INL/RPT-23-74346
Revision 0

Light Water Reactor Sustainability Program

Human and Technology Integration Evaluation of Advanced Automation and Data Visualization

September 2023

U.S. Department of Energy

Office of Nuclear Energy

INL/RPT-23-74346
Revision 0

Human and Technology Integration Evaluation of Advanced Automation and Data Visualization

Casey Kovesdi, Jeremy Mohon, and Kaylee Wilhite

September 2023

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

SUMMARY

While the existing U.S. light-water reactors are highly reliable and safe and provide a significant proportion of carbon-free electricity, the cost of operating and maintaining them has become less competitive compared to other electricity generating sources. The reason for the gap in operating and maintenance costs can be attributed at least in part to the advent of new digital technologies that other electricity generating industries are currently using. Advanced capabilities, including digital instrumentation and control (I&C) systems, advanced automation and analytics, and a greater span of data integration (i.e., connectedness), across these nonnuclear plants have transformed the way work is performed and ultimately given them a competitive advantage in terms of the cost required for operating, maintaining, and supporting them.

To reduce operating and maintenance costs and address the obsolescence of the aging I&C infrastructure of the existing U.S. light-water reactors, the U.S. Department of Energy Light Water Reactor Sustainability Program Plant Modernization Pathway is conducting targeting multidisciplinary research that delivers a sustainable business model to enable a cost-competitive U.S. nuclear industry and develops technology modernization solutions to address aging and obsolescence challenges.

The work described in this report supports these two objectives and describes the demonstration of human and technology integration across recent industry collaborations to support their large-scale digital I&C modifications. This technical report describes the demonstration of the human and technology integration methodology in performing full-scale performance-based human-in-the-loop tests to evaluate plant-specific advanced automation and data visualization applications within these collaborators' digital modifications. This technical report also documents future applications of human and technology integration that expand beyond main control room modernization and digital I&C upgrades, which have been a central focus to date. Thus, this technical report discusses how to implement human and technology integration across new business opportunities and how to develop an evaluation plan that defines measures and criteria and documents key assumptions to support full plant modernization.

ACKNOWLEDGEMENTS

The authors would like to thank all staff from Constellation Energy Generation, Southern Nuclear Corporation, and Sargent and Lundy in the continued collaboration that makes this research possible. This report was made possible through funding by the United States Department of Energy Light Water Reactor Sustainability Program. Lastly, we would like to thank Alison Hahn and Jason Tokey of the Department of Energy, as well as Craig Primer and Bruce Hallbert of Idaho National Laboratory for championing this effort.

CONTENTS

FIGURES

TABLES

ACRONYMS

AI	artificial intelligence
B-NUM	Brief Nuclear Usability Measure
CAT	critical abilities and tasks
CEG	Constellation Energy Generation
CFR	Code of Federal Regulation
ConTA	control task analysis
CUD	comms usage diagram
CWD	critical work domain
DEG	Digital Engineering Guide
DIF	difficulty, importance, and frequency
DOE	Department of Energy
EPRI	Electric Power Research Institute
GTA	groupware task analysis
HAZCADS	Hazards And Consequences Analysis for Digital Systems
HED	human engineering discrepancy
HFE	human factors engineering
HSI	human-system interface
HSSL	Human-Systems Simulation Laboratory
HTA	hierarchical task analysis
HTI	human and technology integration
I&C	instrumentation and controls
INCOSE	International Council on Systems Engineering
IFE	Institute of Energy Technology
IO	integrated operations
ION	integrated operations for nuclear
ISO	International Organization for Standardization
ISV	integrated system validation
LWR	light-water reactor
LWRS	Light Water Reactor Sustainability
ML	machine learning
NASA-TLX	National Aeronautics and Space Administration – Task Load Index
NRC	Nuclear Regulatory Commission
O&M	operating and maintenance

OE	operating experience
OER	Operating Experience Review
OSA	Operational Sequence Analysis
OSD	Operational Sequence Diagram
PTPG	People, Technology, Processes, and Governance
R&D	research and development
SART	Situation Awareness Rating Technique
SEQ	single ease question
SME	subject matter expert
SNC	Southern Nuclear Corporation
SOCA	Social Organization and Cooperation Analysis
STAMP	Systems Theory Accident Modeling and Process
STPA	System Theoretic Process Analysis
TERA	Technical, Economic, and Risk Analysis
THEA	Technique for Human Error Assessment
TTA	tabular task analysis
V&V	verification and validation
VDU	visual display unit
WDA	work domain analysis
WRO	work reduction opportunity

HUMAN AND TECHNOLOGY INTEGRATION EVALUATION OF ADVANCED AUTOMATION AND DATA VISUALIZATION

1. INTRODUCTION

Nuclear power is a safe, reliable, and carbon-free electricity generating source for the United States. The existing U.S. light-water reactors (LWRs) have consistently provided, on average, roughly 20% of the nation's electricity generation, and yielded the highest capacity factor of over 90% over the past two decades[1], as seen in Figure 1.

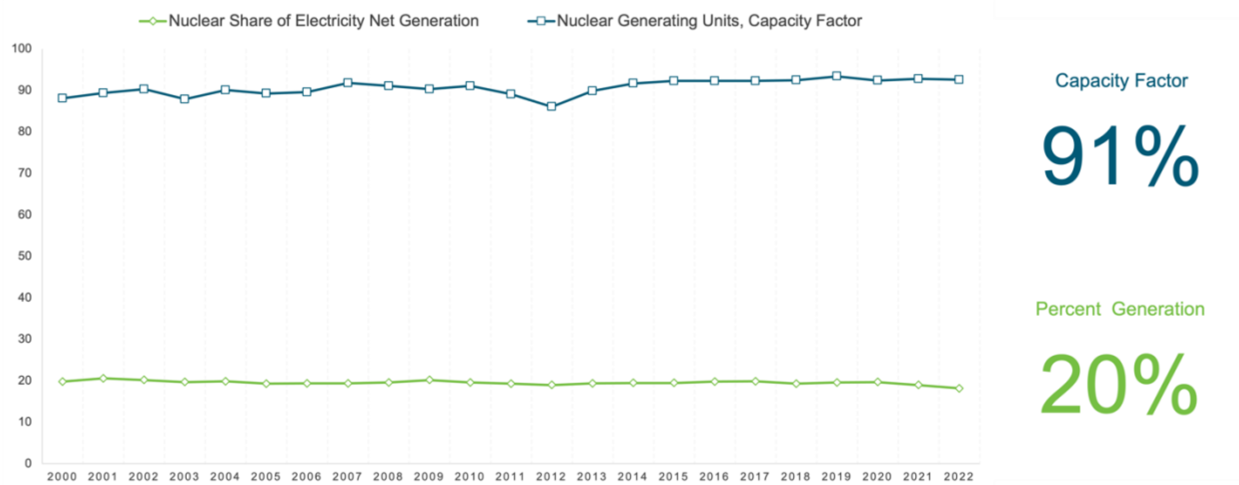


Figure 1. Nuclear power generation and capacity factor over the past two decades.

While the existing U.S. LWRs are highly reliable and safe and provide a significant proportion of carbon-free electricity, the cost of operating and maintaining them has become less competitive compared to other electricity generating sources. The reason for the gap in operating and maintenance (O&M) costs can be attributed at least in part to the advent of new digital technologies that other electricity generating industries are currently using. Advanced capabilities, including digital instrumentation and control (I&C) systems, advanced automation and analytics, and a greater span of data integration (i.e., connectedness), across these nonnuclear plants have transformed the way work is performed and ultimately given them a competitive advantage in terms of the cost required for operating, maintaining, and supporting them. To reduce O&M costs and address the obsolescence of the aging I&C infrastructure of the existing U.S. LWRs, the U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program Plant Modernization Pathway is conducting targeted research and development (R&D) to keep the existing U.S. nuclear power plants economically viable and extend their lifespans by improving their performance through two complementary mission areas:

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

The DOE LWRS Program Plant Modernization Pathway is accomplishing this mission through a multidisciplinary R&D approach. This report describes a demonstration of human and technology integration (HTI) aspects of the LWRS Program Plant Modernization Pathway. The intent of this technical

[1] Data from https://www.eia.gov/totalenergy/data/annual/.

report is to document the most recent collaborations with industry in demonstrating HTI in performing full-scale, performance-based, human-in-the-loop tests to evaluate plant-specific advanced automation and data visualization applications; it also documents future HTI applications that expand beyond main control room modernization and digital I&C upgrades, which have been a central focus to date. To this end, this report discusses how to implement HTI across new business opportunities and how to develop an evaluation plan that defines measures and criteria and documents key assumptions to support full plant modernization. Specifically, the work described in this report is broken up into six additional key sections.

- Section 2 describes the U.S. DOE LWRS Program Plant Modernization Pathway key and cross-disciplinary R&D areas
- Section 3 presents and discusses the Integrated Digital Environment Roadmap, which presents key phases that characterize major digital upgrades, follows a systems engineering approach, and covers how the R&D areas described in Section 2 are applied across the project lifecycle
- Section 4 focuses on the role and execution of HTI, covers the HTI objectives and scope, shares enabling tenets that characterize effective HTI execution to meet its objectives, and discusses the method for HTI, as originated from INL/EXT-21-64320, which uses the Integrated Digital Environment Roadmap as a common framework for its application
- Section 5 provides a summary of the continued demonstration of HTI across major U.S. industry pilot projects and builds on the work described in INL/RPT-22-68472, INL/RPT-22-70538, and INL/RPT-22-71395 by adding lessons learned from the most recent efforts in these projects
- Section 6 discusses next steps in this R&D, highlights how HTI can be applied to plant areas beyond the main control room, and proposes a two-phased approach, characterized by *scoping* HTI to address critical functions and tasks impacted by a major upgrade and the *detailed analysis* of these functions and tasks to ensure safe, reliable, and efficient use of the proposed technology
- Finally, Section 7 concludes with final remarks and next steps with this research area.

2. PLANT MODERNIZATION RESEARCH

There are four key R&D areas under the U.S. DOE LWRS Program Plant Modernization Pathway. These include integration operations for nuclear (ION), digital infrastructure, data architecture and analytics, and HTI. These areas have different focuses but complement each other to support the pathway mission. Further, there has been recent focus on implementing cross-disciplinary research in information automation and digitalization. These areas are characterized in Figure 2. The next subsections describe these areas in terms of their scope, objectives, and relevant work to delivering a sustainable business model and developing technology modernization solutions that collectively enable the U.S. nuclear industry to be cost competitive while addressing aging and obsolescence challenges.

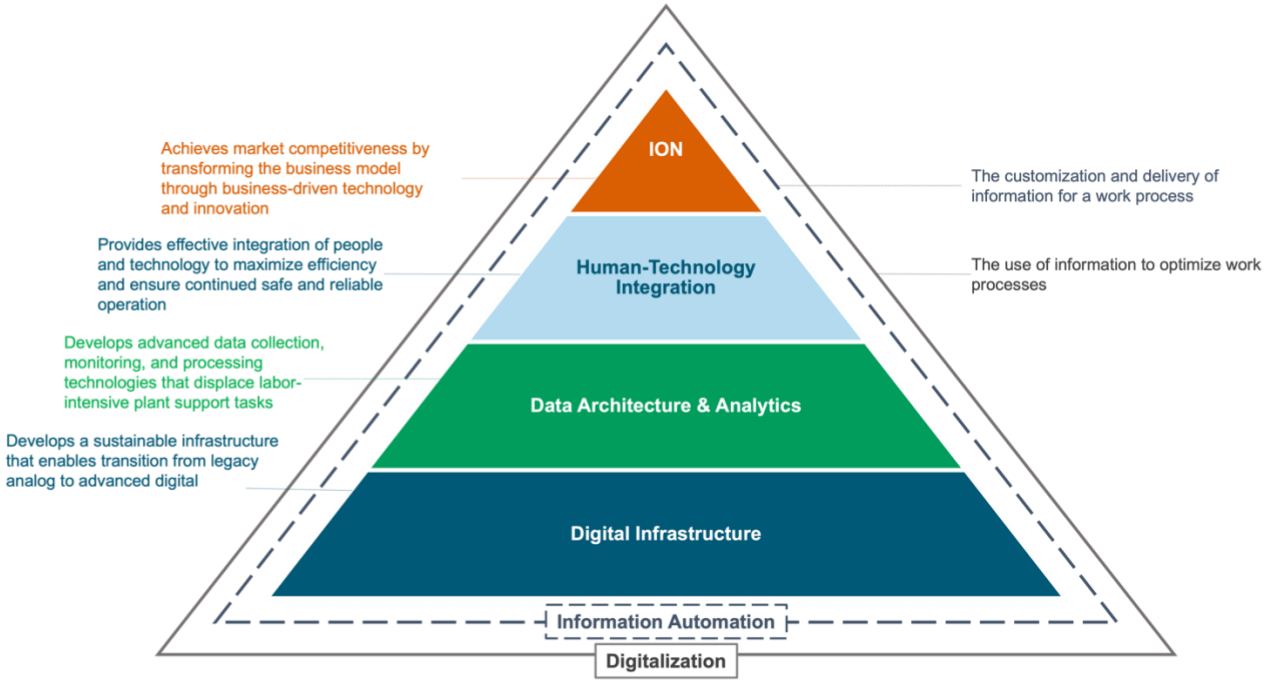


Figure 2. R&D areas of the U.S. DOE LWRS Program Plant Modernization Pathway (adapted and generalized from INL/EXT-21-64580).

2.1 Key Research and Development Areas

The fundamental goal of the pathway is to extend the life and improve the performance of the existing LWR fleet through modernized technologies and improved processes for plant operation and power generation. This effort is both technical and sociotechnical in nature and thus requires a multidisciplinary effort. A strategic assessment of the economic viability of how business-driven digital technology can transform the way work is done is accomplished through ION. Moreover, a sustainable infrastructure that enables an effective transition of legacy analog equipment into advanced digital equipment is accomplished through digital infrastructure. Advanced technologies are developed through data architecture and analytics and are integrated into the digital infrastructure to eliminate labor-intensive tasks. Finally, to ensure that the advanced technologies and changes to existing processes and training can be safely, reliably, and effectively used, HTI is applied.

2.1.1 Integrated Operations for Nuclear

The primary goal of ION is to deliver a sustainable business model that enables a cost-competitive U.S. nuclear industry. ION is rooted in the concept of integrated operations (IO), which was a driving concept in the renewal of the North Sea oil and gas industry (Thomas et al., 2020). IO can be characterized as a new way of doing business through the strategic use of technology that enables people to remotely monitor processes, seamlessly access important information, and collaborate across different geospatial regions to perform work safely and in an environmentally friendly way (Rosendahl and Hepsø, 2013). Within the oil and gas industry, IO addressed challenges of having personnel, suppliers, and systems located across different geospatial locations (i.e., onshore, offshore, and in other countries), as seen in Figure 3.

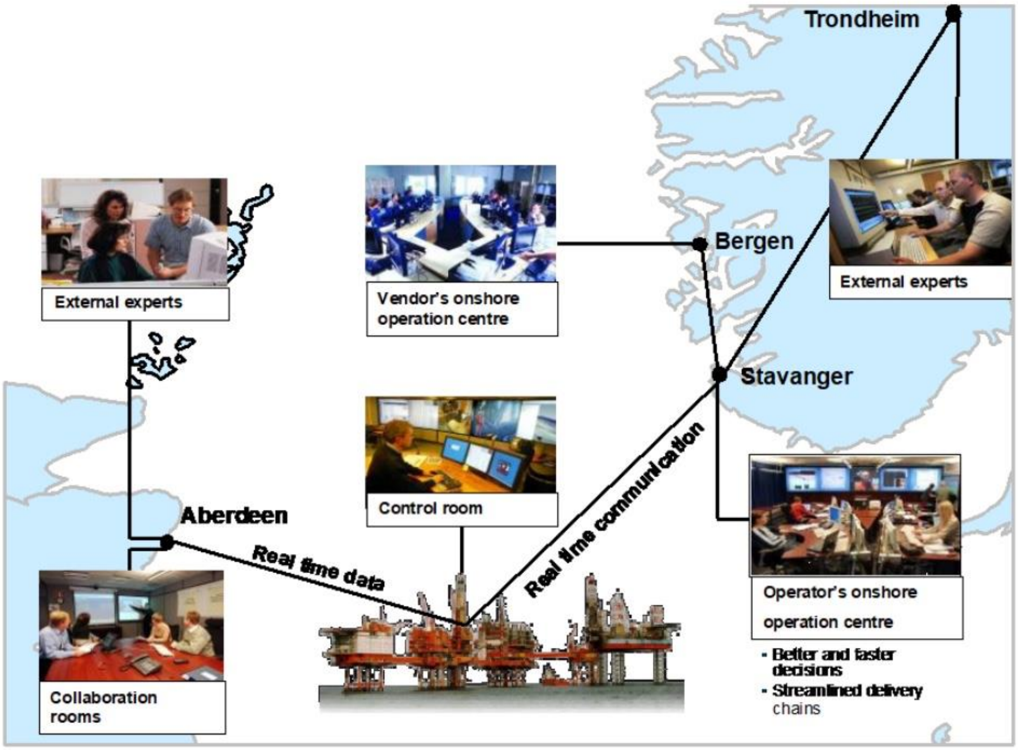


Figure 3. The IO concept (adapted from INL/EXT-20-59537).

IO's philosophy to strategically use technology to enable real-time coordination, monitoring, and information exchange to perform work significantly reduced O&M costs for the industry (Thomas et al., 2020). The IO way of performing work required the oil and gas industry to fundamentally rethink how work could be performed through IO's principle of *capabilities thinking* (Rosendahl and Hepsø, 2013). Key steps include defining the operational context, defining the core capabilities (i.e., through identifying key decisions that the organization must make to meet its objectives), defining the subcapabilities, evaluating and defining the capabilities' resources through the lens of people, technology, processes, and governance, (PTPG), and developing an implementation plan that enables IO.

These four steps and holistic analysis of the impact of transformational change through PTPG provides the foundation of ION. ION's use of capabilities thinking and PTPG is represented in Figure 4.

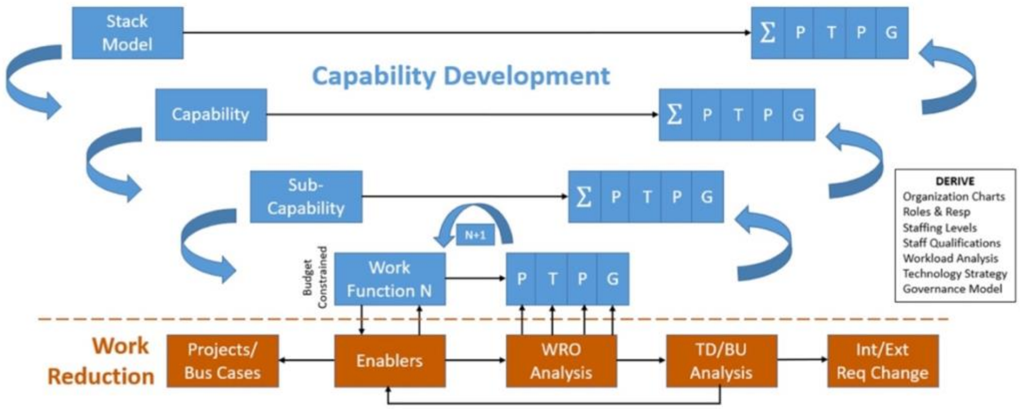


Figure 4. The ION capabilities framework (adapted from INL/EXT-20-59537).

ION follows a top-down approach, as seen in the top left of Figure 4. Similar to defining the operational context of IO, ION begins by determining a market-based price point for generating electricity that maintains market competitiveness (Remer et al., 2023). The total O&M budget is then allocated to key plant resources (capabilities). Capabilities, such as *operate the plant*, are decomposed further into subcapabilities and work functions. At the work function level, work reduction opportunities (WROs) are identified and assessed through the impact on PTPG. This assessment is at the bottom of Figure 4. As more WROs are identified and assessed, the implemented technologies can be rescaled to new work functions, subcapabilities, and capabilities, as shown toward the right of Figure 4. Recently, ION developed a target cost reduction of one-third to remain cost competitive by considering technologies that could be used within the next 3–5 years; this work was described as ION Generation 1 (Remer et al., 2023). A set of WROs was identified and clustered into 10 critical work domain (CWDs). These CWDs are outlined in Figure 5 and provide a basis for targeted R&D across the other LWRS Plant Modernization Pathway research areas.

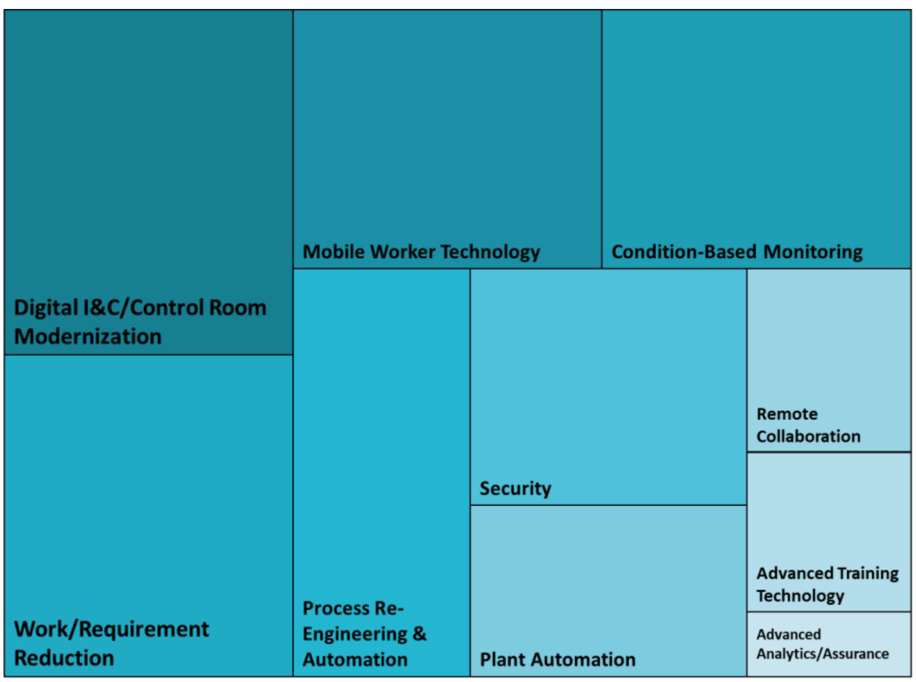


Figure 5. CWDs of ION Generation 1 (adapted from INL/RPT-22-70538).

2.1.2 Digital Infrastructure

As described in INL/EXT-21-64580, the digital infrastructure effort establishes the comprehensive physical and logical foundation to support advanced capabilities, such as those developed in data architecture and analytics and informed through ION. The digital infrastructure is presented through several levels adapted from the Purdue Enterprise Reference Architecture, as illustrated in Figure 6.

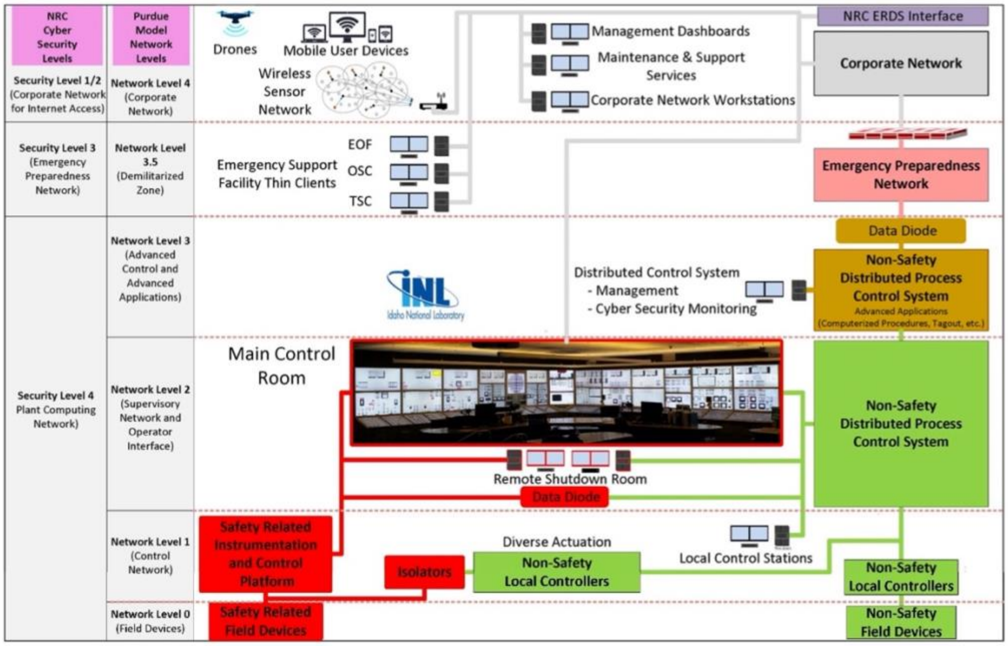


Figure 6. Simplified digital infrastructure (adapted from INL/EXT-21-64580).

The Purdue Model network levels (i.e., ranging from Levels 0 to 4) are depicted from bottom to top and are characterized by the functions performed and associated requirements of these functions. Inversely, the U.S. Nuclear Regulatory Commission (NRC) Cybersecurity Levels that address governing requirements of 10 Code of Federal Regulation (CFR) 73.54 are depicted in an inverse order of the Purdue Model network levels (i.e., ranging from Levels 4 to 1). The digital infrastructure framework depicted in Figure 6 champions utilizing a two platform I&C approach, using a digital safety system and nonsafety distributed control system; it also maps how the specific types of software applications and hardware required to operate, maintain, and support the plant can be incorporated across the infrastructure in a way that addresses regulatory requirements while ensuring the cost associated with the entire equipment lifecycle is economically viable to receive subsequent license renewals to operate for a total of 80–100 years. The digital infrastructure provides the I&C framework that will support plant transformation as identified through ION and by using technologies developed and demonstrated across industry and with data architecture and analytics.

2.1.3 Data Architecture and Analytics

Data architecture and analytics develops and demonstrates advanced monitoring and data processing capabilities to replace labor-intensive plant support tasks. These capabilities leverage machine learning (ML) and artificial intelligence (AI) techniques to automate burdensome tasks to significantly increase efficiencies and reduce both system and human errors (Agarwal et al., 2022). There have been diverse use cases demonstrated in this area, including condition-based monitoring (Agarwal et al., 2022), automated outage risk and technical specification compliance (St Germain, Masterlark, Priddy, and Beck, 2019), automated work packages (Al Rashdan, Oxstrand, and Agarwal, 2016), computer-based procedures for field workers (Oxstrand, Le Blanc, and Bly, 2016), and automated fire watch (Al Rashdan, Griffel, and

Powell, 2019). The application of these advanced capabilities provides a significant opportunity to reduce costs across plant support functions by transforming the way work is done at the plant, transitioning from labor-centric to technology-centric models. Their integration across the digital infrastructure, as seen in Figure 6, are seen at Purdue Model Level 4.

2.1.4 Human and Technology Integration

Any large-scale plant transformation effort is both a technical and *sociotechnical* endeavor. Following this perspective, the reason for a nuclear power plant is to produce electricity, which is achieved through purposeful functions. The functions that comprise the plant are achieved through the cooperation between technological systems and people who perform work. The interaction between people and the systems and the interaction between people within the organization necessary for operating, maintaining, and supporting the plant is of primary focus for HTI. Specifically, the HTI research area utilizes human factors engineering (HFE) frameworks, principles, methods, and tools to ensure the safe, reliable, and efficiency use of the new technologies considered through the other LWRS Program Plant Modernization Pathway research areas. Section 4 covers the HTI research area in more detail; although, it is worth noting here that the scope of HTI spans several important topics, including:

- The design of human-system interfaces (HSIs), procedures, and training
- The design of information to support organizational decision-making and situation awareness (see Section 2.2.1)
- The design of the workstation and workplace
- The design and application of AI/ML and implications associated with trust and transparency
- Technology acceptance, impacting worker attraction and retention, with emerging technology
- Considerations of emerging technology on organizational effectiveness and teamwork.

2.2 Cross-Disciplinary Areas

Two recent cross-disciplinary plant modernization research areas include information automation and digitalization.

2.2.1 Information Automation

The information automation research area focuses on the customization and delivery of information to support work processes within the plant. Specifically, this research area is currently focusing on improving nuclear power plant performance through systematically developing information availability solutions that enable more timely decision-making in this area. The current state of industry is to leverage the site's corrective action program for the performance improvement process. However, with only this data, more time is needed to trend key performance parameters for investigating significant events. This research area is therefore developing a cost-effective issue resolution process that uses information automation and AI/ML applications to identify these trends more quickly and enable proactive decision-making. The research also emphasizes taking a sociotechnical approach and is leveraging methods such as cognitive work analysis (e.g., Dainoff, Hettinger, and Joe, 2022) and system theoretic process analysis (STPA; Levenson and Thomas, 2018) to identify parts of the systems that involve human interaction. Within this framework, we posit that information automation can be modeled as an "information control structure" to provide a functional map of the sociotechnical system. Interaction points indicated in the information control structure are then used to assess and identify potential weaknesses in the system's information exchange structure. As such, opportunities to apply AI/ML applications can be leveraged at these points.

2.2.2 Digitalization

Digitalization is the process of incorporating digital technologies into business processes to improve performance, such as through increased efficiencies or reduced error. It therefore utilizes the digitization of work tools (e.g., electronic work packages or information automation) to transform the way in which work is performed. An important element to digitalization is to leverage seamless digital environments, which seamlessly integrate information from plant systems and processes for staff to perform work. This research is focusing R&D on leveraging capabilities like electronic work packages, smart planning and scheduling technologies, dynamic instructions, and data analytics like information automation to improve performance, reliability, and safety across the plant. Figure 7 shows an illustration of how digitalization is being put into context in this emerging R&D area.

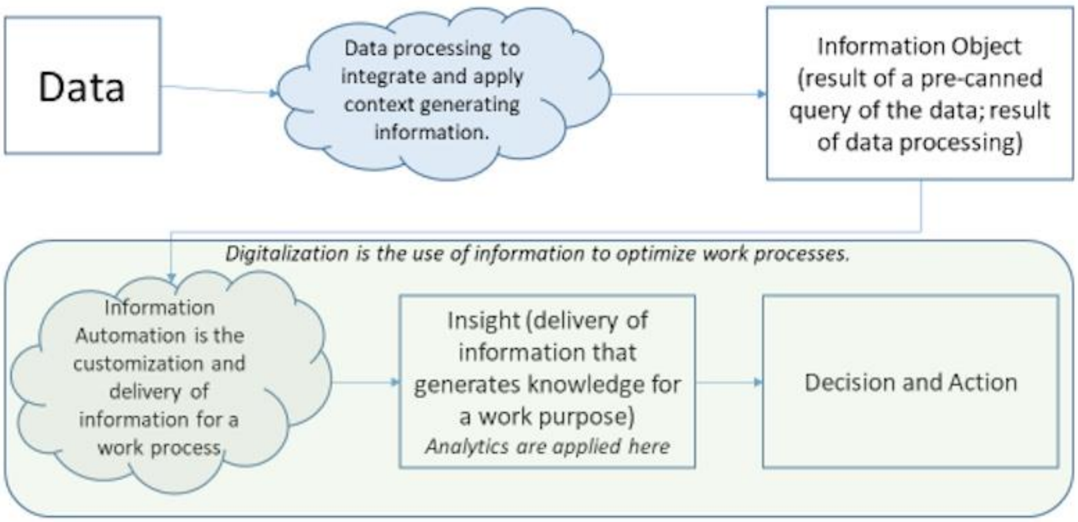


Figure 7. Process map of the relation between information automation and digitalization research areas.

3. A SYSTEMS ENGINEERING APPROACH TO MODERNIZATION: THE INTEGRATED DIGITAL ENVIRONMENT ROADMAP

Applying *systems engineering* as a holistic approach to manage large-scale nuclear power plant digital modifications has gained momentum in the U.S. industry (Electric Power Research Institute [EPRI], 2021). Per the International Council on Systems Engineering (INCOSE), systems engineering can be defined as (i.e., **bolding with underlines** represents our emphasis):

> …An **interdisciplinary approach** and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality **early in the development cycle**, documenting requirements, and then proceeding with design synthesis and system validation while **considering the complete problem**: operations, costs and schedule, performance, training and support, test, manufacturing, and disposal. Systems engineering integrates all the disciplines and specialty groups into a **team effort** forming a **structured development process** that proceeds **from concept to production to operation**. Systems engineering considers both the business and technical needs of all customers with the goal of providing quality product **that meets the user needs** (INCOSE, 2015).

As highlighted, there are several important characteristics emphasized in INCOSE's definition. First, systems engineering is interdisciplinary in nature, requiring perspectives from many domains working as a team. Secondly, systems engineering is applied both early in and throughout the project lifecycle (i.e., this entails the operation and decommissioning of systems). Finally, a key point here is that systems engineering uses a structured process that considers multiple inputs (e.g., cost and schedule, performance, training) while also being driven to meet user (i.e., stakeholder) needs.

The scope of systems engineering goes beyond nuclear power, is suited for the design and evaluation of complex systems, and is predicated on the concept of “systems science and systems thinking,” which focuses on identifying, exploring, and understanding patterns of complexity (INCOSE, 2015). Complex systems, like nuclear power plants, exhibit interactions that can be unpredictable and nonlinear and can result in emergent patterns. In such systems, traditional engineering approaches that use decomposition to understand specific subsystems and components must be balanced with approaches that understand the system as a whole using iterative exploration and adaption. As such, a foundational principle of systems thinking and systems engineering is to leverage both traditional and integrative engineering approaches.

The EPRI Digital Engineering Guide (DEG) is an applied framework of systems engineering to support significant digital modifications for nuclear power plants. The scope of the DEG goes beyond the scope of this technical report, so we refer the reader to EPRI Technical Report 3002011816 (2021) for more information. Although, it should be noted here that the DEG is an industry-endorsed engineering process that has been leveraged to support U.S. digital upgrades, such as with Constellation Energy Generation’s (CEG’s) safety-related digital upgrades (e.g., Hunton et al., 2021).

The DEG supports a multidisciplinary approach, including HFE as one of the primary subdisciplines (see Figure 8), to:

- Focus on meeting stakeholder needs with acceptable risk (i.e., following a graded approach)
- Meet requirements with opposing constraints
- Follow a multidisciplinary approach that does not allow any single discipline to govern the solution
- Focus on minimizing development and lifecycle costs through a holistic and integrative approach (Kovesdi, Mohon, and Pedersen-San Miguel, 2023).

