INL/RPT-22-68472
Revision 0

Light Water Reactor Sustainability Program

Demonstration and Evaluation of the Human-Technology Integration Function Allocation Methodology

August 2022

U.S. Department of Energy

Office of Nuclear Energy

INL/RPT-22-68472
Revision 0

Demonstration and Evaluation of the Human-Technology Integration Function Allocation Methodology

Casey Kovesdi
Paul Hunton
Jeremy Mohon
Rachael Hill
Jeffrey Joe
Tina Miyake
Stacey Whitmore

August 2022

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

SUMMARY

There is an imminent need for the existing nuclear power plants to reduce their operating and maintenance (O&M) costs to remain economically viable. Digital technology, including automation, provides a significant opportunity for the existing nuclear power plant fleet to transform the way in which work is accomplished, reducing O&M costs, and allowing the fleet to remain economically competitive. One notable opportunity to significantly reduce O&M costs pertains to modifications to the plant equipment and main control room (MCR).

Existing instrumentation and control (I&C) technologies in the MCR are highly analog, costly to operate and maintain, and demand a high cognitive and physical workload from plant staff (i.e., operators). Digitalizing the MCR has a range of broad economic benefits, including improved plant performance and reduced manual work. Further, digital I&C systems can fundamentally change the way in which plant staff operate the plant; this is the concept of operation. Human-technology integration is important to ensure that impacts to the concept of operation are done in a way that account for capabilities of people and technology. Human-technology integration employs human factors engineering (HFE) methods and principles to maximize the benefits of digital technology, reducing human error, improving overall decision-making and usability.

The U.S. Department of Energy Light Water Reactor Sustainability Program is applying human-technology integration research to ensure digital technologies are safe, reliable, and efficient. This paper documents the demonstration of the human-technology guidance developed by the Light Water Reactor Sustainability Program from a first-of-a-kind digital I&C upgrade, specifically addressing function analysis and allocation for a new digital I&C system that included changes in automation levels.

The program’s specific approach is included in this work, following lessons learned. This document serves as a resource for industry to follow in applying human-technology integration and HFE to digital modifications, specific to function analysis and allocation. The lessons learned should be considered in the planning and execution of HFE activities that support such digital modifications.

ACKNOWLEDGEMENTS

The authors would like to thank Paul Krueger, Scott Schumacher, Mark Samselski, and the entire operations team at Constellation Energy. Further, the team would like to thank Brandon Rice, Thomas Ulrich, Jacob Lehmer, Tim Whiting, and all other staff of Idaho National Laboratory and partnering organizations who were closely involved in the planning and execution of this work. This report was made possible through funding by the United States Department of Energy Light Water Reactor Sustainability Program. Lastly, we would like to thank Alison Hahn and Bill Walsh of the Department of Energy, as well as Craig Primer and Bruce Hallbert of Idaho National Laboratory for championing this effort.

CONTENTS

SUMMARY iii

ACKNOWLEDGEMENTS v

ACRONYMS xi

1. INTRODUCTION 1

2. SCOPE OF AUTOMATION 4

3. BACKGROUND AND EXISTING INDUSTRY GUIDANCE FOR FUNCTION ALLOCATION 6
   - 3.1 Standards and Guidelines 7
     - 3.1.1 NUREG-0711: HFE Program Review Model 7
     - 3.1.2 NUREG/CR-3331: Methodology for Allocating Nuclear Power Plant Control Functions to Human or Automatic Control 8
     - 3.1.3 NUREG-0700: Human-System Interface Design Review Guidelines 9
     - 3.1.4 EPRI 3002011816: Digital Engineering Guide 9
     - 3.1.5 EPRI 3002004310: Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification 10
     - 3.1.6 IEC 61839: Nuclear Power Plants – Design of Control Rooms – Functional Analysis and Assignment 10
   - 3.2 Technical Reports on Function Allocation for Next Generation Reactors 11
     - 3.2.1 BNL-90424-2009: Trends in HFE Methods and Tools and Their Applicability to Safety Reviews 11
     - 3.2.2 BNL-91017-2010: Human-system Interfaces to Automatic Systems - Review Guidance and Technical Basis 12
     - 3.2.3 INL/EXT-13-28601: Draft Function Allocation Framework and Preliminary Technical Basis for Advanced SMR Concept of Operations 12
     - 3.2.4 INL/EXT-13-30117: Development of a Technical Basis and Guidance for Advanced SMR Function Allocation 13
   - 3.3 Challenges with Existing Guidance 14
     - 3.3.1 Existing Guidance Focuses on “Blank Slate” Design 14
     - 3.3.2 Limited to Safety with Minimal Guidance on Power Production 15
     - 3.3.3 Minimal Real-World Use Cases in the U.S. 15
     - 3.3.4 Does Not Explicitly Address Team Dynamics 15
   - 3.4 Emerging Methods 16
     - 3.4.1 Analyze Operational Demands and Work Requirements 16
     - 3.4.2 Explore Alternative Distribution of Work 17
     - 3.4.3 Examine Interdependencies Between Automation and People 17
     - 3.4.4 Explore Function Allocation Trade-Space 19
     - 3.4.5 Integrating Methods for Nuclear Power Plant Function Allocation 21

4. HUMAN-TECHNOLOGY INTEGRATION METHODOLOGY 23
   - 4.1 Function Analysis and Allocation 24
     - 4.1.1 Step 1: Function Analysis 25
     - 4.1.2 Step 2: Identify Scenarios 25
     - 4.1.3 Step 3: Allocation of Function 25

4.1.4 Step 4: Document the Results of Function Analysis and Allocation 26
4.2 Perform Task Analysis 26
4.2.1 Step 1 - Identify Tasks 27
4.2.2 Step 2 - Develop High-Level Task Descriptions 27
4.2.3 Step 3 - Perform Detailed Task Analysis 28
4.2.4 Step 4 - Document Results of Task Analysis 28
4.3 Integrate Risk Analyses 28

5. DEMONSTRATION OF THE UPDATED FUNCTION ALLOCATION METHODOLOGY WITH INDUSTRY 29
5.1 Background 29
5.2 Function Analysis and Allocation 32
5.2.1 Inputs to Functional Requirements Analysis and Function Allocation 34
5.2.2 Step 1 – Function Analysis 39
5.2.3 Step 2 – Identify Scenarios 40
5.2.4 Step 3 – Perform Functional Allocation 40
5.2.5 Step 4 – Documentation and Use of Results 50
5.3 Task Analysis 50
5.3.1 Inputs to Task Analysis 52
5.3.2 Methodology and Procedure 55
5.4 Use of Results 66

6. LESSONS LEARNED 67
6.1 HFE Planning 67
6.1.1 Team Composition and Dynamics 67
6.1.2 Methodological Considerations 67
6.2 HFE Execution 68
6.3 Licensing 70

7. CONCLUSIONS 72

8. REFERENCES 74

FIGURES

Figure 1. LWRS Program Plant Modernization focus areas. 1
Figure 2. Key work domains that offer greatest opportunity for cost savings....2
Figure 3. Scope of automation (adapted and enhanced from Sheridan 2002). 4
Figure 4. Digital infrastructure using the Purdue Network Model to enable advanced automation. 5
Figure 5. HFE phases and elements in NUREG-0711 (2012). 7
Figure 6. Decision matrix for allocation of functions (adapted and enhanced from NUREG/CR-3331). 8
Figure 7. Levels of automation for nuclear power plant applications (adapted from NUREG-0700 2020). 9
Figure 8. Vertical slide through a plant's functional hierarchy for ensuring safety (adapted and enhanced from NUREG-0711 2012). 14
Figure 9. Team considerations for function allocation (Joe et al. 2015). 15
Figure 10. Coactive system model (adapted from Johnson et al., 2014). 18
Figure 11. Function allocation table template (adapted from Waterson, Gray, and Clegg, 2002). 20
Figure 12. Integrated function allocation toolset (adapted and expanded from Roth et al., 2019). 22
Figure 13. Human-technology integration methodology. 23
Figure 14. Crosswalk of the Human-Technology Integration Methodology with NUREG-0711. 23
Figure 15. Human-technology integration requirements (adapted from INL/EXT-21-64320). 24
Figure 16. Function allocation extent based on modernization scope and initial allocation. 26
Figure 17. Task considerations (adapted from NUREG-0711, 2012). 27
Figure 18. Comparison of Standard Review Process and the Alternate Review Process 30
(from DI&C-ISG-06, 2018). 30
Figure 19. Relation of HFE guidance from DI&C-ISG-06, IEEE 603, and IEEE 1023. 31
Figure 20. Demonstration of INL/EXT-21-64320 to SR I&C upgrade. 32
Figure 21. Overview of FA&A performed. 33
Figure 22. SR I&C upgrades in the context of ION. 35
Figure 23. Scope of function allocation for SR I&C upgrade. 41
Figure 24. FA&A Workshop general workflow. 42
Figure 25. SME observation guide for the FA&A Workshop. 43
Figure 26. NASA-TLX standardized survey instrument. 44
Figure 27. SART standardized survey instrument. 45
Figure 28. B-NUM standardized survey instrument (adapted from Kovesdi and Joe, 2019). 46
Figure 29. Post-scenario discussion workflow for FA&A Workshop. 47
Figure 30. Contributors to observational difficulties. 47

Figure 31. Post-scenario questions informed from decision ladder framework of CWA. 48
Figure 32. Decomposition of tasks for performing task analysis. 50
Figure 33. Overview of task analysis. 51
Figure 34. 3D model showing pre-task analysis modifications and 5th percentile female reach envelope..52
Figure 35. Configuration of Human-Systems Simulation Laboratory for the Task Analysis Workshop. 54
Figure 36. Process for determining HFE level of activity through project screening (adapted from EPRI 3002004310, 2015). 56
Figure 37. Task screening and tailoring process for task analysis..57
Figure 38. Landscape of HFE methods and measures for nuclear power plant modernization (adapted and enhanced from Kovesdi, Joe, & Boring, 2018). 60
Figure 39. Crew procedure use during Task Analysis Workshop. 61
Figure 40. Walkthrough analysis general workflow for the Task Analysis Workshop..............................62
Figure 41. Photograph of the Task Analysis Workshop walkthrough analysis..63
Figure 42. Task description tables. 65
Figure 43. Typical HFE schedule overlaid with the Standard Review and Alternate Review Processes. 71
Figure 44. Extending human-technology integration in capture evaluating organizational readiness. 72

TABLES

Table 1. Fitts List (1951). 6
Table 2. Function allocation criteria from IAEA TECDOC-668 and used in IEC 61839..........................10
Table 3. Function allocation techniques listed in BNL-90424-2009...11
Table 4. Function allocation methodology requirements. 19
Table 5. Primary standards and guidance used for function allocation...29
Table 6. Applicable HFE design guidance from NUREG-0700 Revision 2 (2002). 53
Table 7. Task Analysis method selection. 59
Table 8. General questions for the task analysis post-scenario discussion..64

ACRONYMS

3D	Three-Dimensional
B-NUM	Brief-Nuclear Usability Measure
BCA	Business Case Analysis
CTA	Cognitive Task Analysis
CWA	Cognitive Work Analysis
D3	Diversity and Defense-in-Depth
DCS	Distributed Control System
DEG	Digital Engineering Guide
DIF	Difficulty, Importance, and Frequency
DOE	Department of Energy
EPRI	Electrical Power Research Institute
FA&A	Function Analysis and Allocation
FAT	Factory Acceptance Testing
HA	Human Action
HFE	Human Factors Engineering
HSI	Human-System Interface
HSSL	Human-Systems Simulation Laboratory
I&C	Instrumentation and Control
IA	Interdependence Analysis
IAEA	International Atomic Energy Agency
ID	Identification Document
IEC	International Electrotechnical Commission
IEEE	Institute for Electrical and Electronics Engineers
INL	Idaho National Laboratory
ION	Integrated Operations for Nuclear
ISG	Interim Staff Guidance
ISV	Integrated System Validation
LWRS	Light-Water Reactor Sustainability
MCR	Main Control Room
NASA	National Aeronautics and Space Administration
NRC	Nuclear Regulatory Commission
NSR	Non-Safety Related
O&M	Operating and Maintenance

OER	Operating Experience Review
OPD	Observability, Predictability, and Directability
OSA	Operational Sequence Analysis
OSD	Operational Sequence Diagram
PRA	Probabilistic Risk Assessment
R&D	Research and Development
RRCS	Redundant Reactor Control System
RSR	Results Summary Report
SART	Situation Awareness Rating Technique
SME	Subject Matter Expert
SR	Safety-Related
STPA	System Theoretic Process Analysis
TCO	Total Cost of Ownership
TLX	Task Load Index
U.S.	United States
UFSAR	Updated Final Safety Analysis Report
V&V	Verification and Validation
VDU	Video Display Unit

DEMONSTRATION AND EVALUATION OF THE HUMAN-TECHNOLOGY INTEGRATION FUNCTION ALLOCATION METHODOLOGY

1. INTRODUCTION

Nuclear power provides approximately 20% of electricity generation to the United States (U.S.). Nearly half of the nation's non-greenhouse-gas-emitting electric power generation is nuclear power, providing a significant role in mitigating climate change. However, existing nuclear power plants are being challenged economically as other electricity generating sources, like natural gas and renewable energy sources, have seen reduced operating and maintenance (O&M) costs for a variety of reasons, including changes to the energy market, as well as added government subsidies for resources like solar and wind (Remer, Thomas, Lawrie, Martin, & O'Brien, 2021). As a result, there is an imminent need for existing nuclear power plants to reduce their O&M costs to remain economically viable.

Digital technology, including automation, provides significant opportunity for the existing nuclear power plant fleet to transform that way in which work is accomplished to reduce O&M costs and allow the fleet to remain economically competitive. To enable this transformation of work, the U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program is conducting targeted research and development (R&D) to develop technologies and solutions that improve the economics and reliability, sustain safety, and extend the operational lifespan of the existing fleet. This is being enabled through several R&D pathways. One pathway, Plant Modernization, is addressing nuclear plant economic viability through the innovation of digital technologies and business-model transformation. These research objectives are accomplished through the four research focus areas shown in Figure 1.

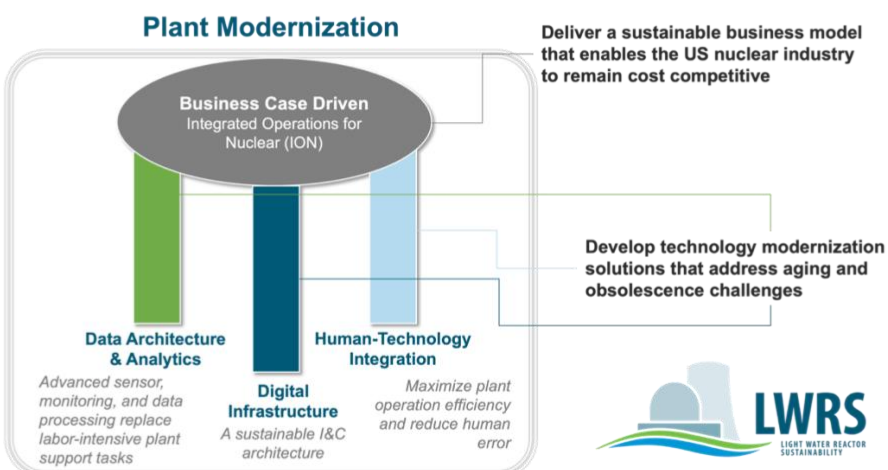


Figure 1. LWRS Program Plant Modernization focus areas.

As seen in the figure, Integrated Operations for Nuclear (ION) drives the R&D of technology modernization solutions that support the mission by addressing nuclear plant economic viability challenges through delivering a sustainable business model. Recent R&D under the ION domain can be found in INL/EXT-20-59537 (2020) and INL/EXT-21-64134 (2021). This work notably has identified several work domains and associated opportunities to develop, demonstrate, and deploy innovative solutions, including digital technologies, to significantly reduce O&M costs that will enable continued operation of the existing fleet. For instance, Remer and colleagues (2021) investigated key work domains that provide the greatest opportunity for O&M cost savings in the next 3–5 years; these domains are shown in Figure 2. The mosaic graph presents these domains as a function of their relative magnitude in O&M savings.

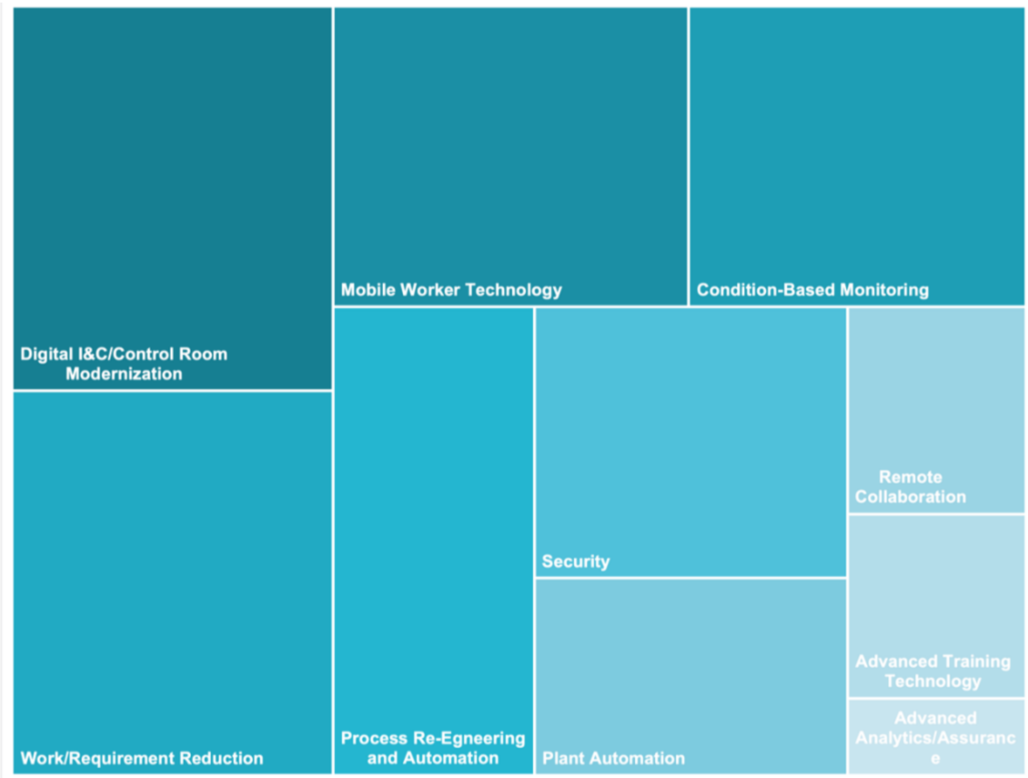


Figure 2. Key work domains that offer greatest opportunity for cost savings.

