plan that is integrated with program plans and milestones. A list of methods is given in this report and addressing human and technology integration evaluation, including cognitive workload, situation awareness, communications, and human error.
- **Conduct Analyses and Translate Findings.** The third stage focuses on translating findings and results into useful forms for prototype and formal designs.

4. REALIZING A TRANSFORMATIVE NEW-STATE VISION

Soon after the end of World War II, politicians, scientists, journalists, and business leaders were eager to focus on peaceful, practical uses for nuclear energy (Walker and Wellock 2010). By the 1950s, they predicted commercial nuclear power would have a critical role in meeting future U.S. energy needs. Winning the “nuclear power race” was framed as the need to maintain the U.S.’s prestige and dominance in science. The Atomic Energy Act of 1954 allowed the development of nuclear energy for peaceful, commercial purposes. By the 1960s, several reactors were in operation, and by the late 1960s, the designs for the plants called for the ability to generate 1,000 megawatts. However, as time passed, the public opposition to nuclear power grew due to concerns over radiation. After the 1973–1974 energy crisis, Congress divided the Atomic Energy Commission, who originally developed and regulated nuclear technology for commercial purposes, into the U.S. Energy and Development Administration and the U.S. NRC. This division of development and regulation avoided the “fox guarding the henhouse” problem.

The main concern of the NRC at the time of its inception was reactor safety. In 1979, a partial meltdown of the core in one of the reactors occurred at Three Mile Island. Very little radiation escaped. But this incident led the NRC to place a greater emphasis on human factors. The NRC created stricter regulation on operator training, testing, and licensing. Moreover, the use of simulators and I&C testing was emphasized as well. The accident at Chernobyl in 1986, which did result in massive amounts of radiation leakage, was another blow to the nuclear industry’s public image. Thus, long before the accident at Fukushima Daiichi (Japan) in 2011, the U.S. nuclear industry has operated under strict regulations with safety in mind. In terms of safety and energy production, the nuclear industry has been extremely successful (Lesser 2019). But the nuclear industry is a conservative—errs on the side of safety—culture. A single accident can be very salient to the public even if fatalities do not occur and can influence the economic future of NPPs. Several plants have closed due to public opposition (Thomas et al. 2020). But public perceptions can be fickle depending on what the public views as the greater threat. More recently, public awareness of the global threat of climate change due to carbon has gained prominence.

Permanent closures of reactor units have primarily been due to political or economic reasons. The business model for the current fleet of reactors was designed with 1960s technology in mind (Lesser, J.A. 2019). Specifically, a large labor force is required to operate, maintain, and support the plant. In contrast, other industries have moved towards a more technology-centric approach, leveraging the advances in digital technology to reduce O&M costs. By incorporating automation, staffing costs and errors can be reduced. The nonphysical aging (i.e., obsolescence) of technology is a critical issue when it comes to I&C (Krivanek 2020). In countries such as the U.S., regulations can make upgrading from analog to completely digital I&C difficult. Krivanek (2020) argues that this particular difficulty could lead to the potential closure of nonprofitable plants due to the inability to maintain the obsolete technology. Indeed, the nuclear industry is at an inflection point in which it must adapt to remain economically viable (Walker and Wellock 2010; Lesser, J.A. 2019; Thomas et al. 2020).

The purpose of this work is to describe an advanced decision support tool that conceptualizes the NPP control room of the future and leverages automation. Thus, a description detailing how automation has been incorporated in other industries, as well as the goal of optimizing human-automation collaboration, is described first. Next, this paper explores the challenge of the risk-adverse culture of the nuclear industry that has been practiced since the inception of the atomic era and the problem of the missing modernization roadmap (Walker and Wellock 2010). Additionally, we will discuss a description detailing how HFE is an essential part of the solution to these problems as well as an introduction to the ADAPT concept and its anticipated impact.

4.1 Automation

Automation is a pervading technology in industry. The decreased cost of sensor technologies (i.e., inputs) and increased computing power and software applications (i.e., data analysis and available action responses) drive the increased use of automation. The decreased need for costly human labor and increased use of automation as a safety control incentivize industry to adopt more automation in their products. To be automated is a blanket term for a thing that can perform a constrained task without human intervention (Nof 2009). To perform a task, automation will (Parasuraman, Sheridan, and Wickens 2000):

- acquire information through sensors or inputs
- analyze the information against programmed constraints
- select an action to return the system state to within the programmed constraints
- enact the selected action restarting this continual process.

This process is easy to understand in simple examples. Cruise control in vehicles senses vehicle speed, compares the speed to the pace set by the user, determines how the vehicle speed should be adjusted, then selects and enacts the matching action. All four stages are not required for a function to be automated. For instance, automation could suggest the proper action to maintain speed providing decision support to the driver. The benefits of automation are exemplified here as well. Cruise control takes over an action that is mundane, continuous, and simple, allowing the driver to focus on other hazards on the road. Automation can replace tasks humans used to perform so that their focus can be used more effectively for tasks automation cannot perform. In the cruise control example, the car will maintain its speed better, saving fuel by keeping the engine running more efficiently at a single speed and allowing the human to focus on tasks such as avoiding traffic, route selection, and staying on the road. This is the promise automation has for all systems; greater operating efficiency and offloading tasks from the human to increase their allocation of cognitive resources to more complex tasks (Mosier and Skitka 1996). Automation shifts the role humans play in system control, usually from manual operation to more supervisory tasks. As a supervisor, the human ensures automation is performing properly and intervening when it fails or encounters a situation requiring human attention. The shifting role is seen in popular classifications of automation such as the "levels of automation" framework (Sheridan and Verplank 1978). The paradox of automation is that the more control of the system is allocated to automation, the more difficult it becomes for the human to efficiently and correctly intervene when most needed (Onnasch et al. 2014; Endsley and Kaber 1999).

4.2 Automation in Industry

4.2.1 Automotive

The automotive industry was an early adopter of automation. Though, it was largely on the production side, hidden from public view, using automated manufacturing systems to improve consistency and increase safety. Though other safety issues arose with the use of robotics, the manufacturing output increased. As more automated support systems arrive in the driver's seat, the Society of Automotive Engineers (SAE 2018) released their own level of automation (LOA) framework. The levels are discrete and used to classify different driver technologies. Undeniably, the driver can be interacting with multiple automated agents of different levels at once. It seems that the industry's attempts to minimize the negative human performance effects of increased vehicle automation mostly consist of auditory alarms to reengage human attention.

4.2.2 Aviation

Automation in aviation has increased flight safety immensely (Dehais et al. 2015). Incorporating all levels of automation from warnings to full flight control in autopilot systems, aviation is well-known for the avionics in the cockpit. However, aviation also has well-known failures of automation that lead to emergency situations or crashes. Some attribute these failures of automation to “a failure to design for a coordinated team effort across human and machine agents as one cooperative system” (Sarter and Woods 1997). The failings of the Boeing-737 Max can also be attributed to a failure to account for the interaction between new automation and a poor consideration of the pilots using the automation (Spielman and Le Blanc 2020). These failings have brought about a perspective of automation that includes the human agent as part of the larger system operation.

4.2.3 Power Generation

Fossil fuel and some advanced nuclear power designs are using automation to reduce the personnel required to monitor and diagnose each power generating unit. Historically, one crew is assigned one power generating unit to monitor and maintain safety and operating efficiency. However, by offloading the mundane tasks, a single crew can monitor and maintain multiple units, reducing operations cost. Some fossil plants use a centralized remote monitoring facility for many units. The NuScale Small Modular Reactor concept houses up to 12 units in a single facility and is operated by a single crew. Cases like these show the benefits of automation observed in application.

The opportunity to leverage automation is clear as the nuclear industry in the United States seeks to upgrade their control rooms. The challenge is adding automation that is built off the lessons from other industries. Automation must be designed to incorporate and communicate with the operator. Learning from the automotive industry, it should avoid shifting the operators to a supervisory role only fixing emergent issues. As with the automotive industry, there exists a nuclear-specific taxonomy of automation (O’Hara and Higgins 2010). Learning from the aviation industry, plants must build the automation with consideration for the interaction between new automation and operator’s new roles and concept of operations. A human-centered approach discussed in Billings’ (2018) book “Aviation Automation: the Search for a Human Centered Approach” calls out some high-level guidelines for automation that include:

- Automation systems should be comprehensible.
- Automation should ensure operators are not removed from command role.
- Automation should support SA.
- Automation should never perform or fail silently.
- Management automation should improve system management.
- Designers must assume that operators will become reliant on reliable automation.

These six high-level guidelines inspire creating automation that is clear and understandable to the user. The user knows how to use it and when. When automation fails, the user knows why and may be able to correct it. These ideas are part of a growing research body into automation that promotes positive human-automation collaboration (HAC).

4.3 Human-Automation Collaboration

HAC, an element of human and technology integration, is the concept that human capabilities are augmented by automated functions. Humans are not being replaced by automation. Their roles are shifting as a result but not towards obsolescence and not towards purely supervisory roles. Their new role is integrated with advanced automated capabilities such as decision-making and command roles.

Consider a highly automated vehicle (SAE 2018) that can handle nearly every driving condition. The human operator still selects the destination, but the vehicle may recommend routes with different benefits such as speed, scenery, or safety (e.g. weather conditions). The driver is the only knowledgeable agent capable of this decision for their purpose. Further, the vehicle communicates to the driver when sensors are not receiving the information necessary to perform their function. In that event, the driver assumes that function manually. The conversation and understanding between the driver and the vehicles current capabilities is the basis of human-automation collaboration.

This automated vehicle is almost entirely self-capable. Achieving a similar capability level in a control room requires a suite of sensors and applications with access to all plant data available. Integrating the operator into the immense amount of information is a difficult task. It requires, like the vehicle, a host of automated functionalities at all levels of automation. An HAC taxonomy by Bruni and colleagues (2007Bruni, S., J. J. Marquez, A. Brzezinski, C. Nehme, and Y. Boussemart. 2007) details another framework for understanding HAC. Their approach defines different roles performed in a control situation then breaks those roles down by LOA. Five LOAs for each of three roles is illustrative of the possible complexity of building an integrated human-automation system. They also account for how decisions and actions are communicated between the human and system.

4.4 Barriers to Adoption

The ability for the U.S. nuclear industry to compete in a diverse energy market continues to be the greatest threat to the long-term sustainability of the existing NPP fleet (Kovesdi et al. 2020). Other electricity generating sources, such as natural gas and renewables, have seen decreased operational costs attributed to changes in the energy market, as well as the use of advanced automation. Indeed, the use of advanced automation has demonstrated significant cost reductions in other industries by providing drastic improvements in operation through optimizing the major plant functions and processes that are important for efficient energy production (e.g., White 2005). Conversely, the U.S. nuclear industry has been reluctant in adopting such new capabilities like advanced automation due to the barriers described in Sections 2.1 and 2.2.

4.5 Addressing the Barriers with Human Factors Engineering

The role of HFE is essential in addressing the human-technology integration challenges to develop a transformative new state. The application of HFE early in the planning phases of a digital modification presents many benefits, adding clarity to the new-state vision and roadmap towards reaching it. By applying methods and tools that leverage the scientific knowledge of people's cognitive and physical capabilities, critical design decisions, including selecting technologies, can be made early to inform a new concept of operations when including HFE in these decisions. HFE can apply design principles that help guide the integration of new capabilities by ensuring that important attributes for operating the plant safely and efficiently are included. These HFE principles applied early on can inform the configuration of specific capabilities like advanced alarms, overview displays, procedures, as well as decision support and control automation technologies that ensure efficient and safe operations, enhanced SA, reduced workload, and optimized workplace ergonomics.

The use of HFE testing and evaluation methods like usability tests and operator-in-the-loop studies can verify and validate the implementation of these designs (Boring et al. 2015). Equally important, HFE is grounded in human-centered design approaches (ISO 13407 1999) that focus the system design on meeting the user needs, organization, and use context (i.e., characteristics of the user, tasks, and environment); HFE ensures that the domain knowledge necessary for the system is accounted for in the design to maximize usability and minimize human error traps. HFE methods and frameworks can also be used to characterize the cultural and organizational factors that influence technology adoption. Collectively, the early HFE involvement can help provide a clear new-state vision that is both transformative and achievable. HFE addresses the human-technology integration challenges associated with the barriers to technology adoption by comprehensively considering the PTPG aspects important to a transformative new state. The following section highlights an advanced new-state control room concept that strategically leverages technology like advanced automation to improve operational efficiency and ensure safety. This work serves as a foundation for highlighting how advanced technologies can be configured to holistically transform the NPP operating model from labor-centric to technology-centric.

4.6 Analytics-Decision Support Advanced Procedure Tool

Figure 8. ADAPT concept of an integrated NPP concept (adapted from INL/EXT-20-57862 2020).

ADAPT is an integrated control room operations technology that combines decision support, online monitoring, real-time collaboration with field operations, and plant and data analytics (Kovesdi et al. 2020). The ADAPT concept uses COTS technology, such as sensors for analytics, technology for gathering field data, data modeling, and decision support capabilities, to help transform NPP operations from labor-centric to technology-centric. ADAPT leverages each of the mentioned capabilities and integrates them in a single operator workstation to manage plant operations in a safe and reliable way.

4.6.1 ADAPT Development

Many NPPs in the U.S. are in the process of extending their operational lifespans through license renewals. However, license extensions often reveal the severity of operating with worn down and obsolete equipment. Part of the renewal process includes a strategy to ensure that the infrastructure of the plants can maintain safe and reliable power generation. When equipment must be fixed, but cannot be replaced due to obsolescence, a common strategy is to modernize (Kovesdi et al. 2020). Some NPPs have completed partial or piecemeal digital modifications but lack a comprehensive vision for a complete digital transformation of their facilities. Many plants have attempted integrating a new digital system into an old process, which has caused an increase in costs rather than the original goal of reducing costs.

Previous research from the LWRS Program Plant Modernization Pathway evaluated how enabling technology will create a positive business transformation that will reduce costs and improve performance. ADAPT builds on the framework from the LWRS Program Plant Modernization Pathway by applying the role and value of HFE to an innovation approach by assessing and identifying technologies to help reduce O&M costs while maintaining safety and reliability in NPPs. ADAPT development was driven by a need to reduce O&M costs, streamline communication between the main control room and field workers, integrate plant information, increase the operator’s SA, and reduce the operator’s mental workload.

4.6.2 ADAPT Capabilities

ADAPT combines advanced capabilities for a fully integrated NPP, such as an integrated control room, decision support, online monitoring, and real-time collaboration with field and other operations outside of the control room. The ADAPT concept uses four HSIs to support plant operations all integrated into a single workstation in the main control room (Figure 8). ADAPT is showcased with a variety of HSIs organized in a hierarchal manner and includes a plant overview display system, task overview display system, task-based display system, and secondary task display system. The hierarchy of HSIs was developed intentionally to support operator SA at multiple levels (i.e. plant-level SA and task-level SA). The following sections will discuss how the ADAPT capabilities are used.

4.6.2.1 Plant Overview and Task Overview Display Systems

The plant overview display system provides at-a-glance monitoring for high-level plant information for operator's plant-level SA. Operators use the plant overview display system for normal and abnormal operations. The display is dynamic, and changes based on the real-time plant status. For example, to signal the operator when entering abnormal operations, the overview screen will adjust to present additional information related to the abnormal operations. The task overview display system provides task-specific information for operator's task-level SA. The task overview HSI provides more task-specific detailed information than the plant overview and changes based on the operator's decision to engage with a task. The task overview also provides dynamic monitoring information but is more detailed to the task at hand whereas the plant overview provides high-level plant monitoring information.

4.6.2.2 Task-Based and Secondary Task Display Systems

The task-based display system provides the operator task-relevant indications, computer-based procedure instructions, automatic support, decision support information, and an online monitoring of plant systems. This HSI provides a comprehensive information display and indications needed for the operator to complete tasks and procedures in the control room by guiding the operator through the task. This display is both dynamic and interactive (i.e., the operator can control equipment). Embedded soft controls are included in the procedure when operators must adjust plant parameters while performing tasks in the procedure. The secondary task display system supports operators in providing any additional information that is relevant to the task, such as piping and instrumentation diagrams, detailed valve status, historical trends, and any other information needed to assist safe and reliable operations. The secondary screen allows the operator to customize information based on what is most helpful when performing tasks.

4.6.2.3 Decision Support and Online Monitoring

Decision support and online monitoring are incorporated into the display systems through alerts and warnings signaling the operator to conditions that require attention. Online monitoring uses advanced technology, such as equipment sensors, to alert operations to current plant conditions that may require attention or maintenance. The operator can choose to continue with their current task or address the maintenance as needed. Decision support is incorporated in the task-based display system by alerting the operator to abnormal or emergency situations that require immediate attention and providing information on how to diagnose and resolve the issue; related information shown on the overview displays is highlighted as well in these abnormal or emergency situations. Additionally, decision support automation is incorporated to support performing routine tasks.

4.6.3 Impact of ADAPT

The features of ADAPT, including an integrated control room, decision support, online monitoring, and real-time collaboration with field personnel, were selected with careful consideration based on their potential to reduce costs by transforming staffing levels, improving scheduling, and enhancing communication across the plant. Reducing operations and maintenance costs while by modernizing NPPs creates a transformative business process that will help the nuclear industry remain economically competitive in the energy market while maintaining safety and reliability.

4.7 Final Remarks

With the threat of obsolescence and the rising costs of operation in the U.S. nuclear industry, legacy NPPs have started to modernize. While the nuclear industry is working to catch up to 20th century technology, other industries are busy deploying 21st century technology, namely automation. Automated technologies are on the rise globally, and multiple industries, including aviation and automotive, have enlisted automation to streamline processes and reduce operating costs. Although nuclear is slower to adopt such technologies, advanced concepts such as NuScale's small modular reactor designs have been identified as potential restorative solutions. However, the introduction of new design concepts has identified multiple technical and cultural barriers. Main barriers to adoption include a risk-adverse culture for change and the lack of a clear vision roadmap to modernize. While the importance of technical barriers should not be ignored, each plant likely has unique technical challenges that no singular solution could exclusively solve. In contrast, the cultural barriers present are not only similar across specific plants but are also similar across the entire nuclear industry.

To be clear, both cultural and technical barriers must be addressed to ensure the viability of the legacy nuclear fleet, but until plants are able to develop a clear vision and roadmap to modernize, technical barriers will remain largely unavailing. Conversely, cultural barriers can and should be addressed promptly. The LWRS Program investigated introducing automation into the nuclear industry, which resulted in ADAPT, an integrated control room operations technology that includes decision support, online monitoring, real-time collaboration with field personnel, and plant analytics. Additionally, ADAPT challenges the status quo regarding cultural expectations for automation integration in the nuclear industry. ADAPT is the first step of many to address the risk-adverse culture for change by demonstrating how an integrated and automated control room functions as well as the subsequent benefits to be realized.

5. A PROCESS TO ACHIEVE A TRANSFORMATIVE NEW-STATE VISION

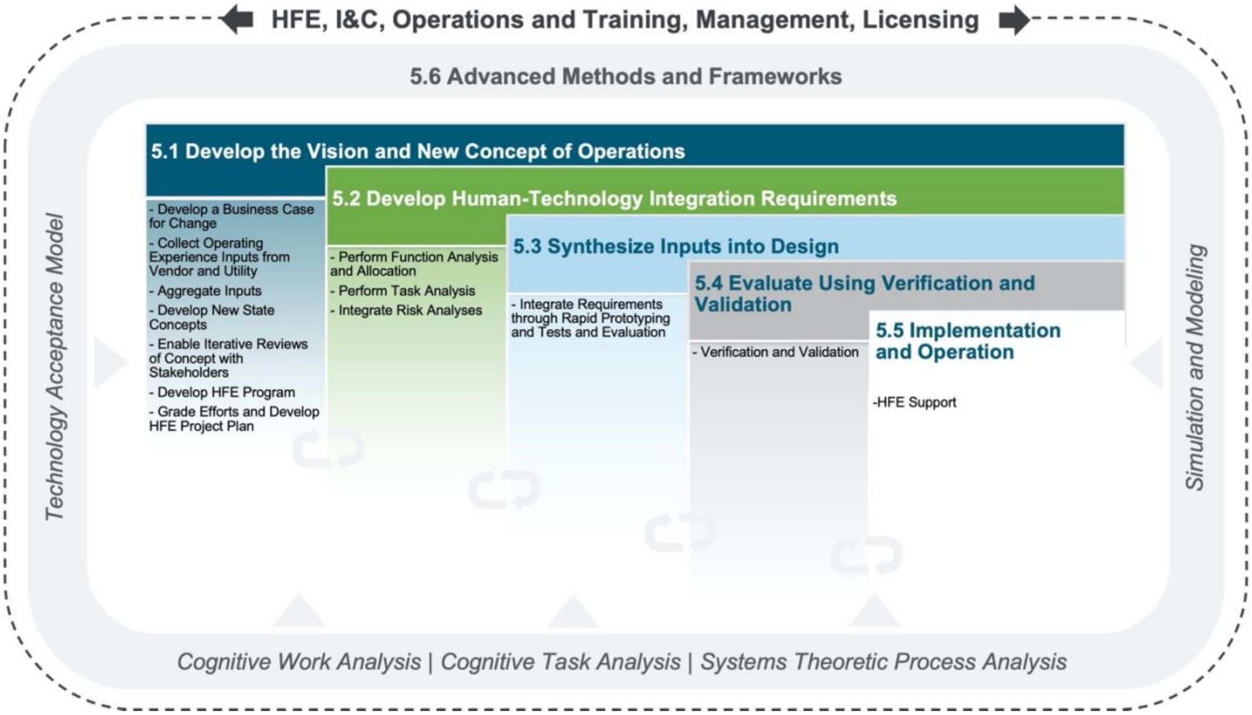


Figure 9. A methodology to evaluate the adoption of advanced automation to achieve a transformative new state.

Figure 9 provides a methodology overview that can be used to evaluate and implement advanced technologies, such as automation, to reduce O&M cost while ensuring safety and reliability by addressing the human and technology challenges associated with these upgrades. The figure has several characteristics that are important to note. First, the outer layer of the figure presents the need for a multidisciplinary team to support the upgrade. This guide corresponds with the underlying nature of SE and is referenced in several standards and guidance documents, including EPRI 3002011816 (2018), EPRI 3002004310 (2015), IAEA No. NR-T-2.12 (2021), and INL/EXT-18-51212 (2018). Second, the figure includes key phases that align with existing guidance, such as EPRI 3002011816 and NUREG-0711 (2012), including developing a vision and concept of operations, developing human and technology integration requirement, synthesizing design, evaluating, implementing, and operating.

This approach is intended to be used within the main control room and across other plant functional areas, such as maintenance and supporting functions, following the appropriate grading. The figure purposefully provides an overlap across these phases to highlight that while phases to the left begin sooner, the activities are inherently iterative and can be revisited even as the project lifecycle matures. As technology evolves, the process should account for new possibilities of emerging capabilities that enable market competitiveness. To summarize, key high-level criteria that this process addresses are:

- **Builds on Industry Best Practices.** The process builds on existing standards and guidance, such as NUREG-0711, EPRI 3002011816, EPRI 3002004310, IAEA No. NR-T-2.12, and research from the LWRS Program. The work here extends this guidance across the plant (identified from business case analyses), includes references to advanced methods that can be leveraged, and provides new guidance for the use of HFE first principles to inform the new-state vision and concept of operations to ensure safety and reliability.

- **Multidisciplinary.** The process focuses on HFE activities required to perform large-scale modifications; however, there is requirement that the process includes close communication with key stakeholders that are part of the multidisciplinary team, including senior management, operations and training, I&C, HFE, licensing, vendor, and other parties. The nature of the project requires business needs to identify the most impactful opportunities to modernize. Further, domain expertise is needed throughout to properly elicit knowledge to develop a technical foundation for design decisions; this knowledge, collected from operations and other subject matter experts (e.g., Section 5.1.2), is integrated with HFE first principles (refer to Sections 5.1.4.1 and 5.1.4.2) to provide a scientific and systematic approach.
- **Graded Approach.** Uses a graded approach to apply the appropriate level of detail in rigor to analysis (e.g., Section 5.1.7).
- **Addresses the Physical and Functional Changes.** Comprehensively accounts for the physical and functional changes that are part of the modification. This includes developing descriptions and models of the control centers in scope, as well as defining a new concept of operation.
- **Emphasizes Early HFE Involvement.** Focuses on supporting early HFE involvement to help define the vision so that the vision and concept of operations initially incorporates best practices for human and technology integration; this can be used to help inform COTS vendor selection and configure a selected vendor's capabilities to meet utility needs.
- **Allows Iterative Feedback.** The process is intended to support iterative feedback throughout the lifecycle of the project. This includes updating the vision and concept of operations through downstream activities like function and task analysis, rapid prototyping and multistage evaluation, as well as ensuring monitoring for issues when implemented.

The activities in each phase are described consistently. Each activity has a summary figure, see Figure 10.

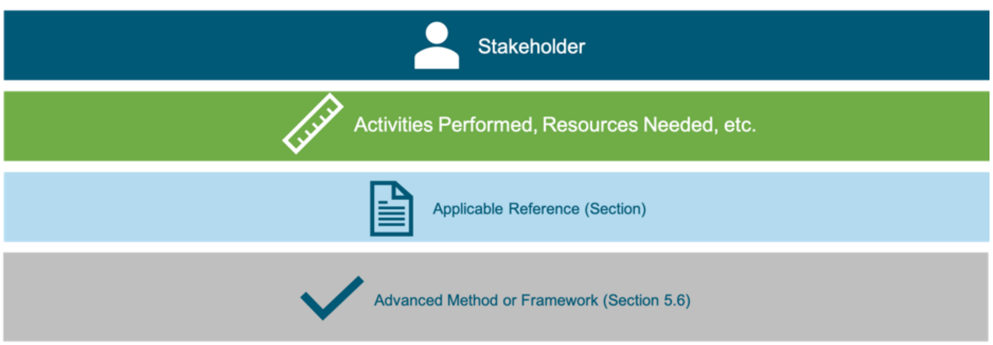


Figure 10. Summary sheets for each activity described

For each activity, key stakeholders, or those who should be directly involved in the activity, are suggested in the dark blue. Specific activities, resources needed, or tools are presented in green. Applicable standards, guidelines, and LWRS Program reports are provided where applicable in light blue; these mostly pertain to the documents in Section 3.3. Finally, where applicable, advanced methods and frameworks are highlighted in gray. A detailed description of these methods and frameworks are further presented in Section 5.6. The advanced methods and frameworks may be useful across more than one phase; hence, Figure 9 shows them encompassing all phases. The selection of any given advanced method should be driven by the breadth of the modification, the project schedule and constraints, the team composition, and the underlying problem space to which a given method serves useful in enhancing the results of the activity. Refer to Section 5.6 for a detailed review of these advanced methods when considering the specific activities described in Sections 5.1–5.5.

5.1 Define the New-State Vision and Concept of Operations

The process for defining the new-state vision and concept of operations requires both a bottom-up (i.e., understanding the utility needs and vendor capabilities) and top-down (i.e., applying overarching design principles) approach. As shown in Figure 11, the new-state vision and concept of operation builds upon existing guidance by including both a bottom-up and top-down approach to develop a new-state vision. That is, a bottom-up approach is taken to identify the utility's goals for modernizing, the bounding constraints of the project such as scope and schedule, relevant operating experience (OE), understanding of the selected vendor's capabilities, and other considerations that impact the modification efforts. The top-down approach refers to the application of design criteria, or new-state first principles, that help guide the development of a new-state vision by informing what attributes of an advanced concept of operations and use of technology improve performance and reduce cost. The first principles are comprised of high-level design criteria that allow the project team to crosswalk the vendor's available capabilities to specific attributes to enable a transformative change in the existing NPP operating model. Figure 11 captures the integration of these bottom-up and top-down approaches through the intersection of utility needs and vendor capabilities (i.e., bottom-up) and first principles in performing this crosswalk (i.e., top-down). This section describes the relation of each of these activities.

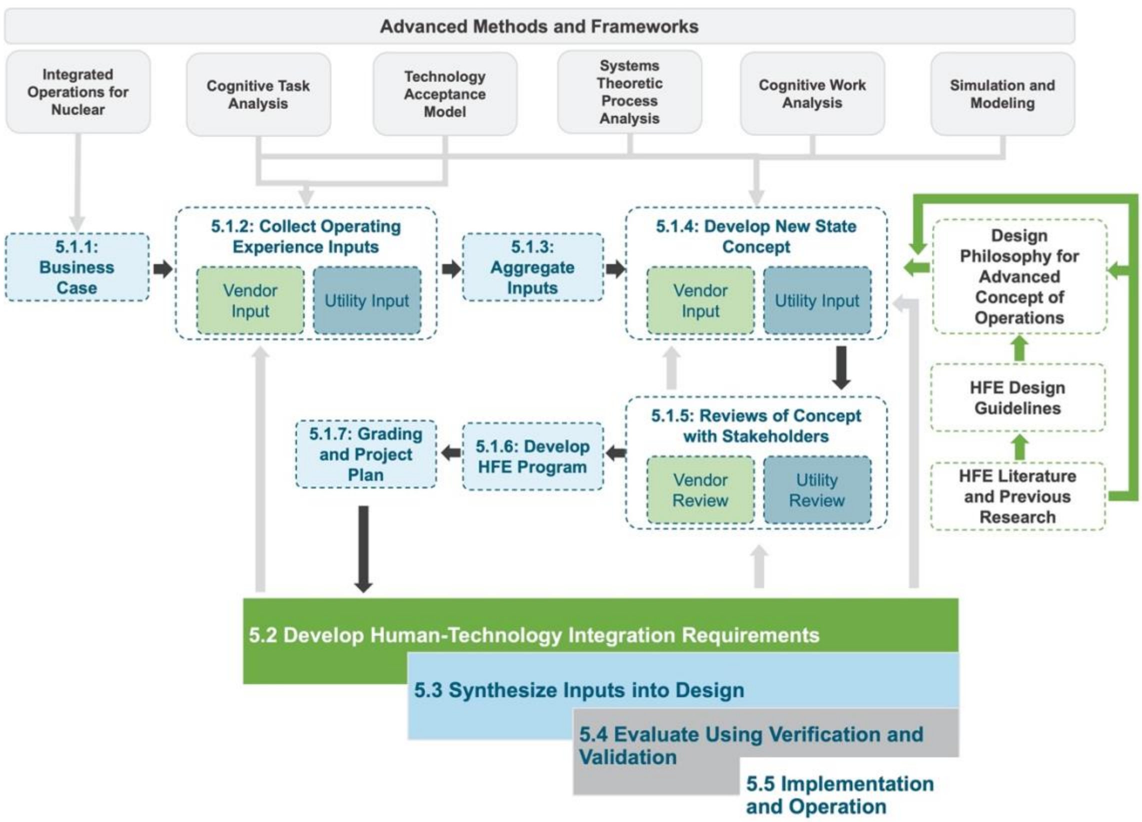


Figure 11. New-state vision general methodology and process.

There are a few points about the proposed methodology worth noting.

First, the methodology is intended to be flexible enough to support utilities who are in the early stages of planning, as well as utilities who have developed a detailed plan or have undergone previous plant modifications. For example, a utility who has not yet selected a vendor and has not yet developed a vision can begin the process from a "blank slate" perspective, guided by the business case, OE, and other inputs described later. Utilities who have completed previous modifications or are in the process of modifying their plant may also revisit the activities in this phase to ensure that their vision and concept of operations is aligned, that the selected vendor capabilities are most current, or that any downstream activities (e.g., function analysis or HSI design) are aligned with the vision. Deviations between the high-level guidance described here with detailed results from downstream activities may suggest either changes needed to the modifications or changes to the vision, depending on the nature, impact, or cost.

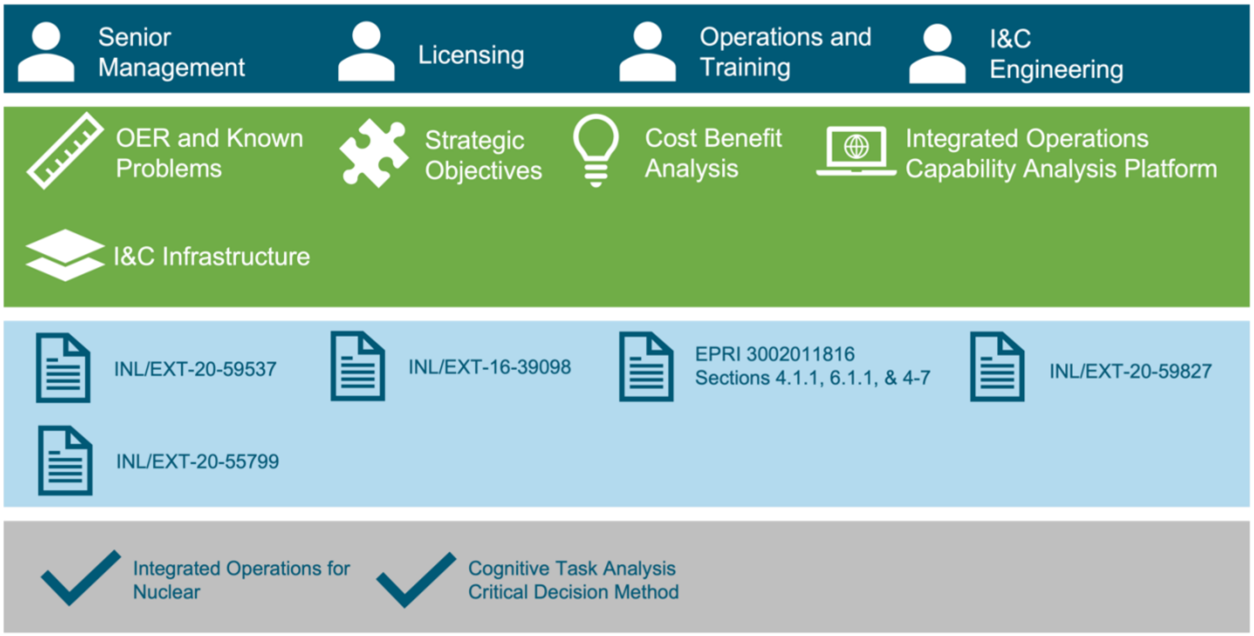
Second, it should be no surprise that the new-state vision developed is iterative. New input or changes in scope or direction should be accounted for and included in later iterations of the new-state vision, as described in the previous example above with utilities who have completed previous modifications or are in the process of modifying their plant. This is represented by the feedback loops in the process portion of Figure 11 from downstream HFE activities to new-state vision development.

Third, it should be emphasized that the first principles (shown in the green flow region) are meant to add clarity of the possibilities in enabling a transformative new state when configuring available vendor capabilities (e.g., computer-based procedures, advanced alarm systems, or decision support), rather than provide stringent requirements expected of the utility when developing their new-state vision. In this sense, the first principles facilitate identifying what is important for a given capability, as well as understanding why those specific attributes are important from a HFE standpoint. Ultimately, continued conversations, lessons learned, and technical expertise from the vendor determine how specific features and functions can support these first principles to the extent practical.

Fourth, as emphasized in the primary framework (refer to Figure 9), defining the new state and concept of operations requires good collaboration and communication between the entire team, including appropriate utility staff, vendor staff, and those who are responsible for applying the first principles (herein referred to as the HFE team). The HFE team may be comprised of members from within the utility or from supporting research organizations. Members of the HFE team should be versed in both the literature and methods of HFE; the reader is suggested to refer to NUREG-0711 (2012) for guidance on the composition of an HFE design team. While this methodology focuses on the HFE considerations within SE, the underlying methodology developed here may have broader implications to other domains of SE and across the plant's functional areas to support the fundamental business goals of the transformation, such as those described in ION (Thomas et al. 2020).

A final point is that the proposed methodology is intended to be facilitated in parallel with other important modernization planning activities, such as developing the migration strategy needed to reach the new state (EPRI 3002004310 2015). By working in parallel with other important modernization activities, the scope, schedule, and other constraints can be used as input here. The following subsections describe each of the steps shown in the Figure 11. It is expected that the HFE team will be responsible in facilitating this methodology; however, important interactions with team members from the utility and vendor are described where appropriate.

5.1.1 Develop the Business Case for Change



Change to existing NPPs should be based on the proposed value of the modifications through a business case. Thomas and colleagues (2020) in INL/EXT-20-59537 emphasize that the transformation of the NPP operating model cannot take place by "automating existing work processes." Rather, technology must be used to fundamentally change the way in which work is done. Following ION (see Section 5.6.1), a business case for change should be informed by setting a target goal (e.g., price points for producing electricity) to which specific work functions can be analyzed across the NPP organization and infrastructure to identify opportunities where change can be made to the people, processes, and technology under its governance to reduce cost. The next step is to identify where there are opportunities to reduce costs across the NPP organization using COTS technology combined with changes to processes and people (e.g., training, job requirements). The application of technology may serve multiple opportunities across the NPP organization. The accumulation of work reduction opportunities for a given technology or set of technologies can be used to develop a business case.

For example, senior management may define a strategic goal of reducing total operating and maintenance cost by 33% of the course of some targeted timeframe to remain economically viable. To meet this goal using ION, work reduction opportunities across operations, maintenance, and support NPP organizations can be identified using methods and tools described in Section 5.6.1 like the ICAP. Commonalities of enabling COTS technology can be identified from ICAP to develop a business case that will ultimately influence the new-state vision and concept of operations. Likewise, Thomas, Lawrie, and Niedermuller (2016) provide detailed business cases for control room technologies in INL/EXT-16-39098; these insights may be used to understand how specific enabling technologies like computer-based procedures, task-based displays, automation, and other available capabilities can be used to reduce O&M cost.

Collecting input from operations and training has a role in providing insights into the business case. For example, existing OER may be collected to identify where there are human error traps that can impact safety, reliability, and efficiency. Insights from this feedback can be used by HFE in conjunction with operations to identify ways in which technology can be optimally integrated considering the particulars of the plant and project scope. The critical decision method from the cognitive task analysis method (Section 5.1.2) can be applied to enrich OER.

Finally, an important element in developing a business case is understanding the impact of new technology on the existing and proposed infrastructure, including developing a strategy to effectively migrate technology in a way that is cost-effective and reduces risk. An advanced (i.e., technology-centric) new-state and concept-of-operations model is implemented using a concentric circle approach informed by the business case (i.e., through ION); the concentric circle representation corresponds to the Purdue Model Network Levels as a standard industry framework. Working from the inside-out, enabled functionality expands to enable improved performance and support a lower total ownership cost as described below. Control systems provide the foundation for the technology-centric concept of operation. The capabilities provided by these control systems are represented by the four innermost circles (i.e., blue, green, brown, and red) in Figure 12.

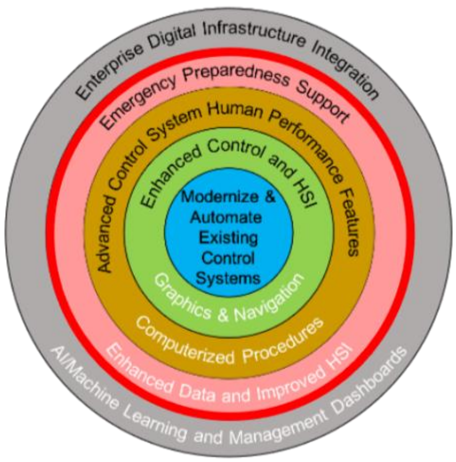


Figure 12. Concept-of-operations implementation target.

1. **(Blue) Modernize and Automate Existing Control Systems.** At the most rudimentary level, I&C replacement systems need to provide the like-for-like functionality of the original systems to continue to support plant operation. This can solve technology obsolescence issues and reduce total ownership cost using digital features to perform self-diagnostics and eliminate calibrations (e.g., Hunton and England 2019).

2. **(Green) Enhanced Control and HSI.** Modern digital I&C systems, however, provide enhanced control capabilities through the automation of processes that are manually controlled. They can also provide improved HSIs using graphic displays and improved navigation through those displays to enhance operator situation awareness, improve usability (i.e., reduce secondary task burden), and reduce workload. For example, the integration of information from analog displays that once were presented across the control room can now be integrated into a digital HSI display. The integration of information enables the operator to reduce visual scanning for improved situation awareness, workload, and reduced demands on accessing information (Kovesdi et al. 2020). Section 4.6.2.1 provides examples of digital HSI displays that can be realized at this I&C level.

3. **(Brown) Advanced Control System Human Performance Features/ (Red) Emergency Preparedness Support.** Advanced control system software applications can further enhance SA, reduce workload, and aid in efficient plant operation. Advanced features include, but are not limited to, computer-based procedures and task-based displays and lockout/tagout applications that are dynamically linked and logically coupled to the control systems (e.g., Section 4.6.2.2 describes the integration and use of these features in an advanced concept). These applications are linked to the enhanced control system and HSI features and function together as an integrated set to affect improved plant operation and control. Through this I&C infrastructure, the dynamic linking of

information can be provided to other control facilities, such as emergency preparedness facilities (shown in red).

The bold red control system boundary shown in Figure 12 is important because the capabilities described within it are governed by the Cybersecurity Rule, 10 CFR 73.54. Outside of this boundary is fourth level of technology implementation:

4. **(Gray) Enterprise Digital Infrastructure Integration.** The enterprise digital infrastructure envelopes the control systems and includes the utility information technology networks and applications. Here, even more advanced capabilities that can reduce cost can be realized. The deployment of decision support tools, drones and robots, online monitoring and predictive maintenance, as well as real-time field communication capabilities are enabled (e.g., refer to Section 4.6.2.3).

The result is an integrated whole that provides much more capability than the sum of its constituent parts. Both benefits and potential HFE impacts of automation are considered on existing operational and maintenance functions. It is worth noting that the concept of operations can be informed by subsequent HFE activities (i.e., such as those described later in Sections 5.2–5.5); hence, an initial definition of the concept of operations should be developed and treated as a living document (i.e., this is performed following Sections 5.1.2–5.1.7, described next). Areas that require further granularity can be noted and revisited when more information is collected. Nonetheless, high-level HFE considerations can be identified and focused on in later activities following the Purdue Model Framework. Figure 13 illustrates the concentric circle model as specific network layers in the Purdue Model Framework. The general capabilities described above are shown in Figure 13.

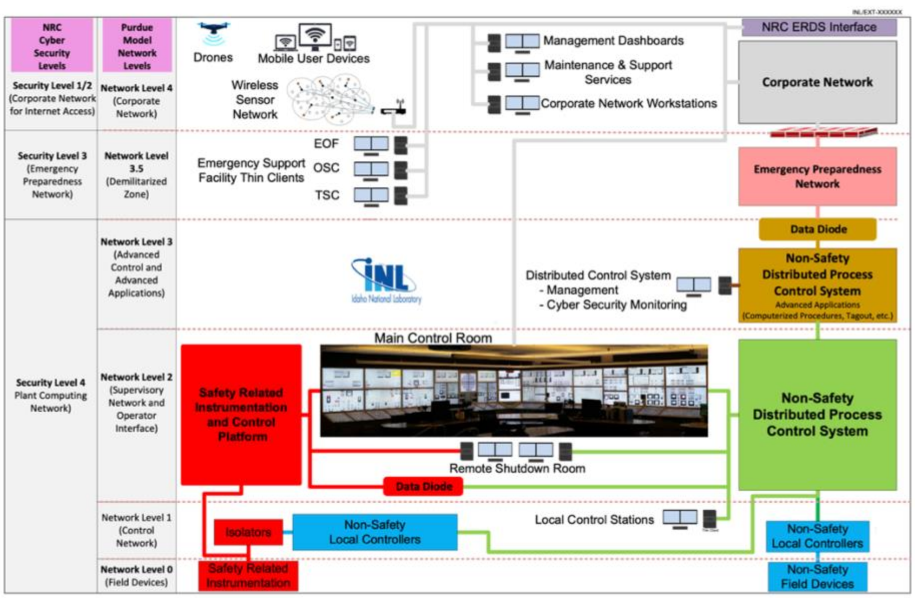


Figure 13. I&C infrastructure model using the Purdue Network Model.