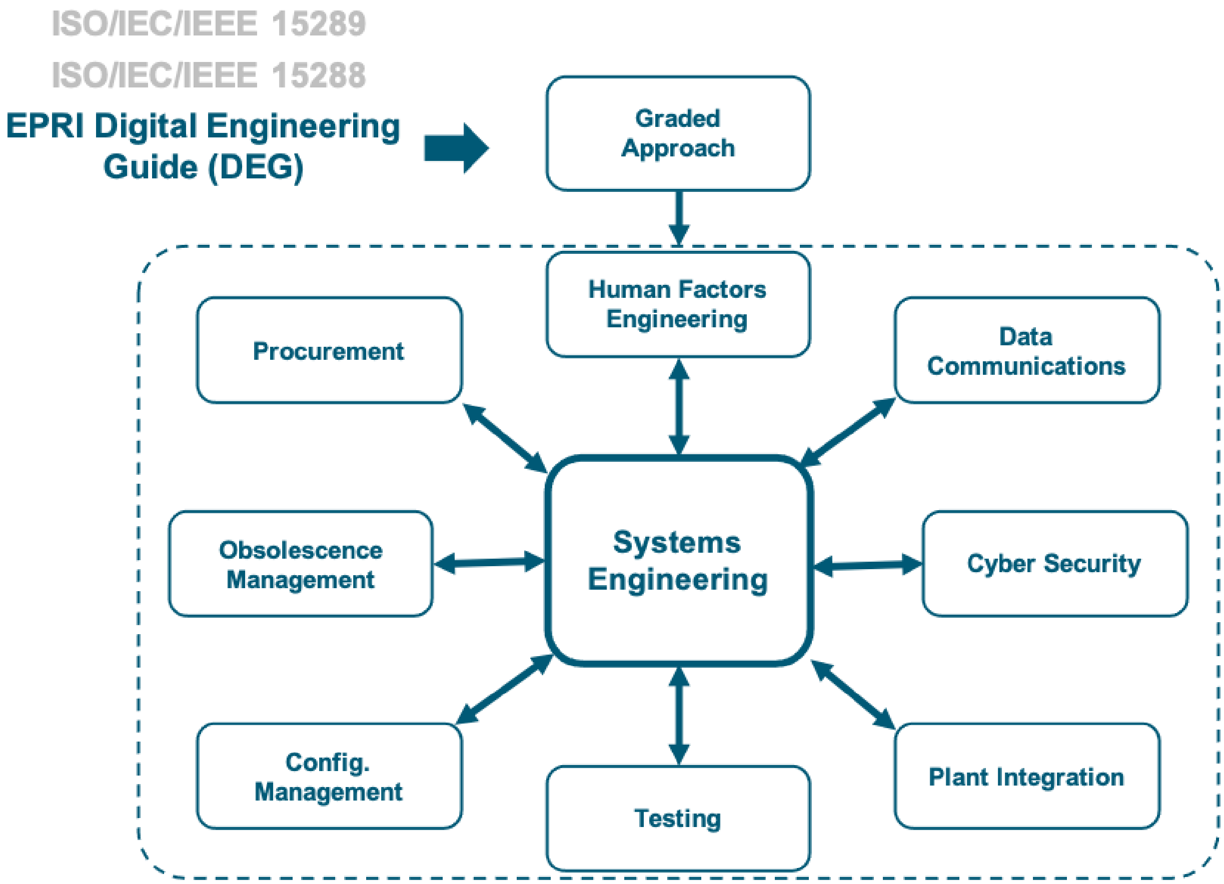


Figure 8. DEG breadth of disciplines (adapted from INL/EXT-21-64320).

The DEG (2021) applies general systems engineering and domain-specific guidance across distinct engineering phases, representing the lifecycle of a major digital modernization project. These phases include initial scoping, conceptual design, detailed design, installation planning, installation, testing, closeout, and O&M. Figure 9 outlines these key project lifecycle phases. maps key technical activities performed by the LWRS Program Plant Modernization Pathway (i.e., with HTI highlighted), and introduces a new phase called *strategic planning*.

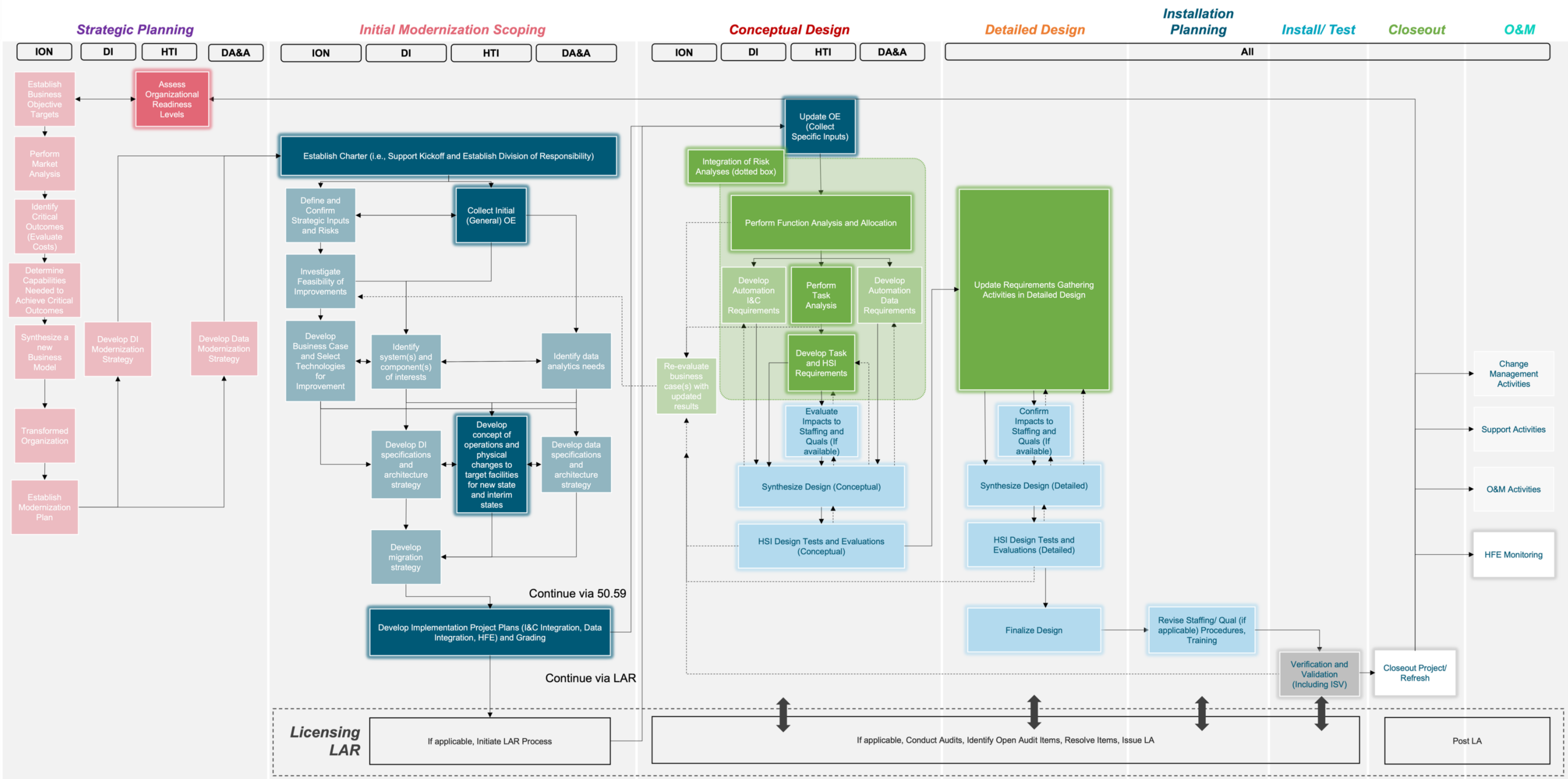


Figure 9. Integrated Digital Environment Roadmap.

3.1 Strategic Planning

Strategic planning refers to the initial stage in which the organization (i.e., utility) performs early organizational and economic assessments related to the strategic changes necessary for ensuring the continued operation of its existing plants. The assessments are typically informed through top-down business objectives that define the planned cost reductions to remain economically viable (Remer et al., 2023). An output of this phase is to enable senior leadership to clearly communicate the vision, mission, and strategic objectives throughout the organization to enable transformation such that economic, technical, and safety risks are accounted for across each scoped and implemented modification (Aqel, 2012).

From a Plant Modernization Pathway perspective, ION is a major contributor to strategic planning. The activities involved through ION include:

- Establishing business objective targets
- Performing market analysis
- Identifying critical outcomes
- Evaluating costs for modernizing
- Determining the capabilities needed to achieve the identified critical outcomes
- Synthesizing these capabilities into a new business model to transform the organization
- Establishing a modernization plan.

Establishing business objective targets entails defining the set cost reductions needed for the organization to remain economically competitive. In recent ION research, a collection of WROs grouped into 10 CWDs were identified and estimated to support a one-third reduction in O&M costs (refer to Figure 5). While the validation of these estimates is underway, the identification of these WROs and results documented in reports such as INL/RPT-22-68671 can serve as a basis for setting strategic objectives.

There are many factors that affect the economic results of implementing ION. Therefore, the next steps entail performing a market analysis, identifying critical outcomes, evaluating costs for modernizing, and determining the capabilities needed to achieve these outcomes. These analyses will be influenced by whether the site(s) are in a regulated or deregulated energy market, existing technological investments, and the state of the existing I&C infrastructure, as well as other external factors including current policies and cost of other electricity generating resources. The results of these analyses will inform what capabilities are needed to achieve the target cost reductions.

These capabilities are synthesized into a cohesive set of modernization project plans that account for their holistic influences on PTPG to transform the way work is performed across the organization. The notion here is that the work necessary for operating, maintaining, and supporting the plant will be accomplished more efficiently and without sacrificing safety by re-allocating PTPG resources with business-minded innovations that address specific WROs (Remer et al., 2023). The U.S. nuclear industry's workforce of the future may look like what is seen in Figure 10. That is, staff will be able to support a broader range of tasks and processes without impacting workload using innovative technologies (e.g., AI/ML, drones, connected devices). The worker of the future will essentially be multiskilled, performing multiple functions that improve his or her utilization. They will be empowered through technology to confidently perform a wide range of tasks that currently require highly specialized training, oftentimes left to tacit knowledge.

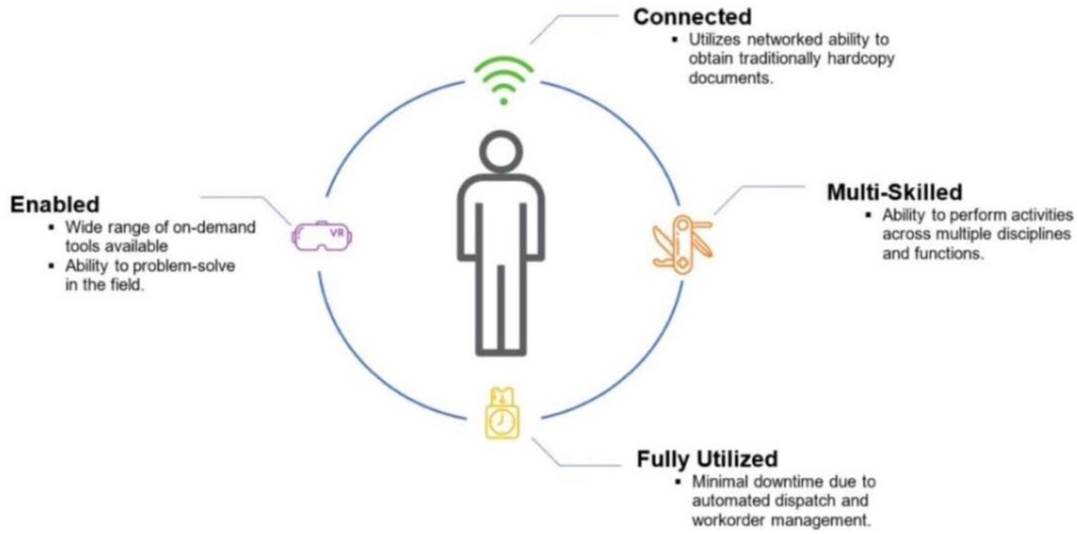


Figure 10. Characteristic of the worker from the future (adapted from INL/EXT-21-64134).

From the HTI perspective, there are natural tie-ins to ION assessment activities. For one, the existing roles, responsibilities, and impacted functions must be analyzed to understand how the proposed technologies will change the way work is performed. This analysis is necessary to support what is referred to as *joint optimization*, which refers to the design of work systems that equally focus on the technological and personnel subsystems while also accounting for external factors (Hendrick and Kleiner, 2001). Relatedly, a technology or stack of technologies should be assessed in terms of their *human readiness level* (Figure 11).

Phase	HRL Level
Basic Research and Development Scientific research, analysis, and preliminary development on paper and in the laboratory occur. This phase culminates in a validated proof of concept that addresses human needs, capabilities, limitations, and characteristics.	***HRL 1:*** Basic principles for human characteristics, performance, and behavior observed and reported ***HRL 2:*** Human-centered concepts, applications, and guidelines defined ***HRL 3:*** Human-centered requirements to support human performance and human-technology interactions established
Technology Demonstrations The technology is demonstrated at increasing levels of fidelity, first in the laboratory and later in relevant environments. This phase concludes with demonstration of a representative system in a high-fidelity simulation or actual environment, with evaluation of human systems designs provided by representative users.	***HRL 4:*** Modeling, part-task testing, and trade studies of human systems design concepts and applications completed ***HRL 5:*** Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design ***HRL 6:*** Human systems design fully matured and demonstrated in a relevant high-fidelity, simulated environment or actual environment
Full-Scale Testing, Production, and Deployment Final testing, verification, validation, and qualification occur, with human performance evaluations based on representative users. This phase concludes with operational use of the system and continued systematic monitoring of human-system performance.	***HRL 7:*** Human systems design fully tested and verified in operational environment with system hardware and software and representative users ***HRL 8:*** Human systems design fully tested, verified, and approved in mission operations, using completed system hardware and software and representative users ***HRL 9:*** System successfully used in operations across the operational envelope with systematic monitoring of human-system performance

Figure 11. Human readiness levels (adapted from ANSI/HFES-400:2021 Table 4-1).

The American National Standards Institute Human Factors and Ergonomics Society recently released a standard, ANSI/HFES-400:2021, on human readiness levels to provide a way to evaluate, track, and communicate the readiness of technology for safe and effective use. The intent of this standard is to provide an equivalence to the established technology readiness levels for effective human-system integration. As seen in Figure 11, there is a one-for-one mapping between technology readiness and human readiness. A primary goal of using ANSI/HFES-400:2021 is to determine the existing human readiness of a proposed technological solution and to ensure that the solution is matured to the point of being operational with accounting for its context of use.

The results of a human readiness assessment in this context provides a way of determining the extent of subsequent HFE technical activities necessary in the downstream engineering phases such as with initial scoping (Section 3.2). The standard is intended to be followed by a trained and experienced HFE practitioner, but it provides a detailed description of assessing human readiness at each level on the scale, including working examples. With all of this guidance, the LWRS Program Plant Modernization Pathway is developing tools to support industry in performing such assessments as described in this section, see Section 0 for additional details.

3.2 Initial Scoping

Initial scoping is the first phase described in the DEG (2021) and is the first phase undergoing any significant digital modification. It includes identifying system(s) or components of interest and planning for the design, testing, and implementation of these system(s) or components. Initial scoping is an engineering phase bounded by a specific modernization effort, such as modernizing the main control room. The direction in which these specific efforts are identified and prioritized is guided from the results of strategic planning, as well as lessons learned from previous engineering efforts (Figure 12). That is, the strategic planning phases gives direction and prioritization of specific digital modernization projects based on their value to the business. Lessons learned from previous projects are also applied to ensure that the strategic objectives can be optimally met without negatively impacting previous modifications and ensuring best practices are considered.

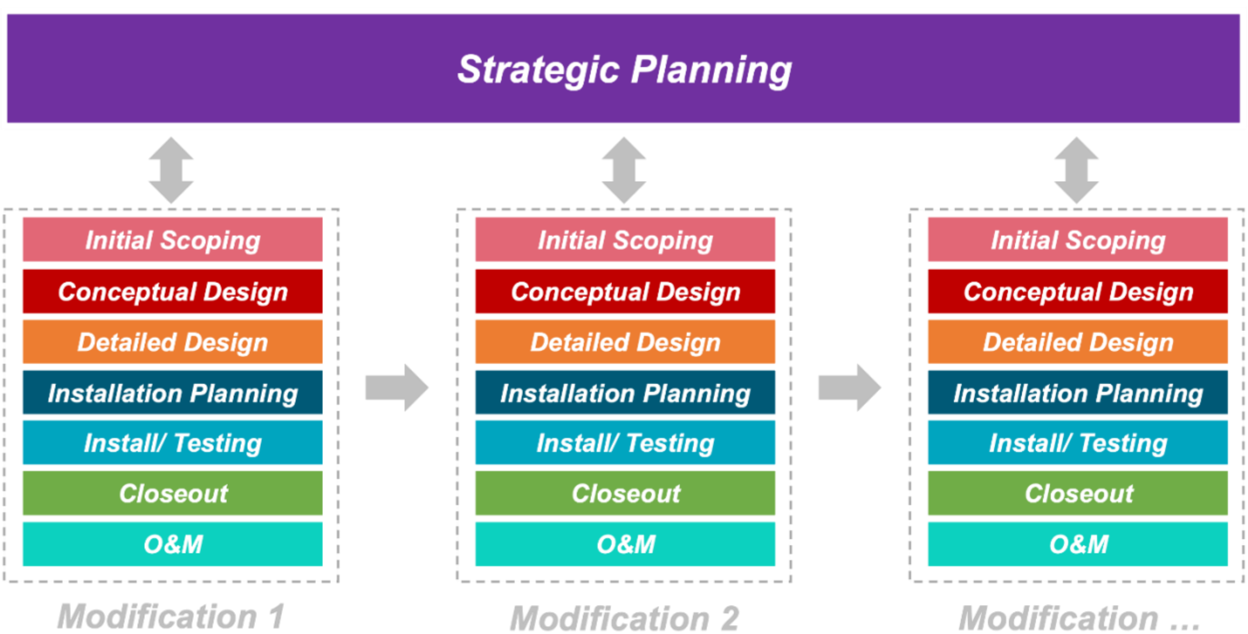


Figure 12. Conceptual relationship of strategic planning to the downstream DEG engineering phases.

The activities within initial scoping that enable considering the outputs of strategic planning and of previous projects entail confirming strategic inputs and risks within ION and its downstream sets of activities (refer to Figure 9), as well as collecting initial operating experience (OE) through HTI. These activities are ultimately used as inputs in developing a migration strategy and implementation plan, encompassing:

- A digital infrastructure strategy (i.e., refer to INL/RPT-21-64580)
- A vision and examined impacts of the existing concept of operations (i.e., refer to INL/RPT-22-70538)
- A data architecture strategy (i.e., refer to INL/RPT-22-70350).

3.3 Conceptual and Detailed Design

There are two complementary phases of design. *Conceptual design* is the first of the two design phases, which is characterized by activities that support the development of high-level requirements for the proposed system. It is important at this phase to identify potential design tradeoffs and design deficiencies when the proposed system is less mature and project costs and risk are lower. Notable engineering activities performed during conceptual design include:

- Performing a detailed operating experience review (OER) of the system work domain and related technologies
- Identifying bounding technical requirements
- Performing a requirements analysis
- Performing hazard analyses of the proposed system
- Performing a function analysis, function allocation, and task analysis of the proposed system
- Evaluating the impacts of the proposed changes to staffing, qualifications, training, and procedures
- Developing an HSI style guide for the proposed system
- Addressing engineering tradeoffs using formative tests and evaluation.

HTI plays a crucial role in conceptual design in ensuring that the hardware, software, and human components are integrated in a way that captures the capabilities of each. INL/EXT-21-64320 provides a detailed description of technical activities that can be performed to ensure an effective integration for safe, reliable, and efficient use. Enabling tools within this guidance includes the use of simulation and modeling techniques to enable early operator-in-the-loop tests and digital human modeling to identify potential design deficiencies using conceptual prototypes of the proposed system.

Detailed design builds from the conceptual design by inheriting the requirements, design specifications, and results from early tests and evaluations to converge the design before installation, testing, and project closeout. The activities utilized in conceptual design may be iterated across detailed design to enable this convergence. It is therefore expected that fewer design deficiencies and tradeoffs are identified during detailed design compared to conceptual design and are generally those that were unable to be addressed earlier on due to the design’s level of maturity. For instance, if a limited scope prototype was used during conceptual design, it is likely that design deficiencies due to the integration of the new system with the existing system could not be tested. Thus, such findings can only be identified when the proposed system is tested in a more integrated manner during detailed design. Together, both conceptual and detailed design activities should yield high confidence that the new system will function as intended, enabling safe and reliable use.

3.4 Installation Planning, Testing, Closeout, and Monitoring

The remaining engineering phases are grouped in this section for brevity; the EPRI DEG (2021) and LWRS Program reports INL/EXT-21-64320 and INL/RPT-23-71395 provide details on these phases. Though, it is noted here that verification and validation (V&V) planning and execution are major activities performed here. V&V provides objective evidence that the installed integrated system accurately implements its requirements and that the system can be used by personnel in a safe and effective manner (EPRI, 2021). The scope of V&V includes focused activities that span across the related subdisciplines described within the DEG (refer to Figure 8). Within the domain of HTI, V&V has significant implications from both project and regulatory perspectives (NUREG-0711, 2012).

According to the U.S. NRC NUREG-0711 (2012) guidance, V&V serves to comprehensively determine that the HFE design confirms to design principles and enables users to safely perform their tasks while meeting operational goals. V&V includes the subactivities shown in (Figure 13), which are summarized in Table 1.

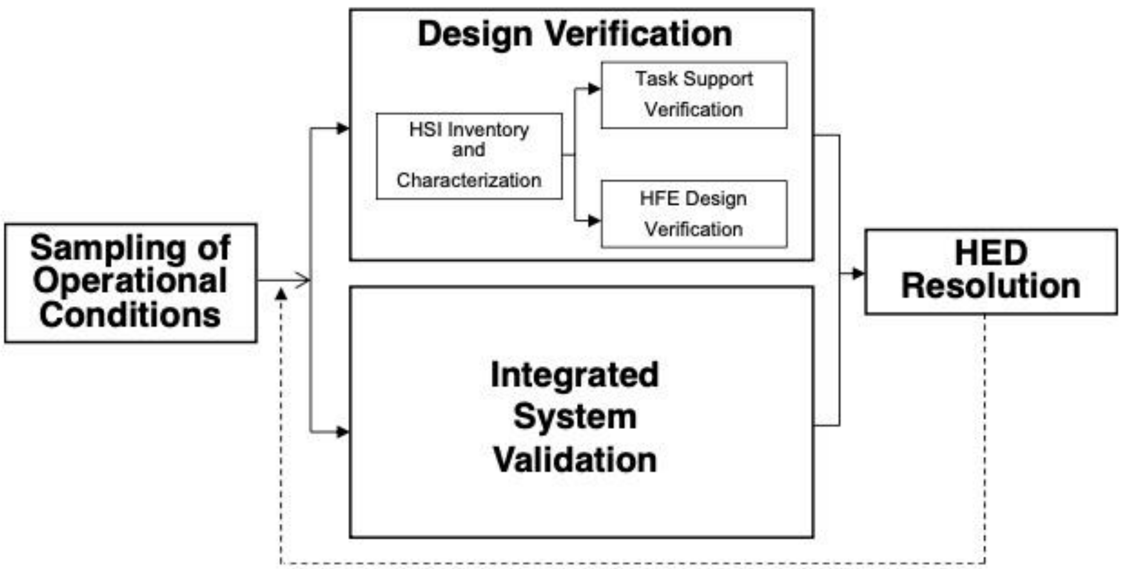


Figure 13. Overview of V&V activities (adapted from NUREG-0711, 2012).

Table 1. Summary of HFE V&V activities described in NUREG-0711 (2012).

Subactivity	**Description**	**NUREG-0711 (2012) Section**
Sampling of Operational Conditions	To identify a sample of operational conditions that comprise conditions representative of the types of events that could occur during plant operation. To include operational conditions that reflect characteristics that are expected to contribute to the system's performance. To consider the safety significance of the HSIs.	Section 11.4.1
Design Verification (HSI Inventory and Characterization)	To accurately describe all HSI displays, controls, and related equipment within the scope as defined by the operational conditions.	Section 11.4.2.1
Design Verification (Task Support Verification)	To ensure that the HSIs provide the needed alarms, information, controls, and task support for personnel (users) to complete their tasks.	Section 11.4.2.2
Design Verification (HFE Design Verification)	To ensure that the HSIs are designed with accounting for peoples' capabilities and limitations through the conformance of HFE guidelines such as NUREG-0700 (2020).	Section 11.4.2.3
Integrated System Validation (ISV)	To validate, using performance-based tests, that the integrated system (i.e., including hardware, software, procedures, and people) can perform their tasks to operate the plant safely through the range of operational conditions identified.	Section 11.4.3
Human Engineering Discrepancy (HED) Resolution	To identify and disposition HEDs through all V&V activities. The scope of this subactivity entails determining which of those HEDs require correction (i.e., those with direct safety consequences) and tracking that these HEDs are corrected prior to installation.	Section 11.4.4

4. HUMAN AND TECHNOLOGY INTEGRATION

This section describes the LWRS Program HTI research area, including its objectives, scope, and the HTI methodology described in INL/EXT-21-64320 that has been demonstrated across key industry collaborations as discussed in Section 5.

4.1 Objectives and Scope

HTI ensures the safe, reliable, and efficient use (i.e., jointly optimizing PTPG) of innovative technologies introduced to an existing nuclear power plant. This section expands on the objectives and scope of HTI.

4.1.1 Focusing on Safety, Reliability, and Joint Optimization

The HTI objectives are to ensure that proposed innovations (i.e., identified through ION and other modernization scoping efforts) can be safely and reliably used while also maximizing efficiencies by accounting for the impacts to PTPG (referred to as *joint optimization*). The way in which HTI achieves these objectives is by following a *graded approach* in evaluating the impacted functions and tasks posed by the modification. That is, HTI applies HFE principles and methods, discussed in Section 4.2, across the lifespan of a major digital modification to the impacted functions and tasks of interest. Because the breadth of impacted functions and tasks can be large, the graded approach ensures that particular focus is given to those of high relevance to plant safety, personnel safety, or economic risk (e.g., plant availability), as illustrated in Figure 14.

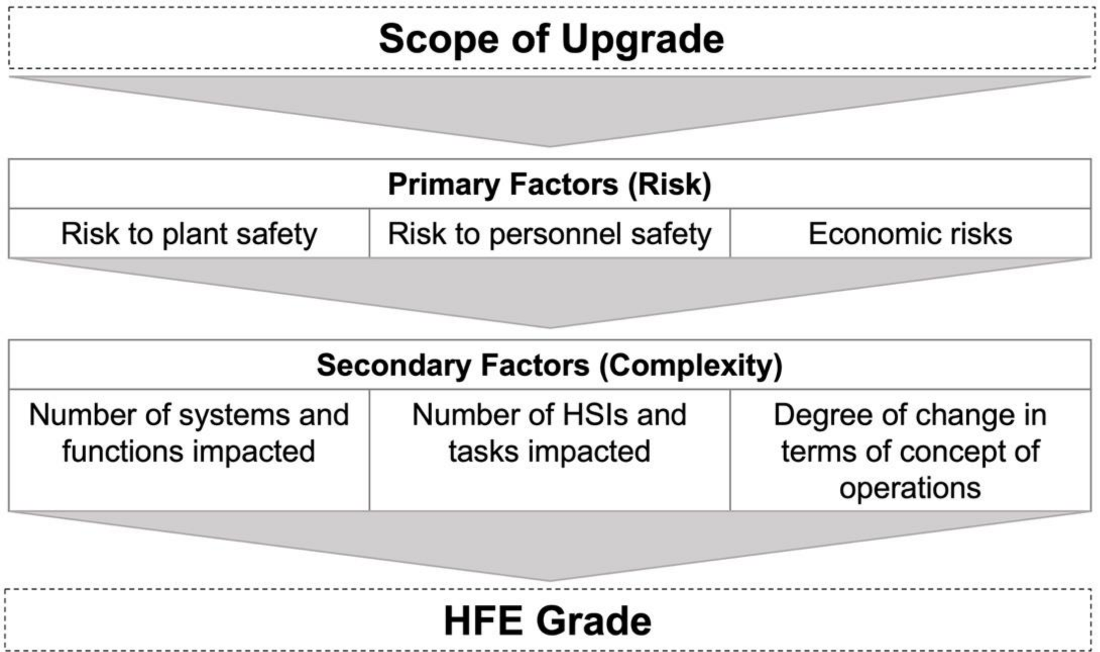


Figure 14. HFE grading considerations (adapted from INL/RPT-22-70538).

Further, the extent of change posed by the innovations or digital modifications may range from narrowly changing the way work is performed at a plant today to significant changes to PTPG that transform the processes in place to perform work. As seen in Figure 14, the graded approach addresses the latter (referred to as complexity) to ensure that the highest priority is given to the impacted functions and tasks of greatest risk and entail the most complex changes to work.

4.1.2 Addressing Macro- and Microlevel Considerations

To comprehensively address the HTI element in digital transformation, both a macro- and microlevel approach is needed. Within HFE, the subdiscipline of *macroergonomics* is used to address the former while traditional HFE (often referred to as *microergonomics*) is used to address the latter (Hendrick and Kleiner, 2001). Both approaches are complementary to each other and can be conceptualized as shown in Figure 15.

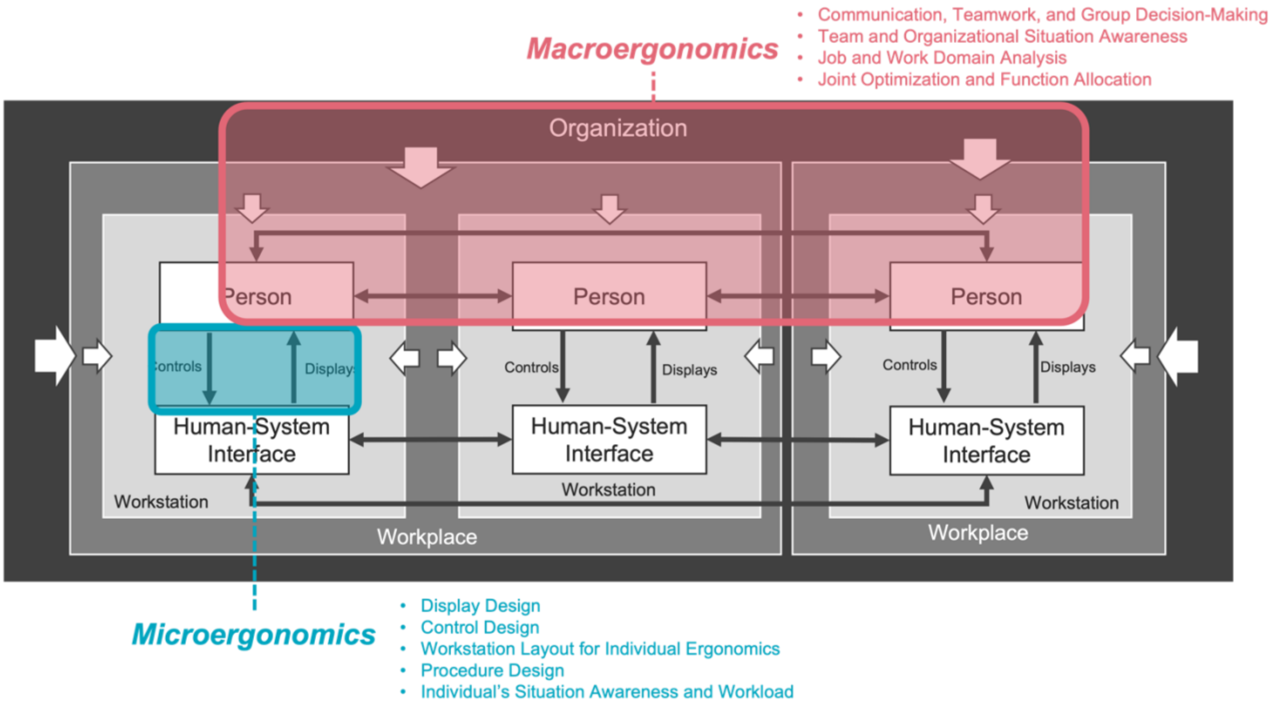


Figure 15. Addressing macro- and microlevel considerations for HTI.

Starting in the center (teal region), traditional HFE focuses on the interaction between the person and the HSIs. This interaction refers to HFE design guidance related to the identifying and formatting of information presented on the display (i.e., also including procedures). Further, the selection of controls (both hardwired and available via software) is considered based on the plant equipment being manipulated and the nature of the task performed by the individual. Concerns related to an individual's situation awareness and workload are of focus within the microergonomics approach. The use of HFE design guidelines such as NUREG-0700 (2002) pertaining to the placement and design of displays and controls are used in combination with traditional HFE methods like usability testing, individual task analysis, and workload and situation awareness assessments.

Moving outward within the salmon-colored region of Figure 15, macroergonomics is applied. Macroergonomics expands the focus of HFE beyond the individual in understanding how technology affects organizational performance, teamwork and coordination, and the overall design of the work system beyond a single user. Aspects of crew and team coordination, decision-making, and communication are examined within the workplace and across workplaces of the organization; thus, HFE methods like task analysis are expanded to enable a joint optimization of the PTPG necessary to perform work. Both macro- and microaspects of work should be addressed to comprehensively ensure safe and reliable use that also takes advantage of new technologies to enable people to perform work in a way that is cost effective. An example of how both macro- and microergonomics are used is illustrated in Figure 16, which was used in support of one of the key industry collaborations elaborated on in Section 5.1.

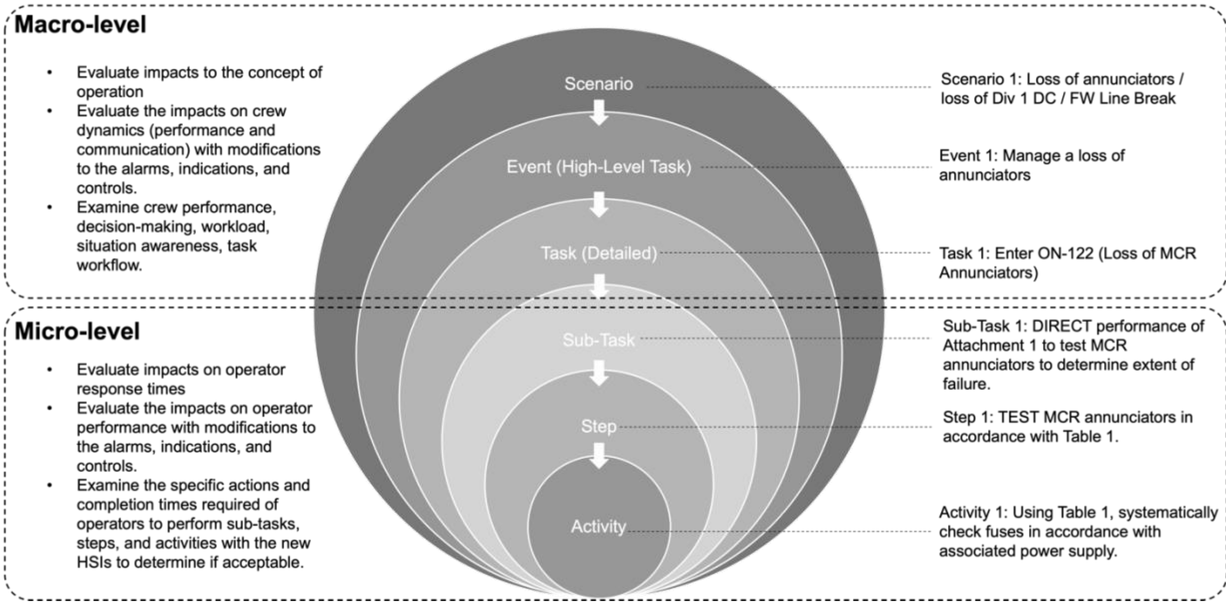


Figure 16. Decomposition of tasks for performing task analysis (adapted from INL/RPT-22-68472).