One notable domain shown from the mosaic graph is digital instrumentation and control (I&C) and control room modernization, in the top left of the graph. The challenge space here is that existing I&C technologies in the main control room (MCR) are highly analog, costly to operate and maintain, and demand high levels of cognitive and physical workload from plant staff (i.e., operators). Digitalizing the MCR has a range of broad economic benefits, including:

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

Digital I&C systems can fundamentally change the way in which plant staff operate the plant; this is known as the concept of operation. Operators who once adapted to and leveraged the characteristics of the analog I&C in existing MCRs will be impacted using digital technologies. Some examples of notable changes may include:

- Go from standing to sitting at digital workstations
- Using large overview displays for sensemaking as opposed to relying on the vast amounts of readily viewable analog indications
- Using data visualization techniques and integration to support situation assessment, diagnosis, and response planning
- Managing alarms differently as a result of new capabilities that filter and prioritize incoming alarms

- Using computer-based procedures that offer new capabilities unseen in paper-based analogs
- Using increased levels of automation to control the plant, which changes operation from tactical (i.e., at-the-boards) to more supervisory.

These characteristics indeed require careful understanding of the human-technology integration considerations (refer back to Figure 1) that are part of changing the concept of operation. For instance, assigning plant functions to people and automation (i.e., function allocation) requires understanding the capabilities of both people and the technology (i.e., automation) at hand. Human-technology integration employs human factors engineering (HFE) methods and principles to maximize the benefits of digital technology while reducing human error traps. Human-technology integration and HFE is applicable to all opportunities where there are end users interacting with technology and processes to perform work. This report documents the results of demonstrating human-technology integration guidance developed in 2021 by the U.S. DOE LWRS Program and reported in:

> Kovesdi, C.R., Spielman, Z.A., Mohon, J.D., Miyake, T.M., Hill, R.A., & Pederson, C. (2021) Development of an Assessment Methodology That Enables the Nuclear Industry to Evaluate Adoption of Advanced Automation, INL/EXT-21-64320, United States. https://doi.org/10.2172/1822880

The demonstration of the human-technology integration and function allocation guidance was based on a first-of-a-kind digital modification described later in this report. The report is structured into several sections:

- Section 2 provides the background of automation and how it applies to nuclear power plant modernization
- Section 3 provides background into function allocation with relevant standards and guidelines, including existing challenges with using this guidance and discussion of emerging HFE methods
- Section 4 presents elements of the work developed in 2021, documented in INL/EXT-21-64320, that pertain to function allocation
- Section 5 presents the demonstration of the function allocation guidance summarized in Section 4 to a first-of-a-kind digital modification
- Section 6 highlights lessons learned from this demonstration
- Finally, Section 7 concludes this work and provides next steps.

2. SCOPE OF AUTOMATION

Automation can be characterized as:

> *(a) The mechanization and integration of the sensing of environmental variables (by artificial sensors); (b) data processing and decision-making (by computers); and, (c) mechanical action (by motors or devices that apply forces in the environment) or information action by communication of processed information to people* (Sheridan, 2002, p. 9).

In this sense, automation has many similarities to that of human information processing such that automation (as with people) acts on a specific goal by perceiving information, processing this information for sensemaking to make decisions from it, and formulating a response to then act upon. For people, this is achieved through perception, cognition, and action (e.g., Wickens, Gordon, Liu, & Lee, 2004). Automation achieves a similar outcome through artificial sensors (perception), computer processors (cognition), and mechanical actuators and displays (response planning and execution). As previously presented in INL/EXT-21-64320, Figure 3 illustrates the scope of automation as it applies to modern technology.

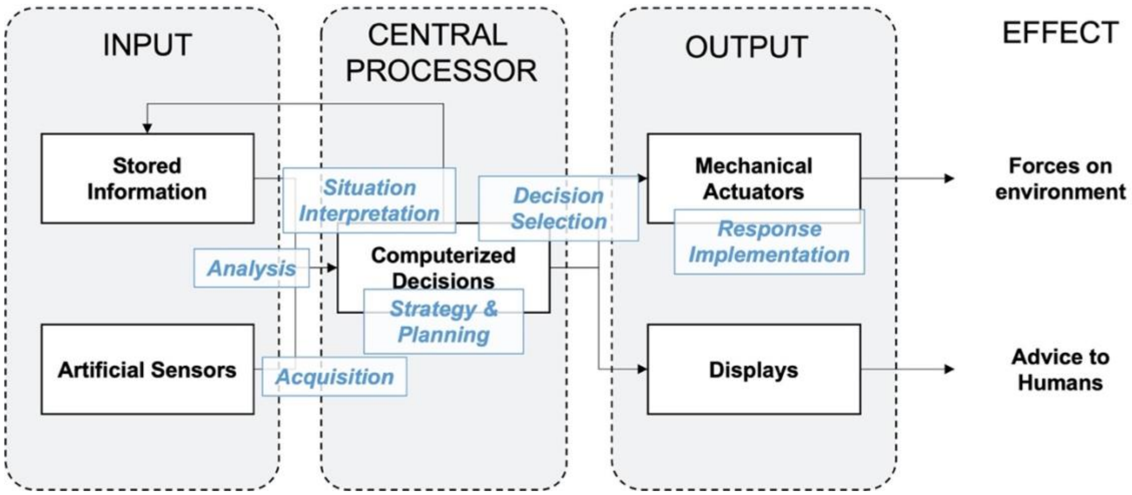


Figure 3. Scope of automation (adapted and enhanced from Sheridan 2002).

Nuclear power plants utilize automation in a variety of ways and can be categorized in four types (EPRI 3002004310, 2015):

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

Within a nuclear power plant, the types of automation support different work functions across the plant. For example, control automation is a type of automation with a specific purpose to operate the plant by performing sequences of action on plant equipment. Administrative task automation is used to improve work performed in support and maintenance plant functions and may include applications ranging from electronic work packages and chemistry sampling to general database integration.

Figure 4 below is work developed by Hunton and colleagues (2019), which presents a digital infrastructure that enables the use of advanced automation and digital capabilities. This digital infrastructure is described around the Purdue Model, as seen on the left side. The figure is a simplified diagram of information flow from plant sensors and devices (blue) to safety (red) and non-safety (green) and up through higher levels of the infrastructure, leading to the corporate business network in gray. The specific role of automation types can be realized at different levels on the digital infrastructure. That is, control automation is used to control equipment and can be achieved from the distributed control system (DCS), shown with the integration of a safety (red) platform, a non-safety platform (green), and non-safety DCS advanced applications (burnt orange). Information and decision aids that support operations can also be realized here through advanced automation like computerized operator support systems, computer-based procedures, etc. The corporate network can house applications that support other areas of the plant in which administrative automation can be seen.

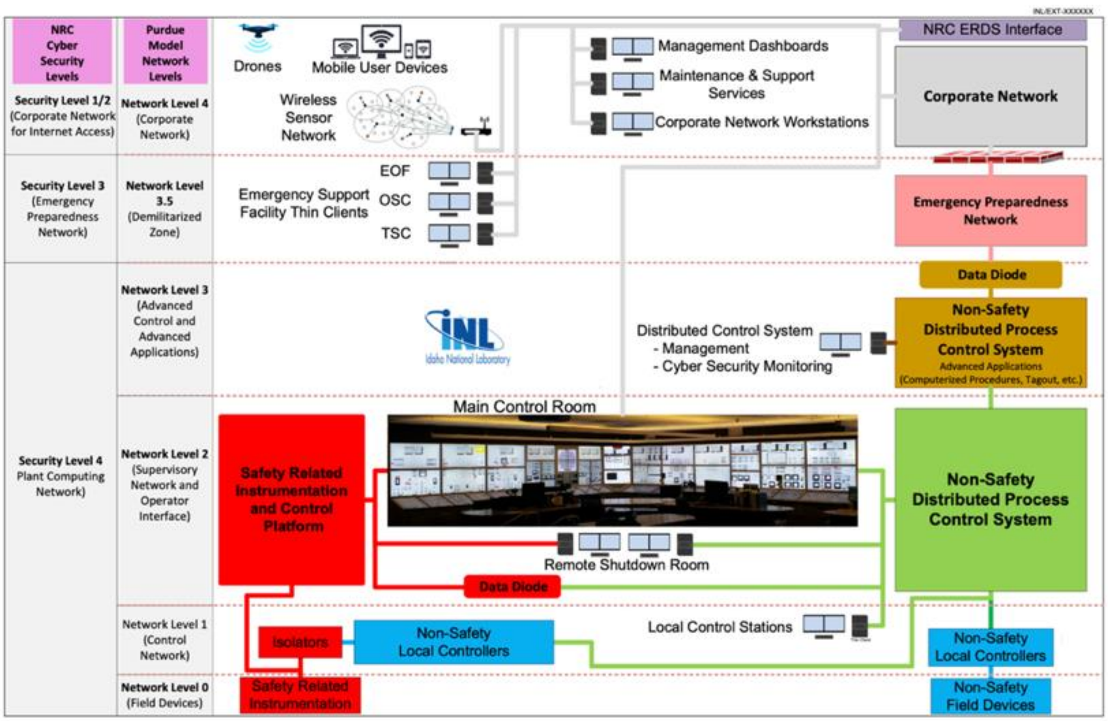


Figure 4. Digital infrastructure using the Purdue Network Model to enable advanced automation.

When performing function analysis and allocation (FA&A), all types of automation must be considered. Moreover, it is important to note that *where* on the infrastructure the automation resides will have implications on the way function allocation may be performed, determined by its scope, risk level, and other considerations. That is, following a graded approach, the level of rigor may be focused on high risk, safety-critical functions that require timely action by operators. Automation that is administrative in nature and does not have high economic or safety risk may be of less concern. This work describes a graded approach to function allocation. The following section describes a brief history of function allocation in a human factors sense. The intent is to inform the reader of primary resources within the human factors and nuclear community for function allocation to which this work builds on.

3. BACKGROUND AND EXISTING INDUSTRY GUIDANCE FOR FUNCTION ALLOCATION

Function allocation can be traced to the original work performed by Paul Fitts (1951). The Fitts List provided a dichotomized list of abilities that people and machines are better suited at (Table 1).

Table 1. Fitts List (1951).

People Are Better At	Machines Are Better At
• Ability to detect a small amount of visual or acoustic energy • Ability to perceive patterns of light or sound • Ability to improvise and use flexible procedures • Ability to store very large amounts of information for long periods and recall relevant facts at the appropriate time • Ability to reason inductively • Ability to exercise judgment	• Ability to respond quickly to control signals and apply great force smoothly and precisely • Ability to perform repetitive, routine tasks • Ability to store information briefly and then to erase it completely • Ability to reason deductively, including computational ability • Ability to handle highly complex operations (i.e., to do many different things at once)

The notion of Fitts List is to provide design guidance in assigning functions to either people or machines, based on their qualities reflected in the list. As interpreted from Fitts List, functions better suited for machines should be automated whereas functions better suited for people should be assigned to the person. There have been numerous criticisms of using Fitts List in real-world applications (e.g., Fuld, 1993; Sheridan, 2002), and this paper is surely not within scope of providing a detailed critique. Though, some of the more salient critiques are as follows:

- **A False Dichotomy.** The assignment between people and automation is not truly a dichotomy, rather there’s an element of cooperation between agents (Sheridan, 2002; Wickens et al., 2004).
- **Overly Simplified.** There are generally numerous combinations in which a function can be carried out between automation and people, and applying the list is short sighted (particularly for complex systems); this is compounded in that responsibly assigning a function requires a priori knowledge of context to which the function is being assigned (Sheridan, 2002; Wickens et al., 2004).
- **Leftover Problem.** There are concerns of a leftover problem in which functions are decided on a technology-centered approach (as opposed to user-centered) based on whether it is technically feasible to automate, leaving “leftover” functions to the person (Roth et al., 2019; Wickens et al., 2004).
- **Outdated Guidance.** A final criticism, perhaps the most salient, is that the guidance is aged, given that it was developed in 1951 (Sheridan, 2002; Wickens et al., 2004). Certainly, with ever-evolving technology, including but not limited to the advent of computers and artificial intelligence, the qualities described in each column of the list are almost certain to change.

Despite these criticisms, Fitts List is still regarded as a useful starting point in function allocation (e.g., Fuld, 1993; De Winter & Dodou, 2014). It has generated scientific debate among the human factors community and has served as a basis for standards and guidelines that have expanded on Fitts List to more elaborate process-related approaches for performing function allocation in complex systems, like nuclear power plants. Building on Fitts List, the next section presents standards and guidelines related to FA&A.

3.1 Standards and Guidelines

3.1.1 NUREG-0711: HFE Program Review Model

The U.S. Nuclear Regulatory Commission (NRC) HFE Program Review Model (NUREG-0711 2012) does not so much provide FA&A guidance but rather provides detailed process guidance to support the NRC staff in their reviews of HFE programs. However, FA&A is an integral part of NUREG-0711, as seen in Figure 5.

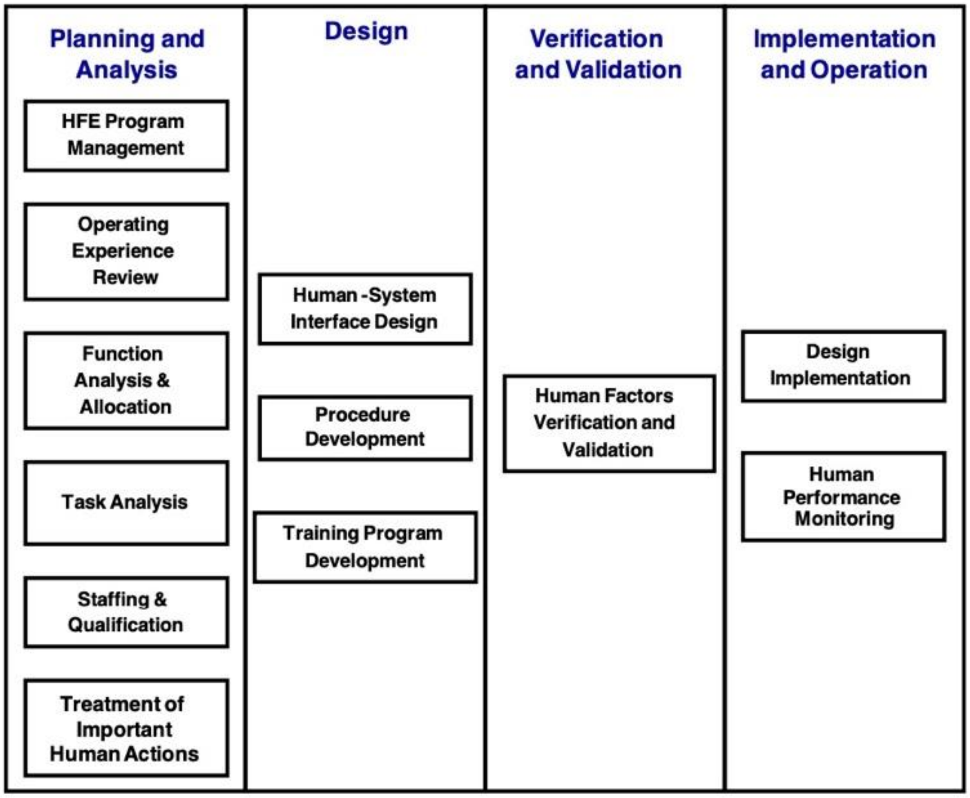


Figure 5. HFE phases and elements in NUREG-0711 (2012).

The review criteria presented in NUREG-0711 is meant to verify that the application has defined the functions that must be carried out to satisfy the plant's safety and power generation goals (i.e., function analysis) and has allocated those functions to people and automation such that peoples' capabilities are accounted for (i.e., leveraging their strengths and avoids their limitations). There are a total of nine criteria given to ensure that:

- A structured approach that reflects HFE principles was followed.
- The FA&A process is iterative so that it can be reused when modifications are considered.
- A hierarchical analysis of functions to decompose functions to identify requirements is incorporated.
- The approach allocates functions based on technical bases that can be justified.
- For functions allocated to people, the approach considers secondary allocations (e.g., automation as a backup) and clearly defines all functions allocated to people.

3.1.2 NUREG/CR-3331: Methodology for Allocating Nuclear Power Plant Control Functions to Human or Automatic Control

The U.S. NRC provides detailed guidance for function allocation in NUREG/CR-3331 (1983). This document provides one of the earliest guidance for function allocation in the design of nuclear power plants and has been used as a foundational methodology for forthcoming standards and guidelines, such as NUREG-0711 and others described later. NUREG/CR-3331 was developed to create specific guidance for nuclear power plants in performing function allocation or evaluating allocation in an existing design. The intent was to provide a method that can ensure function allocation is done through an "orderly" and "rational" approach.

NUREG/CR-3331 follows a rigorous and deductive approach to allocation between people and automation through a series of decisions. The results of following NUREG/CR-3331 fall on a decision matrix shown in Figure 6.