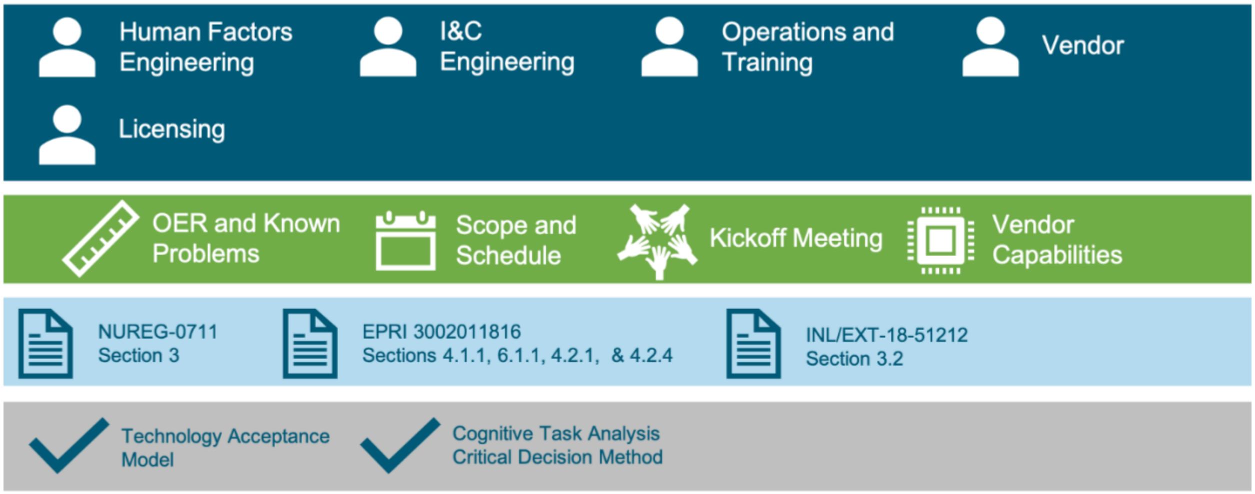
Using this framework, HFE can focus key questions regarding:

(1) Who the users will be?

(2) What OE, relevant standards and guidelines, and previous technical research can be used to inform the design (guiding principles in Section 5.1.4.1)?

(3) What technical requirements that may impact technology configurability should be considered?

5.1.2 Collect Operating Experience: Utility Input and Vendor Input



Both utility and vendor inputs are essential in developing a transformative new-state vision. In each case, these inputs should be considered higher level given that the focus of this effort is conceptual in nature and is meant to capture broad attributes of the new state that will subsequently drive more specific detailed requirements in later phases (EPRI 3002011816 2018; EPRI 3002004310 2015). Collecting utility input assembles information, concerning:

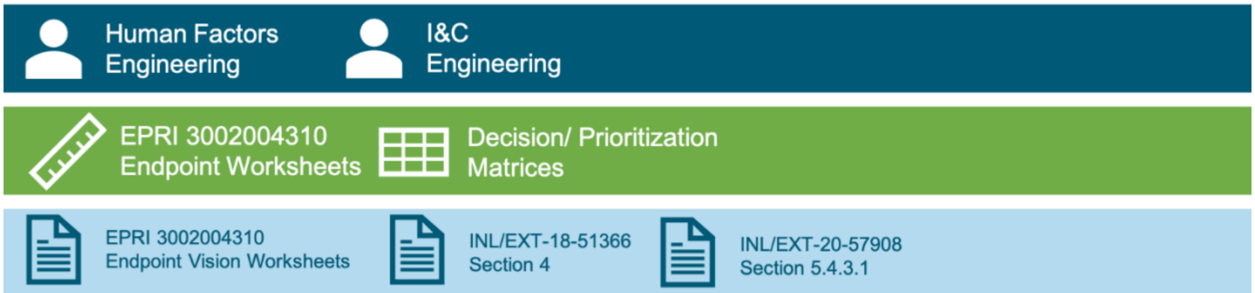
- An understanding of the business goals that are driving the new-state vision (EPRI 3002011816 2018) and their potential impacts to the people, processes, technology, and governance in place (Thomas et al. 2020)
- The scope of the project, including identified NPP systems and associated technical requirements (including relevant documentation where available, such as the procurement specification; EPRI 3002011816 2018)
- Project constraints, including cost, schedule, licensing effort and risk, and migration plan (EPRI 3002004310 2015; ISO/IEC/IEEE 15288 2015; ISO/IEC/IEEE 15289 2017)
- The identification of utility stakeholders and team members who will be responsible for providing input and managing the project (ISO/IEC/IEEE 15288 2015; ISO/IEC/IEEE 15289 2017)
- Available OE from the existing plant and proposed technology to be implemented (NUREG-0700 2012)
- Desired changes made to the NPP per feedback from plant staff and stakeholders (EPRI 3002004310 2015)
- Any other assumptions, constraints, or important considerations that impact the project.

If a vendor has not yet been selected, the OE, desired changes, and other inputs described above can serve in selecting a vendor that supports operational and project needs. The purpose of collecting vendor input is to capture the specific capabilities available and the capabilities being proposed for the new-state vision. Here, this descriptive information about the proposed capabilities is most beneficial when provided at a high level (i.e., describing the major functions and features the capabilities provides). For both utility and vendor inputs, the sources of information may come from a combination of sources, ranging from informal interviews to formal documents like procurement specifications, vendor specifications and white papers, or other formal reports (e.g., OER report; NUREG-0711 2012).

The application of cognitive task analysis (Section 5.6.3) techniques like the critical decision method can be applied to identify previous incidents that present cognitive challenges with the existing technology;

this knowledge can be used to enrich OER. Demonstrations of available vendor capabilities serve as invaluable input for operations at utilities (Joe, Hanes, and Kovesdi 2018). The technology acceptance model (TAM; Section 5.6.5) is one framework that can be used to characterize the factors that influence technology acceptance (Davis, Bagozzi, and Warshaw 1989). TAM suggests that giving personnel early exposure through demonstrations allows for greater familiarity and may have a positive impact.

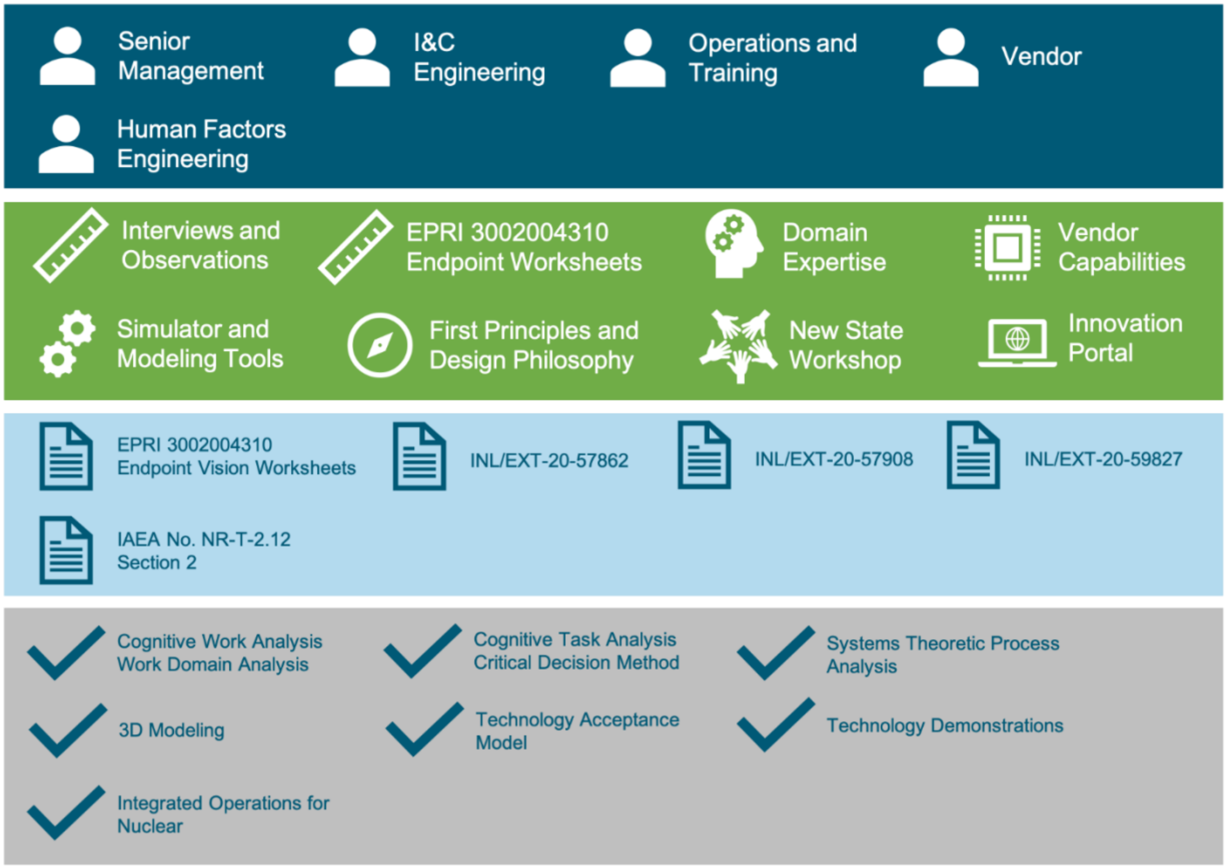
5.1.3 Aggregate/Validate Inputs



Once the utility and vendor inputs from Section 5.1.2 have been collected, these inputs will need to be aggregated and documented into a manageable format to support their use in developing the new-state concept. The EPRI 3002004310 (2015) endpoint definition worksheets serve as a detailed starting template to describe the key changes envisioned in the new state regarding the major changes in concept of operation, HSIs, and failure management. Adding to these worksheets, this work adds a section to document the impacted systems across each migration phase and the notable operational and HFE impacts based on the scope of these impacted systems. The aggregated information collected in these worksheets should then be validated with utility stakeholders and others involved to ensure it is accurately captured and completed.

Where input aggregation is not trivial, several other tools listed in INL/EXT-18-51366 (adapted from the Six Sigma methodology) may be useful. For instance, where there are conflicting inputs (e.g., OE suggesting an automation enhancement, but the capability is not available from the vendor), tools like force field analysis, Pugh analysis (i.e., decision matrices), and interviews and discussions can be used to work through the benefits and limitations of conflicts to come to a consensus. In cases where prioritization is needed, tools like NGT can be applied to form a consensus based on the prioritization of inputs across the team. The NGT tool is further discussed by Dainoff and colleagues (2020) in INL/EXT-20-57908 as a tool that can be used to improve knowledge elicitation and aggregation. Its benefit lies in being widely known in many industries, has a track record in the nuclear industry, and can be applied flexibly where consensus is needed.

5.1.4 Develop New-State Concept Based on Inputs



A new-state vision specifies both the characteristics of new systems being implemented, as well as the changes that the modifications have on the concept of operations (EPRI 3002004310 2015). Just as there are multiple inputs needed to define the new state, the new-state definition may be characterized through different outputs. Developing these outputs should hence entail describing the physical and functional aspects of the vision. The two key outputs as described in IAEA No. TR-T-2.12 (2021) that comes out of developing a new-state concept are a:

- Description of the physical changes to the control center(s)
- Description of the new concept of operations.

The process for developing these outputs particularly benefits from the use of a multidisciplinary team, strong collaboration, a clear understanding of the vendor's capabilities and the utility's needs, as well as a set of guiding principles that can ensure that the synthesis of the inputs, needs, and constraints is done such that safety and reliability are not impeded. It is likely that when performing this activity, a collection of knowledge elicitation methods is needed, and iterations through multiple meetings (formal and informal) may be practical. Following guidance from IAEA No. TR-T-2.1, what is most critical in this activity is to answer: *where*, *which*, *who*, *when*, *what*, *how*, and *why*. The mapping of these key items to the outputs and deliverable mechanisms are listed in Table 1.

Table 1. Mapping of IAEA TR-T-2.12 outputs for defining a new state and concept of operations.

Key Questions *(Taken directly from IAEA TR-T-2.12)*	**Description of the physical changes to the control center(s)**	**Description of the new concept of operations**
The where: The geographical and physical locations of the HSIs and HSI components.	Goal 1: Characterizes the physical locations of the new HSIs. Deliverable A.	—
The which: The known HSIs and HSI components. This will often be determined based on the I&C architecture and the list of locations.	Goal 2: Describes the scope and extent of modifications performed to the plant, indicating the systems impacted, as well as the associated components and HSIs. Deliverable B.	—
The who: The intended users of each HSI or HSI component. This will often be determined based on overall staffing decisions.	Goal 3a: Characterizes the anthropometric and ergonomic considerations of the control center with regards to the intended users. HFE guidance here pertains to room layout, accessibility, and workstation/workplace ergonomics. Can be performed using the models developed in Goal 1. Deliverable A.	Goal 3b: Defines the HSIs impacted (the which) within the location (the where) in combination with defining the users that will perform specific functions and tasks. Required staffing levels should be considered (e.g., see U.S. NRC NUREG-1791 with MCR defining 10 CFR Part 55 requirements). Deliverable C.
The when: When a given HSI or HSI component is to be operated, relative to the main plant state and conditions.	—	Goal 4: Describes temporal characteristics of human-technology interaction, including the activities, tasks, flows, precedence, and concurrencies in scope of the modification, at a high level. This includes describing the use of systems/functions and their HSIs across primary plant modes like startup, steady state, shutdown, etc. Deliverable C.
The what: The main functions and their main characteristics to be provided by each HSI or HSI component (e.g. alarm management or computer-based procedures [CBPs]), possibly depending on the "when."	Goal 5a: Describes the placement and locations of the primary capabilities being considered in the control center. This includes the layout and design of the workstations that may incorporate CBPs, HSIs, or the placement of alarm annunciators, group-view displays, etc. Deliverable A.	Goal 5b: Describes the enabling technologies that are considered in the concept of operations. Changes between existing and new concept of operations is important to document. At a high level, the levels of automation should be described. Deliverable C.

The how: Expectations on HSIs or HSI components usage, O&M in a given environment.	Goal 6a: Characterizes the physical characteristics of the workstations and workplace of the new state with regards to its impact on using the technologies. Deliverable A.	Goal 6b: Describes how the technologies and capabilities (what) will be used by the users to operate, maintain, or support the plant. At a very high level, this should describe how the user will monitor and detect, assess situations (diagnose), plan responses, and execute responses with the new capabilities. Differences between the existing state should be documented. Deliverable C.
The why: Rationale to clarify the reader's understanding of specific events found in operational concept scenarios.	Goal 7: Provide a technical basis for design decisions with the application of technology, user roles, and environmental considerations. Deliverable C.	
Deliverable Key A - Deliverable via visualization, model, or other artifact that represents physical changes and impacts B - Itemized list or database C - Description of changes and concept of operations		

Collecting responses to the items in this table should be completed following the business case, OE and design inputs from end users, the vendor platform's capabilities, the I&C infrastructure, the desired capabilities being considered, and the application of first principles that support safety and reliability with human-technology integration, as visually represented in Figure 14.

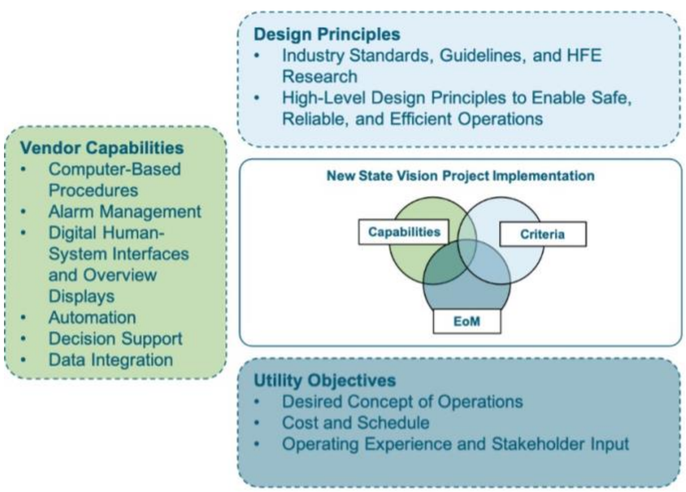


Figure 14. Aligning utility needs, vendor capabilities, and first principles for a safe and reliable new state.

The key questions and associated outputs shown in the table above require good alignment between the utility needs, vendor capabilities, and application of first principles to ensure that human-technology integration challenges are addressed. This work recommends using 3D modeling software to help visualize the as-is, interim, and new-state physical changes (see Section 5.6.6.1). The application of EPRI

3002004310 (2015) endpoint vision worksheets can support defining the concept of operations. To this point, this work provides an adapted tool that includes first principles applied to the themes in these EPRI worksheets to guide the discussion of important attributes of the new-state vision and concept of operations. The subsequent subsections describe the development and value of these first principles and the facilitation of guides that embed these principles. The application of these forms of worksheets may be completed through a facilitated workshop with key stakeholders for completion. They serve as "living documents" such that subsequent downstream activities shown in Figure 9 can further inform the vision.

5.1.4.1 First Principles: Background into the Development of a Design Philosophy

To successfully transform an NPP, a design philosophy is needed to ensure uniformity, impact, and usability across all NPP technologies. This is a complex undertaking. For instance, dynamic instructions, a complex technology on its own, is one of many capabilities that might be integrated in an advanced MCR. Researchers from the DOE LWRS Program have developed a design philosophy that is accessible and usable for utilities while guiding their new-state vision.

The LWRS Program has engaged in supporting the existing U.S. NPP fleet to transform their operating model to be more efficient without risk to safety or reliability. The HFE team from the LWRS Program is developing a method for NPPs in their new-state vision. The methodology builds upon and incorporates existing guidance, thus including the following: the usual bottom-up collection of OE, human error traps, regulatory budget, scoping constraints, facilitated guidance (e.g., EPRI 3002004310 2015). The facilitated guidance includes worksheets for how new technology will impact normal and abnormal operations, failure management, and HSI design aspects. The design philosophy provides a set of criteria of what an advanced control room needs to transform operations to a more efficient model that ensures safety and reliability.

Since the criteria is distilled from resources, such as U.S. NRC design and process standards (i.e., NUREGs), EPRI 3002004310 (2015), and U.S. DOE LWRS Program control room modernization research, it inherently complies with regulatory guidance. If the criteria are met, it can optimize the HSI without compromising safety or reliability. Also, with access to resources, such as the publicly available NUREG and U.S. DOE LWRS Program HFE research, there is background documentation that explains in more detail how the criteria can be met.

Developing the Design Philosophy

To build the design philosophy content, the HFE team has gleaned and distilled a representative portion of HFE guidance, standards, research, and previous design philosophy guidance. Notable resources include:

- EPRI 3002004310: Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification (2015)
- INL/EXT-18-44798: Control Room Modernization End-Sate Design Philosophy (Le Blanc et al. 2018)
- INL/EXT-20-58538: Demonstration and Evaluation of an Advanced Integrated Operations Concept for Hybrid Control Rooms (Kovesdi et al. 2020)
- INL/EXT-19-55529: Human Factors Engineering Insights and Guidance for Implementing Innovative Technologies from the Nuclear Innovation Workshop: A Summary Report (Kovesdi et al. 2019)
- INL/EXT-20-59537: Analysis and Planning Framework for Nuclear Power Plant Transformation (Thomas et al. 2020)
- INL/EXT-16-39808: Design Guidance for Computer-Based Procedures for Field Workers (Oxstrand, Le Blanc, and Bly 2016)
- Supporting the Future Nuclear Workforce with Computer-based Procedures (Oxstrand and Le Blanc 2016)

- NUREG 0700: Rev 3 Human-System Interface Design Review Guidelines (2020)
- Human-System Interfaces to Automatic Systems: Review Guidance and Technical Basis (O'Hara and Higgins 2010)

The Role of the Design Philosophy

A design philosophy is a collection of principles that is created to achieve a transformative new state. Many factors influence how a single plant may reach their new-state design. The plant's budget is a constraining factor. Also, plant management may have different levels of technology acceptance. The capabilities of the partnering vendor will vary, resulting in different new-state technology combinations. In addition, the scope of the modernization effort is a constraining factor. Communicating these factors is important to a successful transformation. The key to achieving a successful transformation amidst these factors is following the set of principles as the endpoint.

The design philosophy permeates all stages of a modernization. For instance, using NUREG-0711 (2012) as an explanatory framework, the role of design philosophy can be seen at all phases. Design philosophy helps unify the HFE design team's vision and establish design goals during the planning and analysis phase. Also, performing an OER may provide insight into the most impactful transformations to maintain plant safety and operating efficiency. The solution does not come from plant operators, but instead, it comes from cross-referencing the design philosophy with an OER's information to identify key problem areas to focus resources on and select vendor capabilities accordingly.

The design philosophy acts as a structured methodology to translate the functional requirements to designers and vendors during the design phase (as described later in Section 5.2.1). When selecting vendor capabilities, the utility can ask "will this capability meet the principles laid out in the design philosophy for this purpose?" In addition, providing the design philosophy upfront can improve communication with the vendor by avoiding unwanted technologies or a lack of capabilities. It communicates the functional requirements of the design. After development and trial implementations, discovering that a product does not serve its intended purpose is both time consuming and costly.

Relying on the high-level guidance of a design philosophy supports HFE V&V activities. The design philosophy's principles are the benchmark to verify and validate designs. Since they are based in HFE principles from standards, guidance, and research, they represent the best practices of modern control room operations. Discrepancies between the design and the design philosophy deserve additional treatment and redesign until conformity is reached. Using a design philosophy from the beginning has cultural implications as well. Accepting the principles during the initial phases of planning builds internal buy-in from management, end users, and designers. It defines what a successful design can achieve. To operate competitively with an advanced plant's concept of operations, the design strategy should be used as a foundation for transformation.

Benefits of the Design Philosophy

There are several advantages of the design philosophy worth noting that support transformative change and innovations that utilities can apply to reduce their operating costs while ensuring safety. The following benefits are all interrelated and demonstrate how the design philosophy can guide the industry (i.e., research organizations, vendors, utilities, and regulators) in undergoing a transformative change with minimal risk to ensure the long-term sustainability of the existing fleet.

Serves as a common resource for utilities and vendors

First, since the philosophy provides a set of guiding overarching principles that govern the design (ANSI/ISA-101.01 2015; Hollified et al. 2008); it serves as a common resource allowing utilities and vendors to focus on aspects of the design and implementation that are important to reducing costs and ensuring safety for a given technology. These sets of guiding principles offer a foundation and technical basis for making design decisions that configure available technologies to enable new capabilities, drive down costs, and ensure safety. To ensure there is a solid rationale for design decisions made, the design philosophy offers a way to allow traceability across these guiding principles and to their technical bases.

Guides further development of technology

The philosophy also offers guidance specifically for vendors and research organizations who are developing, demonstrating, and deploying enabling technologies (Kovesdi et al. 2019). For instance, the philosophy can provide vendors a roadmap for future R&D necessary for commercializing specific technologies that are less mature in terms of technology readiness level (TRL) and human readiness level (HRL). Also, it can be implemented when specific principles are identified as important, but there are gaps in available COTS technology. Hence, the philosophy serves as an R&D roadmap for the vendor to make sure the most important functions are available to utilities. From a research organization standpoint, the philosophy offers similar benefits. Where there are identified gaps in capabilities and TRL/HRL is even lower, the philosophy provides a similar roadmap for R&D at earlier stages to bring new capabilities that are important to driving down costs while maintaining safety and reliability.

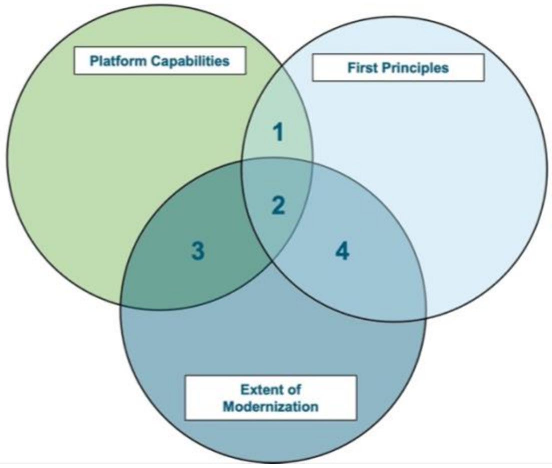
Provides common ground across industry to follow

Perhaps most influential, the design philosophy offers a common ground across the entire nuclear industry. This provides several important and interrelated benefits that are necessary for transformational change. For instance, it provides a unified framework of available technologies needed to address the specific challenge of ensuring the long-term sustainability of the existing NPP fleet. The framework provides a consistent, strategic, and structured approach to ensure that costs can be reduced and safety can be maintained across utilities. As previously discussed, the philosophy's guiding principles allow commonality across plants for an improved exchange of lessons learned (e.g., OE) that will avoid costly rework when implementing advanced technologies. While minimizing uncertainty and risk, the lessons learned serve as a roadmap for utilities to follow and go beyond like-for-like replacement when embarking on performing modifications in a phased manner (Le Blanc et al. 2018).

Another benefit of the design philosophy is that, through a common framework (e.g., sociotechnical framework), there may be a greater acceptance and adoption of technology that minimizes uncertainty and risk. TAM is a sociotechnical model of technology acceptance that theorizes technology acceptance and use are driven by two latent factors, including the technology's perceived usefulness and perceived ease of use (more details are found in Section 5.6.5; Davis, Bagozzi, and Warshaw 1989). If a technology is not perceived to be useful or easy to use, a user is less accepting of the technology and will not adopt it. Interestingly, an individual's experience influences the perceived usefulness and ease of use with the technology or similar products. By offering access across industry to different technologies, TAM suggests that there will be greater familiarity with the technologies available; therefore, the perceived usefulness and ease of use would be better calibrated to support greater technology acceptance.

A final benefit worth mentioning is that the application of a design philosophy provides common ground to support regulatory guidance and reviews. By providing consistency across industry, the philosophy offers a harmonized strategy to address outdated technology, reduce costs, and maximize safety. Utilities and vendors will not only benefit, but regulators, such as the U.S. NRC, may be able to develop more specific guidance and regulatory review criteria that are aligned with the specifics of the philosophy's principles. Therefore, uncertainty and risk are minimized to reduce rework and to streamline regulatory and licensing activities without sacrificing quality and safety.

5.1.4.2 Applying the First Principles and Design Philosophy



Interaction Region	Description	Implications
1	There is a COTS capability that has true value but is not known by utility.	Use TAM framework to inform utility of the value.
2	There is complete alignment.	Implement using SE and HFE methods.
3	There is a COTS capability that the utility believes they need but has no real value.	Identify alternative capabilities that support utility better.
4	There is a utility need with known value, but no COTS capability.	Perform R&D to bring up TRL/HRL.

Figure 15. Implications of alignment between vendor, utility, and first principles.

The design philosophy guides the new-state vision and configuration of technology by applying HFE first principles to the characteristics and features of the desired concept of operations. As a tool, the EPRI 3002004310 (2015) endpoint vision worksheets serve as the foundation for applying HFE first principles to the integration of the HSI and I&C capabilities to the concept of operations. The worksheets are intended to serve as living documents where they are updated as needed. The EPRI worksheets provide a systematic way of capturing the goals and characteristics of the new-state vision, broadly covering aspects of the new concept of operation, use of technology and added capabilities, and considerations in failure management. The worksheets have been adapted in this work to be used in conjunction with the first principles to support the top-down approach in identifying what is important for a given capability and understanding why those attributes are important. Hence, for each item in the worksheet, specific principles that describe characteristics of a transformative new state are provided to help in guiding the desired new state and the configuration of available vendor capabilities.

The worksheets have also been expanded from their original form to include emerging technical capabilities that have been identified in recent research. The overarching design principles from the advanced control room concept have been distilled across the adapted worksheets to support the review. Table 2 provides an example of applying these distilled principles in the worksheet. A detailed list of these principles that can be used to facilitate discussion between the utility and vendor are provided in Appendix A. Ultimately, these worksheets support facilitating discussion across the entire team to develop a transformative yet achievable new state, informed by design principles that support efficient operations and improved human and technology integration.

Table 2. Example new-state vision worksheet for diagnosing/troubleshooting during abnormal operation.

Abnormal Operation			
Activity	Diagnose and troubleshoot problems with the plant process, systems, and equipment		
First Principle	Provide relevant procedures, automated status monitoring, and decision support during diagnostic activities.		
Principle Short Label	All control system functions should focus to support operator diagnostic and mitigative tasks.		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs

Alarms	- MCR alarms pertain only to operators and conditions they have the capability to diagnose and act on	*Is alarm filtering desired?*	*Is alarm filtering available? How is this accomplished?*
Overview Displays	- When exploring/diagnosing failures consequential/relevant information should be present on one screen to reduce mental and physical workload on the operator - Integral formats should be used to communicate high-level, status-at-a-glance information where users may not need information on individual parameters to interpret the display. Additional Information: Since integral displays do not display individual parameters, they are most appropriate for general status monitoring - Displays should contain all information for the safe operation of a system including information from related systems if there are system dependencies that must be considered by the operator	*What is the vision for using digital HSIs and overviews for continuously available/ visible indications important to safety and situation assessment?* *Will group-view displays be considered?* *Will dedicated operator workstations be considered?* *How will the crew coordinate information to effectively diagnose and troubleshoot problems?*	*How will leading indications that support situation assessment be displayed?* *Is there capability to display all information for safe operation in a continuously visible or continuously available format? (e.g., SPDS)* *How will related information be consolidated on one screen?* *How will related information be integrated into a single visual? (e.g., trends, configural displays)*
Task-Based Display	- Task/State-based displays: When displays are partitioned into multiple pages, function/task-related data items should be displayed together on one page. Relations among data sets should appear in an integrated display rather than partitioned into separate display pages	*Will dedicated operator workstations be considered?* *Is there a current style guide in place for grouping information and navigation?* *Are task-based/ situation-based displays desired?*	*Describe the navigation scheme. How does the platform enable efficient navigation?* *How will related information be consolidated on one screen?* *Are task-based displays available?*
Is there any OE on the activity described?			

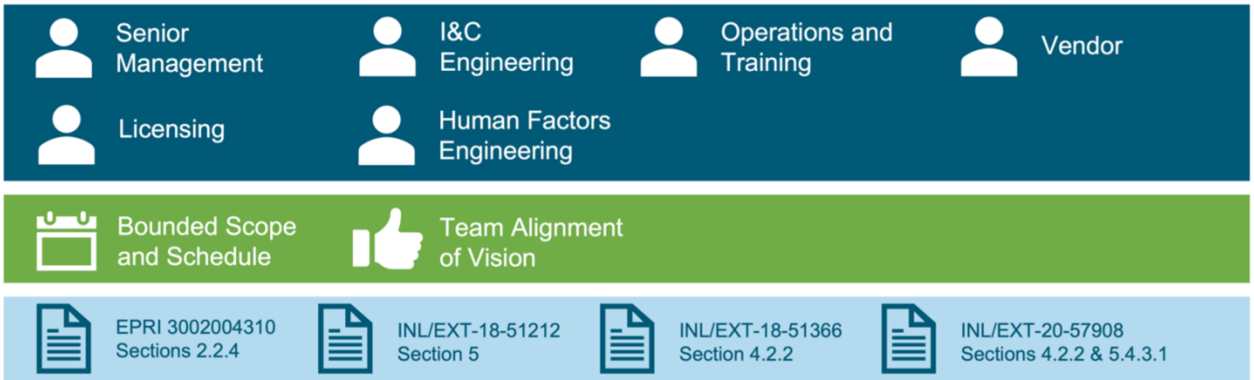
In the illustration in Table 2, the new-state vision can be aligned through a facilitated discussion with the design team (i.e., including management, engineering, operations and training, vendor, and HFE); the discussion is focused around the first principles, utility desires, proposed technology, and any OE related to the topic. The EPRI worksheets provide a basis of the discussion based on topics important to the concept of operations. In this case, characteristics of the new state concerning diagnosing and troubleshooting during abnormal conditions is the topic. A first principle that is important to supporting safety and reliability for this characteristic is "Provide relevant procedures, automated status monitoring, and decision support during diagnostic activities." The principle can be met through multiple design controls and providing a detailed specification at this time is beyond scope. Rather, the facilitation should cover high-level considerations of how the technology, procedures, training, and other controls will be realized in the new state to support the principle. To guide the discussion, the principles are coupled with specific examples of how capabilities seen in an advanced control room concept (i.e., creating from assembling HFE design standards, guidelines, and research) support the principle. Targeted questions for the utility and vendor can be asked to understand whether these capabilities are being considered and are feasible using COTS features and functions. Shown in Table 3, a simple mapping of alignment can then be performed to represent the design space as seen in Figure 15. Through a qualitative analysis (e.g., refer to INL/EXT-20-58538 [2020] in Section 4.1.3) of responses collected, the responses between utility and vendor can be reviewed being aligned or not aligned with the principle (1 = aligned; 0 = no aligned). The responses can then be mapped to the Venn Diagram shown in Figure 15 to determine the interaction region and its implication.

Table 3. Scoring alignment using new-state vision worksheets.

	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs	Venn Diagram Region in Figure 15	Comment/ Resolution
Alarms	1	1	1	2	Complete alignment
Overview Displays	0	1	1	3	Utility desired feature and vendor provide alignment without clear technical basis. Review bases and determine appropriateness of feature
Task-Based Display	1	0	1	1	Utility needs aligning of value of COTS technology.

Complete alignment shown in alarms (e.g., first principle suggest alarm filtering, utility desires alarm filtering, and vendor provides this capability) is represented as [1,1,1] and spans Region 2 (complete alignment). Overview displays show that a vendor provides a feature, and the utility believes they desire it without any basis in the first principle for diagnosing and troubleshooting during normal operations (e.g., using animation over a mimic on a tank); the matrix is [0,1,1] and covers Region 3 Figure 15. The implication here is to revisit the feature being proposed to understand its potential impact on human-system performance and whether there are alternative features that better support the principle. Finally, the task-based display provides alignment with the first principle and vendor capability, but the utility does not want it (e.g., the vendor provides a troubleshooting and diagnosis display with leading indications, and utility does not want it). The matrix here is [1,0,1] and the region is 1. The implication is to provide the utility an opportunity to learn more about the value of the capability, how it can fit in their training and procedures, and improve performance (e.g., a quicker and more accurate diagnosis). Not shown, but in cases where there is a principle with a known need and not a COTS solution (e.g., [1,1,0]), further inspection can be performed to understand whether a solution has been explored. If so, further inspection can be made to understand its TRL and HRL and support targeted R&D to increase its maturity.

5.1.5 Enable Iterative Reviews of Concept with Stakeholders



The developed new-state concept should be reviewed and aligned by both the utility and vendor. A schedule should also be bounded with any interim phases to understand how and when the new state will be reached. At a high level, the vision should be defined and aligned upon with the following outputs of Section 5.1.4:

- Description of the physical changes to the control center(s)
- Description of the new concept of operations.

For instance, the outputs that characterize the new state from Section 5.1.4 should be reviewed and confirmed by the utility and vendor (NUREG-0711 2012). Vendor feedback regarding how their specific capabilities can address the first principles ensures that the proposed concept can be achieved within the bounded scope and schedule of the project. As previously noted, utility, vendor, and research organizations should be closely integrated through the new-state vision definition process; hence, there should be no surprises when reviewing and agreeing upon the new-state concept (e.g., EPRI 3002004310 2015; INL/EXT-18-51212 2018). Hence ideally, team alignment should be resolved while developing the new-state vision and concept of operations described in Section 5.1.4.

In cases where decisions need further examination, a decision tool like Pugh Analysis, NGT, and focus groups can be applied to resolve any discrepancies across team (INL/EXT-18-51366 2018; Section 4.2.2). Further, Dainoff and colleagues (2020; INL/EXT-20-57908 Section 4.2.2 & 5.4.3.1) describe the application of the Intervention Design and Analysis Scorecard in combination with NGT as a structured approach to support cross-functional team alignment whereby the team can share their impacts, concerns, and needs, and these needs can be prioritized through consensus.

The completion of developing new-state concepts and their reviews from both the utility and vendor are highly iterative in nature. After completing development of the initial new-state vision through this methodology, the entire team should be completely aligned in the subsequent tasking activities, vision, and major focal points for HFE evaluations that ensure success in achieving the new state.

5.1.6 Develop HFE Program

The HFE Program provides guidance in ensuring that the modifications envisioned meet the regulatory requirements and expectations concerning HFE (INL/EXT-18-51212 2018). Though, it should be no surprise that the careful consideration of technologies that will encompass the new-state vision should be conceptualized in a way to support good human factors design using the first principles discussed in detail in Section 5.1.4. Indeed, the process described here emphasizes that HFE should be integrated very early on in the modification process, even before the modification request is put in place at the utility. The HFE Program and subsequent HFE implementation plans further ensure the safety and reliability of the modification.

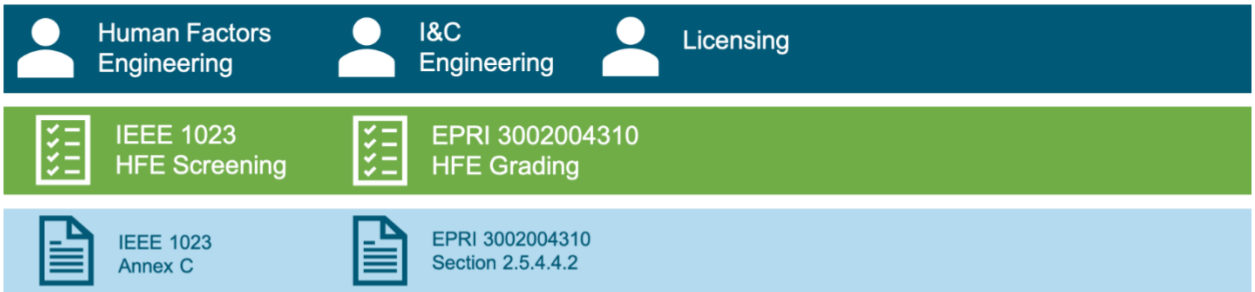
To implement the vision within the bounding schedule, the HFE Program provides specific guidance that can be followed fleet-wide (if needed) on how the HFE activities will be managed, the technical analyses performed to understand the human-technology integration requirements, the use of standards and guidelines for design synthesis, V&V considerations, and implementation and human performance monitoring considerations (EPRI 3002004310 2015). Section 2 of NUREG-0711 provides an industry-accepted set of HFE activities to considered in the program (refer to Figure 4).

While NUREG-0711 (2012) was designed to account for new NPP designs, it can still be applied to modifications. An important distinction here is that the focus of HFE activities should focus on modifications being made to the operating NPP (EPRI 3002004310 2015). In this sense, it is possible to perform a subset of the 12 elements in NUREG-0711; hence, grading the efforts is prudent to ensure the appropriate level of rigor needed to ensure the engineering activities are cost-effective without sacrificing safety and reliability considerations. For example, the level of HFE effort needed for a modification of a chart recorder on an ancillary system is significantly less than an upgrade to a new distributed control system that enables integrated workstations, digital HSIs, and other modern capabilities. A final point is that while NUREG-0711 is intended to be applied to modifications to the MCR, the HFE activities described are indeed staple methodologies and can provide value to modifications outside of the MCR.

EPRI 3002004310 (2015) provides detailed guidance into the development of an HFE Program in Section 2.5.4. Though, LWRS Program report INL/EXT-18-51212 (2018) provides practical guidance in developing the HFE Program. Notable takeaways include:

- A graded approach is prudent when implementing HFE activities.
- HFE should be integrated as early as possible and throughout the process; the NUREG-0711 phases and elements provide a recognized framework that can be followed while accounting for proper grading. HFE can make the greatest impact if it is integrated early such as the conceptual design or before. HFE can even support vendor selection (i.e., see Section 5.1.4).
- The HFE Program documentation level of detail should be sensitive to the audience at hand. Having a summary and detailed report may be useful depending on who will be reviewing (e.g., senior management or engineering).
- Iterative tests and evaluations, using simulators and modeling, is an important tool for identifying issues early.

5.1.7 Grade Efforts and Develop HFE Project Plan



A phased approach is a typical path that utilities take to modernization (e.g., INL/EXT-18-51107 2018). The phases may entail different scope regarding the associated risk and complexity of the modification. Hence, it is important to grade the level of effort in performing HFE activities to appropriately calibrate the right level of rigor needed. The following process shown in Figure 16 provides a suggested framework that can be followed.

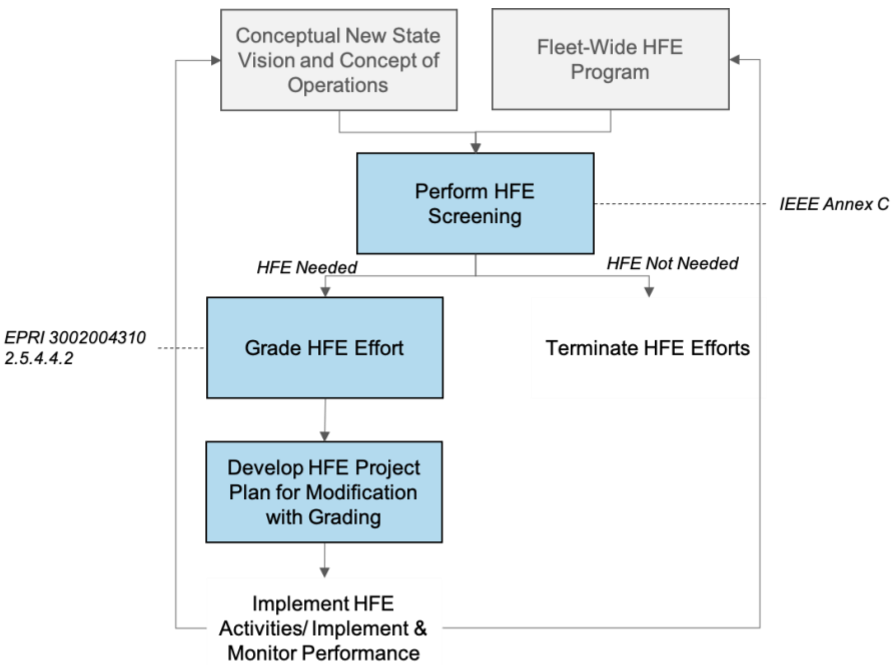


Figure 16. HFE screening and grading process.

Once the new-state vision and concept of operation has been developed with a bounded scope and schedule (i.e., including planned phases) and an HFE Program is established, HFE efforts for the modification can be screened to determine whether HFE is needed. The focus of screening and grading should reflect the modification under consideration and the specific changes made (i.e., delta) from the existing state. For example, if there are no changes in automation, then FA&A would not be invoked.

IEEE 1023 (2020) provides a screening tool in Annex C that can be used to determine whether HFE is needed. The checklist comprehensively screens for impacts to the tasks, workstation and workplace design (e.g., changes to a control board), and individual components. If YES is marked on any one criterion, the results should be reviewed by the team to determine if HFE is needed. Next, a grading is applied to determine the level of effort needed in performing HFE activities for the modification. EPRI 3002004310 (2015) provides a decision chart that can be used to grade the efforts into three categories: low, medium, and high. High denotes the greatest level of rigor, respectively. The decision chart accounts for primary and secondary factors. For primary, risk is evaluated in terms of nuclear safety level per probabilistic risk assessment (PRA or licensing), risk to personnel safety, and economic risk. The maximum risk value from these three categories is used. Next, the level is reviewed by secondary factors, including the number of HSIs impacted, number of tasks impacted, number of systems impacted, and degree of change in concept of operations. The latter may be determined based on the extent of change in automation and degree of impact to team dynamics (e.g., substantial modifications to communication between the control room and field, interactions between crew). The secondary factors can adjust the level to a higher grade (e.g., Level 3 to Level 2).

An example of a grading scheme is provided in Table 4, illustrating the impact of primary (risk) and secondary (complexity) factors to the HFE activities that would be performed for FA&A and task analysis. EPRI 3002004310 provides detailed guidance on tailoring HFE activities following the graded approach; this guidance can also be used in the HFE activities described here. Appendix B also provides a full set of gradings for the HFE activities described in this report.