It is worth noting here that, while there was high focus on evaluating the specific interactions and impacts to workload of the manual operator actions under study (microergonomics) concerning the use of the new safety and nonsafety HSIs, the overall impact of the new HSIs on crew performance, decision-making, and team situation awareness was examined to understand how the new HSIs impacted the current concept of operation. Thus, a scenario-based approach was used and macroergonomic considerations related to crew performance could be evaluated through these scenarios. Also, within these scenarios, the manual operator actions under study could be evaluated in detail to ensure that the HSIs did not negatively impact an operator's ability to safely control the plant.

4.1.3 Enabling Tenets

The following are pertinent overarching principles (referred to here as enabling tenets) to the planning and execution of the methodology described in Section 4.2. Because HTI should be graded and scaled according to the scope of the digital modification and project circumstances, these tenets can ensure that HTI is being adequately addressed in a consistent and systematic manner.

Tenet 1. **Moves toward a transformative "new state" and concept of operations.** The "new state vision" refers to the specification of both the characteristics of new systems being implemented and the effects that the modifications have on the concept of operation (i.e., the way in which the plant is operated, as well as maintained and supported). The new vision should follow the design tenets described under the digital infrastructure, namely being informed through the tenets of ION and following a digital infrastructure framework that ensures the "new state" is not the "end state," meaning that it can be expanded to support future innovations and capabilities and provide a means of periodic refresh in a cost-effective manner (see Digital Infrastructure Tenets 1–12 in INL/EXT-21-64580). HTI should be expanded across all levels of the digital infrastructure (see Figure 17). Thus, HTI focuses on ensuring that the HSIs across these levels of the infrastructure support the needs of the users to perform their jobs and tasks, as well as ensuring that the HSIs provide a consistent experience across the enterprise by applying HFE design principles (Tenet 5) to the visual design and navigation of the HSIs in use.

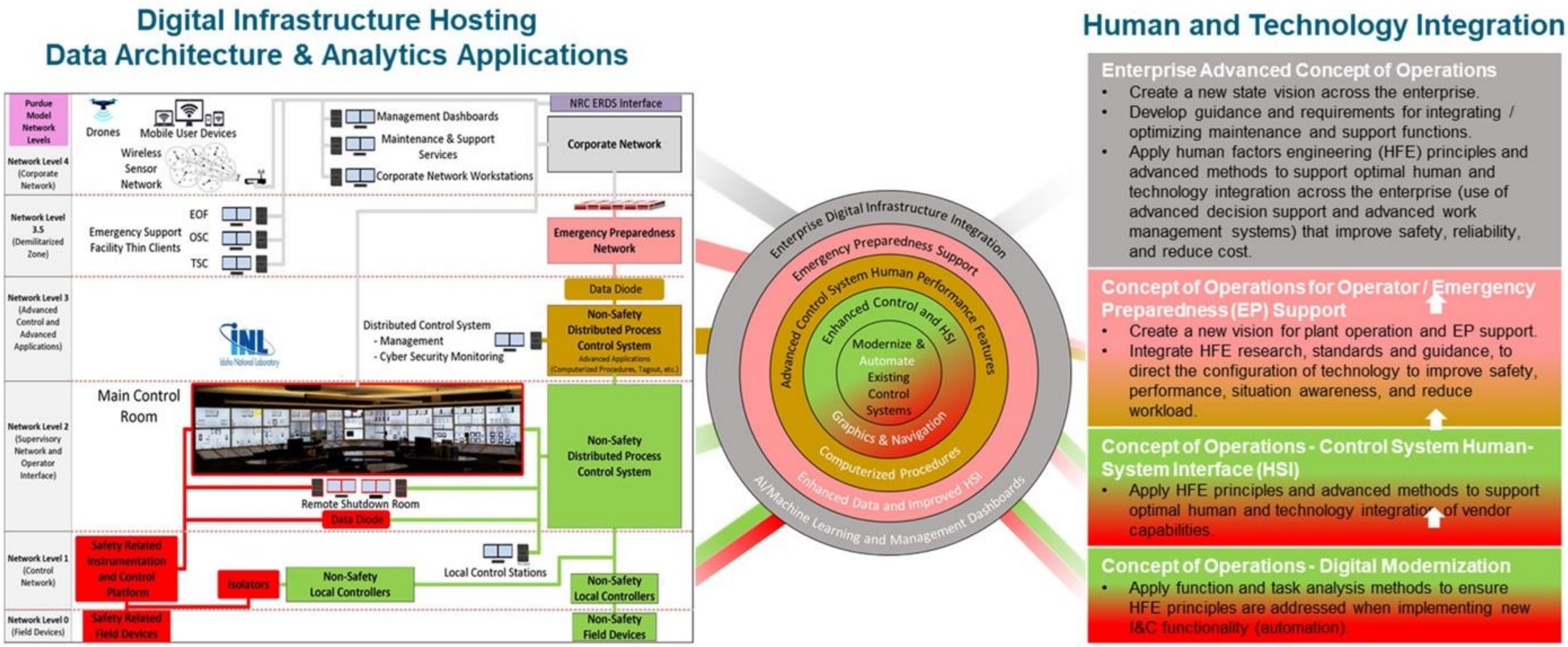


Figure 17. Intersection of digital infrastructure and HTI.

Tenet 2. **Applies a multidisciplinary approach.** To effectively execute HTI in a larger project that incorporates user needs (Tenet 3) with other important project considerations, such as technical feasibility, cost, and regulatory requirements, a multidisciplinary team is needed early and throughout the project.

a. Planned HTI activities, such as those defined in the HFE program (Tenet 4), should identify key stakeholders in the planned HFE and HTI activities and major milestones. Stakeholders should broadly account for senior management, operations, training, engineering, and licensing, among other technical disciplines that are central to the scope.
b. A clear division of responsibility must be made for identified stakeholders for effective collaboration within the scope, budget, and schedule of the project. To this end, a general approach is to have subteams with distinct responsibilities. Refer to Section 5.1 for an illustration of how subteams were utilized.

Tenet 3. **Follows a holistic user needs approach.** A fundamental component of HTI is to develop work systems that follows a human centered (needs based) approach. Such an approach identifies the goals of the business and objectives of the work domain. HTI then performs systematic analyses of the work performed under these domains to support the business, which includes identifying the role(s) of each staff member, their jobs, and tasks required of them to perform work. HTI considers the interplay between the organization, job requirements (i.e., including task and information needs), technology used, environment to which work is performed, and communication and coordination between staff and intelligent agents to accomplish work. This interplay is considered the *context of use* and is used to define the needs of the user(s) of the work system. This aspect of HTI spans micro- and macrolevel considerations (refer to Section 4.1.2) and is fundamental throughout the project lifecycle and is applied with consideration of human-centered design principles (Tenet 5).

Tenet 4. **Executes a strategic HFE program plan.** This tenet ensures that an integrated and comprehensive HFE strategy (i.e., herein referred to as the HFE program) is in place. The HFE program should cover the lifecycle of upgrades, enable a graded approach, and ensure the safe and reliable operation of the plant; it also may be applied to support joint optimization between people and technology to improve existing work and processes in work domains beyond the command and control of the plant. The HFE program should therefore address the following considerations adapted from NUREG-0711:

a. *The goals and scope of the program.*
    i. The program should describe its goals, or objectives, in human-centered terms. These terms include identifying key HFE performance goals that the program focuses on meeting. These objectives should therefore include: reducing human error traps, optimizing workload levels, improving situation awareness (individually and organizationally), improving confidence in decision-making, reducing training burden, improving team communication and coordination, and improving the overall usability and efficiency of the work performed by plant staff.
    ii. Assumptions and constraints should be identified and help support bounding the program; this includes identifying any changes to staffing levels (i.e., such as through ION) or uses of new advanced technologies. In this case, the development of the new vision and concept of operations should inform how work is performed now, and how the vision and new concept of operations will change the way work will be performed upon realization.
    iii. The program should specify a clear duration that should be considered throughout the lifecycle of the project, including initial scoping, conceptual and detailed design, and implementation and monitoring.

iv. The program should be applied to the main control room, remote shutdown facility, technical support center, emergency operations facility, and local control stations. It may also extend beyond these facilities (i.e., such as in other work domains identified through ION), following a graded approach to support good engineering practices.
v. The program should address aspects of the HSI, procedures, and training program in place. Within the training program, the program should (at a minimum) incorporate staff identified in 10 CFR 50.120: instrument and control technicians, electrical maintenance personnel, mechanical maintenance personnel, radiological protection technicians, chemistry technicians, engineering support personnel, and other staff who perform safety-related tasks.
vi. Impacted plant personnel should be identified, including licensed operations (per 10 CFR 55) and others identified to be impacted by the project.
vii. The program should address the potential effects of a modification on staff performance. The anticipated impacts on the concept of operations in developing the vision and new concept of operations may be used as an input.
viii. The program should follow a user-centered approach such that identified plant staff are involved through the project to provide their perspectives and evaluation of the proposed changes.

b. *HFE Team and organization.*
   i. The primary organization responsible for the program should be defined. This includes defining the team members and their responsibilities and their organizational placement and authority. The program should describe team's composition including level of expertise in HFE, engineering, and other critical domains identified.

c. *HFE and HTI process and procedures.*
   i. The program should include a process to enable the team to execute its responsibilities. The process should provide procedures to enable the assignment of HFE activities to team members, support program and project management making design decisions, ensure the traceability and configuration control of design decisions, and perform HFE reviews.
   ii. The process and procedures should be integrated in other plant design activities. For instance, the process in place should enable the results of planned HFE activities to serve as input into subsequent design and engineering activities for the project. Major project milestones (e.g., factory acceptance testing, submission of a license amendment request) should be identified and incorporated into the integration to link the results generated by the program and the project at large.
   iii. The HFE activities performed as part of its established process should generate documentation (i.e., result summary reports), particularly for aspects of the project that necessitate NRC staff review.

d. *Issue tracking.*
   i. The program should include a tracking system to enable a systematic means for managing HFE issues identified throughout the lifecycle of the project.

e. *Technical HFE activities.*
   i. Technical HFE activities such as the elements described in NUREG-0711 Revision 3 (i.e., OER, function analysis and allocation [FA&A], task analysis, etc.) should be described in terms of their applicability and status across the project.
   ii. A graded approach should be considered in determining the applicability and extent of performing HFE activities. A clear basis should be given for activities determined not applicable. If the project is executed in distinct phases, the grading

should account for the specific scope and extent of modernization for the given phase.

iii. The planning and execution of identified HFE activities should be tied to the developed program process and be linked to the larger project schedule and associated major milestones.

iv. Applicable standards should be identified as they apply to the HFE technical activities performed.

v. Key facilities (e.g., such as the use of a simulator facility) should be identified where used in applicable HFE activities.

Tenet 5. **Uses HFE standards and design principles.** Design principles identified from common standards and guidelines like NUREG-0700 (2002) are applied in combination with HFE technical activities to arrive at design solutions that balance user needs with HFE design guidance. A key product of this is an HSI style guide. The HSI style guide provides the "blueprint" of key design components for the design and functionality of the HSIs used to perform work and ensure consistency across applications and platforms. It should be informed through a combination of the application's native capabilities, technical lessons learned from HFE activities (from the program plan), and use of design principles. This is reflected in Figure 18, to which the platforms (in green) can be extended beyond the control system and into specific business applications across the corporate network, as reflected in Figure 6.

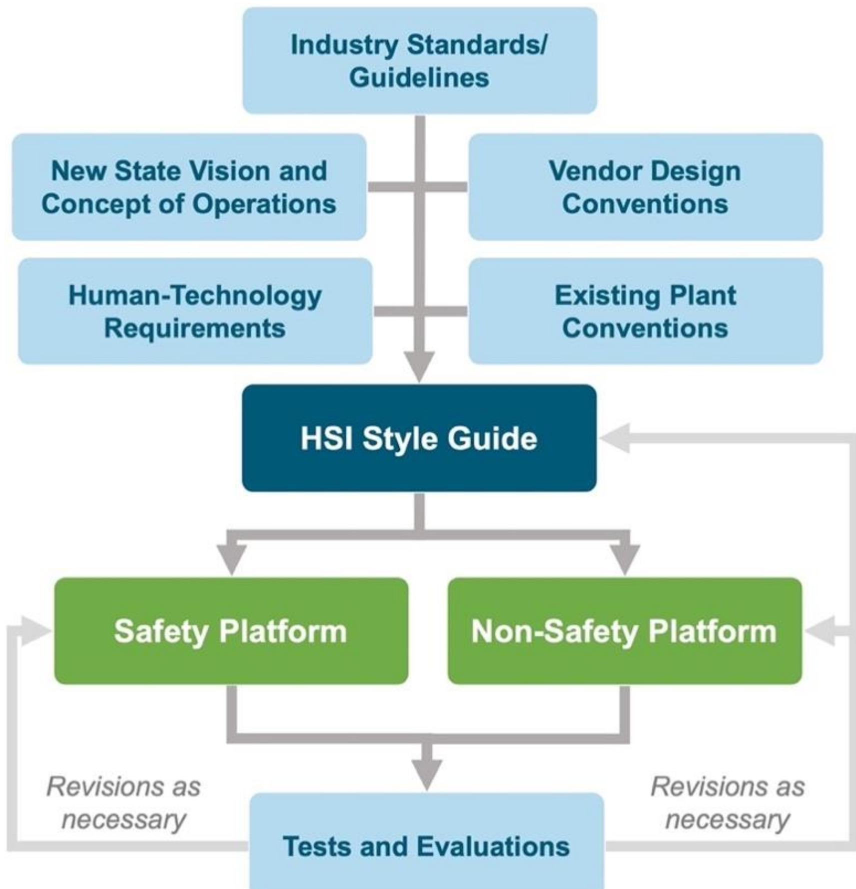


Figure 18. Application of the HSI style guide (adapted from INL/RPT-23-71395).

4.2 Human and Technology Integration Methodology

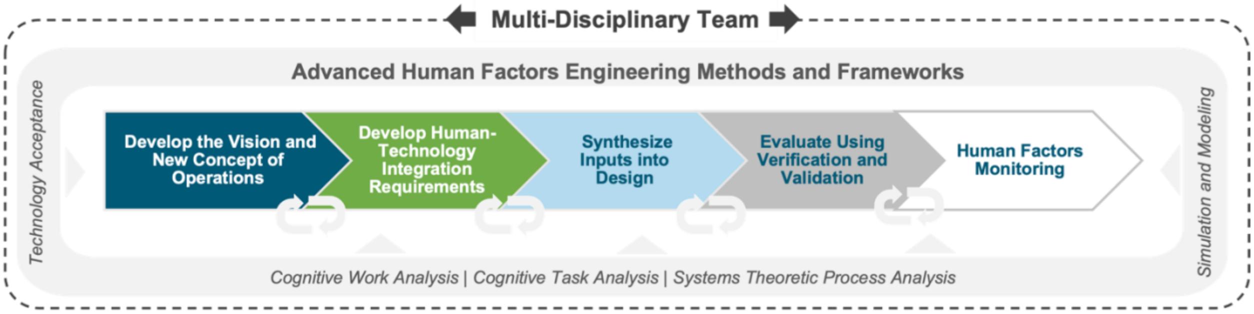


Figure 19. HTI methodology (adapted from INL/EXT-21-64320).

The HTI methodology (Figure 19) was developed by the LWRS Program, and elements of the method have been demonstrated with two U.S. nuclear power plant utilities as a part of their large-scale digital modification plan. Currently, the work between utilities is ongoing and guidance is continuing to be applied. Additional information is available in INL/EXT-21-64320 (2021), INL/RPT-22-68472 (2022), and INL/RPT-22-70538 (2022).

First, the HTI methodology is used to build on industry standards and is intended for industry to use for adopting advanced digital I&C technologies. Secondly, HTI guidance emphasizes both early and iterative HFE involvement. Figure 19 shows a linear phase process from left to right across the colored phases. However, the progression from each of the phases may be iterative, allowing earlier phases to be revisited at any point in time. Utilities are not limited by which HTI they begin with and may choose to start with later phases and then revisit earlier HTI phases.

Third, the methodology is intended to be used with cross-functional multidisciplinary teams to ensure that project stakeholders' input is received throughout the project. Multidisciplinary teams may consist of HFE, operations, management, engineering, training, and other key stakeholders in the project. Having a multidisciplinary team helps to prevent unnecessary rework and address project needs on a regular basis. Fourth, the methodology uses a graded approach to help ensure that the project receives the proper level of rigor applied to the project, such as evaluating risks and the level of project complexity. Using a graded approach helps to ensure that the proper resources are utilized correctly without overburdening the scope, schedule, or project budget.

Fifth, advanced techniques are leveraged throughout the project, such as simulation, modeling, and HFE methodologies, to inform the requirements for new digital technology being integrated into the plant. The following sections will highlight some of the important activities of the five phases along with other HTI goals of processes used for successful HTI. All the phases build on each other, and each phase employs feedback loops into the design to inform and bound the design.

5. INDUSTRY DEMONSTRATIONS

5.1 Implementation of Digital Safety-Related Upgrades

Most U.S. LWRs utilize original I&C safety systems. These systems are safe and reliable but are becoming prohibitively costly to maintain due to obsolescence issues (Hunton et al., 2021). A collaboration between CEG and the U.S. DOE LWRS Program was recently established to engage in a first-of-a-kind safety-related digital I&C system upgrade. This effort demonstrates the viability of completing a major digital modification to an LWR I&C safety system and serves as a roadmap for performing such significant modifications in the United States. The scope of this project entails implementing safety and nonsafety I&C into a U.S. boiling-water reactor plant (Hunton et al., 2021).

This work has been documented in previous work samples, generating industry lessons learned. The following are publicly available technical reports and publications available at the time of this report:

Broader I&C Aspects of the Projects

- **INL/EXT-20-59809**—Safety-Related Instrumentation & Control Pilot Upgrade Initial Scoping Phase Implementation Report and Lessons Learned
- **INL/RPT-23-72105**—Safety-Related Instrumentation and Control Pilot Upgrade: Conceptual - Detailed Design Phase Report and Lessons Learned
- "Safety-Related Instrumentation and Control Pilot Upgrade: Initial Scoping Phase Implementation and Lessons Learned" in Nuclear Technology.

HTI and HFE

- **INL/RPT-22-68472**—Demonstration and Evaluation of the Human-Technology Integration Function Allocation Methodology
- **INL/RPT-23-71395**—Demonstration of the Human and Technology Integration Guidance for the Design of Plant-Specific Advanced Automation and Data Visualization Techniques

A summary of previously completed activities related to HTI is given next, following the recently completed preliminary validation effort. It is expected that the summary of previously completed activities should provide enough context to understand how the recently completed activities fit within the larger scope of the project. However, the reader may refer to the technical reports listed above for more details.

5.1.1 Previously Completed Activities

Previously completed HTI activities in support of CEG's safety-related digital upgrades are summarized below.

5.1.1.1 Human Factors Engineering Program Management

The HFE program management plan was developed to support HFE activities in the safety-related pilot project and cover the applications of current and new HSIs impacted by the project upgrades. The intent of the HFE program management plan is to support the currently planned and future upgrades by applying an HFE graded approach. The graded approach to the HFE plan enables a scalable approach for applying HFE to future projects based on safety risks and the complexity of the planned upgrade. The HFE program management plan helps to ensure that the HFE activities scoped across the project are complete, within reason, and address safety and risk criteria during license submittals. NUREG-0711 guidance is used with the HFE program management plan to ensure that elements and activities performed are dispositioned with justification throughout the project lifecycle.

5.1.1.2 Operating Experience Review

An HFE OER methodology was applied based on the NUREG-0711, Rev. 3 review criteria (2012), EPRI 3002004310 (2015), and the results and process used to perform OE reviews with previous utilities. HTI and HFE researchers collected detailed OE related to the proposed safety-related I&C upgrade design based on existing and human performance issues. A workshop conducted in the plant training a simulation facility was used to capture additional OE to identify potential issues. OE was also collected from operator surveys and observations of scenarios based on the safety-related upgrade to understand how current and future tasks will function.

The objectives of acquiring OE information are relevant to evaluate the potential impact on design and operational considerations and to make it available for further HFE analysis activities. Information based on HFE-related safety, availability, events, issues, and information on past operational performance along with similar inputs from various U.S. nuclear power plants was included in the OER. The OER is used to track and address potential and existing human issues early and throughout the project to prevent issues from being overlooked. The OER results have used to address potential issues throughout the project as part of the HFE program management plan.

5.1.1.3 Function Analysis and Allocation

A FA&A workshop was completed as part of HFE activities to identify and allocate responsibilities for changes to plant control functions and to improve safety and availability while also accounting for strengths and limitations of both humans and automation. Inputs to the function analysis included the project scope through preliminary design documents, new state vision vendor capabilities, OER, concept of operations, and the tasks impacted by the upgrade. Scenarios were identified and used to identify where operator tasks were expected to change. The scenarios also provided opportunities to identify potential human errors when changing from manual to shared or automatic functions, increased workload, changes to operator roles and responsibilities and opportunities for improved safety and economic performance.

The FA&A workshop was performed at the plant training simulator with qualified main control room crews. The human factors engineers recorded and documented observations in real time and completed surveys and interviews with operators upon the completion of each scenario. The findings from the FA&A workshop were used as input into future workshops to find the operational difficulties, key decisions made, and impacts of the modifications of each scenario.

5.1.1.4 Task Analysis

The task analysis workshop was used to examine the functions assigned to plant personnel to achieve successful performance as well as additional information needed to support development of HSIs, procedure modifications, and training for plant personnel. The task analysis method used for the workshop consisted of a series of walkthroughs during nine scenarios in the Idaho National Laboratory Human-Systems Simulation Laboratory (HSSL) simulator testbed. Two operators performed the scenarios, and other key stakeholders were available to support the workshop during the post-scenario discussions. Operators, researchers, and key stakeholders participated in design reviews, and operators provided comments and feedback based on their plant OE throughout the workshop.

5.1.1.5 Impacts to Staffing and Qualification

Impacts to staffing and qualification requirements at the site were evaluated based on the results of previous HFE activities performed during the conceptual design phase. Results from the FA&A, task analysis workshops, and OER indicated that there were no fundamental impacts to the staffing and qualification requirements in the main control room. No changes to required staffing levels or basic qualifications were found to be within the scope of the project.

5.1.1.6 Treatment of Important Human Actions

Important human actions were evaluated with initial screenings used to determine the extent of potential HFE impacts. Credited tasks were identified using key documentation from the utility, including the final safety analysis report, the defense in depth and diversity analysis, and the probabilistic risk analysis (i.e., these were defined as Level 1 tasks). Credited tasks were assigned different priority levels based on risk levels. Level 1 priority tasks were tasks not being automated without manual override or having a high potential for nuclear safety or economic impacts. Priority 2 tasks were automated tasks that do not require manual override and uncredited tasks that have medium potential nuclear safety risks or economic impacts. The treatment of these Level 1 important human actions was reflected across the HFE activities described in the HFE program plan. For instance, these Level 1 tasks were analyzed at a microlevel (refer to Figure 16) in support of task analysis during conceptual verification (Section 5.1.1.9) and preliminary validation (Section 5.1.2.1).

5.1.1.7 Human-System Interface Style Guide Development

The HSI style guide was developed to provide specific guidance and recommendations for creating new and modified HSIs for the project. The style guide helps to ensure consistency across the HSIs across the safety and nonsafety displays and included guidelines and recommendations from NUREG-0700 (2002), existing plant conventions, industry standards and guidelines vendor standard features and functions, and the new state vision and concept of operations. The style guide covers several pertinent topics such as designs for soft controls for touch interaction, color and labeling, display fonts and symbols, information architecture, navigation structure, and formatting of information on display pages. The style guide was informed throughout the conceptual design HFE activities, including the task analysis workshop. Feedback from the task analysis workshop between vendor conventions and the current plant conventions was added into the style guide to support further design efforts for additional workshops.

5.1.1.8 Review Impacts to Procedures and Training

The engineering and design team was responsible for reviewing impacts to procedures and training to enable plant operations. Scenarios were reviewed prior to and during the conceptual verification workshop to enable the use of the HSI displays. The modified procedures were used to:

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

5.1.1.9 Conceptual Verification

Conceptual verification was performed as part of the HSI design to verify that the HSIs being developed along with the procedure changes were progressing to the future V&V activities, preliminary validation, and ISV. Conceptual verification was used as an extension of the FA&A and task analysis workshops to evaluate the important impacted human actions for the safety and nonsafety systems. The conceptual verification workshop was used to present the HSI displays in a limited fidelity to walk through scenarios with operators. A scenario-based approach was used to perform the conceptual verification workshop, by further refining the results from the FA&A and task analysis workshops. The impacted important human actions were evaluated to ensure that the actions would be able to be completed within the time available.

OSDs were developed based on Level 1 manual actions. Level 1 tasks identified in the OSDs were evaluated to determine whether other tasks would have impacted the operators' abilities to accurately and reliably complete Level 1 manual actions successfully. The temporal OSD was developed and used to present the sequence of interactions between the controls and actions the operating crew would need to perform for each Level 1 action. Sequences of actions were presented from top to bottom from the action start through completion. The OSDs were used by the HFE Team to construct timelines for analysis to ensure that the manual actions would be reliably performed within the available time.

Operators during the conceptual verification workshop performed walkthroughs of each scenario and used a think-aloud protocol verbalizing their intended actions and provided feedback on the HSIs and procedures. The conceptual verification workshop was completed in a part-task simulator at Idaho National Laboratory. The prototype fidelity was static in nature; however, navigation on the HSIs was available for the operator to use on both safety and nonsafety HSIs. The conceptual verification results identified several design improvements for the HSIs and procedures to perform Level 1 manual actions successfully in the time available. The results from the conceptual verification workshop were used as input to the planning of further V&V activities.

5.1.2 Recently Completed Activities

Recently completed HTI activities in support of CEG's safety-related digital upgrades entails the completion of preliminary validation.

5.1.2.1 Preliminary Validation

The primary objective of preliminary validation was to provide high confidence that the time required for credited manual operator actions impacted by this upgrade satisfy the success acceptance criteria for ISV using HSIs developed for the project, along with associated procedure changes. Preliminary validation was performed in accordance with the HFE program plan and previous HFE activities completed for the project (refer to Section 5.1.1), as well as U.S. NRC "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition" Chapter 18 Attachment A (2016). Further, a second objective of preliminary validation was to comprehensively evaluate human actions beyond the impacted credited manual actions regarding the usability of the proposed HSIs and modified procedures in performing these tasks, ensuring overall crew situation awareness, and enabling effective teamwork and coordination (i.e., addressing the macrolevel considerations, such as those referred to in Section 4.1.2).

Both objectives were addressed by developing specific scenarios that provided maximum coverage of the impacted tasks and impacted credited manual operator actions. These scenarios were identified by the design team from earlier HFE activities (refer to 5.1.1) and carried through to preliminary validation. This scenario-based approach was used to better represent situations that operators are presented with during training and evaluation simulator drills where multiple, unlikely, and potentially challenging failures can occur. The scenarios enabled evaluations of the operator's ability to perform the manual actions under study in circumstances with increased scenario complexity to frame the specific manual action under evaluation in that situational context. Additional actions beyond the manual actions under study could be evaluated in terms of how the proposed HSIs and modified procedures impacted overall crew performance, at a macrolevel. To emphasize, this approach was done as "good engineering practice" and not to have the study of additional manual actions identified outside the licensing basis or the use of these "more challenging" scenarios alter the licensing basis for the site in any way.

The following subsections outline key elements of this activity, including the preliminary validation methodology, and highlight important lessons learned as appropriate throughout.

Use of Independent Teams

The early involvement of a multidisciplinary team enabled the timely execution of HFE activities for the project leading up to and through preliminary validation. The team enabled effectively identifying scenarios, designing early concepts, and identifying key design tradeoffs, as well as addressing logistical considerations with implementing a simulator integration strategy leading into preliminary validation. For the project, different disciplines were included from operations and training, licensing, engineering, the vendor, and HFE. These disciplines were grouped into four independent teams, listed in Table 2. Each team had a clear division of responsibility and role to support for the project.

Table 2. Example team composition and division of responsibility.

Team Name	Team Role(s)	Team Composition
HSI Design and Procedure Modification Team	To create the HSI design concepts to produce design inputs. To then iterate and refine the design of the HSIs to conform to those inputs and established HFE principles. To identify and propose procedural changes to enable plant operation with the new digital I&C.	Site engineering and operations personnel with significant knowledge of: The legacy plant I&C and HSIs being upgraded. Plant operations (or relevant subject matter experts [SMEs]). Use of existing operating procedures. Vendor staff who have a significant understanding of the capabilities of the selected platforms.

Team Name	Team Role(s)	Team Composition
HFE Process Team	To ensure that the project establishes and then executes the HFE activities described in the HFE program plan.	Staff with significant knowledge of HFE and experience applying HFE in main control room modernization.
HSI and Procedure Validation Team	To evaluate whether the modified HSIs and procedures acceptably promote plant operation.	The ultimate "end users" of the HSIs and procedures being developed, including qualified and licensed operations personnel from the site.
Simulator Team	To support integration of the simulator and HSI concepts to enable interactive capabilities in an immersive simulator environment. To run the simulator during HFE activities and assess the ability of the operators to use the upgraded HSIs.	A combination of simulator engineering personnel and site simulator training personnel.

Inputs to Preliminary Validation

Preliminary validation is the second iteration shown in blue in Figure 20 (Pass 2). The steps leading into preliminary validation (i.e., as shown in Figure 20), serving as inputs, are summarized below. A crosswalk of key HTI guidance documents are listed to the side; hence, sections from NUREG-0711 (2012) relevant to the HFE activity applied for the project are provided, as well as the HTI process described in INL/EXT-21-64320. Design guidance from NUREG-0700 (2002) is also listed appropriately.

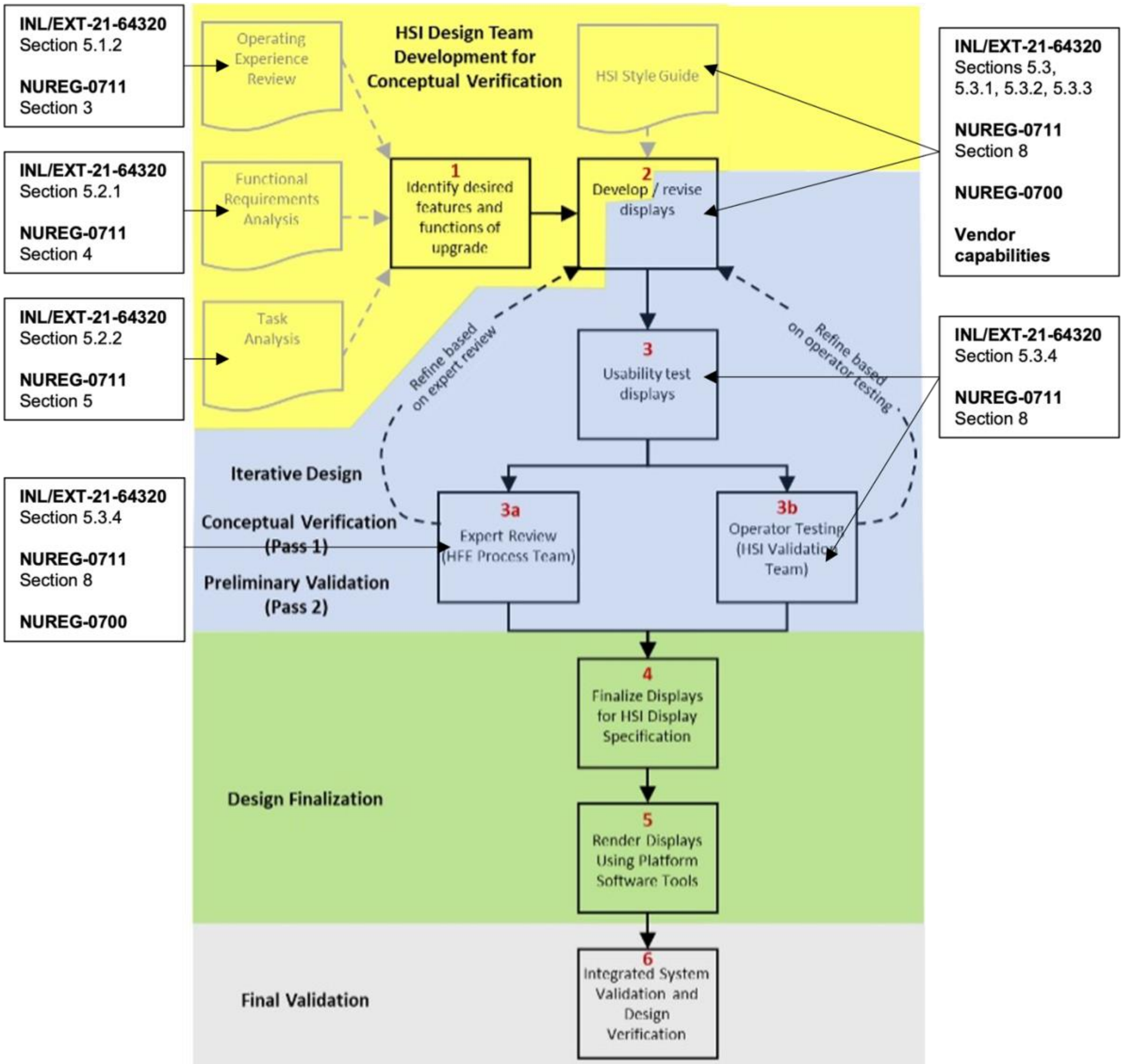


Figure 20. Iterative process used for preliminary validation (adapted and enhanced from INL/RPT-23-71395).

Step 1. Identify Desired Features and Functions of the Upgrade.

Desired features and functions of the new HSIs were identified through the HFE technical activities described in Section 5.1.1—notably including the findings related to the design of the new HSIs (including information requirements, automation enhancements, and other task considerations such as updates to procedures) out of the OER, FA&A, and task analysis activities.

Step 2. Develop and Revise Displays.

The desired features and functions are used by the HSI Design and Procedure Modification Team to develop (and revise through iteration) HSI displays. The initial development of the HSI displays is shown in yellow in Figure 20. These HSIs are developed using inputs from Step 1, the HSI style guide, and subsequent tests and evaluations, as shown as the passes in Step 3. As the HSI displays are iteratively created, evaluated, and refined, they become the input used by the vendor to develop production HSIs (Steps 4 and 5).