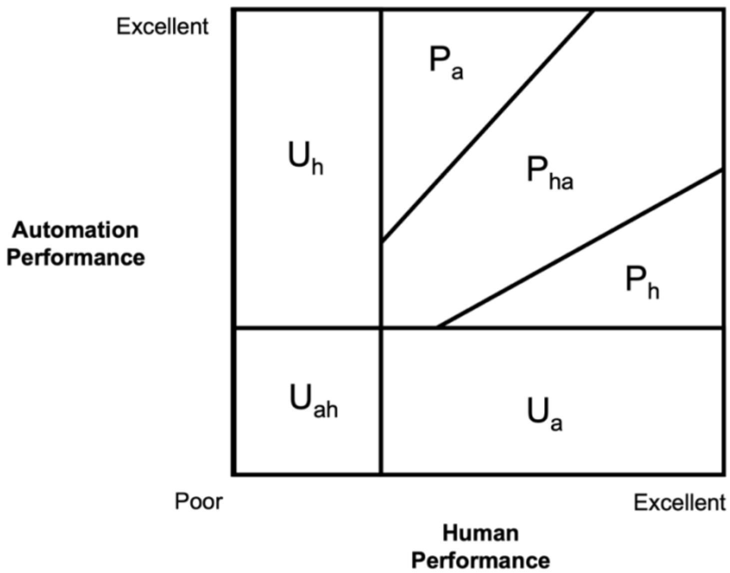


Figure 6. Decision matrix for allocation of functions (adapted and enhanced from NUREG/CR-3331).

The matrix shows automation performance on the y-axis and human performance on the x-axis. Specific regions within the plane show whether allocation is unacceptable (U) or preferred (P) for humans (h) and automation (a). In a region where allocation is unacceptable, the allocation to the other (i.e., whether be automation or human) is required. For instance, the bottom right region, where human performance is excellent and automation performance is poor, states that automation is unacceptable so thus allocation to the human is required. There are cases where it is unacceptable for both, as seen in the bottom left. When both automation and humans are good to excellent in performance, the decision is less straightforward. In that case, preference is given to the assignment of function and depends on whether performance is slightly better for one than the other. There is the middle region (P_{ha}) that is indifferent to the assignment of function.

The decision criteria used in NUREG/CR-3331 first begin with addressing whether assignment is mandatory whether because of law or regulation or even technically feasible. Next, functions are further decomposed into information processing qualities (sensory, cognitive, and motor behaviors) to evaluate the suitability of people and automation. Suitability is assessed through means like expert judgment and tools given in the appendices of NUREG/CR-3331 that present human performance data that can be used to support decision-making.

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

The U.S. NRC Human-System Interface Design Review Guidelines (NUREG-0700 2020) provides a comprehensive list of detailed HFE design guidelines. The guidance spans from general human-system interface (HSI) design elements to specific system, workstation, and workplace design guidance. Automation is an explicit topic in NUREG-0700 in the third revision. Specifically, the guidance focused on the interaction with the HSIs used to control and monitor automation. Automation guidance is described in the following areas:

- *Automation Displays:* Refers to the characteristics of displays used for monitoring automation.
- *Alerts, Notifications, and Status Indications:* Concerns with the design and manner of notifying operators about the need for automation, status indications related to automation, terminating automation, cautions, warnings, and alerts related to automation.
- *Interaction and Control:* Refers to the characteristics of controlling automation.
- *Automation Modes:* Concerns modes of operation, such as with indicating current mode state and alerting of changes to modes.
- *Automation Levels:* Concerns the extent to which a task is automated, including assignment to manual, automated, or shared responsibility (Figure 7).
- *Adaptive Automation*: Concerns guidance in applying adaptative automation (dynamic and flexible assignment of function) based on certain criteria, such as if an operator's workload is overburdened.
- *Computerized Operator Support Systems*: Specific guidance on decision support tools like computerized operator support systems that aid operators in situation assessment and response planning.
- *HSI Integration*: Guidance on the integration of automated systems in the larger context of the MCR and addressed key considerations related to ensuring consistency and availability of supporting materials.

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

Figure 7. Levels of automation for nuclear power plant applications (adapted from NUREG-0700 2020).

3.1.4 EPRI 3002011816: Digital Engineering Guide

The Electric Power Research Institute (EPRI) Digital Engineering Guide (DEG) (EPRI 3002011816 2018) provides nuclear-specific guidance in applying systems engineering to support the installation of new and modified I&C technologies in nuclear power plants. The guidance is multidisciplinary in nature and HFE is one of the core engineering disciplines described. FA&A is noted as core activities in HFE and is also captured as a systems engineering activity. As such, the DEG considers FA&A as an activity broader than HFE that requires a multidisciplinary team. The overarching goals are to ensure technical requirements are sufficiently defined and analyzed (function analysis) so that the functions can be allocated to people or automation (allocation) based on an understanding of the capabilities of automation and people. System architecture (or modifications to it) is defined to support function analysis. The system architecture and scope drive the extent of modernization and consequently influences HFE. For large-scale modifications, HFE becomes highly involved. In such a case, the DEG provides guidance to refer to EPRI 3002004310 (2015), described next.

3.1.5 EPRI 3002004310: Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification

Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification pairs with NUREG-0711 (2012) and provides detailed guidance for the execution of HFE activities in the design of new nuclear power plants and modifications to existing plants. The guidance given on FA&A here closely follows the methodology presented in NUREG/CR-3331 (1983), among other sources (e.g., Sheridan, 2002). EPRI 3002004310 (2015) further follows a graded approach and includes a 17-step methodology. This methodology addresses defining (or addressing changes) to the concept of operations, performing function analysis, defining scenarios for evaluation, performing function allocation, and evaluating the impacts of allocation on other functions. The outputs of function allocation include automation requirements and HA (i.e., functions allocated to people fully or partially) that serve as inputs into task analysis.

3.1.6 IEC 61839: Nuclear Power Plants – Design of Control Rooms – Functional Analysis and Assignment

International Electrotechnical Commission (IEC) 61839 is an international standard that provides guidance for FA&A for the design of automation systems in nuclear power plants. IEC 61839 is applicable to the design of new nuclear power plants and modifications to existing nuclear power plants. The process for performing FA&A begins at the operational goals (i.e., availability and safety) to which functions are identified and decomposed into subfunctions that can be analyzed to determine their basic informational flow and processing requirements. Tasks are then identified and analyzed via task analysis techniques, and the results of the task analysis inform function allocation. Verification and validation (V&V) activities are then performed in isolation and later as an integrated system for later evaluation of assigned functions. The standard cites International Atomic Energy Agency (IAEA) TECDOC-668 (1992) for additional guidance in performing FA&A. Notably, function allocation is based on assignment to one of four categories is described in Table 2.

Table 2. Function allocation criteria from IAEA TECDOC-668 and used in IEC 61839.

Functions that must be automated	Functions that are better served from automation	Functions that should be given to people	Functions that should be shared
• Rapid or long-term processing of large quantities of data • Tasks requiring high-accuracy information (data processing or manipulation) • Those requiring high repeatability • Those requiring rapid performance • Those where the consequences of error are severe	• Lengthy tasks that require high consistency or high accuracy • Tasks the result in boredom • The use of automation may bring improvement to the design of the job	• Require heuristic or inferential knowledge • Require flexibility in performing	• Require a combination of automation and human abilities; e.g., use of automation to detect and annunciate and operators make judgments and take executive decision

Functions that must be automated	Functions that are better served from automation	Functions that should be given to people	Functions that should be shared
• Those where errors cannot readily be retrieved (corrected) • Those which must be carried out in an unacceptably hostile environment			

3.2 Technical Reports on Function Allocation for Next Generation Reactors

The following section presents a series of technical reports that disseminate the role of emerging nuclear power plant technologies and HFE implications, such as with function allocation. These reports present state-of-the-science guidance and considerations for emerging technology that will be seen in next generation reactor technologies (i.e., Generation IV nuclear power plants and small modular reactor technologies).

3.2.1 BNL-90424-2009: Trends in HFE Methods and Tools and Their Applicability to Safety Reviews

BNL-90424-2009 details HFE methods and tools regarding applicability to safety reviews. One of the main methods discussed is FA&A. The purpose of the FA&A review is to ensure that all essential functions required to satisfy operational and safety objectives have been identified. After all essential functions have been identified, functions can be allocated to human and systems resources in a way that leverages human strengths and avoids human limitations. There are several techniques presented on function allocation, as indicated in Table 3.

Table 3. Function allocation techniques listed in BNL-90424-2009.

Method/Tool	Key Features
Business Process Modeling	Articulates the “who, what, when, where, and why” of business processes supported by Business Process Engineering Language software
Command, Control, and Communication Techniques for Reliable Assessment of Concept Execution	Command and control team information flow
Improved Performance Research Integration Tool	Enables trade-offs between human resources, system-human function allocation, and system performance using Army/military conventions
Plant-Human Review & Effectiveness Decision Tool (PHRED)	Improved Performance Research Integration Tool adapted to nuclear power operations
Ship System Human Systems Integration for Affordability and Performance Engineering	A suite of manpower analysis tools that include function allocations
Top Down Function Analysis	Top-down function analysis
Scenario-Based Function Allocation	Holistic approach to function allocation

Additionally, this report details software development methods, tools, and techniques that are playing a prominent role in functional requirements analysis and function allocation. Software tools address the process, timing, and resource requirements for function accomplishment. This report also entails an industry expert evaluation of a comprehensive list of commercially available requirements management tools. This evaluation identified key features of each requirements management tool, along with the criteria used to evaluate them. The key features and evaluation criteria are intended to support designers in finding the most appropriate tools and can serve as a method for comparing them.

3.2.2 BNL-91017-2010: Human-system Interfaces to Automatic Systems - Review Guidance and Technical Basis

BNL-91017-2010 details guidance and methodologies that support human-system interfaces to automatic systems. The objective of this research is to develop guidance for reviewing an operator HSI with integrated automation. This report characterized important HFE aspects of automation, based on how automation is implemented in current systems. The HFE aspects are based on the following six dimensions:

- Levels of automation
- Functions of automation
- Processes of automation
- Modes of automation
- Flexibility of allocation
- Reliability of automation.

Additionally, BNL-91017-2010 presents a literature review on the effects of the discussed aspects of automation on human performance and on the design of HSIs. The technical basis established from the literature is used to develop guidance for reviewing designs and includes the following seven topic areas:

- Automation displays
- Interaction and control
- Automation modes
- Automation levels
- Adaptive automation
- Error tolerance and failure management
- HSI integration.

This report also includes author insights into the automation-design process, operator training, and operations.

3.2.3 INL/EXT-13-28601: Draft Function Allocation Framework and Preliminary Technical Basis for Advanced SMR Concept of Operations

This report details a draft function allocation framework and a preliminary technical basis for advanced small modular reactor concept of operations. Advanced small modular reactors are unique compared to traditional nuclear power plants from development and assembly to the concept of operations. These reactors apply more extensive automation compared to existing light-water reactors. Given these unique circumstances, new concepts of operations models must be researched and developed for advanced small modular reactors. An important element of the concepts of operations pertains to describing the characteristics of the proposed system with regards to who will use it and how it will be used. It is used to communicate system characteristics of the plant to all stakeholders, provide the basis for the design of HSIs, procedures, and training programs, as well as serve as a key input into subsequent HFE analyses.

The concept of operations is developed by conducting an in-depth analysis of operating characteristics and associated technologies will be used by the plant. In support of this objective and goal, three important research areas were included:

- Operating principles of multi-modular plants
- Function allocation models and strategies affected by the development of new, nontraditional concept of operations
- The requirements for human performance, based upon work domain analysis and current regulatory requirements.

This report summarizes the theoretical and operational foundations for the development of a new functional allocation model for advanced small modular reactors, including the application of work domain analysis. The report also highlights changes in research strategy prompted by a confirmation of the importance of applying the work domain analysis methodology to a reference advanced small modular reactor design. Further, it describes how this methodology will enrich the findings from this phase of the project in the subsequent phases and helps in identifying metrics and focused studies to determine human performance criteria to support the design process.

3.2.4 INL/EXT-13-30117: Development of a Technical Basis and Guidance for Advanced SMR Function Allocation

This technical report details the development of a technical basis and guidance for advanced small modular reactor function allocation, which includes the following three key activities:

- The development of a framework for the analysis of the functional, environmental, and structural attributes of advanced small modular reactors
- The effect that new technologies and operational concepts would have on the way functions are allocated to humans or machines or combinations of the two
- The relationship between new concepts of operations, new function allocations, and human performance requirements.

This report directly relates to the previously discussed report (INL/EXT-13-28601) evaluating automation integration implications. The challenges of integrating automation capabilities into advanced small modular reactors will not only impact technical and functional elements of the concept of operations but also the overall O&M costs. Due to these challenges, this report evaluates why it is necessary to develop new concept of operation models as well as new models of function allocation and human performance requirements. This report also explains the relationship between these requirements and how old paradigms and methodologies are no longer suitable for the analysis of evolving concepts. The report further explains how the development of new models and guidance for concepts of operations needs to adopt a state-of-the-art approach, such as work domain analysis. The primary goal of this methodology is to identify and evaluate specific human factors challenges related to nontraditional concepts of operations and the associated changes in the allocation of functions to human and system agents. This includes developing a framework for the analysis of advanced small modular reactor functions, structures and systems using the work domain analysis methodology.

3.3 Challenges with Existing Guidance

The following challenges can be summarized based on reviewing the literature and through subsequent discussion with industry.

3.3.1 Existing Guidance Focuses on "Blank Slate" Design

Current guidance provides a detailed and rigorous process that certainly has merit in addressing the criteria described in NUREG-0711 (2012), which provides particular benefit in the development of a new plant where the applicant begins with a "blank slate." It provides a structured methodology that can be performed iteratively to describe the hierarchical relation of high-level functions to the specific equipment. This detailed understanding then, in theory, can be used to responsibly assign functions to people or automation through the careful understanding of the function itself and how it impacts people.

For existing nuclear power plants, such guidance may not provide the most direct means to performing FA&A for digital upgrades at existing plants (Hunton & England, 2019). Digital upgrades at existing plants come with unique constraints, such as using commercially available qualified vendor digital technology (i.e., distributed control systems) that can be configured in a limited number of ways, either due to regulatory or technical constraints. As illustrated in Figure 8, digital modifications to an existing plant are less focused on defining new functions and rather on understanding how these current functions are managed and what impacts the new digital modifications will have on the concept of operations. Hence, the management of functions is an area of focus.

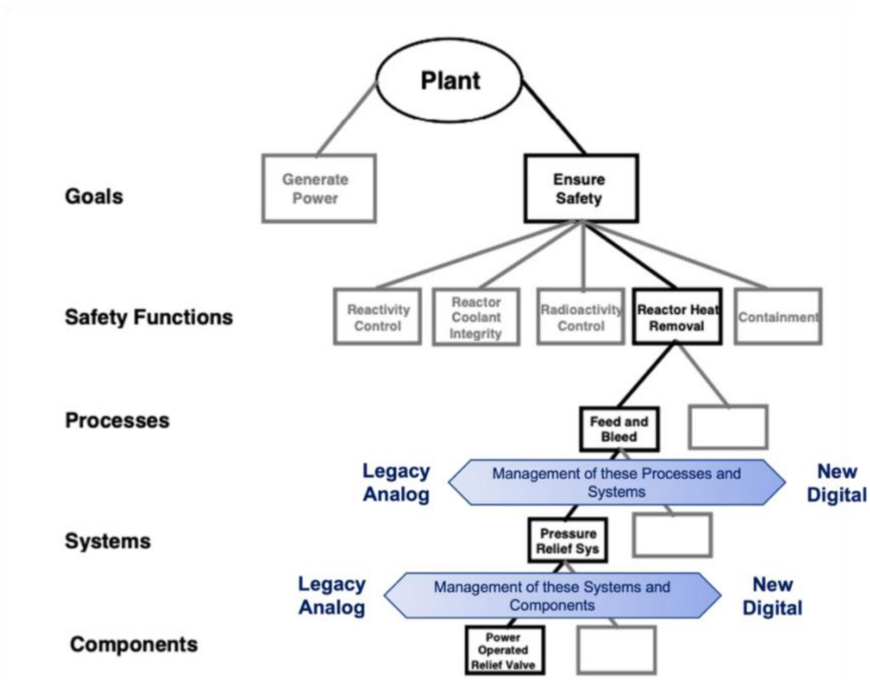


Figure 8. Vertical slide through a plant's functional hierarchy for ensuring safety (adapted and enhanced from NUREG-0711 2012).

The question of how to allocate functions is not purely an empirical one, decided by HFE. Rather, function allocation is a multidisciplinary endeavor in which human factors engineers must work closely with other disciplines to carefully understand what is possible (i.e., deemed from regulatory, technical, or economic considerations) and what configuration between automation and people provides the best suite to perform the function safely and reliably.

3.3.2 Limited to Safety with Minimal Guidance on Power Production

The methodologies provided previously have traditionally focused on plant safety where there has been little focus on power generation (Kovesdi et al., 2021). That is, at least within the public domain, function decomposition and allocation between people and automation has focused primarily on safety-related systems and with lesser focus on the secondary (i.e., power generation) side of the plant. It is important to note that, with changing energy markets in the U.S., there is an emerging need for existing nuclear power plants to identify ways in which O&M costs can be reduced to remain economically viable (Kovesdi et al., 2021). Hence, a need for understanding function allocation in the context of production is highly important.

A strategy for function allocation should holistically consider functions outside of plant safety and consider other applicable to functional areas outside of the MCR. For instance, research defined from ION has identified several opportunities to significantly reduce costs across the plant (Remer et al., 2021). Maintenance and support functions may benefit from automation in which the focus is less on plant safety, but rather on power generation optimization and applying human-automation integration principles that maximize the capabilities of both automation and people.

3.3.3 Minimal Real-World Use Cases in the U.S.

Unlike task analysis, which has been expanded upon and arguably used extensively in nearly all domains in which HFE is involved (e.g., Kirwan & Ainsworth, 1992), FA&A is less documented. To this end, the number of real-world use cases of function allocation, such as those described in NUREG/CR-3331 (1983), available to the public domain is notably limited. As a result, applying and tailoring a function allocation approach like NUREG/CR-3331 remains less straightforward when compared to more traditional methods that fall under the umbrella of task analysis. As such, the industry would benefit from additional real-world guidance in demonstrating function allocation, particularly with modern digital technology.