Table 4. Grading scheme for function and task analysis.

<table>
<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
o Impact on hypothesized levels of automation, information processing
o Team dynamics</td></tr>
<tr><td>Low</td><td>Medium</td><td>High</td></tr>
<tr><td rowspan="2">Risk
“Primary Factors”
• Risk Analysis
• Risk to Personnel
• Economic Risk</td><td>Low</td><td>Level 3

Methods
– OER
– Operator Preference
– Expert Judgment</td><td>Level 3

Methods
– OER
– Operator Preference
– Expert Judgment</td><td>Level 2

Methods
– OER
– FA&A Methodology of the most troublesome use cases</td></tr>
<tr><td>Medium</td><td>Level 2

Methods
– OER
– FA&A Methodology of the most troublesome use cases</td><td>Level 2

Methods
– OER
– FA&A Methodology of the most troublesome use cases</td><td>Level 2

Methods
– OER
– FA&A Methodology of the most troublesome use cases</td></tr>
</table>

			– *Task Analyses (Walk-Throughs, or HTA/ TTA)*	– *Task Analyses (Walk-Throughs, or HTA/ TTA)*
	High	Level 2 ***Methods*** – *OER* – *FA&A Methodology of the most troublesome use cases*	Level 1 ***Methods*** – *OER* – *FA&A Methodology of all use cases* **Advanced Methods (Suggested)** – *STPA*	Level 1 ***Methods*** – *OER* – *FA&A Methodology of all use cases* **Advanced Methods (Suggested)** – *STPA* – *CWA Techniques*

Ultimately, the grading levels inform the HFE project plan that is used for the specific modification. The project plan should follow the guidance provided from the HFE program and be tailored with the right level of rigor from the grading.

5.2 Develop Human-Technology Integration Requirements

The purpose of developing human-technology integration 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. There are three primary activities in this phase including:

- FA&A (Section 5.2.1)
- Task Analysis (Section 5.2.2)
- Integration with Risk Analyses (Section 5.2.3).

These activities are performed in the level of detail defined by the HFE grading (Section 5.1.7). The primary inputs into these activities include:

- The Business Case (Section 5.1.1)
- OER Results (Section 5.1.2)
- New-State Concept and Concept of Operations (Section 5.1.4)
- The HFE Program (Section 5.1.6)
- The HFE Grading (Section 5.1.7).

Figure 17 highlights the suggested flow between FA&A, task analysis, and integration of risk analysis.

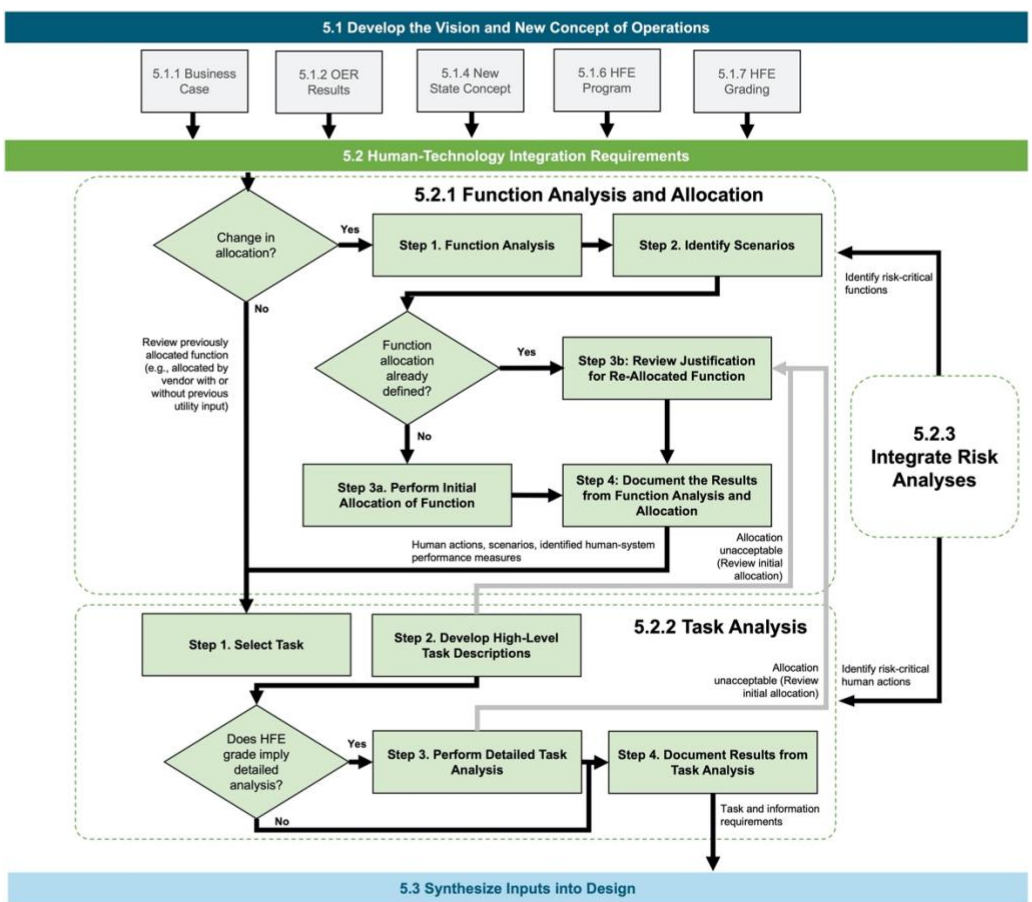
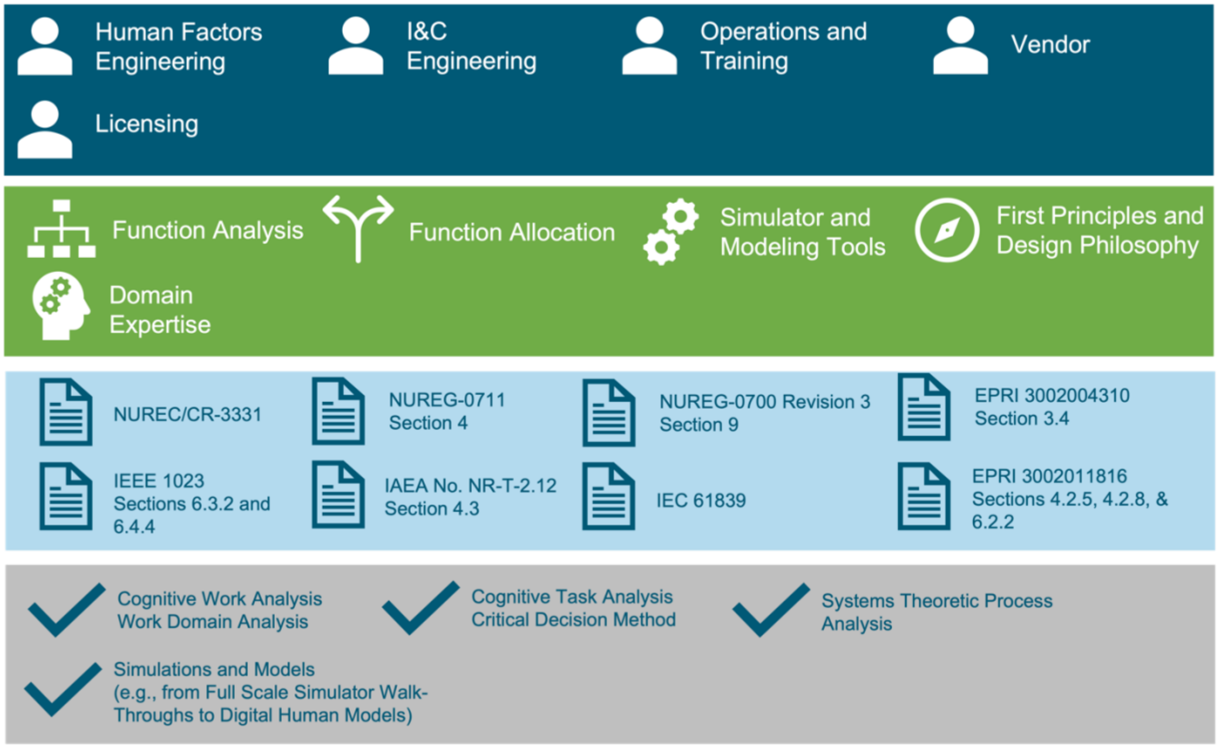


Figure 17. Human-technology requirements methodology and process.

5.2.1 Perform Function Analysis and Allocation



FA&A provides a means to perform an early evaluation, through analytical approaches to review reallocated functions, functions left unallocated, with or without reason, and the justifications for all. Some plants may opt to perform a level of function allocation early on, either perfunctory or operations based. In any case, this stage is intended to address all previous allocation decisions as well as review reallocation tasks to functions that require addressing to provide a technical basis for these decisions. Figure 17 illustrates how either or both situations are handled in the method addressed in this section, seen in FA&A Steps 3a and 3b, respectively.

There are two primary activities in FA&A.

- **Function Analysis.** First, all functions are analyzed; functions that have forgone reallocation are analyzed and hold potential for reallocation decisions. Namely, *function analysis* refers to identifying and defining the new and changed functions resulting from the modernization effort required to satisfy plant safety and availability goals. Use cases are identified by domain experts that demonstrate the changes in function.

- **Function Allocation.** Second, *function allocation* is performed to review the justifications for reallocated functions to provide feedback given the available support technology within the context of first principles defined in the design philosophy; the identified use cases that demonstrate the allocation of function are generally applied in this review. It is important to review justifications of function allocation at this stage to ensure alignment between plant goals, vendor capabilities, and necessary operator support as defined by the new-state vision and concept of operations (Section 5.1.4). As illustrated back in Figure 15, it is important to ensure that all opportunities of utilizing technology at Intersection Regions 1 and 2 are not overlooked or improperly implemented.

If the case is that some functions were overlooked or otherwise not reallocated, FA&A provides a means to which these functions can be readdressed to evaluate additional opportunities to allocate responsibilities and support operator performance within the context of plant goals. FA&A uses inputs from

Section 5.1 to holistically consider aspects of the proposed allocation's economic benefits, cost and feasibility, regulatory implications, alignment to the vision, and consideration of the strengths and limitations of the people and technology to accomplish its goal. FA&A provides a means of ensuring that the function can be accomplished safely, reliably, and efficiently; here, it ensures that operators are equipped with the right support given the responsibility to maintain awareness and carry out plant objectives in accordance with plant safety and performance goals.

5.2.1.1 Key Definitions for Functions and Automation

NPPs have a hierarchical structure of functions, subfunctions or processes, systems, and components, and the term "function" can be used at any level of the hierarchy, from high-level plant functions, such as safety functions, or to a lower-level description of the purpose of individual pieces of equipment (NUREG-0711 2015). Before considering the function allocation, it is necessary to complete a functional analysis to determine the objectives, performance requirements, and constraints associated with each function, to define the activities and tasks that must be performed and provide a framework for understanding the role of personnel and automation in those tasks, and to ask if automation or human involvement is essential or preferred for various functions (NUREG-0711 2015).

It is also important to define what "automation" essentially is to adequately assign responsibility to each agent. Sheridan (2002) broadly defines automation as:

> *(a) The mechanization and integration of the sensing of environmental variables (by artificial sensors); (b) data processing and decision-making (by computers); and, (c) mechanical action (by motors or devices that apply forces in the environment) or information action by communication of processed information to people* (p. 9).

Figure 18 is a recreation of the automation model provided in Sheridan (2002), which illustrates the scope of automation. The model contains *inputs*, a *central processor*, *output*, and an *effect* on the function that is pertains to. Inputs can be characterized by information from the environment that is acquired via *artificial sensors* and information retrieved and analyzed from memory as *stored information*. Information is then met in the central processor where *computerized decisions* are made to interpret situations, form strategies and planning, and perform decision selection. The processed information is then used in response implementation via mechanical actuators or displayed to provide advice and feedback to the person.

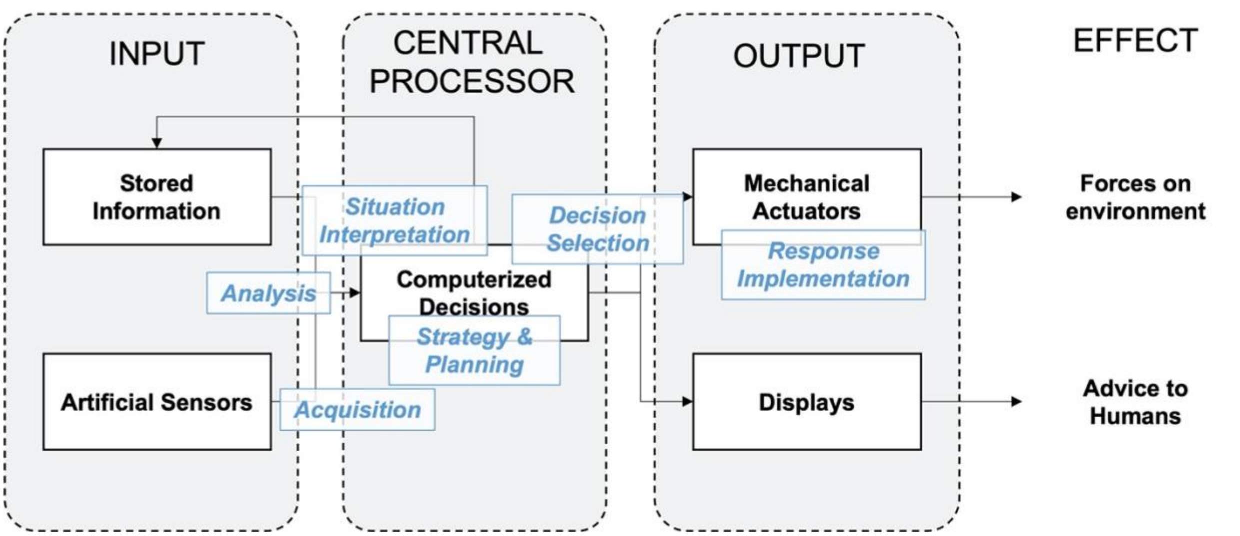


Figure 18. Scope of automation (adapted and enhanced from Sheridan 2002).

Historically, in NPPs "automation" has meant replacing the role of humans in plant processes or process control functions with machines. In the past, most functions were either automated, and were thus performed without human involvement, or were alternatively manually performed by humans. However, with modern technology, there are many types and levels of automation to consider, as highlighted from Sheridan's (2002) foundational work in Figure 18. EPRI 3002004310 (2015) summarizes key NPP automation types as:

- **Control Automation.** This type of automation involves the system performing tasks by manipulating equipment automatically; for example, the automatic insertion of control rods when a reactor trip is detected is a control automation process. This sort of automation improves efficiency and reliability while also reducing staffing and training.
- **Information/Decision-Aiding Automation.** This is automation that involves the system making information available to assist in monitoring and decision-making. This may include functions such as integrating, analyzing, and interpreting data before presenting it to personnel. This type of automation helps to improves personnel situational awareness.
- **Interface Management Automation.** With this type of automation, the system lessens the workload of managing and working aspects of the user interface. One example of interface management automation is the system providing a link to the correct procedure when an alarm occurs.
- **Administrative Task Automation.** Finally, this sort of automation facilitates the system performing administrative tasks automatically, such as recording data, sending messages, and updating databases.

Reallocated functions transfer responsibility from human operators to automation. This can happen in many forms as all, or partial, responsibility may be transferred. Though nominal differences exist, operators' cognitive functions in the control room can be characterized by six general cognitive functions (O'Hara and Higgins 2010; EPRI 3002004310 2015; Parasuraman, Sheridan, and Wickens 2000; Sheridan 2002): information acquisition, information analysis, situation interpretation, strategy and planning, decision selection, and response implementation. Automated technologies in their variety of forms assist with one or more of these six cognitive functions performed by a human operator. All cases of function allocation offload one of these tasks to support automation. Though the permutations of automated support are better represented by a sliding scale, it is helpful to conceptualize four types of automation that may assist an operator.

5.2.1.2 Overview of the FA&A Methodology

Deciding how each function is best served by automation is the primary purpose of function allocation. Reviewing how each function is reallocated to ensure operator support and primary plant goals are achieved is the purpose of function analysis. The following method as outlined by Figure 17 elaborates on how to perform FA&A to best serve task analysis. Outputs of the FA&A should cover the following:

- **Function Analysis (Steps 1 & 2)**. Determination of the safety or performance impacts of the function and appropriateness of the allocation (human or support system). This includes appropriately decomposing the function by its goals, subfunctions, processes, and systems based on its grading.
- **Function Allocation (Step 3)**. Identification of functions allocated to people, whether fully or in a shared manner (i.e., these functions are called HAs). These HAs are evaluated in FA&A to ensure that people's capabilities are leveraged with technology to ensure plant safety, reliability, and efficiency. The HAs are used in task analysis for a detailed review to develop task and information requirements that inform HSI design.
- **Results Summary Report (Step 4)**. A report (Step 4) documenting the results of FA&A (Step 1), including a description of the function (e.g., functional decomposition) and identified HAs that will

be analyzed in task analysis, use cases/scenarios (Step 2), as well as any recommended changes in allocation of function based on the methodologies used (Step 3).

The following FA&A methodology is predicated on the assumption that at least a perfunctory function allocation activity has been performed. However, there is a contingency within this methodology to handle function allocation activities. Though presented in a linear process flow, the stages are flexible to accommodate the scope and schedule of the project. For instance, if the operations and training team has limited availability, it may be prudent to combine Step 1 and 2, identifying scenarios as function knowledge elicitation is occurring. What is most important is answering the following three questions:

- Has the function been sufficiently defined so that all the HAs were described for normal, abnormal, and emergency conditions?
- Has the allocation of functions been reviewed and confirmed to reach or exceed plant performance and safety goals by using the appropriate balance, in terms of accounting for the capabilities (and limitations), of the people and technology?
- Are operators equipped with the right support given the function to maintain awareness and carry out plant objectives in accordance with plant safety and performance goals?

The four steps of FA&A are described next.

5.2.1.3 Step 1: Function Analysis

Function analysis serves to identify and define new and changed functions that support the higher vision and first principles for improved plant operation. It is important to maintain the target vision in this analysis to ensure that reallocated functions support plant safety and performance goals and avoid changes that are made for the singular reason of having the available automation to do so. The analysis should describe the functions of interest in sufficient detail to perform a review of function allocation decisions and evaluate subsequent impacts. Also, the HAs impacted by the reallocation should be identified, described, and documented. In the same manner, new HAs that emerge from reallocated functions require identification, description, and documentation as well.

The primary inputs for function analysis include OER (Section 5.1.2), the new-state vision and concept of operation (Section 5.1.4), and HFE grading (Section 5.1.7). It must also consider the business case (Section 5.1.1), capabilities and limitations of vendor offerings (also see Section 5.1.4), and plant I&C infrastructure considerations (Section 5.1.4). FA&A requires a multidisciplinary approach including:

- **Human Factors Engineering** team to ensure that proposed function allocations are justified in achieving plant performance and safety goals. HFE can also ensure that operators are sufficiently supported to perform their tasks given the proposed changed. This team can help propose the need to expand I&C capabilities or request further development from vendors if the outcome matches the cost.
- **Operations and Training** to ensure all impacted or necessary functions are identified, add insight to the impact on HAs affected, and identify procedures and dependent plant systems relating to a function of interest.
- **I&C Engineering** to ensure that the adequacy of current or future plant capabilities match the support automation proposed for reallocated functions.
- **Vendor Experts** to ensure that the capabilities of product sufficiently support operator performance and well-being as well as help new-vision operations meet plant safety and performance goals.

A variety of methods exist to carry out function analysis but not all are created equal. Selecting a method is based on the grade assigned a given function, the effort achievable for the function analysis, and the outcomes deemed necessary by the plant to achieve a successful and licensable modernization. Table 5 lists the methods, team, and outcomes for function analysis, following a graded approach described in Section 5.1.7.

Table 5. Step 1 FA&A process methods and outcomes with graded approach.

Process Methods	Team Members	Expected Outcomes
OER (Section 5.1.2) Results *Perform regardless of grading*	• HFE • Operations • Training	• An initial list of expected and hypothesized reallocated functions and impacted systems related to each • A determination of the value of the function to plant safety and performance objectives • A determination of the function's level of complexity (e.g., temporal demands, physical demands, accuracy demands, cognitive demands such as calculations, conditional procedure steps, number of team members involved)
Structured Interviews *Perform for Level 2 (Medium)* *See Appendix C	• HFE • Operations • Training • Engineering	• A determination of the function's level of complexity (e.g., temporal demands, physical demands, accuracy demands, cognitive demands such as calculations, conditional procedure steps, number of team members involved) • Identification of previously determined important human actions
Team Discussions *Perform for Level 2 (Medium)* *See Appendix C	• HFE • Operations • Training • Engineering	• Identification of previously determined important human actions • An initial list of expected and hypothesized reallocated functions and impacted systems related to each • A determination of the value of the function to plant safety and performance objectives
CTA Techniques **Critical Decision Method (Cognitive Demands) (Section 5.6.3.4)** *Perform for Level 1 (High)*	• HFE • Operations • Training	• A determination of the function's level of complexity (e.g., temporal demands, physical demands, accuracy demands, cognitive demands such as calculations, conditional procedure steps, number of team members involved)
CWA Techniques **Work Domain Analysis**	• HFE • Operations • Training	• A determination of the function's level of complexity (e.g., temporal demands, physical demands, accuracy demands, cognitive demands such as calculations, conditional

Abstraction Hierarchy (Means-End Relationship Across Functions) (Section 5.6.2.1) *Perform for Level 1 (High)*		procedure steps, number of team members involved) • A determination of the value of the function to plant safety and performance objectives
STPA (Control Structure and Unsafe Control Actions) (Section 5.6.4) *Perform for Level 1 (High)*	• HFE • Operations • Training • Engineering	• A determination of the value of the function to plant safety and performance objectives • A determination of the extent of reallocation compared to the existing state • A determination of the function's level of complexity (e.g., temporal demands, physical demands, accuracy demands, cognitive demands such as calculations, conditional procedure steps, number of team members involved)

All methods for higher grades can be applied to lower grade methods if desired. However, lower grade methods cannot be singularly applied to functions with a higher grade. There is an overlap in the outcomes of each method, but no method is expected to yield all four results. It is possible that multiple methods are necessary to achieve all outcomes if the situation requires. The four outcomes contain the following:

- An initial list of expected and hypothesized reallocated functions and impacted systems related to each
- A determination of the value of the function to plant safety and performance objectives
- A determination of the function's level of complexity (e.g., temporal demands, physical demands, accuracy demands, cognitive demands such as calculations, conditional procedure steps, number of team members involved)
- A determination of the extent of reallocation compared to the existing state (e.g., was the function traditionally fully manual and now there will be added decision support or a fully automated process?)

Once complete, the first step of FA&A should yield at least two general outputs: a list of reallocated functions and impacted systems related to each and a review and confirmation that appropriate grades determine the level of effort in Steps 2–4. Further, the results of the second output may require updating a functions grade level based on the risk/complexity. In any case, the result is an understanding of the resources necessary to ensure proper allocation based on the function.

5.2.1.4 Step 2: Identify Scenarios

A scenario should be identified for each identified function impacted by function reallocation. Identifying scenarios becomes more important for functions graded with higher risk and complexity significance. Scenarios identify situations that represent when the function has the most impact on safety and performance or is most frequently performed so it can be realistically evaluated in later HFE activities, including task analysis (Section 5.2.2), HSI tests and evaluations (Section 5.3.4), and V&V (Section 5.4).

Previous activities including OER (Section 5.1.2), the new-state vision and concept of operation (Section 5.1.4), and HFE grading (Section 5.1.7) are relevant inputs. Relevant procedures should be identified and reviewed. The following team is suggested for identified scenarios:

- **Human Factors Engineering Team** to review and confirm scenarios are representative of the tasks important to include for evaluating identified functions.
- **Operations and Training Team** to provide their breadth of procedural knowledge as well as when the functions of interest are most critical or most frequently performed. It is expected that a set of scenarios may be provided, then paired down later based on input from all teams.
- **I&C Engineering Team** may be important to identify scenarios that test new system updates.

Structured interviews are the primary tool for identifying scenarios (Table 6). The level of rigor (i.e., structure in systematically collecting scenario information) is dependent on the HFE grading.

Table 6. Step 2 FA&A process methods and outcomes with graded approach.

Process Methods	Team Members	Expected Outcomes
Structured Interviews or Team Discussions ***Perform for Level 3 (Low)***	• HFE • Operations • Training	• One scenario that covers expected scope of the function.
Structured Interviews or Team Discussions ***Perform for Level 2 (Medium)*** **Refer to Target Information, Appendix D for criteria, and Appendix E for documentation form (optional).**	• HFE • Operations • Training • Engineering	• A collection of the most troublesome scenarios that represent the anticipated range of operational conditions, events, evolutions, and activities for validating the function(s) under test. • A sufficient variety of test scenarios will cover the expected scope of relevant normal, abnormal, and emergency operations. • Scenarios should adequately test the interaction between the function and the individual as well as the function and the team. • Identification of frequently performed functions. • Identification of relevant procedures the apply to the selected scenarios.
Structured Interviews or Team Discussions ***Perform for Level 1 (High)*** **Refer to Target Information, Appendix D for criteria, and Appendix**	• HFE • Operations • Training • Engineering • PRA (if needed to identify time-critical actions)	• A comprehensive collection of scenarios meeting NUREG-0711 requirements of a sufficient variety to represent the anticipated range of operational conditions, events, evolutions, and activities for validating the function(s) under test.

Process Methods	Team Members	Expected Outcomes
E for documentation form (optional).		• A sufficient variety of test scenarios will cover the expected scope of relevant normal, abnormal, and emergency operations. • Scenarios should adequately test the interaction between the function and the individual as well as the function and the team. • Identify frequently performed functions. • Identify relevant procedures that apply to the selected scenarios.

The primary output of Step 2 entails identified scenarios that are described at the level of detail per HFE grading.

5.2.1.5 Step 3: Allocation of Function

Step 3 is split into two sub-steps where one of the two are performed depending on whether the vendor has provided a function allocation proposal (Figure 17).

- *Step 3a (Perform initial reallocation and review)* should be carried out for functions identified as impacted by reallocation but has not yet been explored with how automation may support the function.
- *Step 3b (Review justification for reallocated functions)* should be carried out for functions that have been reallocated, which should be all the functions that have been reviewed for previous steps of FA&A.

Step 3a: Perform initial reallocation and review

Step 3a is performed when the function has no a priori allocation of function. Step 3a provides a technical basis for the assignment of functions to people or automation, based on the capabilities of people and technology. The decision criteria that determine the allocation of function is largely based on NRC guidance, namely NUREG/CR-3331 (1983), which has been cited in more recent standards and guidelines, including EPRI 3002004310 (2015) and IAEA TR-T-2.12 (2021). Appendix F provides a set of decision criteria to perform function allocation here, which is based on these standards.

Additionally, Appendix G provides a comprehensive approach to performing allocation of function. This approach is based on a collection of guidance, including O'Hara and Higgins (2010), EPRI 3002004310 (2015), Parasuraman and colleagues (2000), and Sheridan (2002). Appendix G provides a basis to describe the function in terms of cognitive functions for the current and proposed states and determine the level of acceptability in terms of hypothesized impacts on human-system performance using a consensus-based approach. Impacts on human-system performance can be rated via team consensus and graphed (example shown in Figure 19).

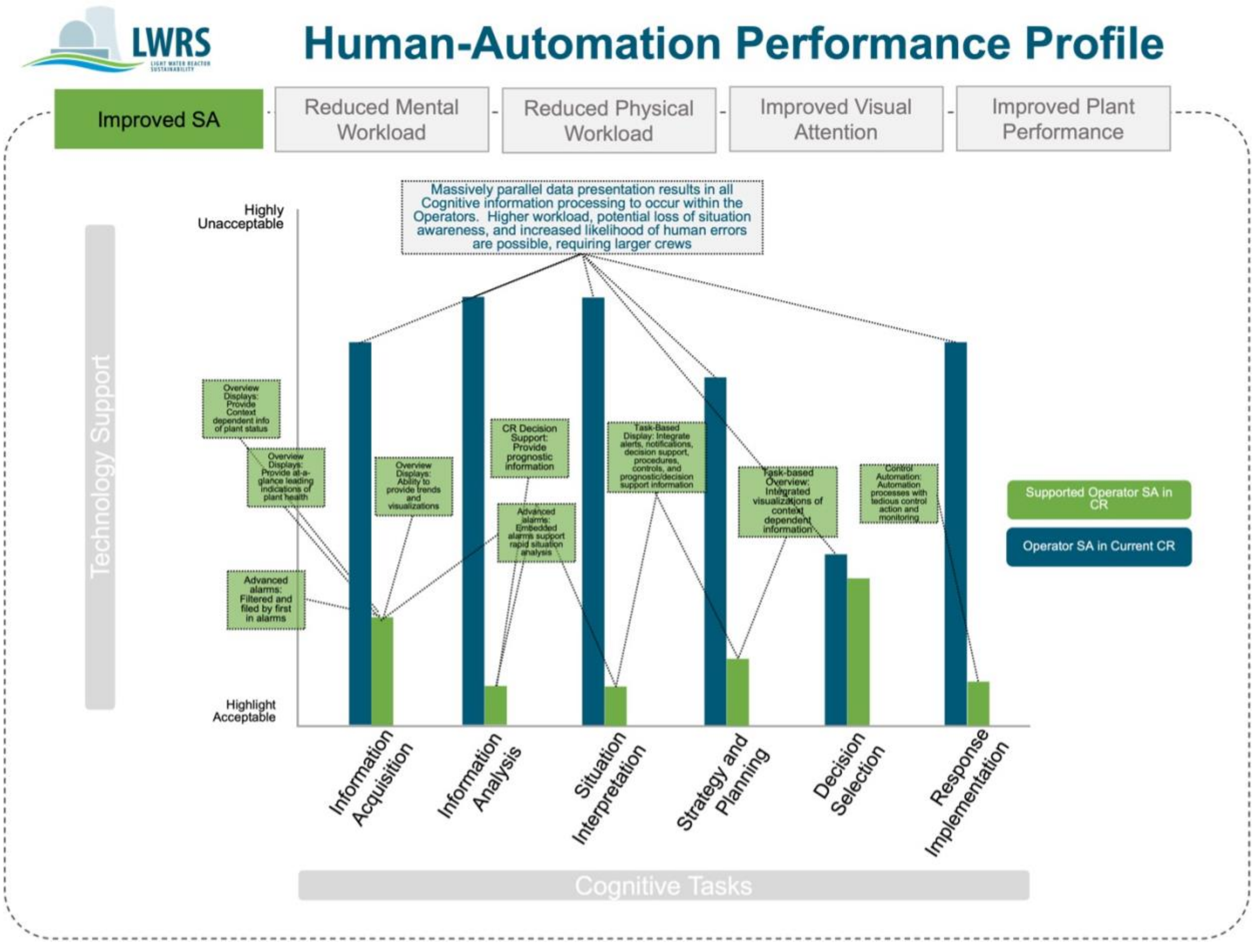


Figure 19. Example function allocation human-automation performance profile from Appendix G.

Using the representation, inferences can be made to achieve the expected outcomes of this process. The expected outcomes include:

- A review of systems containing vendor reallocated functions for impact on plant safety and performance goals
- A determination of cohesion between reallocation decisions with the concept of operations and new-state vision
- An assurance that reallocation decisions align with plant I&C capabilities
- Assurance that scenarios selected to evaluate functions are representative and high impact
- A determination of the extent that reallocated function changes important human actions (e.g., supporting or negatively impacting decision-making, situation awareness).

Inputs that support addressing these tools are done as a team through expert judgment, informed through OER, first principles and new-state vision, domain knowledge, and additional standards and guidelines related to automation (e.g., NUREG-0700 2020).

Step 3a is highly multidisciplinary. All team members should be involved: Human Factors Engineering, Operations and Training, I&C Engineering, Vendor, and Licensing. Licensing experts can provide bounding technical requirements when reallocating the function. All previous inputs and outputs from Steps

1 and 2 are used in Step 3a; these inputs will inform the process methods for this step. Suggested methods to perform Step 3a are listed in Table 7.

Table 7. Step 3a FA&A process methods and outcomes with graded approach.

Process Methods	Team Members	Expected Outcomes
Expert Judgment ***Perform for Level 3 (Low)***	• HFE • Operations • Training	• Initial allocation function using expert judgment. • Operator preference and OER results as inputs can be used.
Structured Interviews or Team Discussions ***Perform for Level 2 (Medium)*** ***Perform checklist in Appendix F to guide discussion**	• HFE • Operations • Training • Systems Engineering • I&C Engineering	• Initial allocation of function using structured approach that accounts for the capabilities of automation and people.
Structured Allocation of Function ***Perform for Level 1 (High)*** ***See Appendix G***	• HFE • Operations • Training • Systems Engineering • I&C Engineering	• Initial allocation of function using detailed structured approach that accounts for the capabilities of automation and people.
OSD (Temporal Demands) ***Perform for Level 1 (High)***	• HFE • Operations • Training	• If time critical, an OSD to inform initial allocation of function to ensure the decision accounts for the capabilities of automation and people.
STPA **(Control Structure and Unsafe Control Actions)** ***Perform for Level 1 (High)***	• HFE • Operations • Training • Systems Engineering • I&C Engineering	• If STPA is used, a control structure, set of unsafe control actions (UCAs), and set of loss scenarios that inform initial allocation of function to ensure the decision accounts for the capabilities of automation and people.
CWA Techniques **Control Task Analysis (Decision Ladders)** ***Perform for Level 1 (High)***	• HFE • Operations	• If CWA is used, results from the control task analysis decision ladders that help to understand the decision processes made across automation and people to inform initial allocation of function to ensure the decision accounts for the capabilities of automation and people.

Step 3b: Review justification for reallocated functions

Step 3b is performed when there is an allocation of function already defined; here, the team reviews the justification given to the allocation using a similar approach to what is described in Step 3a. All team members should be involved in Step 3b: Human Factors Engineering, Operations and Training, I&C Engineering, Vendor, and Licensing. Here, instead of identifying what the function should be, Step 3b reviews the acceptability of the allocation already made using a structured approach, including the use of Appendix F and Appendix G. It should also be noted that Step 3b is interfaced with task analysis (Section 5.2.2), HSI tests and evaluation (Section 5.3.4), and V&V (Section 5.4) when it is determined that the allocation of function is not acceptable.

Table 8. Step 3b FA&A process methods and outcomes with graded approach.

Process Methods	Team Members	Expected Outcome
Expert Judgment ***Perform for Level 3 (Low)***	• HFE • Operations • Training	• A review of allocated function using expert judgment. • Operator preference and OER results as inputs can be used.
Structured Interviews or Team Discussions ***Perform for Level 2 (Medium)*** ***Perform checklist in Appendix F to guide discussion**	• HFE • Operations • Training • Systems Engineering • I&C Engineering	• A review of allocated function using structured approach that accounts for the capabilities of automation and people.
Structured Allocation of Function ***Perform for Level 1 (High)*** ***See Appendix G***	• HFE • Operations • Training • Systems Engineering • I&C Engineering	• A review of allocated function using detailed structured approach that accounts for the capabilities of automation and people.
OSD (Temporal Demands) ***Perform for Level 1 (High)***	• HFE • Operations • Training	• If time critical, an OSD to inform initial allocation of function to ensure the decision accounts for the capabilities of automation and people.
STPA **(Control Structure and Unsafe Control Actions)** ***Perform for Level 1 (High)***	• HFE • Operations • Training • Systems Engineering • I&C Engineering	• If STPA is used, a control structure, set of UCAs, and set of loss scenarios that review the allocated function to ensure the decision accounts for the capabilities of automation and people.
CWA Techniques **Control Task Analysis (Decision Ladders)** ***Perform for Level 1 (High)***	• HFE • Operations	• If CWA is used, results from the control task analysis decision ladders help to understand the decision processes made across automation and people to review the allocated function to ensure the decision accounts for the capabilities of automation and people.

Outcome of Steps 3a and 3b

The output of Steps 3a and 3b entails the evaluation of impacts on human/automation allocation on HAs and impacted system, including impact to plant safety and performance. Technical bases can be made for allocated and reallocated functions. The output should thus make it possible to confirm the following:

- Alignment with any applicable bounding technical requirements
- Alignment with overall vision and concept of operations and OER findings
- Alignment with vendor I&C capabilities (considering feasibility, cost, anticipated benefits)
- Alignment with human capabilities (physical and cognitive).

Step 4: Document the results of function analysis and allocation

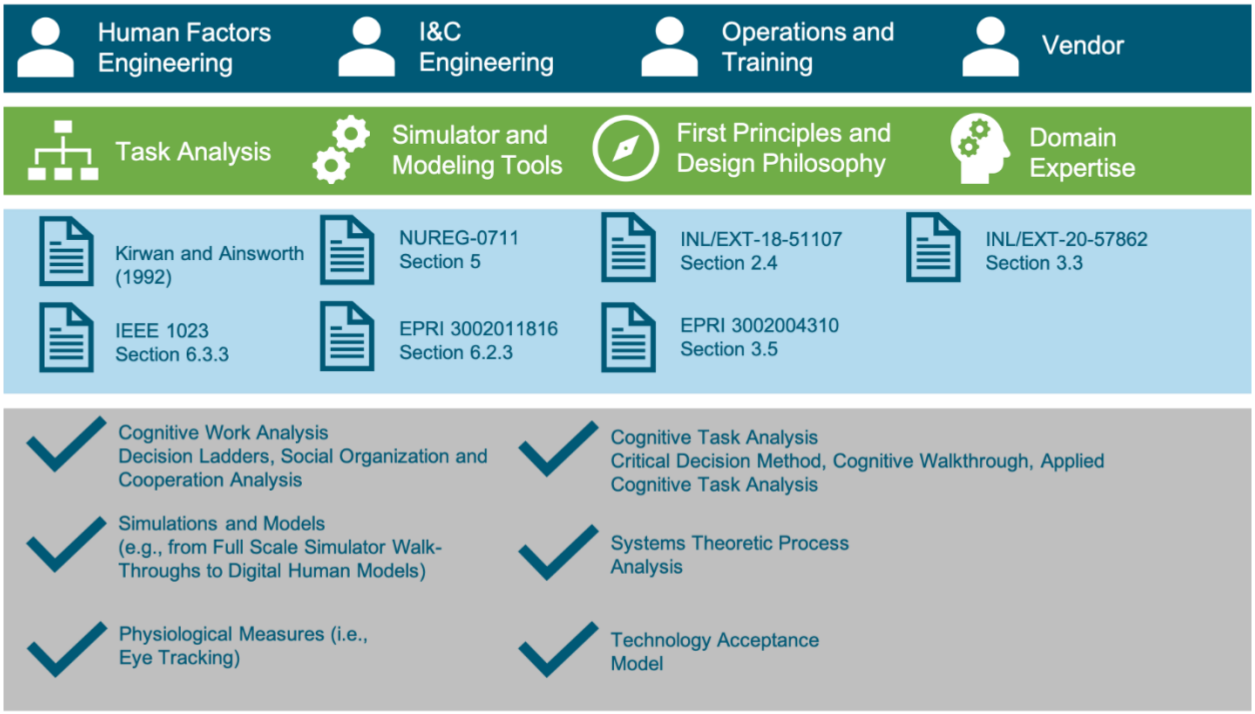
The objective of Step 4 is to document the Has, associated technical bases, and the preliminary system design requirements, including automation requirements. The documentation serves as the primary input to task analysis (Section 5.2.2). Table 9 outlines the level of detail for documentation based on the HFE grading.

Table 9. Step 4 FA&A process methods and outcomes with graded approach.

Process Methods	Team Members	Expected Outcomes
High-Level Documentation of FA&A ***Perform for Level 3 (Low)***	• HFE • Operations • Training	• High-level description of the function, including expect role of automation and human. • Summary of basis for allocation (e.g., expert judgment, operator preference).
Detailed Documentation of FA&A ***Perform for Level 2 (Medium)***	• HFE • Operations • Training • Engineering • Procedure Writer	• Description of the most impacted changes (i.e., from the most troublesome scenarios) in function allocation. • Description of expected impacts on personnel (cognitive and physical demands). • Mapping of relevant scenarios and their associated procedures that pertain to the allocated function to support subsequent HFE activities that will validate the appropriateness of allocated function. • Summary of automation requirements. • Technical basis for allocation (e.g., expert judgment, operator preference).
Detailed Documentation of FA&A ***Perform for Level 1 (High)***	• HFE • Operations • Training	• Description of all impacted changes in function allocation.

	• Engineering • Procedure Writer	• Description of expected impacts on personnel (cognitive and physical demands). • Mapping of relevant scenarios and their associated procedures that pertain to the allocated function to support subsequent HFE activities that will validate the appropriateness of allocated function. • Summary of automation requirements. • Technical basis for allocation (e.g., expert judgment, operator preference).

5.2.2 Perform Task Analysis



There are several different task analysis methodologies (e.g., Kirwan and Ainsworth 1992). The methodology described here crosswalks the recommendations made in NUREG-0711 (Section 5). Additionally, any emerging task demands associated with the transition from a traditional concept of operations to one incorporating greater levels of automation are described here. In the following paragraphs, a set of common task analysis methods that support the objectives covered in NUREG-0711 (Section 5) are discussed. The following steps should be performed for task analysis.

5.2.2.1 Step 1 - Identify Tasks

The first objective is to identify the specific tasks that operators will complete to accomplish their functions. In terms of plant design and modification, a graded approach is taken to ensure that activities that protect public health and safety are prioritized. Thus, all important HA must be included with a greater focus on safety HAs. Applicants use probabilistic and deterministic analyses to identify these important safety-related HAs (Section 5.2.3). The tasks chosen for the analysis must include the full range of plant operating modes: startup, normal operations, low-power and shutdown conditions, transient conditions, abnormal conditions, emergency conditions, and severe accident conditions. Within this range of operating modes, the tasks included should cover the following:

- Tasks that have been designated as not important but would have a negative consequence if executed incorrectly
- Tasks that are new, such as tasks in new systems or procedures
- Tasks that will be performed differently than before
- Tasks involved in monitoring automated systems that are important to plant safety
- Tasks related to automated support aids (e.g., computer-based procedures)
- Tasks involved in identifying the failure or degradation of automation and subsequent backup responses

– High demand tasks (e.g., high levels of workload)

– Tasks critical to plant safety that are implemented during maintenance, tests, inspections, and surveillances

– Tasks involving potential concern for employee safety (e.g., maintenance tasks in containment)

According to NUREG-0711, the applicant should describe the criteria used to decide which tasks were included in the analysis. Additionally to risk analysis integration (Section 5.2.3), the HAs identified in FA&A (Section 5.2.1) serve as a key input into task analysis, as well as OER (Section 5.1.2).

5.2.2.2 Step 2 - Develop High-Level Task Descriptions

The second step focuses on creating high-level task descriptions by identifying the alarms, information, controls, and task support needed to perform the tasks under analysis. Thus, the applicant begins the task analysis by detailing the actions operators must undertake. The level of detail must be sufficient to define the alarms, information, controls, and task support required to successfully complete the task. As relevant to the task, the detailed task narratives should include the following: alerts, information on parameters and feedback concerning adequacy of action taken, decision-making, response, teamwork and communication, workload, task support, workplace factors, situational and performance shaping factors, and hazard identification. The applicant must also identify the relationships between the tasks and estimate how long it will take to perform each task. The applicant must identify the number of people needed to successfully complete the task. The knowledge and skills needed to complete the task must be identified. The task analysis will be iterative and updated as the analysis progresses and as the design is better defined.

NUREG-0711 and EPRI 3002004310 (2015) align with one another in their recommendations for task analysis. Task analysis inputs are the OER, identified important HAs and potential errors, HAs from the function allocation and modification design, identified affected system design, and design requirements. EPRI guidance aligns with NUREG-0711's two objectives for task analysis. The output from the task analysis will serve as the task requirements input to the HSI design. Additionally, task considerations will serve as input for other HFE activities (see Table 10).