Step 3 (Iteration 1). Usability Test Displays.

The HSI displays developed in Step 2 are evaluated for usability (i.e., safe, reliable, and efficient use). This is shown in blue in Figure 20 as an iterative process. This evaluation has two fundamental components: expert review and operating testing.

Step 3a. Expert Review.

Expert review is the process where HFE subject matter experts (SMEs) from the HFE Process Team review the HSIs using a combination of expert experience, established design guidance like NUREG-0700 (2002), and HFE principles. The HSI style guide is used to incorporate these criteria, specific to the HSI displays in question, as the HFE SME reviews guidance from the style guide for compliance. Representative aspects included in this review entail legibility considerations, anthropometric considerations, and general display formatting for usability. Tools such digital human models or specialized software like the software tool to evaluate luminance contrast for legibility (Kovesdi, 2022; Figure 21) are used to support the SME in the review. The results of this activity identify design deficiencies that should be dispositioned.

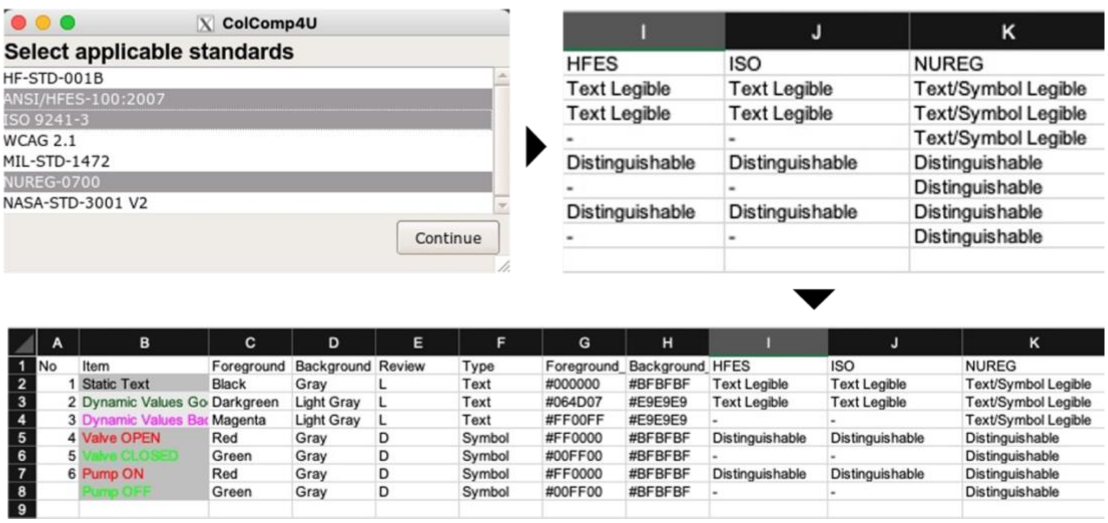


Figure 21. Luminance contrast software developed by Kovesdi (2022).

Step 3b. Operator Testing (Conceptual Verification).

Operator testing, often termed usability testing or design testing, is the process of assessing the degree to which the designed system can be used effectively by the target user (operators) that collectively make up the HSI Validation Team. Performance measures are collected to support this assessment, and these measures range from user satisfaction to characteristics of human-system performance (e.g., see Kovesdi, Joe, and Boring, 2018). Figure 22 outlines common measures used in usability tests; details of this figure are provided by Kovesdi et al. (2018).

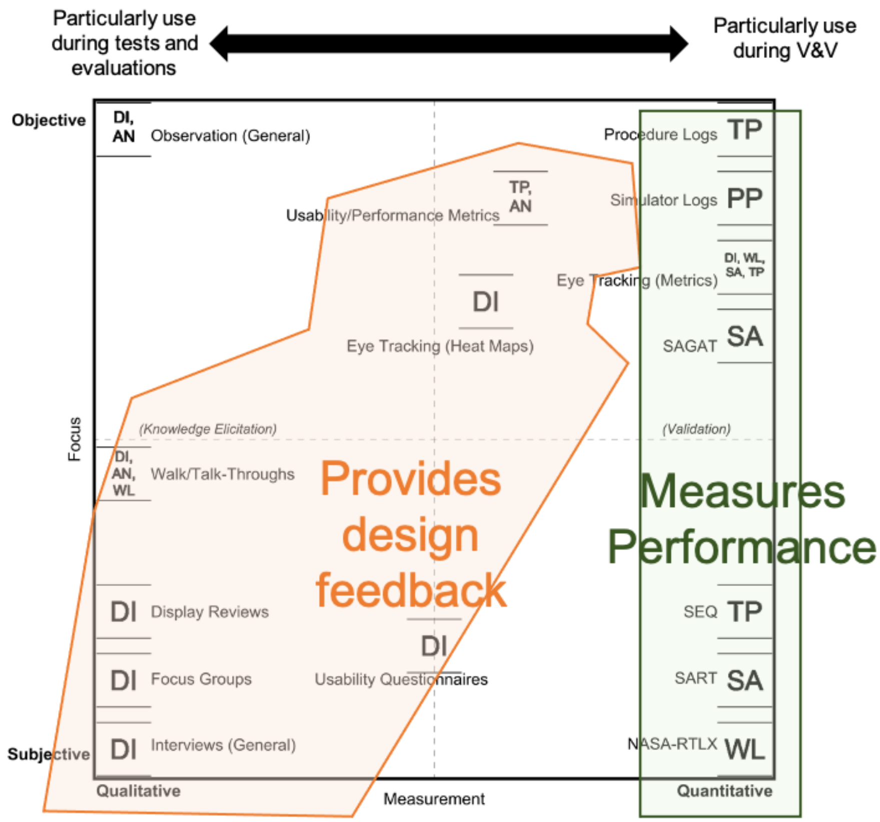


Figure 22. Landscape of HFE methods and measures (adapted from Kovesdi, Joe, and Boring, 2018).

In the case of the usability testing of the safety and nonsafety HSI displays, the objective was to ensure that operators understand and can operate the HSI elements to perform their tasks safely and reliably. This included monitoring the plant through the new HSI displays, navigating between different displays, and controlling parts of the plant using these HSIs. The usability testing is ideally *formative*, meaning it is used not only to verify the usability of the designed system but also to help specify the design in an iterative fashion. The Institute of Electrical and Electronics Engineers Standard 2411 (2021), *IEEE Guide for Human Factors Engineering for the Validation of System Designs and Integrated Systems Operations at Nuclear Facilities*, refers to formative usability tests as “design tests,” which is distinguished from validation tests.

Usability testing can range from walkthroughs with nonfunctional mockups to scenario testing using fully functional prototypes. The level of HSI display fidelity and functionality is a product of the resources of the HSI design team and the degree to which the new functionality diverges from current plant operations. Within the project, the level of fidelity followed such progress. During task analysis, a small set of HSI displays were mocked up and presented static. The focus was on the displays alone rather than the integrated system. During conceptual verification, a larger set of HSI displays were rendered and additional functionality was included. That is, navigation between the displays was enabled and access to the actual simulator model was available to begin evaluation as an integrated system. Acceptance criteria were established during conceptual verification and used during preliminary validation to support performance-based tests. The results from these tests were used to inform the HSI displays rendered for preliminary validation and to provide high confidence that the operators could use the new HSIs and modified procedures to safely and reliably perform the manual actions under study.

Acceptance Criteria for Performance-Based Testing

Manual Actions under Study

The manual actions under study were evaluated using established acceptance criteria developed during conceptual verification. The criteria followed the “Guidelines for Using Timelines to Demonstrate Sufficient Time to Perform the Actions,” provided in Appendix A of NUREG-1852 (2007), “Demonstrating the Feasibility and Reliability of Operator Manual Actions in Response to Fire.” The fundamental basis of this guidance is to evaluate the *time required to perform the action* (including diagnosis and implementation time) to the *time available* to determine if there is adequate *time margin* (Figure 23).

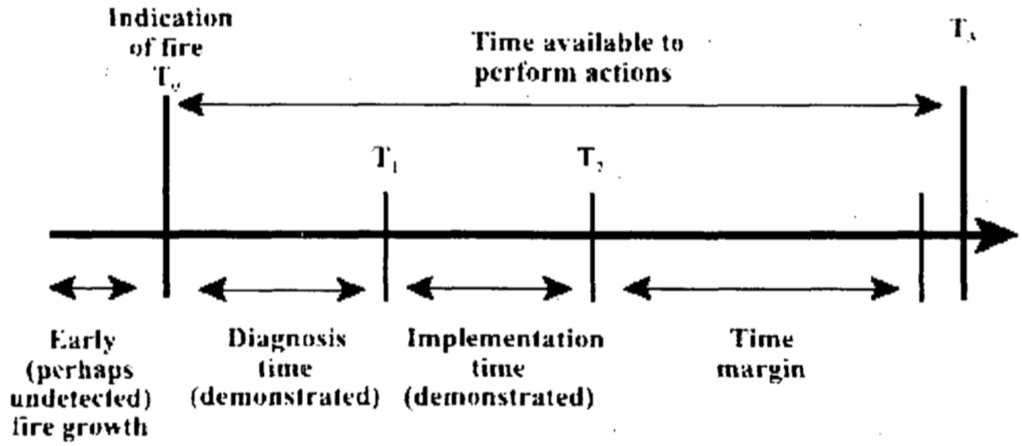


Figure 23. Timeline guidance for evaluating manual operator actions (adapted from NUREG-1852 2007).

The HFE Process Team constructed timelines during conceptual verification to provide estimated times. They used OSDs to document the interactions between the crew and equipment necessary for diagnosis and response implementation. The manual actions were identified as falling under two types of actions: those that are self-revealing in nature (Type 1) and those that reveal over time (Type 2). That is, some actions were inambiguous in nature and the diagnosis had little uncertainty (Type 1) whereas other actions were ambiguous in terms of diagnosis and therefore had greater uncertainty.

The HFE Process Team characterized these actions as Type 1 or Type 2 actions by using Rasmussen’s decision ladder framework from cognitive work analysis (Stanton et al., 2017; Figure 24). The Type 1 tasks required little knowledge-based decision-making (as seen by the shortcut from the left to right side of the decision ladder). For example, in the event of a loss of offsite power, the detection and diagnosis of such an event is self-evident by the loss of illumination in the main control room coupled with specific patterns of alarms. Therefore, the onset of these conditions immediately provides the crew with the state of the system, and they could formulate a response to mitigate the event.

Task 2 tasks require knowledge-based decision-making (i.e., referred to by the project as symptom-based decision-making). In the event of a leak of an unknown size, diagnosis was less salient and required the crew to investigate further upon formulating an appropriate response plan. Depending on how the event unfolded, the crew may have diagnosed an event such as a leak before even requiring the manual action under study. The time available for these types of tasks were generally greater than the Type 1 tasks; however, it was important to ensure that the information provided on the new HSIs was complete and usable to ensure appropriate situation awareness, workload, and timely response.

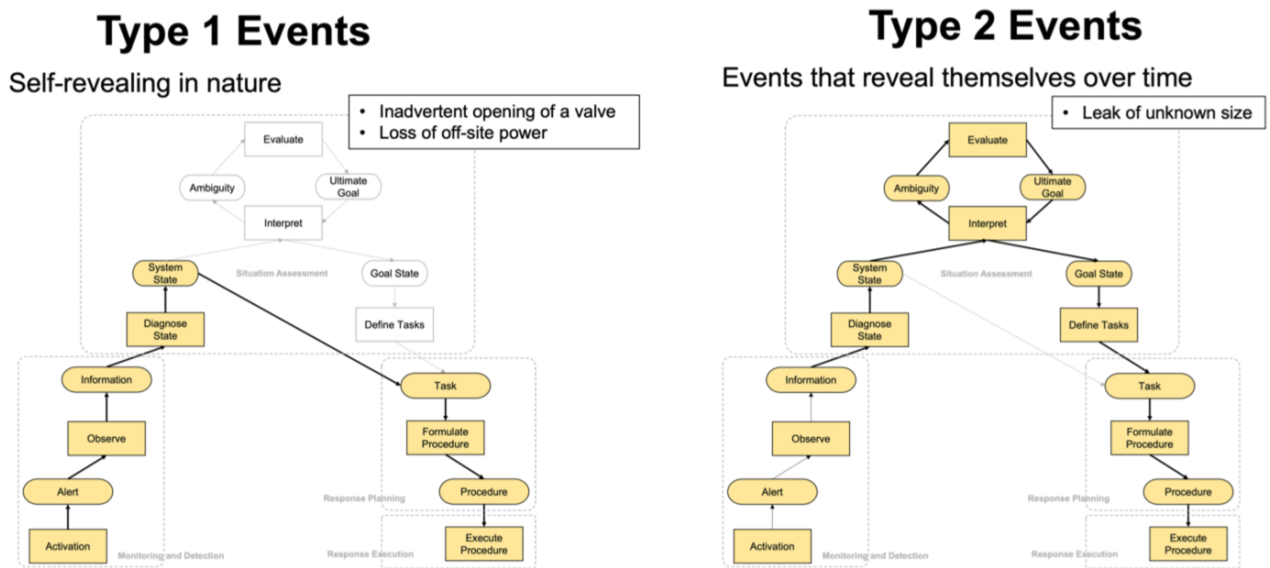


Figure 24. Types of manual actions as characterized by decision ladders from cognitive work analysis (adapted from INL/RPT-23-71395).

The acceptance criteria captured the characteristics of these two types of manual actions under study. Additional acceptance criteria beyond the licensing basis were used as good engineering practice.

Note that additional measures captured during preliminary validation were used for diagnostic criteria to provide insights into observations made during the scenario runs, including:

- Operational difficulties and unsolicited comments (as recorded through an electronic data capture form)
- Perceived workload and difficulty (as measured by the National Aeronautics and Space Administration Task Load Index [NASA-TLX] and Single Ease Question [SEQ])
- Perceived situation awareness (as measured by the Situation Awareness Rating Technique [SART])
- Overall system usability (as measured by the Brief Nuclear Usability Measure [B-NUM])
- Overall teamwork and crew performance (as measured by a behavioral observation scale based on the Halden SCORE methodology).

Testbed

To best support the goals and meet the review criteria for preliminary validation, a near full-scope, single-unit main control room simulator was used. This simulator was assembled leveraging the Idaho National Laboratory HSSL. This hybrid simulator environment was used to observe Validation Team operator performance when performing challenging scenarios involving the manual operator actions under study.

The HSSL facility was prepared to support preliminary validation, which involved obtaining and arranging sufficient visual display units (VDUs) and configuring the computer network to accept the software used to drive the operations training simulator at the site. The HSIs were loaded into the HSSL computer network, and their functionally verified. This included both the new HSIs created for the upgrade and the digital representation of legacy HSIs that remain. The resultant modified procedures were also printed and made available in the HSSL for preliminary validation.

As with conceptual verification, relative locations of the new HSIs with adjacent remaining legacy HSIs in the main control room were established. The size of the HSSL also permitted the presentation of much more of the main control room for preliminary validation than was available for conceptual verification. The HSSL leveraged the models used in the site's training simulator provided on the glasstop panels.

Pilot Testing

A dry run was completed between February 17 and 20, 2023, in the HSSL. This activity's primary purpose was to ensure readiness for preliminary validation and included:

- To verify all attendees were processed for badging.
- To verify completeness of HSIs and procedures.
- To verify functionality of HSSL and prototype HSIs installed.
- To confirm completeness of data collection tools, including data recording forms, audio and visual devices, and general notes.
- To familiarize operators (Validation Team) with the HSSL and site simulator installed. Note, part of familiarization took place at the site using a part-task simulator, which provided access to a set of safety and nonsafety HSIs.
- To perform piloting testing of the operator-in-the-loop steps to be performed during preliminary validation.

Preliminary Validation Methodology

Prior to the execution of the preliminary validation methodology (Figure 25), all attendees were provided a safety brief of the facility and given overview presentations to discuss the objectives of the project and preliminary validation and set ground rules for attendees observing the operator-in-the-loop tests. Familiarization of the modified HSIs, procedures, and main control room layout represented in the HSSL was completed before performing preliminary validation. This familiarization also entailed providing expectations for the Validation Team and others in performing the tasks. That is, the crew was instructed to perform a talk-through of tasks performed on the legacy HSIs, as opposed to controlling them from the glasstop bays.

The reason for performing a talk-through with the legacy HSIs was that these HSIs were not central to the tasks under evaluation for preliminary validation and the interaction of these controls on the glasstop did not accurately reflect response characteristics as expected in the site training simulator. However, all manual actions under study using the new HSIs were to be performed. The Simulator Team also simulated certain plant maneuvers analogous to the automation enhancements expected by the upgrades; this approach enabled the HFE Process Team to evaluate the macrolevel crew performance regarding team situation awareness when using the new HSIs during monitoring of these automation enhancements. The process used for preliminary validation is presented in Figure 25; this process was repeated for each scenario.

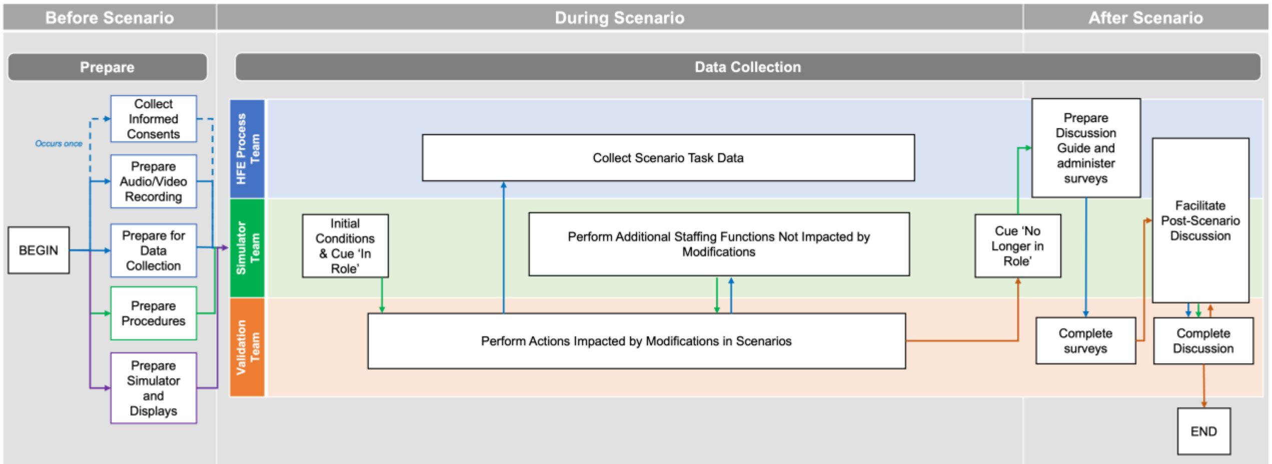


Figure 25. Preliminary validation process.

The three phases were before the scenario (prepare), during the scenario, and after scenario completion (data collection). Within each phase, there was a set of standardized activities to be completed. There were different types of data collection during the scenarios:

- For tasks that were not manual actions under study, general observational data was collected. Video recording devices were used to record the operator actions (performed by the Validation Team) using the revised procedures and HSI displays. General task data was collected regarding the use of alarms, indications, procedures, and controls by the HFE Process Team.
- For tasks that were manual actions under study, guidance from NUREG-0800, Chapter 18, Attachment A, Phase 2 (2016) was leveraged. Specifically, the OSDs created from conceptual verification and estimated time to perform these impacted manual actions was performed by Validation Team in a structured manner to support evaluation using the established acceptance criteria. The HFE Process Team observed the actions and verbalizations being made and compared them to the OSDs developed using an electronic data capture tool (Figure 26). Video recording devices were used to collect visual observational data of these operator actions using the revised procedures and new HSI displays. Where there were deviations, the HFE Process Team would probe the rationale as to why such deviations occurred.

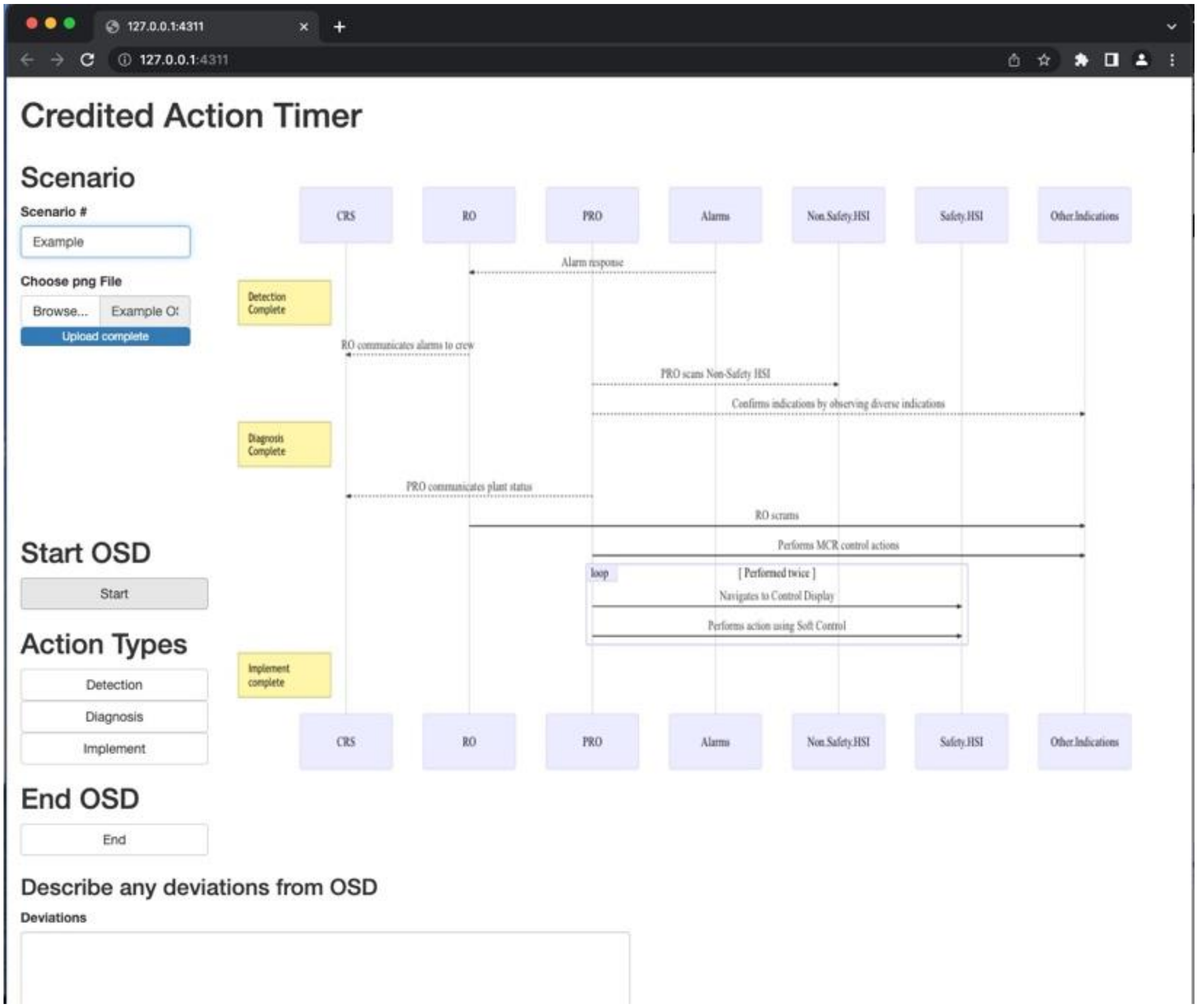


Figure 26. Custom timeline analysis tool with generic OSD presented (adapted and enhanced from INL/RPT-23-71395).

Before Scenario

Prior to completion of the scenarios, informed consent forms were administered to the Validation Team; this only occurred before the first scenario. Next, the HFE Process Team briefly introduced the general workflow of the preliminary validation workshop (Figure 25) and the use of audio and visual recording of operator actions to help determine indications and displays used during the scenario to the Validation Team. The Validation Team was reminded that:

- Their participation is being requested because of their knowledge and expertise
- The information being collected is being used to design or evaluate the HFE aspects of the HSIs and procedures and NOT to evaluate their performance
- The anonymity of personnel will be maintained, and their comments will be treated as anonymous and will be coded using a Participant ID scheme.

The HFE Process Team then administered a standard scenario packet to observers, particularly for the NRC and DOE. The packet included a summary of the scenarios being run and the corresponding OSD for the manual actions under study within the scenario. The HSI Design and Procedure Modification Team ensured that the procedures were all available prior to the scenario execution.

The HFE Process Team then prepared the audio and video recording devices and electronic data collection tools before beginning each scenario. The Simulator Team prepared the site simulator loaded in the HSSL by setting up the initial conditions.

During Scenario

Each scenario started when the Simulator Team communicated, “you are in role.” This cue started the onset of each scenario, and the HFE Process Team started the audio and video recording devices and logged the time of the cue using the electronic data collection form (e.g., by pressing “start” in the form shown in Figure 26).

Separate members of the HFE Process Team collected different aspects of crew performance. For instance, a human factors engineer was responsible for logging the timing data for the manual actions under study using the electronic tool in Figure 26; the data collected was validated with a member of the Simulator Team with significant training experience who captured timestamps. Two human factors engineers used a spreadsheet with a timestamping capability to record the actions performed throughout the scenario. A senior I&C engineer with 30 years of nuclear operations experience then observed the scenario from a “big picture” perspective to observe crew dynamics, coordination, and overall teamwork.

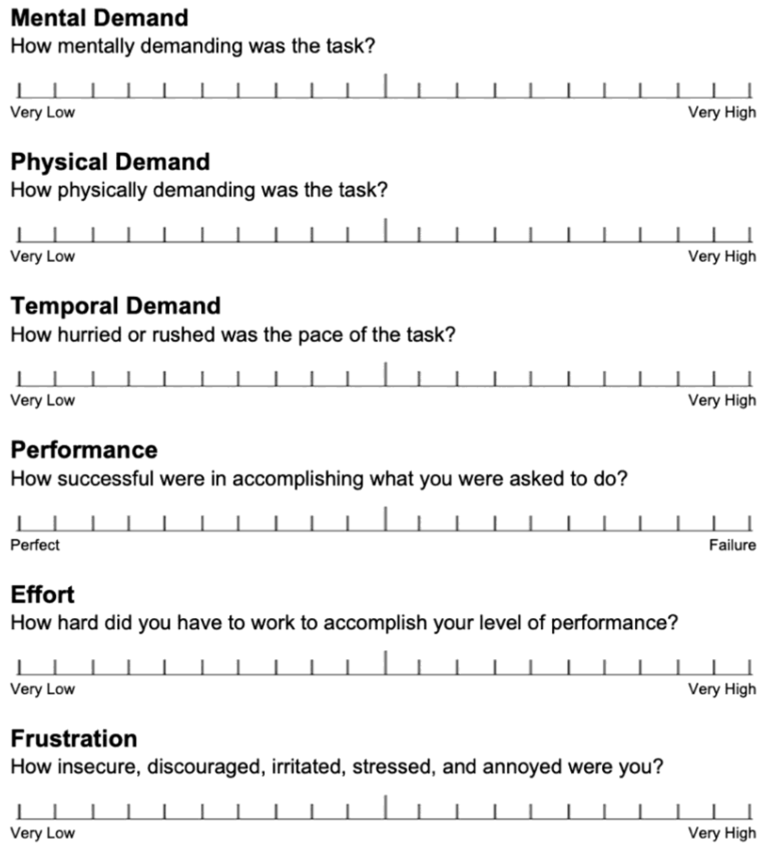
The Validation Team performed their tasks without interruption by any observers so that timing data was not artificially biased. As previously mentioned, they verbalized specific actions on the legacy HSIs, but the crew was instructed to walk up to the controls and point at the control of intent. Where the Validation Team interacted with the new HSIs, the operator would perform the task naturalistically. A final point worth mentioning was that simulator data was recorded during the scenario. This data was used to verify post-scenario timing data for analysis.

After Scenario

After the completion of a scenario, the HFE Process Team administered the post-scenario survey packet. These packets included the NASA-TLX, SART, SEQ, and B-NUM. These paper surveys provided a baseline qualitative assessment of self-reported workload and situation awareness and were administered as a packet. The responses were treated as *diagnostic criteria* (as opposed to being *dispositive*—pass or fail) regarding whether workload, situation awareness, or system usability affected overall crew performance or impacted any of the manual actions under study. Operators were instructed to answer these questions as quickly and accurately as possible after completing each scenario. After completion of the surveys, a semistructured discussion was faciliated by the HFE Process Team.

NASA-TLX

The NASA-TLX (Figure 27) is an industry-accepted tool for measuring and evaluating workload, as described in NUREG/CR-7190, “Workload, Situational Awareness, and Teamwork” (2007). The NASA-TLX is a post-scenario rating method to assess workload, comprising six different dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. Each dimension (i.e., question) typically uses a standardized scale (e.g., 1 = low; 20 = high) where higher values denote a greater workload. A common practice is to remove the 15 pairwise comparisons and only use the rating scales for each workload dimension. Workload can be evaluated by each dimension and holistically from aggregating the individual scales.



Mental Demand
How mentally demanding was the task?
Very Low — Very High

Physical Demand
How physically demanding was the task?
Very Low — Very High

Temporal Demand
How hurried or rushed was the pace of the task?
Very Low — Very High

Performance
How successful were in accomplishing what you were asked to do?
Perfect — Failure

Effort
How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration
How insecure, discouraged, irritated, stressed, and annoyed were you?
Very Low — Very High

Figure 27. NASA-TLX standardized survey instrument.

Single Ease Question

SEQ is a standardized single-question post-trial subjective rating method, using a 1–7 rating scale to measure the perceived ease of completing a task (i.e., herein referred to as perceived difficulty). The SEQ is a widely used survey tool in usability engineering for software systems and is generally inversely correlated with the NASA-TLX. That is, lower SEQ values (e.g., one) denote a lower perceived ease of task completion whereas higher SEQ values (e.g., seven) denote a higher perceived ease of task completion.

Situation Awareness Rating Technique

SART is a self-report standardized survey that measures perceived situation awareness (Figure 28) with a series of standardized questions using a seven-point rating scale (1 = low; 7 = high). These questions aggregate into three primary dimensions: understanding, demand, and supply.

Understanding refers to one's general understanding of the situations and is a combination of information quantity, information quality, and familiarity. Demand refers to one's attentional demands (i.e., like workload) and is a combination of task complexity, variability, and situation instability. Finally, supply refers to one's attentional supply and is a combination of attentional arousal, focusing of attention, spare mental capacity, and mental concentration. The relationship of these three dimensions score a common situation awareness measure from the following equation: situation awareness = understanding – (demand – supply). A composite situation awareness score is derived from SART where a greater value denotes greater situation awareness. SART is also cited in NUREG/CR-7190 but is cautioned as a primary source to measure situation awareness; hence, preliminary validation used SART in combination with naturalistic observation and semistructured questions described in the post-scenario discussion.

Perceived Situation Awareness: SART

Instability of Situation
How changeable is the situation? Is the situation highly unstable and likely to change suddenly (High) or is it very stable and straightforward (Low)?

1 = Low	2	3	4	5	6	7 = High

Complexity of Situation
How complicated is the situation? Is it complex with many interrelated components (High) or is it simple and straightforward (Low)?

1 = Low	2	3	4	5	6	7 = High

Variability of Situation
How many variables are changing within the situation? Are there a large number of factors varying (High) or are there very few variables changing (Low)?

1 = Low	2	3	4	5	6	7 = High

Arousal
How aroused are you by the situation? Are you alert and ready for activity (High) or do you have a low degree of alertness (Low)?

1 = Low	2	3	4	5	6	7 = High

Concentration of Attention
How much are you concentrating on the situation? Are you concentrating on many aspects of the situation (High) or are you focused on only one (Low)?

1 = Low	2	3	4	5	6	7 = High

Division of Attention
How much is your attention divided by the situation? Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?

1 = Low	2	3	4	5	6	7 = High

Spare Mental Capacity
How much mental capacity do you have to spare in the situation? Do you have sufficient to attend to many variables (High) or nothing to spare at all (Low)?

1 = Low	2	3	4	5	6	7 = High

Information Quantity
How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)?

1 = Low	2	3	4	5	6	7 = High

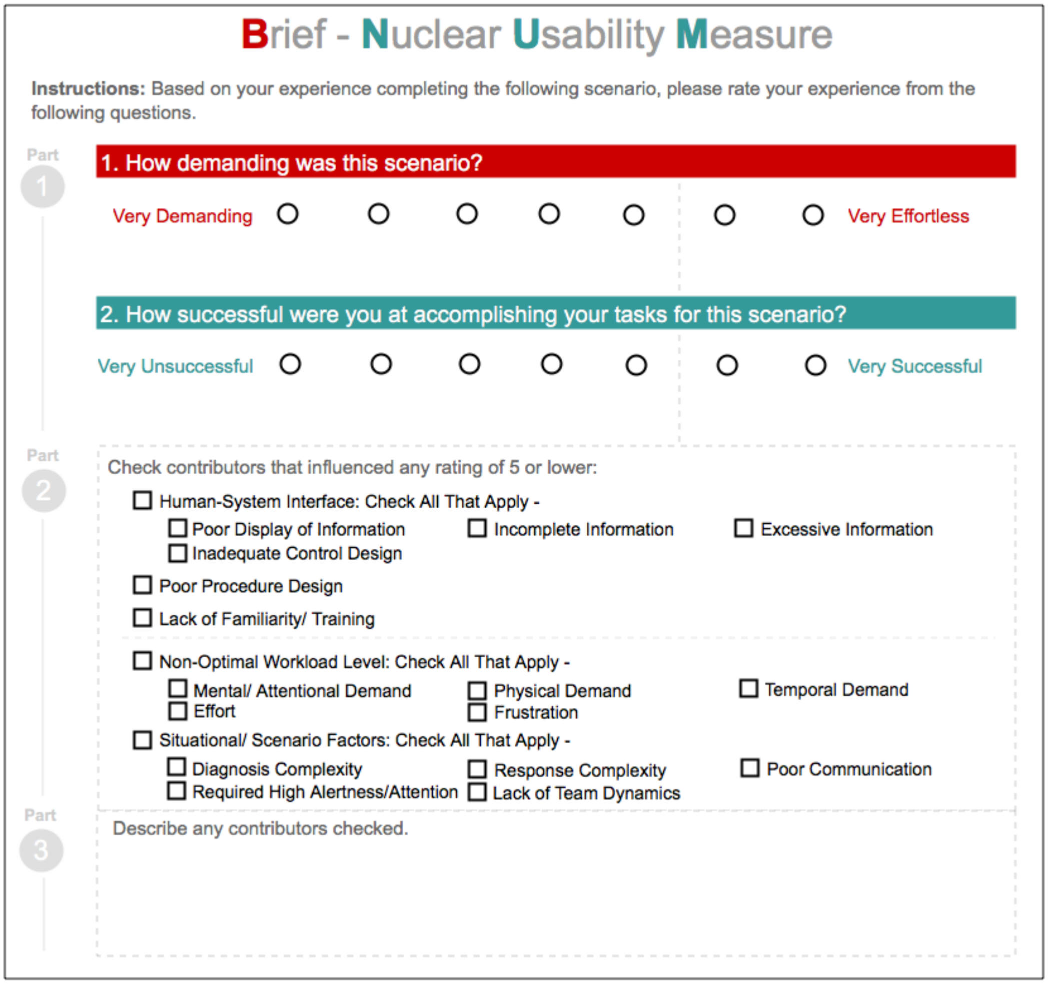
Familiarity with Situation
How familiar are you with the situation? Do you have a great deal of relevant experience (High) or is it a new situation (Low)?