3.3.4 Does Not Explicitly Address Team Dynamics

Joe and colleagues (2015) position the need to consider social factors, such as teamwork (including people and automation), communication, trust, and creating shared mental models. The guidance to date has primarily focused on only "micro-ergonomic" factors, such as the perception, cognition, and action of the operator. However, "macro-ergonomic" considerations must also be addressed for effective allocation (Figure 9).

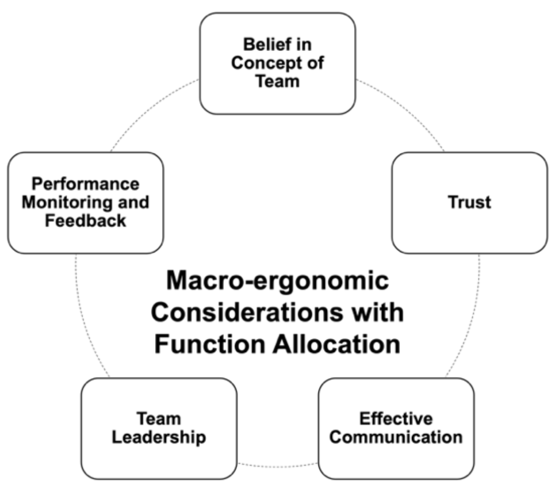


Figure 9. Team considerations for function allocation (Joe et al. 2015).

The ways in which automation is applied can fundamentally change the concept of operations, crew dynamics, and even organizational factors. Hence, there is a need to broaden how function allocation is addressed by considering these "macro-level" sociotechnical considerations.

3.4 Emerging Methods

Despite these challenges, among others, with traditional function allocation approaches, there has been a growing body of literature exploring alternative ways function allocation can be addressed. Namely, research performed by Roth and colleagues (2019) discusses emerging methods for addressing function allocation in new paradigms between people and advanced autonomous technologies (e.g., autonomous industrial process systems, vehicles, and robotics). Roth and colleagues' position that addressing function allocation requires not just one approach but an *integrated* approach that encompasses four key areas:

- Analyze operational demands and work requirements
- Explore alternative distribution of work across automation and people (i.e., authors refer to this as human-machine teaming)
- Examine interdependencies between automation and people required for effective teaming
- Explore trade-spaces of alternative human-machine teaming options.

The following subsections describe the exploration of emerging methods to address function allocation "in an era of human autonomy teaming" around these four key areas.

3.4.1 Analyze Operational Demands and Work Requirements

A fundamental consideration in function allocation is understanding the nature of the work being performed and corresponding challenges that come with it. By understanding the very nature of the work being performed (i.e., not just the tasks required to perform the work), Roth and colleagues (2019) posit that function assignment can be better informed. Going beyond routine use cases and understanding how automation and people jointly operate to attend to non-routine and perhaps emergent conditions is important in designing resilience into the system. Cognitive task analysis (CTA) and cognitive work analysis (CWA) are promising methods well suited for analyzing operational demands and work requirements. CTA and CWA are meant to be complementary to each other, as each has different philosophies (Jameison, 2003).

3.4.1.1 Cognitive Task Analysis (CTA) – Knowledge Elicitation Techniques

CTA provides a broad set of task data collection and representation techniques that focus on the cognitive elements of work (Crandall, Klein, & Hoffman, 2006). Knowledge elicitation methods like the critical decision method can be used to understand in detail how operators performed important decisions with the technology, based on actual incidents. There are several different CTA approaches, including but not limited to (see Stanton et al., 2013; Stanton, Salmon, Walker, & Jenkins, 2017; Crandall et al., 2006):

- Critical Decision Method and Critical Incident Technique
- Concept Mapping
- Cognitive Walkthrough
- Applied CTA
- Concurrent Observer Narrative Technique.

An important characteristic of CTA, regardless of specific techniques, is that each approach focuses on eliciting knowledge from subject matter experts (SMEs) on elements of work. Specifically, CTA seeks to understand the cognitive aspects of work and resulting challenges that come with it. This information can then be used to inform subsequent system design. Ultimately, CTA enriches design knowledge to effectively assign functions to people or automation (Kovesdi et al., 2021).

3.4.1.2 Cognitive Work Analysis (CWA) – Work Domain Analysis

CWA is rooted in nuclear power plant design (Rasmussen 1979) and is a sociotechnical framework that models complex work systems through multiple layers of constraints. The CWA framework offers a set of tools that can be used in conjunction or separately at each constraint layer, depending on the needs of the analysis (Stanton et al., 2017). The phases of CWA include:

- *Work Domain Analysis* – defines the work environment and its underlying purpose under analysis
- *Control Task Analysis* – defines the activities (work functions, situations, and key decisions) required to achieve the system objectives
- *Strategies Analysis* – defines the strategies afforded within the work domain in which activities are performed
- *Social Organization and Cooperation Analysis* – examines the distribution of work across all agents within a system (i.e., whether assigned to people or automation)
- *Worker Competencies Analysis* – examines the competencies (knowledge, skills, and abilities) required of people to perform work within the system.

CWA offers specific tools at each phase to evaluate the work domain. CWA's scope goes beyond function allocation; however, it can be used to address function allocation considerations. Work domain analysis can define the purpose of the system and available functions. The abstraction hierarchy is a common tool used to support work domain analysis that provides a graphical way of showing the interrelations of a system's functional purpose, its values and priorities, its constraints, its higher level functions, its physical functions, and specific systems and components. Figure 8 provides an example of an abstraction hierarchy typically be seen from CWA. The abstraction hierarchy can represent an existing system and proposed system to highlight key functions being impacted. The results may be best suited to show global impacts on the concept of operations with significant changes proposed for the system and its work domain.

3.4.2 Explore Alternative Distribution of Work

Complementary to analyzing the operational demands and work requirements, the CWA and abstraction hierarchy can be extended and used to explore different options of work distribution across a proposed automation (Roth et al., 2019). CWA's control task analysis phase and use of contextual activity templates are proposed. Contextual activity templates provide a way of mapping specific work functions to work situations. Following work domain analysis, higher level and system-level functions can be mapped to specific situations in which the functions are performed (Stanton et al., 2017). Situations are generally mapped across the x-axis and functions are mapped down the y-axis, creating a two-by-two matrix. Within the matrix, the use of specific functions is graphically depicted for typical and all possible situations. A key output of contextual activity templates is the explicit traceability of functions to the situations in which they occur. Contextual activity templates can be extended with the social organization and cooperation analysis phase of CWA to identify the specific agents (i.e., people and automation) responsible for executing a function within a given situation.

3.4.3 Examine Interdependencies Between Automation and People

The assignment of responsibility between people and automation must be analyzed in terms of the interactions required to perform work and how joint performance between people and automation can be optimized (Roth et al., 2019). This has bearing in addressing key function allocation changes to existing nuclear power plants in which the functions and situations may be already defined. However, the management of these functions can be fundamentally changed with new digital technology. For example, a legacy plant may have previously required nearly all manual actions to perform a turbine startup. With the emerging digital technology seen in a modern DCS, automation may enable evolutions of the startup to be allocated to control automation in which the operator is supervising the automation. Understanding the interactions between agents is critical to ensure optimal joint performance. The following approaches are described as tools to examine the interaction between automation and people.

3.4.3.1 CWA – Control Task Analysis: Decision Ladders

One such way of examining the interactions between agents is by the decisions required to perform work, regardless of who is responsible in making these decisions. Decision ladders are one such tool within the CWA toolkit explicitly designed to examine the critical decisions made by the human-automation team to perform work. This tool provides a framework to evaluate the flow of information and associated decisions demanded by each agent for perceiving, deciding, and acting on the information. The interdependencies of information flow between agents can be examined to decide whether the allocation of functions supports effective teamwork between agents, including people and automation (Roth et al., 2019).

3.4.3.2 Coactive Design (Johnson et al., 2014)

Coactive Design expands on traditional task analysis and focuses on joint performance between people and automation (Johnson et al., 2014). The work originated out of human-robot interaction research and is based on the coactive system model, as shown in Figure 10.

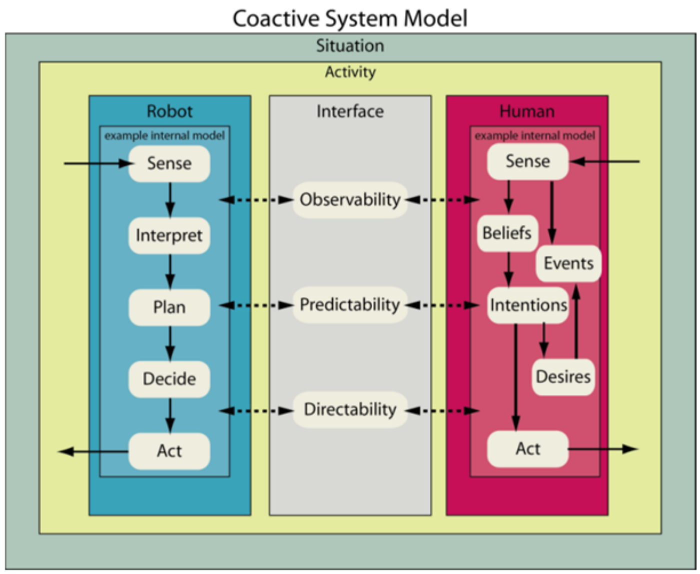


Figure 10. Coactive system model (adapted from Johnson et al., 2014).

At its core, the model presents a closed-loop relationship between human and automation actors. The interaction between agents is enabled by the interface. The interface serves as an intermediary for automation and people and is characterized in terms of *observability*, *predictability*, and *directability* (OPD). Observability refers to making one's status observable to others (i.e., knowledge in the world). Predictability refers to the need for an agent's actions to be observable and reliable. Finally, directability refers to having the ability of one agent to direct the behavior of others and vice versa. The OPD framework allows identification of teamwork requirements based on these qualities. The OPD framework is used in the Coactive Design method and used during the construction of the Interdependence Analysis (IA) table.

The IA table is an extension from tabular and hierarchical task analysis. It describes the specific tasks required regardless of function assignment. Next, there are several unique characteristics that extend the task analysis. First, each sub-task is described in terms of "Identifying Required Capacities for Tasks." Capacities refer to the informational needs, knowledge, skills, and abilities including sensing, perception, decision-making, and action needs of a sub-task. The IA table allows an evaluation of each identified capacity within a given sub-task in terms of the viability for each agent's role (i.e., function allocation). Primary performing of a capacity and supporting team members (i.e., including automation) are evaluated by the extent that they can be viably supported. Different combinations are enumerated to evaluate different options for function allocation. Feasibility and interdependence are then evaluated using OPD as a framework. Feasibility is evaluated based on whether the primary performer and supporting team member for a given capacity is achievable or not. OPD is evaluated for related capacities (e.g., sensing is required before interpreting) to develop requirements. The Coactive Design approach provides a systematic way of analytically evaluating possible combinations of function allocation; the output that comes from Coactive Design can then be evaluated through usability testing or other complementary human-centered design approaches.

3.4.3.3 Other Advanced Methods: System Theoretic Process Analysis (STPA)

Beyond work from Roth and colleagues (2015) described above, a final method worth mentioning is the System Theoretic Process Analysis (STPA) framework that comes out of systems engineering. That is, STPA is a systems engineering hazard analysis approach that looks at the system holistically by focusing on the interactions between components (Levenson & Thomas, 2018). The primary feature of STPA that describes this interaction, or interdependencies, is the control structure; here, the operator (and even organization) is included in the control structure, and the functions can be modeled through defining the control actions and feedback necessary to perform the function. Loss scenarios and unsafe control actions are then described using the control structure. The framework enables the design team to identify ways to mitigate unsafe control actions very early in the conceptual design. STPA may be used in conjunction with other function allocation approaches as a hazard analysis to better inform allocation of function design decisions.

3.4.4 Explore Function Allocation Trade-Space

Roth and colleagues (2019) position that function allocation is part of a larger systems engineering process in which tradeoffs are made in the development of complex systems. This position agrees with existing standards and guidance in the nuclear industry, such as DEG (2018). Function allocation tradeoffs range beyond human factors considerations to include cost, technical feasibility, and mandated regulatory requirements to name a few. The U.S. nuclear industry has subscribed to guidance seen in NUREG/CR-3331 and related guidance covered above. However, Roth and colleagues (2019) offer additional approaches that address broader sociotechnical considerations, such as those described by Joe and colleagues (2015) including teamwork. These entail Sociotechnical Methods from Waterson, Gray, and Clegg (2002), as well as simulation and modeling techniques.

3.4.4.1 Sociotechnical Method for Designing Work Systems

Waterson, Gray, and Clegg's (2002) approach to function allocation was in response to an earlier work (Older, Waterson, & Clegg, 1997), which examined the advantages and disadvantages of existing function allocation approaches. Their work identified a set of requirements that function allocation for modern technology should include. These requirements are captured in Table 4.

Table 4. Function allocation methodology requirements.

Categories	Requirement 1.	Provide coverage between people and automation, including shared roles
	Requirement 2.	Incorporate dynamic allocation
Issues	Requirement 3.	Consider people's job satisfaction
	Requirement 4.	Include specific decision criteria for allocation
	Requirement 5.	Consider tradeoffs for decision criteria
	Requirement 6.	Enable quantitative evaluations for tradeoffs
Approach	Requirement 7.	Consider a multidisciplinary approach and end users
	Requirement 8.	Enable end users to make informed decisions for allocation
	Requirement 9.	Apply early in the design process
	Requirement 10.	Be easy to learn and apply (i.e., practical)
Coverage	Requirement 11.	Examine the system as a whole

	Requirement 12.	Be applicable to complex systems
	Requirement 13.	Be adaptable to different situations
	Requirement 14.	Useful for new and existing systems
	Requirement 15.	Be useful and apparent to stakeholders that it is in fact useful
Design	Requirement 16.	Be structured and systematic
	Requirement 17.	Be low cost and efficient to use
	Requirement 18.	Be consistent with existing tools and techniques

Waterson and colleagues' approach to function allocation followed a process with seven discrete yet iterative stages:

Stage A. First, end users are identified and asked to develop a number of alternative allocation choices for the system. For existing systems that are being modified, the way in which the existing system functions is documented as a baseline reference. The authors suggest describing each allocation in terms of scope, boundary, vision (and basis), level of automation, organization structure, roles impacted, expected benefits, cost, implications, preferences, and rationale. An outcome of this stage is to feed requirements specification that is common in procuring complex systems.

Stage B. Next, a mandatory allocation of function is identified and assigned accordingly to people or automation. Waterson and colleagues (2002) provide a template in which to capture allocation of function (Figure 11).

Task No.	Task Name	Category of Criteria	Criteria	Options			Rationale	Other Details	Issues Arising
				H	M	H-M			
Preference				Overall Rationale					
H	M	H-M							

Note: H = Human only; M = machine only; H-M = dynamic.

Figure 11. Function allocation table template (adapted from Waterson, Gray, and Clegg, 2002).

Stage C. Following the mandatory assignment, remaining specific tasks are allocated provisionally between people and automation. Decision criteria for assignment are provided that account for system-level goals, cultural and organizational issues, resources, peoples' skills, task considerations, work organization issues, and technology issues (i.e., such as feasibility and cost).

Stage D. Similar to Stage C, tasks allocated to people are further defined in terms of assignment to different roles.

Stage E. Next, sets of circumstances in which dynamic allocation is beneficial are identified. Assignments captured in Stage C and Stage D are thus reexamined when evaluating the necessity and possibility for dynamic allocation of function.

Stage F. All allocated functions are then reexamined from a holistic view (e.g., do the provisional allocation of function from previous stages work when integrated together?).

Stage G. Final assignment of function is made upon iterative feedback across all previous stages and documented.

3.4.4.2 Simulation and Modeling

The notion of applying simulation and human-in-the-loop testing is not new to function allocation guidance (EPRI, 2015; Kovesdi et al., 2021). Not surprisingly, applying performance-based tests via simulation offers a wealth of opportunity to identify and mitigate critical design issues and ultimately inform allocation decisions. Simulation and modeling paired with rapid prototyping enables operators to perform realistic tasks with the proposed system to collect performance-based and user feedback. The design team, including vendor, utility stakeholders, operations, and HFE can observe these issues within a realistic context to come to effective design decisions (Kovesdi et al., 2021). Hence, simulation and modeling can be applied in combination with all other methods previously described to provide empirical bases for allocation decisions. This approach offers the "gold standard" in terms of addressing tradeoffs, especially with complex systems like nuclear power plants (Joe & Kovesdi, 2021).

3.4.5 Integrating Methods for Nuclear Power Plant Function Allocation

The challenges faced by industry in performing function allocation for large-scale digital modifications can be characterized by:

- Too much focus on new build design
- Too much emphasis on safety and not enough on power production
- Minimal real-world examples
- Falls short of addressing team dynamics.

Roth and colleagues (2019) offer an integrated approach to addressing function allocation for modern digital technology. The approach emphasizes a need to use a comprehensive set of methods and frameworks to address function allocation, based on range of considerations that go beyond Fitts List and traditional function allocation approaches. Function allocation is hence described in terms of four broad considerations:

- Analysis of operational demands and work requirements
- Exploring alternative distribution of work
- Examining interdependencies between people and automation
- Exploring the function allocation trade-space.

The approach hence prescribes specific sets of tools based on these unique considerations.

The scope of a digital modification resulting in a change in function allocation may decide what considerations are to be considered and consequently what methods and tools should be used. Figure 12 provides a framework based on Roth and colleagues (2019) and STPA (Levenson & Thomas, 2018) to address function allocation for large-scale digital modifications at U.S. nuclear power plants.