Table 10. Task analysis guidance crosswalk between NUREG-0711 and EPRI 3002004310.

<table>
<tr><td colspan="2">Inputs:
• OER
• Important HAs and potential errors
• HAs from FA
• Modification design, affected system design and design requirements (i.e., design information about the planned modifications, workplace and workstation design, procedures)</td></tr>
<tr><th>EPRI 3002004310</th><th>NUREG-0711</th></tr>
<tr><td>Identify tasks, assign risk significance, identify reusable task analyses</td><td>Identify the specific tasks personnel perform to accomplish their functions</td></tr>
<tr><td>Develop high-level task descriptions and select task analysis methods</td><td rowspan="3">Identify the alarms, information, controls, and task support needed to perform those tasks.</td></tr>
<tr><td>Apply task analysis methods and develop detailed task descriptions</td></tr>
<tr><td>Identify task requirements and additional considerations</td></tr>
<tr><td colspan="2">Outputs:
• Task requirements as input to HSI design.
• Task considerations for input to other HFE activities.</td></tr>
</table>

Generally, HAs identified from FA&A (Section 5.2.1) are the starting basis for task analysis. These HAs are then described at a high-level to include information such as (EPRI 3002004310 2015; NUREG-0711 2012):

- Alerts
- Information
- Decision-making
- Response
- Teamwork and communication
- Workload
- Task support
- Workplace factors
- Situational and performance shaping factors
- Hazard identification

This high-level information can be completed using existing task analyses, review of procedures, interviews with operations and training, or other related resources (EPRI 3002004310 2015).

5.2.2.3 Perform Detailed Task Analysis

Next, detailed task analyses are selected and performed based on the supporting information above. Several task analysis methods are suggested below, as well as in Appendix H (e.g., Kirwan and Ainsworth 1992; EPRI 3002004310 2015). A tool that automates many of the task analysis methods can also be used (Kovesdi and Le Blanc 2020). The tool allows the human factors engineer to work through a set of action sequences once to provide multiple task analysis outputs, including OSDs, heat maps, link analysis, timeline and workload analysis, and a tabular task analysis format.

Tabular Task Analysis

Tabular task analysis (TTA) is a decomposition technique that details each step and sub-step. Consequently, TTA is a bottom-up approach that provides a task and information requirements at the step and sub-step levels. TTA is detailed and structured but remains flexible in collecting specific alerts and information requirements concerning the task. Similarly, TTA captures information on the following for the tasks being analyzed: cognitive and decision-making requirements, workplace and task support elements, teamwork and communication considerations, situation and performance shaping factors, and identifying hazards. The amount of detail this method provides is highly desirable; however, it can be time consuming.

Hierarchical Task Analysis

Hierarchical task analysis (HTA) is also a decomposition technique; however, it is a top-down approach and, thus, begins with goals, sub-goals, operations, and task plans. This method also provides information and task requirements. In terms of alerts and information requirements, HTA provides information on what information is needed. Where and how the information will be captured is less clear. HTA in its original instantiation does not include cognitive or decision-making elements. It is a base analysis from which other task analysis approaches are launched from. Similarly, HTA does not capture workplace or task support information. Teamwork, communication considerations, situation and performance shaping factors, and the ability to identify hazards are also not explicitly addressed.

Link Analysis

Link analysis focuses on the activity flow between different sections of a system in performing a task. Link analysis specifically focuses on the connections and, thus, is a good method to collect information on the communication between operators. This analysis would support collecting information on alerts and indications. Link analysis can help in understanding the sequence of events and can be used with graph analyses. It does not explicitly address cognitive and decision-making factors, workplace and task support elements, situation and performance shaping factors, or hazard identification. This method focuses on aggregate sequences and not individual interactions.

Applied Cognitive Task Analysis

Applied cognitive task analysis (ACTA) (also described in Section 5.6.3.4) is a structured approach that describes the cognitive demands of a task or scenario. Information requirements collected are information needs, training, and cognitive demands. ACTA progresses through four main phases: task diagram interview, knowledge audit interview, simulation interview, and cognitive demands table. To understand the definition of a task and what expertise is required for a task, the analyst can collect alert and information requirements. This analysis method formally collects information on cognitive and decision-making factors. This feature is the primary benefit of this method. Additionally, ACTA also can collect information on workplace and task support information, such as workarounds and decision aids. During the cognitive demands table phase, cognitive aspects of teamwork and communication can be collected. Situation and performance shaping factors and hazards related to cognitive demands can be collected as well. This method also is time consuming due to the multiple sessions.

Goals, Operators, Methods, and Selection Rules

Goals, operators, methods, and selection rules (GOMS) is an analysis method to understand human computer interaction. Goals are defined as what the person intends to achieve. Operators are the actions taken to reach the goal. Methods are defined as the sequences of operators to reach the goal. GOMS recognizes that there is more than one method to reach a goal. If there is more than one method, selection rules are used to decide which method is preferable over others. This method comes with certain assumptions. The first assumption is that skilled behavior can be organized as a set of productions. The second assumption is that all behavior can be viewed as goal directed. The third assumption is that, if an obstacle is encountered, the system will break the obstacle down into smaller problem definitions. Then, the system will work through these problem spaces until the obstacle is overcome. GOMS can provide information on how performance changes and how long it takes to complete tasks. GOMS decomposes how the person interacts with a system into primitive actions. Actions can be either physical, cognitive, or perceptual. Usually, these actions involve using a software interface. The granularity can be adjusted to capture the level of detail the analyst wants. The output is described as goals, operators, methods, and selection rules, task specifics, and performance data for different scenarios. GOMS follows the taxonomic conventions consistent with goal-directed processing, declarative and procedural knowledge, production rules, and perceptual and cognitive processing. A specific computer language has not been developed for GOMS. It is a theoretically motivated modeling and analysis method. The GOMS method does not have an error model. Risk profiles would need to be generated by the analyst based on their own definitions. GOMS is meant to be used after HSI requirements have been selected. Other groups have developed software; see Kovesdi and Joe's (2019) "Exploring the Use of Cognitive Models for Nuclear Power Plant HSI Evaluation" for a review of common GOMS-based cognitive modeling tools.

Talk-Through/Walk-through Analysis

A talk-through is a verbal demonstration of a walk-through. A walk-through is a knowledge elicitation technique where a domain expert (i.e., also referred to as subject matter expert) demonstrates a set of tasks (i.e., often using procedures) to describe it, highlighting potential issues or identifying the important actions (Kovesdi, Joe, and Boring 2018). Both talk- and walk-through analyses are commonly used for knowledge elicitation. The following is a description of the talk-through/walk-through method that was used at Seabrook. The talk-through in the simulator occurred in the following way:

- Senior reactor operator read the basis of the procedure and then more questions about purpose and functions.
- As the senior reactor operator read the procedure, one to two reactor operators performed each step. The reactor operators stopped after each step to permit human factors engineers and I&C engineers with HF training to observe or take measurements, ask questions, comment, take notes (objectives, decision criteria, displays required/available, controls required/available, consequences of error, etc.)

Each nonoperator review team member had a copy of the procedure with columns for objective, criterion, displays required and available, controls required and available, consequences of error, and other. These columns were to the right of each step in the procedure.

- For "objective," the reviewer needed to consider what the purpose of that step was. Sometimes, there were multiple objectives. If the purpose wasn't clear, the reviewer needed to make note of the lack of clarity. The reviewer needed to consider what was to be achieved and how to achieve it.
- For "decision criteria," the reviewer needed to know how the operator was to know that they had completed the step. What variable to look at? What fixed number or other variable to compare it to? What does successful completion mean here? Are there gray areas here? Is it clear when the operator has successfully completed the task? Does this change depending on operating mode or some other variable?
- Under "displays required and available," the reviewer needed to consider what was the necessary information to be displayed to the operator (e.g., variables, quantitative or qualitative, position, rate, dynamic range, accuracy, scale units, and what direction of indication was consistent with expectations). The reviewer needed to assess whether there was any missing information.
- Under "controls required and available," the reviewer needed to know what variables needed to be controlled and to what accuracy and what was the range or was control exerted through one or more discrete settings. Did the operator enter a value or was it adjusted continuously? What was the force, direction, and displacement of the operator action? Is this needed and is it consistent with the display?
- For "consequences of error," the reviewer needed to know what could result from an operator error. If the step was not completed correctly, would the consequences be apparent to the operator? Would it be critical?
- For "other," the reviewer made any other notes about problematic issues that didn't fit in the other categories.

Dynamic real-time walk-throughs were conducted in which all time-critical procedures were repeated. The walk-throughs were nonintrusive, which meant observers did not make any commentary. Observers could take note of timing, inter-operator coordination, and body movements. The team also was able to observe functional recovery guidelines and critical safety function status trees.

Follow-up assessments on design changes were conducted. Changes compared to existing board. Task analyses were completed multiple times with each session lasting two–five days. Parts of the procedure were repeated.

Control Task Analysis (Cognitive Work Analysis)

Control task analysis (ConTA) is the second phase of CWA (Section 5.6.2.2). The purpose of ConTA is to document what decisions are made and the states and processes that are involved in a particular control task. Lamoureux and Chalmers (2016) used the modeling tool, the decision ladder, to conduct the ConTA. Section 5.6.2.2 describes ConTA within the context of the larger CWA framework. The reader may refer to this section if ConTA is applied in CWA. The advanced methods that apply to task analysis can be found in Section 5.6, and include cognitive task analysis, STPA, eye tracking, and the TAM.

Operational Sequence Diagrams

The study of how a task is accomplished in terms who is involved and what controls and information is needed is often well suited for operational sequence analysis and its output, OSDs (Kirwan and Ainsworth 1992; Kovesdi and Le Blanc 2020). OSDs provide a graphical means to visualize the sequence of a task, whether spatially or temporally.

The application of spatial OSDs can be applied to understand the information and task requirements of how an operator must navigate the physical environment to accomplish the task. This information allows the human factors engineer to understand the order of operation to complete a task, the physical demands of searching for information and controls, and the specific locations to which the operator must go to complete the task. Insights from the spatial OSDs can help with HSI design (Section 5.3) through informing *what information* should be grouped (to reduce excessive navigation) and *what systems* should be accounted for in a task.

Temporal OSDs provide a way of representing the order in the time that a task is carried out. The benefits of temporal OSDs often serve to inform where there may be an excessive workload in terms of temporal demands. For example, if there is a known time limit in performing a task, excessive information and control actions seen by the operator in the sequence may be readily identified and this input can invoke re-evaluating the function allocation (Section 5.2.1).

Workload Analysis

A workload analysis evaluates the physical and cognitive demands of a task (Kirwan and Ainsworth 1992; EPRI 3002004310 2015; Kovesdi and Le Blanc 2020). In its most general form, workload analysis may be supported through timeline analysis (e.g., such as OSDs) to understand the time demands of performing a task to a given time limit (Kirwan and Ainsworth 1992; EPRI 3002004310 2015). Time completion estimations may be supported through known completions or through modeling approaches (e.g., see GOMS above or simulation techniques in Section 5.6.6.2).

With time-critical actions, if a task requires more completion time than what is available, the temporal workload is exceeded, and the task requirements need to be re-examined in function allocation (Section 5.2.1). Likewise, the cognitive workload can be evaluated using self-reporting techniques in combination with simulation and modeling (Kovesdi and Le Blanc 2020; Kovesdi, Joe, and Boring 2018). Section 5.6.6.2 provides insights into the use of simulation to support walk-through analyses that focus on workload. Further, Section 5.3.4 highlights common HFE methods that can be used to evaluate workload; a detailed review of workload measured can be found in NUREG/CR-7190 (2015).

5.2.2.4 Document Results of Task Analysis

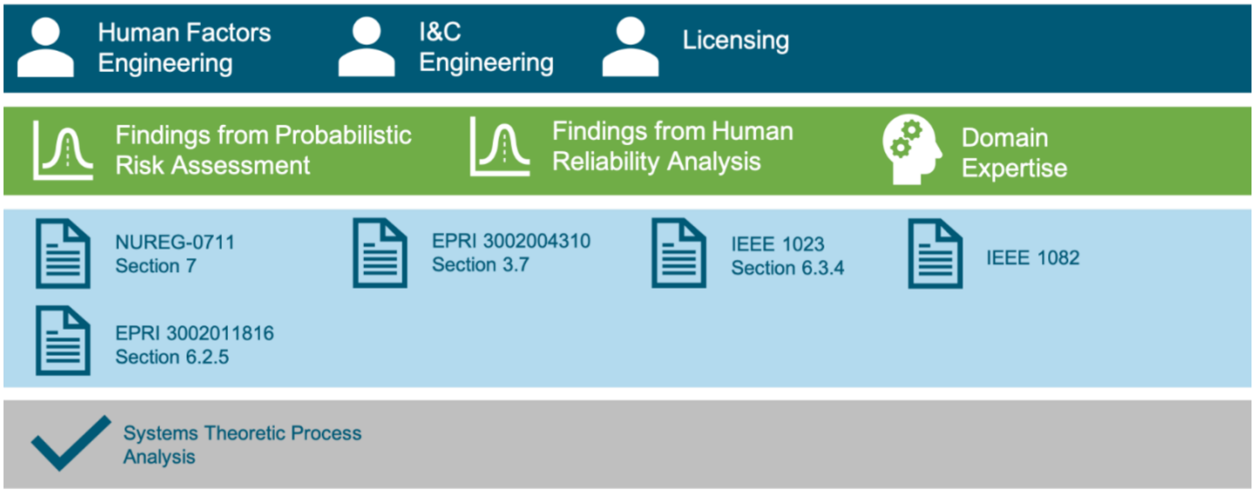
The results of the task analysis should be documented in a result summary report. Within this report, the primary outputs include descriptions of the methodology and rationale for use, the tasks and scenarios considered, as well as the task and information requirements identified from the high-level and detailed analyses. Specific task and information requirements, as described in NUREG-0711, include the:

- Identification of hazards
- Estimated time to perform each task
- Number of people (i.e., crew) to perform each task

– Knowledge, skills, and abilities required.

These outputs will be used as technical bases for design synthesis (Section 5.3) and V&V (Section 5.4).

5.2.3 Integrate Risk Analyses



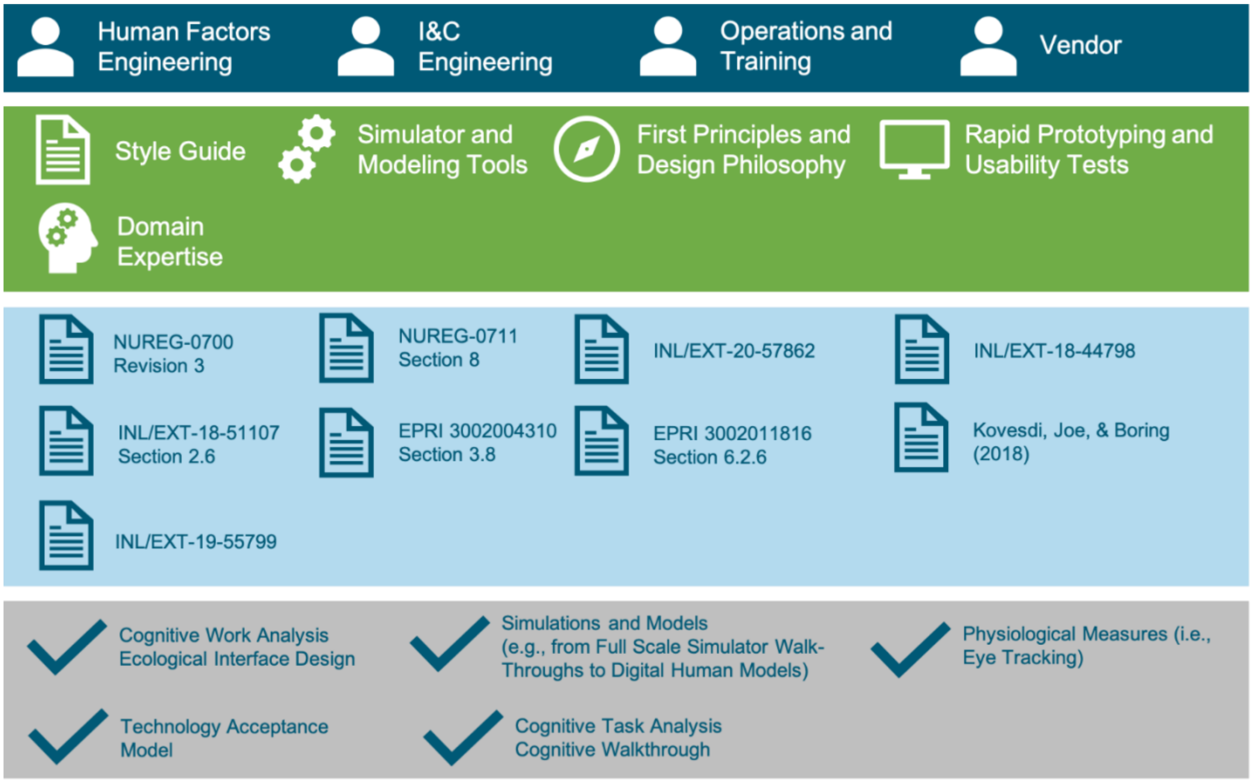
The HAs that are risk-important should be identified and documented across the HFE activities described in (EPRI 3002004310 2015; NUREG-0700 2012). Within this report, these HFE activities include:

- OER (Section 5.1.2)
- FA&A (Section 5.2.1)
- Task analysis (Section 5.2.2)
- HSI design (Section 5.3)
- V&V (Section 5.4)
- Implementation and operation (Section 5.5).

In upstream activities like OER, FA&A, and task analysis, focused questions can be administered to understand impacts of the existing and proposed system configuration on the risk of human error. For example, focused questions administered to licensed operators during OER of previous incidents attributed to a human error caused by the system should be identified and documented accordingly. For FA&A and task analysis, there should be a focus on the impacts of function allocation and associated task and information requirements as they impact the risk of human error. The application of HFE design principles should be applied to mitigate any identified risk and further reviewed in later HFE activities, such as HSI design, V&V, and implementation and operation.

If STPA is being used (Section 5.6.4), the use and reuse of unsafe control actions (UCAs) and associated loss scenarios can serve as a framework for documenting potential human errors where either outputs or inputs interact with the operator from the control structure. Ultimately, any planned modifications that are part of the new and interim states must achieve acceptable levels of safety and reliability. The application of integrating risk analyses is important in achieving these goals.

5.3 Synthesize Inputs into Design



The design synthesis (or HSI design) translates the vision, concept of operations, and human-technology integration requirements into the HSI characteristics and functions that will be safely and effectively used by plant personnel (NUREG-0711 2012). Here, the inputs from the vendor capabilities, alignment to the new-state vision and concept of operations, utility human-technology integration requirements, and results from early tests and evaluations must be accounted for and aligned appropriately (Figure 20).

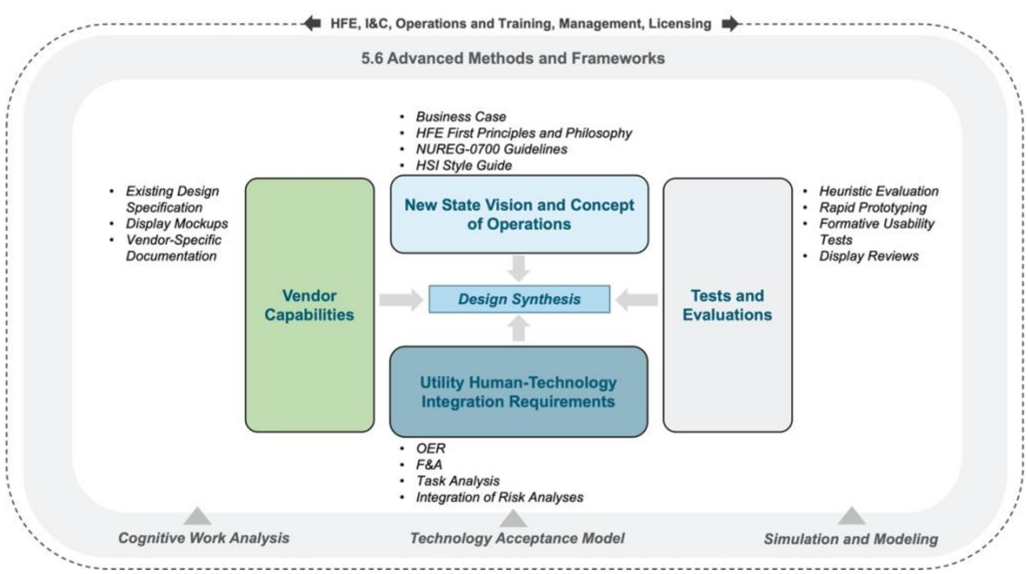


Figure 20. Inputs and activities for synthesizing inputs into design.

A key outcome that comes from this synthesis is the development or update of the HSI style guide along with finalized HSI designs (EPRI 3002004310 2015; NUREG-0711 2012). Per NUREG-0711 Section 8 (2012), the HSI style guide is the document that contains HFE guidelines that are specific to the modification/system at hand. The HSI style guide ensures that state-of-the-art HFE principles and task and information requirements are considered in a consistent manner such that they meet the vision and concept of operations within the configurability of the vendor's platform. In a substantial transformation that encompasses the entire plant or fleet, the basis of a style guide becomes particularly important. The following subsections describe how the four specific inputs are applied in design synthesis to develop a HSI style guide.

5.3.1 Consider Vendor Capabilities

To ensure cost-effectiveness during the design, development, implementation, and operation of the modification and its associated HSIs, it is important to be sensitive to the capabilities and limitations of the selected vendor platform's standard features and capabilities (INL/EXT-19-55799 2019). A detailed description of ensuring an effective lifecycle support strategy is provided in INL/EXT-19-55799. Though, from a HFE standpoint, it is important to note that the application of design principles, recommendations given from tests and evaluations, and inclusion of task and information requirements should be integrated in a way that is bounded by the vendor's test regimen and is within their scope of future hardware and software migration. In other words, all things being equal, having a design feature that satisfies all other HFE requirements and inputs and is part of the standard configuration package of the HSI will reduce costs in development and in lifecycle management. Reviewing vendor design documentation is important in design synthesis. Further, to successfully ensure that design inputs are integrated effectively, a multidisciplinary team that includes key stakeholders from the utility, vendor, and HFE is critical to identify paths forward and to resolve potential conflicting inputs where appropriate.

5.3.2 Apply Principles Guiding the Vision and Concept of Operations

The HSI designs and style guide should be consistent with the vision and concept of operations for the envisioned and interim states. As discussed in Section 5.1.4, the use of first principles should be applied across the vision, concept of operations, and consequentially realized in the design synthesis. The principles provide examples of the application across seven general capabilities, including alarms, overview displays, task-based displays (i.e., including computer-based procedures, digital HSIs, soft controls, and interface management), decision support, automation, real-time communication, and equipment monitoring.

The guiding principles provide high-level guidance into the functional and physical considerations of the new state, which are grounded in HFE research. Moreover, the application of detailed guidance and lessons learned can be applied here to inform the HSI style guide where the first principle applies. Table 11 illustrates the translation of first principles discussed in Section 5.1.4 to detailed guidance that are encompassed from the principle. As seen in Table 11, the first principles used to inform the new-state vision and concept of operations can be applied in detail during design by referencing the detailed guidance that comprise the principle.

Table 11. Translation of first principles to detailed guidance.

Normal Operations	
Topic: Equipment switching and tagging	
Principle	**Detailed Guidance**
Interlocks, lockouts, and lockins should be designed to indicate which actions are being blocked and what conditions activated the block (NUREG-0700, Rev 3 2020).	**NUREG-0700 7.3.4-3 Visibility of Interlocks, Lockouts, and Lockins** Interlocks, lockouts, and lockins should be designed to indicate which actions are being blocked and what conditions activated the block. *Additional Information: A lockout blocks inputs that it considers*

Normal Operations	
Topic: Equipment switching and tagging	
Principle	**Detailed Guidance**
	unacceptable or not achievable. When this occurs, the user should be able to determine why an input was blocked and what inputs are acceptable, especially for context-sensitive validation in which complicated rules may be used for assessing the acceptability of an input value. An interlock should inform the user of the condition(s) that activated it and the conditions that must be satisfied to release it. Lockin features should show the user what action is being "locked in" (i.e., the action that is being caused to operate without interruptions) and how it can be canceled.
Remove labor-intensive actions, such as performing manual equipment switching when possible, while giving the operator the right to override as needed [INL/EXT-20-58538 2020, pp. 36]	**INL/EXT-20-58538, pp. 36** Task Workflow LOA **Finding 20: ADAPT's philosophy of re-allocating verification steps to automation, where plant equipment in the correct state would be omitted from operator verification, was considered acceptable** Researchers discussed with one operator (OP5) the underlying philosophy of ADAPT's task-based display system where the system omits certain steps that do not require immediate action, based on having data from the plant. For example, in some procedures there are steps to verify that certain plant equipment is in a given state. With the use of online monitoring data, ADAPT's philosophy is to essentially omit procedural steps that do not require the operator to take action. If the equipment is in the correct state, then the operators will proceed forward in the procedure; however, if the equipment is not in the correct state, then ADAPT will provide the correct course of actions needed. The intent of this philosophy is to reduce burden on the operator. However, within this new concept of operations, it is important understand certain circumstances to which this underlying philosophy is no longer useful. Hence, researchers followed on to this discuss by asking if there were any situations where ADAPT's philosophy may not work (i.e., see Q32 in Table 12). OP5 did not identify specific situations where ADAPT's philosophy of omitting verification steps would not work (i.e., OP5 was generally positive towards this approach). Though, OP5 did note important ways in which operators interact with their existing procedures that could serve as design input for ADAPT. OP5 mentioned that there are times when the operators must perform a series of steps (e.g., two or three) in a row where the steps are read and then performed within a timely manner (e.g., operating multiple equipment of the same type in sequence). In the existing control room, there are physical indications and controls on the control board; however, the way in which these activities are performed digitally may be cumbersome if designed improperly such as in a way that requires excessive or untimely clicking. OP5 closed this discussion by favoring the use of automation in this context such as by automating control sequences, providing lockouts where operators can only perform actions in the acceptable timeframe, as well as track actions made by multiple operators.

A final point worth mentioning is that the use of CWA may enhance the application of HFE first principles through the application of Ecological Interface Design (EID), which can be leveraged through the work domain analysis (Section 5.6.2.1) phase (e.g., Le Blanc et al. 2018; Stanton et al. 2017; Burns and Hajdukiewicz 2017; Hettinger et al. 2020). EID takes the approach that system users must make decisions within the work domain (Burns and Hajdukiewicz 2017). As such, EID positions that the work domain must be systematically analyzed to understand to goals and constraints in place that enable users to make these decisions. Finally, EID posits that visualization can be used to show the user the constraints within the work domain to enhance decision-making.

Philosophically, the application of EID differs from traditional user-centered approaches that base design decisions primarily on the feedback collected from end users. Instead, following the constraints-based basis of CWA, EID posits that users do not always know all the constraints, particularly with complex systems like NPPs. Thus, users may not provide complete feedback of all possible circumstances that the NPP may endure, so design decisions cannot fully anticipate the unexpected. Here, EID provides an explicit display of the system constraints that govern the system through visualization. EID applies visualizations that present the system state across its constraints through an analysis of the work domain at hand, which is part of the larger CWA framework.

It's important to recognize that CWA and EID do not discredit collecting input from domain experts; rather, the input that is collected (e.g., either through interviews, documents) are focused on understanding the work domain, as opposed to focusing on the preferences of certain design features. Pragmatically, a combination of traditional user-centered approaches that is discussed throughout this report, and referenced resources like NUREG-0711, EPRI 3002004310, and other documents are still very useful in design synthesis, as lessons learned from previous OE and knowledge elicitation from end users like licensed operators provided vital feedback (e.g., Boring et al. 2015). Though, the use of EID and its principles may further enhance design, especially if CWA is already applied. An example of EID in recent work by the LWRS Program comes from work published in INL/EXT-20-57862 (Kovesdi et al. 2020; Figure 21).

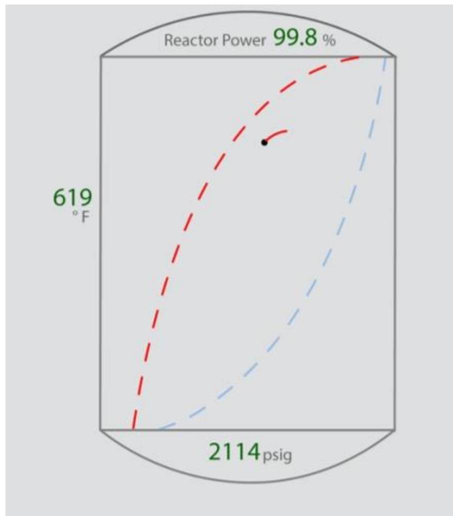


Figure 21. Application of EID in the ADAPT concept plant overview display system.

The development of this visualization came from a combination of EID and user-centered design methods. User-centered design approaches were used to identify key parameters important to plant health, including specific numerical values that are important to be visible. EID was applied on several display elements, including the integration of temperature and pressure within the primary side of the NPP. In this visualization, the graphic presents the constraints of temperature and pressure within the reactor, including normal and abnormal operating states (high and low), as indicated by the red and blue dotted lines. The dot indicates current state, and the red dotted line provides trending information of where temperature and pressure were previously. At a glance, the operator has a detailed reference to these core indications, their relations, and trending of these.

5.3.3 Integrate Utility Human-Technology Integration Requirements

Integrating technology should take a *needs-based approach* such that the task and information requirements collected in OER, FA&A, task analysis, and integration of risk analyses are a foundation in making design decisions to the modifications at hand. Human error traps that were previously identified, technical, task, and information requirements, and automation considerations must be accounted for in the HSI design and style guide. These considerations should also be reviewed within the context of the vendor's platform capabilities and first principles. Some considerations coming from OER, FA&A, task analysis, and integration of risk analyses that are pertinent to design include:

- Have lessons learned and issues been adequately addressed where appropriate?
- Were human error traps previously identified from risk analyses been adequately addressed?
- Were the bounding technical requirements (where applicable) adequately addressed?
- Are all the use cases (scenarios) identified from the FA&A and task analysis accounted for in the design?
- Has the allocation of personnel and automation been appropriately applied?

– Are the task and information requirements adequately addressed?
  - Do the displays (alarms and indications) provide complete information?
  - Can the information and controls be effectively accessed in a timely manner?
  - Can the displays (alarms and indications) be viewed in an ergonomic manner (i.e., within viewing angles and meeting legibility requirements)?
  - Can the controls be accessed in an ergonomic manner (i.e., within reach and within the physical capabilities of people)
– Will the displays (alarms and indications) support situation awareness?
– Are there any impacts on cognitive and physical workload?

5.3.4 Deploy Tests and Evaluations

The synthesis of vendor capabilities, principles, and human-technology integration requirements should be confirmed using tests and evaluations. Tests and evaluations performed with the design are different from V&V (EPRI 3002004310 2015). With the former, the intent is to identify design issues and correct these issues before the design is finalized; tradeoffs between design decisions can be made using rapid prototyping and comparative usability tests within a simulator testbed. The latter (discussed in the next section) is typically performed when the design is finalized, and the intent is to confirm that the design meets the human-system performance goals. The latter may include acceptance criteria whereas the former may utilize qualitative measures. A framework that can be applied to understand how common HFE methods and measures can be effectively applied come from Kovesdi, Joe, and Boring (2018), as shown in Figure 22.

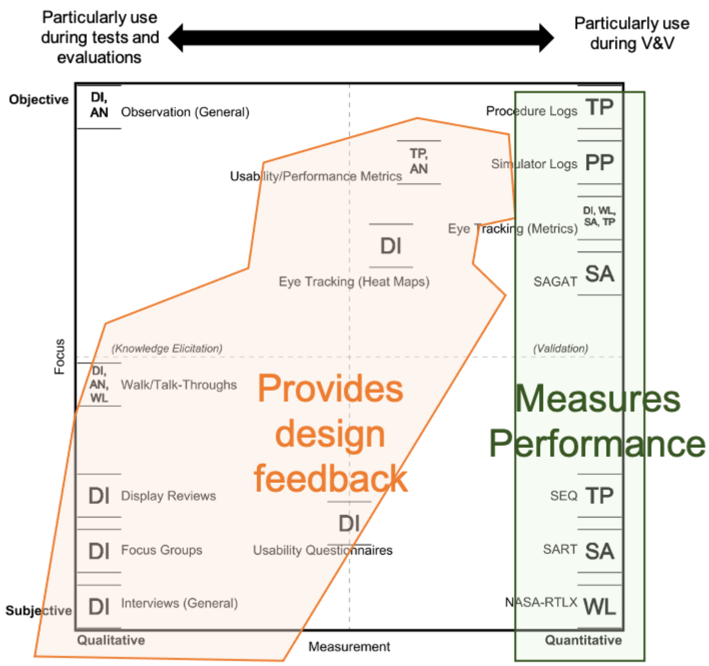


Figure 22. Landscape of HFE methods and measures (adapted from Kovesdi, Joe, and Boring 2018).

Figure 22 provides a mapping of common HFE methods and measures across three dimensions; the figure adds additional context to highlight where each method and measure can be best leveraged depending on supporting tests and evaluations or V&V. The y-axis maps to the degree of being subjective or objective, as described in IEEE 845. Measures that are objective include data that is collected from human behavior and subjective measures include data that comes from people's judgment and opinions. Methods and measures in-between include a combination of objective and subjective measures. The x-axis denotes the degree of being qualitative or quantitative. Qualitative data refers to descriptive data whereas quantitative provides a degree of measurement. Finally, the embedded letters refer to the dimensions of addressing one or more human-system performance criteria described in NUREG-0711. These include DI – Design Input, PP – Plant Performance, TP – Task Performance, SA – Situation Awareness, WL – Workload, and AN – Anthropometric/Physiological Factors.

For tests and evaluations that are geared for identifying design issues and correcting them in rapid prototyping lend towards utilizing methods that support design input. Here, combining display reviews, interviews and focus groups, talk-/walk-throughs, usability questionnaire with performance measures, and eye tracking (if applicable) can be useful in early tests and evaluations. For instance, most of these methods are flexible and can be applied with even static representations of the displays, or limited functioning prototypes (see INL/EXT-18-51107 2018). Eye tracking (Section 5.6.7) can provide important insights on *where* operators have focused most of their attention, which can be followed up with interviews to understand *why*. Combined, the human factors engineer can triangulate on whether the HSI design can be improved through the application of design principles.

The use of HFE guidelines should be used to perform heuristic evaluations and verification of the designs. Guidelines from NUREG-0700 provide detailed guidance that can be applied to the designs and subsequently inform the style as a technical basis into design decisions made. The application of these guidelines complements other tests and evaluations that require end users. For example, Boring et al. (2015) developed a framework called Guideline for Operational Nuclear Usability and Knowledge Elicitation. In its most basic form, there are two fundamental activities included: verification (expert review) and validation (usability tests). The former is completed using design guidelines, such as those seen in NUREG-0700 (2020), whereas the latter includes the methods and measures described in Kovesdi and colleagues (Kovesdi et al. 2018) above. Again, the selection of detailed guidelines can be informed by the first principles used in developing the vision and concept of operations. Cognitive walk-throughs may also be applied with the prototype concepts to identify potential design issues through the lens of specific use cases (Section 5.6.3.4). This approach can complement a review using NUREG-0700.

Finally, it is worth mentioning that the tests and evaluations are enabled through rapid prototyping. These prototypes provide varying levels of detail, which depend on the design questions at hand (i.e., a detailed discussion of simulation and modeling techniques is provided in Section 5.6.6). For example, questions related to the layout, visual design, use of color, and labeling can be reviewed using static mockups of concepts. Aspects of technology acceptance, usability, workload, and situation awareness may require a degree of dynamic functionality to test.

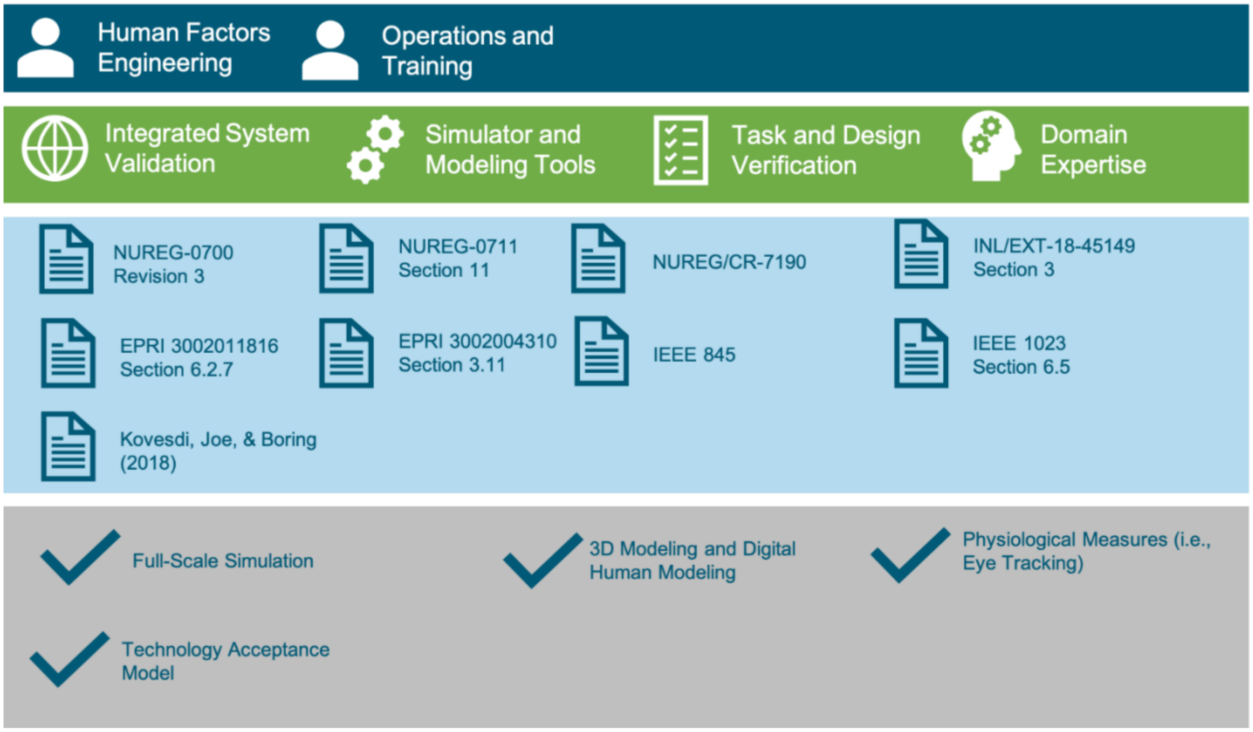
5.3.5 Interactions of Design with Procedures, Training, Staffing, and Qualifications

Changes in HSIs and the synthesis of information and task requirements in design has a strong relation with procedure development, training, and staffing and qualification. Fundamentally, this interplay is associated with the early HFE activities described in Section 5.1 including developing the new state and concept of operations, which begins developing a conceptual understanding of what the new state is envisioned to do and how the personnel are intended to interact with the plant. There may be a business case that identifies applying automation to enhance efficiency in maintenance applications that can further reduce staffing requirements. Downstream human-technology integration requirement activities like FA&A and task analyses (Section 5.2.2) may provide technical guidance in applying technology that ensure safety and reliability while still reducing staffing levels. With the design here, the new information and task requirements that come out of Section 5.2 then inform design requirements and consequently the impacts to procedures, training, and staffing and qualification. Tasks that have been automated will fundamentally change the role of staff by changing their roles, combining duties, or removing tasks that were previously performed. Procedures and training are consequently impacted to reflect these new requirements, such as making updates to the task performed, information and controls to use, and specific cautions and warnings that apply. Moreover, staffing and qualifications may change depending on the nature of the change to the duties performed. In a maintenance example, automated certain surveillance tasks may allow for one personnel to perform the previous work of two. In this process, there may be some additional needs for the one personnel to monitor of the automation to ensure it is properly working.

The impact of design on procedures, training, and staffing and qualification is particularly notable with the application of CBPs. Here, CPBs can enable a range of new possibilities, including embedded step logic in Type 2 systems or, if soft controls are embedded, seen in Type 3 systems (IEEE 1786 2021). Increased control automation can also place the operator in a supervisory role, requiring him or her to monitor the automation and veto decisions and actions made as needed. The work described in Section 4 summarizes the culture and sociotechnical impacts of advanced technologies like CBPs and automation when integrated, as described in the ADAPT concept.

It is important to keep operations/maintenance, training, and procedure writers involved in the design process so that they understand the impacts to procedures, training, and staffing and qualifications. CWA (Section 5.6.2) social organization and cooperation analysis can serve as a useful tool in characterizing the specific roles and responsibilities of agents, including automation and personnel across specific work domains and activities and situations. Further worker competencies analysis can be used to describe the psychological and physical requirements of the staff.

5.4 Evaluate using Verification and Validation



The intent of V&V is to comprehensively determine that the design conforms to HFE design principles and that plant personnel (i.e., the users of the system) can successfully perform their tasks to ensure safety and meet the operational goals (NUREG-0711 2012). Per NUREG-0711, V&V entails four activities: sample of operational conditions, design verification, integrated system validation (ISV), and HED resolution (Figure 23).

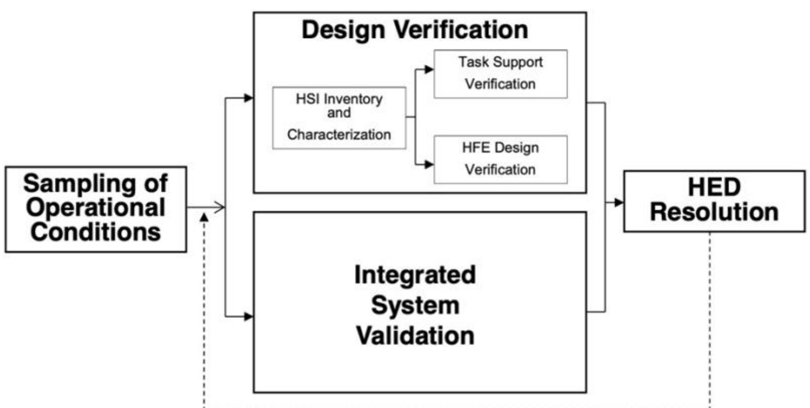


Figure 23. Overview of V&V activities (adapted from NUREG-0711 Figure 11-1).

As described earlier in Section 5.3.4, V&V activities differ from tests and evaluations that occur during design based on their intent. Tests and evaluations occur earlier to inform and refine the design specification before V&V. V&V tests the final design to ensure that requirements are met (NUREG-0711 2012). Within V&V, *sampling of operational conditions* occurs first. Sampling is pertinent with large-scale modifications, such as those implying a transformational change in the concept of operations, so that an adequate cross-section of functions and HSIs are evaluated to accomplish the V&V goals. It should be noted that insights from OER (Section 5.1.2), the sampling of scenarios from earlier activities like FA&A (Section 5.2.1), task analysis (Section 5.2.2), or tests and evaluations (Section 5.3.4) may be used to help sampling scenarios. Although, it is important to ensure that the level of detail described in NUREG0-0711 Section 11.4 is adequately described. The purpose of sampling operational conditions is ultimately to support design verification and ISV.

There are several sub-activities described in *design verification*, including HSI inventory and characterization, task support verification, and HFE design verification. HSI inventory and characterization describes the inventory, or extent, of displays, controls, and equipment within scope of the modification for V&V. Important information pertaining to the inventory of impacted controls and indications may be collected in a repository, such as a database, and include:

- Related system and subsystems
- Associated function(s)
- Location in workplace
- Nature of modification (e.g., migrated analog-to-digital)
- The display and control characteristics, including specific information sources, formatting, control types, associated with time-critical HAs, etc. (EPRI 3002004310 2015).