1 = Low	2	3	4	5	6	7 = High

Figure 28. SART standardized survey instrument.

<u>Brief Nuclear Usability Measure</u>

Finally, the survey packet included the B-NUM, a recently developed survey tool (Kovesdi and Joe, 2019; Figure 29). The B-NUM is an aggregated survey meant to measure self-reported workload and situation awareness based on two key questions. The tool was derived from NASA-TLX and SART but adds an additional quality of collecting diagnostic information on the responses. That is, the survey responder has the capability to check performance shaping factors (i.e., contributors) to low ratings for self-report workload and situation awareness. The responder can then describe the specific attributes of these contributors in more detail in an open text field. The advantage of using B-NUM in this sense is to collect early feedback on contributors to low situation awareness and high workload to better inform design.



Brief - Nuclear Usability Measure

Instructions: Based on your experience completing the following scenario, please rate your experience from the following questions.

Part 1

1. How demanding was this scenario?

Very Demanding ○ ○ ○ ○ ○ ○ ○ Very Effortless

2. How successful were you at accomplishing your tasks for this scenario?

Very Unsuccessful ○ ○ ○ ○ ○ ○ ○ Very Successful

Part 2

Check contributors that influenced any rating of 5 or lower:

- ☐ Human-System Interface: Check All That Apply -
  - ☐ Poor Display of Information
  - ☐ Incomplete Information
  - ☐ Excessive Information
  - ☐ Inadequate Control Design
- ☐ Poor Procedure Design
- ☐ Lack of Familiarity/ Training
- ☐ Non-Optimal Workload Level: Check All That Apply -
  - ☐ Mental/ Attentional Demand
  - ☐ Physical Demand
  - ☐ Temporal Demand
  - ☐ Effort
  - ☐ Frustration
- ☐ Situational/ Scenario Factors: Check All That Apply -
  - ☐ Diagnosis Complexity
  - ☐ Response Complexity
  - ☐ Poor Communication
  - ☐ Required High Alertness/Attention
  - ☐ Lack of Team Dynamics

Part 3

Describe any contributors checked.

Figure 29. B-NUM standardized survey instrument.

<u>Post-Scenario Discussion</u>

A member of the HFE Process Team facilitated a semistructured discussion with the Validation Team. The responses collected from the survey were used to query the rationale for certain responses related to perceived workload, situation awareness, and system usability. That is, the responses from the surveys were analyzed qualitatively and not statistically for two reasons. First, preliminary validation data set was not large enough to support a formal statistical analysis. Second, and most importantly, the intent of the surveys was to provide *diagnostic criteria* for evaluating the degree to which the new HSIs and modified procedures may have affected perceived workload, scenario difficulty, and situation awareness when performing the tasks demanded of them in each scenario. These aspects of the evaluation were not *dispositive* (i.e., pass or fail) in nature and were based on expert judgment from qualified personnel from the Simulator Team. Thus, the survey responses were used in combination with expert observation to decide whether any perceived difficulties or ratings indicating high perceived workload or low situation awareness were attributed to the new HSIs, modified procedures, familiarity, training, characteristics of the scenario (situational), or a limitation of the simulation environment (artifact), as seen in Figure 30.

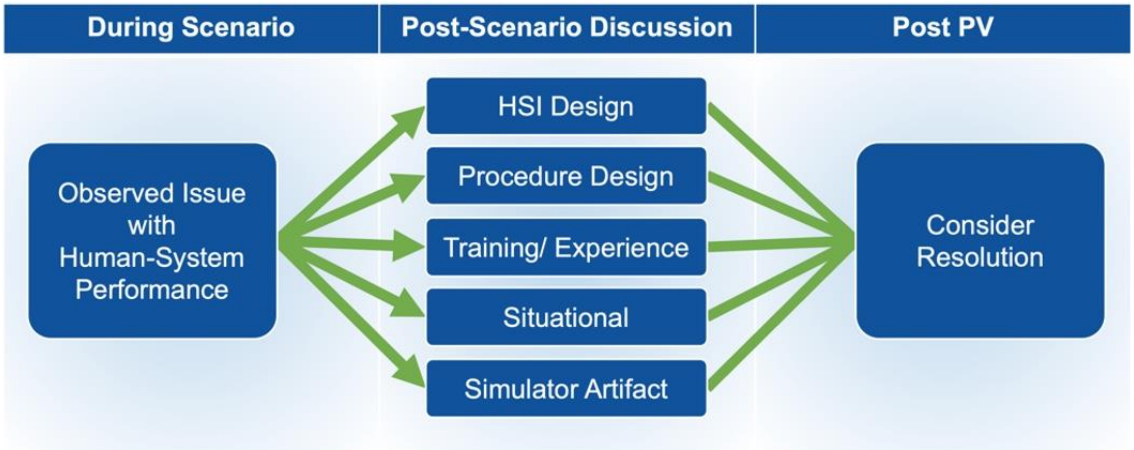


Figure 30. Contributors to observed difficulties, perceived workload, and perceived situation awareness.

This qualitative analysis not only accounted for whether specific contributors negatively or positively impacted perceived workload, situation awareness, or overall system usability but also the "net effect" of these contributors on overall crew performance. For example, to determine the acceptability of workload, the analysis accounted for resulting impacts to response times, situation awareness, and general impacts to crew coordination, communication, and teamwork. In instances where workload was high but considered "acceptable" by the Validation Team, overall acceptability also accounted for how the upgrades improved information availability, plant control, or overall situation awareness through added plant data integration, use of the HSIs, or use of added automation. There may be an increase in workload when additional information that once was previously unavailable is integrated into the main control room. However, there is a "net positive" if such new capabilities enable the crew to perform their tasks more efficiently, with increased situation awareness and not having to rely on field communications to perform the same task.

5.2 Developing a Fleetwide Modernization Vision

Southern Nuclear Corporation (SNC) is committed to sustaining their existing nuclear fleet for continued carbon-free electricity production. SNC is driven to meet this goal through a systematic fleetwide modernization strategy that will leverage business-driven innovations and technology solutions across their sites to reduce O&M costs. SNC is looking ahead to leverage available digital I&C capabilities and advanced main control room technologies and concepts, such as those seen in INL/EXT-19-55788 (2019), to improve the way their plants are operated. SNC is also focused on modernizing a wide range of different plant maintenance and support functions to reduce cost through this strategic effort.

SNC is collaborating with both the LWRS Program and Sargent and Lundy, a global leader in power and energy modernization, to support the development of fleetwide requirements that will drive this effort. To date, this collaboration has generated two HTI reports:

- **INL/RPT-22-70538**—Demonstration and Evaluation of the Human-Technology Integration Guidance for Plant Modernization
- **INL/RPT-23-71395**—Demonstration of the Human and Technology Integration Guidance for the Design of Plant-Specific Advanced Automation and Data Visualization Techniques

A summary of previously completed activities related to HTI is given next, following the recently completed activities, such as the advanced main control room demonstrations in partnership with the Institute of Energy Technology (IFE) and recent strategic partnership with Sargent and Lundy to continue the main control room modernization efforts following HTI guidance developed by the LWRS Program.

5.2.1 Previously Completed Activities

Previously completed HTI activities in support of SNC's fleetwide modernization plan are summarized below.

5.2.1.1 Initial Scoping Activities

The initial scoping activities involved identifying systems and components being planned for the modernization project. The initial scoping phase involves establishing a business case for modifications and identifying the overall extent of the modifications for the nuclear power plant. Current sites are operating safely and reliably; however, there is a business need to address obsolescence challenges to reduce O&M costs. SNC is considering the use of advanced digital technologies to transform how the plants are being operated, maintained, and supported to help reduce O&M costs. The efforts in this collaboration with SNC and Sargent and Lundy have focused on a single site; however, the continuing collaboration will be expanded across the entire fleet. The primary goals of the collaboration are to address the needs of end users in operations, maintenance, and engineering to create standardization across the fleet to reduce training costs, consolidate support, and improve performance through modern technologies.

HTI and HFE are important in the scoping phase to identify existing design issues, collect stakeholder needs, and ensure the design incorporates HFE design principles. Notable HFE activities performed during the initial scoping include establishing a charter for the project, collecting initial OE, and developing a new state vision and concept of operation. Further information and descriptions of activities performed during initial scoping are available in INL/RPT-22-70538.

5.2.1.2 Perform Kickoff Meeting and Collect Initial Operating Experience

An initial kickoff meeting with SNC was held at the site's training simulator, which contained a current version of the existing simulator and another configuration with current planned digital modifications. Operators, during the meeting, had a chance to perform training scenarios and interact with the new digital modifications in the new control room configuration and provide feedback to the meeting participants. HTI researchers (HFE Team) were present during the meeting to observe operators during scenarios using the digital modifications and collected OE during discussions with operators after scenarios. Endpoint vision worksheets from EPRI 3002004310 (2015) were used to gather and collect input from operators on the new modifications in the control room and how the modifications supported the scenarios performed. Feedback from operators was used to support the development of HTI requirements for future control room operations.

5.2.1.3 Develop Initial Three-Dimensional Model of the New Vision

Current plant operators provided early feedback to help develop the new vision main control room during the initial kickoff meeting. Feedback from operators was collected from interviews, discussions, walkthroughs, and talk-throughs during the initial visit to the plant. Operators discussed needs and requirements to maintain safe and effective plant operations, such as having available hard controls and new workstations. Operator feedback was collected and provided to the engineering and design team to begin the development of three dimensional (3D) models.

The 3D model was developed from a computer-aided design file based on laser scans of the current main control room. Images were provided to the HFE Team to combine and edit using photo editing software to provide a visually scaled representation of the main control room. After the 3D model was completed and reviewed by the engineering and design team for accuracy, anthropometric consideration reviews using NUREG-0700 guidance and recommendations were completed. The anthropometric consideration reviews evaluated line of sight, viewing angles, functional reach, legibility, and readability to identify if operators would be able to successfully view and interact with new modifications successfully in the future and endpoint configurations of the main control room.

5.2.1.4 Perform Static Concept of Operations Workshop

The static concept of operations workshop was held in the Idaho National Laboratory's HSSL to gather additional feedback from operators on the new state vision and concept of operations for the future main control room. The workshop was used to familiarize operators with the current layout of the main control room and then provide exposure to new advanced control room concepts, including plant and overview displays, computer operator support systems, and an advanced data analytics and procedure tool. The goal of introducing the advanced concepts to the operators was for operators to consider different possibilities of how operations could be transformed in the main control room.

3D models were used during the workshop to provide visualizations of the current and future states of the main control room. Operators were also taken to a visualization laboratory to experience the endpoint vision of the main control room through virtual reality tools. Endpoint vision worksheets were used during the workshop to help identify relevant HFE impacts and considerations from operators on the endpoint vision of the main control room.

5.2.2 Recently Completed Activities

Recently completed HTI activities in support of SNC's fleetwide modernization plan are summarized below.

5.2.2.1 Perform Demonstration of Advanced Main Control Room Concepts

An advanced main control room concept demonstration workshop was completed along with researchers from IFE June 19–22, 2023 in the HAMMLAB in Halden, Norway. This demonstration workshop allowed operators from the site to perform walkthroughs with advanced main control room concepts in the HAMMLAB using the generic pressurized-water reactor as the simulator model. Demonstrations of advanced main control room technologies and features such as large screen and operator work displays supported operators increased situation awareness (McDonald, Braseth, and Joe, 2019). Figure 31 illustrates the information hierarchy for the IFE advanced control room features.

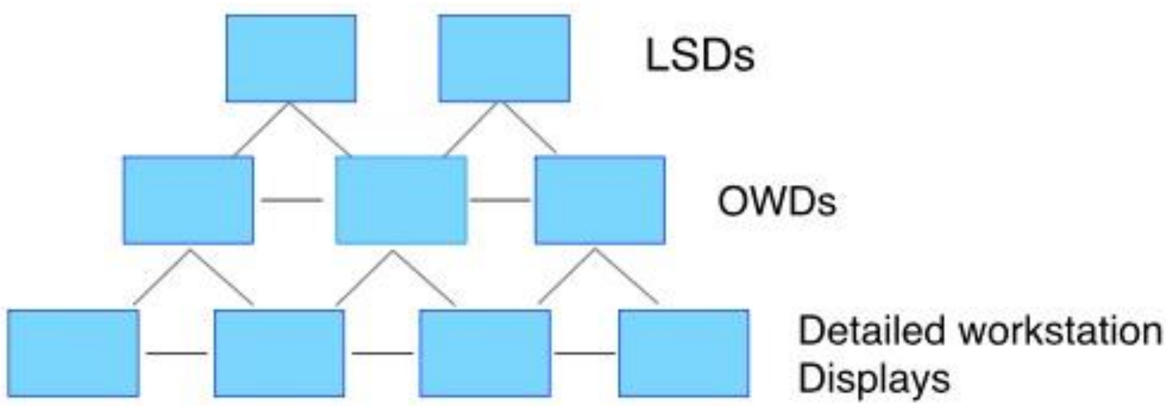


Figure 31. Advanced main control room IFE concepts information hierarchy (adapted from INL/EXT-19-55788).

This workshop integrated these features with the design philosophy of an existing U.S. nuclear power plant distributed control system or HSI vendor (Figure 32). The purpose of this workshop was to demonstrate how such features could be pragmatically incorporated and to demonstrate their benefits in terms of improved operational performance, such as improved decision-making, situation awareness, and reduced workload.

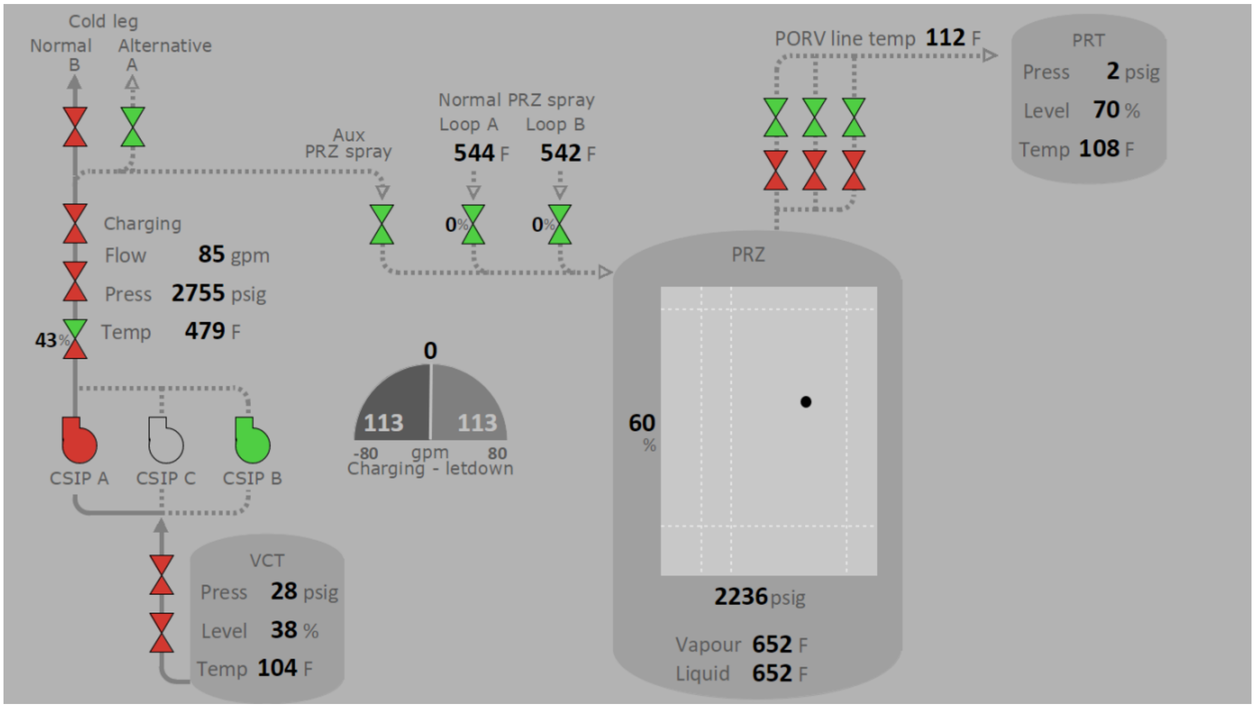


Figure 32. Example of an advanced main control room HSI display from IFE.

At the workshop, SNC operators were first introduced to the HAMMLAB and began training and familiarization on the generic pressurized-water reactor. This training took place on the first day. On the second day, the operators walked through a set of scenarios using the advanced concepts to provide feedback on the use of these HSIs to support their abilities in effectively performing the tasks demanded by the scenarios (Figure 33).

Figure 33. Photograph of the advanced main control room concepts workshop in the HAMMLAB.

IFE and LWRS Program researchers facilitated a discussion around the use of these displays in terms of supporting teamwork and coordination, task support, and situation awareness and managing workload levels. For instance, LWRS researchers utilized a standard set of semistructured questions at the end of each scenario including:

Introductory

- What is your overall impressions of this configuration?
- What worked well? What did not work well?

Crew performance, teamwork, situation awareness, workload, and task support

- How well or not well did this configuration support:
  - Your abilities to mitigate the transient? What could be done to improve this?
  - Crew coordination and communication? What could be done to improve this?
  - Your ability to establish and maintain situation awareness of plant? What could be done to improve this?
  - Your ability to manage mental workload? What could be done to improve this?

HSI usability (i.e., alarms, overviews, and workstation)

Clarity of Information

- Does information appear to be organized logically on the screen?
- Is the information on the screen easy to see and read?
- Do screens appear uncluttered?
- Is it easy to find the required information on a screen?

Display Consistency

- Are abbreviations, acronyms, codes and other alphanumeric information used consistently throughout the system?
- Are the displays consistent between each other?

Task Compatibility

- Are the labels used easy to recognize and understand?
- Is information presented and analyzed in the units with which the user normally works?
- Is information presented in a way that fits the user's view of the task?
- Does the organization and structure of the system fit the needs of the task?

System Feedback

- Is the feedback provided by the configuration appropriate for the task?

Explicitness

- Is the system well organized?
- Is the layout of information obvious?

Appropriate Functionality

- Is the way in which information is presented appropriate for the tasks?
- Does each screen contain all the information that the user feels is relevant to the task?

Flexibility and Control

- How would you rate the system in terms of flexibility and control?

Configuration and number of VDUs

- Was the arrangement of the VDUs acceptable or not acceptable?
- Was there an adequate or inadequate number of VDUs to support situation assessment?

General closing questions

- Is there anything else not previously covered that should be considered to improve the endpoint vision HSIs or configuration?

The results of this workshop will inform SNC's digital modernization strategy and be used as a technical basis for SNC's fleetwide style guide and common fleet requirements.

6. EXTENDING HUMAN AND TECHNOLOGY INTEGRATION BEYOND THE MAIN CONTROL ROOM

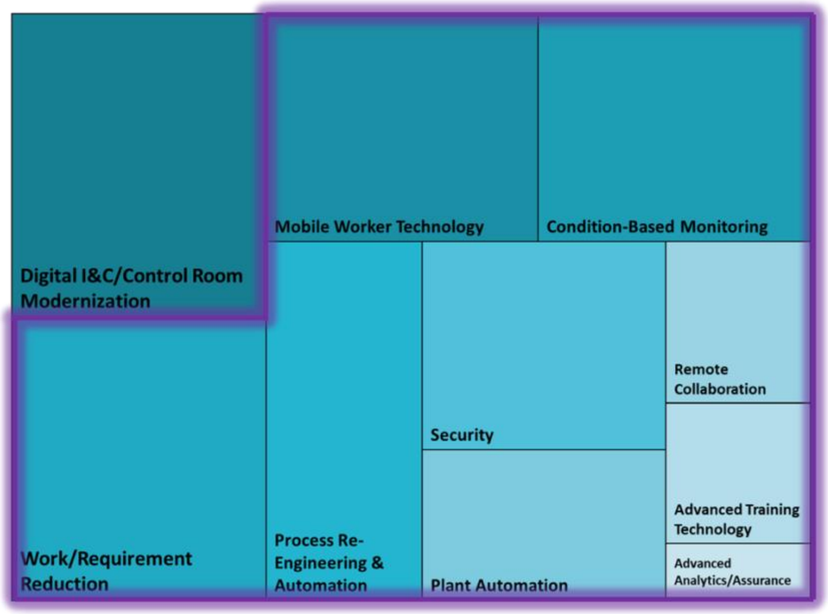


Figure 34. Extending HTI beyond digital I&C and control room modernization (adapted and enhanced from INL/RPT-22-70538).

HTI benefits WROs beyond digital I&C and control room modernization (Figure 34). In these other domains, the role of HTI focuses on jointly optimizing PTPG such that work can be significantly streamlined without sacrificing safety or reliability. In other domains, there are a few notable characteristics that require tailoring the approach described in Section 4.2 and INL/EXT-21-64320.

First, unlike the main control room, the level of formalization, or degree to which the jobs within the domain are standardized, may be notably less than the work in the main control room (Hendrick and Kleiner, 2001). Therefore, the tasks that personnel perform may be less proceduralized or require less training, so the way in which work must be analyzed, designed, and evaluated must account for these differences. For instance, HTI must be able to account for the possibility of a work domain being less documented or contain deviations to how tasks are *actually performed* versus how they are intended to be performed. On this note, there may be multiple roles who perform certain tasks, so such distinctions between responsibilities may not be as clear cut. Second, the source of data available to the worker may be less reliable or accessible whether due to technological or environmental limitations. HTI must understand the bounding constraints within the domain when making recommendation for new innovations that support work.

Third, within some domains, there may be different emphases on *risk*, where some tasks may be less central to plant or personnel safety and more central to plant productivity. The grading of functions and tasks under analysis should address these differences while not losing sight of safety. Fourth, the use environment under analysis may be less apt to simulation techniques that use full-scope testbeds. Thus, other tests and evaluation techniques may be needed to analyze functions and tasks of interest. Finally, the sheer breadth of tasks within a domain may be significant, so grading the effort will be strongly emphasized.

The next subsections propose an extension to the methodology described in Section 4.2 to support modernization beyond the main control room, as informed through ION. Specifically, these subsections discuss the role of HTI within the context of a multidisciplinary analysis to scope potential WROs during strategic planning, referred to as technical, economic, and risk analysis (TERA; Figure 35). The purpose for developing TERA is twofold. First, because utilities typically have either performed or are scoping modernization activities, one purpose of TERA is to assess these existing or proposed projects within the umbrella of ION to determine whether the proposed solutions can be further expanded following ION. For example, a modernization project may have a very specific focus on improving a subset of processes with proposed technology. However, through TERA, the assessment may identify several other areas that could also benefit from the original proposed modernization effort scoped by the utility. This enables strategic modernization through ION. A second purpose of TERA is to provide a multifaceted analysis of the existing solution proposed, looking at the opportunity through a technical, economic, and risk lens. In some cases, a proposed solution may require substantial resources that were not originally planned for by the utility based on either technical, economic, or safety risk. TERA systematically assesses these risks.

Within the technical risk assessment element of TERA, risk is assessed through the lens of PTPG in which a proposed innovation is assessed by the impact on PTPG. Governance is encapsulated within the proposed impacts to people, technology, and processes. HTI focuses on the interaction between people and technology within a new proposed process. This is analyzed through a human readiness screening process following detailed analysis (Figure 35). The next subsections describe the screening and detailed analyses, illustrated in Figure 35.

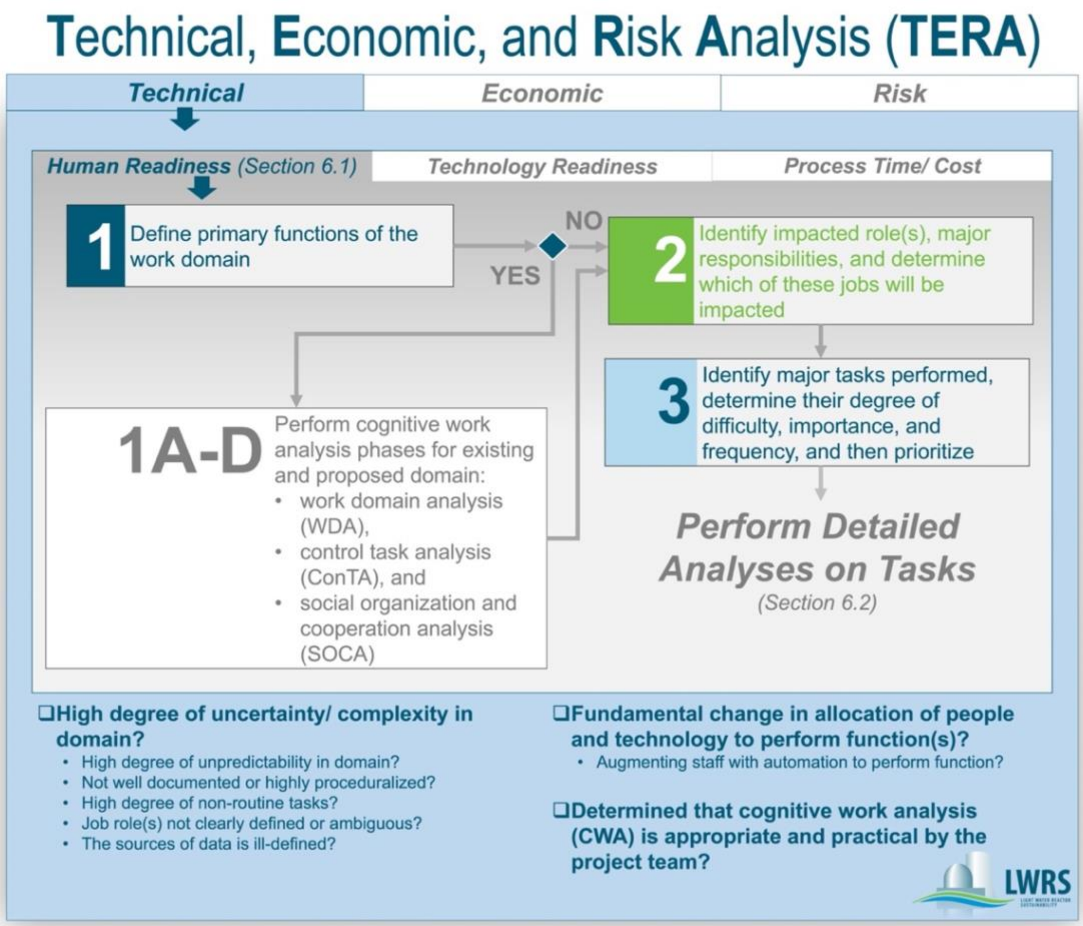


Figure 35. Role of HTI to evaluate potential WROs.

We propose that the human readiness assessment module of TERA can be incorporated as part of the HTI methodology, as seen in Figure 36. That is, the human readiness assessment for WROs beyond the main control room is included as the initial phase. Section 6.1 therefore extends Phase 1 of the HTI methodology to address additional WROs beyond main control room modernization. It should be emphasized, however, that there should be a high degree of integration between HFE efforts involved in the main control room and elsewhere to ensure a cohesive vision that leverages the new capabilities enabled by a modern digital I&C infrastructure. The double-sided arrow in Phase 1 of Figure 36 indicates that the development of the vision and concept of operations should be interrelated to the other WROs under analysis. For instance, where new data integration capabilities are enabled through digital I&C, these features and functions would be incorporated in the analysis of related WROs that would leverage such data. The detailed analyses described in Section 6.2 can be expanded into the subsequent phases in the methodology shown in Figure 36, following a graded approach.

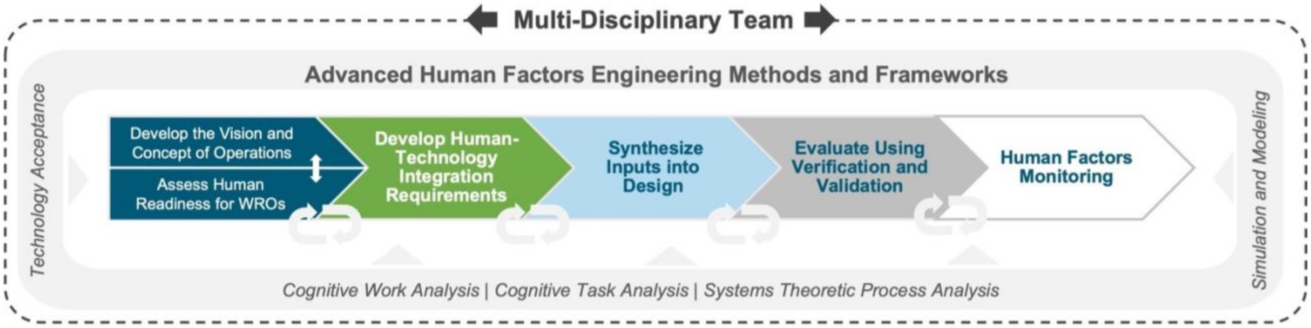


Figure 36. Revised HTI methodology incorporating TERA.

6.1 Scoping Efforts

This section describes the first part of the human readiness assessment within the TERA framework. Specifically, the three steps illustrated in Figure 35 are described next in detail. These steps are derived based on previous HTI R&D documented in INL/EXT-21-64428, which follows a sociotechnical approach.

6.1.1 Step 1. Identify Primary Functions of the Work Domain

The first step is identifying the impacted functions of the work domain. This step is essential to understanding the reasons for the work domain itself as it pertains to operating, maintaining, or supporting the plant. A distinction must be made here between the high-level functions defined at this step and system-level functions that pertain to the existing technology in place that supports these high-level functions. This step is concerned with the former as it provides context for further analysis. That is, this step provides added clarity to the analysis in establishing a means-end analysis to the proposed innovations that will support a given work domain.

Defining these high-level functions enables the purpose-related allocation of function for new technology. Step 1 here refers to defining the *goals*, *safety functions,* and *processes* of the domain in Figure 37. Although, in this step, safety functions are broadened to *all high-level functions* within the plant such as support plant availability and generate power. In essence, this step begins to develop the initial foundation of an abstraction hierarchy, which is a critical artifact in the work domain analysis (WDA) phase of cognitive work analysis.

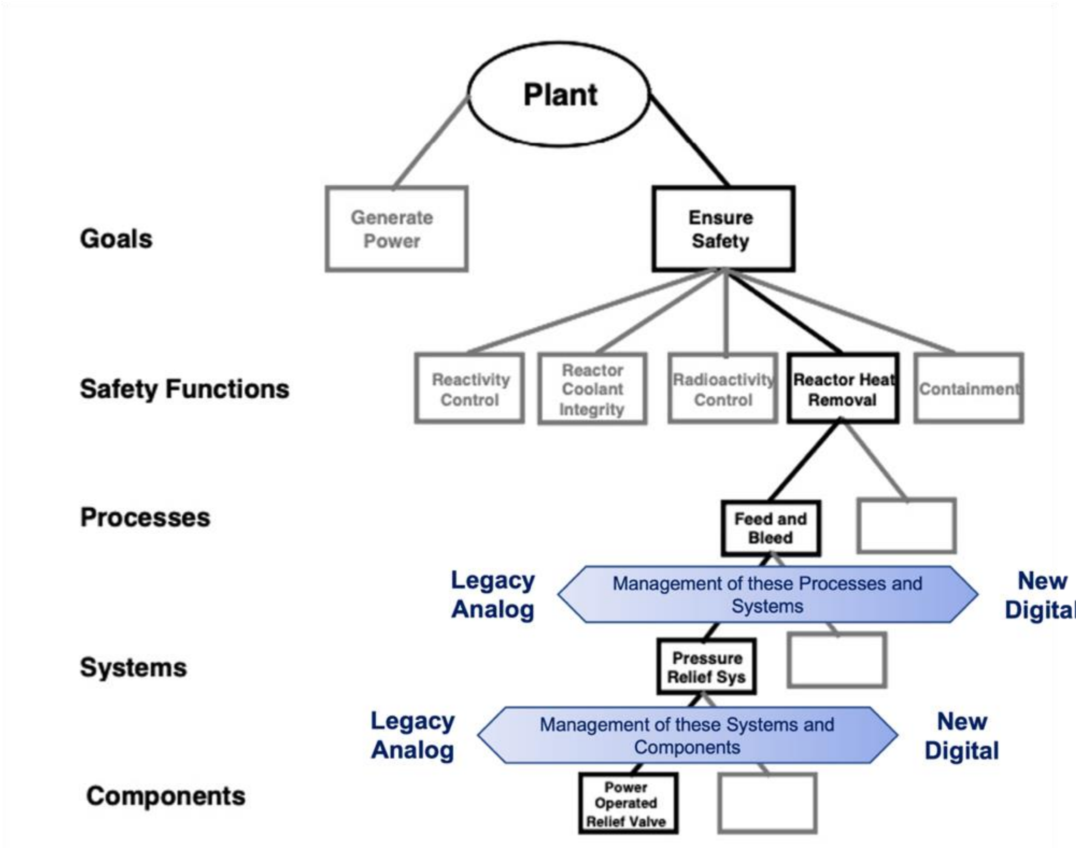


Figure 37. Vertical slide through a plant's functional hierarchy for ensuring safety (adapted and enhanced from NUREG-0711 2012).

These high-level functions are identified using a combination of reviewing existing documentation (e.g., concept of maintenance or existing procedures documentation) and interviewing stakeholders within the domain. Specifically, probe questions can be used to collect this information. The following are such questions, adapted from Read et al.' development of prompt questions for the cognitive work analysis design toolkit (2016) to support this effort:

Functional Purpose of the Domain

- For what reason(s) does the <work system> exist?
- What are the highest-level objectives or ultimate purpose of the <work system>?
- What needs of the plant does the <work system> satisfy?

Constraints, Values, and Priorities

- What kinds of constraints does the environment impose on the <work system> (e.g., hazards, communication)?
- What values are imposed on the <work system> (e.g., safety, excellence)?
- What regulations or governing requirements are imposed on the <work system>?

Purpose-Related (High-Level) Functions

- What functions are performed in the <work system>?
- What functions are required to achieve the purpose of the <work system>?

- What functions are required to satisfy the values imposed on the <work system>?
- What functions are required to satisfy the regulations or governing requirements imposed on the <work system>?