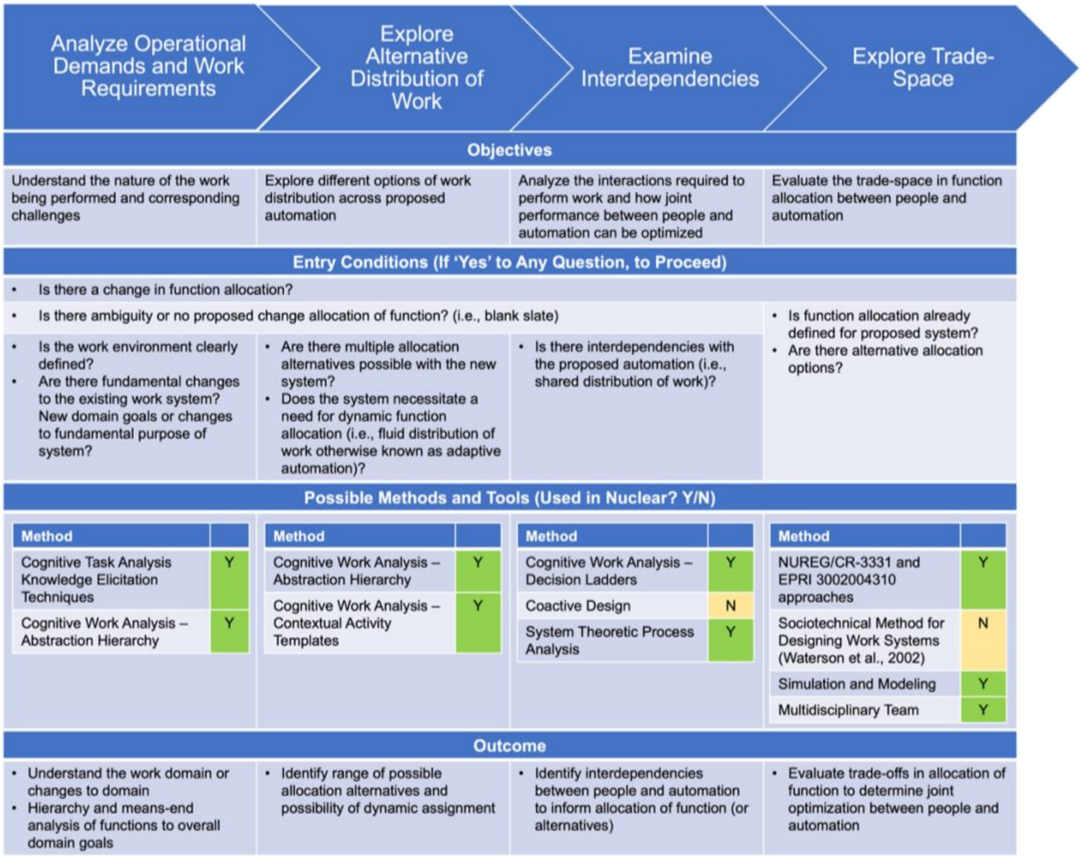


Figure 12. Integrated function allocation toolset (adapted and expanded from Roth et al., 2019).

The framework suggests that function allocation should be addressed based on the considerations identified from Roth and colleagues. There are "entry conditions" that determine whether a specific consideration is in scope or not. If the scope of the modification creates a "yes" response to any one of the questions corresponding to a consideration, the consideration should be addressed using one or more of the methods identified by Roth et al. (2019) and others like STPA, where applicable. Furthermore, as seen in the figure, specific methods are traced to whether they have been used in the nuclear industry by a "Y" for yes or "N" for no. It is not to say that a method not been used in the industry is irrelevant; rather, it is important to note that a justification of the technical basis of choice should be given. The outcome of performing function allocation using the suggested methods are defined at the bottom.

The outputs of each of the four function allocation considerations should build on each other. That is, significant changes that completely alter the plant's mission and concept of operation may require analyzing operational demands and work requirements. Where modifications are significant but not to the extent of fundamentally changing work performing at the plant, functions and the distribution of work may be understood, but system-level alterations in functions may necessitate the need to reexamine interdependencies and tradeoffs. An example of the former may entail adding an entirely new system that expands the plant goals (e.g., repurposing heat for hydrogen production that can be used beyond electricity generation). The latter may entail digital modifications to existing plant systems to which the plant is licensed to; here, automation may be added or modified so interdependencies and tradeoffs must be addressed.

The next section describes the inclusion of this framework to a broader methodology that supports the adoption of advanced technology in terms of addressing human and technology integration across the entire lifespan of a large-scale project.

4. HUMAN-TECHNOLOGY INTEGRATION METHODOLOGY

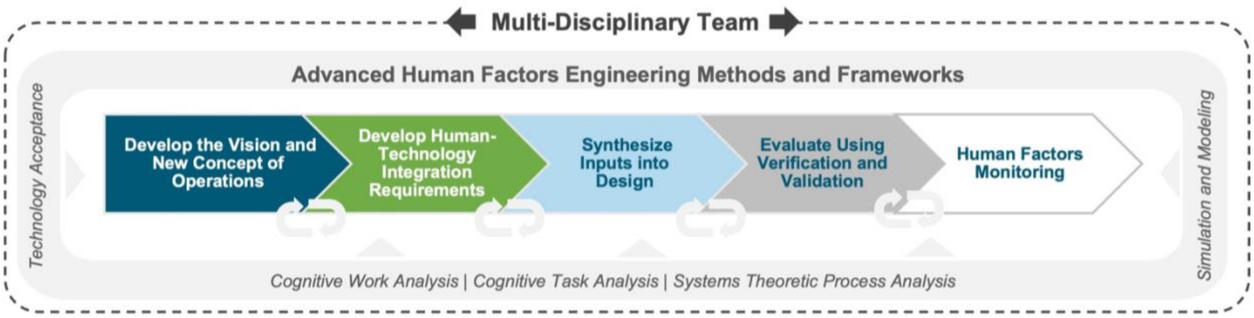


Figure 13. Human-technology integration methodology.

Figure 13 presents a human-technology integration methodology that can be applied to support large-scale digital modifications over the lifespan of the project. The guidance centers around five distinct yet iterative phases that correspond to first developing a vision and realization of the new concept of operation through requirements development, design, V&V, and HFE monitoring. The guidance is based on industry-endorsed standards and guidelines, including NUREG-0711 (2012), EPRI 3002011816 (2018), EPRI 3002004310 (2015), IAEA No. NR-T-2.12 (2021), and IEEE 1023 (2004). Additional guidance developed from the U.S. DOE LWRS Program is also captured in the methodology through the application of lessons learned in control room modernization and using HFE design principles.

The methodology also emphasizes the need for a multidisciplinary team and includes application of advanced HFE methods and frameworks shown in the gray outer box. Figure 14 highlights the relation between the human-technology integration methodology and the regulatory model shown in NUREG-0711. Each of the 12 elements in NUREG-0711 are mapped directly in the human-technology integration methodology. Additionally, the human-technology integration methodology adds additional guidance and activities to provide specific direction in developing a new state that enables continued cost competitiveness with other electricity generating sources while applying HFE throughout the lifespan of modernizing.

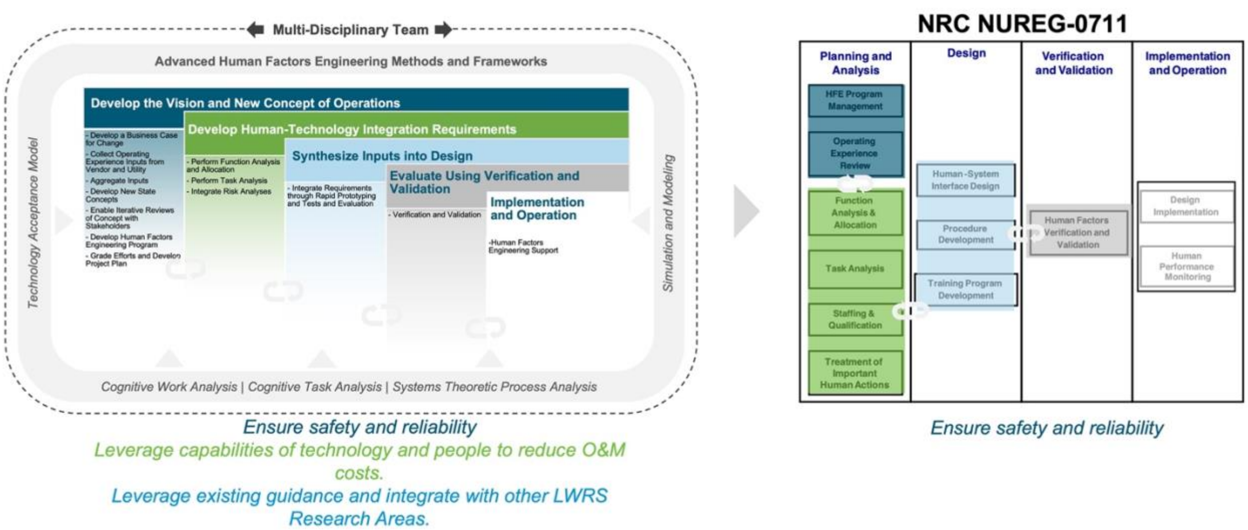


Figure 14. Crosswalk of the Human-Technology Integration Methodology with NUREG-0711.

The details of this methodology are documented in INL/EXT-21-64320; this work focuses primarily on the human-technology integration requirements shown in green, as it includes use of FA&A, task analysis, and integration of risk analyses (see Figure 15). The elements of this figure are summarized in the subsequent sections.

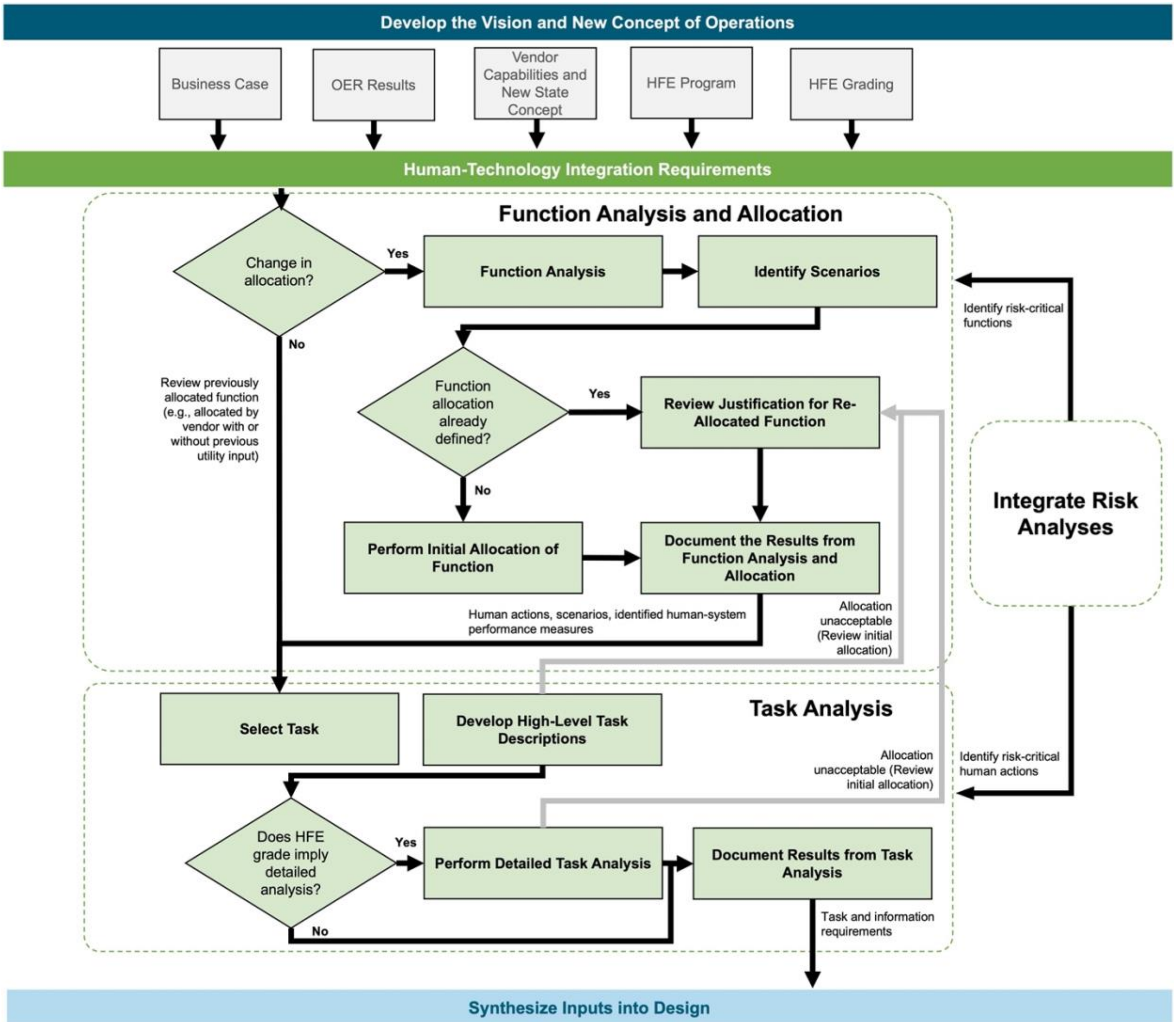


Figure 15. Human-technology integration requirements (adapted from INL/EXT-21-64320).

4.1 Function Analysis and Allocation

FA&A is presented around four primary steps:

- **Function Analysis (Step 1)**. Determination of the safety or performance impacts of the function and appropriateness of the allocation (human or support system). This includes appropriately decomposing the function by its goals, subfunctions, processes, and systems based on its grading.
- **Scenario Identification (Step 2)**. Scenarios are identified that demonstrate impacted functions allocated to people (human actions [HAs]) and tasks to support the evaluation of allocation tradeoffs.
- **Function Allocation (Step 3)**. Identification of functions allocated to people, whether fully or in a shared manner (i.e., these functions are called HAs). These HAs are evaluated in FA&A to ensure that people's capabilities are leveraged with technology to ensure plant safety, reliability, and

efficiency. The HAs are used in task analysis for a detailed review to develop task and information requirements that inform HSI design.

- **Results Summary Report (Step 4)**. A report (Step 4) documenting the results of FA&A (Step 1), including a description of the function (e.g., functional decomposition) and identified HAs that will be analyzed in task analysis, use cases and scenarios (Step 2), as well as any recommended changes in allocation of function based on the methodologies used (Step 3).

4.1.1 Step 1: Function Analysis

The purpose of function analysis, as it applies to modifications, is to identify and define new and changed functions in the scope of the modification. From an HFE standpoint, existing (and new) functions are identified and described in sufficient details to support function allocation. Function analysis should be a multidisciplinary approach, and the design team should include vendor, I&C engineering, operations, licensing, and HFE personnel. The selected platform should be considered in terms of leveraging its native capabilities (Hunton et al., 2019). Another important element of function analysis is to begin identifying important HAs that are impacted by the modification. Important HAs include credited operator actions from risk analyses like diversity and defense-in-depth (D3) analyses, updated final safety analysis report (UFSAR), and probabilistic risk assessment (PRA). The identification of impacted important HAs will drive subsequent FA&A activities, described next.

4.1.2 Step 2: Identify Scenarios

Next, scenarios are identified for each impacted function. These scenarios offer a way of evaluating impacted tasks and functions within their operational context. The identification of scenarios also can be carried forward in later HFE activities like task analysis, HSI design tests and evaluations, and V&V (i.e., integrated system validation [ISV]). Inputs that can be used in identifying scenarios can come from operating experience review (OER), as well as operational SMEs. Criteria that can be used for identifying scenarios include a demonstration of (adapted from EPRI 3002004310 and Kovesdi et al., 2021):

- Functions that substantially change the concept of operation
- Functions involving time critical tasks
- Functions that are frequently performed
- Functions that are important to safety, production, system availability, and equipment protection
- Functions that are not well understood because they are infrequently performed
- Functions that are currently manual and difficult to perform and result in human error traps
- New functions resulting from modernization
- Functions and tasks identified from OER
- Enhancements of the system and operator performance by automating all or part of system functions or operator tasks
- Parallel activities requiring operation that may interfere with the function’s performance.

4.1.3 Step 3: Allocation of Function

One salient update to FA&A made by Kovesdi and colleagues (2021) is that function allocation is split into two sub-steps.

- **Step 3a (Perform initial reallocation and review).** Performed when there is not an initial allocation of function made

- **Step 3b (Review justification for reallocated functions).** Performed when there is an initial allocation of function made.

With plant modifications, there likely will be a proposed initial allocation of function (Step 3b). This may be driven by the standard digital control system's available capabilities. Depending on the circumstance of whether functions are defined, and if the function is initially allocated, the scope of function allocation may vary in terms of the considerations that need to be addressed. Revisiting Roth and colleagues' (2019) framework for function allocation, Figure 16 shows the extent of function allocation based on the scope of the digital modification and whether an initial allocation has been made. Changes that fundamentally alter the goals of the plant require beginning with analyzing the operational demands of these changes. For changes that do not fundamentally change the plant's goals but do alter system-level functions and require an initial assignment to people or automation (i.e., no initial allocation of function), Step 3a is performed and maps to "exploring alternative distributions of work" as seen in Figure 16 (also refer back to Figure 12 for detailed framework). When functions have an initial allocation, the function allocation should examine interdependencies of tasks and related functions based on the initial allocation of function. Trade-space between alternative allocations should be explored through simulation, modeling, and a combination of HFE methods previously described.

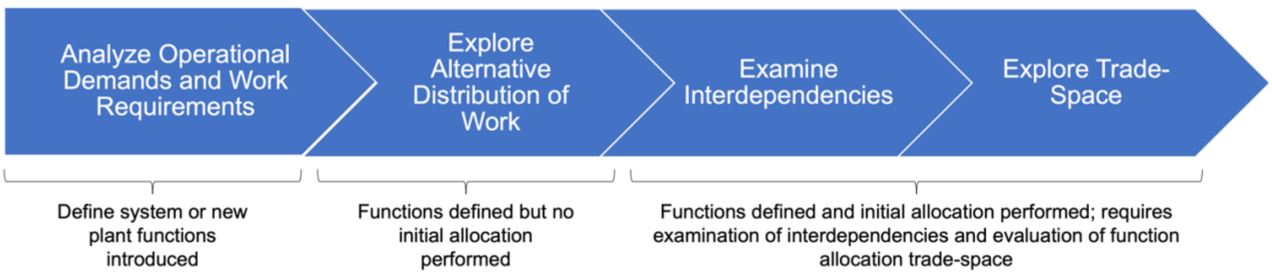


Figure 16. Function allocation extent based on modernization scope and initial allocation.