Task support verification pertains to addressing the availability of alarms, controls, displays, and task support items needed for plant personnel to perform their task. An HED may be documented when there are missing task support items, a mismatch in task requirements, or there are unneeded HSIs for any other task (NUREG-0711 2012). Task support verification may be performed using static or dynamic (functional) HSIs; performance measures (e.g., Figure 22) may be identified for ISV but are not typically formally used in verification (EPRI 3002004310 2015).

HFE design verification pertains to the suitability of the modification, accounting for peoples' capabilities and limitations (NUREG-0711 2012). Here, verification involves the evaluation of the HSI style guide and design criteria used (i.e., the NRC applies NUREG-0700 when no style guide is available). The review entails systematically reviewing the criteria against each guideline and marking them as being *acceptable* or *discrepant*. HEDs are identified when there is a discrepant criterion.

Another important element of V&V is *ISV*. ISV validates, using performance-based tests, the complete (integrated) design. NUREG-0711 Section 11.4.3 describes in detail the considerations for ISV, including:

– Validation team
– Test objectives
– Testbeds (also see Section 5.6.6.2 this report)
– Plant personnel
– Performance measures (also see Section 5.3.4 and Section 5.4 of this report) and test design
– Data analysis and HED identification
– Validation conclusions.

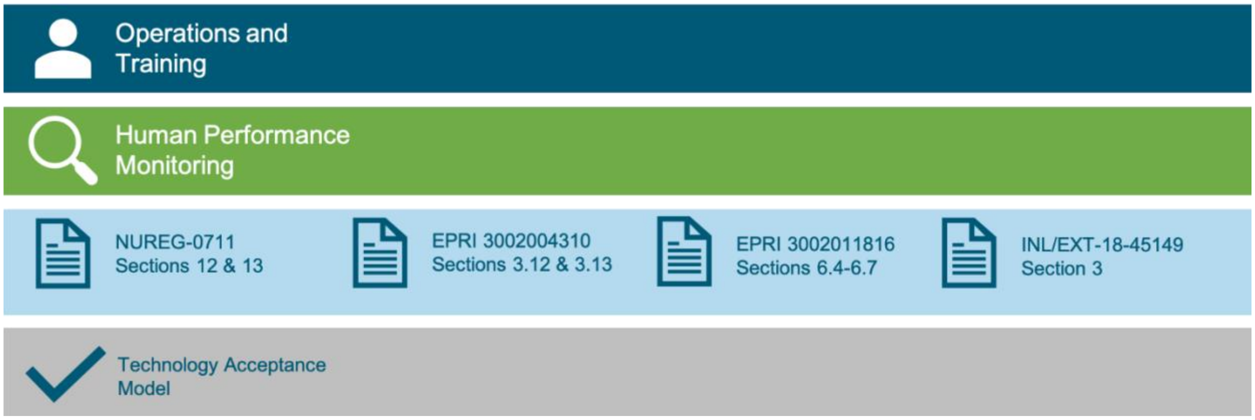
It's important to note that ISV entails simulated use, or operator-in-the-loop studies, to validate that the design conforms to the requirements. For modifications, another important consideration is whether the modification has any negative impacts on human-system performance (i.e., such as to plant performance, task performance, workload, situation awareness, team communication, and anthropometry) compared to the existing (as-is) state (Joe and Kovesdi 2021). In the case where equivalence is important (e.g., ensure safety and reliability), ISV measures and analysis may consider statistical equivalence testing as a way of evaluating practical equivalence across human-system performance with the existing and new state. NUREG/CR-7190 provides guidance on selecting methods and measures for ISV that address human-system performance. Kovesdi, Joe, and Boring (2018) provide an abbreviated set of common methods that support the evaluation of human-system performance (refer to Section 5.3.4). A crosswalk of these methods is also found in INL/EXT-18-45149 (2018) that mapped specific measures to their application to the elements described in NUREG-0711 (and primarily V&V) where LWRS Program human factors researchers supported digital modifications for a U.S. NPP utility.

Finally, *HED resolution* should be documented in V&V (NUREG-0711 2012). The HEDs identified in design verification and ISV should be traceable to the tasks and functions performed, plant systems impacted, impacts on safety, and broader issues with the HED. HEDs should be categorized that the ones that require *correction* are clear; these HEDs include ones that are safety-important, impacting plant/personnel performance or violating technical requirements. Design solutions should be described for the HEDs requiring correction. HEDs that are not corrected must be dispositioned by the utility.

There are other resources and standards that provide V&V guidance. IEEE 1023 (2020) and 845 (2011) provide guidance for HFE validation. IEEE 1023 provides general guidance for NPP modifications in which testing and evaluation is part of the overall HFE process. IEEE 1023 aligns with the guidance from EPRI 3002004310 and NUREG-0711 and references applying IEEE 845 guidance for selecting and applying evaluation techniques. Within IEEE 845, there is a detailed review of the characteristics important for selecting and applying human-system performance measures (IEEE 845 Section 3.3.1). IEEE 845 also distinguishes between objective and subjective measures; it is important to note that IEEE 845 makes the case for utilizing both types of measures. To this end, Figure 22 above builds on this guidance to provide a framework for selecting common measures. A final point worth noting is that IEEE 845 emphasizes a need to use a diverse set of measures. That is, IEEE 845 stresses that a single measure may not provide sufficiently valid results (e.g., due to various limitations). As a result, multiple methods and measures are important.

This point can be seen in the measurement and evaluation of workload. Workload is a construct that cannot be directly observed. Thus, the measures that are used make inferences of workload characteristics. These measures (i.e., including observations, physiological measures [Section 5.6.7], and self-reporting) have their own strengths and limitations. As a result, using multiple measures can triangulate findings to make better inferences of workload.

5.5 Implementation and Operations



HFE should be involved during the implementation and in-service monitoring (operations) of the modification. EPRI 3002004310 (2015) illustrates that HFE's primary role during implementation is to ensure that the modification has been implemented accurately by reflecting the results from previously described HFE activities. This final verification may include ensuring the design is integrated as specified, all HEDs are closed out, and any other HFE considerations that could not be adequately verified are done; for example, lighting and illumination requirements from NUREG-0700 (2020) may need to be verified at this time in an as-built condition. Technology acceptance (i.e., if identified as a measure; Section 5.6.5) and OER (Section 5.1.2) should be continuously collected.

HFE in-service monitoring in operations should also be considered. Technology acceptance (i.e., if identified as a measure) and OER are both important to collect for consideration of subsequent modification phases (EPRI 3002004310 2015). HEDs related to the HSIs, procedures, and training should be captured and documented using an established tracking system invoked by the utility.

5.6 Advanced Methods and Frameworks

The following section describes advanced methods and frameworks that support the core set of HFE activities described above. This section describes the application of ION, CWA, cognitive task analysis, STPA, TAM, modeling and simulation, and physiological measures (eye tracking) in terms of their application to the activities in the methodology described in this report. For each advanced method, a snapshot is provided using the core methodology framework (Sections 5.1–5.5) and the specific activities where the method applied is **<u>bolded and underlined</u>**; a blue bar labeled "Applicable" also highlights where the advanced method applies in terms of phases. A summary of the outputs, resources needed, key benefits, challenges using, and overall impact[2] is first given for each.

5.6.1 Integrated Operations for Nuclear

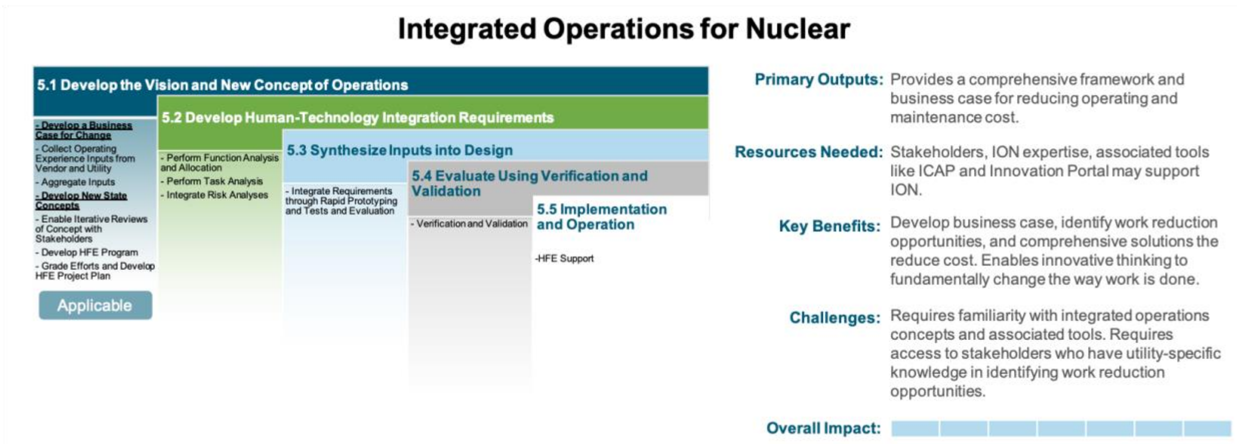


Figure 24. Application of ION techniques.

An important element of ION is the capability stack model. The capability stack model was created as part of the ION development model to identify PTPG of NPP plant activities to identify areas where work reduction opportunities may be used to decrease O&M costs. The model was created in partnership with Xcel Energy and the LWRS Project to create a structured approach to achieve the future state of cost-of-business objectives. Using a top-down approach, the model can be used for identifying the plant capabilities on an organizational level and working down to the work functions and potential work reduction opportunity areas. PTPG in each of the areas is developed to examine current costs, what technology is used now, governance and legal requirements to understand how the current work can be transformed using new technology. A bottom-up approach can be used with the capability stack model by first analyzing the work functions and work reduction opportunities and moving up to the capabilities. An internet-based tool called the ICAP was created from the capability stack model to develop a tool for structuring a business case for work reduction opportunities. The reader should refer to Thomas and colleagues (2020) in INL/EXT-20-59537 for a detailed understanding of ION and its theoretical foundations. Within this work, the intersection of ION and human-technology integration can be seen in Section 5.1.1. That is, ION can be used as a framework for developing a business case(s) to modernize. It is here in combination with intersection with I&C that specific human-technology integration considerations can be made, including the implications of specific capabilities that can be reasonably integrated within project's scope, schedule, and within an I&C infrastructure that lowers the total ownership cost.

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[2] Impact ratings are based on subject matter expert judgment in the area of HFE based on the degree to which the method supports ensuring safety and reliability. The rating also accounts for ease of using based on multiple factors, including hardware/software, staff, expertise, and time needed to perform. The impact rating is meant as a guide.

5.6.1.1 Integrated Operations Capability Analysis Platform

The ICAP is a software tool that has been developed by LWRS Program researchers at INL to capture the results from an IO process and incorporate PTPG into the model (Mohon et al. 2021). The capability stack model was used to develop the structure of the ICAP tool by adding in information from the left side, starting with plant capabilities, then adding in work function and work reduction opportunities. PTPG information has been connected to each section to develop a business case for how the technology could be used for reducing O&M costs.

There are three important outcomes of ICAP:

- To ensure that all work/process changes, technology deployments, and organizational changes have direct tie-in to the business case
- To provide a quantitative basis for ensuring the cost of performing work functions in the future can be accomplished on budget
- To provide a means of aggregating business cases across the work functions (plant-wide) that can benefit from a given work reduction opportunity, such as through technology or processes (Kovesdi et al. 2020).

The ICAP provides four featured tools called capabilities, sub-capabilities, work functions, and work reduction opportunities, and two supporting features called manage organizations and manage indicators. Once the information has been developed and added into the ICAP tool, a business case can be created using a tool called the business case analysis model created by EPRI.

5.6.1.2 Innovation Portal

The Innovation Portal tool was created from a 2019 LWRS Pathway innovation workshop to identify areas and technologies that can be implemented in NPP's leading to work reduction opportunities (Kovesdi et al. 2019). While the Innovation Portal is in development, it will be a web-based tool designed as a roadmap presenting information on enabling technologies, advanced capabilities, and integrated technologies. The Innovation Portal tool was originally designed as a standalone tool but will be interfaced into ICAP. The Innovation Portal will serve as an R&D information resource of emerging technologies and capabilities that can support work reduction opportunities found in ICAP. The Innovation Portal will provide detailed information of candidate technology, including associated technical literature, such as those developed under the DOE LWRS Program (Kovesdi et al. 2020).

5.6.2 Cognitive Work Analysis

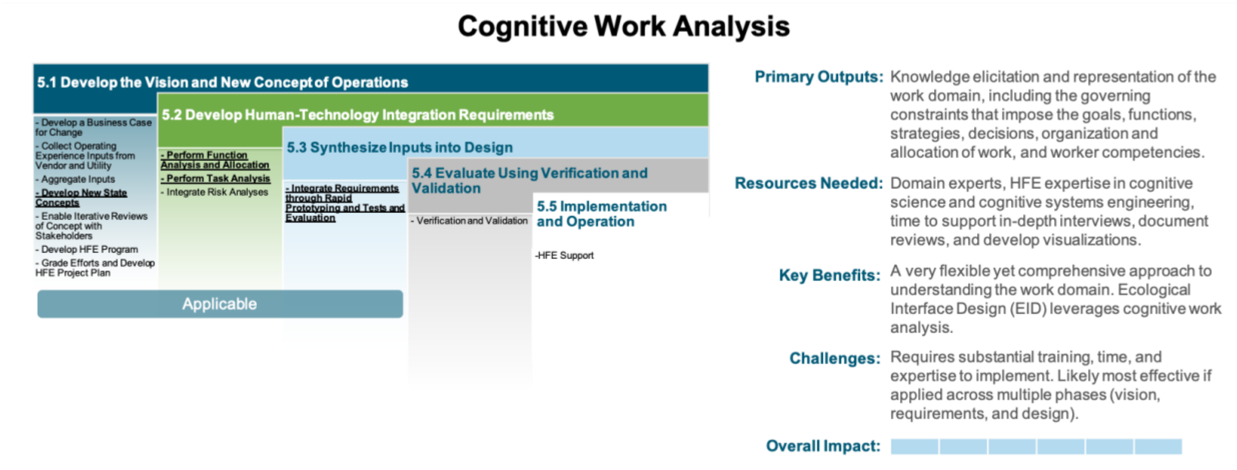

Figure 25. Application of CWA techniques.

With origins in the nuclear industry, the CWA framework offers a structured approach to system design (Hugo 2015). CWA is goal-driven and focuses on the underlying constraints that govern the work domain, as opposed to focusing on existing tasks or ways in which work is completed (Stanton et al. 2017). That is, rather than focusing on how work is currently done as a core design basis, CWA allows for understanding what could be done within the defined work domain and its constraints. This fundamental philosophy of CWA makes it advantageous in the design of first-of-a-kind systems where tasks may still be ill-defined. In this specific case, where existing NPPs must undergo substantial transformation in the way in which work is currently done, CWA also seems fitting to model the underlying constraints posed on the domain. “Disruptive” solutions can therefore be offered since their design bases are not based solely on existing practices.

CWA is comprised of several phases, including work domain analysis (WDA), ConTA, strategies analysis (StrA), social organization and cooperation analysis (SOCA), and worker competencies analysis (WCA). It should be noted that the intent of these CWA phases is not prescriptive; rather, the application of each phase is based on its relevance to the problem at hand. Further, while there is an assumed linear progression with completing each phase as needed, the reality is that many of the phases may be performed in iterations where modifications to certain phases may indeed inform previous phases. Each phase is described next.

5.6.2.1 Work Domain Analysis

WDA is foundational to CWA. WDA defines the goals and constraints (i.e., functional structure) of the domain (Hugo 2015; Stanton et al. 2017). The constraints that govern the domain are either purposefully built or are artifacts of natural phenomena. An important part of WDA is the decomposition of the domain and its constraints through different levels of abstraction. These layers of abstraction comprise a mapping of higher level system goals and associated values and priorities down to the specific physical objects, proprieties, and functions that support them. The mapping provides a hierarchy of links across these different layers of abstractions to develop means-end relations that form the basis for understanding *what* constraints govern the domain, *why* they exist, and *how* they are currently or could be achieved. The literature characterizes this mapping as the what-how-why triad (Hugo 2015).

In complex systems like NPPs, there can be one-to-many relations across the domain hierarchy. One effective tool to characterize the relations in such situations is the abstraction hierarchy (AH; Stanton et al. 2017). The AH provides a graphical representation of the means-end links across the layers of abstraction, representing the what-how-why triadic relationship across the layers in achieving the domain goal. The AH can be thought of as a hierarchical network graph to which each defined entity of the domain in a given layer is represented as a node and the means-end relations are represented as the edges, intersecting nodes at the different layers. For a given layer of the graph, a node (i.e., a "what") can be traced upward in abstraction to *why* it exists and downward in abstraction to *how* it is achieved within the domain. While the number of layers may be flexible, the AH is traditionally defined through five layers. These layers include the *domain purpose*, *domain values*, *domain functions*, *physical functions*, and *physical objects* (Hugo 2015). The format of these layers is presented from top-to-bottom.

The domain purpose represents the reason why the domain exists. The domain values represent the values and priorities in determining how well the goal is achieved. The domain functions represent the purpose-related functions used to support the values and goals of the domain. These functions are presented independent of any object-specific requirements. To this end, the AH provides the physical functions at the next layer to provide the object-specific functions necessary for achieving the domain functions. Finally, the bottommost layer represents the physical objects, or entities, that are comprised within the domain space.

The inputs used to perform WDA and to develop the AH come from a synthesis of multiple sources (Stanton et al. 2017). These inputs include some combination of existing documents, interviews with domain experts, and observational or simulation methods. Like many other methods, the general WDA process first entails defining the objectives of the analysis and any project considerations, such as time constraints, available resources, or any key assumptions important for the project. These considerations help define the boundaries of the analysis to ensure objectives are met within the scope of the project. Available resources (inputs) should be identified to develop the initial AH. The AH is then constructed using these initial inputs and modified through an iterative review with domain experts until satisfactory. Stanton and colleagues (2017) offer practical insights into developing the AH. The authors suggest starting by completing the topmost and bottommost layers; once these are completed, the middle layers are completed to converge the goals and known objects through connecting the domain functions to physical functions.

The AH is one major output of WDA. The AH provides a comprehensive understanding of the entire domain in different degrees of granularity. Hence, with developing a new-state vision, the analyst may use these insights to understand the bases for the existence of specific technologies and their functional capabilities. The AH can also be used to support an understanding of what combinations of technologies and their physical functions are needed to achieve the domain functions that provide value to the domain. Additionally, the AH provides prerequisite information needed for the subsequent phases of CWA.

5.6.2.2 Control Task Analysis

ConTA complements WDA by identifying the specific situations where the identified functions from the domain are needed (Stanton et al. 2017). A contextual activity template (CAT) is developed to depict the intersection of specific functions (developed at the domain- or physical-level) from WDA to the situations where they are needed. While there are different variants of CAT formats, the structure takes a matrix form where functions are presented by row and situations are presented by column. The end results of completing a CAT in ConTA is to develop an understanding of where specific functions do occur, where functions can occur, and where functions do not occur.

ConTA also considers aspects of decision-making for the activities carried out across the work domain. A common tool used within the CWA framework entails the use of decision ladders (Rasmussen 1986; Stanton et al. 2017). The decision ladders provide a structured way to characterize the data processing activities undergone by the entire system and the knowledge acquired at each process in accomplishing a control task. The decision ladders can model the data processing activities and knowledge acquired for both people and technology (e.g., with the use of decision support). This approach can offer insights in understanding possible decision shortcuts that could be made in the situation and their potential consequences. Further, the decision ladders can serve as a key resource in understanding the effects of automating certain decision processes. This output can support the design of automated systems and be valuable in establishing human-system performance observational criteria during testing and evaluation. Figure 26 illustrates an example of a decision ladder for an adaptive cruise control (ACC) system to support FA&A. The figure highlights key decision-making questions made for the ACC system and driver. The colors represent the allocation of function as manual, shared, or automated.

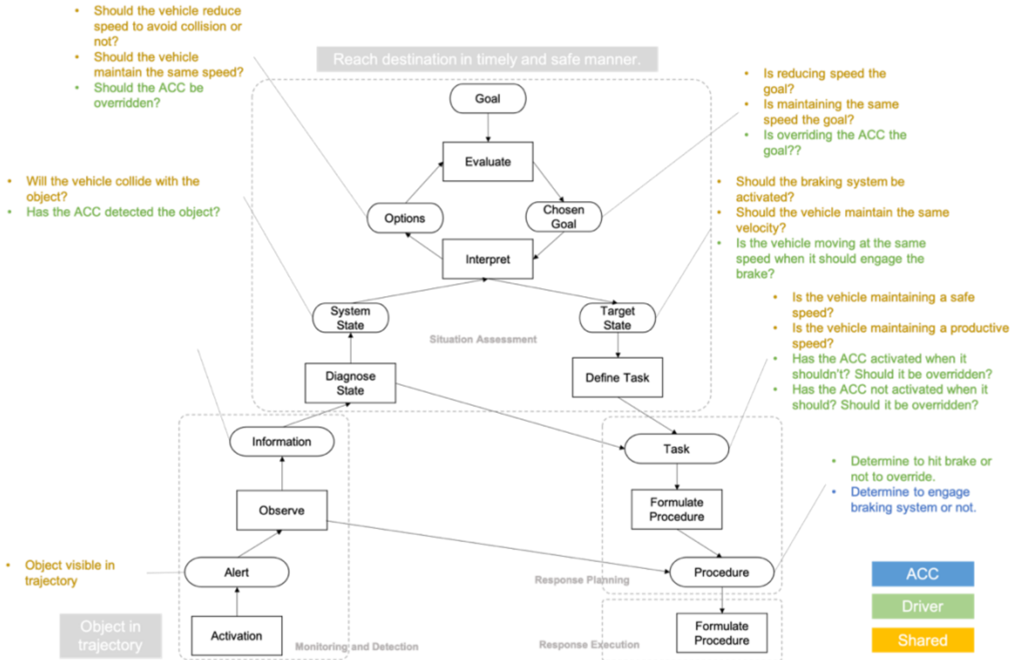

Figure 26. Example decision ladder to illustrate function allocation for an ACC system.

5.6.2.3 Strategies Analysis

StrA describes the way in which the activities identified in ConTA can be completed (Stanton et al. 2017). StrA acknowledges that activities can be completed in different ways (i.e., strategies) depending on certain conditions and whether the activity is performed by automation or by a person. A visual representation of StrA is generally depicted as an information flow chart (Hugo 2015). The chart is bounded by an initial and ending condition. Within these bounds, each strategy that can be carried out is depicted as a sequence. Where multiple strategies are possible, the chart shows each sequence in parallel.

5.6.2.4 Social Organization and Cooperation Analysis

The SOCA phase focuses on the specific roles and responsibilities of each agent (i.e., both technology and people) within the context of team coordination (Stanton et al. 2017). SOCA first focuses on identifying the specific roles in the system. The roles contain both human and automated agents. The identified roles can then be traced across the products of WDA, ConTA, and StrA to show how each role is assigned to the functions, control tasks, and strategies previously identified. Consequently, a notable output of SOCA is an understanding of who is responsible for specific activities within the domain.

5.6.2.5 Worker Competencies Analysis

The final phase of CWA is WCA. WCA identifies the human agents' psychological and physical requirements in performing specific activities for a given role (Hugo 2015). Rasmussen's skills, rules, and knowledge (SRK) taxonomy is one such framework used in WCA to model the psychological requirements (e.g., Rasmussen 1986; Stanton et al. 2017). Using the SRK framework, WCA can help in analyzing the way in which people make decisions depending on various conditions and level of expertise. Like SOCA, WCA complements the outputs of other CWA phases. For instance, the SRK framework can be applied to the decision ladders developed in ConTA to characterize the way in which skill-based, rule-based, and knowledge-based decision-making is applied at each decision process from the ladder.

5.6.2.6 Applying CWA to New-State Vision and Concept of Operations

Table 12 outlines the specific phases of CWA and how they apply to developing a new-state vision and concept of operations.

Table 12. CWA phases.

Phase	Application
WDA	The AH from WDA can provide a unique value to the development of first principles used in the assessment methodology designed to inform how enabling technologies can best be configured to maximize their value. That is, the selection of specific capabilities in the new state should be guided by the specific qualities they can offer to promote efficient operations while maintaining safety. The first principles defined what the capability is and why it is important to the transformation. This information is used to address how available vendors can integrate these first principles. The AH can be used to map specific technologies to their functional characteristics that make them beneficial. These characteristics can then be mapped upward to higher level goals. Refer to Section 5.1.4 for the application of WDA on the new-state vision. Further, the AH in WDA can be used to support function decomposition in FA&A (5.2.1) and the HSI design in the application of EID (Section 5.3).
ConTA	The CAT can be used to identify where certain physical functions are used in known plant situations (e.g., identification of functional operating modes may benefit from CAT [Section 5.2.1]). These functions can then be evaluated in terms of decision processes using the decision ladder to show differences from the existing to new state, which can support evaluating changes in the cognitive aspects of the task (Sections 5.2.2).
StrA	Expanding on ConTA, StrA can focus on the differences in strategy from the existing state to the new state. StrA may enable a qualitative comparison between existing NPP strategies to possible strategies of a new-state NPP for a given activity. The output may offer insights into the ways technology or process changes can be best leveraged to improve efficiencies while also ensuring optimal safety. This information can support task analysis (Section 5.2.2) by identifying focal areas in subsequent HFE activities like HSI design and V&V.
SOCA	Roles and responsibilities can be mapped across previous CWA products. The application of SOCA provides a way to understand who will ultimately perform certain tasks within the new state. In the case where there are already well-defined roles, any changes identified from SOCA may be used to inform the operations concept and subsequently any impacts to staffing and qualifications or training. SOCA can be used to evaluate FA&A and task analysis activities in terms of determining task requirements given a specific allocation of function (Sections 5.2.1 & 5.2.2).
WCA	WCA can provide useful information regarding the human agents' requirements in performing specific activities in the domain. Completion of task analysis can provide insights into WCA (Section 5.2.2). This information can inform subsequent industry standard NPP HFE activities described in NUREG-0711, such as HSI design, and V&V (Hugo 2015). By understanding the effects of automation on the plant staff's decision processes, design decisions can be better informed.

5.6.3 Cognitive Task Analysis

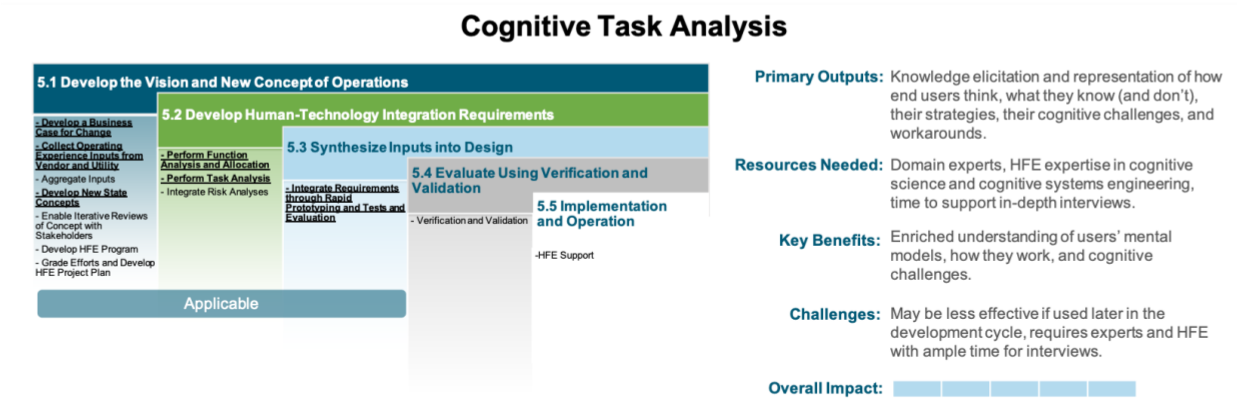

Figure 27. Application of cognitive task analysis techniques.

Cognitive task analysis is considered a broad class of methods that address the cognitive processes used by people and technology (Stanton et al. 2013). The application of cognitive task analysis has been seen as being particularly useful in eliciting and representing knowledge and cognitive processes in complex dynamic systems like NPPs, especially with the growing use of automation and decision support systems. Crandall, Klein, and Hoffman (2006) provide detailed guidance in performing cognitive task analysis; their work distills the fundamental objectives of the methodology to help the analyst sift through the variants of unique techniques that fall under the greater cognitive task analysis umbrella. In their work, they separate cognitive task analysis into three key phases: knowledge elicitation, data analysis, and knowledge representation. Here, each phase is critical in collecting domain knowledge of the system and using this information to inform end products, such as design solutions, procedures, training, and staffing and qualification.

5.6.3.1 Knowledge Elicitation

At its core, cognitive task analysis collects knowledge and cognitive requirements from the domain experts of the work environment in question. *Knowledge elicitations* methods can be described in terms of how and where data is collected. Regarding *how*, elicitation techniques largely fall under interviewing domain experts, allowing experts to self-report, observing domain experts, and automated data collection (Crandall, Klein, and Hoffman 2006). It should come to no surprise that the core set of techniques are a staple to HFE and can support other purposes (e.g., EPRI 3002004310 2015; Kovesdi, Joe, and Boring 2018). Each approach has its strengths and weaknesses; some of these are summarized by Kovesdi and colleagues (2018) and a mapping of common NPP HFE methods are listed above (Section 5.3.4).

For *where* data is collected, Crandall and colleagues (2006) listed four elements to consider. First, "where is in time" should be considered when eliciting knowledge, whether from past events, present events, or forecasting future events. Retrospective data collection can elicit data from previous incidents that provide insights into the cognitive processes required of experts in detecting, diagnosing, problem solving, and responding to these challenging situations. The input may provide a rich understanding of operators' mental models, information requirements, bottlenecks, workarounds, and other contextual information that is important for decision-making. Of course, a pitfall with retrospective data is that it draws on memory and experience, which can become distorted and subject to inaccuracies. Concurrent data collection can avoid those pitfalls but may be disruptive to the task at hand and may be limited in scope to which specific events being observed in the present comprehensively capture the cognitive considerations of the work domain in question. Future events are another way of collecting data, which has its own considerations, such as how well experts can forecast events based on their experience.

The second element of consideration for *where* pertains to the "where in the scale of realism" data provides useful insights. Cognitive task analysis is an applied HFE approach that can be used to capture cognition in the real world; this includes interviewing experts in their actual work domain, as well as observing them when performing real tasks. However, simulations can also be useful, especially when the system in question is not available. Hence, cognitive task analysis techniques can be applied in simulator studies to collect a similar knowledge input in a formative sense. Crandall and colleagues (2006) warn that the human factors engineer must be sensitive to the fact that, for most cases, simulations often exercise predefined scenarios or uses in question. Thus, the cognitive task analysis methods can only apply to specific sets of predefined use cases, and this can leave in question other considerations of the work domain that are not part of the constrained simulation. There are other considerations, like elements of stress and anticipation, that may not be fully captured in simulation.

A third element pertains to "where in task difficulty" is the data being considered. There may be routine tasks, challenging tasks, and anomalies that are important to consider. For transformation, it's likely that routine tasks and some challenging tasks may identify opportunities to for task efficiency improvements. On the other hand, there may be some challenging tasks and rare tasks that impact safety. In any case, the task difficulty selection should be guided by the work goals, which likely reflect both safety and efficiency.

Finally, there is an element of generalizability of the knowledge elicited to consider. That is, there may be cases where a more general knowledge of the work domain is of interest. This may include establishing a general understanding of the specific systems or functions that operators work with in normal or abnormal operations. On the other hand, event-specific information may be needed, such as understanding the information requirements needed to effectively detect, diagnose, and respond to transients. Certain cognitive task analysis techniques can support these different goals better than others.

5.6.3.2 Data Analysis

With other HFE methods, data analysis is important to effectively translate data into information that can be used to make accurate and impactful recommendations to system design. As seen previously in Figure 22, the data that certain methods produce can range depending on the construct at hand, degree of qualitative/quantitative, and degree of being subjective or objective. In each case, there are different data analysis approaches. For cognitive task analysis, which leverages collecting knowledge (descriptive/qualitative) data that can be either objective or subjective, a good qualitative data analysis is particularly important (i.e., the left side of Figure 22).

INL/EXT-20-58538 (2020) describes a standard and systematic approach to qualitative data analysis that can be useful for cognitive task analysis. Thematic analysis (Figure 28) is a systematic process of translating qualitative notes into themes and insights that can be used to represent knowledge in cognitive task analysis.

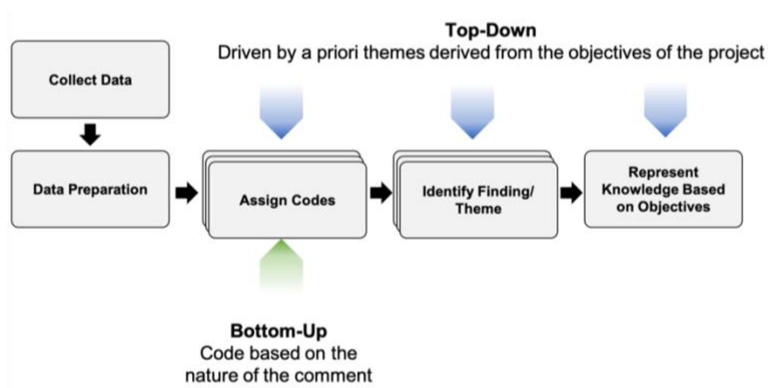

Figure 28. Thematic data analysis for qualitative data (adapted and extended from INL/EXT-20-58538 2020).

A detailed description of the process is beyond the scope of this report. A general outline of the process entails aggregating notes taken from knowledge elicitation in a structured way (e.g., a spreadsheet). Next, the notes are assigned a *code* that is based on combining a priori themes (or objectives) of the project with the particulars of the qualitative data. For example, a top-down objective may be to identify notes that hint at *cognitively challenging aspects of the task*. Aspects of the freeform note that support this would be coded with a tag name. Unique details of the note that are deemed important by the human factors engineer are also coded (bottom-up). Themes and findings are further identified by aggregating the codes and iterating on them as necessary. The format and way in which data are analyzed can be difficult to boil down to a formula; however, having a systematic approach ensures consistency and traceability to decisions made when performing a thematic analysis. Ultimately, the analysis should support the objectives of the goal of applying cognitive task analysis.

5.6.3.3 Knowledge Representation

Knowledge representation entails the presentation and communication of insights gained to support the problem at hand (Crandall, Klein, and Hoffman 2006). There are many approaches to representing the findings from cognitive task analysis. Though generally, the format in which knowledge products from the cognitive task analysis are represented fall under narratives, timelines, tables and categories, charts and diagrams, and concept maps. Table 13 highlights how these formats may be used to support developing a transformative new state that adopts advanced technology.

Table 13. Cognitive task analysis knowledge representation formats.

Format Types	Most applicable for:
Narratives	Describe incidents from OER that identify opportunities to enhance performance or improve safety (Sections 5.1.1, 0, and 5.1.4).
Timelines	Support parts of FA&A and task analysis where there are particular cognitive and temporal challenges (Sections 5.2.1 and 0). For example, cognitive task analysis results may be integrated in OSD.
Tables and Categories	Applicable across all HFE activities where cognitive task analysis is used (e.g., Sections 5.1.1, 0, 5.1.4, 5.2.1, and 0).
Charts and Diagrams	Visually represent relationships and characteristics of elicited knowledge elements. An example of one approach is seen in Figure 26 above (decision ladder). Here cognitive task analysis can elicit the knowledge needed to develop the decision ladder. Charts and diagrams may be particularly useful in FA&A and task analysis (Sections 5.2.1 and 0).
Concept Maps	Concept maps represent a visual representation of the knowledge structure, or mental model, of the work domain or task. Concept maps apply beyond cognitive task analysis but have served useful as a tool to represent knowledge structure (Crandall, Klein, and Hoffman 2006). INL/EXT-20-57908 provides examples of concept mapping (Figure 27 in Dainoff et al. 2020). One potential use case for concept maps may be in the functional decomposition to support FA&A (Section 5.2.1).

5.6.3.4 Specific Techniques

As described, cognitive task analysis is a broad class of methods that focuses on understanding the knowledge domain or work and associated cognitive challenges as applied to system design. The previous subsections described the general phases that cognitive task analysis entails. There are many unique methods that follow these three phases, and a detailed list of these goes well beyond the scope of this report (i.e., refer to Crandall, Klein, and Hoffman 2006; Stanton et al. 2013; or BNL-90424-2009 2009). However, there are a few specific methods that are worth mentioning, as they can apply to the HFE activities described in this report, which are described below.

Critical Decision Method and Critical Incident Technique

Critical decision method and critical incident technique are semi-structured interview approaches that rely heavily on the retrospective data collection of previous incidents. They rely on eliciting knowledge from expert domain users (Crandall, Klein, and Hoffman 2006; Stanton et al. 2013). Both techniques provide the same output (knowledge from expert users) and follow a similar structure; hence, they are not differentiated for the purposes of this report. First, an incident is identified by the domain expert, usually motivated by identifying ones that are anomalies or challenging. Next, specific a set of interview probes are selected by the human factors engineer to elicit specific detailed information of the incident from the expert. The probes are performed in several "sweeps" (Crandall, Klein, and Hoffman 2006). The first sweep, the expert is asked generally to recall the incident and recall the specific challenging aspects of the task. The challenging aspects are then asked to be detailed through a story of what was performed and what made it most challenging. A timeline may be created from the story in a second sweep, working with the domain expert. The story is detailed more through the timeline and critical decision points are mapped to the event. The next sweep involves understanding the perceptual and cognitive bases for these decisions and actions taken as shown from the timeline. The outputs may be an illustrative timeline that documents the challenges, decisions made, perceptual cues, cognitive processes, and actions taken. This information may be tabulated as needed. This approach can be very labor intensive and requires skill from the interviewer to "ask the right questions" and ensure the discussion is on track. Its use may be particularly useful in enriching OER in developing the new state (Sections 5.1.1, 0, and 5.1.4). This input may also serve useful in downstream HFE activities like FA&A (Section 5.2.1) and task analysis (0) if time and resources are available.

Applied Cognitive Task Analysis

ACTA provides a structured set of knowledge elicitation, analysis, and representation activities to support system design (Stanton et al. 2013). The approach is performed using interviews and observations to elicit knowledge and uses diagrams and tables for analysis and representation. ACTA is performed first by observing the work domain in question. Here, the objective is for the human factors engineer to gain familiarity with the work domain. Next, a *task diagram interview* is performed to gain a general understanding of the tasks that are performed. Insights may be gained from observation done previously, and ultimately, the task diagram interview's product should be a decomposition of the task in question (e.g., such as through a hierarchical task analysis). Next, the *knowledge audit* is performed to understand the cognitive requirements and expertise/training needed to perform the tasks identified in the task diagram interview. Stanton and colleagues (2013) provide a list of items that may be useful here, including elements of diagnosis, situation awareness, perceptual demands and skills, tacit knowledge (tricks of the trade), workarounds, metacognition, and anomaly detection; collecting examples of each is useful to gain insight.

Next, a *simulation interview* is performed. Here, a scenario is identified by the domain expert and the expert then talks through the scenario (i.e., often retrospectively from previous incidents). The human factors engineer asked focused questions at key steps to understand how the items in the knowledge audit were used, what actions were taken, cues and information used, potential error, and other contextual information that may be useful. The end result of ACTA is a *cognitive demands table*, which describes and summarizes the elicited knowledge in a structured way.

In sum, ACTA provides a systematic way of collecting cognitive requirements. Though one should be mindful that the activity may take upwards of three separate interviews with domain experts. Thus, if time is critical, it may be difficult to integrate into the project's schedule. Given that ACTA requires time and resources, it may be best suited for a dedicated task analysis described in Section 5.2.2.

Cognitive Walk-through

The cognitive walk-through is cognitive task analysis methodology grounded in usability and interface design where the human factors engineer works through specified tasks and asked targeted questions from the lens of the user (Mohon et al. 2021). The activity is performed by identifying the task, performing a traditional task analysis to understand the correct course of action, and then working through the sequence of actions while asking a set of targeted questions that help in understanding where there may be specific problems. Stanton and colleagues (Stanton et al. 2013) describe a set of detail questions that can be applied; however, Spencer (2000) provides an abbreviated list of questions:

- Q1. Will the user know what to do at this step?
- Q2. If the user does the right thing, will the user know they did the right thing and are making progress toward their goal?

Cognitive walk-throughs are best served in tests and evaluations during design (Section 5.3.4). An example of its application can be found in INL/EXT-21-63101. The approach was coupled with other usability evaluation techniques to improve the usability of the ICAP and Innovation Portal tools described in Section 5.6.1. Cognitive walk-throughs offer the least resource intensive approach of the methods, which can make it accessible, especially during design as an early usability evaluation tool.

5.6.4 System Theoretic Process Analysis

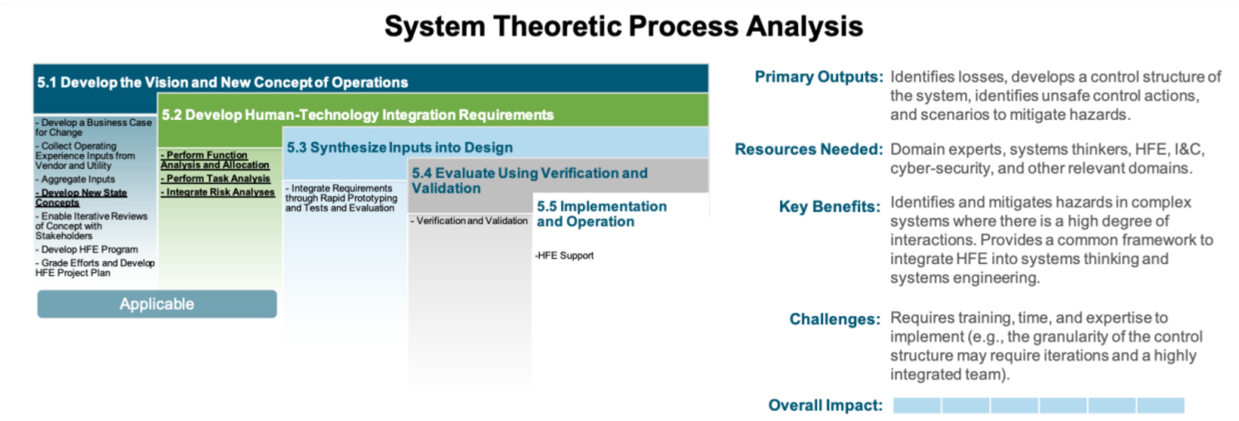

Figure 29. Application of system theoretic process analysis.

Leveson and Thomas (2018) provides an in-depth handbook on performing STPA, and the reader should refer to this resource as needed. The handbook is publicly available:

- https://psas.scripts.mit.edu/home/get_file.php?name=STPA_handbook.pdf

Moreover, there are several other key resources that describe STPA within the context of applying to HFE and sociotechnical analysis. These include:

- INL/EXT-20-57908 (Addressing Human and Organizational Factors in Nuclear Industry Modernization: An Operationally Focused Approach to Process Methodology)
- INL/EXT-20-60264 (Guidance on Including Social, Organizational, and Technical Influences in Nuclear Utility and Plant Modernization Plans)

Here, STPA is discussed within the context of applying to HFE and the development of a new-state vision. The resources listed provide the core basis for what is described about STPA in this report. Using these references, an overview of STPA is described. Next, a discussion on recent guidance on the use of STPA in a NPP transformation is given. Finally, a discussion of how STPA can be extended into HFE is discussed, relating to the specific activities described in this report.

5.6.4.1 Overview of STPA

STPA is a hazard technique that is rooted in systems theory; it differs from traditional hazard analyses that decompose the system into components, which are analyzed in isolation. Rather, STPA treats the system as a whole and considers the *interaction* between components of the system (Levenson and Thomas 2018). The approach accounts for people and organizational factors within the system. The fundamental foundation of STPA's analyses is done through modeling the system as a *control structure* (Figure 30).