The following probe questions can be adapted and are meant to serve as a resource for identifying the high-level functions of the work domain. They are not required to be answered in their entirety and can be adapted if determined to be appropriate. The completion of step one should begin to answer parts of the question tiers described above. This information can be captured in text but visualized using the abstraction hierarchy for a functional decomposition of the domain (e.g., Figure 38). Figure 38 illustrates an abstraction hierarchy to represent the conduct of chemistry. The first three of five layers of the abstraction hierarchy are completed: purpose (goals), values and constraints, and purpose-related functions. Specific roles identified within chemistry are represented by colors where appropriate under the purpose-related functions. This figure serves as a useful way to quickly visualize how these higher-level functions interrelate and who is involved. This serves as a basis for subsequent analyses in Steps 2 and 3.

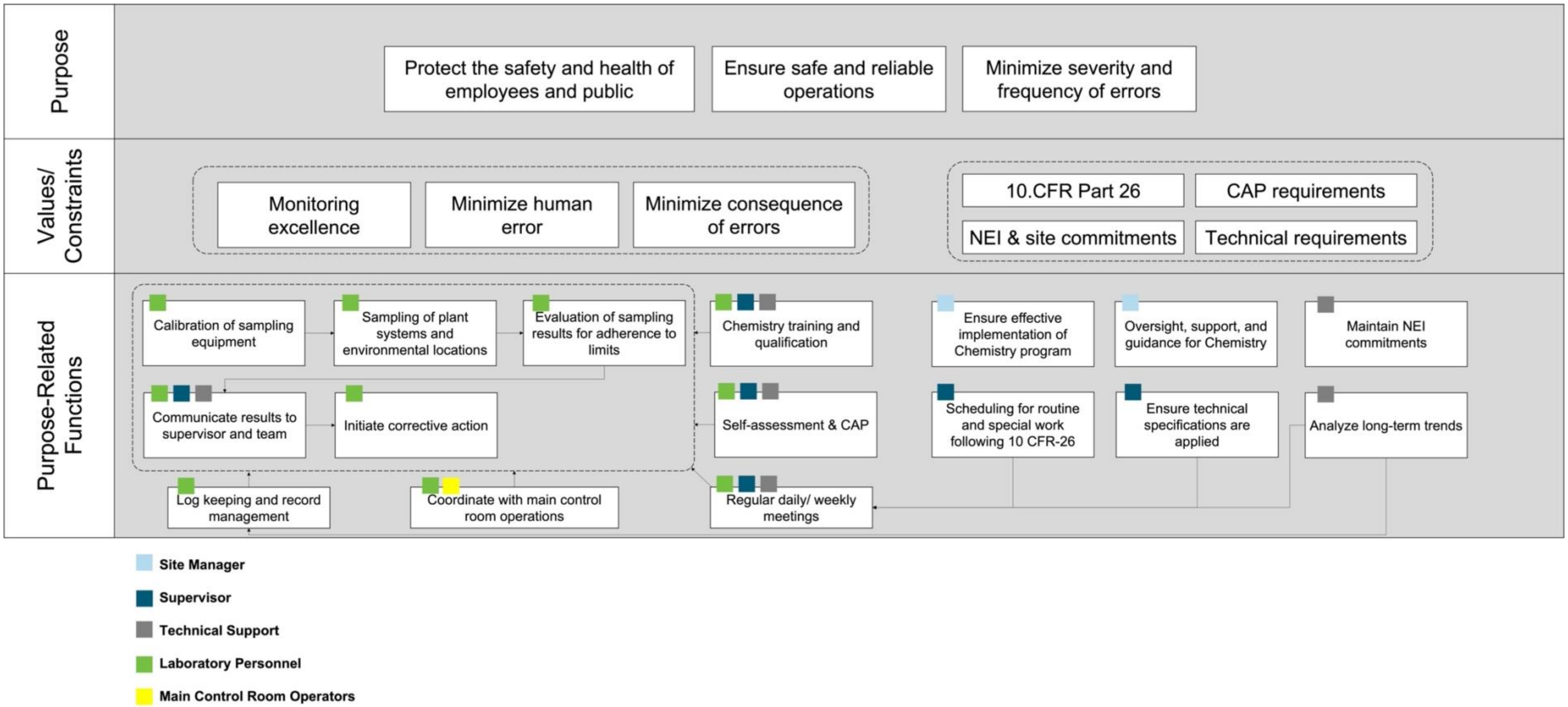


Figure 38. Functional domain example for conduct of chemistry (genericized).

6.1.2 Determine the Need for Cognitive Work Analysis

Before transitioning to Step 2, a decision point is made, as indicated in Figure 35. This decision point refers to whether the WRO under analysis could benefit from completing three of the five primary phases of cognitive work analysis: WDA, control task analysis (ConTA), and social organization and cooperation analysis (SOCA). These selected phases are based on a previous sociotechnical analysis (Schmid, Korn, and Stanton 2020) who leveraged WDA, ConTA, and SOCA to reduce staffing levels needed from the flight deck within the domain of commercial aviation. In short, the authors leveraged WDA to model the existing work domain, such as seen in Step 1 here, but further elaborated on the specific agents and system-level functions currently required using ConTA and SOCA. To note, these two additional layers would be seen below the three layers in Figure 38, indicating a means-end relation between higher-level functions to lower-level and system-level functions and specific agents (i.e., equipment, people, and other artifacts that support these functions).

Building off the results of WDA, ConTA was then used to map specific work situations to the functions represented by WDA; this step delineates certain modes of operation that are invoked by different situations or conditions. A tool used in ConTA to map these relations is the contextual activity template, which is a matrix that cross-tabulates functions to situations by its rows and columns, respectively. Finally, SOCA was applied to model the allocation of functions to the proposed system modifications. SOCA describes what specific roles are responsible for each specific function across the specified situations. A common way that SOCA is indicated is by color-coding functions by roles responsible, like in Figure 38.

The purpose of a cognitive work analysis is to provide a framework for analyzing the work domain, by looking at it through different constraints, including the governing functions and its purpose (WDA), conditions and decisions made at each function (ConTA), strategies used (strategies analysis), the people and automation involved (SOCA), and the knowledge, skills, and abilities required of the people to perform work (worker competency analysis). A detailed description of the cognitive work analysis is provided by Stanton et al. (2017). Though it is worth noting that, while cognitive work analysis is a robust and flexible framework that is highly useful in analyzing sociotechnical systems and supporting function allocation (e.g., Roth et al., 2019), applying it can be labor-intensive and requires HFE expertise. Therefore, this work suggests only using the WDA, ConTA, and SOCA phases of cognitive work analysis if the following conditions are met:

- Does the work domain have a high degree of uncertainty or complexity?
    - Is there a high degree of unpredictability in the success of the functions?
    - Is the domain not well documented?
    - Is the domain not highly proceduralized?
    - Is there a high degree of nonroutine tasks?
    - Are the job roles not clearly defined or are ambiguous?
    - Are the data sources unclear or ill defined?
- Is there a fundamental change in the allocation of people and technology?

One useful framework that may be used to determine whether cognitive work analysis may be leveraged is Perrow's Classification Scheme (1967; Hendrick and Kleiner, 2001; Table 3). In essence, work domains that are ill defined and have a high degree of variety in the way in which work is performed (nonroutine) may benefit from the use of cognitive work analysis. In the case with the chemistry example, the domain is arguably predictable, well documented, contains mostly routine tasks, and has clearly defined job roles. In fact, a level of SOCA was performed in Figure 38 without formally completing cognitive work analysis to elaborate this point.

Table 3. Perrow's sociotechnical classification scheme.

	Routine with few exceptions	High variety with many exceptions
Well defined and analyzable	**Routine** Well defined problems with few exceptions (e.g., assembly line).	**Engineering** Many exceptions but can be handled using well defined logical processes.
Ill defined and unanalyzable	**Craft** Fairly routine with problem solving relying on experience, judgment, and intuition.	**Nonroutine** Many exceptions and problems that are difficult to analyze.

6.1.3 Step 2. Identify Impacted Roles and Responsibilities

Step 2 entails identifying the impacted roles and their responsibilities. Sources of data that may be used include existing documentation, results from cognitive work analysis (if used), or interviewing stakeholders like in Step 1. The goal of this step is to essentially begin mapping the responsibilities of available staff that support key functions within the work domain, beginning with identifying pain points within these responsibilities as currently performed, and then identifying applicable WROs that address these pain points. Key questions to ask include:

Identify Roles Responsible for Performing Functions.

- What role(s) are responsible in the performance and/or support of the identified functions?
- Who are the main roles of the work domain?

Identify Primary Jobs and Responsibilities for the Identified Roles.

- What are the major responsibilities for the roles identified?
- What jobs do these personnel perform?

Characteristics of the Roles and Responsibilities.

What knowledge, skills, and abilities are required of these personnel?

- What training is required of these personnel? How often? How formal?
- What is the degree of formalization, or degree to which the jobs within the <work system> are standardized?
- What is the degree of centralization, or degree to which formal decision-making is concentrated in a relatively few individuals, groups, or levels high within the organization?

Determine Impact of Roles and Responsibilities.

- Which of the identified roles and responsibilities are significantly impacted by the proposed transformation?
- Are there roles and responsibilities that are highly problematic (i.e., error prone, inefficient, costly, or unnecessarily complex)?

The results from Step 2 may be best suited in tabular format. An example of a completed table, using a hypothetical example, is provided in Table 4.

Table 4. Roles and responsibility mapping.

No	Purpose-Related Functions	Responsibilities (Functions and Tasks)	Role(s)	Current State	Current Pain Points	WRO	ION State	Proposed State	Human Factors Impacts
1	Ensure effective implementation of chemistry program	Manage the activities of chemistry and environmental personnel to ensure the objectives of station and fleet programs are achieved.	Site Manager	Make executive decisions based on OE taken from in-person meetings.	Results can be time intensive due to time required for data collect and analysis.	CB-1	Existing and new in-line sampling and analysis can automate a significant portion of this plant activity. Once installed, these systems pull either a continuous or intermittent sample, analyze for controlled parameters, and then return the samples to the fluid stream or dispose of them in some controlled waste process. They transmit the results to a monitoring data base for processing including alerts for actionable results, initiation of work requests, routing for approvals, and archiving for plant records.	Considering implementation of automated in-line sampling system, as described in ION.	Detailed analysis on availability of existing data and potential new data available from the new system. Understand how this data can be leveraged to support decision-making.
2	Oversight, support, and guidance for chemistry	Conduct regular meetings with section personnel to communicate progress and identify strengths and weaknesses.	Site Manager	In-person meetings relying on combination of self-report and data collected in #5.	See #1.	CB-1	See #1.	See #1.	See #1.
3	Ensure technical specifications are applied	Ensure the sampling, analysis, and administration of the chemistry and environmental procedures are completed and maintained as required by technical specifications.	Supervisor	Manually review data from log in #5 and compare to technical specification.	Data is difficult to extract during in-person discussions without proper analysis tools. Some workarounds like Excel used to support these meetings, but this tool can only be used as an aid.	CB-1	See #1.	See #1.	See #1.
4	Sampling of plant systems and environmental locations	Sample and analyze plant systems and environmental locations as required by site procedures and instructions.	Laboratory Personnel	Manually collect samples and take samples back to chemistry laboratory for analysis.	Task requires considerable time to perform, is labor-intensive, and is error prone due to its manual nature.	CB-1	See #1.	See #1.	Detailed task analysis to focus on the most labor-intensive aspects of sampling and in understanding how the new system can impact the existing process.
5	Log keeping and record management	Review and enter information into the chemistry log or database.	Laboratory Personnel	Manually record data in notebook and enter data into the database.	Data recording is highly manual and error prone.	CB-1	See #1.	See #1.	See #4.
6	Regular daily and weekly meetings	Participate in daily and weekly meetings.	Supervisor, Technical Support, Laboratory Personnel	In-person meetings relying on combination of self-report and data collected in #5.	See #3.	CB-1	See #1.	See #1.	See #1.

6.1.4 Step 3. Identify Major Tasks and Prioritize

The final step to the screening phase entails identifying and prioritizing the major tasks that are part of the impacted roles and responsibilities under analysis. The approach taken here is based on the task analysis method and critical abilities and tasks (CAT) analysis in supporting the prioritization of identified tasks (Stuster, 2019). Specifically, the CAT analysis is a task analysis methodology that first develops an inventory of tasks under study. It then focuses on generating a systematic way of describing each task. Finally, tasks are prioritized by generating a composite score in terms of the task's degree of difficulty, importance, and frequency (DIF) performed. Critical abilities can be generated from the CAT analysis as well if the staffing and qualifications are substantially changed. The following questions and tools can be applied for Step 3.

For selected jobs, identify the major tasks performed for each role.

- Is there a record of existing tasks under the identified job function?
- If no, what are the major or primary task(s) required of each role in performing their job? Develop task statements using a systematic task analysis format adapted from (Stuster, 2019):
  - What is done?
  - To what is it done?
  - How is it done?
  - Why is it done?
    - ***Example:*** *Inspect circuit board, visually, to detect scorching or other evidence of electrical short.* <*What*><*to What*><*How*><*Why*>

Characterize the Tasks by Their Degree of Difficulty.

Table 5. Difficulty score for a task.

<table>
<tr><td rowspan="4">DIFFICULTY</td><td>Difficulty (D) is the degree of how difficult the task is to perform. This refers to the degree of mental or physical workload required.</td><td>Score</td></tr>
<tr><td>The activity (task) is very simple, is easy to perform, and requires the least amount of rigor (low).

Very few steps to complete
Knowledge and skills common to daily work
Easily learned with minimal instructions needed
Few communication demands or distractions
Low time pressure, physical burden, or cognitive effort</td><td rowspan="3">Low (+2.7)

Medium (+5.7)

High (+7.7)</td></tr>
<tr><td>The activity (task) is difficult to perform and requires some rigor (medium).

Some complex aspects of work
Some knowledge and skills unique to the task
Some communication demands or moderate distractions
Moderate time pressure, physical burden, or cognitive effort</td></tr>
<tr><td>The activity (task) is very difficult (high) to perform and requires high levels of rigor.</td></tr>
</table>

	Several complex aspects of work Many steps to complete Significant knowledge and skills unique to the task High communication demands or distraction Requires knowledge-based decision-making (e.g., inductive reasoning) High time pressure, physical burden, or cognitive effort	
	Is a procedure used?	Yes (-1.5) No (0)
	DIFFICULTY TOTAL	

Characterize the Tasks by Their Degree of Importance.

Table 6. Importance score for a task.

	The importance (I) of the task is based on the degree of risk associated with it.	**Score**
IMPORTANCE	The task is low risk. Consequences of improper task execution have negligible impact on plant safety, personnel safety, plant availability, or loss of sensitive or business-important information.	Low (+1) Medium (+3) High (+5)
	The task is medium risk. Consequences of improper task execution have potential impact on plant safety, personnel safety, plant availability, or loss of sensitive or business-important information.	
	The task is high risk. Consequences of improper task execution have direct impact on plant safety, personnel safety, plant availability, or loss of sensitive or business-important information.	
	IMPORTANCE TOTAL	

Characterize the tasks by their degree of frequency performed.

Table 7. Frequency score for a task.

	Frequency (F) refers to how often the task is performed.	**Score**
FREQUENCY	The task is performed more often than quarterly (high).	High (+1) Medium (+3)
	Task frequency is performed less often than quarterly but more often than annually (medium).	

	Task frequency is performed less often than annually, outage only, or designated as an infrequently performed task (low).	Low (+5)
	FREQUENCY TOTAL	

Develop and reuse aggregate DIF scores for each task. Prioritize based on these DIF scores.

Next, the scores captured from each of the tables above are aggregated by multiplying the total scores, such as DIF = Difficulty × Importance × Frequency. The scores can be appended into a table like what is shown in Table 4 and sorted by the highest DIF scores for prioritization. The team will need to determine a threshold cutoff for tasks in the event there are a substantial level of tasks. Tasks that do not make the cutoff can be backlogged for future analysis. The tasks that are prioritized and selected by their DIF scores are determined to be "screened in," and will be further analyzed using the methods described in Section 6.2.

6.2 Detailed Methods

Leveraging the handbook from Stanton et al. (2013), *Human Factors Methods: A Practical Guide for Engineering and Design*, and related sources, this section describes the subsequent detailed HTI methods for analyzing the identified tasks in Section 6.1 to support ION-defined WROs beyond main control room and digital I&C modernization. Within this context, developing the vision and new concept for operations outside of the control room is an important aspect that must be explored. As outlined in INL/RPT-22-68671, there are WROs, like preventative maintenance, that can and should implement new technology to ensure that nuclear power remains a viable source of clean energy. The following tables highlight detailed methods for consideration, based on their characteristics of being a:

- Hazard analysis and risk assessment technique (Table 8)
- Function allocation technique (Table 9)
- Task description and decomposition technique (Table 10)
- Design and testing technique (Table 11).

It is worth noting that these groups broadly follow the phases described in INL/EXT-21-64320 and shown in Figure 36 as an update, beginning at *Developing Human-Technology Integration Requirements through V&V*. The colors of the table headers correspond to the colors for each of the phases in the HTI methodology. It is therefore suggested to apply one method from each table to address HTI across the project lifecycle, following a graded approach. The next subsections describe each of these techniques and links their applicability to CWDs within the ION framework.

Table 8. Hazard analysis and risk assessment techniques.

Method	Training/ Application Time	Advantages	Disadvantages
Technique for Human Error Assessment (THEA)	Low/Medium	Highly structured procedure. Utilizing the method in early design can eliminate issues later in the design cycle.	Limited scope or use. Resource intensive. Terminology may be difficult for non-HFE professionals.
Systems Theory Accident Modeling and Process	High/High	Utilized in many domains.	Resource intensive. Complex to conduct.

Method	**Training/ Application Time**	**Advantages**	**Disadvantages**
(STAMP) and Related Frameworks (i.e., STPA)		Can be used for accident analysis, hazard analysis, and developing accident prevention requirements.	Needs large amount of detailed data for comprehensive investigation.
Hazards and Consequences Analysis for Digital Systems (HAZCADS)	High/High	Integrates STPA and fault tree analysis into a cohesive method. Can be utilized at any stage (design, implementation, operation). Can be applied to both digital and analog systems.	Limited scope or use. Novel method being validated. Requires formal training. Resource intensive. Complex to conduct.

Table 9. Function allocation techniques.

Method	**Training/ Application Time**	**Advantages**	**Disadvantage**
Decision Ladders (i.e., in Cognitive Work Analysis Framework)	High/High	Leverages the cognitive work analysis framework. Focuses on decision-making in terms of human-system teaming. Effective approach for determining information requirements that support decision-making across normal and abnormal situations.	Requires HFE expertise. Resource intensive. Complex to conduct.
Coactive Design	High/High	Examines interdependency between people and automation to holistically support interaction requirements. Extends off task description and	Requires HFE expertise. Complex to conduct. Limited scope or use. Novel method being validated.

Method	**Training/ Application Time**	**Advantages**	**Disadvantage**
		decomposition methods.	
Sociotechnical Method for Designing Work Systems	Medium/Medium	Examines function allocation trade space. Extends off traditional function allocation methods like Fitts's List.	Requires HFE expertise. Complex to conduct. Limited scope or use. Novel method being validated.
Fitts's List	Low/Low	Easy to apply. Widely used and accepted across industry.	Does not address teamwork or interdependencies. Applies criteria that may not address function allocation with emerging technology. Often seen as creating the "leftover" problem of allocating most functions to automation and leaving the person with leftover functions (negatively impacting joint optimization).

Table 10. Task description and decomposition techniques.

Method	**Training/ Application Time**	**Advantages**	**Disadvantage**
		Common Approaches	
Hierarchical Task Analysis (HTA)	Medium/Medium	Input for a variety of HF methods. Extensive use in numerous domains. Provides a description of a task.	Only provides descriptive information. Does not provide information on the cognitive components of a task. Time consuming to implement.
Tabular Task Analysis (TTA)	Low/Medium	Can be developed by directly expanding on results produced in Section 6.1 (e.g., tables produced).	Time-consuming to implement.

Method	Training/ Application Time	Advantages	Disadvantage
		Flexible method that can be catered toward the goals of the analyst. Can provide information on numerous components of an interface.	
Specialty Approaches			
Groupware Task Analysis (GTA)	Medium/High	Provides the design team with the current state of the system. Output provides redesign recommendations.	Time consuming to implement. Limited scope or use. Large team required to conduct the method.
Operational Sequence Analysis and OSDs	Medium/High	Graphically depicts a task or scenario. Useful for characterizing interactions between people and machines when performing a task. Useful for team-based tasks or scenarios.	Depicting large, complex tasks is time consuming and laborious.
Comms Usage Diagram (CUD)	Low/Medium	Provides detailed description of the task. Technology used is analyzed and recommendations are provided.	Limited scope or use. Time consuming to implement.

Table 11. Design and testing techniques.

Method	Training/ Application Time	Advantages	Disadvantage
Cognitive Walkthrough	Medium/Medium	Low cost. Provides design feedback without access to users. Provides useful output for interface design	The analyst should be skilled in the method to utilize its full potential.

Method	Training/ Application Time	Advantages	Disadvantage
		based on a task perspective (complementary to heuristic evaluation).	
Heuristic Evaluation	Low/Low	Low cost. Provides design feedback without access to users. Provides useful output for interface design based on a design principal perspective (complementary to cognitive walkthrough).	Generally limited to user interfaces. Does not address design issues from a task perspective. Often finds issues that are cosmetic in nature.
Usability Testing	Medium/High	Provides design feedback from actual users. Considered a staple method in HFE for this reason. Enables a wide range of data collection methods, ranging from observations, interviews, and physiological measures.	Time consuming to implement. The analyst should be skilled in the method to utilize its full potential (i.e., anyone can facilitate a usability test but requires someone versed in HFE to facilitate one effectively).

6.2.1 Hazard Analysis and Risk Assessment Techniques

This section describes applicable hazard analysis and risk assessment techniques outlined in Table 8.

6.2.1.1 Technique for Human Error Assessment

THEA is classified within the human error identification and accident analysis methods and provides a structured assessment to help identify potential user interaction issues. THEA has traditionally been used to aid in interface design, but its domain of application is generic (Stanton et al., 2013). THEA is utilized as a design method but can also be utilized retrospectively to give additional data and support to numerical analyses (Pocock et al., 2001).

How to Perform the Method

THEA utilizes two primary inputs to assess the system design. The first input for THEA consists of a detailed system description to gain an overview of the design being considered; the system description typically utilizes an expert with the system or within the domain of the application. The second input consists of usage scenarios that provide actions within the system and contextual factors that impact the actions within the system. These contextual factors provide insight into the situations in which the action happened and the opportunities for error within the system. To provide as much context as possible, a template consisting of the following information is used within the THEA framework is shown in Table 12.

Table 12. THEA template (adapted from Stanton et al., 2013).

Agents	The human agents involved and their organization. The roles played by the humans, plus their responsibilities and goals.
Rationale	Why is this scenario an interesting or useful one to have picked?
Situation and Environment	The physical situation that the scenario takes place in, including environmental and external triggers, problems, and events that happen within in this scenario.
Task Content	Provide information about the task. What task(s) are performed? Which procedures exist and will they be followed as prescribed?
System Context	What devices and technology are involved? What usability problems might participants have? What effects can users have?
Action	How are the tasks carried out in context? How do the activities overlap? Which goals do actions correspond to?
Exceptional Circumstances	How might the scenario evolve differently, either as a result of uncertainty in the environment or because of variations in agents, situation, design options, and system and task context?
Assumptions	What, if any, assumptions have been made that will affect this scenario?

Task Description and Goal Decomposition

The next step is to create a task description and goal decomposition. The task description is typically achieved through an HTA. An HTA provides a structured approach to describing the goals, plans, and intended actions that an operator would perform in the chosen scenario for investigation. The HTA can then be used to break down the goals of the task into operations (Stanton et al., 2013).

Perform Error Analysis

Next, the error analysis is conducted based on a structured, checklist-style approach that aids the analyst in identifying potential errors. The analyst asks questions about the scenario utilizing the THEA framework. The possible failures and associated questions from Pocock et al. (2001) are highlighted in Table 13.

Table 13. Examples of cognitive failure and associated THEA questions (adapted from Pocock et al., 2001).

Stage	**Cognitive Failure(s)**
Goals Are items triggered by stimuli in the interface, environment, or task? Does the user interface "evoke" or "suggest" goals? Do goals come into conflict? Can a goal be achieved without all its "subgoals" being correctly achieved?	Lost/unachievable/conflicting No triggering/activation Triggering/activation at wrong time, or wrong goal activated
Plans Are there well practiced and predetermined plans? Can actions be selected in situ, or is preplanning required? Are there plans or actions that are similar to one another? Are some used more often than others?	Faulty/Wrong/Impossible
Actions	Slip/lapse

Is there physical or mental difficulty in executing the actions? Are some actions made unavailable at certain times? Is the correct action dependent on the current mode? Are additional actions required to make the right controls and information available at the right time?	
Perception and Interpretation Are changes (resulting either from user action or autonomous system behavior) perceivable? Are the effects of actions perceivable immediately? Does the item involve monitoring, vigilance, or continuous attention? Can the user determine relevant information about the state of the system? Is the relation of information to the plans and goals obvious? Is complex reasoning, calculation, or decision-making involved? Is the correct interpretation dependent on the current mode?	Failure to perceive correctly Misinterpretation

For credible errors, the investigator records the error, the cause of the error, and the consequences of the error. The layout for conducting the error analysis consists of the question, causal issues, consequences, and design issues (Stanton et al., 2013).

Design Recommendations

Upon completion of the analysis, the investigator can then give design recommendations or remedies for the identified errors. There is no set guidance on the recommendations to be given, so the analyst's best judgment is necessary.

Advantages and Disadvantages

The advantages of THEA that are highlighted by Stanton et al. (2013) are:

- THEA provides a structured approach to human error identification
- Easy to learn and use
- Potential problems can be identified and fixed before implementation
- Utilizes high-level prompts to guide the analyst
- Error questions have associated consequences and design issues
- Generic in application
- Provides insight into user difficulties with interface design.

The disadvantages of the THEA that are highlighted by Stanton et al. (2013) are:

- THEA does not use any error modes
- Resource intensive and time consuming
- Error consequences and design issues are limited and generic
- Currently, there is no validation evidence
- Creating an HTA, task decomposition, and scenario description create additional work
- The jargon utilized in this method may be troublesome for non-HF practitioners.

Industry Applications

THEA, as mentioned by Stanton et al. (2013), is generic in domain application and has been used in the aviation industry for flight deck studies to provide human error analysis in the early design phase (Fields et al., 1997). Additionally, THEA has recently been expanded into the field of usability with a study that explored using THEA for e-textbook usability (Jardina and Chaparro, 2015).

ION Application

THEA is a potential method that can be used to aid in the development and evaluation of HSIs and work systems. Since THEA is structured and accessible to non-HFE professionals, the method can be applied by anyone and may be particularly useful if used by someone familiar with the interface under analysis.

6.2.1.2 Systems Theory Accident Modeling and Process

STAMP is classified as an accident analysis method that utilizes a systems theory perspective to explore the causes of accidents (Stanton et al., 2013). The STAMP method considers the social structures within an organization and attributes accidents to not only system failures but also safety issues and improper system development (Zhang et al., 2022). Although STAMP is typically used for accident analysis, the method may also be helpful for hazard analysis, developing accident prevention systems, and risk assessment. The concepts included within the STAMP analysis are constraints in the system, control loops and process models, and levels of control within the sociotechnical system. STAMP does not provide a means to lay blame to parties involved in accidents but instead investigates sociotechnical systems to understand which part of the system contributed to the accident (Levenson, 2004).

How to Perform the Method

The following steps are used to perform STAMP.

Define Tasks for Analysis

The task that will be analyzed should be identified; this should align with those identified and prioritized in Section 6.1. Additionally, the goals and boundaries of the analysis must be created to ensure the analyst is investigating the appropriate and relevant information (Stanton et al., 2013).

Collect Data

The next step is to gather relevant and detailed information about the accident (if applicable), domain, and organization. Useful information for this step includes accident reports (if applicable), task analysis of the system and task, inquiry reports, interviews with personnel within the organization, documents applicable to the domain (regulations, standards, operating procedures), and interviews with SMEs within the organization or domain (Stanton et al., 2013).

Create Hierarchical Structure of Control

After gathering the relevant data, the analyst can then construct the control structure within the organization. To do this, the analyst needs to identify the main people involved in the accident (if applicable) or are involved in the system process by using the data collected previously. The people identified in this step will most likely be spread throughout the control structure. Additionally, people who produce guidelines, policies, and protocols are helpful to identify during this step. A graph outlining the people involved should then be created to highlight their position within the hierarchical structure of the organization. After developing the control structure, the constraints within the organization are then highlighted by incorporating arrows that show the flow and type of communication between the levels. An example of the STAMP adapted from Stanton et al. (2013) is highlighted in Figure 39.

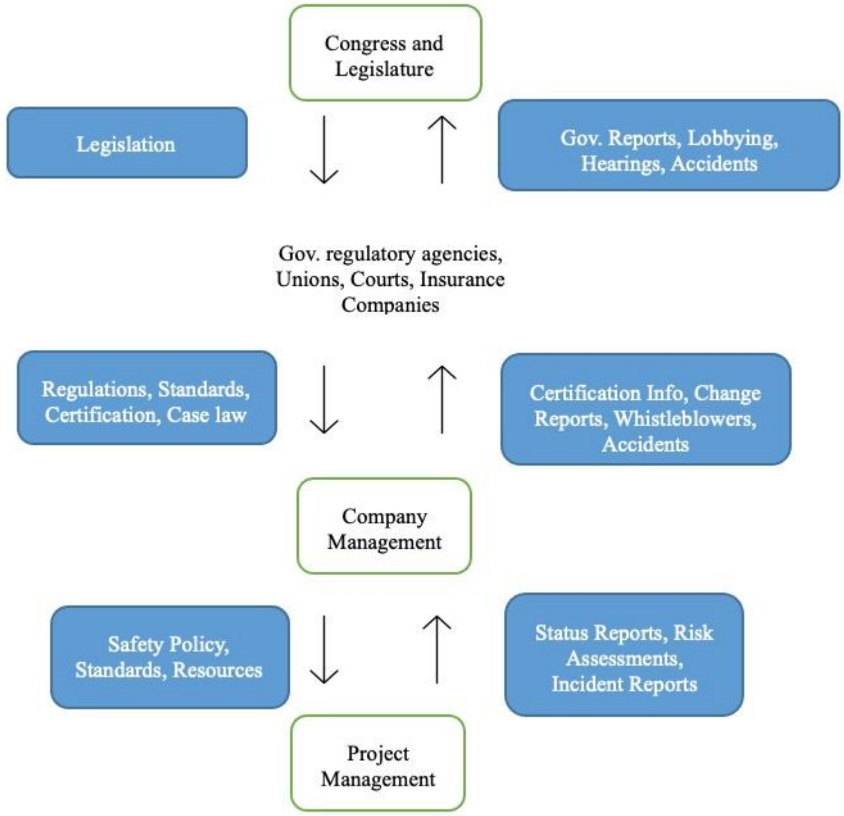


Figure 39. STAMP control structure.

Classify Flawed Controls

The next step is to use the identified elements within the control structure to classify each according to the classification of flawed control. The classification system should be applied to each interaction within the control loops. Table 14 shows the classification of flawed control as found from Leveson (2004).

Table 14. STAMP flawed control classification (adapted from Levenson, 2004).

1. **Inadequate Enforcement of Constraints (Control Actions)**
    - 1.1 Unidentified hazards
    - 1.2 Inappropriate, ineffective, or missing control actions for identified hazards
        - 1.2.1 Design of control algorithm (process) does not enforce constraints
            - Flaw(s) in creation process
            - Process changes without appropriate change in control algorithm (asynchronous evolution)
            - Incorrect modification or adaptation
        - 1.2.2 Process models inconsistent, incomplete, or incorrect (lack of linkup)
            - Flaw(s) in creation process
            - Flaw(s) in updating process (asynchronous evolution)
            - Time lags and measurement inaccuracies not accounted for
        - 1.2.3 Inadequate coordination among controllers and decision makers (boundary and overlap areas)
2. **Inadequate Execution of Control Action**
    - 1.1 Communication flaw

1.2 Inadequate actuator operation
1.3 Time lag

3. **Inadequate or Missing Feedback**
   1.1 Not provided in system design
   1.2 Communication flaw
   1.3 Time lag
   1.4 Inadequate sensor operation (incorrect or no information provided)

Review and Finalize Analysis

Upon completion of the initial STAMP analysis, the analyst should then review the work (with an SME if possible) to check that all failures were identified and integrated into the model. This process is iterative, and multiple versions are to be expected (Stanton et al., 2013).

Advantages and Disadvantages

The advantages provided by Stanton et al. (2013) include:

- Control flaws classification provides different levels of analysis, which allows for a more holistic exploration of the accident or hazard
- Provides a way to investigate relationships between factors and nonlinear interactions
- Can be used for accident analysis, hazard analysis, and development of safety and risk assessments
- STAMP is used in many domains
- STAMP has a taxonomy for potential failures and a control structure template to help the analyst
- The method is systemic and supported by an abundance of contemporary HFE research.

The disadvantages provided by Stanton et al. (2013) include:

- STAMP is resource intensive
- STAMP requires an immense amount of detailed data to conduct a holistic investigation
- The method might not be able explore reasoning behind actions.

Industry Applications

STAMP is a widely used method that is generic in nature, which allows it to be applied to any domain with complex sociotechnical structures. STAMP was utilized in the military to explore friendly-fire incidents, the incident which resulted in the loss of the Milstar satellite, and a contamination incident in which Escherichia coli was introduced into a water supply in Canada (Leveson, 2004). Another study utilized STAMP to explore the Sewol Ferry accident and found that STAMP was a more reliable method than Accimap because of its structured approach (Goncalves Filho et al., 2019). Additionally, STAMP was used as a safety assessment of road tunnels and their ventilation systems (Kazaras et al., 2012). Finally, Alvarenga et al. (2014) recommended the utilization of STAMP within the nuclear industry for human reliability analysis.

ION Application

STAMP is a generic accident and hazard analysis technique that could aid in modeling the sociotechnical structures of tasks outside of the control room and can be applied in any area where people interact with technology and team members. This method could potentially be applied outside of the control room to identify hazards in preventative maintenance, planning, scheduling, automated assistance, and physical security. To note, STAMP has been applied in the LWRS Program research area of information automation (refer to Section 2.2.1).

6.2.1.3 Hazards and Consequences Analysis for Digital Systems

HAZCADS was developed by EPRI and is a combination of methods (e.g., STPA, probabilistic risk analysis, and fault tree analysis) used to support the hazard analysis of new digital I&C systems within nuclear facilities (EPRI 3002016698, 2021). The goal of the HAZCADS method is to complement the DEG (2021) and provide digital system designers with a structured approach to identify plant and system hazards, potential consequences, and risk sensitivity. Because HAZCADS is not publicly available without purchase, the reader may refer to EPRI 3002016698 (2021).

Advantages and Disadvantages

Advantages include:

- HAZCADS combines two methods to provide a more holistic understanding of the system and potential failures
- The STPA provides guidance to the analyst on how to conduct the method
- HAZCADS provides information for the design of digital systems
- Created specifically for the nuclear industry.