The output of function allocation (Step 3) results in a design decision for allocating functions identified within the modification. The design decision is driven by the design team and can be informed through analytical or empirical approaches. Specific considerations include alignment with:

- Any applicable bounding technical requirements
- Overall vision and concept of operations and OER findings
- Vendor I&C capabilities (considering feasibility, cost, anticipated benefits)
- Human capabilities (physical and cognitive).

Empirical approaches including human-in-the-loop testing via simulator testbeds offer the "gold standard" approach in evaluation automation impacts (e.g., Sheridan, 2002).

4.1.4 Step 4: Document the Results of Function Analysis and Allocation

The results of design decisions made for FA&A should be documented in a result summary report (RSR). This output should correspond to the expectations described in NUREG-0711 Section 4 (2012).

4.2 Perform Task Analysis

Task analysis is also described around four primary steps. These steps are:

- **Identify Tasks (Steps 1)**. The first step is to identify the specific tasks that operators must complete to accomplish the functions being impacted by the modification.

- **Develop High-Level Task Descriptions (Step 2)**. The second step is to develop high-level descriptions of the impacted tasks in terms of the alarms, information, controls, and task support needed.
- **Developed Detailed Task Descriptions (Step 3)**. Next, detailed task analyses are performed, using the high-level task descriptions developed. The level of detail required for specific tasks follows a graded approach.
- **Results Summary Report (Step 4)**. A report (Step 4) documenting the results of task analysis should be completed.

4.2.1 Step 1 - Identify Tasks

Tasks impacted by the modification should be identified through screening. Additionally, it is helpful to understand whether the identified impacted tasks are safety important or not. Credited operator actions, such as those from risk analyses, that are impacted should be identified and prioritized when addressing in task analysis and subsequent HFE activities.

4.2.2 Step 2 - Develop High-Level Task Descriptions

Identified tasks that are screened in from Step 1 of the task analysis should be described through high-level narratives in terms of the alarms, information, controls, and task support required to accomplish the tasks. Figure 17 outlines the possible scope of topics described from NUREG-0711 when developing high-level task descriptions.

Topic	Example
Alerts	• alarms and warnings
Information	• parameters (units, precision, and accuracy) • feedback needed to indicate adequacy of actions taken
Decision-making	• decision type (relative, absolute, probabilistic) • evaluations to be performed
Response	• actions to be taken • task frequency and required accuracy • time available and temporal constraints (task ordering) • physical position (stand, sit, squat, etc.) • biomechanics - movements (lift, push, turn, pull, crank, etc.) - forces needed
Teamwork and Communication	• coordination needed between the team performing the work • personnel communication for monitoring information or taking control actions
Workload	• cognitive • physical • overlap of task requirements (serial vs. parallel task elements)
Task Support	• special and protective clothing • job aids, procedures or reference materials needed • tools and equipment needed
Workplace Factors	• ingress and egress paths to the worksite • workspace needed to perform the task • typical environmental conditions (such as lighting, temp, noise)
Situational and Performance Shaping Factors	• stress • time pressure • extreme environmental conditions • reduced staffing
Hazard Identification	• identification of hazards involved, e.g., potential personal injury

Figure 17. Task considerations (adapted from NUREG-0711, 2012).

It is worth noting that oftentimes grouping tasks into higher level tasks through events and scenarios can allow a task analysis with greater context (EPRI, 2015). That is, tasks are generally not performed in isolation; rather, multiple tasks are performed in series or in parallel to accomplish some higher level goal. For example, a turbine startup may be considered a higher level goal to which multiple tasks are performed.

Describing and evaluating the tasks performed within the context of a higher level task can evaluate not only the tasks themselves but also the interaction of tasks when performed in succession or in parallel.

4.2.3 Step 3 - Perform Detailed Task Analysis

Detailed task analyses should be completed, particularly on tasks that are of safety significance. For instance, impacted credited operator actions should be evaluated based on whether there is an adequate time margin between the time available to the time required to perform the action (NUREG-0800, 2016). A method that evaluates the activities performed and the time required employs the operational sequence analysis (OSA) and operational sequence diagram (OSD). Depending on the scope of detailed task analysis, other methods can be applied as well. Kirwan and Ainsworth (1992) describe several detailed task analysis approaches; these methods among others are also found in EPRI 3002004310 (2015) and INL/EXT-21-64320 (2021) and include:

- Hierarchical task analysis
- Tabular task analysis
- Link analysis
- OSA and OSD
- Talkthrough and walkthrough analysis
- Workload analysis and timeline analysis
- Applied CTA
- Decision ladders.

4.2.4 Step 4 - Document Results of Task Analysis

The results of design decisions made for task analysis should be documented in an RSR. This output should correspond to the expectations described in NUREG-0711 Section 5 (2012).

4.3 Integrate Risk Analyses

As touched on in the FA&A and task analysis, a graded approach should be followed such as by focusing on the functions and tasks of significance. From a safety standpoint, significance may be defined by those functions and tasks that are identified in probabilistic (PRA) or deterministic (D3 or UFSAR) risk analyses, like impacted credited manual operator actions. Economic risk can also be considered. Other risk analysis like STPA may be considered to identify loss scenarios and "unsafe control actions" that result in loss scenarios. In whichever focus of risk, an important element of risk analysis integration is its use in enabling a graded approach for other HFE activities, like FA&A and task analysis.

5. DEMONSTRATION OF THE UPDATED FUNCTION ALLOCATION METHODOLOGY WITH INDUSTRY

5.1 Background

The FA&A and task analysis activities that are part of the human-technology integration methodology reported in INL/EXT-21-64320 and in Section 4 above were demonstrated to support a safety-related digital modification at a U.S. nuclear power plant. This section describes the specific approach followed in demonstrating the methodology along with other standards and guidelines such as those listed in Table 5.

Table 5. Primary standards and guidance used for function allocation.

NRC	• NUREG-0800, *Standard Review Plan: Chapter 18 Human Factors Engineering* (2016) • NUREG-0711, *Human Factors Engineering Program Review Model* (2012) • NUREG/CR-3331, *Methodology for Allocating Nuclear Power Plant Control Functions to Human or Automatic Control* (1983) • NUREG-1764, *Guidance for the Review of Changes to Human Actions* (2007) • NUREG/CR-7190, *Workload, Situation Awareness and Teamwork* (2015)
EPRI	• EPRI 3002004310, *Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification: Guidelines for Planning, Specification, Design, Licensing, Implementation, Training, Operation, and Maintenance for Operating Plants and New Builds* (2015)
IEEE	• IEEE 1023, *Recommended Practice for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations and Other Nuclear Facilities* (2020)

The specific results coming from this work have been omitted; elements of the methodology shown in the next subsections served as an RSR to support the utility's HFE licensing efforts. It is worth noting that the general scope of the digital upgrade entails modifying several safety systems and migrating some functions performed by safety systems to non-safety system. The upgrade is also transitioning scoped functions from analog to digital I&Cs. This modification is following the recently revised *Digital Instrumentation and Control Interim Staff Guidance* (DI&C-ISG-06) *Licensing Process,* Revision 2, (2018). DI&C-ISG-06 as revised now provides both the Tier 1, 2, and 3 review process (the "Standard Process for Licensing Reviews" (Section C.1) and the new "Alternate Review Process" (Section C.2). The flow charts for each process are shown side-by side in Figure 18 to allow for direct comparison.

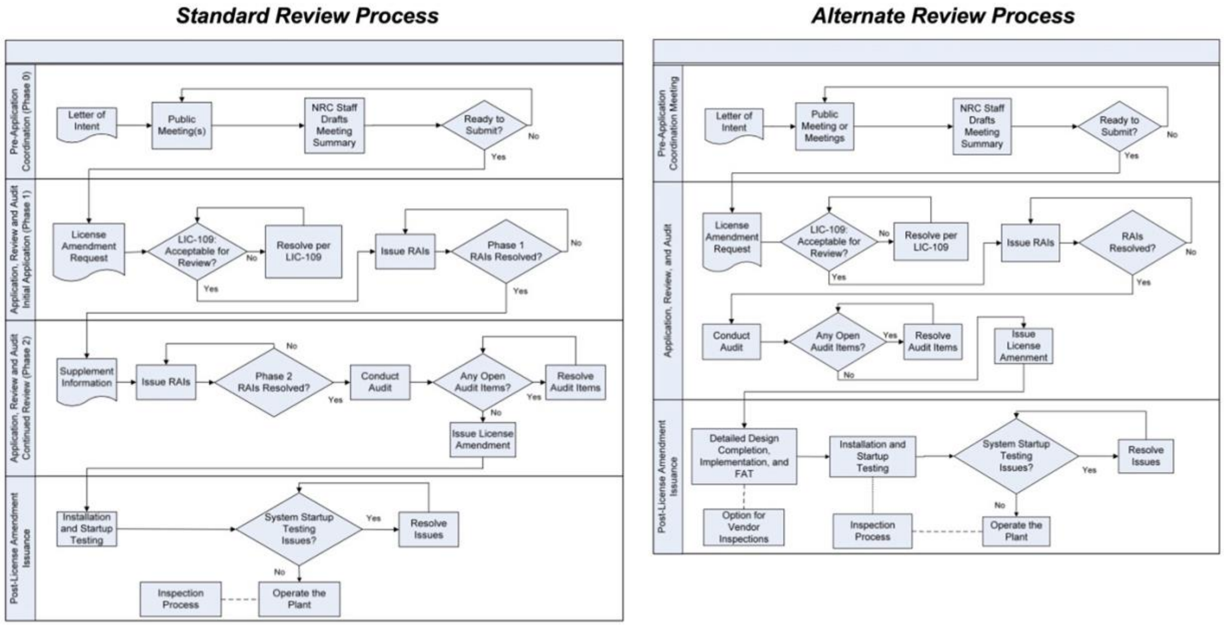


Figure 18. Comparison of Standard Review Process and the Alternate Review Process

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

A benefit of the Alternate Review Process is that it omits Phase 2 (Application, Review, and Audit Continued Review) submittals from the Standard Review Process. When following the Alternate Review Process, the license amendment request (LAR) is submitted to the NRC and can be approved by the NRC prior to factory acceptance testing (FAT), as opposed obtaining LAR approval after FAT in the Standard Review Process. The net effect of using the Alternate Review Process is to shorten the schedule for obtaining LAR approval (reducing project schedule risk) and obtain NRC technical approval before FAT (reducing technical and associated cost risks) associated with receiving and resolving NRC requests for additional information at the end of the design and test cycle. The key enabler to allow an applicant to pursue the Alternate Review Process is to leverage a safety platform that has already received a generic safety evaluation report (SER).

Function allocation is a critical element of both Alternate Review Process and the Standard Review Process. DI&C-ISG-06 explicitly states that the reviewer should evaluate whether the range of system response times fall within the response times credited by the accident analyses (e.g., PRA, D3 analysis, and UFSAR). Further, *HFE* is referenced in DI&C-ISG-06 as an element to be addressed. The licensee is expected to describe the framework used to design and develop the digital I&C safety-related systems and this includes performing:

> *…appropriate human factors engineering for the human-system interfaces throughout the development process* (DI&C-ISG-06, Section D.4.1 [p. 41]).

Specific standards that apply to HFE in DI&C-ISG-06 can be traced to Institute for Electrical and Electronics Engineers (IEEE) 603 (2018) and IEEE 1023 (2020). DI&C-ISG-06 Table D.1 presents a crosswalk of applicable sections from IEEE 603 (i.e., referring to Section 5.14 as shown below).

> *Human factors shall be considered at the initial stages and throughout the design process to assure that the functions allocated in whole or in part to the human operator(s) and maintainer(s) can be successfully accomplished to meet the safety system design goals, in accordance with IEEE Std 1023.* (IEEE 603 Section 5.14)

IEEE 1023 (2020) is the primary technical standard cited in IEEE 603. The HFE guidance in IEEE 1023 is shared using a general engineering process model described as the Star model. Figure 19 shows the relation between DI&C-ISG-06, IEEE 603, and IEEE 1023, illustrating the primary elements of the Star model.

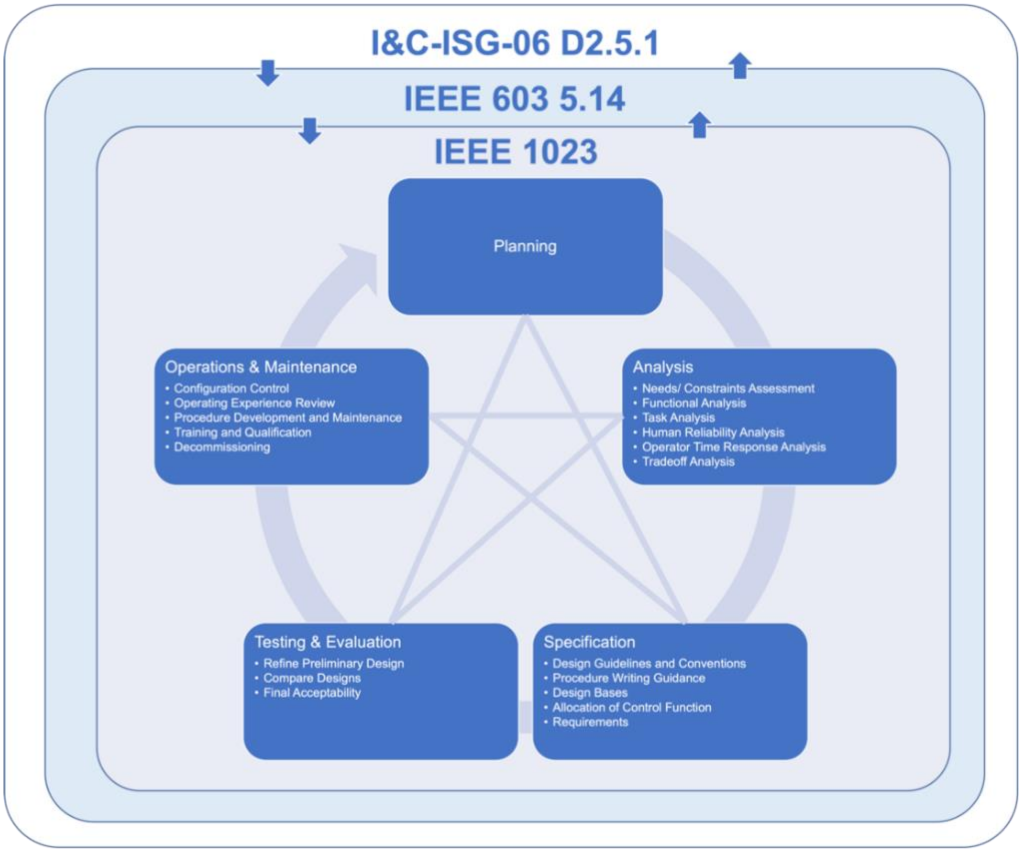


Figure 19. Relation of HFE guidance from DI&C-ISG-06, IEEE 603, and IEEE 1023.

The role of HFE is also a critical element in DI&C-ISG-06 by nature of being part of the regulatory review guidance: NUREG-0800 Chapter 18 (2016). NUREG-0800 Chapter 18, *Human Factors Engineering*, references NUREG-0711 (2012) and NUREG-1764 (2007) as primary technical resources. NUREG-0711 provides guidance for the regulator to review the licensee's submittals of modifications and new builds; however, the guidance is often considered "good engineering practice" and is followed by applicants as a general HFE process, when also accounting for a graded approach (EPRI 3002004310, 2015). Guidance between NUREG-0711 and IEEE 1023 are in essence complementary to each other; although, the Star model presented in IEEE 1023 is more general and not intended to be applied at face value (IEEE 1023, 2020).

This work demonstrates the first-of-a-kind use of the human-technology integration and function allocation guidance following the Alternate Review Process provided in DI&C-ISG-06. The HFE activities followed guidance from INL/EXT-21-64320, IEEE 1023, and NUREG-0711. Figure 20 presents the scope of this work as it relates to INL/EXT-21-64320, IEEE 1023, and NUREG-0711. Specifically, this work describes the demonstration of the second phase of the human-technology integration methodology (i.e., develop human-technology integration requirements), which is shown in green. The work described was completed using a multidisciplinary team of HFE, I&C engineering, operations, training, and vendor personnel. Further, they used advanced methods, including simulation and modeling techniques, decision ladders from the CWA framework, and CTA techniques.

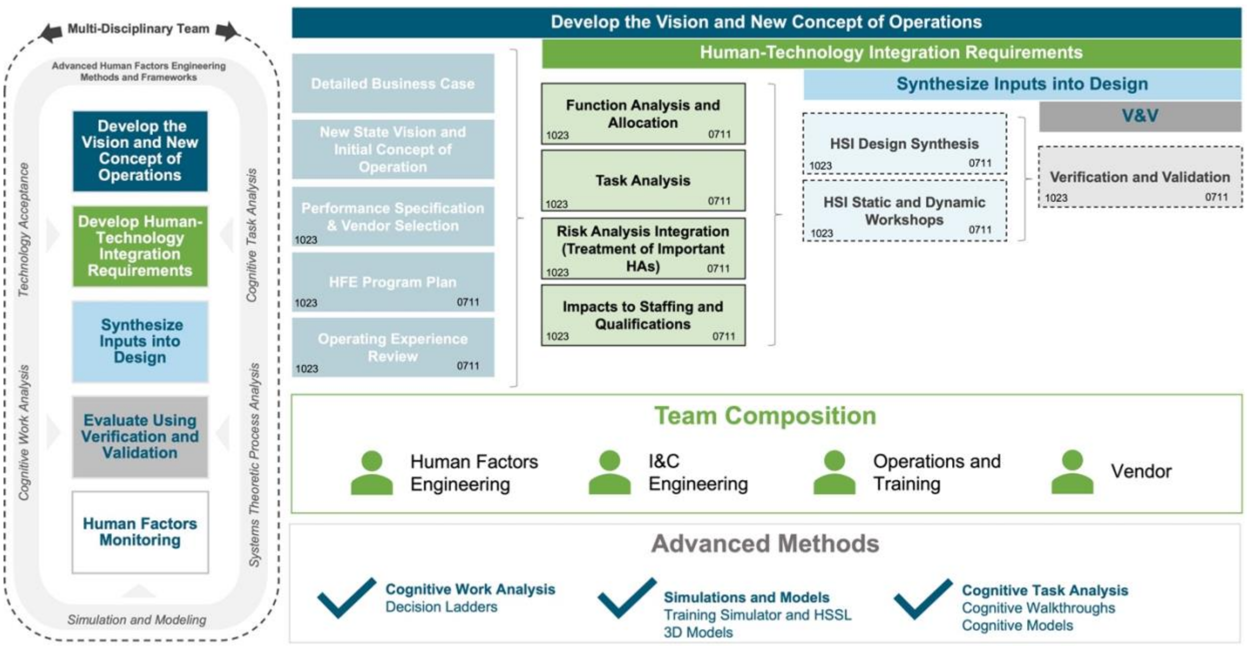


Figure 20. Demonstration of INL/EXT-21-64320 to SR I&C upgrade.