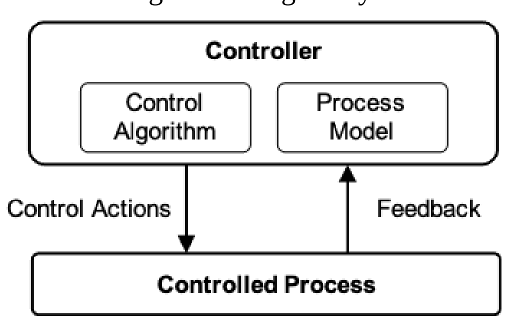

Figure 30. Basic STPA control structure (adapted from Levenson and Thomas 2018).

The control structure consists of control loops between a controller and controlled process. The controller (always placed above to denote higher authority) performs control actions to manage a process and receives feedback from the process. The controller has a process model that includes the beliefs and decision-making processes that utilize feedback. There is a control algorithm that executes the control actions required to control the process. This underlying framework forms the bases for identifying hazards that can occur within any one element of the control structure and interactions between elements. The following steps are suggested in performing STPA, as described in Levenson and Thomas (2018). It should be emphasized that it is critical to include a multidisciplinary team in performing each step of STPA. In essence, STPA provides a common framework/tool to which specific disciplines within the project team (e.g., see EPRI 3002011816 2018; Section 3.1.3) can contribute to mitigate system hazards.

Step 1. Identify the Purpose for Analysis - Page 15 of Levenson and Thomas (2018)

The first step is to identify the purpose for an analysis. In doing this, the essence of STPA is defined, such as by identifying the losses of concern and associated hazards that can lead to a loss. Losses are the consequences that are to be avoided and are structured by loss of life/injury, damage, failure of mission, decreased satisfaction, loss of information, environmental loss, or loss of power generation. These negative consequences (losses) are caused by hazards when the conditions are unfavorable. Hazards are linked to losses and can form a one-to-many relationship. Levenson and Thomas (2018) provide a structured approach to documented and tracing losses to hazards (e.g., page 18).

Step 2. Develop the Control Structure - Page 22 of Levenson & Thomas (2018)

The control structure is then developed to perform a STPA hazard analysis on the losses and hazards identified. Figure 30 above highlights the fundamental elements of a control structure. Here, the granularity of the control structure will largely depend on the purposes of the project and team identified. Generally, control structures may begin as broad and become more detailed as needed to support the analysis in question. Thus, a more general structure may be developed when exploring new-state vision concepts and implications of changing the concept of operations (e.g., including advanced automation), as shown in Section 5.1.4. The control structure may be as general as modeling the entire plant or the scope of systems being upgraded. In later sections, such as FA&A, task analysis, and risk analyses (Section 5.2.3), the control structure may be further detailed to the specific functions in questions or within the scope of the analysis. The determination of the level of detail is highly dependent on the team's discretion and scope of the analysis.

Step 3. Identify Unsafe Control Actions - Page 35 of Levenson and Thomas (2018)

As seen in Figure 30, UCAs are control actions that *could* lead to a hazard, consequently causing one or more losses. Levenson and Thomas describe four ways in which control actions can be unsafe (i.e., types):

- Failing to provide a control action (omission)
- Providing a control action that leads to a hazard, an inherently unsafe action (commission)
- Providing a safe control action but done so sequentially incorrect either too early, too late, or in wrong order (commission)
- Providing a safe control action but done so that it is temporally incorrect, being either too long or stopping too soon (commission).

UCAs can occur from the system, person, or organizational level, and are detailed more for root cause in the next step. At this point, UCAs are listed within the context of the four possibilities for each control action, mapping to the hazard(s) that is associated with it. There is a structured way in which UCAs are documented, such as by:

- <Controller> <Type> <Control Action> <Context> [<Link to Hazard(s)>]

Page 36 of the handbook provides an example, using a brake system for illustration of the format.

Step 4. Identify Loss Scenarios - Page 42 of Levenson and Thomas (2018)

Finally, causal factors that lead to UCAs and therefore hazards and losses are described (i.e., noted as *loss scenarios*). There are two important questions to consider in defining loss scenarios:

- Why would UCAs occur (i.e., what characteristics about the interaction between sensors, feedback, process model/beliefs, and control algorithm may create the UCA)?
- Why would the control action be improperly executed or not executed?

These questions are often attributed to failures in the controller, inadequate algorithm, unsafe control input, and inadequate process/belief model. Page 46 of the handbook provides guidance on developing loss scenarios. Levenson and Thomas (2018) describe first considering the influencing factors on the process model and beliefs that could lead to UCAs. Next, causal factors that can lead to the identified influencers are documented. Scenarios that include the influencing factors and causes are detailed. The causes are detailed based on causes of inadequate feedback and causes of controls actions improperly executed or not executed.

5.6.4.2 Applications of STPA in Existing NPP Guidance

The STPA methodology has been adopted recently in the NPP industry, specifically within the guidance by EPRI. At the highest level, EPRI 3002011816 (also known as the DEG; see Section 3.1.3) provides an SE framework for digital modifications. Within the DEG's guidance on use and reuse of hazard analysis during conceptual design, STPA is referenced as a methodology that can be applied, among other risk analyses. Specifically, the DEG considers STPA as a candidate hazard analysis approach for high-risk and high-complexity modifications (EPRI 2018). At the time of this report, there has been additional guidance developed by EPRI that further support completing the activities described in the DEG. Two of which provide explicit reference to using STPA:

- EPRI 3002016698 (HAZCADS: Hazards and Consequences Analysis for Digital Systems - Revision 1, 2021)
- EPRI 3002018387 (DRAM: Digital Reliability Analysis Methodology, 2021).

The DEG is considered a parent guidance document to which HAZCADS and DRAM are applied when the DEG calls for hazard analysis. HAZCADS is first applied to analyze the proposed modification using the first three steps of STPA (EPRI 3002018387 2021). The identified UCAs are further screened using PRA approaches that help determine risk significance. DRAM (2021) is then applied as one of four downstream applications that reduce risk. In other words, the DEG, HAZCADS, and DRAM focus on answering the following three questions (EPRI 3002018387 2021):

- DEG: What I&C design meets the stakeholder needs?
- HAZCADS: How risky is the I&C design?
- DRAM: Is the I&C design good enough?

In DRAM, the fourth step of STPA (identify loss scenarios) is seen. DRAM separates factors into random (e.g., random failure) and systematic (e.g., failure from a deterministic mechanism). While these guidance documents are new, they offer a proposed process that integrates STPA in the NPP hazard analysis framework and as part of a larger SE approach to modernization.

5.6.4.3 Extensions of STPA into HFE and Sociotechnical Analysis

STPA has recently gained attention in the HFE community. That is, INL/EXT-20-57908 and companion report INL/EXT-20-60264 describe how STPA can be applied to address HFE and sociotechnical challenges. INL/EXT-20-57908 provides a theoretical basis for applying a sociotechnical analysis to NPP modernization (Dainoff et al. 2020). The report presents the application of STPA, among other frameworks, within the context as solutions to solving high-level problems. One problem that is described is the need to obtain valuable *tacit*, or undocumented, knowledge from experts. It is here where Dainoff and colleagues posit that STPA can be used as a tool to elicit tacit knowledge. That is, STPA can be used as a tool among a team of experts to elicit targeted information, such as what could go wrong within the context of interacting elements of the control structure. Dainoff and colleagues (2020) also discuss how STPA can be further extended into HFE, by representing the operator's mental model. The proposed extension is based on work done by France (2017) who proposed extending the STPA control structure to include central elements to human information processing (Figure 31).

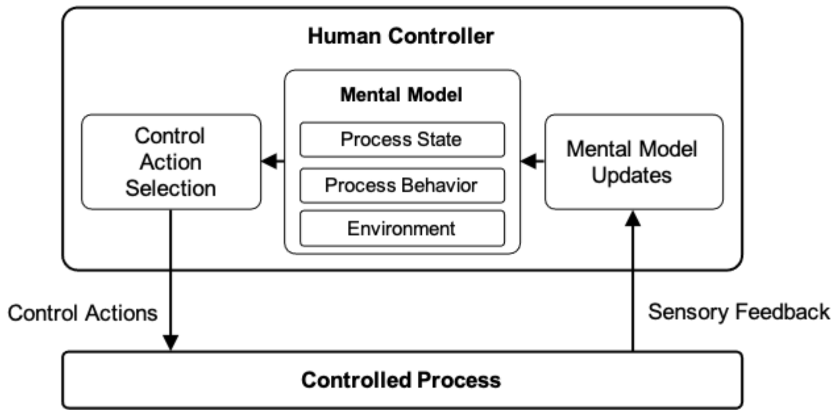

Figure 31. Engineering for humans extension of the STPA control structure (adapted from France 2017).

The extension enables the human factors engineer to work readily within the team performing STPA (France 2017). Further, the developed UCAs can be assessed in the loss scenarios to uncover attributing causes from an HFE standpoint, enhancing the richness of the scenarios through this extension. Fundamentally, the extension accounts for the perceptual, cognitive, and motor considerations of the person (i.e., what could go wrong?). Within each element of the human controller (Figure 30), attributes of failure and causes are defined, such as (high-level design heuristics are sub-bulleted—refer to NUREG-0700 [2020] for details):

- **Sensory feedback**: Poor/inadequate feedback leads to UCA.
    - Ensure adequate design feedback (e.g., clear labels, values).
- **Mental model updates**: Attention was not appropriately allocated to the task, leading to UCA.
    - Ensure cues of most importance are most salient.
- **Mental model (process state)**: Inaccurate understanding of the situation.
    - Ensure feedback is clear and attention is properly allocated.
    - Provide complete and compatible information.
- **Mental model (process behavior)**: Accurate understanding of the situation, but inaccurate understanding of the correct decision to be made.
    - Make course of action and correct decision apparent.
- **Mental model (environment)**: Accurate understanding of the situation and understanding of course of action, but misapplies ruleset (e.g., misjudges situation).
    - Ensure the system provides adequate notifications and alarms.
    - Ensure mode state is clear.

    - Design for environment constraints (i.e., see EID in Section 5.3.2 and CWA in Section 5.6.2).
- **Control action**: Inaccurate implementation of control action due to physical, processing, or temporal limitations.
    - Ensure proper function allocation to ensure tasks can be performed within the capabilities of people.
    - Ensure workload is not too high.
    - Design for the physical considerations of people.

5.6.5 Technology Acceptance Model

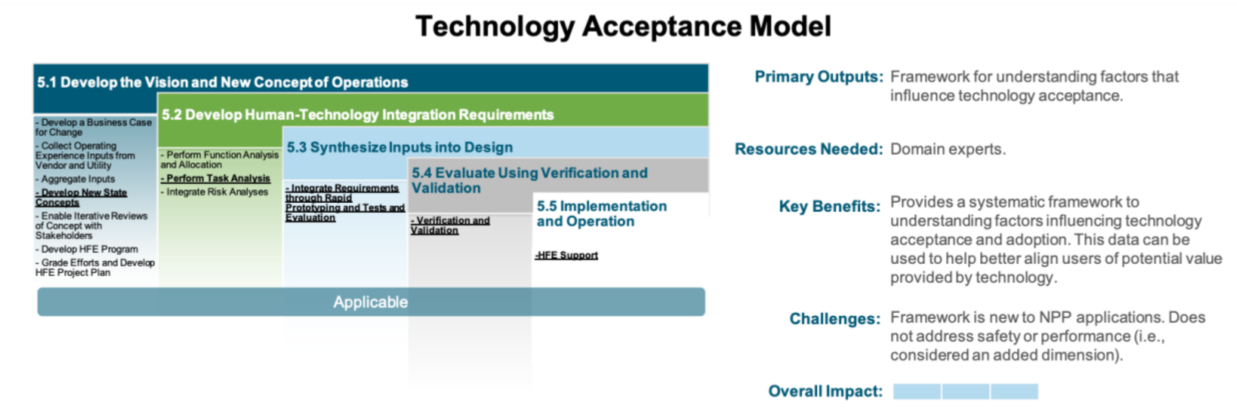

Figure 32. Application of the technology acceptance model.

At a glance, it may be reasoned that the relevance of technology acceptance is less significant in industries where there is a mandatory use of technology like in NPPs. Yet, it is important to note that the end users of the technology at NPPs (e.g., licensed operators) are strongly encouraged to be involved in the entire modernization process (Joe and Kovesdi 2018). In early stages, utilities typically select a vendor with available technology that can be configured to develop new capabilities that improve plant performance and efficiency (Hunton and England 2019). The identification and selection of new technology for the new-state vision ultimately requires "buy-in" from the stakeholders and end users.

Here, we've reasoned that the organization's attitude and intent of adopting a new technology is an important factor in the implementation of a given technology to achieve the plant's new-state vision. That is, we posit that, if the end users of the technology have a negative attitude about a candidate technology, the technology will likely not be considered in the new-state vision and ultimately not implemented. As a result, the new-state vision may be less transformative and fail to leverage technology to the greatest extent in reducing costs and improving performance.

5.6.5.1 Using TAM as a Framework for Technology Acceptance

TAM is a candidate model to support the technology adoption characterization. TAM is an established framework that characterizes the factors that contribute to the attitudes and behaviors of using technology (Davis, Bagozzi, and Warshaw 1989); the underlying basis of TAM is that perceived usefulness (PU) and perceived ease of use (PEOU) contribute to the attitudes and behaviors toward using technology. TAM has been applied across several domains, including information technology, healthcare systems, robotics, autonomous vehicles, and even urban planning (e.g., Marangunić and Granić 2015). Through these applications, there have been several extensions to the original TAM, with one notably pertaining to the adoption of automation (Ghazizadeh, Lee, and Boyle 2012). A description of TAM and its extensions relevant to technology adoption in the nuclear industry is described next.

Introduction to the Technology Acceptance Model

The TAM framework theorizes that actual use, herein referred to as technology adoption, is driven by the intent to use or adopt (Davis, Bagozzi, and Warshaw 1989). The intent is consequentially influenced by the attitude towards using or adopting, which is further influenced by the internal PU and PEOU variables. PU, PEOU, attitude, and intention are all internal variables of TAM that drive actual use. Further, these internal variables are influenced by external variables, which may be domain specific (Marangunić and Granić 2015). Figure 33 illustrates TAM and the relations between internal and external variables.

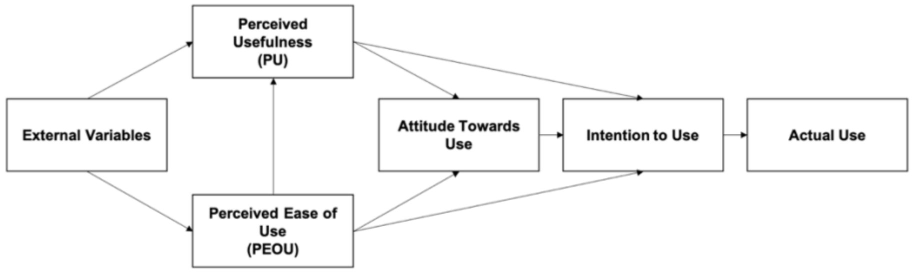

Figure 33. Original TAM framework for technology acceptance.

PU is the degree to which a user believes the technology will benefit them in their work (Sauro and Lewis 2016). TAM suggests that, as the PU of a given technology increases, the attitude and intention towards using will also increase, which will consequentially lead to actual use or technology adoption. PEOU is the degree to which a user believes using the technology will be effortless. TAM theorizes that PEOU positively influences the PU, attitude towards using, and intention to use. As the PEOU increases, PU, the attitude towards using, and the intention to use also increases, leading in turn to actual use.

Applications and Extensions of the TAM

Since TAM's initial development (Davis, Bagozzi, and Warshaw 1989), it has been extensively used and extended to include additional variables dealing with the particulars of the specific domains that it has been applied to (Marangunić and Granić 2015). While a detailed literature review of TAM's extensions goes beyond this paper, it is worth highlighting that Marangunić and Granić (2015) referenced over 20 extensions from the original TAM. The authors characterized these extensions into four generalized categories, including expansions of the model through external variables, factors from other theories, added contextual factors, and added usage measures.

Modifications to TAM via external variables can be characterized as added specificity to the external variables seen in Figure 33. Examples of external variables include confidence in technology, as well as prior experience with similar technology. Added factors from other theories refer to the addition of internal variables to TAM to increase the predictive validity of the model for specific research applications. Examples of added factors include the inclusion of trust (Marangunić and Granić 2015), task-technology compatibility (Ghazizadeh, Lee, and Boyle 2012), and perceived risk (Zhang, Tao, Qu, Zhang, Lin, and Zhang 2019). Added contextual factors refer to the inclusion of overall moderating variables such as gender or specific cultural and technology characteristics that moderate the relations seen in TAM (Marangunić and Granić 2015). Usage measures include added measures that influence actual use, such as the attitude towards using and intent to use.

One such extension of TAM with application to technology acceptance for NPP modernization is the Automation Acceptance Model (AAM), developed by Ghazizadeh and colleagues (2012). AAM was developed to serve as a generalized integrated framework for assessing the adoption of automation. While TAM is a core constituent of AAM, AAM borrows from the cognitive engineering literature to include task-technology compatibility and trust in the model (see Figure 34).

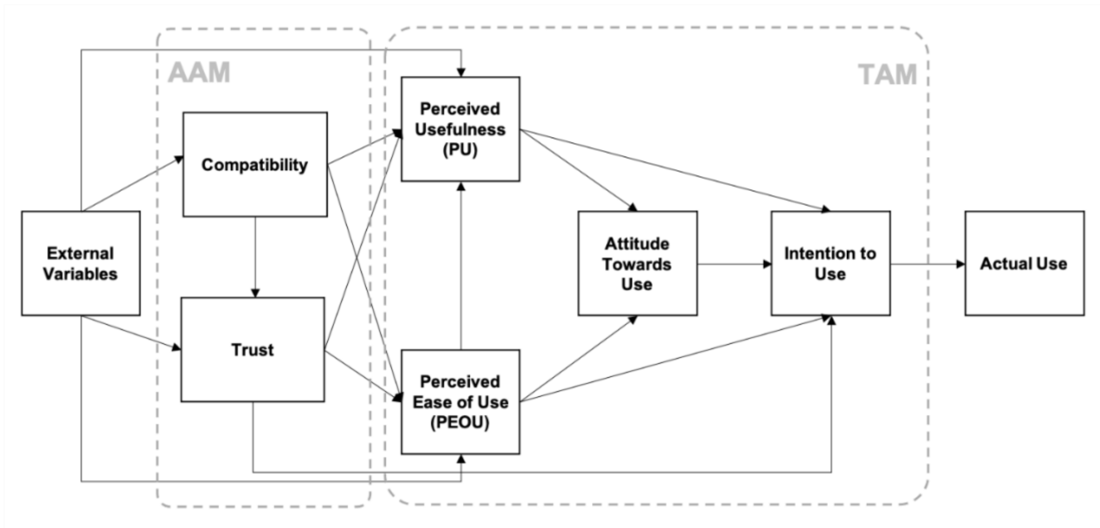

Figure 34. AAM: An extension of TAM to address acceptance of automation.

Task-technology compatibility refers to the extent to which automation matches the needs of the task performed by users (Ghazizadeh, Lee, and Boyle 2012). Compatibility pertains to the integration of appropriate levels of automation to perform the task. Compatibility applies to integrating the appropriate level of automation based on the demands of the task, including its degree of complexity, predictability, and criticality. In a simple, highly predictable, and noncritical situation, high compatibility may refer to designing the system with high levels of automation where the transparency of the automation is less important. Conversely, a less predictable, complex, and critical situation may lend itself towards a system's design having lower levels of automation or maximizing automation transparency to ensure the utmost levels of situation awareness and system resilience.

Trust in automation is considered to mediate the relation between people and technology and is greatly influenced by the perceived system reliability and one's experience with the given system (Ghazizadeh, Lee, and Boyle 2012). An important consideration with trust is the calibration to ensure an appropriate use of automation. All things equal, calibrated trust is characterized by displaying a lower trust with less reliable systems and a higher trust with more reliable systems.

AAM hypothesizes that the perceived task-technology compatibility is influenced by the degree of agreement between the design of automation and the user's past experience with similar technology. The relation between compatibility and attitude towards using is mediated by PU and PEOU; thus, high compatibility positively contributes to PU and PEOU, which positively influences the attitude towards use. Further, compatibility directly influences trust. AAM theorizes that trust influences the intent to use through direct and mediating relations between PU and PEOU.

Collectively, AAM suggests that high task-technology compatibility will have a positive influence on trust, as well as PU and PEOU, which will consequentially positively influence the attitude to use. Moreover, high compatibility coupled with increased experience with a technology may positively influence trust. Higher trust has a positive influence on PU and PEOU, as well as the intention to use. Figure 34 illustrates these relations of compatibility and trust to TAM, as theorized in AAM.

A final extension worth noting includes perceived risk. While Ghazizadeh and colleagues (2012) indirectly discuss perceived risk and its influence on trust, recent research from Zhang and colleagues (2019) explicitly modeled perceived risk in the TAM framework. The authors' work was developed within the context of public acceptance for automated vehicles. Their work empirically tested the model through structural equation modeling and confirmed an overall good model fit.

Notably, their model, herein referred to as the perceived risk TAM, included perceived risk to safety, privacy (i.e., analogous to the cybersecurity risk discussed earlier), and trust. Perceived risk to safety was found to significantly influence trust. Zhang and colleagues' work (2019) builds on the technology acceptance for autonomous vehicles, which may be qualitatively different from the application of technology adoption in process control applications like NPPs. Nonetheless, the explicit inclusion of interrelating perceived risk with trust warrants consideration in its role in technology acceptance for advanced digital technologies in NPPs where higher levels of autonomy are generally desired to reduce O&M costs.

5.6.5.2 Applying TAM to Technology Acceptance in NPPs

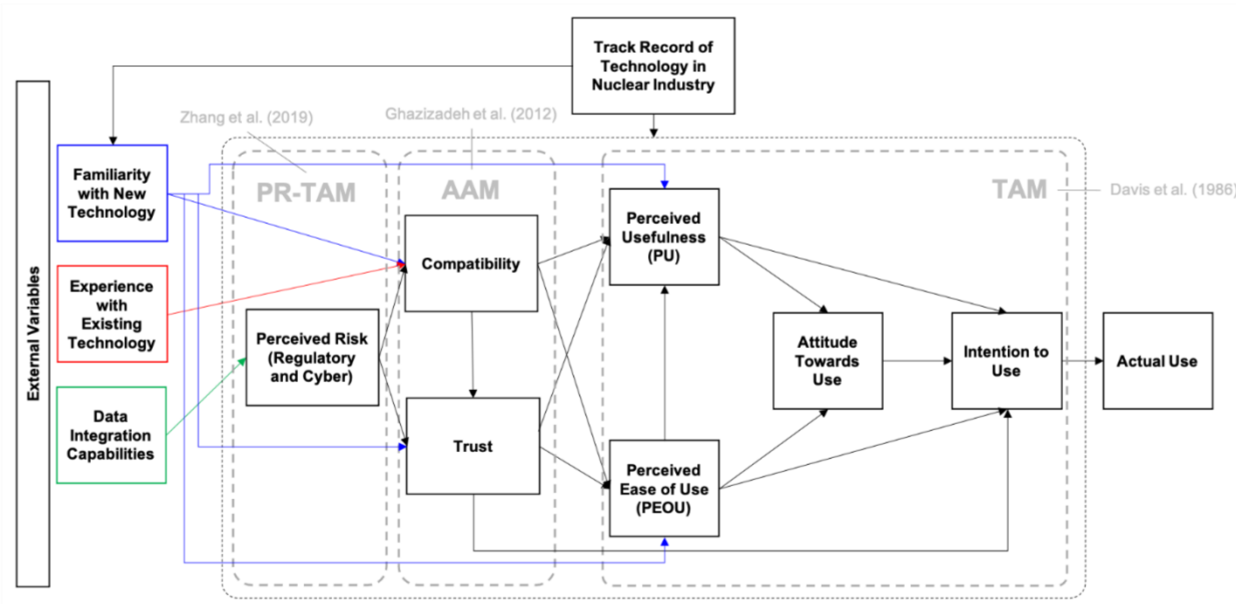

Figure 35. An extension of TAM to conceptualize technology adoption for NPPs.

The proposed framework for characterizing the factors that influence technology acceptance in NPP modernization builds on the TAM frameworks discussed previously (see Figure 35). That is, the TAM for NPP modernization (TAM-NPP-M) expands on TAM, AAM, and perceived risk -TAM by including three explicit external variables (i.e., familiarity with the new technology, familiarity with existing technology, and the technology's data integration capabilities) and one moderating variable (i.e., the technology's track record in the nuclear industry). Here, familiarity with the new technology refers to one's awareness and experience with the proposed technology being implemented. Familiarity can be gained through gaining an awareness of the technology's capabilities through the operating experience at other plants, attending demonstrations of the technology, and being involved in the overall modernization process. Experience with existing technology refers to the extent of familiarity one has with existing technology and their comfort using it. Data integration capability refers to the extent that the given technology enables data from non-safety and safety plant systems to be distributed to new applications that support plant-wide decision-making. Finally, the track record of a given technology in the industry refers to the operating experience of a given technology implemented across the nuclear industry; the track record can have a negative or positive impact on the overall TAM-NPP-M model, depending on its operating experience.

TAM-NPP-M hypothesizes that the degree of familiarity with new technology will directly influence task-technology compatibility, trust, PU, and PEOU (blue paths in Figure 35). For instance, a high degree of familiarity with the new technology will better inform task-technology compatibility, trust, PU, and PEOU given that the technology is suited for the task and is reasonably reliable. Experience with the existing technology also influences compatibility (red path in Figure 35). An operator who has extensive experience with legacy technology and has little familiarity with the new technology may be reluctant to accept the technology. Moreover, if the operator is familiar with the new technology, but it is radically different from the existing technology, the operator may perceive the new technology as less compatible. In either case, a negative influence on compatibility will also negatively influence trust, PU, PEOU, and consequentially overall attitude and intent to use.

TAM-NPP-M also hypothesizes that the technology's degree of data integration capability has a direct influence on perceived risk (green path in Figure 35). That is, it is hypothesized that technology with a high data integration capability would be perceived to have higher regulatory and cybersecurity risks, all things equal. Finally, the track record of the given technology in the nuclear industry is hypothesized to moderate the relations in TAM-NPP-M. Technology that is well vetted from positive operating experiences would positively influence technology acceptance throughout overall model; likewise, negative industry-wide operating experiences would have the opposite effect. A lack of an industry track record may also negatively influence familiarity with the new technology, as well as negatively influence compatibility and trust both directly and indirectly.

5.6.6 Simulation and Modeling

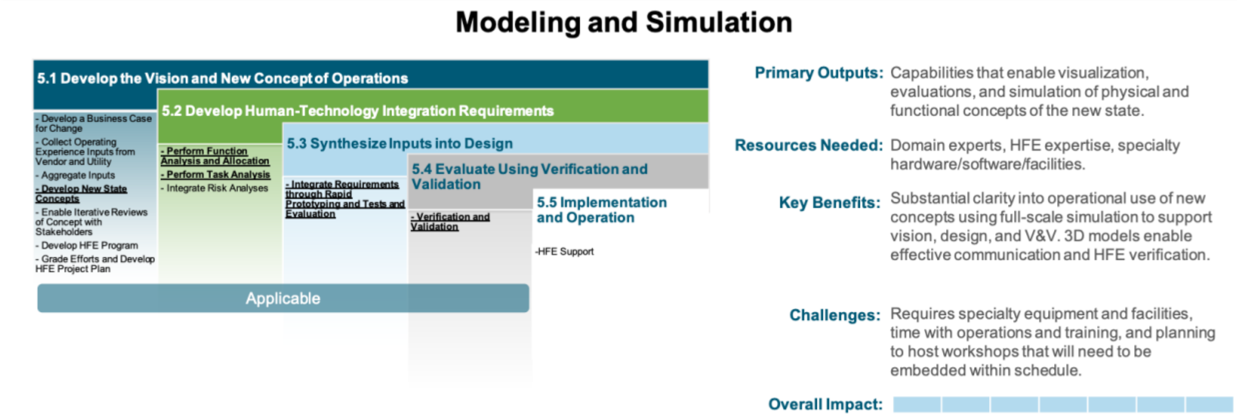

Figure 36. Application of simulation and modeling techniques.

Simulation and modeling present a broad set of approaches that can be applied across HFE activities to support visualizing, communicating, and evaluating human and technology integration consideration. The use of 3D models is described first, and simulation is presented next, discussing the application of a simulation of varying fidelity.

5.6.6.1 3D Modeling

3D modeling is a powerful tool to support visualizing the changes made from the existing state to the new state. These models can enable effective communication with stakeholders by demonstrating what the new state will look like. These models can also support early and formal human factors evaluations of the workstations and workplace using HFE principles seen in NUREG-0700 and other guidelines (EPRI 3002004310 2015; NUREG-0700 2020; INL/EXT-20-57862 2020). For instance, the application of the 3D models can be used to review changes made to the control boards as they impact the tasks in task analysis. Further, design input regarding the location and placement of the HSIs on the control boards can be informed from the results of these evaluations. The models can directly support formal verification and validation directly when evaluating the anthropometric factors concerning the modification. The model can indirectly support operating experience review and function analysis and allocation. That is, when performing knowledge elicitation activities, the models may serve as a visual reference to the control center for reference (e.g., if the training simulator is not available).

For example, Figure 37 and Figure 38 illustrate modifications made to the MCR from the existing state to the new state. The models provide important visualizations of the HSI concepts applied to the new-state vision to communicate to stakeholders and perform HFE evaluations (Figure 39).

Figure 37. Baseline control room

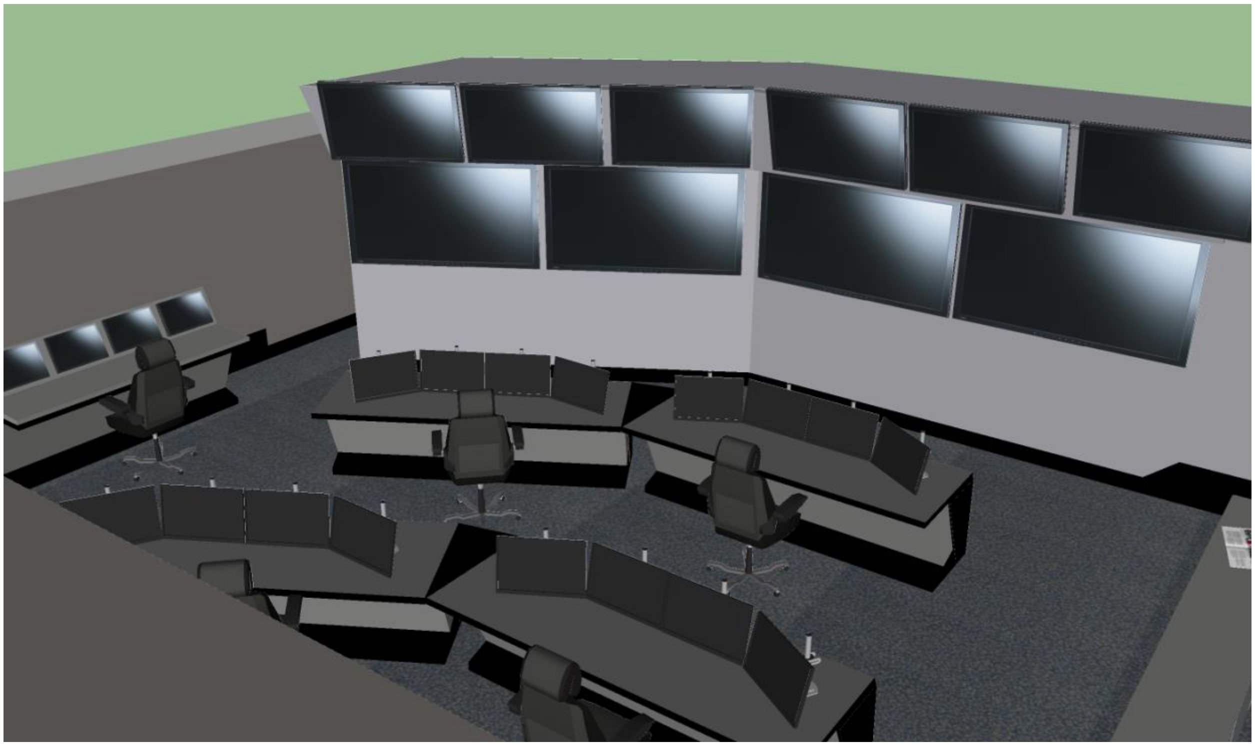

Figure 38. Conceptual design of a new-state vision.

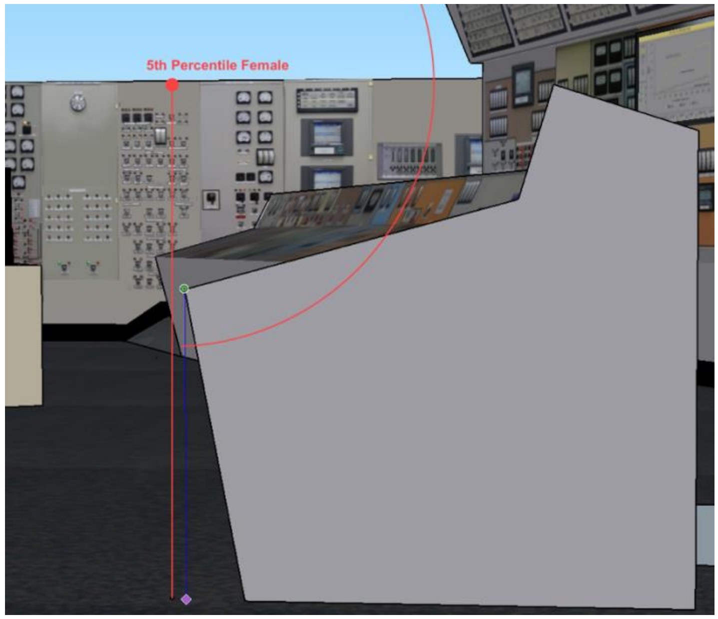

Figure 39. Reach assessment using NUREG-0700.

5.6.6.2 Simulator Testbeds

In understanding operator performance, data collection has been a particular challenge for researchers (Boring et al. 2019). In the area of human reliability analysis, efforts were made to validate human error probabilities. These efforts primarily relied on full-scope simulators with trained operators. The challenges in this type of study involved coordinating with utilities, recruiting trained operators, and the complexity of a full-scope simulator. To address these challenges, researchers (e.g., Massaiu and Fernandes 2017; Pawlak and Vicente 1996; Ulrich et al. 2017) have developed alternative methods to collect data. In turn, these methods can be applied to other research efforts beyond validating human error probabilities, such as the HFE activities described in the work. These alternative methods have their advantages and disadvantages. Thus, the application of each approach should be weighed based on their merits.

Microtasks and HFE Experiments

Microtasks are similar to experimental methods in which a variable is manipulated to create two or more conditions that are compared to one another (Massaiu and Fernandes 2017). Common control room identification tasks involve reading, checking, verifying, counting, comparing, calculating, and recording plant parameters and processes. Microtasks involve questions about these tasks and present these questions successively. The responses are automatically logged and graded for correctness. Reaction time is automatically logged as well. Reaction time is measured from the time the question appears to the operator's indication to move on to the next question. All questions must be answered; however, a "don't know" response was an option. Answers could be changed provided operators had not moved on to the next question (i.e., going back was not an option). For accuracy and reaction time analyses, "don't know" responses are not included.

Massaiu and Fernandes (2017) provide an example of how microtasks can contribute to tests and evaluations for advanced HSIs. Massaiu and Fernandes tested operators' reliability in a variety of common control room tasks using analog and digital HSIs. They found that operators do not differ in terms of the type of HSIs but that the type of task was more important in predicting reliability. Massaiu and Fernandes' data was collected using a plant training simulator with 16 operators. Some phenomena maybe difficult to detect with only 16 operators. For these types of studies, microworlds would be more appropriate.

HFE experiments are applied when a specific human factors research questions is of focus and needs high experimental control (ANSI 035A 2000). That is, HFE experiments typically begin with a research question and a hypothesis that is based on existing research. The purpose of the experiment is to test the hypothesis using an experimental design. In this sense, the conditions of interests that are being tested are denoted as the independent variable, and the variable being measured is the dependent variable. A candidate research question may be:

– *How does the impact of color affect the efficiency of detecting an alarm?*

Color in this case is an independent variable being systematically changed to observe differences in detection performance (i.e., the dependent variable) for alarms. Conditions for testing may include consistent environment, noise, lighting, distraction levels, and so on. The experimental control in HFE experiments allows for a reduction in confounding factors that may also influence performance and can be statistically analyzed. Thus, HFE experiments can provide highly quantitative insights into a specific design question when greater confidence in making a conclusion is needed. Tradeoff evaluations in tests and evaluations (Section 5.3.4) lend towards the application of HFE experiments. An example use case of where HFE experimentation was applied can be found in INL/EXT-18-51107 (2018).

Conversely, the inherent nature of having high experimental control reduces a level of realism that may be seen in a full-scale simulation. Further, there may be unique complexities of interests (confounds) that *are* of interest that lend themselves towards full-scale simulation. For example, ISV (Section 5.4) falls on the opposite end of the spectrum where the use of a qualified training simulator with a near as-built condition is appropriate.

Microworlds and Part-Task Simulators

Microworlds are a simplified version of the system (e.g., feedwater system) under study (e.g., Boring et al. 2019; Joe and Kovesdi 2021). By creating a representation that does not involve all the intricacies of the actual system, non-experts can be trained to use the system. Ulrich and colleagues (2017) developed a microworld for nuclear systems called Rancor. The graphics framework from the Advanced Nuclear Interface Modeling Environment (Boring, Lew, and Ulrich 2017) was incorporated into Rancor. Additionally, Rancor relies on a reduced-order model of heat and steam production and a game-like representation of power production. In their human reliability analysis studies (e.g., Boring et al. 2019), Rancor has been used to compare the performance of student participants to operators, and they found that the student participants' performance can be generalized to operators. Because nuclear power plant control rooms are only recently undergoing upgrades incorporating greater levels of automation and digitalization, these more modern HSIs need to be investigated further (Boring et al. 2019). Microworld studies can be used to further our understanding of how humans interact with greater levels of automation and digitalization before they are incorporated into the plant.

With Rancor, researchers can run scenarios like full-scope simulators (Boring et al. 2019). For example, Rancor can run a startup scenario in which the reactor is configured to produce steam, which in turn, generates electricity. In an actual NPP, startup can take an entire day. With simulations such as Rancor, this process can be programmed to take minutes. Rancor permits errors to be introduced into the scenario for researchers to study how operators—novice and experts—respond to errors in the control room. Information is automatically logged, including plant parameters, scenario characteristics, fault insertion types and times, operator actions, and automation interventions. An additional benefit to Rancor is the ability to incorporate eye tracking (Section 5.6.7) and freeze probes to ask questions (e.g., situation awareness questions).

There are advantages and disadvantages to using microworlds, such as Rancor (Boring et al. 2019). Rancor was developed over several years to attain the realistic representation of the process under study. New microworld programs would most likely take a similar amount of time to develop to reach a similar level of realism. Thus, if going the route of using a microworld, an established program, such as Rancor, would be expediate the project. Despite being able to generalize findings from studies using student operators to actual operators, it is always good practice to continue to exercise caution when generalizing from students to actual operators. A situation might exist in which the finding might not generalize. Despite these disadvantages, microworlds still hold a lot of promise. Its application is particularly promising for supporting tests and evaluations (Section 5.3.4) and even helping to address key research questions important to enhancing the human readiness levels of emerging technology (Section 5.1.4.2).

A full-scope simulator is a very complex setup as it seeks to simulate the entire control room. The microworld can provide more control by focusing on the system of interest without including potential confounds. This level of control would support studying human factor variables in addition to design principles. Furthermore, the microworld reduces the amount of space needed to study the system because it is presented in a compressed form. Additionally, because novices can be trained on the microworld, these novices might be the ideal participants to understand how new operators or trainees might respond to the new HSI. Finally, microworld studies have greater power than studies relying on full-scope simulators with licensed operators as participants because the latter has fewer participants than the former.

Full-Scale Simulators

Full-scale or full-scope simulators are valuable tools in studying new and older HSI designs (Joe and Kovesdi 2021). One such simulator is the one located at INL in the Human System Simulation Laboratory (HSSL). The HSSL simulator uses the same software used in qualified training simulators at NPPs. Consequently, it has the same functions as the control room at an NPP and has the capability to model normal, abnormal, and emergency conditions. Furthermore, the HSSL simulator can be configured into different layouts and mimic both digital and analog boards. The provides flexibility that is not reachable in qualified training simulators to rapid test and evaluate emerging technology concepts in realistic manner that runs same the fundamental simulator plant logic. Figure 40 provides an illustration of the HSSL; note, the HSSL has recently been upgraded to support additional advanced plant configurations (Section 5.1.4.2). Full-scale simulators enable human factors engineers to perform detailed use cases, such as those performed in training, with advanced technology prototypes that are fully functional to mature the technology's human readiness and identify human error traps well before they are being implemented.

Figure 40. Picture of the HSSL, a full-scale, fully reconfigurable simulator.

Qualified Training Simulators

In terms of mimicking an actual NPP control room, a qualified training simulator at an NPP is as close as a researcher can get to an actual control room without being in one (Joe and Kovesdi 2021). To be qualified, the simulator must meet standards of simulator fidelity. The standards establish the functional requirements for the simulator and for the testing of the operators. Both the HSSL simulator and the qualified training simulators provide high ecological validity. For situations in which a high degree of realism is necessary, the tradeoff of fewer participants and higher cost might well be worth obtaining the greater degree of realism. Joe and Kovesdi (2021) compared an analog and a digital I&C in two qualified training simulators. The two simulators were located at identical NPPs; however, one had not been upgraded yet to the new digital I&C. Although not a true experiment, this situation was a golden opportunity to study operator performance using the two I&C systems. Operators were assessed and observed across normal, abnormal, and emergency situations. The scenarios focused on how the new system supported operators' cognitive processes and ability to perform control actions. The two systems did not differ in ease of completing tasks. The new HSI was better in cognitive workload, and the existing HSI was better in terms of situational awareness. Studies such as Joe and Kovesdi's comparison of two HSIs in qualified training simulators are an excellent demonstration to regulators that the new HSI is a safe upgrade. The use of qualified simulators is particularly critical for ISV (NUREG-0711, 2012; Section 5.4).

5.6.7 Physiological Measures: Eye Tracking

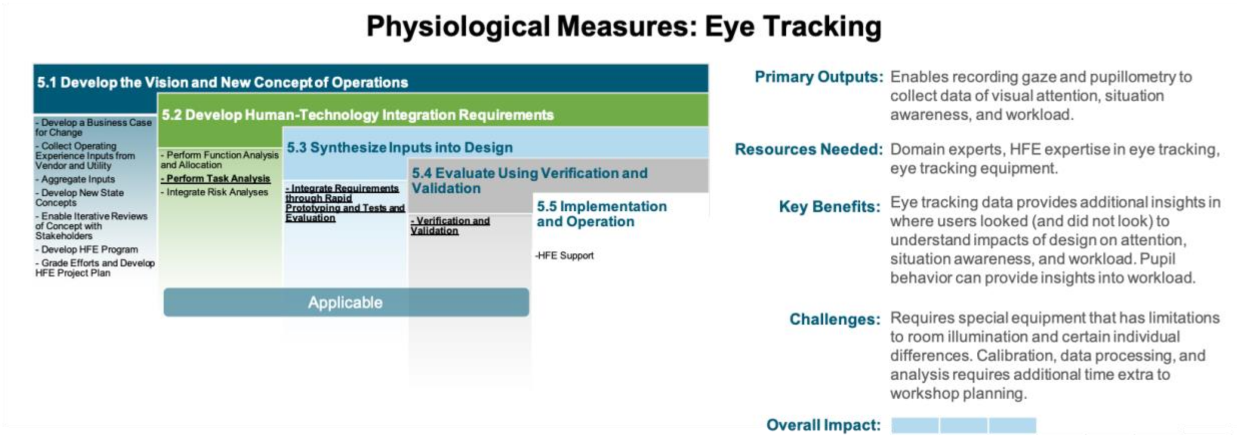

Figure 41. Application of eye tracking.