Disadvantages include:

- EPRI recommends taking a paid training course to learn how to conduct this method
- A diverse multidisciplinary team is needed to conduct HAZCADS
- An STPA practitioner is recommended to be included on the analysis team.

Industry Applications

The HAZCADS method was created for the nuclear industry to provide a better means of conducting a hazard analysis on digital systems.

ION Application

HAZCADS was created for the nuclear industry to aid designers in identifying hazards and subsequent consequences, so this method can be applied wherever digital systems are used within the plant.

6.2.2 Function Allocation Techniques

The function allocation techniques outlined in Table 9 are described in detail in INL/RPT-22-68472, Section 3.4. Collectively, the function allocation toolset described is characterized in Figure 40. This figure characterizes how such function allocation methods can be applied to address very specific considerations including analyzing operational demands and work requirements, exploring alternative distributions of work, examining interdependencies between people and automation, and exploring function allocation trade spaces.

Analyze Operational Demands and Work Requirements	Explore Alternative Distribution of Work	Examine Interdependencies	Explore Trade-Space
Objectives			
Understand the nature of the work being performed and corresponding challenges	Explore different options of work distribution across proposed automation	Analyze the interactions required to perform work and how joint performance between people and automation can be optimized	Evaluate the trade-space in function allocation between people and automation
Entry Conditions (If 'Yes' to Any Question, to Proceed)			
• Is there a change in function allocation?			
• Is there ambiguity or no proposed change allocation of function? (i.e., blank slate)			• Is function allocation already defined for proposed system? • Are there alternative allocation options?
• Is the work environment clearly defined? • Are there fundamental changes to the existing work system? New domain goals or changes to fundamental purpose of system?	• Are there multiple allocation alternatives possible with the new system? • Does the system necessitate a need for dynamic function allocation (i.e., fluid distribution of work otherwise known as adaptive automation)?	• Is there interdependencies with the proposed automation (i.e., shared distribution of work)?	
Possible Methods and Tools (Used in Nuclear? Y/N)			
Method Cognitive Task Analysis Knowledge Elicitation Techniques: Y Cognitive Work Analysis – Abstraction Hierarchy: Y	**Method** Cognitive Work Analysis – Abstraction Hierarchy: Y Cognitive Work Analysis – Contextual Activity Templates: Y	**Method** Cognitive Work Analysis – Decision Ladders: Y Coactive Design: N System Theoretic Process Analysis: Y	**Method** NUREG/CR-3331 and EPRI 3002004310 approaches: Y Sociotechnical Method for Designing Work Systems (Waterson et al., 2002): N Simulation and Modeling: Y Multidisciplinary Team: Y
Outcome			
• Understand the work domain or changes to domain • Hierarchy and means-end analysis of functions to overall domain goals	• Identify range of possible allocation alternatives and possibility of dynamic assignment	• Identify interdependencies between people and automation to inform allocation of function (or alternatives)	• Evaluate trade-offs in allocation of function to determine joint optimization between people and automation

Figure 40. Integrated function allocation toolset (adapted from INL/RPT-22-68472).

6.2.3 Task Description and Task Decomposition Techniques

This section describes applicable task description and task decomposition techniques outlined in Table 10.

6.2.3.1 Hierarchical Task Analysis

The HTA is one of the most widely used techniques and typically serves as input for other HFE methods. An HTA describes the actions and activity within a task and highlights the goals, subgoals, plans, and operations to conduct the task (Stanton et al., 2013). Figure 41 illustrates a typical HTA output.

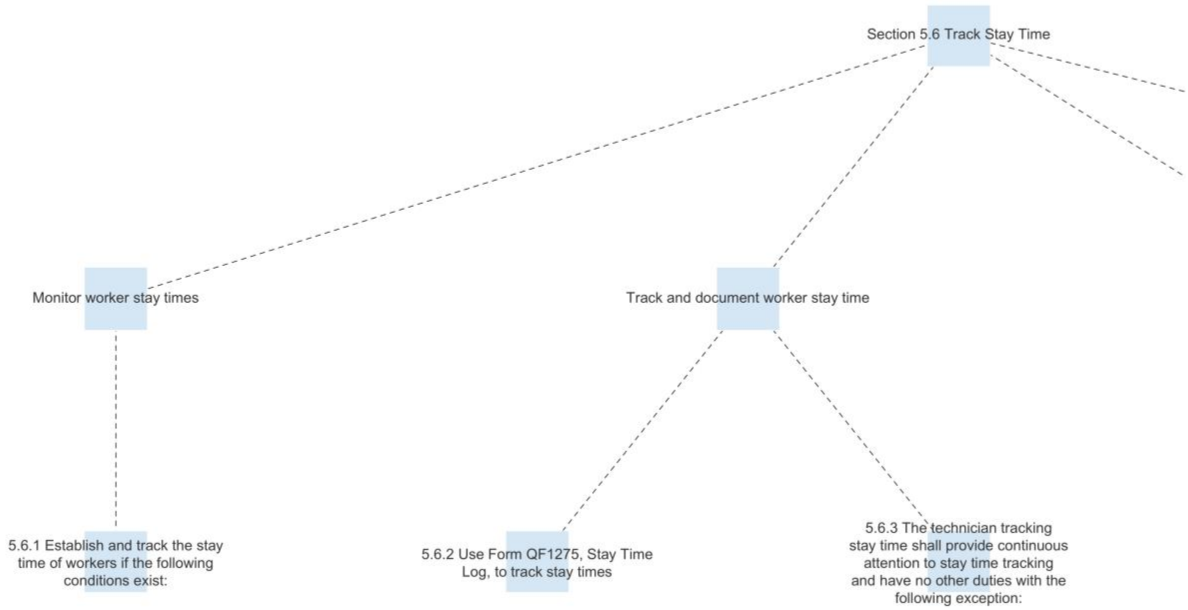


Figure 41. Example hierarchy developed from task analysis.

How to Perform the Method

The following steps are used to perform HTA.

Define the Task

The first step for conducting an HTA is to understand what task is being analyzed and why; the output of Section 6.1 can be used here. An HTA is generic in nature, so having a clear picture of what is being analyzed is necessary. An example of defining the task is conducting an HTA of a routine maintenance task to discover any procedural errors within the task instructions.

Collect Data

Data about the task is then collected to inform the analysis. The information necessary to conduct an HTA are the steps involved in the task, technology used, interaction between people and machines, decision-making components, and task constraints. There are multiple avenues to collect the necessary information but typically interviews with SMEs, walkthroughs, and questionnaires are used (Stanton et al., 2013).

Determine the Primary Goal of the Task

The main goal of the task should be the overall reason for conducting it. The main goal should be broad and brief. Examples of a main goal include writing a research paper, changing a flat tire, or building a desk.

Determine the Subgoals

Next, the subgoals of the task need to be determined. Typically, there are four or five subgoals, but that is in no way the requirement. The subgoals should be meaningful and contribute to achieving the main goal when combined. Some possible subgoals for building a desk are gathering tools and information, building the desk cabinet, building the drawer frame, and building the inner desk components.

Decompose the Subgoals

The subgoals are then broken down into other subgoals and operations. This process continues until the appropriate operation for the task is identified. The lowest level of the HTA should always be an operation. Operations are the actions needed to complete the subgoals and main goal and are completed by the agent within the system. Examples of an operation for building a desk are gather a hammer and screwdriver, lay out cabinet parts, and hammer nails into the cabinet.

Plan Analysis

After decomposing the subgoals and getting to operations within the task, the analyst can then add the plan to the HTA. Plans show how the goals are achieved with each step. The basic plan in an HTA is to do Step 1, then 2, then 3, and so forth. Plans do not need to be linear. Below is a list for the types of plans that can be used in an HTA:

- Linear: Do 1, then 2, then 3
- Nonlinear: Do 1, 2, and 3 in any order
- Simultaneous: Do 1, then 2 and 3 at the same time
- Branching: Do 1 if *X* is present. Then do 2 and then 3, but if *X* is not present then exit
- Cyclical: Do 1, then 2, then 3 and repeat *Y* times
- Selection: Do 1, then 2 or 3.

Advantages and Disadvantages

The advantages of an HTA highlighted by Stanton et al. (2013) are:

- Minimal training is required to learn the method and it is easy to implement
- Output is useful and used for a wide range of domains (error analysis, interface design, function allocation)
- Flexible and quick to use in most cases
- Generic
- Can be used as input or to supplement other methods.

The disadvantages of the HTA highlighted by Stanton et al. (2013) are:

- The output provides a description of the task rather than an analysis of the task
- Does not provide information for design solutions
- Does not incorporate cognitive elements of the task under analysis
- May become time consuming and labor-intensive for large tasks
- Requires the analyst to be competent in HF data collection techniques like interviews and observations
- Reliability is questionable; two analysts may produce different results on the same task
- Requires lots of practice before becoming proficient in the technique.

Industry Applications

The HTA has been applied in a wide range of industries. Some examples include procedural tasks like changing printer cartridges and analyzing surgical techniques and air traffic control systems. Additionally, an HTA has been used for creating training processes in the petrochemical industry and analyzing team collaboration in the medical industry (Annett, 2004).

ION Application

The HTA is a general-purpose method that typically serves as input for many other human factors methods. This task analysis method would most likely be used in conjunction with other methods for designing and assessing areas in the nuclear power plant.

6.2.3.2 Tabular Task Analysis

The TTA is another method to describe and analyze tasks or scenarios by outlining the steps and interfaces needed to perform the task. The bottom-level steps from an HTA are used as input to complete the analysis. The TTA can provide information about the interfaces used in the task, potential errors, feedback, and error consequences. This is not an exhaustive list of what the TTA can provide since the method is flexible and can be modified to fit the task under analysis (Stanton et al., 2013).

How to Perform the Method

The following steps are used to perform TTA.

Define the Task

The first step is to understand the task or scenario for analysis. The information needed for the TTA includes the task under analysis, the system within the task, the environment, and the agents involved in the task (Stanton et al., 2013).

Collect Data

Data about the task then needs to be gathered to aid in analysis. The data needed includes the task steps, task sequence, the technology used in the task, the agents in the task, and the communication between agents, technology, and other team members. To collect this information, observations, interviews, and questionnaires are typically used. Utilizing a combination of data collection techniques is recommended so that the task and interactions between agents is captured comprehensively (Stanton et al., 2013).

Conduct HTA

Using the data collected in the previous step, the analyst should then create an HTA to describe the task under analysis (see Section 6.2.3.1; Stanton et al., 2013).

Convert the HTA into a Tabular Format

The HTA created in the previous step is then converted to tabular format by placing the bottom-level operations from the HTA into columns (Stanton et al., 2013). Figure 42 provides an example of TTA previously used by Kovesdi et al. (2021).

Sub-Tasks Required *(Sub-Tasks that are not included in the procedure?)*	Information Needed to Perform Tasks/ Sub-Tasks *(What information is needed to monitor, make and implement decisions, and get relevant feedback?)*	Sources of Information *(Where is this information found?)* *(e.g., procedures, manuals, direct observation, displays, verbal communication, knowledgable source such as person, etc.)* *Is obtaining any information problematic?*
Survey immediately prior to beginning work if radiological conditions are unknown or potentially unstable.	1. Understanding of work to be performed, and required equipment to perform work (job coverage requirements) 2. Familiarity with work environment 3. Radiation and contamination levels (historical and current) 4. RWP and ALARA Plan Need to know what kind of work is being planned, where in the space the work will be conducted, low-dose waiting areas, what activities are being conducted, can we relocate people or body position to minimize exposure, e.g., can a shield be used (manually placed). RWP - type in all the info we want. Dose and dose rate set points. Need a pre-job survey. Planning procedure helps us determine max dose rate. Getting to the point where it's beginning to be automated. Data from pre-job survey is needed. Might have to send somebody to go do it.	1. Radiation Work Permit (RWP) and ALARA Plan 2. Memory, PTZ cameras, debriefing 3a. (Historical) Recent surveys, RP logs, Condition Reports 3b. (Current) Dosimeters, (GEDDS?) RWPs - Old work orders are accessed to obtain information specific to the job. Typing in key words heps to identify relevant work orders. They have a speech-to-text option for this as well. Need to understand what you're looking for - drill-downs are there. Historical job files - hard copies of previous work orders. Maybe reference them once a month. if it's possible to find it on the computer, would rather do it that way. "Most info I need is on the computer."

Number and type of workers involved (e.g., RP techs, supervisors, and workers)	Key Interactions with Others *With whom?* *About what?* *How accomplished? (remote, face-to-face, etc.)* *Bottlenecks?*	Criticality of the Interactions for Task Completion and Personnel Safety *(e.g., increased radiation condition that possibly causes need for immediate action, time running out to complete the job before dose rate exceeded)*	Estimated time to per *(Used to evaluate oppo that will reduce time to p*
Most jobs will only take one person unless you need someone to help build the survey. Supervisor, who reviews and approves the survey. Maintenance workers will sometimes be asked to come along and show how they intend to go about the work, positioning, etc. We will sometimes make recommendations to the maintenance workers about body positioning, work processes, worker selection, etc. - particularly for major evolutions.	One rad tech is in the room and another who is remote. Rad tech obtains survey approval from supervisor. "Sometimes there can be bottlenecks with maintenance but 90% of the time there aren't."	"If we don't get the survey we can't plan the work and if we can't plan the work then we'll be holding up important activities - so it's critical that we get the serves when we need them."	10-15 minutes to physic approx. 15-30 minutes t are the data recorded? If a prior record exists, t might only take about 5

Figure 42. Portion of TTA used in previous LWRS Program sociotechnical R&D (adapted from INL/EXT-21-64428).

Choose Categories for Analysis

Categories for analysis are then chosen and entered into the TTA. The categories for analysis are dependent on the task under analysis. If the goal of the analysis is to explore design-induced errors, some categories that may be helpful relate to errors, consequences, and remedies (Stanton et al., 2013). INL/EXT-21-64428 utilized TTA, which is also shown in Figure 42. This work used a number of different categories ranging from perceptual, cognitive, and physical demands of each subtask to the applicability of potential innovations to support the subtask in question.

Complete TTA

After defining the categories, the analyst can then go through the table and fill out the boxes that correspond with the category and task step. This step is typically completed using a walkthrough analysis, interviews and observations with an SME, or a heuristic evaluation. There is no set standard on which technique to use for completing the TTA (Stanton et al., 2013).

Advantages and Disadvantages

The advantages of the TTA highlighted by Stanton et al. (2013) are:

- Flexible and can provide a comprehensive analysis of the task
- TTA is easy to learn and implement
- Generic

- Analyst decides the categories for analysis, which allows numerous aspects of the task to be evaluated.

The disadvantages of the TTA highlighted by Stanton et al. (2013) are:

- Although potentially exhaustive, the TTA may be time consuming to implement due to constructing an HTA and collecting data
- Reliability is questionable
- An HTA is sufficient in most tasks and scenarios.

Industry Applications

The TTA has been used in multiple industries, such as aviation and nuclear (Stanton et al., 2017; Staples, 1993). Typically, the TTA is utilized alongside an HTA for holistic view of the task under analysis. One instance of the TTA in the nuclear industry is its use in the design and development of the MAPLE-X10 reactor. Both an HTA and a TTA were used to provide information on tasks for verifying the design, identifying training requirements, and providing a foundation for other assessments like human reliability analysis (Staples, 1993). TTA was also applied in previous work to support modernizing the radiological protection work domain (Kovesdi et al., 2021). As such, this method is very robust and flexible to be applied across a range of applications.

ION Application

The TTA is a generic task analysis method that can be used in conjunction with an HTA to provide specific information on the task since the analyst chooses the categories for analysis.

6.2.3.3 Groupware Task Analysis

The GTA is a method that provides an analysis of team and system activities to aid in the design of systems and processes. The advantage of this method is that it models the task in the current state as well as the redesign of the current system. The current state of the system (Task Model 1) is a description of the current state of the system while the redesign state (Task Model 2) envisions what the system will be like with the integration of changes (e.g., new technology and processes). The task models give a holistic view of the system by incorporating agents (people who perform within the system), work (task[s] under analysis), and situation (description of the environment and object within the environment) (Stanton et al., 2013; Van Welie and Ven Der Veer, 2003).

How to Perform the Method

The following steps are used to perform GTA.

Define the System

To begin, the system under analysis should be defined. The domain of application for this method is generic, so a clear view on what exactly is being investigated is necessary. Some examples of system definitions are control rooms, preventative maintenance, and security systems (Stanton et al., 2013).

Collect Data

Data on the existing system structures must be collected first. This may include data from existing documentation or discussions with domain experts. Some techniques that can be used to gather information on the existing system are interviews, observational analysis, and questionnaires. To gain a holistic view of the system under analysis, the data collection should be comprehensive by identifying task steps, procedures, interfaces, personnel, and the environment (Stanton et al., 2013).

Construct Task Model of the Existing System

The first task model can be constructed after sufficient data about the system and its components are collected. Task Model 1 should include a description of the task as it is currently implemented with the agents, work, and situation (Stanton et al., 2013). Agents within the system typically refer to people or teams of people but can also refer to the system itself. Additionally, the roles that the agents within the system play must also be considered. Roles refer to the skills and tasks that agents within the organization have, and multiple agents may play the same role (Van Welie and Van Der Veer, 2003). Work refers to the tasks and actions performed within the system. Tasks vary in their levels of complexity, and more complex tasks can be split between agents and roles within the system. These tasks can then be decomposed into specific actions. Context is necessary when identifying actions because an action in one system may mean something different in another system. The situation refers to the environment within the task world and the objects within that environment that are necessary to perform the task. Objects are not only physical items but may also be abstract or conceptual things like passwords, gestures, or signatures (Van Welie and Van Der Veer, 2003).

Construct Task Model of the Proposed System

The second task model can be constructed after Task Model 1 is complete. The goal of Task Model 2 is to redesign the current system to incorporate technological answers to problems and requirements within the system. To construct Task Model 2, the design team meets and discusses the redesign. The redesign discussions are typically completed by utilizing focus groups or brainstorming sessions (Stanton et al., 2017). Task Model 2 may be structured the same way as Task Model 1 but should be a prescriptive model that describes the task as it will be after the system redesign (Van Welie and Van Der Veer, 2003).

System Redesign

After both task models are constructed, the system redesign can take place. The redesign is dependent on what the system under analysis is and the direction that the design team would like to go. Van Welie and Van Der Veer (2003) provide an in-depth discussion of ways design teams can work on the redesign based on the system under analysis. The main questions that Van Welie and Van Der Veer (2003) emphasize should be answered are:

- What are the critical tasks?
- What is the frequency of those tasks?
- Are those tasks always performed by the same user?
- What types of users are there?
- What are the roles of the users?
- Which tasks correlate with the roles?
- Which tasks should be revocable in the system?
- Which tasks have irrevocable consequences?
- What errors can be expected?
- What are the error consequences to the user?
- How can prevention be utilized for these errors?

Advantages and Disadvantages

The advantages provided by the GTA as found by Stanton et al. (2013) include:

- A detailed description of the system, its requirements, and specific issues are provided by a GTA

- Task Model 2 has the potential to provide technologies for redesign and current availability
- The design team is provided with a potentially comprehensive and detailed understanding of the current system and its problems
- Suited to analyze existing command and control systems
- The GTA can model complex systems that have multiple users.

The disadvantages of the GTA as found by Stanton et al. (2013) include:

- Resource intensive and time consuming
- Limited use and evidence in literature
- Provides limited guidance to investigators
- A large team is necessary to conduct a GTA.

Industry Applications

The domain of application is generic for the GTA (Stanton et al., 2013). Past uses for the GTA include highly complex system redesigns for companies that produce high-tech machines, safety and security systems, and control room layouts (Puerta Melguizo et al., 2006; Van Welie and Van Der Veer, 2003).

ION Application

The GTA is a generic method suited for a complex system redesign that could aid in identifying and redesigning tasks to account for new technology outside of the control room. The GTA can also be utilized in conjunction with other HFE methods (e.g., HTA, TTA, or STAMP) to provide a comprehensive analysis of the system.

6.2.3.4 Operational Sequence Analysis

Operational sequence analysis and its output, the OSD, is a process charting method used to graphically describe interactions between technology, agents, and team members within a system. The output of an OSD presents the overall task process with symbols to represent interactions between the components (i.e., or agents—human or technology) of the system. OSDs can be adapted to the level of task complexity, which can range from simply depicting a task flow to modeling interactions and communication between team members during the task (Stanton et al., 2013).

How to Perform the Method

The following steps are used to develop an OSD.

Define the Task under Analysis

The first step is to clearly define the task and understand the activity and agents that are necessary for task completion (Stanton et al., 2013). This may entail a subset of tasks within a scenario (i.e., use case; refer to microlevel tasks from Figure 16) or consist of an individual task in isolation.

Collect Data

Data on the task must be collected to construct an OSD. Typically, observational studies and interviews with people involved in the task are used to gather the necessary information for the OSD (Stanton et al., 2013).

Define the Task

After collecting the necessary information, the analyst can then construct an HTA or TTA to gain a description of the task. The type of task analysis that is chosen depends on the analyst and their needs and goals. In some cases, a simple task list is sufficient, but it is recommended to combine OSDs with other task analysis methods like TTA or HTA for a more holistic approach (Stanton et al., 2013).

Construct the OSD

After sufficiently describing the task, the analyst can then construct the OSD. It is recommended to utilize the OSD template for the analysis, which includes the title of the task or scenario, a timeline, and a row for each agent involved in the task. The analyst can then walk through the HTA while constructing the OSD to ensure that nothing is missed in the task. Arrows are used to represent the flow of activity and information between the agents in the system. The other symbols used in the analysis should correspond to the symbols found in the HTA. The technology used in the task should also be included in the OSD (Stanton et al., 2013). An example OSD is shown in Figure 43.

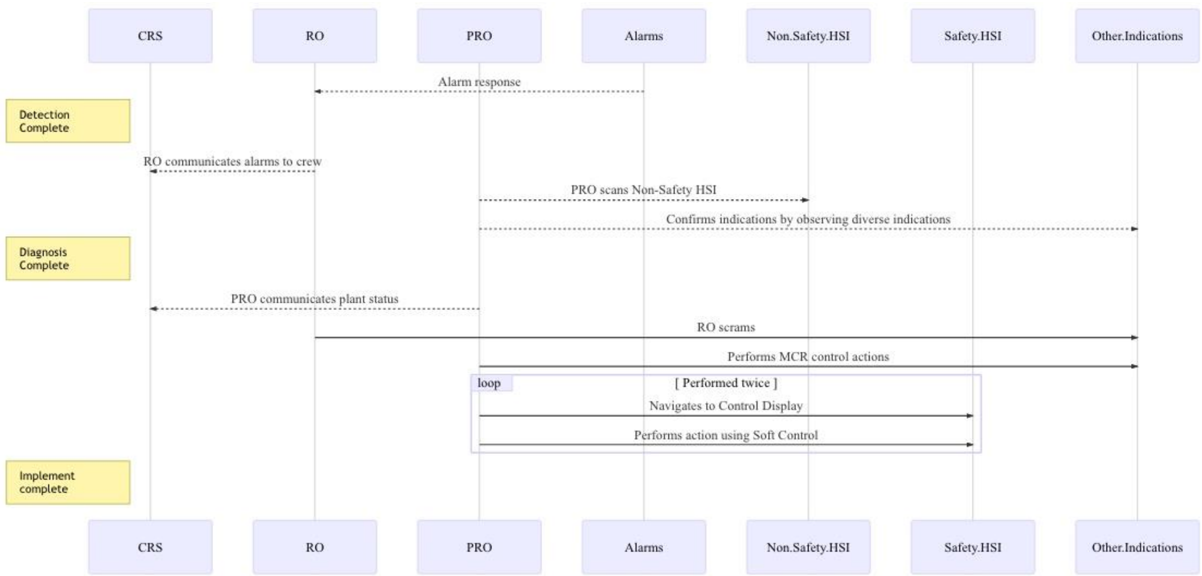


Figure 43. Example OSD.

Optional Extensions to OSD

<u>Calculate Operation Loading Figures.</u>

If needed, the analyst can then incorporate operation loading figures. Operation loading figures are calculations that refer to how involved an agent was in the task under analysis. These calculations are performed on each operation within the OSD and are completed on items such as decisions, operations, and delays in the task (Stanton et al., 2013).

<u>Add Results from Other Task Analyses.</u>

Other results from different methods can be incorporated into the OSD if deemed necessary. The OSD is flexible and can accommodate a variety of other analyses, such as a coordination demands analysis, which provides information on teamwork (Stanton et al., 2013).

Advantages and Disadvantages

The advantages of the OSD highlighted by Stanton et al. (2013) are:

- Provides an exhaustive analysis that includes task flow, task activities, agents, communication between agents, and technology used in the task
- Output provides information on teamwork and is particularly useful for distributed and collaborative tasks

- Provides a graphical representation of the relationship between tasks, team members, and the technology used for the tasks
- Applied in a variety of domains (including nuclear power control room modernization)
- Flexible and can be modified according to the needs of the analysis
- Requires minimal training to conduct.

The disadvantages of the cognitive walkthrough highlighted by Stanton et al. (2013) are:

- Application may be time consuming and collecting initial data is resource intensive
- OSDs can become cluttered for complex tasks
- Current symbols for processes are limited
- Reliability is questionable (requires domain expertise to construct accurate OSDs).

Industry Applications

The OSD has been used in numerous domains to model tasks and processes. To support the safety-related digital upgrades with CEG, OSDs were developed for identified manual actions under study. These OSDs were used to understand the task sequence of key activities related to detection, diagnosis, and action implementation. The OSDs served as input then into developed acceptance criteria for the conceptual verification and preliminary validation activities.

Further, OSDs have been used across many other industries, demonstrating their effectiveness to a wide range of applications. For instance, Harris et al. (2015) utilized an OSD to explore the allocation of work within the development of a single-pilot cockpit for a commercial aircraft. The authors found that the OSD provided a rigorous yet simple way to analyze function allocation in novel designs (Harris et al., 2015). Another application of the OSD was to explore zoo exhibit inefficiencies by modeling the relationships between the animals, zookeepers, and zoo visitors (Kelling et al., 2012). Stanton et al. (2022) used an OSD to model the interactions between drivers and automation within a car. The OSD was used to model anticipated driver actions, and the authors found that the OSD accurately modeled driver behavior during handover of control (Stanton et al., 2022).

ION Application

The OSD is a generic process charting method that can be used to model interactions in a task. Since the OSD is generic, the method can potentially be applied in the majority of the WRO areas. Specifically, the OSD may be particularly useful in modeling maintenance tasks, physical security, implementing drones and robots, and remote assistance.

6.2.3.5 Comms Usage Diagram

The comms usage diagram (CUD) is a type of team assessment method that describes collaboration between workers and teams of workers that are spread throughout different locations. Ultimately, the CUD provides information on how and why communication occurs, technology used in communication, and the advantages and disadvantages for the technology used during communication (Stanton et al., 2013).

How to Perform the Method

The following steps are used to perform CUD.

Define the Task

A clear understanding of the task or scenario is necessary for an accurate representation of communication. Stanton et al. (2013) recommends creating an HTA to gain a clear picture of the task. Defining the task or scenario helps the analyst understand what is needed for the data collection phase.

Collect Data

The next step is to collect the relevant data on the scenario or task. A variety of techniques can be used and typically include observational studies, questionnaires, and interviews. Data should include information on the activity conducted, the people involved with the task, steps of the task, communication between the people involved, technology used for communication, and the geographical locations of the people involved (Stanton et al., 2013).

Create a Transcript

After data collection, a transcript of the task should be created using the information from observations, questionnaires, and interviews as input. According to Stanton et al. (2013), the transcript should include the communication between the people involved in the task and the technology used for communication.

Construct CUD

The last step is to construct the graphical representation of the task or scenario using the transcript from the previous step (see Figure 44). The diagram should include a description of the activity conducted, the geographical location of the activity, the communication between the team members, the type of technology used for communication, and the advantages and disadvantages of that type of technology. Additionally, it is helpful to have space for recommended technology if necessary. Arrows are used to show the flow of information between the people involved in the task or scenario (Stanton et al., 2013). It is worth noting that the CUD is similar to an OSD but with a specific emphasis on communication between different geographical locations.

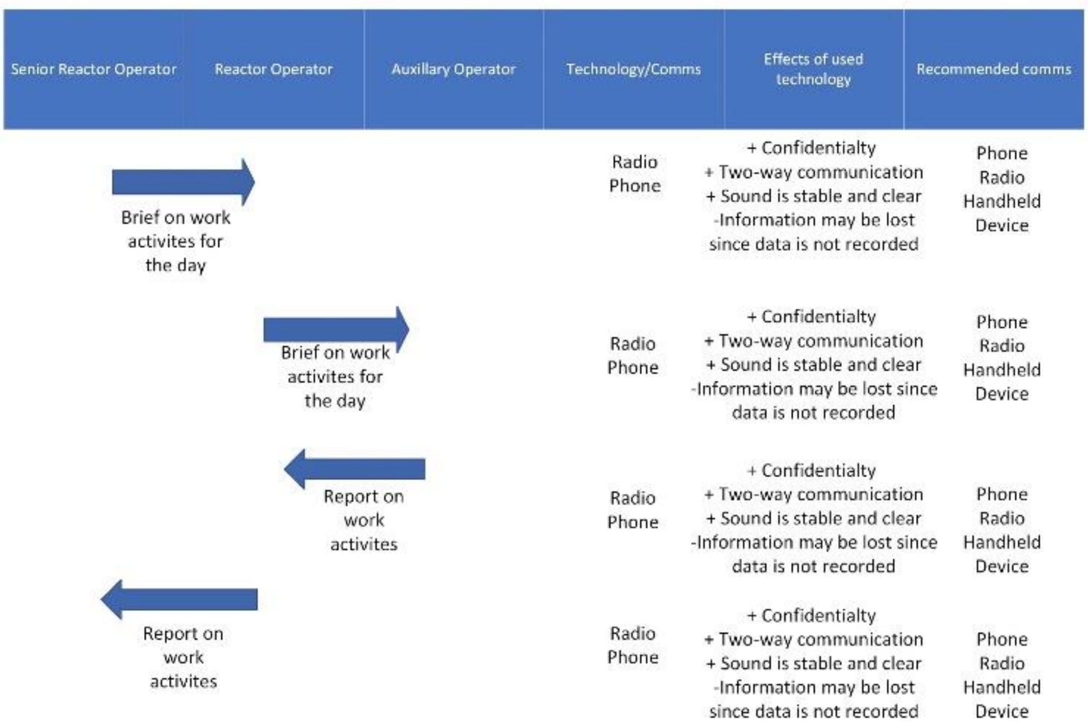


Figure 44. Example CUD diagram.

Advantages and Disadvantages

The advantages to a CUD as provided by Stanton et al. (2013):

- The method is simple, easy to use, and requires minimal training for implementation

- The output of the CUD is helpful because it provides a description of the task and the communication involved in the task
- The CUD is useful in emphasizing communication flaws
- The CUD is useful for teamwork analysis and collaboration
- The method is adaptable and could be made more comprehensive by adding in time, errors, and workload
- CUD is a generic method that can be applied to any domain that utilizes distributed communication and collaboration.

The disadvantages as highlighted by Stanton et al. (2013):

- The CUD can be time consuming when analyzing complex tasks
- The data collection phase of the CUD is time consuming and may require multiple analysts if the task under analysis is dispersed across vast geographical locations
- There is no available validity or reliability on the method
- Limited use of the method in literature
- Limited guidance on how to conduct the method is available.

Industry Applications

The CUD was initially used within the medical domain to analyze communication between hospital staff and patients (Watts and Monk, 1998) but has been also used to analyze command, control, communications, computers, and intelligence infrastructure (Walker et al., 2006).

ION Application

The CUD is a generic method that can provide information on the types of technology utilized for task completion, communication between team members, and tasks outside of the control room. Some specific areas that the CUD could potentially be applied are areas with a distributed means of communication like remote assistance and physical security. The CUD can also be used in conjunction with other methods to provide a holistic analysis for design recommendations.

6.2.4 Design and Testing Techniques

This section describes applicable design and testing techniques outlined in Table 11.

6.2.4.1 Cognitive Walkthrough

The cognitive walkthrough is a method used to evaluate interfaces based on cognitive aspects related to the user. The goal of the cognitive walkthrough method is to explore usability issues and causes early in the design process. Additionally, the cognitive walkthrough method helps the analyst explore ease of learning with the system (Polson et al., 1992; Stanton et al., 2013).

How to Perform the Method

The following steps are used to perform CUD.

Select the Task

The first step is to choose a task or set of tasks for analysis. If a thorough examination of the interface is warranted, multiple tasks that span the range of usability for the system should be chosen for analysis. If the analyst is pressed for time, specific tasks that are the most representative of the interface should be chosen so valuable data is gathered (Stanton et al., 2013).

Create Task Descriptions

The next step is to describe the selected tasks. An HTA is recommended to provide a holistic description of each chosen task for analysis (Stanton et al., 2013). However, any of the other methods listed in Section 6.2.3 may apply (e.g., the TTA or OSD).

Determine the Correct Sequence of Task Actions

The analyst then needs to determine the appropriate action sequence for each of the tasks under analysis and should rely on the created task description to understand the correct sequence of actions to complete the tasks (Stanton et al., 2013).

Identify the Users

Potential users of the interface should then be identified and noted. It is recommended that user groups are created for the interface and subsequent tasks (Stanton et al., 2013).

Define the Users' Goals

After identifying users of the interface, the analyst then needs to consider the goals of the user. The analyst should make note of the goals that the user has at the beginning of the task. These goals are determined by the analyst and rely on their best subjective judgment. The task descriptions for each task can help guide the analyst in this process (Stanton et al., 2013).

Analyze Interactions Between Users and Interfaces

The last step in the cognitive walkthrough is for the analyst to evaluate the interactions between the users of the system and the interface. This step is achieved by the analyst walking through each of the selected tasks and following the cognitive walkthrough criteria from Polson et al. (1992), as highlighted in Table 15.

Table 15. Cognitive walkthrough criteria (adapted from Polson et al., 1992).

1. **Goal Structure for this Step**
    - 1.1 Correct goals: What are the appropriate goals for this point in the interaction? Describe as for initial goals.
    - 1.2 Mismatch with likely goals: What percentage of users will not have these goals, based on the analysis at the end of the previous step? Based on that analysis, will all users have the goal at this point, or may some users have dropped it or failed to form it? Also check the analysis at the end of the previous step to see if there are unwanted goals, not appropriate for this step, that will be formed or retained by some users.
2. **Choosing and Executing the Action**
    - 2.1 Availability: Is it obvious that the correct action is a possible choice here? If not, what percentage of users might miss it?
    - 2.2 Label: What label or description is associated with the correct action?
    - 2.3 Link of label to action: If there is a label or description associated with the correct action, is it obvious, and is it clearly linked with this action? If not, what percentage of users might have trouble?
    - 2.4 Link of label to goal: If there is a label or description associated with the correct action, is it obviously connected with one of the current goals for this step? How? If not, what percentage of users might have trouble? Assume all users have the appropriate goals listed in Section 1.
    - 2.5 No label: If there is no label associated with the correct action, how will users relate this action to a current goal? What percentage might have trouble doing so?
    - 2.6 Wrong choices: Are there other actions that might seem appropriate to some current goal? If so, what are they, and what percentage of users might choose one of these?