It should be noted that earlier work related to the development of the new state vision and concept of operations can be found in INL/EXT-19-55852 (2019) and INL/EXT-20-59537 (2020). The next subsections describe the specific methods used to support FA&A, task analysis, risk analysis integration, and impacts to staffing and qualifications. The results of these activities will drive design synthesis activities and V&V, as shown in Figure 20. Design synthesis and V&V activities have not yet been performed at the time of this report.

5.2 Function Analysis and Allocation

Function analysis is the assignment of the control and management of functions to personnel (manual control), automatic systems (automated control), and a combination of both (shared control). Taking advantage of functional control capabilities provided by the design modernization and allocating these management functions appropriately between manual and automated control will reduce human errors and inappropriate actions. This will result in improved system safety and economic performance.

The allocation of control functions to either machines or humans can be determined by a number of factors, such as:

- Technology capability and limitations (i.e., technical feasibility)
- Human capability and limitations
- Operational requirements
- Nuclear safety requirements
- Equipment protection requirements
- Regulatory requirements
- Organizational requirements
- Cost, productivity, and economic factors

- Guidance for allocation of control functions is provided in NUREG/CR-3331, “A Methodology for Allocation of Nuclear Power Plant Control Functions to Human and Automated Control” (1983).

  This FA&A methodology was based upon:

- The principles described in Section 4 of NUREG-0711 (2012)
- Section 3.3 of EPRI 3002004310 (2015), which provides HFE guidance for control room design and modification
- IEEE-1023, which provides recommendations for applying HFE
- Section 5.2 of INL/EXT-21-64320 (Kovesdi et al., 2021).

A graded approach was followed, so only FA&A activities needed for the modification were performed. A major benefit of applying the graded approach is eliminating unnecessary work with the assurance that all necessary HFE activities are complete. Changes in allocation of the management of functions to personnel or to automated systems (i.e., changes in the level of automation) were identified. The reason for identifying these changes in allocation is that changing the control of functions and allocations may impact the conceptual design and personnel roles, responsibilities, and workload. FA&A methods are applied to identify new and changed functions and to allocate them between automation and personnel.

Functions addressed in these evaluations included not only process control and protection functions but also other required functions, such as collecting data, evaluating, or comparing data, tracking parameters over time, calculating values, retrieving needed information displays, and other secondary tasks. Decision criteria on what automation features to include into the design was based on their impact to personnel workload and potential for human error. New automation features offer opportunities to reduce burden on operators and maintenance technicians and improve human performance. FA&A results were used by the HFE team and other engineering groups involved in the modernization effort, such as with the task analysis element. The results will be also applied to subsequent elements in the design process (e.g., HSI design and HFE V&V). Figure 21 provides an overview of the FA&A process based on EPRI 3002004310 (Section 3.4.4) and INL/EXT-21-64320 (Section 5.2).

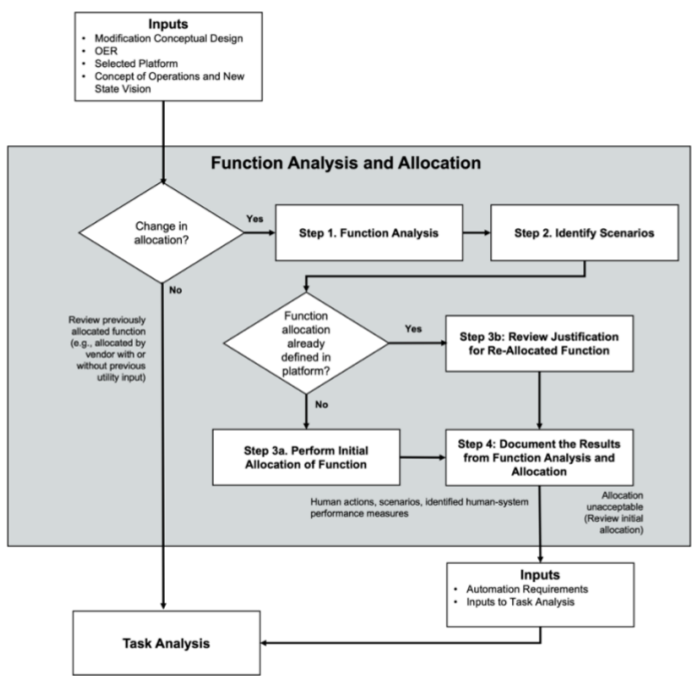


Figure 21. Overview of FA&A performed.

5.2.1 Inputs to Functional Requirements Analysis and Function Allocation

The allocation of functions to either machines or humans can be determined by several factors:

- Technology capability and limitations (i.e., technical feasibility)
- Human capability and limitations
- Operational requirements
- Nuclear safety requirements
- Equipment protection requirements
- Regulatory requirements
- Organizational requirements
- Cost, productivity, and economic factors.

All of these factors were considered during FA&A to ensure that resources were applied in the most cost-effective manner. Resulting from an assessment of these factors, each function allocation opportunity was determined by the following criteria (based primarily on principles described in NUREG/CR-3331):

- Need for alarm handling
- When large amounts of data must be stored
- Need for extensive data analysis or calculation
- Availability of proven technology
- Need for auto configuration
- When it is consistent with design practice
- When decision-making is too complex for humans (e.g., based on complex calculations)
- When events occur too rapidly for the human to respond
- When the operating crew prefers automation
- When complex sequences must be controlled
- When it would be too costly for human operation.

The following were indications for potential human control of all or part of a process:

- When automation is not feasible or too costly
- When the system can provide adequate cognitive support
- When the process is not excessively difficult
- When human operation will provide job satisfaction
- When it is a regulatory or policy requirement.

In 2020, the utility entered into a public-private partnership with the U.S. DOE's LWRS Program to explore the feasibility of performing a pilot SR I&C upgrade project at the utility. LWRS research directly contributed to the execution of the project initial scoping phase of the utility's SR I&C effort. The LWRS report INL/EXT-20-59809 (2020) provides a detailed summary of this effort. The FA&A considerations as described above were generally considered during the initial scoping phase of this project and are further discussed below.

5.2.1.1 Modification Project Initiation Phase Scoping and Vendor Selection

Light-Water Reactor Sustainability Project Research as Applied to Project Scope

New State Vision

LWRS Program Plant Modernization Pathway is oriented around properly applying digital upgrades in a manner that maintains or improves safety, improves plant operational performance, and reduces O&M costs to enhance economic viability. A LWRS research document that addresses this effort was INL/EXT-19-55852, “Nuclear Power Plant Modernization Strategy and Action Plan” (2019). Further efforts to expand and refine the nuclear plant operating model transformation presented in this document are being pursued under ION Research. ION is generally described in INL/EXT-20-59537, “Analysis and Planning Framework for Nuclear Plant Transformation” (2020).

The new state vision model shown in Figure 22 is an adaptation of a similar figure from INL/EXT-19-55852. This concept was applied to the utility SR I&C upgrade effort to guide initial scoping research activities to ensure that plant and work function modernization enabled by the utility SR I&C upgrade achieve strategic business objectives while maintaining and enhancing safety and operational performance. This work also reflects elements of Section 5.1 of INL/EXT-21-64320 in developing a business case, new state vision, and concept of operations.

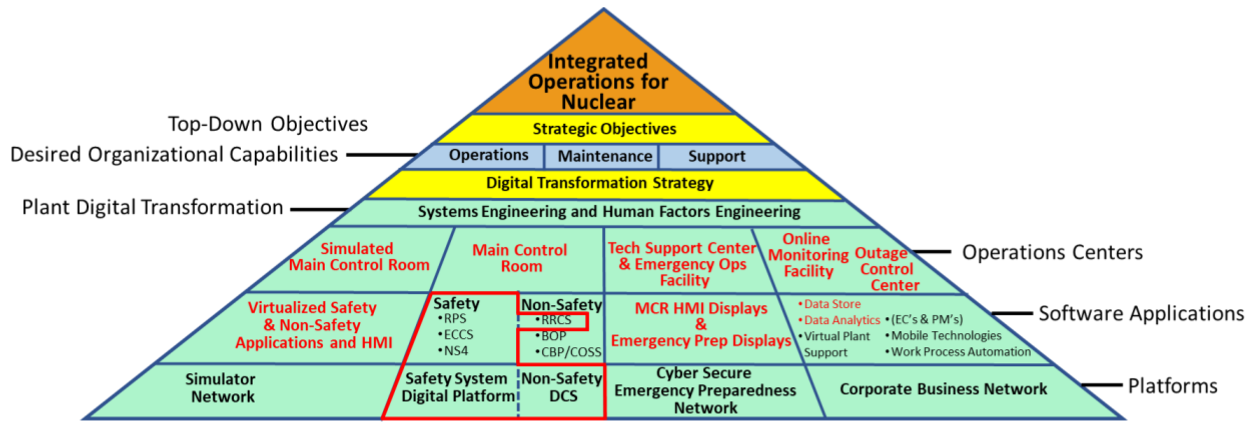


Figure 22. SR I&C upgrades in the context of ION.

Following ION, nuclear power plant budgets are created using a market-based electricity price point to derive total operating, maintenance, and support costs to support this price (top down). Work is also analyzed for opportunities to aggressively focus workload on essential functions that can be resourced within available budgets (bottom-up). Work functions are then configured into the operating model. Process innovations and technologies are then applied as an integrated set by using systems engineering and HFE. This promotes a business-driven digital transformation strategy that reformulates the traditional labor-centric model to one that is technology centric. This transformation lends itself to fewer onsite staff focused on daily operations, increasing plant safety, reliability, and situational awareness. The transformation strategy, along with process changes, supports employing centralized maintenance and support functions or outsourcing these functions to on-demand service models.

A tenet directing the larger digital transformation strategy in general, and the SR I&C upgrade project is that the replacement of current equipment is not to simply to provide like-for-like functionality when compared to the existing equipment. Instead, digital upgrades are undertaken to fully leverage the capabilities of the technology as part of a holistic effort to establish a “New State” that reduces the Total Cost of Ownership (TCO) for facilities that deploy them for the balance of the plant operating period.

Project Scope Bounded

It was during the project initiation phase that the scope of the SR IC upgrade was established. This scope is outlined in Figure 22 in red and includes:

- A common, SR, Plant Protection System (safety system) platform that will implement the functions of the following boiling-water reactor systems as applications:
  - Reactor Protection System
  - Nuclear Steam Supply Shutoff System – also referred to as the Primary Containment Isolation System in other boiling-water reactors
  - Emergency Core Cooling Systems
- A Non-Safety Related (NSR) platform to host the existing SR Redundant Reactivity Control System (RRCS) function. In accordance with 10 CFR 50.62, *Requirements for reduction of risk from anticipated transients without scram (ATWS) events for light-water-cooled nuclear power plants*, the RRCS must remain fully independent of the safety system (transmitters may be shared) but does not have to be constructed of SR components. Consequently, the RRCS will be upgraded using a NSR DCS. This DCS is expected to host most of the NSR functions in the unit. This includes a segment of DCS to receive data from the safety system and perform the channel check function, alerting the operator to significant disagreement in safety system and RRCS inputs.

A tenet was established that both the safety system and the NSR DCS are to be expandable. The safety system and NSR DCS are intended to become the “target platforms” onto which the functions of other obsolete I&C systems are migrated. Over time, the number of diverse I&C systems will be substantially reduced. By digitizing I&C plant information and passing it unidirectionally to other data networks, remote monitoring and data analytics capabilities are enabled to further reduce facility TCO. Coordinating I&C technology upgrades with training simulator upgrades also reduces facility TCO. These opportunities are reflected in the red text items in Figure 22.

Light-Water Reactor Sustainability Program Research Products for Bounded Scope

Functional Requirements Baselines

MPR Associates, Inc. was subcontracted by the LWRS Program to lead the authoring of two vendor-independent functional requirements baseline documents based upon the utility scope identified above, including the following from INL/EXT-20-61079 (2020):

- A SR safety system platform and application functional requirements baseline (Appendix A)
- A NSR DCS platform requirements and application requirements baseline for the RRCS (Appendix B).

MPR coordinated extensively with engineering, operations, training, simulator, and licensing personnel from the utility and with LWRS researchers in the creation of the functional requirements baselines. As an LWRS research product, these baseline documents are generally intended for use by the larger nuclear industry. The baseline documents were tailored to the utility plant design and reflect design concept decisions made by LWRS research and utility design participants to achieve objectives associated with the utility’s digital transformation plans.

Business Case Analysis

As part of the initial scoping phase, ScottMadden and Associates was subcontracted by the LWRS Program to lead the authoring of a limited distribution safety analysis for digital SR I&C system modernizations (Hunton, England, Lawrie, Jessep, et al., 2020). The objectives of this research product include:

- Providing a bottom-up approach to:
    - Establish labor and material costs for the current systems within the defined I&C upgrade scope
    - Identify expected labor and material benefits enabled by the upgrade design concept
    - Validate the expected benefits with SMEs
- Demonstrating the methodology used to perform a detailed financial analysis, including:
    - Estimation of annual benefits related to organizational workload reductions for both online and outage work. This included both quantitative benefits (which were included in the business case analysis [BCA] result) and qualitative benefits (which were identified as areas of additional potential savings but were not included in the BCA result).
    - Estimation of annual benefits related to materials and inventory expenditures
    - Valuation of avoided lifecycle costs associated with escalation of material expenditures
    - Valuation of the modernization over the lifecycle of the station
- Illustrating the scale of benefits that can be expected from a modernization of SR I&C systems at a two-unit nuclear power plant
- Providing example worksheets and templates to support a BCA of similar efforts by other utilities
- Providing lessons learned and opportunities for utilities that might subsequently implement a similar digital modernization effort.

5.2.1.2 Use of LWRS Research Products

Performance Specification and Vendor Selection

While the functional requirement baseline documents as described above were informed by the design requirements of the utility's facility, they were not tailored to best apply to the specific project requirements for the utility. In order to tailor the functional requirements baseline information to the utility, the information provided by them was reformulated into a utility-specific performance specification.

A performance specification defines the functional requirements for the system, the environment in which the system operates, and interface characteristics but does not describe how a requirement is to be achieved. The utility believed that this would allow the vendors an opportunity to provide their best design and cost-effective solution, since the research team members outside of the utility were not intimately aware of vendor products being offered because of vendor proprietary information constraints.

The performance specification provided a high-level system hierarchy and all the criteria that prospective vendors would be graded against, in accordance with the EPRI DEG (2018), Section 5.1.1. It used most of the requirements developed in the functional requirement baseline documents. The performance specification was further vetted and revised to address comments from potential vendors and the utility stakeholders, including engineering and operations, to ensure that the solution being solicited met the requirements.

Use of the performance specification provided the foundation of documenting required operational capabilities into an integrated system design through the concurrent consideration of all lifecycle needs. The specification provided a robust, systems engineering approach that balances total system performance and TCO. Leveraging the functional requirements baseline research documents described above and utilizing the systems engineering process allowed the utility to describe the solution required to meet utility needs.

The performance specification was used by the utility to solicit proposals from vendors. The ability of the solicited vendors to provide a system conforming to the performance specification was a critical metric used to select the vendor for this project.

Project Economic Analysis and Project Approval

A utility-specific economic analysis was founded on the LWRS BCA research as summarized above. This provided more well-rounded and detailed material and labor cost data to evaluate the monetary benefit that digital modernization and pursuing the safety system project can enable. The utility-specific economic analysis also permitted adjusting those benefits as sensitivities to the base business case assumptions and evaluating the influence on the project's Net Present Value. The utility developed a resource-loaded project schedule during the late project initiation stages. The primary goal was to baseline the project schedule from a work breakdown structure developed from:

- Nuclear Energy Institute "Standard Design Process," IP-ENG-001
- Nuclear Energy Institute "Standard Digital Engineering Process," NISP-EN-04
- EPRI DEG (2018)
- Digital Instrumentation and Control Interim Staff Guidance (DI&C-ISG-06), Revision 2, License Amendment Request Alternate Review Process.

This schedule also provided early insight into resource demands from reviewing resultant resource histograms that influenced the project staffing plan. This effort was used to validate that project costs were bounded as required by the utility's business practices. As a result of this work, the utility management authorized the project to proceed into concept and detailed design phases.

Creation of Requirements and Design Specifications and Other Necessary Inputs

The requirements contained in the performance specification were used by the selected vendor as a starting point for the system requirements specifications. This information was controlled using standard quality management software to support the migration to a requirements management system.

5.2.1.3 Operating Experience Review

An HFE OER was performed for the utility in accordance with the HFE Program Plan of this SR I&C upgrade project. The OER methodology applied was based on NUREG-0711, Rev. 3 review criteria, guidance in EPRI 3002004310 (2015), and the process and results from prior INL operational experience studies with several other utilities. The OER broadly captured a baseline understanding of the current conduct of operations at the utility and collected insights into potential impacts of the SR I&C upgrades on the conduct of operations. Problematic tasks with the existing I&C were also identified along with use cases (scenarios), which were carried forward in FA&A and task analysis. Other operational experience items, including desired operator automation aids and desired features, were identified broadly from interviews and surveys. This and other pertinent OER information were used as inputs to the FA&A and to the task analysis.