Eye tracking is a widely used physiological measure that captures when, where, and how long a person is looking at something within the environment (Kovesdi et al. 2018). A detailed description of eye tracking is beyond the scope of this section, and the reader should refer to Kovesdi and colleagues (2018) for detailed information.

There are three primary characteristics of eye movements that are captured through eye tracking: *fixations*, *saccades*, and *pupil size*. Fixations are the pauses in eye movement during which information is inferred to be cognitively processed through foveal vision whereas saccades refer to the eye movements. Pupil size refers to the size of the pupil over time and has been known to correlate with arousal, workload, and lighting. The duration of fixations is sometimes inferred to refer to the extent of cognitive processing required (e.g., Jacob and Karn 2003; Kovesdi et al. 2018). Saccades also provide use information for HFE. For example, the extent of movement (i.e., amplitude) can be used to evaluate scan efficiency. For example, an interface that enables shorter eye movements is visually more efficient than an interface that requires the user to scan further distances to receive the same information. An example of using eye tracking to perform tests and evaluations of concept HSIs is shown in Figure 42.

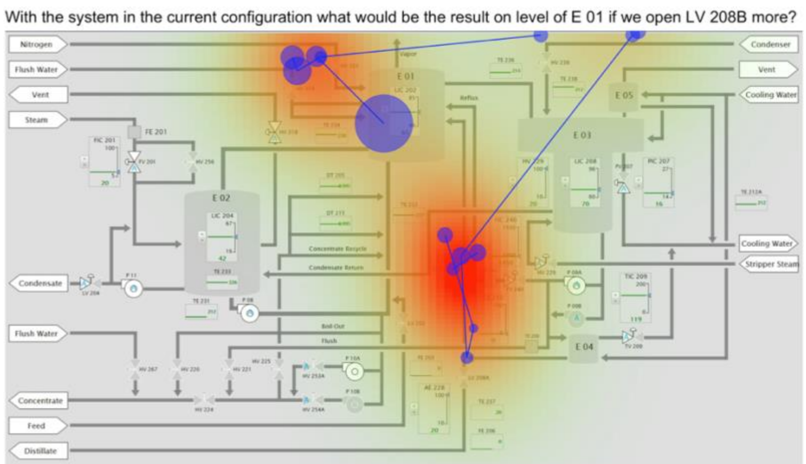

Figure 42. Example eye tracking data (data adapted from INL/EXT-18-51107).

In Figure 42, the blue nodes represent fixations, and the lines represent saccades. In this evaluation, human factors engineers were interested in evaluating the impact of plant equipment color on the mimic display and flow paths. The evaluation used eye tracking as one measure to evaluate the impact on visual performance and attention. Targeted questions were asked in a microtask (Section 5.6.6.2), and eye tracking was used to measure fixation, saccade, and pupillometry. A detailed list of eye tracking measures used are described in INL/EXT-18-51107, but some key measures included fixation duration, fixation frequency, and saccade length. As shown in the figure, the size of the node represents greater fixation duration, and the length of the lines represent further eye movements. The aggregate of these measures was collected and evaluated as part of a multimethod/multi-measure approach to interface evaluation. The color gradients (i.e., also known as a heat map) provided qualitative insights of their visual attention. Collectively, the results provided design recommendations for color use based on objective HFE measures, rather than opinion.

Eye tracking can provide useful information of attention, workload, and elements of usability (e.g., scan efficiency) to support task analysis, tests and evaluations, and V&V. Measures highlighted above and dwell measures (i.e., aggregate fixations over an area of interest) can provide insightful descriptive information to support HFE activities. Table 14 summarizes the key measures and uses in this report.

Table 14. Common eye tracking measures and application to key HFE activities.

Measures	Metric (HFE Construct)	HFE Activity Supported	Considerations
Live Gaze Feed	Live Eye Tracking Video Feed (Visual Attention)	Task Analysis (Section 5.2.2), Design Tests and Evaluation (Section 5.3.4)	Full-scale simulators and realistic scenarios are favorable
Heat Maps	Heat Map (Visual Attention)	Task Analysis (Section 5.2.2), Design Tests and Evaluation (Section 5.3.4)	Flexible across varying levels of fidelity
Dwell Metrics	Proportion of Time Spent in Area of Interest (Visual Attention, Interface Usability)	Task Analysis (Section 5.2.2), Design Tests and Evaluation (Section 5.3.4)	Test and evaluation
Fixation and Saccade Metrics	Fixation Duration (Mental Workload) Fixation/Saccade Count (Interface Usability) Nearest Neighbor Index (Mental Workload) Saccade Amplitude (Mental Workload) Time to First Fixation (Interface Usability)	Design Tests and Evaluation (Section 5.3.4), V&V (Section 5.4)	Best when used in controlled experiments
Pupillometry	Pupil Size (Mental Workload)	Task Analysis (Section 5.2.2), Design Tests and Evaluation (Section 5.3.4), V&V (Section 5.4)	Best when used in controlled experiments; sensitivity is generally a concern in applied settings

Eye tracking was also tolerated by operators in full-scale simulation studies (Kovesdi et al. 2018), suggesting that it can be applied in a variety of simulator settings. The potential considerations when using it, however, is that:

- specialized equipment is needed
- training/experience for effectively using the tools
- the equipment may have limited battery life
- eye tracking often requires calibration, which can add time to the study protocol.

6. CONCLUSION

Nuclear power continues to have a critical role in providing safe, reliable, and economical carbon-free electricity. As many of the U.S. NPP fleet begin subsequent license renewal to extend their operating life, the opportunity to greatly modernize existing NPP infrastructure and capabilities can have a significant positive impact on continued safe, reliable, and economic operation. Nonetheless, this integration of new technology requires careful attention to the technical and sociotechnical challenges that are embodied in transformational changes to the operating model of these plants. Addressing the human-technology integration element must be considered to ensure that new capabilities, like advanced automation, offer an economic benefit and are configured such that people can ultimately control the plant safely and reliably.

This work presents a methodology to enable the adoption of new plant capabilities like automation by addressing the human and technology integration challenges that have hindered wide-scale integration of technology today. Guidance and standards in SE and HFE form the foundation of this methodology; nonetheless, this work extends current guidance by integrating the lessons learned from previous R&D from the DOE LWRS Program and other sources as *first principles* to guide the development of a new vision and concept of operations, ensuring key elements that ensure safety and reliability are considered. Further, this work integrates with business case approaches like ION and advanced and emerging methods in HFE and risk analysis (i.e., including CWA, cognitive task analysis, STPA, TAM, and simulation and modeling) to support challenges associated with better aligning the perceived value of technology, addressing regulatory uncertainties, and supporting the functional decomposition of power generation systems. Detailed guidance is given in this work, providing a description of key activities, methods, and resources needed to achieve a transformation new-state vision that ensures safety, reliability, and effective decision-making and situation awareness (e.g., as seen in Figure 1).

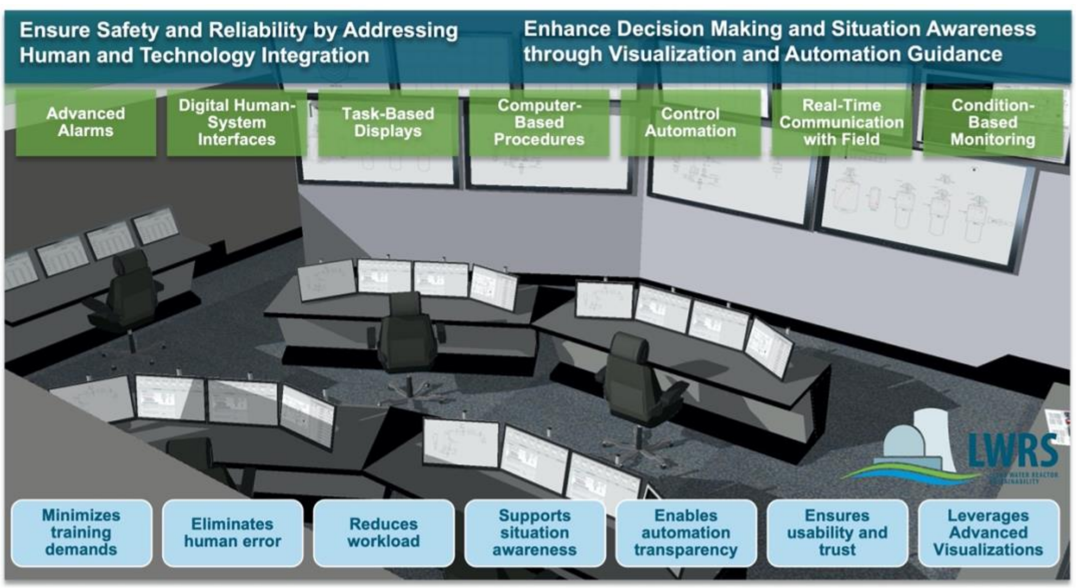

Figure 1 (repeat). Concept advanced new state that address human and technology integration challenges.

The next step in this research entails continued collaboration with partnering industry collaborators to evaluate the effectiveness of the guidance provided that it will ultimately enable transformative change to their existing operating model. Key outputs of future work include lessons learned and updates to this guidance, as well as HFE/human-technology integration technical bases for the integration of advanced digital capabilities for both COTS and future technologies.

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Appendix A
New-State Vision Definition Worksheets

The following worksheets are structured around the EPRI 3002004310 (2015) endpoint vision worksheets. These tools provide additional guidance through the use of first principles that describe characteristics of each EPRI topic that is important to safety and reliability. Further these worksheets highlight how enabling capabilities can support these principles. The questions listed as Utility/Vendor Inputs are used to facilitate discussion around how these first principles are being supported. The first set provides a list of guides for abnormal (including emergency) operations, and the second set provides a list of guides for normal operation. A reference key is provided at the bottom where the citations are called out.

ABNORMAL OPERATIONS

Abnormal Operation			
Activity	Identify and respond to plant equipment failures and other situations requiring operator action.		
First Principle	Support rapid detection and diagnosis of deteriorating plant conditions.		
Principle Short Label	Rapid diagnosis and response support		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Alarms	- Alarm primary design to notify human operators of out-of-parameter conditions that could threaten equipment, environment, product quality, and human safety. Attract attention to undesirable process conditions that require human action [13] - MCR alarms pertain only to operators and conditions they have the capability to diagnose and take action on [13]	*Are there any pain points with the existing alarm design? Alarm salience and detection? Interpretation?* *Is alarm filtering desired?*	*How will alarm cues be presented to operators?* *What design bases are applied to ensure that alarms are salient to operators?* *Is alarm filtering available? How is this accomplished?*
Overview Displays	- Quick assessment of plant response to diagnostic and mitigation techniques [6,7] - Operators should be able to quickly assess the overall state of the plant through leading indications without moving to multiple locations [6,7]	*Does the modification entail any time-critical actions?* *Are there any notable pain points with the existing indications in making a quick plant assessment and diagnosis? Missing information? Poor format?*	*How will leading indications that support situation assessment and diagnosis be displayed?* *How will related information be consolidated on one screen?*
Task-Based Display	- Equipment/processes triggering alarm has embedded indication to help operators associate alarms with problem space [13] - Task-based displays adjust display to support diagnosis and response monitoring	*Is the integration of alarm information on digital HSIs desired?* *Would dynamic HSI displays that provide context-dependent information to*	*Are alarms embedded in digital HSIs displays?* *Are there specific displays to support fault diagnosis and response planning?*

Abnormal Operation			
Activity	Identify and respond to plant equipment failures and other situations requiring operator action.		
First Principle	Support rapid detection and diagnosis of deteriorating plant conditions.		
Principle Short Label	Rapid diagnosis and response support		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
		support normal/abnormal conditions be desired?	
Decision Support	- In response to situations requiring operator action, the associated procedure (associated with alarm or equipment failure response) is automatically presented and available at the moment of need [13]	*Are computer-based procedures desired?* *Is decision support to help in situation assessment desired?* *Is decision support to help in response planning desired?*	*Are computed-based procedures available? What capabilities are there?* *What decision support is available for operators in situation assessment and response planning? How is this information made available and integrated in the workstation?*
Control Automation	- Tasks that require monitoring but are not useful to diagnostic actions should be performed by automation (e.g., maintaining tank levels or water temperatures) - All control automation should clearly communicate goals and predicted capability of performing actions	*Is there any desire to automate any new functions related to responding to equipment failures?*	*Are there any capabilities available for automating functions related managing abnormal situations?*
Is there any OE on the activity described?			

Abnormal Operation			
Activity	Diagnose and troubleshoot problems with the plant process, systems, and equipment		
First Principle	Provide relevant procedures, automated status monitoring, and decision support during diagnostic activities.		
Principle Short Label	All control system functions should focus to support operator diagnostic and mitigative tasks.		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Alarms	- MCR alarms pertain only to operators and conditions they have the capability to diagnose and act on [13]	*Is alarm filtering desired?*	*Is alarm filtering available? How is this accomplished?*
Overview Displays	- When exploring/diagnosing failures, consequential/relevant information should be present on one screen to reduce the operator's mental and physical workload [6,7] - Integral formats should be used to communicate high-level, status-at-a-glance information where users may not need information on individual parameters to interpret the display. Additional information: Since integral displays do not display individual parameters, they are most appropriate for general status monitoring [17] - Displays should contain all information for the safe operation of a system including information from related systems if there are system dependencies that must be considered by the operator [5]	*What is the vision for using digital HSIs and overviews for continuously available/visible indications important to safety and situation assessment?* *Will group-view displays be considered?* *Will dedicated operator workstations be considered?* *How will the crew coordinate information to effectively diagnose and troubleshoot problems?*	*How will leading indications that support situation assessment be displayed?* *Is there the capability to display all information for safe operation in a continuously visible or continuously available format? (e.g., SPDS)* *How will related information be consolidated on one screen?* *How will related information be integrated into a single visual? (e.g., trends, configural displays, etc.)*
Task-Based Display	- Task/state-based displays: When displays are partitioned into multiple pages, function/task-related data items should be displayed together on one page. Relations among data sets should appear in an integrated display rather than partitioned into separate display pages [2]	*Will dedicated operator workstations be considered?* *Is there a current style guide in place for grouping information and navigation?* *Are task-based/ situation-based displays desired?*	*Describe the navigation scheme. How does the platform enable efficient navigation?* *How will related information be consolidated on one screen?* *Are task-based displays available?*
Is there any OE on the activity described?			

Abnormal Operation			
Activity	Respond to accidents using emergency operating procedures.		
First Principle	Enact automated control system actions to bring plant to safe space while providing operators with dynamic instructions, systems monitoring, and future steps to anticipate.		
Principle Short Label	Decision support and dynamic instructions for emergency operating procedures		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Overview Displays	- Present supporting documents and information at relevant moments to support proper mitigative actions or monitoring of plant changes [12,19]	*Is linking relevant information to digital displays like overviews to Emergency Operating Procedures desired?*	*What capabilities are there for providing leading indications to support accident response?*
Decision Support	- Dynamic work instructions offer automated support in many ways. Dynamic instructions should adhere to the following principles if applied to emergency operating procedures [12] - *Provide Context-Sensitive Information Everywhere Possible* - *Support All Expected Task Flow Characteristics* - *Support Expected Level of Flexibility in Performing Task* - *Guide Worker Through Logical Sequence of the Procedure* - *Provide Information Needed to Control Path Through the Procedure* - *Provide Computerized Support Where Appropriate and Possible* - *Include Functionality That Improve Communication* - *Provide a Method to Review and Save Records* - Additional Information: See Table 5-1 in [19] for more information and technical basis for teaming with automation	*Are dynamic instructions for an accident response desired?*	*Are there capabilities to provide decision support for emergency operations?*
Is there any OE on the activity described?			

Abnormal Operation			
Activity	Maintain situation awareness		
First Principle	Coordinate information on displays to provide at-a-glance plant status and response to current task at hand. Develop clear communication method between operator and automated system components with decision support, task status, and future actions.		
Principle Short Label	Context- and condition-based information to support SA		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Overview Displays	- System overviews should provide an abstracted representation of overall system status - System overviews should provide functional information and provide physical information in the form of simplified process mimics where appropriate (see Section 2.5 for more detail) - System overviews should contain embedded information, such as trends, indications of alarm states, indication of process control parameters - System overview should be designed for use by an operator at the boards for a hybrid control room. System overview may also be used to provide shared SA in the control room by way of other operators or supervisors accessing a duplicate display from a workstation. Overviews do not need to be designed to be read from across the control room - System overviews should be designed to be task-based. The number and type of tasks supported will vary by system but will include the following at a minimum: - Additional high-consequence or critical tasks will be identified for each system based on frequency of task impact of task to operations, and the potential to increase efficiency and safety by	*Are there challenges today in processing information to support decision-making and response for abnormal and emergency conditions?* *What is the vision for using overview displays to support situation awareness in abnormal and emergency conditions?* *Is there a desire to utilize different abstractions of the plant to support situation awareness? Such as plant-level and system/task-level overviews.*	*How will leading indications that support situation assessment be displayed?* *Is there capability to display all information for safe operation in a continuously visible or continuously available format? (e.g., SPDS)* *How will related information be consolidated on one screen?* *Is there alarm integration within the overview displays?*

Abnormal Operation			
Activity	Maintain situation awareness		
First Principle	Coordinate information on displays to provide at-a-glance plant status and response to current task at hand. Develop clear communication method between operator and automated system components with decision support, task status, and future actions.		
Principle Short Label	Context- and condition-based information to support SA		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
	directly supporting those tasks with a tailored task-based display [5]		
Control Automation	- Clear communication to operators when a goal or task failed to be fully completed by automation. [19] - Clear communication to operators when automated capability to maintain or perform plant status or tasks is degrading (allows for mitigative/corrective action from operators) [19] - Automation awareness of operator actions to provide decision support or potential error alerts to operators [19] - Additional Information: See Table 5-1 in [19] for more information and technical basis for teaming with automation	*Is there any desire to automate any new functions related to responding to equipment failures?*	*Are there any capabilities available for automating functions related managing abnormal situations? What feedback is provided to plant personnel if there is automation used?*
Is there any OE on the activity described?			

Abnormal Operation			
Activity	Handle compliance with tech spec conditions.		
First Principle	Provide decision support that keeps operation decisions within equipment and regulatory technical specifications.		
Principle Short Label	Control automation and decision support to operate within technical specifications		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Decision Support	- Provide decision support that keeps operation decisions within equipment and regulatory technical specifications.	*Are there any pain points in maintaining technical specifications?* *Would decision support be desired to support maintaining technical specifications?* *Are there other enhancements to support maintaining technical specifications that are desired?*	*What capabilities are available to support maintaining technical specifications?*
Is there any OE on the activity described?			

<table>
<tr><th colspan="4">Abnormal Operation</th></tr>
<tr><td>Activity</td><td colspan="3">Monitor and control the plant under conditions of degraded or failed I&C/HSI.</td></tr>
<tr><td>First Principle</td><td colspan="3">Information should be presented using a hierarchic approach, enabling users to quickly and easily determine the overall status of I&C systems and subsystems from top-level displays and to access more detailed information on lower-level displays [17]. Control system supports determining and diagnosing degraded conditions and failures</td></tr>
<tr><td>Principle Short Label</td><td colspan="3">Control automation should support detection and diagnosis of degraded or failed systems</td></tr>
<tr><td colspan="4">Discussion Guide</td></tr>
<tr><td></td><td>Characteristics (Examples) of Advanced Concept</td><td>Utility Inputs</td><td>Vendor Inputs</td></tr>
<tr><td>Overview Displays</td><td>- The HSI should provide a representation of the I&C system and its subsystems.

- Additional information: The representation of the I&C system and its subsystems should be sufficiently detailed to enable operators to monitor its performance and detect HSI and I&C degradations, especially those affecting important human actions, as identified in NUREG-0711, Human Factors Engineering Program Review Model, Revision 3, issued November 2012.

- Information should be presented using a hierarchic approach, enabling users to quickly and easily determine the overall status of I&C systems and subsystems from top-level displays and to access more detailed information on lower-level displays [17]
- A display feature should be provided to indicate to the user that the HSIs are operating properly [17]</td><td rowspan="2">Are overview displays to support fault detection and diagnosis desired? Plant-level? System-level?

How are the following detected in the current state?
• Degraded HSIs, information, controls
• Degraded alarms
• Automation failures

How are the following managed in the current state?
• Degraded HSIs, information, controls
• Degraded alarms
• Automation failures

How are task-based displays envisioned to indicate degraded information?</td><td rowspan="2">How do the proposed HSIs and I&C support fault detection?

How is degraded HSIs and I&C managed?

How is degraded information managed?</td></tr>
<tr><td>Task-Based Display</td><td>- The HSI should provide information about each I&C subsystem status and performance parameters [17]</td></tr>
<tr><td>Decision Support</td><td>- The HSI should support users in determining the cause(s) of degraded conditions and failures [17]</td><td>Is decision support desired to support failure identification?</td><td>Are there capabilities to support the operator in failure identification?</td></tr>
</table>

Abnormal Operation			
Activity	Monitor and control the plant under conditions of degraded or failed I&C/HSI.		
First Principle	Information should be presented using a hierarchic approach, enabling users to quickly and easily determine the overall status of I&C systems and subsystems from top-level displays and to access more detailed information on lower-level displays [17]. Control system supports determining and diagnosing degraded conditions and failures		
Principle Short Label	Control automation should support detection and diagnosis of degraded or failed systems		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
	- The HSI should support operators in determining the steps for failure recovery or backup actions, should recovery be impossible [17]	*Is decision support desired to support failure diagnosis?* *Is decision support desired to support failure response planning?*	*Are there capabilities to support the operator in failure diagnosis?* *Are there capabilities to support the operator response planning?*
Control Automation	- Backup systems should be available for HSI and I&C failures [17]	*How is automation failure management currently handled?* *Are there any time-critical human actions that would benefit from additional control automation during abnormal/emergency situations?*	*How are degraded HSIs and I&C associated with automated control actions managed?*
Online Monitoring	- The HSI should allow users to request an HSI or I&C system check [17]	*What form of diagnostic capabilities are being considered?*	*How can users monitor HSI/I&C health in the proposed platform?*
Is there any OE on the activity described?			

Abnormal Operation			
Activity	Monitor and control the plant when the main control room must be evacuated.		
First Principle	Maintain consistency in navigation, plant, and system overviews and the graphic display and control style of auxiliary control HSI [2,6,7,17]		
Principle Short Label	Auxiliary controls have same HSI design as main controls		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Communication Across the Plant	- Maintain consistency in navigation, plant and system overviews and the graphic display and control style [2,6,7,17]	*Are there any challenges in coordinating with remote facilities (e.g., emergency support facilities – emergency operations facility, onsite operational support center, or technical support center)?* *Are there plans integrating information to remote facilities?*	*Does the platform enable broadcasting information to remote facilities?* *If so, do the HSIs follow a standard convention as the HSIs in the control room?*
Is there any OE on the activity described?			

NORMAL OPERATIONS

Normal Operation			
Activity	Monitor the plant process and systems/equipment, including performance monitoring		
First Principle	Operators should be able to quickly assess the overall state of the plant without moving to multiple locations [6,7]		
Principle Short Label	Support rapid assessment of plant safety status		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Alarms	- Plant and task overviews present embedded alarms to highlight affected areas of the plant - Utilizes alerts on task-based display to allocate operator attention when performing another task and the new condition requires immediate attention - Provide alarm filtering capabilities to show originating fault without cascading alarms	*Are there any pain points with the existing alarm design? Alarm salience and detection? Interpretation?* *Are embedded alarms on HSIs desired?* *Is alarm filtering desired?*	*How will alarm cues be presented to operators?* *What design bases are applied to ensure that alarms are salient to operators?* *Is alarm filtering available? How is this accomplished?* *Can alarms be embedded on HSIs? How does this information appear?*
Overview Displays	- Plant and task overview displays context-dependent information based on plant status - Plant overview provides an at-a-glance indication of key plant performance parameters - The overviews provide trends and advanced visualizations to support the operator in monitoring the status	*Are there challenges today with monitoring tasks during normal operation?* *What is the vision for using overview displays to support situation awareness in normal operation?* *Is there a desire to utilize different abstractions of the plant to support situation awareness? Such as plant/system/task-level overviews.* *Are there any leading indications used to monitor plant health that should be trended that are not now?*	*How will leading indications that support situation assessment be displayed?* *Is there capability to display all information for safe operation in a continuously visible or continuously available format? (e.g., SPDS)* *How will related information be consolidated on one screen?* *Is there alarm integration within the overview displays?*
Task-Based Display	- Alerts, decision support, and leading indications are collocated on the task-based displays with procedures to improve monitoring efficiency when performing a task	*Are there challenges integrating information in the existing state for certain tasks?* *Is integration of alarm information on digital HSIs desired?* *Are computer-based procedures desired?*	*Can alarms be embedded on HSIs? How does this information appear?* *Are there computer-based procedures? What are the capabilities?* *Are there any premade task-based displays that can be leveraged?*

Normal Operation			
Activity	Monitor the plant process and systems/equipment, including performance monitoring		
First Principle	Operators should be able to quickly assess the overall state of the plant without moving to multiple locations [6,7]		
Principle Short Label	Support rapid assessment of plant safety status		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
		Are there specific tasks that would benefit from task-based displays?	
Decision Support	- Decision support capabilities provide prognostic information of potential faults before these happen. Information is provided across the display systems to support identification, diagnosis, response planning, and execution	*Are there currently any maintenance challenges today that may benefit from condition-based/prognostic support?* *Are there any operational tasks that are difficult to perform today because they are cognitively burdensome (e.g., requires mental calculation, integration of information)?*	*Are there any enhancements that may support maintenance of the plant being considered? Do these enhancements support decision-making?* *Are there any enhancements that may support operations of the plant being considered? Do these enhancements support decision-making?*
Control Automation	- Increased control automation enables the operator to act in supervisory control of the plant, rather than working in the tedious details of specific control actions. This enables the operator to be able to view higher level information of plant/task/system-level status afforded by the plant overview and task overview	*What is the vision for using control automation to support operations? Will there be changes envisioned to the roles and responsibilities of the operators (e.g., placing operations in more of a supervisory role)?* *Are there any tedious manual tasks that can be automated?*	*What capabilities are available to enable control automation?*
Online Monitoring	- Plant status is collected in the integrated control room through online monitoring capabilities that collect continuous data of plant equipment with sensor input	*Will the vision consider leveraging plant data (e.g., from the corporate network) to support maintenance functions?* *Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*	*What capabilities are available to enable plant monitoring of equipment?* *How is this information integrated in the HSIs used by the intended users (i.e., maintenance, operations)?* *Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*
Is there any OE on the activity described?			

Normal Operation			
Activity	Monitor the plant process and systems/equipment, including performance monitoring		
First Principle	Operators should be able to access system specific information quickly to enhance situational awareness while completing tasks [6,7].		
Principle Short Label	Ensure efficient accessibility of system specific information		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Alarms	- Embedded alarms allow the operator to select one to access detailed information when desired; this can be accomplished by selecting the alarm and requesting more information	*Are embedded alarms on HSIs desired?* *Are there challenges today in maintaining situation awareness? Are there alarm enhancements that may address these challenges?*	*Can alarms be embedded on HSIs? How does this information appear?*
Overview Displays	- The layout of the integrated control room offers different levels of abstraction of the plant: plant-level, task/system-level, and task-based. Depending which screen is viewed, the operator and quickly scan the available displays to enhance situation awareness	*Are there challenges today with monitoring tasks during normal operation?* *What is the vision for using overview displays to support situation awareness in normal operation?* *Is there a desire to utilize different abstractions of the plant to support situation awareness, such as plant/system/task-level overviews?* *Are there any leading indications used to monitor plant health that should be trended that are not now?*	*Are there plant-level overviews?* *Are there system/task-level overviews?* *How do operators access these types of displays? Will they be readily available?*
Task-Based Display	- The task-based display system procedure pane provides step-level information to perform. In these steps, relevant plant data is embedded (and verified) to support situation awareness	*Are computer-based procedures desired?* *Are there specific tasks that would benefit from task-based displays?*	*Are there computer-based procedures? What are the capabilities?* *Can live plant data be integrated in the procedure system?* *Are there any premade task-based displays that can be leveraged?*
Decision Support	- Emergent conditions are sent via alert on the task-based display (and seen with embedded alarms). These cues enable the operator to drill into more	*Are there challenges today in accessing information in the control room?* *Is there a navigation strategy in place today for*	*Are there capabilities available for alerting operations of emergent conditions (e.g., see alarms)?*

Normal Operation			
Activity	Monitor the plant process and systems/equipment, including performance monitoring		
First Principle	Operators should be able to access system specific information quickly to enhance situational awareness while completing tasks [6,7].		
Principle Short Label	Ensure efficient accessibility of system specific information		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
	specific information about the issue is ensure situation awareness - Maintenance activities are also provided as notifications to the operator and supporting personnel. These cues provide reminders and status of plant equipment health and maintenance needs to support situation awareness	*accessing information across the control room? Should this be considered in the vision?* *Would emergent condition alerting benefit operations?* *Would notifications to maintenance of reminders and plant health be desired?*	*Are there maintenance capabilities that can support reminding personnel of equipment health and routine maintenance? How is this information managed?*
Real-Time Communication	- Field operators who need system-level information can utilize the same task-based display system information to perform their tasks and maintain situation awareness. Operators in the main control room can see in real time what the field operators are doing (at a system level and task level) to maintain situation awareness	*Are there challenges coordinating outside the main control room to support operational and maintenance tasks?* *Is there a desire for real-time communication with the field (e.g., provide live status of field actions, shared information)?* *Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*	*Are there capabilities available to support real-time communication?* *Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*
Online Monitoring	- Plant status is collected in the integrated control room through online monitoring capabilities that collect continuous data of plant equipment with sensor input	*Will the vision consider leveraging plant data (e.g., from the corporate network) to support maintenance functions?* *Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*	*What capabilities are available to enable plant monitoring of equipment?* *How is this information integrated in the HSIs used by the intended users (i.e., maintenance, operations)?* *Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*
Is there any OE on the activity described?			

<table>
<tr><th colspan="4">Normal Operation</th></tr>
<tr><td>Activity</td><td colspan="3">Perform or participate in maintenance & testing</td></tr>
<tr><td>First Principle</td><td colspan="3">Improve maintenance and lower cost by using data-driven predictive analytics to schedule maintenance by coordinating with other scheduled maintenance [7,16].</td></tr>
<tr><td>Principle Short Label</td><td colspan="3">Utilize a condition-based approach to maintenance</td></tr>
<tr><td colspan="4">Discussion Guide</td></tr>
<tr><td></td><td>Characteristics (Examples) of Advanced Concept</td><td>Utility Inputs</td><td>Vendor Inputs</td></tr>
<tr><td>Task-Based Display</td><td>- The task-based display system provides a means for plant staff to view notifications related to condition-based maintenance. Detailed information can be accessed as desired and shown on the secondary task display</td><td>Are there challenges today with maintenance and testing?

Would task-based displays benefit maintenance and testing?</td><td>Are there task-based HSIs that can be used to support maintenance? Do these provide the ability to drill into more detailed information to support their task?</td></tr>
<tr><td>Decision Support</td><td>- Predictive maintenance is enabled through decision support capabilities on the task-based display. When equipment maintenance is identified through the system (and does not require immediate attention), a notification is given to operators and plant staff. Maintenance scheduling is enabled automatically, and the operator can view this schedule as desired or enter specific notes as needed</td><td rowspan="2">Is predictive/condition-based maintenance desired?

Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?</td><td rowspan="2">Is predictive/condition-based maintenance available from the platform?

Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?</td></tr>
<tr><td>Online Monitoring</td><td>- Condition-based monitoring is enabled through data integration between plant equipment with sensor input to the control room. "Once operators are alerted that maintenance is needed, operators can choose to continue monitoring the situation or coordinate with maintenance to address any issues with the equipment. Coordinating maintenance activities is key because it reduces the amount of time the plant is shutdown, thereby,</td></tr>
</table>

Normal Operation			
Activity	Perform or participate in maintenance & testing		
First Principle	Improve maintenance and lower cost by using data-driven predictive analytics to schedule maintenance by coordinating with other scheduled maintenance [7,16].		
Principle Short Label	Utilize a condition-based approach to maintenance		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
	minimizing lost revenue." [6, pp. 49]		
Is there any OE on the activity described?			

<table>
<tr><th colspan="4">Normal Operation</th></tr>
<tr><td>Activity</td><td colspan="3">Perform or participate in maintenance & testing</td></tr>
<tr><td>First Principle</td><td colspan="3">Improve outage coordination through enhanced scheduling [6, pp. 49]</td></tr>
<tr><td>Principle Short Label</td><td colspan="3">Improve outage times by eliminating tedious planning tasks</td></tr>
<tr><td colspan="4">Discussion Guide</td></tr>
<tr><td></td><td>Characteristics (Examples) of Advanced Concept</td><td>Utility Inputs</td><td>Vendor Inputs</td></tr>
<tr><td>Task-Based Display</td><td>- The task-based display system provides a means for plant staff to view notifications related to condition-based maintenance. Detailed information can be accessed as desired to be shown on the secondary task display</td><td>Are there challenges today with outage management?

Would task-based displays benefit outage management?</td><td>Are there task-based HSIs that can be used to support outage management? Do these provide the ability to drill into more detailed information to support their task?</td></tr>
<tr><td>Decision Support</td><td>- Predictive maintenance is enabled through decision support capabilities on the task-based display. When equipment maintenance is identified through the system (and does not require immediate attention), a notification is given to operators and plant staff. Maintenance scheduling is enabled automatically, and the operator can view this schedule as desired or enter specific notes as needed</td><td rowspan="2">Is predictive/condition-based capabilities desired for outage management?

Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?</td><td rowspan="2">Is predictive/condition-based maintenance available from the platform for outages?

Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?</td></tr>
<tr><td>Online Monitoring</td><td>- Condition-based monitoring is enabled through data integration between plant equipment with sensor input to the control room. This information can be used with decision automation to auto-schedule necessary maintenance of equipment during outages without staff needing to manually schedule. [6, pp. 50]</td></tr>
<tr><td colspan="4">Is there any OE on the activity described?</td></tr>
</table>

Normal Operation			
Activity	Perform or participate in maintenance & testing		
First Principle	Improve outage coordination through enhanced coordination between staff [6, pp. 49]		
Principle Short Label	Improve outage times by improving coordination between staff		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Task-Based Display	- The task-based display system can share information between staff remotely located during outages to improve situation awareness and mutual awareness (teamwork) when performing tasks during outages	*How is coordination/communication between staff remotely handled today?* *Are there challenges in coordination today for outage management?* *Would shared information be desired to support outage coordination?*	*Are there considerations in enhancing coordination for outages?*
Decision Support	- Decision support can support staff during outages such as by identifying the correct procedure and automatically place-keeping to reduce human error and improve execution times	*Are there challenges today with place-keeping during outages?* *Are computer-based procedures being considered?* *If so, would auto-place-keeping be desired?*	*Are there computer-based procedures? What are the capabilities?* *How is place-keeping handled?*
Online Monitoring	- During outages, real-time communication between staff (e.g., control room and field) can be leveraged to improve communication and reduce outage time	*Would real-time analytics be benefits for outage management?* *Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*	*Is real-time analytics available from the platform for outages?* *Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*
Is there any OE on the activity described?			

Normal Operation			
Activity	Equipment switching and tagging		
First Principle	Interlocks, lockouts, and lockins should be designed to indicate which actions are being blocked and what conditions activated the block [17].		
Principle Short Label	Provide indication of what actions are locked out and what conditions activated the block		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Overview Displays	- Equipment that is locked out will be displayed as *lockout tagout* on the plant and task overview displays to promote situation awareness - Detailed information can be viewed by selecting the *lockout tagout* icon	*Are there issues today with lockout tagout?* *Would indication lockout tagout on digital HSIs be desired?*	*How is lockout tagout handled in the platform?* *How is it presented?*
Task-Based Display	- Procedure pain will identify the correct course of action based on decision support and control automation capabilities - When checking the step logic, live value and equipment indications are given to the operator to understand the conditions activating the block	*Are there challenges today in equipment switching and tagging?* *Would computer-based procedures be desired to support this?* *Would step verification be desired?*	*Are there computer-based procedures? What are the capabilities?* *Is step verification available? How is this managed?*
Decision Support	- Equipment that is locked out (not requiring immediate attention) will be presented to the operator and maintenance staff as an indication on the overview displays and decision logic in the procedure pane of the task-based display will automatically determine the appropriate course of action	*Would enhancements such as decision support to provide guidance on alternative courses of action be beneficial where equipment is tagged out?*	*Are there decision support capabilities that can tell the correct course of action during lockout tagout?*
Online Monitoring	- Plant status is collected in the integrated control room through online monitoring capabilities that collect continuous data of plant equipment with sensor input	*Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*	*Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*
Is there any OE on the activity described?			

Normal Operation			
Activity	Equipment switching and tagging		
First Principle	Remove labor-intensive actions, such as performing manual equipment switching when possible, yet giving the operator the right to override as needed [7, pp. 36]		
Principle Short Label	Remove manual equipment switching to improve efficiencies and reduce human error		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Overview Displays	- Equipment that is locked out will be displayed as *lockout tagout* on the plant and task overview displays to promote situation awareness	*Are there issues today with lockout tagout?* *Would indication lockout tagout on digital HSIs be desired?*	*How is lockout tagout handled in the platform?* *How is it presented?*
Task-Based Display	- Procedure pain will identify the correct course of action based on decision support and control automation capabilities	*Would enhancements, such as decision support to provide guidance on alternative courses of action, be beneficial where equipment is tagged out?*	*Are there decision support capabilities that can tell the correct course of action during lockout tagout?*
Decision Support	- Equipment that is locked out (not requiring immediate attention) will be presented to the operator and maintenance staff as an indication on the overview displays and decision logic in the procedure pane of the task-based display will automatically determine the appropriate course of action		
Control Automation	- The control automation automatically determines functioning equipment from equipment that is put offline	*Would enhancements, such as performing equipment switching automatically, be desired?*	*Would enhancements, such as performing equipment switching automatically, be possible?*
Online Monitoring	- Plant status is collected in the integrated control room through online monitoring capabilities that collect continuous data of plant equipment with sensor input	*Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*	*Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*
Is there any OE on the activity described?			

<table>
<tr><th colspan="4">Normal Operation</th></tr>
<tr><td>Activity</td><td colspan="3">Take readings and log information</td></tr>
<tr><td>First Principle</td><td colspan="3">Information from the field should be collected and recorded automatically and updated in the operator workstation. Incorporating automation here will provide operators with relevant data in real time [6,7].</td></tr>
<tr><td>Principle Short Label</td><td colspan="3">Automatically collect, log, and store plant available information to minimize tedious manual checks</td></tr>
<tr><td colspan="4">Discussion Guide</td></tr>
<tr><td></td><td>Characteristics (Examples) of Advanced Concept</td><td>Utility Inputs</td><td>Vendor Inputs</td></tr>
<tr><td>Online Monitoring</td><td>- Plant status is collected in the integrated control room through online monitoring capabilities that collect continuous data of plant equipment with sensor input
- Plant equipment status is automatically collected and stored to eliminate manual collection of this data</td><td>Is there a desire to leverage plant data to automate reading and logging information?

Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?</td><td>Is it possible to leverage plant data to automate reading and logging information?

Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?</td></tr>
<tr><td colspan="4">Is there any OE on the activity described?</td></tr>
</table>

<table>
<tr><th colspan="4">Normal Operation</th></tr>
<tr><td>Activity</td><td colspan="3">Accomplish shift turnovers</td></tr>
<tr><td>First Principle</td><td colspan="3">The use of computer-based procedures will facilitate shift turnovers. If all data (e.g., work orders, procedures) is automatically stored and now accessible, the new crew does not have to hunt down the information [12].</td></tr>
<tr><td>Principle Short Label</td><td colspan="3">Reduce “information foraging” needed to accomplish shift turnovers.</td></tr>
<tr><td colspan="4">Discussion Guide</td></tr>
<tr><td></td><td>Characteristics (Examples) of Advanced Concept</td><td>Utility Inputs</td><td>Vendor Inputs</td></tr>
<tr><td>Overview Displays</td><td>- Standardized plant overview provides immediate understanding of high-level plant state
- System/task-level overview displays support situation awareness and shift turnover for system/task-level overview information by presenting key indications in an intuitive and consistent format (mimic)
- Configuration of overviews and task-level information is presented at a single workstation to reduce foraging for information</td><td>How is shift turnover accomplished today? Are there challenges?

How will the new vision support shift turnovers? Are there notable differences envisioned?

Are large overview displays being considered?</td><td>Are large overview displays part of the platform?

Will these include plant-level and system-level information to support shift turnover?</td></tr>
<tr><td>Task-Based Display</td><td>- The task-based display provides a consolidation of task-specific information important for shift turnover, such as status of the current task, of leading indications (from indication pane), and of any notifications/alerts, are provided in a single location</td><td>Will task-based or digital HSIs be considered in supporting shift turnover?</td><td>How are digital HSIs envisioned to support the utility in shift turnover?</td></tr>
<tr><td>Decision Support</td><td rowspan="2">- Decision support and control automation remove tedious monitoring and human actions for tasks to support a more supervisory role. Enabling a supervisory role, shift turnover is positively impacted by allowing the incoming operator to perform higher level monitoring activities of the plant</td><td rowspan="2">Are there challenges today in shift turnover resulting from cognitive workload?

Will the vision include decision support and control automation to reduce cognitive burden in enhancing shift turnover?</td><td rowspan="2">What capabilities are available in terms of decision support and automation that reduce cognitive burden for tasks in normal operations?</td></tr>
<tr><td>Control Automation</td></tr>
<tr><td>Real-Time Communication</td><td>- Real-time communication is automatically logged</td><td></td><td>Is real-time communication and data integration across</td></tr>
</table>

Normal Operation			
Activity	Accomplish shift turnovers		
First Principle	The use of computer-based procedures will facilitate shift turnovers. If all data (e.g., work orders, procedures) is automatically stored and now accessible, the new crew does not have to hunt down the information [12].		
Principle Short Label	Reduce "information foraging" needed to accomplish shift turnovers.		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
	from the previous shift and stored/presented on the integrated control room to minimize excessive information foraging	*Is real-time communication to support shift turnover desired?* *Is the integration of plant data being considered to support shift turn over?* *Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*	*the plant (as needed) part of the platform capabilities?* *Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*
Online Monitoring	- Plant status is collected in the integrated control room through online monitoring capabilities that collect continuous data of plant equipment with sensor input		
Is there any OE on the activity described?			

<table>
<tr><th colspan="4">Normal Operation</th></tr>
<tr><td>Activity</td><td colspan="3">On-shift training</td></tr>
<tr><td>First Principle</td><td colspan="3">Promote operator training effectiveness by maximizing task-technology compatibility</td></tr>
<tr><td>Principle Short Label</td><td colspan="3">Promote operator training effectiveness by maximizing task-technology compatibility</td></tr>
<tr><td colspan="4">Discussion Guide</td></tr>
<tr><td></td><td>Characteristics (Examples) of Advanced Concept</td><td>Utility Inputs</td><td>Vendor Inputs</td></tr>
<tr><td>Overview Displays</td><td>- Enable “big picture” thinking that improves learning transfer through the use of (plant/system/task-level) overview displays that allow the operator to grasp the “big picture” more quickly</td><td rowspan="6">How is on-shift training accomplished today? Are there challenges?

How will the new vision support on-shift training? Are there notable differences envisioned?

What technologies are being considered to support training on-shift?
• Overview displays?
• Task-based displays?
• Decision support or automation?
• Real-time communication?
• Online monitoring?

Describe attributes to left as needed.</td><td rowspan="6">What technologies are available to support training on-shift?
• Overview displays?
• Task-based displays?
• Decision support or automation?
• Real-time communication?
• Online monitoring?