2.7 Time-out: If there is a time-out in the interface at this step does it allow time for the user to select the appropriate action? How many users might have trouble?

2.8 Hard to do: Is there anything physically tricky about executing the action? If so, what percentage of users will have trouble?

3. Modification of Goal Structure

3.1 Quit or Backup: Will users see that they have made progress toward some current goal? What will indicate this to them? What percentage of users will not see progress and try to quit or backup?

3.2 Accomplished Goals: List all current goals that have been accomplished. Is it obvious from the system response that each has been accomplished? If not, indicate for each how many users will not realize it is complete.

3.3 Incomplete Goals that Look Accomplished: Are there any current goals that have not been accomplished, but might appear to have been based on the system response? What might indicate this? List any such goals and the percentage of users who will think that they have actually been accomplished.

3.4 "And-Then" Structures: Is there an "and-then" structure, and does one of its subgoals appear to be complete? If the subgoal is similar to the supergoal, estimate how many users may prematurely terminate the "and-then" structure.

3.5 New Goals in Response to Prompts: Does the system response contain a prompt or cue that suggests any new goal or goals? If so, describe the goals. If the prompt is unclear, indicate the percentage of users who will not form these goals.

3.6 Other New Goals: Are there any other new goals that users will form given their current goals, the state of the interface, and their background knowledge? Why? If so, describe the goals, and indicate how many users will form them. Note that these goals may or may not be appropriate, so forming them may be bad or good.

Alternatively, a "streamlined" set of criteria may be used, which was developed by Spencer (2000), as seen in Table 16.

Table 16. Streamlined cognitive walkthrough criteria (adapted from Spencer 2000)

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

Advantages and Disadvantages

The advantages of the cognitive walkthrough highlighted by Stanton et al. (2013) are:

- This method provides a structured technique to analyze user interfaces
- Design flaws can be mitigated since this technique is used early in the design process
- The cognitive walkthrough can be utilized by anyone
- It is easy to learn and implement.

The disadvantages of the cognitive walkthrough highlighted by Stanton et al. (2013) are:

- The technique is limited to ease of learning with interfaces
- This method can become time consuming for large, complex tasks

- The reliability of the method is questionable because it relies on the analyst's best judgment with certain areas of walkthrough guide
- Conducting a cognitive walkthrough requires the analyst to have access to the people who use the technology or are involved in the task.

Industry Applications

The cognitive walkthrough has been used in many domains that require interaction with an interface, such as an HSI. The cognitive walkthrough technique was used to evaluate a cockpit design for three tasks in military aviation (Helander and Skinnars, 2000), to explore the usability of information systems for nurses in a hospital (Farzandipour et al., 2021), and to evaluate the usability of digital games created for aging populations (Santos et al., 2022).

ION Application

The cognitive walkthrough is a method used to evaluate interfaces, so the method can be applied to areas within the nuclear power plant that rely on personnel to utilize interfaces to complete work tasks.

6.2.4.2 Heuristic Evaluation

A heuristic evaluation is a type of interface analysis method that provides a simple and quick approach to evaluating interfaces. During a heuristic evaluation, analysts provide their subjective opinions about the interface regarding usability, errors, and overall design. Typically, heuristic analyses are utilized early and often during the design process to provide a means of obtaining feedback about a product and proposing recommendations (Stanton et al., 2013).

How to Perform the Method

The following steps are used to perform a heuristic evaluation.

Define the Heuristics for Use

The first step is to define the aspects of the system that will be evaluated. The typical aspects of systems for heuristic evaluations include usability and error potential. Within usability, the factors that may be helpful to explore are ease of use, effectiveness, comfort, and efficiency (Stanton et al., 2013). There are different types of heuristics that can be applied, including:

- Nielsen's 10 Heuristics
- Schneiderman's Eight Golden Rules.

Familiarize with the Interface

The analysts conducting the heuristic evaluation should then familiarize themselves with the system or device being analyzed. The analysts can look at instruction manuals (if applicable), watch product demonstrations, or potentially be given a walkthrough of the system or device.

Perform Heuristic Evaluation

Upon familiarization with the system, the analyst can then perform the heuristic evaluation with the selected set of heuristics. During this phase, the analysts provide their opinions about the system or device regarding the design features according to the defined aspects for the evaluation. Analysts should record their opinions, both good and bad, so that recommendations can be provided in the next step. It is recommended to have more than one analyst perform the heuristic evaluation if possible.

Provide Design Recommendations

After completing all tasks on the task list, the analyst can provide recommendations and solutions for problems encountered during the evaluation.

Advantages and Disadvantages

The advantages of the heuristic evaluation highlighted by Stanton et al. (2013) are:

- Simple, quick, and low-cost method for assessing usability
- Minimal training is needed to conduct this method
- The method is flexible and can be applied to any form of device or system
- The output of this method is immediately useful
- Requires few resources
- Since it is a flexible method, it can be applied throughout the design process.

The disadvantages of the heuristic evaluation highlighted by Stanton et al. (2013) are:

- This method may provide poor reliability and validity
- To be effective and worthwhile, SMEs are necessary for this method
- The method is based on subjective opinions
- Lack of consistency between analysts.

Industry Applications

Since the heuristic evaluation is a general method, it is used in many different industries to aid in the development of systems, devices, and products. Some uses of the heuristic evaluation include analyzing healthcare systems and medical devices (Meyeroff and Tremoulet, 2021; Percival et al., 2010), interfaces for wearable devices in the military (Taylor and Barnett, 2013), and interfaces within vehicles (Parkhurst et al., 2019). Additionally, the heuristic evaluation was used in the nuclear industry to analyze the Integrated Capability Analysis Platform and Innovation Portals (Mohon et al., 2021) and control room modernization efforts for digital systems (Ulrich and Boring, 2013).

ION Application

The heuristic evaluation is a general-purpose method for evaluating the usability of interfaces. The heuristic evaluation could be used to evaluate tasks outside of the control room that utilize interfaces.

6.2.4.3 Usability Testing

Usability testing is a method that allows for products, devices, and interfaces to be evaluated in a simple and flexible manner. End users of the product or system are recruited to perform tasks or scenarios with the product so that usability features are evaluated. Usability testing is an important method to employ because it allows designers to understand how the product will be used by their target population and gain feedback about the product so changes can be implemented if necessary.

How to Perform Method

The following steps are generally used to perform a usability test. The reader is encouraged to review detailed guidance such as from Rubin and Chisnell (2008) or in the International Organization for Standardization (ISO) 9241-11:1998(E) in becoming versed in this method.

Define the Goals of the Usability Test

The desired outcome of utilizing usability testing sessions should be identified by the analyst. This is necessary to ensure the correct features of the product are assessed.

Identify Tasks for Testing

The next step is to define the task(s) that need to be performed by the user. If a broad analysis of the system or product is needed, an extensive and exhaustive list of tasks should be created. Sometimes an in-depth test is unnecessary or restrained by finances, so, in this case, the task list should be representative of the system or product within reason.

Conduct Task Analysis for the Tasks

After choosing the appropriate tasks for testing, the analyst can then describe the tasks using task analysis, such as an HTA. The HTA should break down the task into the goals, operations, and plans to provide a clear view of the subcomponents of how the task(s) should be conducted. The HTA is also useful because it provides input for creating the procedure list for the usability test.

Create a Procedure List for Tasks

The next step is to create the procedure list for the task(s). The procedure list should outline the necessary steps for the task, the correct sequence for the steps, and the components from the work system used.

Recruit Participants

After the tasks are outlined and described for the usability test, users can then be recruited to participate in the trials. The chosen participants should be representative of potential users of the product or system.

Brief Participants

Participants should then be introduced to the purpose of the usability test and work system under study. Participants should have full awareness of the testing session, the product or system, and why they are needed for the usability test. Participants should be given the opportunity to become familiar with the product or system during this step and ask questions if they need clarification about the usability test.

Run Test Sessions

Participants can begin performing the first task in the procedure list. The facilitator, or moderator, should not give participants any feedback about their performance or assistance with the task(s). Using audio and visual recording equipment may be helpful for this process so the analyst can refer to the sessions later if needed during analysis. A range of different methods and measures may be used. Referring back to Figure 22, a range of qualitative and quantitative measures can be selected depending on the goals of the test. International standard ISO 9241-11:1998(E) may be used for reference as it provides guidance on how the usability of a system can be specified and evaluated. It includes procedures for measuring usability and explains how measures of user performance and satisfaction can be used to measure how any component of a work system affects the whole system in use.

Administer Appropriate Questionnaires

After the participant completes the session, the analyst should then administer other surveys or analyses as needed. Examples of additional questionnaires that might be useful include workload, situational awareness, and usability measures and surveys. Including additional questionnaires is dependent on the goal of the usability test and what is needed for analysis. Examples of questionnaires are seen in this report in Figure 27, Figure 28, and Figure 29.

Interview Participants and Debrief

Participants can then be interviewed to gain additional insight into opinions about the product or system. This is dependent on the goal of the usability test but typically includes gathering thoughts, opinions, or feedback about the product. Participants should then be debriefed about the test session and given the opportunity to provide more feedback about the system or product that was tested.

Analyze the Data

After completing the testing sessions and interviews, the researcher can then analyze the data from the usability tests. Qualitative coding and analysis may be necessary to analyze the interviews, and statistical analysis may be necessary for the workload, situational awareness, or usability measures if used.

Provide Design Recommendations

After analyzing the data, the analyst can provide design recommendations based on the information gained through the usability tests and supporting questionnaires. The recommendations should then be incorporated into new designs for the product or system.

Advantages and Disadvantages

The advantages of user testing as outlined by Stanton et al. (2013) is:

- Usability testing is simplistic and flexible for usability evaluations
- Usability tests can incorporate a variety of measures (e.g., workload, situational awareness) to assess a variety of features
- The product or system is evaluated by potential end users who can provide feedback or opinions for future designs
- The design recommendations are directly based on user feedback through interviews
- Usability tests allow the designers to see how their product or system will be used
- When usability tests are incorporated throughout the design process, they allow for end-user opinions to be incorporated before finalizing the product
- Usability tests are simple to use and conduct once the appropriate equipment and personnel are obtained.

The disadvantages of user testing as outlined by Stanton et al. (2013) is:

- Usability testing, especially with many participants, is time consuming
- Usability testing provides lots of data that results in a long data analysis process
- End users of the product are not always available or hard to gain access to if the product or system is restricted
- End users may hold biases in favor of old or familiar systems or products.

Industry Applications

Usability testing spans numerous industries and is used for a wide variety of products and user interfaces. Some examples include conducting usability tests on medical devices (Stephens and Mulcare, 2014), different types of radio equipment for the military (Savage-Knepshield, 2009), health applications for older adults (Cornet et al., 2017), and advising forms for a university (Diederiks and Figueroa, 2016). More specifically, within the context of nuclear power plant modernization, usability tests are applied across the systems engineering lifecycle, such as during conceptual design and detailed design. In fact, key collaborations described in Section 5 utilized this approach to elicit design feedback and evaluate the proposed upgrades using performance-based tests. The focus of usability tests can vary in such a way depending on their purpose driven by their use in the larger systems engineering lifecycle. The measures selected will therefore be determined based on the purpose of the test and a useful framework to use can be found in Boring and colleagues (2015) and in Kovesdi and colleagues (2018), also shown in Figure 22 earlier in this report.

ION Application

The usability test is a general-purpose method that evaluates the usability of a product or system. Usability tests can be incorporated to evaluate products, systems, or interfaces found inside and outside of the main control room.

7. CONCLUSIONS

This work describes the demonstration of the HTI methodology across two key industry collaborations. Building on the results from INL/RPT-22-68472, INL/RPT-22-70538, and INL/RPT-22-71395, this work adds recently performed HTI activities, such as preliminary validation, a performance-based test, to support CEG's safety-related upgrades (Section 5.1.2.1), as well as the advanced main control room concept demonstration workshop (Section 5.2.2.1) for SNC to support their endpoint vision definition and planning. Further, this report expands the HTI guidance to address joint optimization considerations for WROs beyond the main control room. This is documented in Section 0 and summarized in Figure 45.

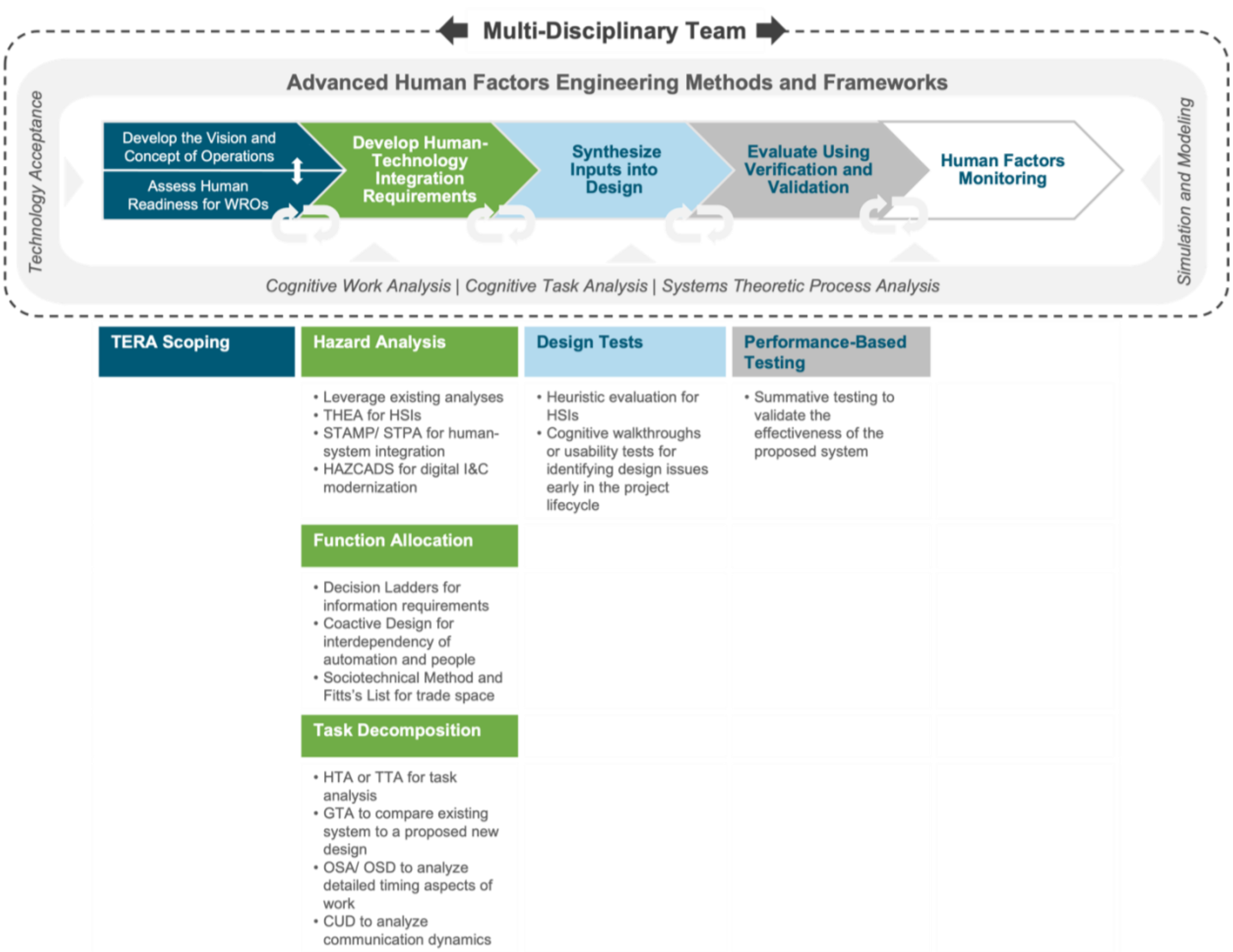


Figure 45. Expanded HTI methodology with detailed methods.

It is intended that the guidance developed in Section 0 will be demonstrated in future LWRS Program research, following a multidisciplinary approach with the other LWRS Program plant modernization research areas.

8. REFERENCES

Agarwal, V., J. Joe, A.V. Gribok, J.A. Smith, J. Oxstrand, and C. Primer. (2022). "Data Architecture and Analytics Requirements for Artificial Intelligence and Machine Learning Applications to Achieve Condition-Based Maintenance." INL/RPT-22-70350. Idaho National Laboratory.

Al Rashdan, A., M. Griffel, and L. Powell. (2019). "Automating Fire Watch in Industrial Environments through Machine Learning-Enabled Visual Monitoring." INL/EXT-19-55703. Idaho National Laboratory.

Al Rashdan, A., J. Oxstrand, and V. Agarwal. (2016). "Automated Work Package: Conceptual Design and Data Architecture." INL/EXT-16-38809. Idaho National Laboratory. https://doi.org/10.2172/1364774

Alvarenga, M. A. B., Frutuoso E Melo, P. F., & Fonseca, R. A. (2014). A critical review of methods and models for evaluating organizational factors in Human Reliability Analysis. Progress in Nuclear Energy, 75, 25–41. https://doi.org/10.1016/j.pnucene.2014.04.004

Annett, J. (2004). "Hierarchical task analysis." In *The Handbook of Task Analysis for Human-Computer Interaction*, edited by Dan Diaper and Neville Stanton, 67–82. Mahwah, NJ: CRC Press.

ANSI/HFES. (2021). "Human Readiness Level Scale in the System Development Process." ANSI/HFES-400-2021.

Aqel, A. M. (2012). *Organizational Readiness to E-Transformation*. Xlibris Corporation.

Center B.P. (2022). *Annual Energy Review 2022*. U.S. Energy Information Administration

Cornet, V. P., Daley, C. N., Srinivas, P., & Holden, R. J. (2017, September). "User-centered evaluations with older adults: testing the usability of a mobile health system for heart failure self-management." In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 61, No. 1, pp. 6-10). Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/1541931213601497

Dainoff, M.J., P.J. Murray, J.C. Joe, A. Hall, J. Oxstrand, L.J. Hettinger, Y. Yamani, and C. Primer. (2022). "Using System-Theoretic Accident Model and Processes and Causal Analysis to Manage Organizational Information to Enable Digitalization and Information Automation." INL/RPT-22-69058. Idaho National Laboratory. https://doi.org/10.2172/1894897.

Diederiks, Y., & Figueroa, I. (2016, September). "The usability of academic advising forms." In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 60, No. 1, pp. 1384-1388). Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/1541931213601319

Electric Power Research Institute. 2015. "Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification: Guidelines for Planning, Specification, Design, Licensing, Implementation, Training, Operation, and Maintenance for Operating Plants and New Builds." Report 3002004310. https://www.epri.com/research/products/000000003002004310

Electric Power Research Institute. 2021. "Digital Engineering Guide: Decision Making Using Systems Engineering." Report 3002011816. https://www.epri.com/research/products/000000003002011816

Electric Power Research Institute. 2022. “HAZCADS: Hazards and Consequences Analysis for Digital Systems – Revision 1.” Report 3002016698. https://www.epri.com/research/products/000000003002016698

Farzandipour, M., Nabovati, E., Tadayon, H., & Jabali, M. S. (2021). Usability evaluation of a nursing information system by applying cognitive walkthrough method. International Journal of Medical Informatics, 152, 104459.

Fields, B., Harrison, M., & Wright, P. (1997). “THEA: Human error analysis for requirements definition.” Report-University OF York Department OF Computer Science YCS.

Goncalves Filho, A. P., Jun, G. T., & Waterson, P. (2019). “Four studies, two methods, one accident – An examination of the reliability and validity of Accimap and STAMP for accident analysis.” Safety Science, 113, 310–317. https://doi.org/10.1016/j.ssci.2018.12.002

Harris, D., Stanton, N. A., & Starr, A. (2015). “Spot the difference: Operational event sequence diagrams as a formal method for work allocation in the development of single-pilot operations for commercial aircraft.” Ergonomics, 58(11), 1773–1791. https://doi.org/10.1080/00140139.2015.1044574

Helander, M. G., & Skinnars, Ö. (2000). “Use of cognitive walkthrough for evaluation of cockpit design.” In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 44, No. 6, pp. 616-619). Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/154193120004400619

Hendrick, H. W., & Kleiner, B. M. (2001). *Macroergonomics: An introduction to work system design*. Human Factors and Ergonomics Society.

Hunton, P. and R. England. 2021. “Digital Infrastructure Migration Framework.” INL/EXT-21-64580. Idaho National Laboratory. https://doi.org/10.2172/1822876.

Hunton, P., England, R., Herrell, D., Lawrie, S., and Samselski, M. (2022). “Safety-Related Instrumentation and Control Pilot Upgrade: Initial Scoping Phase Implementation and Lessons Learned.” *Nuclear Technology*, **209**(3), pp. 366–376. https://doi.org/10.1080/00295450.2022.2053808

Hunton, P., England, R., M. Segner, M. Samselski, G. Bonanni, P. Heaney, D. Herrell, W. Jessup, M. Kerrigan, and S. Lawrie (2020). Safety-Related Instrumentation and Control Pilot Upgrade: Initial Scoping Phase Implementation Report and Lessons Learned. INL/EXT-20-59809. Idaho National Laboratory. https://doi.org/10.2172/1662013.

Hunton, P., England, R., M. Segner, M. Samselski, G. Bonanni, S. Schumacher, and P. Krueger, (2023). Safety-Related Instrumentation and Control Pilot Upgrade: Conceptual – Detailed Design Phase Report and Lessons Learned. INL/RPT-23-72105. Idaho National Laboratory. https://doi.org/10.2172/1983868.

IEEE. 2021. “Guide for Human Factors Engineering for the Validation of System Designs and Integrated Systems Operations at Nuclear Facilities.” IEEE-2411. Institute of Electrical and Electronics Engineers. https://ieeexplore.ieee.org/document/9690140

International Council on Systems Engineering. 2015. Systems Engineering Handbook: A Guide for System Life Cycle Processing and Activities Version 4.

ISO/ IEC. 1998. “Ergonomic Requirements for Office Work with Visual Display Terminals (VDT)s- Part II Guidance on Usability.” ISO/IEC 9241-11:1998(E). International Organization for Standardization. https://www.iso.org/standard/16883.html

Jardina, J. R., & Chaparro, B. S. (2015). “Investigating the usability of e-textbooks using the technique for human error assessment.” Journal of Usability Studies, 10(4): 140–159.

Kazaras, K., Kirytopoulos, K., & Rentizelas, A. (2012). “Introducing the STAMP method in road tunnel safety assessment.” Safety Science, 50(9), 1806–1817. https://doi.org/10.1016/j.ssci.2012.04.013

Kelling, N., Gaalema, D., & Kelling, A. (2012). “Elephant in the break room: The use of modified operational sequence diagrams for the determination of zoo exhibit inefficiencies.” Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 56(1), 1519–1523. https://doi.org/10.1177/1071181312561302

Kovesdi, C. 2022. “A simple tool to evaluate color for legibility and distinguishability when designing digital displays.” Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 66(1), 1519-1523. https://doi.org/10.1177/1071181322661209

Kovesdi, C. and J. Joe. 2019. “Exploring the Psychometrics of Common Post-Scenario Human Factors Questionnaires of Workload, Situation Awareness, and Perceived Difficulty.” INL/CON-18-45444, Idaho National Laboratory. https://www.osti.gov/servlets/purl/1669050.

Kovesdi, C., P. Hunton, J. Mohon, J. Joe, T. Miyake, and S. Whitmore. 2022. “Demonstration and Evaluation of the Human-Technology Integration Function Allocation Methodology.” INL/RPT-22-68472, Idaho National Laboratory. https://doi.org/10.2172/1881859.

Kovesdi, C., J. Joe, and R. Boring. 2018. “A Guide for Selecting Appropriate Human Factors Methods and Measures in Control Room Modernization Efforts in Nuclear Power Plants,” *Proceedings of the International Conference on Applied Human Factors and Ergonomics* 441–452. Springer, Cham. https://doi.org/10.1007/978-3-319-94229-2_43.

Kovesdi, C., J. Mohon, and C. Pedersen-San Miguel. 2023. “Demonstration of the Human and Technology Integration Guidance for the Design of Plant-Specific Advanced Automation and Data Visualization Techniques.” INL/RPT-23-71395, Idaho National Laboratory. https://doi.org/10.2172/1963680.

Kovesdi, C., J. Mohon, K. Thomas, J. Remer, J. Joe, L. Hanes, M. Dainoff, and L. Hettinger. 2021. “Nuclear Work Function Innovation Tool Set Development for Performance Improvement and Human Systems Integration.” INL/EXT-21-64428, Idaho National Laboratory.

Kovesdi, C., Z. Spielman, R. Hill, J. Mohon, T. Miyake, and C. Pedersen. 2021. “Development of an Assessment Methodology That Enables the Nuclear Industry to Evaluate Adoption of Advanced Automation.” INL/EXT-21-64320, Idaho National Laboratory. https://doi.org/10.2172/1822880.

Leveson, N. (2004). A new accident model for engineering safer systems. Safety Science, 42(4), 237–270. https://doi.org/10.1016/S0925-7535(03)00047-X

Levenson, N., and J. Thomas. 2018. “STPA Handbook.” http://psas.scripts.mit.edu/home/get_file.php?name=STPA_handbook.pdf.

McDonald, R., A.O. Braseth, and J. Joe, 2019. "Report for 2.2.1 Task 3: Develop and Document an Advanced Human System Interface for the Generic Pressurized Water Reactor Simulator." INL/EXT-19-55788, Idaho National Laboratory. https://doi.org/10.2172/1567688.

Meyeroff, E., & Tremoulet, P. (2021). Etiometry's T3 Heuristic Evaluation. *Proceedings of the International Symposium on Human Factors and Ergonomics in Health Care*, *10*(1), 37–41. https://doi.org/10.1177/2327857921101015

Mohon, J., Pedersen, C., Kovesdi, C., and Joe, J. 2021. "Usability Evaluation of the Innovation Portal and Integrated Capability Analysis Platform." INL/EXT-21-63101, Revision 1, Idaho National Laboratory. https://doi.org/10.2172/1822922

Oxstrand, J., K. Le Blanc, and A. Bly. 2016. "Design Guidance for Computer-Based Procedures for Field Workers," INL/EXT-16-39808, Idaho National Laboratory. https://doi.org/10.2172/1344173.

Parkhurst, E. L., Conner, L. B., Ferraro, J. C., Navarro, M. E., & Mouloua, M. (2019). Heuristic Evaluation of A Tesla Model 3 Interface. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *63*(1), 1515–1519. https://doi.org/10.1177/1071181319631336

Percival, N. B., Mayer, A. K., & Caird, J. K. (2010, September). "A heuristic evaluation of three automated external defibrillators." In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 54, No. 23, pp. 1921-1925). Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/154193121005402304

Perrow, C. (1967). "A framework for the comparative analysis of organizations." *American Psychological Review*, 32, 194-208. https://doi.org/10.2307/2091811

Pocock, S., Wright, P., & Harrison, M. (2001). "THEA-a technique for human error assessment early in design." York Univ (United Kingdom) Dept of Computer Science.

Puerta Melguizo, M. C., Chisalita, C., & van der Veer, G. C. (2006). "Groupware Task Analysis and distributed cognition: Task modeling in a case of multiple users and multiple organizations." In HCI related papers of Interacción 2004 (pp. 119-135). Springer Netherlands. https://doi.org/10.1007/1-4020-4205-1_10

Read, G. J., Salmon, P. M., Lenne, M. G., Stanton, N. A., Mulvihill, C. M., & Young, K. L. (2016). "Applying the prompt questions from the cognitive work analysis design toolkit: a demonstration in rail level crossing design." *Theoretical Issues in Ergonomics Science*, **17**(4), 354-375. https://doi.org/10.1080/1463922X.2016.1143987

Remer, J., J. Hansen, C. Kovesdi, Z. Spielman, S. Lawrie, L. Martin,, M. Dep, and B. Szews. 2023. "Integrated Operations for Nuclear Business Operation Model Analysis and Industry Validation." INL/EXT-22-68671, Revision 1, Idaho National Laboratory.

Remer, J., K. Thomas, S. Lawrie, K. Martin, and C. O'Brien. 2021. "Process for Significant Nuclear Work Function Innovation Based on Integrated Operations Concepts" INL/EXT-21-64134, Idaho National Laboratory.

Rosendahl, T., & Hepsø, V. (2013). *Integrated Operations in the Oil and Gas Industry: Sustainability and Capability*. Hershey, PA: IGI Global.

Roth, E. M., Sushereba, C., Militello, L., Diiulo, J., and Ernst, K. 2019. "Function allocation considerations in the era of human autonomy teaming." *Journal of Cognitive Engineering and Decision Making* 13(4):199-220. https://doi.org/10.1177/1555343419878038.

Rubin, J., & Chisnell, D. (2008). *Handbook of usability testing: how to plan, design and conduct effective tests*. John Wiley & Sons.

Santos, F. D. S., Salgado, A. D. L., Paiva, D. M. B., Fortes, R. P. D. M., & Gama, S. P. (2022, August). "A specialized cognitive walkthrough to evaluate digital games for the elderly." In Proceedings of the 10th International Conference on Software Development and Technologies for Enhancing Accessibility and Fighting Info-exclusion (pp. 166-171). https://doi.org/10.1145/3357155.3358452

Savage-Knepshield, P. A. (2009, October). "Usability Testing: Making it Work for the Army." In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 53, No. 25, pp. 1868-1872). Sage CA: Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/154193120905302250

Schmid, D., Korn, B., & Stanton, N. A. (2020). "Evaluating the reduced flight deck crew concept using cognitive work analysis and social network analysis: comparing normal and data-link outage scenarios." *Cognition, Technology & Work*, **22**, 109-124. https://doi.org/10.1007/s10111-019-00548-5

Spencer, R. 2000. "The streamlined cognitive walkthrough method, working around social constraints encountered in a software development company." In Proceedings of SIGCHI Conference on Human Factors in Computing Systems, April 1–6, 2000, The Hague, The Netherlands, 353–359. https://doi.org/10.1145/332040.332456.

Spielman, Z., J. Mohon, C. Pedersen-San Miguel, and C. Kovesdi. 2022. "Demonstration and Evaluation of the Human-Technology Integration Guidance for Plant Modernization." INL/RPT-22-70538, Idaho National Laboratory. https://doi.org/10.2172/1963677

St Germain, S., J. Masterlark, R. Priddy, and S. Beck. 2019. "Methods to Automate Assessing Outage Risk and Technical Specification Compliance for Planned Work and Current Plant Conditions." INL/EXT-19-55308, Idaho National Laboratory. https://doi.org/10.2172/1560376.

Stanton, N. A., Brown, J., Revell, K. M. A., Langdon, P., Bradley, M., Politis, I., Skrypchuk, L., Thompson, S., & Mouzakitis, A. (2022). "Validating Operator Event Sequence Diagrams: The case of an automated vehicle to human driver handovers." Human Factors and Ergonomics in Manufacturing & Service Industries, 32(1), 89–101. https://doi.org/10.1002/hfm.20887

Stanton, N. A., P. M. Salmon, L. A. Rafferty, G. H. Walker, C. Baber, and D. P. Jenkins. 2013. *Human Factors Methods: A Practical Guide for Engineering and Design*. CRC Press. https://doi.org/10.1201/9781315587394.

Stanton, N. A., P. M. Salmon, G. H. Walker, D. P. Jenkins, Eds. 2017. *Cognitive Work Analysis: Applications, Extensions and Future Directions*. CRC Press. https://doi.org/10.1201/9781315572536.

Staples, L. J. (1993, October). "The task analysis process for a new reactor." In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 37, No. 14, pp. 1024-1028). Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/154193129303701419

Stephens, R., & Mulcare, M. (2014, June). "Usability Testing of Medical Devices Used by Teams." In Proceedings of the International Symposium on Human Factors and Ergonomics in Health Care (Vol. 3, No. 1, pp. 273-276). Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/2327857914031044

Stuster, J. (2019). *Task analysis: How to develop an understanding of work*. Washington DC: Human Factors and Ergonomics Society.

Thomas, K. D., J. Remer, and C. Primer. 2020. "Analysis and Planning Framework for Nuclear Plant Transformation." INL/EXT-20-59537, Idaho National Laboratory. https://doi.org/10.2172/1668293.

Ulrich, T. A., & Boring, R. L. (2013). Example User Centered Design Process for a Digital Control System in a Nuclear Power Plant. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *57*(1), 1727–1731. https://doi.org/10.1177/1541931213571385

U.S. Code of Federal Regulations, "Operator licenses." Section 10, Part 55 (2022). https://www.nrc.gov/reading-rm/doc-collections/cfr/part055/full-text.html

U.S. Code of Federal Regulations, "Protection of digital computer and communication systems and networks." Section 10, Part 73.54 (2015). https://www.nrc.gov/reading-rm/doc-collections/cfr/part073/part073-0054.html

U.S. Code of Federal Regulations, "Training and qualification of nuclear power plant personnel." Section 10, Part 50.120 (2021). https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0120.html

U.S. Nuclear Regulatory Commission. 2007. "Demonstrating the Feasibility and Reliability of Operator Manual Actions in Response to Fire." NUREG-1852, U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML0730/ML073020676.pdf.

U.S. Nuclear Regulatory Commission. 2007. "Guidance for the Review of Changes to Human Actions." NUREG-1764. Rev 1, U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML0726/ML072640413.pdf.

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

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

U.S. Nuclear Regulatory Commission. 2016. "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants - Human Factors Engineering." NUREG-0800, Chapter 18, Rev. 3, U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML1612/ML16125A114.pdf.

U.S. Nuclear Regulatory Commission. 2015. “Workload, Situation Awareness, and Teamwork.” NUREG/CR-7190, U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML1507/ML15078A397.pdf.

Van Welie, M., & Van Der Veer, G. (2003). Groupware Task Analysis. In E. Hollnagel (Ed.), Handbook of Cognitive Task Design (Vol. 20031153, pp. 447–476). CRC Press. https://doi.org/10.1201/9781410607775.ch19

Walden, D. D., Roedler, G. J., & Forsberg, K. (2015, October). “INCOSE systems engineering handbook version 4: updating the reference for practitioners.” In INCOSE International Symposium (Vol. 25, No. 1, pp. 678-686). https://doi.org/10.1002/j.2334-5837.2015.00089.x

Walker, G. H., Stanton, N. A., Gibson, H., Baber, C., Young, M. S., & Green, D. (2006). “Analyzing the role of communications technology in C4i scenarios: A distributed cognition approach.” Journal of Intelligent Systems, 15(1–4). https://doi.org/10.1515/JISYS.2006.15.1-4.299

Watts, L. A., & Monk, A. F. (1998). “Reasoning about tasks, activities and technology to support collaboration. Ergonomics,” 41(11), 1583–1606. https://doi.org/10.1080/001401398186081

Zhang, Y., Dong, C., Guo, W., Dai, J., & Zhao, Z. (2022). “Systems theoretic accident model and process (STAMP): A literature review.” Safety science, 152, 105596. https://doi.org/10.1016/j.ssci.2021.105596