Describe attributes to left as needed.</td></tr>
<tr><td>Task-Based Display</td><td>- Reduce complexity and cognitive burden to promote more effective training through the presentation of streamlined procedures from the task-based display with decision support. The operator can learn from the system based on its recommended choice and data inputs used to support this decision</td></tr>
<tr><td>Decision Support</td><td rowspan="2">- Decision and control automation capabilities can support “big picture” thinking by putting the training operator in a supervisory role by removing the need for them to perform tedious detailed tasks</td></tr>
<tr><td>Control Automation</td></tr>
<tr><td>Real-Time Communication</td><td>- Real-time communication is automatically logged from previous shift and stored/presented on the integrated control room to minimize excessive information foraging</td></tr>
<tr><td>Online Monitoring</td><td>- Plant status is collected in the integrated control room through online monitoring capabilities that collect continuous data of plant equipment with sensor input</td></tr>
<tr><td colspan="4">Is there any OE on the activity described?</td></tr>
</table>

Normal Operation			
Activity	Startups and shutdowns		
First Principle	Improve efficiencies and ensure situation awareness in performing startup and shutdown		
Principle Short Label	Improve efficiencies and ensure situation awareness in performing startup and shutdown		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Alarms	- Plant and task overviews present embedded alarms to highlight affected areas of the plant - Utilizes alerts on task-based display to allocate operator attention when performing another task and the new condition requires immediate attention.	*Are there any pain points with the existing alarm design unique to startups or shutdowns? Alarm salience and detection? Interpretation?* *Are embedded alarms on HSIs desired?* *Is alarm filtering desired?*	*How will alarm cues be presented to operators?* *What design bases are applied to ensure that alarms are salient to operators?* *Is alarm filtering available? How is this accomplished?* *Can alarms be embedded on HSIs? How does this information appear?*
Overview Displays	- Plant overview provides mode-specific leading indications to monitor the plant during startup or shutdown to reduce information foraging to improve monitoring efficiencies - Task overview provides system-level specific information for monitoring (in mimic format) to support the quick monitoring of the task (startup/shutdown) that improves monitoring efficiencies - The overviews provide trends and advanced visualizations to support the operator in monitoring the status	*Are there challenges today with monitoring tasks during startup or shutdown?* *What is the vision for using overview displays to support situation awareness in startup and shutdown?* *Is there a desire to utilize different abstractions of the plant to support situation awareness? Such as plant/system/task-level overviews.* *Are there any leading indications used to monitor plant health that should be trended that are not now?* *Are there any unique relationships between parameters that would benefit being presented together? E.g., Pressure/ Temperature*	*How will leading indications that support situation assessment be displayed?* *Is there capability to display all information for safe operation in a continuously visible or continuously available format (e.g., SPDS)?* *How will related information be consolidated on one screen?* *Is there alarm integration within the overview displays?* *What graphical formats are available to present multiple parameters in one visualization? Are there constraints that need to be considered from the HSI tool builder?*
Task-Based Display	- Task-based display system presents procedures that provide task-specific information needed for startup or	*Are there challenges integrating information in the existing state during startup/shutdown?*	*Can alarms be embedded on HSIs? How does this information appear?*

Normal Operation			
Activity	Startups and shutdowns		
First Principle	Improve efficiencies and ensure situation awareness in performing startup and shutdown		
Principle Short Label	Improve efficiencies and ensure situation awareness in performing startup and shutdown		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
	shutdown in a single location. Plant data is embedded directly to improve search efficiencies - Task-based display system utilizes decision support within a procedure to recommend best course of action, linking to specific steps from other procedures that are provided directly to eliminate interface management needs - Control automation is leveraged to reduce tedious actions of the operator - Real-time communication with field operators is enabled to provide a common framework of information and to monitor the status of certain activities	*Is integration of alarm information on digital HSIs desired?* *Are computer-based procedures desired?* *Are there specific tasks that would benefit from task-based displays?*	*Are there computer-based procedures? What are the capabilities?* *Are there any premade task-based displays that can be leveraged?*
Decision Support	- Task-based display system utilizes decision support within a procedure to recommend best course of action, linking to specific steps from other procedures that are provided directly to eliminate interface management needs	*Would decision support be desired during startup/shutdown?*	*What capabilities with decision support are there to support startup/shutdown?*
Control Automation	- Control automation is leveraged to reduce tedious actions of the operator	*Are there any tasks that should be automated for startup/shutdown?*	*What capabilities with control automation are there to support startup/shutdown?*
Real-Time Communication	- Real-time communication with field operators is enabled to provide a common framework of information and to monitor the status of certain activities	*Would real-time communication be desired during startup/shutdown?*	*What capabilities with real-time communication are there to support startup/shutdown?*
Online Monitoring	- Plant status is collected in the integrated control	*Are there considerations that need to be considered*	*Are there considerations that need to be considered*

Normal Operation			
Activity	Startups and shutdowns		
First Principle	Improve efficiencies and ensure situation awareness in performing startup and shutdown		
Principle Short Label	Improve efficiencies and ensure situation awareness in performing startup and shutdown		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
	room through online monitoring capabilities that collect continuous data of plant equipment with sensor input	*in implementing these capabilities in the current infrastructure?*	*in implementing these capabilities in the current infrastructure?*
Is there any OE on the activity described?			

Normal Operation			
Activity	Power level changes, including load following		
First Principle	The operator should be aware of the exact power level and reason for the given level.		
Principle Short Label	Improve efficiencies and ensure situation awareness in performing power level changes		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Alarms	- Plant and task overviews present embedded alarms to highlight affected areas of the plant - Utilizes alerts on task-based display to allocate operator attention when performing another task and the new condition requires immediate attention	*Are there any pain points with the existing alarm design unique to startups or shutdowns? Alarm salience and detection? Interpretation?* *Are embedded alarms on HSIs desired?* *Is alarm filtering desired?*	*How will alarm cues be presented to operators?* *What design bases are applied to ensure that alarms are salient to operators?* *Is alarm filtering available? How is this accomplished?* *Can alarms be embedded on HSIs? How does this information appear?*
Overview Displays	- Plant overview provides mode-specific leading indications to monitor the plant during power level changes to reduce information foraging to improve monitoring efficiencies - Task overview provides system-level specific information for monitoring (in mimic format) to support quick monitoring of the task (changing power level) that improves monitoring efficiencies - The overviews provide trends and advanced visualizations to support the operator in monitoring the status	*Are there challenges today with monitoring tasks during changing power levels?* *What is the vision for using overview displays to support situation awareness in changing power levels?* *Is there a desire to utilize different abstractions of the plant to support situation awareness? Such as plant/system/task-level overviews.* *Are there any leading indications used to monitor plant health that should be trended that are not now? Are there better ways to support monitoring changing power levels?* *Are there any unique relationships between parameters that would benefit being presented together (e.g., pressure/ temperature)*	*How will leading indications that support situation assessment be displayed?* *Is there a capability to display all information for safe operation in a continuously visible or continuously available format (e.g., SPDS)?* *How will related information be consolidated on one screen?* *Is there alarm integration within the overview displays?* *What graphical formats are available to present multiple parameters in one visualization? Are there constraints that need to be considered from the HSI tool builder?*

Normal Operation			
Activity	Power level changes, including load following		
First Principle	The operator should be aware of the exact power level and reason for the given level.		
Principle Short Label	Improve efficiencies and ensure situation awareness in performing power level changes		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Task-Based Display	- Task-based display system presents procedures that provide task-specific information needed for power level changes in a single location. Plant data is embedded directly to improve search efficiencies - Task-based display system utilizes decision support within a procedure to recommend best course of action, linking to specific steps from other procedures that are provided directly to eliminate interface management needs - Control automation is leveraged to reduce tedious actions of the operator - Real-time communication with field operators is enabled to provide a common framework of information and to monitor the status of certain activities	*Are there challenges integrating information in the existing state during changing power levels?* *Is the integration of alarm information on digital HSIs desired?* *Are computer-based procedures desired?* *Are there specific tasks that would benefit from task-based displays?*	*Can alarms be embedded on HSIs? How does this information appear?* *Are there computer-based procedures? What are the capabilities?* *Are there any premade task-based displays that can be leveraged?*
Decision Support	- Task-based display system utilizes decision support within a procedure to recommend best course of action, linking to specific steps from other procedures that are provided directly to eliminate interface management needs	*Would decision support be desired during changing power levels?*	*What capabilities with decision support are there to support changing power levels?*
Control Automation	- Control automation is leveraged to reduce the tedious actions of the operator	*Are there any tasks that should be automated for changing power levels?*	*What capabilities with control automation are there to support changing power levels?*
Real-Time Communication	- Real-time communication with field operators is enabled to provide a common framework of	*Would real-time communication be desired during changing power levels?*	*What capabilities with real-time communication are there to support changing power levels?*

Normal Operation			
Activity	Power level changes, including load following		
First Principle	The operator should be aware of the exact power level and reason for the given level.		
Principle Short Label	Improve efficiencies and ensure situation awareness in performing power level changes		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
	information and to monitor the status of certain activities		
Online Monitoring	- Plant status is collected in the integrated control room through online monitoring capabilities that collect continuous data of plant equipment with sensor input	*Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*	*Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*
Is there any OE on the activity described?			

Normal Operation			
Activity	Surveillance testing		
First Principle	Operators need to periodically run a procedure to ensure equip is running as appropriate (e.g., check a pump). The use of CBP would make this more efficient and decrease errors. See guidance for CBP above [12].		
Principle Short Label	Provide context-sensitive information where operators must intervene during surveillance activities.		
Discussion Guide			
	Characteristics (Examples) of Advanced Concept	Utility Inputs	Vendor Inputs
Task-Based Display	- The task-based display system provides a consolidated set of information to operators (and field operators as necessary) to efficiently complete their job - Real-time communication is enabled through the task-based display system to provide a shared understanding (mutual awareness) of progress made	*Are computer-based procedures desired to support surveillance testing?*	
Decision Support	- Decision support provides operators (and field operators as necessary) recommended course of action to streamline completion times	*Would decision support be desired to support surveillance testing?*	*What capabilities with decision support are there to support surveillance testing?*
Real-Time Communication	- In surveillance activities that require operator action and input from the field, real-time communication enables streamlined collaboration between staff to improve efficiencies with surveillance testing	*Would real-time communication be desired to support surveillance testing?*	*What capabilities with real-time communication are there to support surveillance testing?*
Online Monitoring	- Utilize continuous real-time, condition-based monitoring and self-diagnostic equipment to automate applicable surveillance activities	*Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*	*Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?*
Is there any OE on the activity described?			

<table>
<tr><th colspan="4">Normal Operation</th></tr>
<tr><td>Activity</td><td colspan="3">Surveillance testing</td></tr>
<tr><td>First Principle</td><td colspan="3">The use of self-diagnostic and condition-based online monitoring should be used to minimize labor-intensive manually performed inspection, calibration, testing, and maintenance of plant assets. [19]</td></tr>
<tr><td>Principle Short Label</td><td colspan="3">Remove labor-intensive activities where possible to improve surveillance activities</td></tr>
<tr><td colspan="4">Discussion Guide</td></tr>
<tr><td></td><td>Characteristics (Examples) of Advanced Concept</td><td>Utility Inputs</td><td>Vendor Inputs</td></tr>
<tr><td>Overview Displays</td><td rowspan="2">- Presents notifications of the status of surveillance activities completed that do not require immediate operator attention
- Provides feedback on the status of automated surveillance activities and presents this feedback on the task overview and task-based display system</td><td rowspan="2">Are there challenges today with determining the status of equipment and when to complete surveillance tests?

Would presenting notifications for coordinating surveillances be desired in the vision?</td><td rowspan="2">Are there notable enhancements in the proposed platform to support surveillance testing?

What capabilities are there in presenting notifications for surveillance testing? How is this information presented?</td></tr>
<tr><td>Task-Based Display</td></tr>
<tr><td>Online Monitoring</td><td>- Utilize continuous real-time, condition-based monitoring and self-diagnostic equipment to automate applicable surveillance activities</td><td>Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?</td><td>Are there considerations that need to be considered in implementing these capabilities in the current infrastructure?</td></tr>
<tr><td colspan="4">Is there any OE on the activity described?</td></tr>
</table>

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Appendix B
Example HFE Grading

The following grading criteria is an example of an HFE grading plan that can be done to support Sections 5.1–5.5. The grading criteria is based on EPRI 3002004310 (2015) guidance and is not a substitute to its detailed guidance. The criteria here outline the specific activities described in this work as they apply to a graded approach.

<table>
<tr><th colspan="5">Section 5.2 - Human-Technology Integration Requirements
FA&A, Task Analysis, Risk Analyses</th></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, 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 (Walk-Throughs, or HTA/ TTA) 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 (Walk-Throughs, or HTA/ TTA) 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 (Walk-Throughs, or HTA/ TTA) of all impacted human actions

Advanced Methods (Suggested)
–STPA</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 (Walk-Throughs, or HTA/ TTA) of all impacted human actions

Advanced Methods (Suggested)
–STPA
–CWA and cognitive task analysis techniques</td></tr>
</table>

Section 5.3 - Synthesize Inputs into Design

Integrate requirements through rapid prototyping and design

		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, information processing ○ Team dynamics		
		Low	Medium	High
Risk *“Primary Factors”* • Risk Analysis • Risk to Personnel • Economic Risk	Low	Level 3 ***Methods*** – *Consider vendor standard capabilities* – *Select features using preference and judgment*	Level 3 ***Methods*** – *Consider vendor standard capabilities* – *Select features using preference and judgment*	Level 2 ***Methods*** – *Review vendor standard features with results from new-state vision, OER, FA&A, and task analysis.* – *Perform tests and evaluation of most troublesome use cases identified in FA&A and task analysis. Specific activities include NUREG-0700 verification and usability tests.* – *Document HSI in a project-controlled style guide.*
	Medium	Level 2 ***Methods*** – *Review vendor standard features with results from new-state vision, OER, FA&A, and task analysis.* – *Perform tests and evaluation of most troublesome use cases identified in FA&A and task analysis. Specific activities include NUREG-0700 verification and usability tests.* – *Document HSI in a project-controlled style guide.*	Level 2 ***Methods*** – *Review vendor standard features with results from new-state vision, OER, FA&A, and task analysis.* – *Perform tests and evaluation of most troublesome use cases identified in FA&A and task analysis. Specific activities include NUREG-0700 verification and usability tests.* – *Document HSI in a project-controlled style guide.*	Level 2 ***Methods*** – *Review vendor standard features with results from new-state vision, OER, FA&A, and task analysis.* – *Perform tests and evaluation of most troublesome use cases identified in FA&A and task analysis. Specific activities include NUREG-0700 verification and usability tests.* – *Document HSI in a project-controlled style guide.*
	High	Level 2 ***Methods*** – *Review vendor standard features with results from new-state vision, OER, FA&A, and task analysis.* – *Perform tests and evaluation of most troublesome use cases identified in FA&A and task analysis. Specific activities include NUREG-0700 verification and usability tests.*	Level 1 ***Methods*** – *Review vendor standard features with results from new-state vision, OER, FA&A, and task analysis.* – *Perform tests and evaluation of all use cases identified in FA&A and task analysis. Specific activities include NUREG-0700 verification and usability tests.* – *Document HSI in a project-controlled style guide.*	Level 1 ***Methods*** – *Review vendor standard features with results from new-state vision, OER, FA&A, and task analysis.* – *Perform tests and evaluation of all use cases identified in FA&A and task analysis. Specific activities include NUREG-0700 verification and usability tests.* – *Document HSI in a project-controlled style guide.*

<table>
<tr><th colspan="5">Section 5.3 - Synthesize Inputs into Design
Integrate requirements through rapid prototyping and design</th></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, information processing
○ Team dynamics</td></tr>
<tr><td>Low</td><td>Medium</td><td>High</td></tr>
<tr><td></td><td></td><td>– Document HSI in a project-controlled style guide.</td><td>Advanced Methods (Suggested)
– CWA/ EID/ cognitive task analysis
– Simulation and modeling
– Eye tracking
– TAM</td><td>Advanced Methods (Suggested)
– CWA/ EID/ cognitive task analysis
– Simulation and modeling
– Eye tracking
– TAM</td></tr>
</table>

<table>
<tr><th colspan="5">Section 5.4 - Synthesize Inputs into Design
V&V</th></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, 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
– Perform task support verification and design verification using static concepts.
– ISV may be applied by leveraging procedure and training integration.
– Document HEDs for resolution.</td><td>Level 3

Methods
– Perform task support verification and design verification using static concepts.
– ISV may be applied by leveraging procedure and training integration.
– Document HEDs for resolution.</td><td>Level 2

Methods
– Perform V&V in correspondence to NUREG-0711 (Revision 3) Section 11.
– The testbed used may entail a full-scope/full-scale simulator.

Advanced Methods (Suggested)
– Full-Scale Simulation
– 3D Modeling</td></tr>
<tr><td>Medium</td><td>Level 2

Methods
– Perform V&V in correspondence to NUREG-0711 (Revision 3) Section 11.
– The testbed used may entail a full-scope/full-scale simulator.

Advanced Methods (Suggested)
– Full-Scale Simulation
– 3D Modeling</td><td>Level 2

Methods
– Perform V&V in correspondence to NUREG-0711 (Revision 3) Section 11.
– The testbed used may entail a full-scope/full-scale simulator.

Advanced Methods (Suggested)
– Full-Scale Simulation
– 3D Modeling</td><td>Level 2

Methods
– Perform V&V in correspondence to NUREG-0711 (Revision 3) Section 11.
– The testbed used may entail a full-scope/full-scale simulator.

Advanced Methods (Suggested)
– Full-Scale Simulation
– 3D Modeling</td></tr>
<tr><td>High</td><td>Level 2</td><td>Level 1</td><td>Level 1</td></tr>
</table>

		Methods – *Perform V&V in correspondence to NUREG-0711 (Revision 3) Section 11.* – *The testbed used may entail a full-scope/full-scale simulator.* **Advanced Methods (Suggested)** – *Full-Scale Simulation* – *3D Modeling*	***Methods*** – *Perform V&V in correspondence to NUREG-0711 (Revision 3) Section 11.* – *The testbed should entail use of a qualified training simulator.* **Advanced Methods (Suggested)** – *Qualified Training Simulator* – *3D Modeling* – Eye Tracking – *TAM*	***Methods*** – *FA&A Methodology of all use cases* – *High-level and detailed task analyses (Walk-Throughs, or HTA/ TTA) of all human actions* **Advanced Methods (Suggested)** – *Qualified Training Simulator* – *3D Modeling* – Eye Tracking – *TAM*

Section 5.5 - Implementation and Operations *HFE Monitoring*				
		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, information processing ○ Team dynamics		
		Low	Medium	High
Risk *"Primary Factors"* • Risk Analysis • Risk to Personnel • Economic Risk	Low	Level 3 ***Methods*** – *Self-report OE* – *OE collection using standard plant monitoring program*	Level 3 ***Methods*** – *Self-report OE* – *OE collection using standard plant monitoring program*	Level 2 ***Methods*** – *Perform In-Service HFE monitoring* – *OE collection using standard plant monitoring program*
	Medium	Level 2 ***Methods*** – *Perform In-Service HFE monitoring* – *OE collection using standard plant monitoring program*	Level 2 ***Methods*** – *Perform In-Service HFE monitoring* – *OE collection using standard plant monitoring program*	Level 2 ***Methods*** – *Perform In-Service HFE monitoring* – *OE collection using standard plant monitoring program*
	High	Level 2 ***Methods*** – *Perform In-Service HFE monitoring* – *OE collection using standard plant monitoring program*	Level 1 ***Methods*** – *Perform In-Service HFE monitoring* – *OE collection using standard plant monitoring program* **Advanced Methods (Suggested)** – *TAM*	Level 1 ***Methods*** – *Perform In-Service HFE monitoring* – *OE collection using standard plant monitoring program* **Advanced Methods (Suggested)** – *TAM*

Appendix C
Function Analysis and Scenario Identification Guide

Identifying an impacted function:

- What functions have been significantly changed by proposed updates?
- What functions may be slightly changed but are part of a critical system?
- Is there a function that that may be impacted by control room updates?
- Are there functions that could use an update to enhance control room operations?
- Are there functions that could use an update to better align control room operations with safer, more sustainable, or simpler operations?
- Are there system states that are only achievable through a single function?

Describe identified function:

- What is the function's purpose?
- In what modes of operation does this function reside? Startup? Shutdown? Normal Operations? Etc.
- What happens if the function fails to fully execute?
- What are the existing requirements for this function?
    - Are these requirements bounding technical requirements?
- Describe the resources required to perform this function (i.e., time, attention, crew members, procedures, etc.)
- What are possible benefits to adding support to this function?
- What makes performing this function difficult?
- Are there other functions that can achieve the same outcome as the identified function?

Describe proposed changes in the identified function:

- Does the proposed change make sense from an operation's perspective?
    - Does the modification meet an operational needed?
    - Does the modification allow the operator to assume control if necessary?
    - Does the modification support active monitoring? What information or feedback is needed to do so?
    - Are the automation's capabilities and limitations clear? What information or feedback is needed to understand this?
- Are there potential difficulties in the proposed method?
- Could the proposed method reduce the resources (e.g., staffing levels) required to perform this function?
- What resources would be reduced, if not eliminated, to perform this function?
- Does the proposed method change the expected outcome of the function?

Does the proposed method align with the concept of operations for the interim or new-state vision?

Appendix D
Scenario Screening Criteria

The following set of criteria[3] may be asked to operations, training, and engineering to identify scenarios.

- Functions involving time critical tasks
- Functions that are frequently performed
- Involve possible error traps in which operators may make errors
- Enhancement of the system and/or operator performance possible by automating all or part of system functions or operator tasks
- Parallel activities requiring operation that may interfere with the function’s performance
- Important to safety, production, system availability and equipment protection
- New functions and function allocations resulting from modernization
- Not well understood possibly because they are functions not performed before
- Difficult for users to perform
- Problematic (as identified in OER)
- Substantial changes in the concept of operation based on existing state and new state vision

[3] Adapted and expanded from EPRI 3002004310.

Appendix E
Scenario Identification Criteria

An example of a scenario-based evaluation guide is provided below. This template can be completed for each identified scenario.

Scenario Title:	<NAME OF SCENARIO> <#>
Scenario and Task Description	
Scenario Description and Purpose	<SUMMARY OF SCENARIO AND PURPOSE REGARDING EXERCISING FUNCTION(S)>
Main Operator Actions	<SUMMARY OF PRIMARY HUMAN ACTIONS PERFORMED>
Key Systems and Functions (this scenario only)	<LIST OF IMPACTED SYSTEMS AND FUNCTIONS OF INTEREST>
Applicable Procedure(s)	<PROCEDURES>
Planned Scenario Duration	<ESTIMATED TIME>
Initial Conditions	<INITIAL CONDITIONS>
Workload Factors	
Task Criticality (H, M, L)	<H/M/L>
Time Constraints/Required	<RESPONSE>
Task Frequency (H, M, L)	<H/M/L>
Error Tolerance (H, M, L)	<H/M/L>
Location(s) at the Board	<RESPONSE>
Communication Requirements	<RESPONSE>
Information and Decision Requirements	
Alarms, Alerts and Permissive Indicators	<RESPONSE>
Critical Performance Parameters	<RESPONSE>
Evaluation/Diagnosis to be performed	<RESPONSE>
Response/Decision Results	
Course of Action	<RESPONSE>
Human-System Performance Evaluation Criteria	

Detection	Diagnosis/Situation Assessment	Action Selection	Action Execution
For abnormal and emergency conditions, the operator detects an alert, such as from an alarm signal.	Operators perform crew update to declare present plant state and/or changes in operating conditions resulting from the condition diagnosis.	During crew update, operators declare a plan of action and identify procedure(s) to use.	Operators execute the sequence of actions per procedure(s) and interact with various control system(s) via a human-machine interface.
During abnormal and emergency conditions, what alerting cues (e.g., alarms) would we expect to see to cue the operator? *OR* During normal operations, what cues the crew to modify the operating parameters?	What would we expect the operators to conclude and say in the crew update with regard to what they diagnosed?		What are the key points in the procedure(s) that are observable and can tell us they are moving in the correct direction? *AND/OR* Are there other human actions not documented in the procedure(s) that are important to evaluate?
<RESPONSE> ***SUPPLMENT WITH LOA TABLE OR DECISION LADDER***	<RESPONSE> ***SUPPLMENT WITH LOA TABLE OR DECISION LADDER***		<RESPONSE> ***SUPPLMENT WITH LOA TABLE OR DECISION LADDER***

Appendix F
Function Allocation Guide

— Digital versus analogue hardware considerations for relevant systems: Determine if the system should be digital or analogue and consider how this impacts manual operations performance and opportunities for automation.

— Essential automation checklist: Determine which functions need to be automated. Such functions may feature high human error rates and high consequences for errors. Such functions may have the following characteristics:			
	YES	NO	COMMENT
● Manual performance of the function raises health or safety concerns.			
● The function has to be performed very rapidly.			
● The function requires precision beyond human capabilities.			
● The function requires human reliability greater than is available. Human reliability may be determined by using a human reliability analysis (HRA) method.			

— Desirable automation checklist: Determine which functions would benefit from being automated. While humans may perform these tasks, they do not do them well and they may be error prone, even if the errors are not of serious consequence. Such functions may have the following characteristics:			
	YES	NO	COMMENT
● The function is complex and easier for computers to perform;			
● The function requires many repetitive actions that may be fatiguing or boring to operators;			
● The function creates high cognitive workload;			
● The function creates long periods of boredom;			
● The function creates high physical workload or fatigue;			
● The function interferes with the performance of another (manual) function if not automated;			
● The function could be performed more efficiently (e.g. quicker) if automated;			
● The function could reduce staffing levels if automated.			

— Essential human automation checklist: Determine which functions need to be performed manually. In such cases, human reliability exceeds automation reliability. Such functions may have the following characteristics:			
	YES	NO	COMMENT
● The function is a core human responsibility (e.g. communicating to field workers);			
● Automatic response is difficult (e.g. the function is challenging to model in control logic);			
● Personnel must remain ‘in the loop’ (e.g. a human operator needs to take over control or a human operator needs to maintain vigilance and situation awareness);			
● Personnel must retain skills that would be lost if the task were automated.			

Appendix G
Function Allocation and Human-Automation Performance Rating

Perform a detailed function allocation evaluation of the expected human-system performance and acceptability using the form below, which can be used to create a human-automation performance profile figure, as seen in Figure G-1.

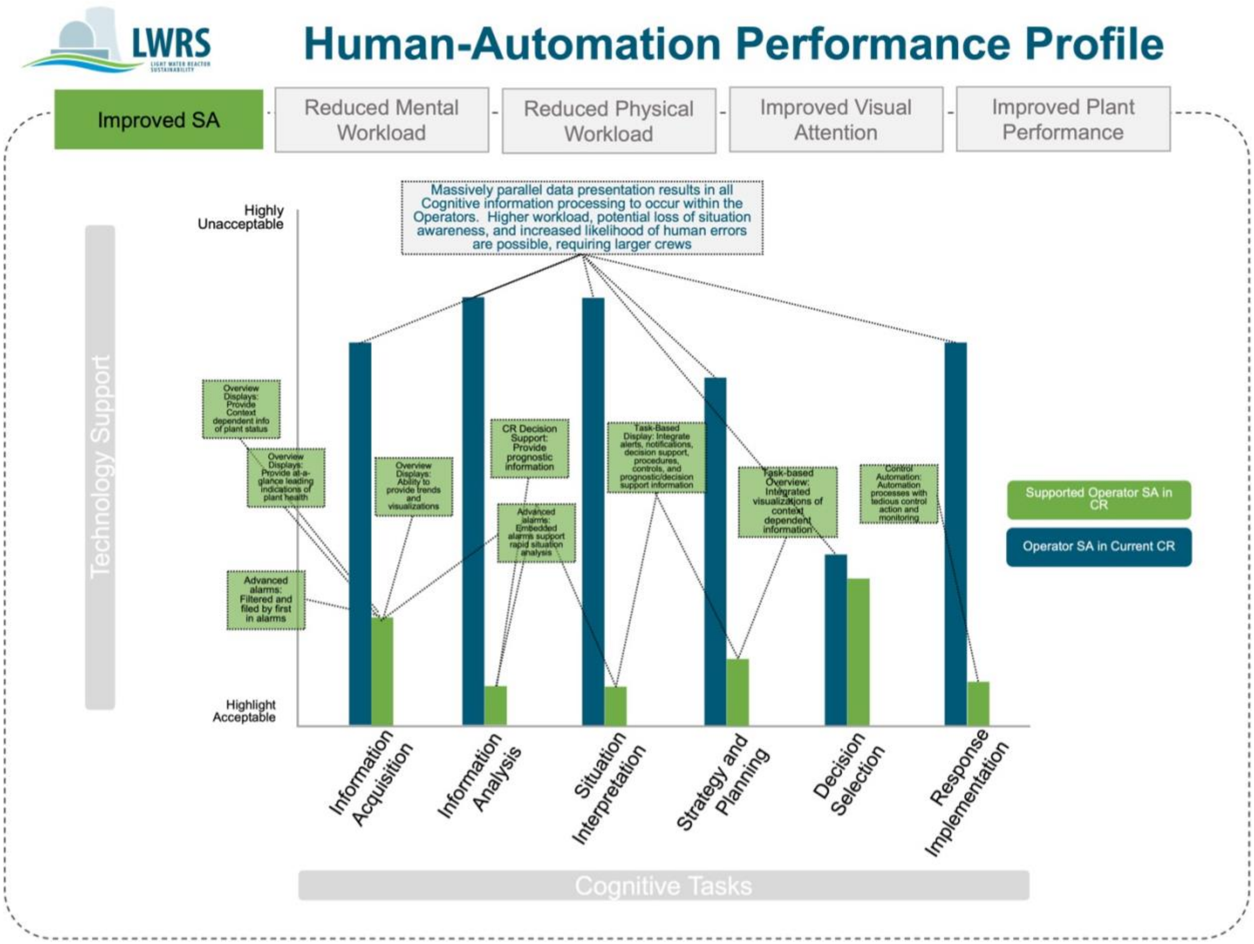

Figure G-1. Human-automation performance profile.

This activity describes:

- What is the human's role in normal and abnormal situations?
- Describe how monitoring, detection, situation assessment, response planning, and response implementation are carried out.
- What secondary, such as interface management or administrative, tasks are typically carried out as part of this function?
- How does the updated method impact the secondary tasks?

The ratings must be completed with the team to determine any potential issues with human-system performance regarding the function allocation.

The following tool may be used to describe the human actions.

Describe the role of automation and role of the human for monitoring, detection, situation assessment, response planning, and response execution (rows). Use the columns to define the levels of automation by automation/human roles (levels of automation are defined per NUREG-0700 Revision 3).

Scenario: ______________________________________

CURRENT STATE					
Functions of Automation	**Levels of Automation**				
	Automation	**Shared**			**Manual**
	Not Serial Operator in the Loop		**Serial Operator in the Loop**		
	Autonomous Operation	**Operation by Exception**	**Operation by Consent**	**Shared Operation**	**Manual Operation**
Monitoring and Detection					
Situation Assessment					
Response Planning					
Response Implementation					
Interface Management					
Administrative Functions					
PROPOSED STATE					
Functions of Automation	**Levels of Automation**				
	Automation	**Shared**			**Manual**
	Not Serial Operator in the Loop		**Serial Operator in the Loop**		
	Autonomous Operation	**Operation by Exception**	**Operation by Consent**	**Shared Operation**	**Manual Operation**
Monitoring and Detection					
Situation Assessment					
Response Planning					
Response Implementation					
Interface Management					
Administrative Functions					
EXPECTED IMPACTS ON HUMAN-SYSTEM PERFORMANCE					

Describe the role of automation and role of the human for monitoring, detection, situation assessment, response planning, and response execution (rows). Use the columns to define the levels of automation by automation/human roles (levels of automation are defined per NUREG-0700 Revision 3).

Scenario: ____

Describe any impacts on human-system performance listed below. The form needs to be completed with operations, training, engineering, and HFE. All responses must be aligned by the team.

Plant Performance

Describe any concerns with plant performance (i.e., plant safety, plant efficiency) for the existing configuration.

Describe any concerns with plant performance (i.e., plant safety, plant efficiency) for the proposed configuration.

Rate the acceptability of plant performance:

Current Allocation of Function

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Proposed Allocation of Function

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Situation Awareness

Describe any concerns with situation awareness for the existing configuration.

Describe any concerns with situation awareness for the proposed configuration.

Rate the acceptability of situation awareness:

Current Allocation of Function

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Proposed Allocation of Function

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Mental Workload

Describe any concerns with mental workload for the existing configuration.

Describe any concerns with mental workload for the proposed configuration.

Rate the acceptability of mental workload:

Current Allocation of Function

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Proposed Allocation of Function

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Physical Workload

Describe any concerns with physical workload for the existing configuration.

Describe any concerns with physical workload for the proposed configuration.

Rate the acceptability of physical workload:

Current Allocation of Function

Describe the role of automation and role of the human for monitoring, detection, situation assessment, response planning, and response execution (rows). Use the columns to define the levels of automation by automation/human roles (levels of automation are defined per NUREG-0700 Revision 3).

Scenario: ____

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Proposed Allocation of Function

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Visual Attention Demands

Describe any concerns with visual attention demands for the existing configuration.

Describe any concerns with visual attention demands for the proposed configuration.

Rate the acceptability of visual attention demands:

Current Allocation of Function

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Proposed Allocation of Function

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Impact to Crew Size

Will there be an impact on crew size?

- ☐ No
- ☐ Yes (If yes, record responses below)

Describe any concerns current crew size with using the function.

Describe any concerns with impact on crew size for the proposed configuration.

Rate the acceptability of impact on crew size:

Current Allocation of Function

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Proposed Allocation of Function

1 - Totally Unacceptable	2 - Unacceptable	3 - Slightly Unacceptable	4 - Neutral	5 - Slightly Acceptable	6 - Acceptable	1 - Perfectly Acceptable

Level	Automation Tasks	Human Tasks
(1) Manual Operation	No automation	Operators manually perform all tasks.
(2) Shared Operation	Automatic performance of some tasks	Operators perform some tasks manually.
(3) Operation by Consent	Automatic performance when directed by operators to do so, under close monitoring and supervision	Operators monitor closely, approve actions, and may intervene to provide supervisory commands that automation follows.
(4) Operation by Exception	Essentially autonomous operation unless specific situations or circumstances are encountered	Operators must approve of critical decisions and may intervene.
(5) Autonomous Operation	Fully autonomous operation. System cannot normally be disabled but may be started manually	Operators monitor performance and perform backup if necessary, feasible, and permitted.

Figure G-2. Figure adapted from NUREG-0700 Rev. 3 (Table 9.1).

Appendix H
Review of Common Task Analysis Approaches

Method	Description/Application	Method Type	Related Methods	Strength	Weakness
Tabular Task Analysis (TTA)	Decomposition technique that takes a bottom-up approach by describing each step and sub-step at a detailed level. Application for information and task requirements (provides detailed view of task and information requirements at the step-level). Ability to collect alerts and information requirements. TTA provides a tabular decomposition of a task that offers a flexible approach to analyzing specific aspects important to the analysis at hand. This includes collecting specific alerts and information requirements needed to perform a task. TTA offers a detailed and structured way of collecting this information. Ability to capture cognitive and decision-making aspects. As described above, TTA enables a flexible approach, such as collecting detailed information regarding cognitive and decision-making aspects needed to perform specific steps in a task. Ability to capture workplace and task support aspects. See above. Ability to capture teamwork and communication considerations. See above. Ability to capture situation and performance shaping factors. See above. Ability to identify hazards. See above.	Task Description	TTA, Link Analysis, ACTA, interface surveys, etc.	Detailed decomposition that can be used to track information and task requirements (e.g., add a column for indications used, cognitive demands).	Can be very time consuming.
Hierarchical Task Analysis (HTA)	Decomposition technique that starts with goals, sub-goals, operations, and plans to execute a task. Application for information and task requirements (generally a foundational approach to other task analysis methods). Ability to collect alerts and information requirements. HTA describes the goals, sub-goals, and steps performed for a task. The descriptions that are entered into the HTA can include	Task Description	TTA, Link Analysis, ACTA, etc.	Top-down approach to composing a task; provides some level of efficiency compared to TTA. There are “tabular” forms of HTA, but these seem to carry forward into TTA.	Descriptive and generally requires extensions of task analysis for further analysis.

Method	Description/Application	Method Type	Related Methods	Strength	Weakness
	alerts and information requirements to understand "what" is needed. Where and how is perhaps less understood with HTA. Ability to capture cognitive and decision-making aspects. HTA in its true form does not consider cognitive and decision-making aspects. Rather, HTA is considered a base analysis from which subsequent task analysis methods are built. Ability to capture workplace and task support aspects. HTA does not typically capture workplace and task support aspects, such as descriptions of environmental conditions or use of job aids. Ability to capture teamwork and communication considerations. Teamwork and communication is not addressed in HTA. Ability to capture situation and performance shaping factors. Situation and performance shaping factors are not explicitly captured in HTA. Ability to identify hazards. Hazards are typically not collected in HTA.				
Link Analysis	Link analysis identifies the connections, or activity flow, between different parts of a system in completing a task. Application for information requirements (sequence of action and grouping, common metrics for a task, navigation). Can also be used to evaluate control actions (task requirements). Ability to collect alerts and information requirements. Link analysis can be used to study the links (communications) between agents, including alerts and indications when performing a task. This information can help understand the general sequence of activities and common sources of information used to perform a task. Ability to capture cognitive and decision-making aspects. Cognitive and decision-making aspects are not explicitly covered in link analysis. Ability to capture workplace and task support aspects. Workplace and task support aspects are not addressed with link analysis. Ability to capture teamwork and communication considerations.	Task Description, Task Evaluation	OSD, network diagrams, graph theory and centrality metrics, transition matrices	Can be extended with graph theory and centrality to quantify importance of frequently access information. Aggregates sequences of action.	Provides an aggregate of sequences, so individual interactions are not readily understood.

Method	Description/Application	Method Type	Related Methods	Strength	Weakness
	Communication channels are explicitly measured in link analysis. Link analysis can be extended using graph theory to measures these channels further quantitatively as needed. Ability to capture situation and performance shaping factors. Situation and performance shaping factors are not considered in link analysis. Ability to identify hazards. Hazards are not considered in link analysis.				
ACTA	Provides a structured approach to collecting cognitive demands associated with a task or scenario. Application in collecting information requirements (information needs, training, cognitive demands). Ability to collect alerts and information requirements. ACTA consists of four main phases: task diagram interview, knowledge audit interview, simulation interview, and cognitive demands table. In defining the task and understanding where expertise is needed, alerts and information requirements can be collected. Ability to capture cognitive and decision-making aspects. ACTA formally captures cognitive and decision-making aspects. This is the primary benefit. Ability to capture workplace and task support aspects. While ACTA is mostly focused on the cognitive aspects of the task, the interviews can capture workplace and task support consideration (workarounds, decision aids, etc.) that are important for the task. Ability to capture teamwork and communication considerations. ACTA can focus on the cognitive elements of teamwork and communication for a task. This would be reflected in the cognitive demands table. Ability to capture situation and performance shaping factors. Situation and performance shaping factors associated with cognitive demands can be readily captured. Ability to identify hazards. Hazards associated with cognitive demands can be readily captured.	Task Data Collection, Task Description, Task Evaluation	Talk-through/ Walk-through	Structured way for collecting cognitive demands of a task	Could be time consuming as there are multiple sessions required per ACTA phases

Method	Description/Application	Method Type	Related Methods	Strength	Weakness
Goals, Operators, Methods, and Selection Rules (GOMS)	Goals are what the user wishes to accomplish. Operators refers to the actions the user takes to accomplish the goal. Methods refer to the series of operators taken to reach the goal. If there is more than one method to achieve the goal, selection rules are used to choose a method. Types of GOMS: Keystroke-level model uses pre-established keystroke-level primitive operator for predictions.	Task Description, Task Evaluation	ACTA	Provides a formal analytical approach to evaluating the temporal, physical, and cognitive demands of a task	GOMS is generally limited to expert use cases (e.g., keystroke-level model). There is little work on using GOMS in hybrid control room states; think times may not be fully reflective of the cognitive activities required of operators in a complex environment like an NPP (Kovesdi and Joe 2019).
Walk-throughs/ Talk-throughs	Both talk- and walk-throughs support the knowledge elicitation of the task by allowing a domain expert to verbalize and demonstrate aspects of task whereby the human factors engineer can query specific questions of the nature of the task at hand (Kirwan and Ainsworth 1992). A walk-through involves a demonstration, and a talk-through only involves verbalization. Summary of key outputs from this approach, per INL/EXT-20-57862, is listed below: • Identification of representative scenario to demonstrate enabling functions of ADAPT • Identification of important NPP parameters to include on the HSI displays • Input the design into the specific formats for identified HSI indications (e.g., trends) • Identification of existing human actions that should be automated • Identification of potential human error traps • Identification of steps with continuous monitoring/continuous action • Human actions with suboptimal workload levels.	Task Data Collection, Task Description, Task Evaluation	ACTA	The talk-through part can be a very thorough, step-by-step analysis of operator actions with reviewers taking detailed notes and asking questions after each step. The walk-through is nonintrusive and in real time, which can give reviewers a more realistic view of how operators interact. Issues can be dissected in the post-hoc evaluation.	Requires access to domain experts. Can be time consuming to structure and analyze a talk- and walk-through.
Control Task Analysis	Control task analysis (CTA) is the second step of cognitive work analysis. The purpose of CTA is to document what decisions are made and the states and processes that are involved in a particular control task. Lamoureux and colleagues (2006) used the modeling tool, the decision ladder, to conduct the CTA.				
OSD	The study of how a task is accomplished, in terms of who is involved and what controls and information are needed, is often well suited for operational sequence analysis and its output, OSDs (Kirwan and Ainsworth 1992; Kovesdi and Le Blanc 2020). OSDs provide a graphical means to visualize the sequence of a task, whether it be spatially or temporally. The application of spatial OSDs can be applied to understand the information and task requirements of how an operator must	Task Description, Task Evaluation	Workload Analysis, Link Analysis	Provides a structured way of representing the temporal and spatial demands of a task. This output can support workload analysis and HSI design.	Can be cumbersome to development, typically requiring specialized software (e.g., Kovesdi and Le Blanc 2020).

Method	Description/Application	Method Type	Related Methods	Strength	Weakness
	navigate the physical environment to accomplish the task. This information allows the human factors engineer to understand the order of operations to complete a task, the physical demands of searching for information and controls, and the specific locations to which the operator must go to complete the task. Insights from the spatial OSD can help with HSI design through informing what information should be grouped (to reduce excessive navigation) and what systems should be accounted for in a task. Temporal OSDs provide a way of representing the order in time that a task is carried out. The benefits of temporal OSDs often serve to inform where there may be an excessive workload in terms of temporal demands. For example, if there is a known time limit in performing a task, excessive information and control actions seen by the operator in the sequence may be readily identified and this input can invoke re-evaluating function allocation.				
Workload Analysis	Workload analysis evaluates the physical and cognitive demands of a task (Kirwan and Ainsworth 1992; EPRI 3002004310 2015; Kovesdi and Le Blanc 2020). In its most general form, workload analysis may be supported through timeline analysis (e.g., such as OSDs) to understand the time demands of performing a task to a given time limit (Kirwan and Ainsworth 1992; EPRI 3002004310 2015). Time completion estimations may be supported through known completions or through modeling approaches. With time-critical actions, if a task requires more completion time than what is available, the temporal workload is exceeded, and the task requirements need to be re-examined in function allocation. Likewise, cognitive workload can be evaluated using self-report techniques in combination with simulation and modeling (Kovesdi and Le Blanc 2020; Kovesdi, Joe, and Boring 2018).	Task Description, Task Evaluation	OSD, Link Analysis, GOMS	Provides a systematic/structured way to evaluate workload.	The approach varies depending on its nature. Analytical methods are available, which do not require simulators or domain experts; however, these are limited in scope. Fuller scale approaches, like the use of simulation, can be more comprehensive but at the cost of requiring time and resources.