5.2.1.4 Initial Main Control Room Concept of Operations

The HFE team's initial understanding of the MCR concept of operations was based primarily on pressurized-water reactor technology and operations techniques. Generically, the concept of operations for a pressurized-water reactor MCR as understood by the HFE researchers was that it is "linear" for both normal operations and casualty response. By linear, what is meant is that during both normal and casualty responses, plant operations are directed by procedures that are typically executed step-by-step in order. These are based upon either performing routine evolutions in the plant or during casualty operations, such as in response to a large-break loss of coolant. Such a concept of operations is amenable to the organization and presentation of digital displays on video display units (VDUs) in a hierarchical format that complements the linear procedure execution to optimize the use of available VDUs and operator performance.

Voice communications between operators were also particularly structured and formal in such an environment. As steps are executed linearly, there is a three-way communication technique that is normally employed between the MCR Control Room Supervisor and a Reactor Operator where:

1. The Control Room Supervisor gets the attention of the Reactor Operator and communicates an order.
2. The Reactor Operator repeats the order back to Control Room Supervisor.
3. The Control Room Supervisor acknowledges the that the order has been correctly received and interpreted by the Reactor Operator.
4. The Reactor Operator performs the order.

The understanding of both linear procedure execution coupled with three-way communication was consistent with the understanding of the vendor personnel for this project. Consequently, it was the expectation that the concept of operation for this nuclear power plant would be similar.

The result of this thinking was that it was assumed that the organization and presentation of digital displays on VDUs for this project would be in a hierarchical format for both normal operation and casualty response and that the linear three-way communication strategy would be strictly employed in the MCR. The understanding of this initial concept of operations was altered because of the FA&A workshop.

5.2.2 Step 1 – Function Analysis

Function analysis identifies and defines new and changed functions that support the higher vision and first principles for improved plant operation. Function analysis describes the functions of interest in sufficient detail to perform a review of function allocation decisions and evaluate subsequent impacts. Also, the HAs impacted by the reallocation are identified, described, and documented. In the same manner, new HAs that emerge from reallocated functions require identification, description, and documentation as well.

Function analysis was initiated through a planning meeting and continued collaboration occurred between operations, engineering, and HFE. This drove the analysis and prioritization of the information identified from the inputs. Specific items pursued included:

- Screening tasks based upon:
  - Whether they were impacted by the modification or not (changes in function)
  - Whether there were tasks that address operator actions identified either as part of the D3 analysis or considered “risk important actions” from the UFSAR, Chapter 15, or from the PRA
- Screening and prioritization of tasks impacted by the upgrade based on task difficulty, importance, and frequency (DIF) scores
- Selecting scenarios that provided maximum “ISV coverage” for the “high priority screened tasks” identified directly above
- Request specific inputs from the utility that INL could review to support FA&A:
  - Explanation of DIF scores and associated training criteria
  - Drill guides (simulator instructor instructions) for selected scenarios
  - Procedures to be used in the execution of selected scenarios
  - The list of all “risk important actions” and the identified time frames for execution.

From pursuing these items, anticipated automation features that were part of the modification plan were captured. Further, SMEs in operations reviewed the known tasks performed within the MCR and screened the tasks being impacted by the upgrade. The screened tasks were then mapped to whether they were part of the UFSAR Chapter 15 events, D3 analysis, or PRA, which defined these tasks as Important HAs. All identified impacted Important HAs were considered for subsequent analysis. Non-Important HAs were further screened based on their DIF score among other operational characteristics to be grouped in specific operational use cases (i.e., scenarios), as described in Step 2 of FA&A.

5.2.3 Step 2 – Identify Scenarios

Operations SMEs developed scenarios for each impacted function and task impacted by the upgrade. Each scenario grouped the impacted tasks together in a way that was contextually appropriate. For instance, tasks are rarely performed in isolation. In many cases, the functions and tasks to be performed are part of a broader plant event (e.g., managing an Anticipated Transient Without Scram). Using scenarios, the analysis of impacted functions and tasks can account for different operational contexts that are important when understanding how any given function and task affects related tasks.

A set of scenarios were identified by the SMEs. To aid in proper allocation of functions within the HSI design and associated tools used by operating personnel, the following activities were performed for scenario identification:

- Identify significant events, scenarios, and procedures impacted by the upgrade scope in which functions and operator tasks will change
- Evaluate the large number of events, scenarios, and procedures expected to be identified, and select the ones expected to have largest positive and negative impacts on operator and system performance
- Describe the events, scenarios, and procedures in sufficient detail so that they can be evaluated.

Criteria considered during the selection of scenarios included:

- Providing the greatest operator error traps and opportunities for human error and poor performance
- Offering the greatest opportunity for improved safety and economic performance
- Involving changes from manual to shared or automatic functions
- Involving the most changes in operator roles and responsibilities
- Involving increased operator workload and/or reduction in operator action times.

Events, scenarios, and procedures identified during OER were retained because they met the criteria above and provided continuity throughout HFE Program execution. These scenarios were hence carried forward and expanded on in support of the FA&A workshop. These scenarios were documented in detail by the SMEs in the simulator guides. The task analysis activities (i.e., described later) also used these scenarios as the basis for analysis. The use of these scenarios was anticipated to be in later HFE activities performed in design synthesis and V&V (i.e., ISV).

5.2.4 Step 3 – Perform Functional Allocation

Because there was an already defined allocation of function for this upgrade, sub-step 3b (Review Justification for Re-Allocated Functions) from Figure 21 above was performed. Specifically, the function allocation analysis consisted of scenario observations at the utility simulation facility using the set of scenarios identified. Specifically, the scenario observations focused on examining interdependencies between tasks to explore the trade-space in function allocation (see Figure 23).

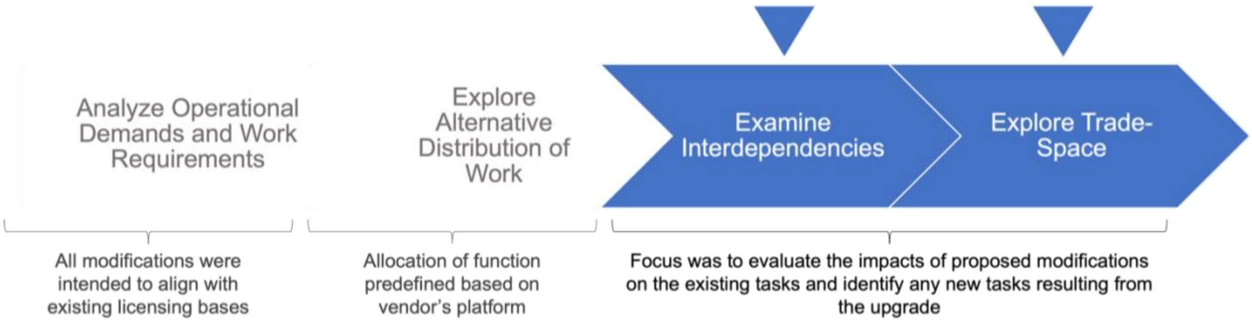


Figure 23. Scope of function allocation for SR I&C upgrade.

The scenarios were performed by licensed operators from the utility while human factors engineers observed, collected notes, and facilitated a suite of semi-structured interview questions. The specific protocol is described next.

5.2.4.1 FA&A Workshop Protocol and Data Collection Tools

Objectives

The purpose of this workshop was to understand the positive attributes and challenges associated with performing tasks using the current HSIs impacted by the upgrade. This information ensures the new HSIs provided by the upgrade improve operator performance and support improved plant operation.

Design Team

The design team consisted of a combination of human factors engineers from INL and utility operations, training, and engineering SMEs.

Detailed Method

Introductions and Overview of the Digital Upgrade Project

Engineering and HFE personnel provided an overview of the project and corresponding HFE activities to operators through a project overview, an overview of HFE, and an overview of the FA&A methodology. A reminder to operators was given, that:

- Their participation was being requested because of their knowledge and expertise and that the information they provide will be used to guide the HSI design.
- Their opinions would guide preferences and requirements for the new designs.
- The information being collected was being used to design or evaluate the HFE aspects of the HSIs and not to evaluate their performance.
- The anonymity of personnel was maintained, their comments were treated as anonymous, and the comments were coded using a participant identification document (ID) scheme.

FA&A Workshop General Workflow Including Scenario Observations

The following diagram (Figure 24) highlights the workflow that was completed during this workshop.

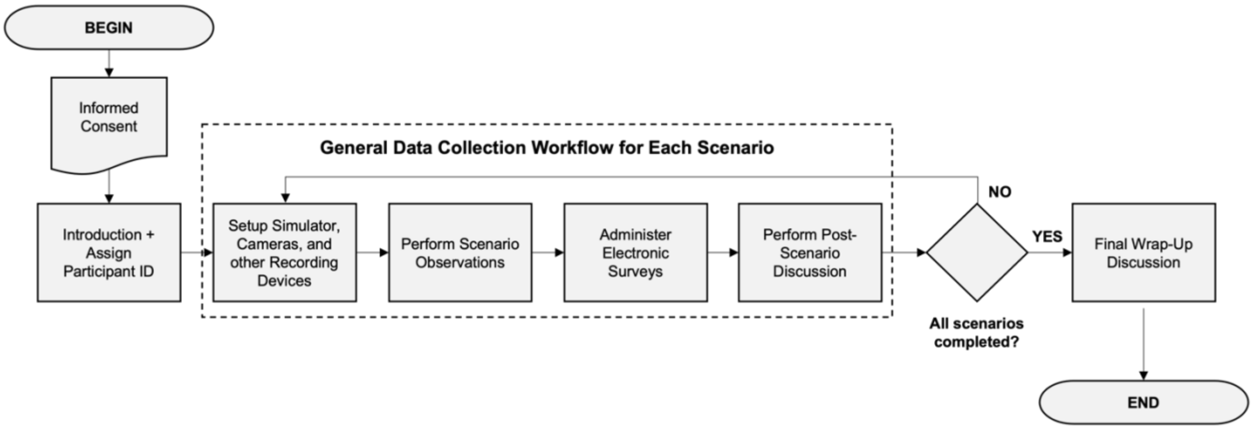


Figure 24. FA&A Workshop general workflow.

Informed Consent

Human factors staff administered printed copies of the informed consent form to participating operators. Upon signing, a brief introduction to the scenario observations was given.

Introduction and Participant ID Assignment

Operators were briefly introduced to the general workflow (Figure 24 above). During this time, engineering, training, and HFE staff provided supporting details to help operators align to the objectives of these observations and expectations when performing these scenarios. While introductions were performed once, the reminders above were given as much as necessary to ensure operators were aligned with the goals of this workshop. Human factors staff recorded participant IDs in a table. These IDs were used throughout the course of this workshop.

Simulator and Data Collection Setup

Utility simulator and training staff prepared the simulator for each scenario by setting up initial conditions and other tasks necessary to run the scenario and enable video recording. The simulator instructor was reminded to provide a cue when the scenario was going to begin (e.g., "in roll") and end (e.g., "you are no longer in role"). Each INL staff was assigned different primary roles for collecting notes. Human factors staff prepared the data collection tools, including a logger to collect observational and self-report data during the scenario. INL staff endeavored to not interfere with the plant operators when they were "in roll." This was to allow the INL staff to garner how the operators used the current interfaces and procedures to perform tasks impacted by the upgrade. The data logger presented individual tasks listed in the simulator guides per scenario and allowed the human factors engineer to collect observational notes, such as unsolicited comments and observed observational difficulties, while the logger timestamped comments.

A SME review worksheet for observation was also prepared by operations experts. The SME review worksheet allowed analysis of crew performance across monitoring, interpretation, strategy, actions, teamwork, and control and verification (Figure 25). The data recorded on these sheets was intended to help focus the post-scenario discussions, if warranted by the SME.

Subject Matter Expert (SME) Scenario Review and Observation

Monitoring refers to how the control room operators gather plant process information. The assessment of monitoring includes what process information the operators attend to, redundancy and diversification of the information obtained.	**Interpretation** refers to how the control room operators interpret the plant status and its progression. The assessment of interpretation includes the understanding of specific events, performance episodes, and the "big picture".	**Strategy** refers to how the control room operators establish main goals and a plan to reach these goals. The strategy assessment looks at how the control room operators understand the strategies provided by the standard operating procedures, and to what extent the operators are capable of adjusting and adapting these strategies when needed.	**Actions** concern the manipulation of systems and components. The focus is on key actions for controlling the plant process.	**Teamwork** concerns the interaction between team members. The evaluation focuses on leadership initiatives to perform consultations and distribute the work; involvement of team members; communication; backup behaviour and team climate.	**Control and Verification** refer to the team's critical thinking about their own work: the correspondence between the situation and the strategy chosen (Le Bot, 2010); the need to adapt plans to the situation; verification of plant process responses; and supervision of the progress towards established goals.
Real-Time Ratings					
1 2 3 4 5 6 NOT ACCEPTABLE ACCEPTABLE **Rating:** **Comments:**	1 2 3 4 5 6 NOT ACCEPTABLE ACCEPTABLE **Rating:** **Comments:**	1 2 3 4 5 6 NOT ACCEPTABLE ACCEPTABLE **Rating:** **Comments:**	1 2 3 4 5 6 NOT ACCEPTABLE ACCEPTABLE **Rating:** **Comments:**	1 2 3 4 5 6 NOT ACCEPTABLE ACCEPTABLE **Rating:** **Comments:**	1 2 3 4 5 6 NOT ACCEPTABLE ACCEPTABLE **Rating:** **Comments:**

Overall Rating Scale Key:

1	2	3	4	5	6
Strongly Not acceptable	Not Acceptable	Acceptability disputable, but probably not acceptable	Acceptability disputable, but probably acceptable	Acceptable	Strongly Acceptable
Requires follow-on discussion to identify possible contributors.				*No follow-on necessary.*	
Rating: **Comments:**				**Rating:**	

Figure 25. SME observation guide for the FA&A Workshop.

5.2.4.2 Scenario Execution, Surveys, and Discussions

Perform Scenario Observations

During the observations, the simulator was sometimes stopped at steps in the procedure where functions were added, eliminated, or changed due to the modernization effort and allocated differently than at present. The operators and others in attendance were asked to discuss these possible changes from existing practices. Normally, this information and these questions were asked during the scenario debriefs. Human factors staff used the data logger, SME scenario review worksheet, and general notes to collect observations. Each human factors staff member had different roles in observing performance. Each member observed a different crew member. This division of responsibility ensured complete and accurate data collection throughout each scenario. Data collection included:

- Task completion times
- Scenario success
- Operational difficulties[a], such as:
  - Managing alarm floods
  - "Ping ponging" across the MCR to take action
  - Difficulties using information (e.g., writing down values that could be trended)
  - Difficulties performing actions
  - Calling out to the field and waiting for the field to take action
  - Noticeable demands on crew coordination and teamwork

[a] The criteria for operational difficulties were informed from OER.

- Unsolicited comments related to the functions and tasks impacted by the SR I&C upgrade

Administer Electronic Surveys

After the completion of the scenarios, human factors staff assisted the operators with accessing the electronic Microsoft Forms surveys of the National Aeronautics and Space Administration (NASA) – Task Load Index (TLX; Hart and Staveland, 1988), Situation Awareness Rating Technique (SART; Taylor, 1990), and Brief-Nuclear Usability Measure (B-NUM as described in Kovesdi and Joe, 2019). These surveys provided a baseline assessment of self-report workload and situation awareness. These surveys were administered as an electronic packet sent to the operators' email address. The NASA-TLX was used to collect self-report data of workload. Operators were instructed to answer these questions as quickly and accurately as possible after completing each scenario.

NASA-TLX

The NASA-TLX (Figure 26; Hart and Staveland, 1988) is an industry-accepted tool for measuring and evaluating workload, as described in NUREG/CR-7190 (2015). 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; 10 = high) where higher values denote greater workload. A common practice is to remove the 15 pairwise comparisons and use only the rating scales for each workload dimension. Workload can be evaluated by each dimension and holistically from aggregating the individual scales.

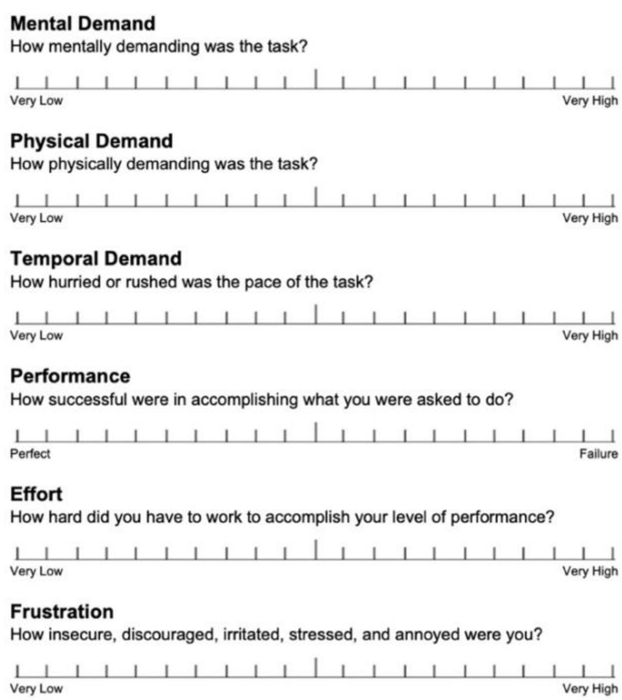


Figure 26. NASA-TLX standardized survey instrument.

SART

The SART is a self-report standardized survey that measured perceived situation awareness (Figure 27; Taylor, 1990). The SART comprises 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 instability of the situation. 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 relationships between 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 (2015) but is cautioned as a primary source to measure situation awareness; hence, this workshop used SART in combination with naturalistic observation and semi-structured questions described in the post-scenario discussion.

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

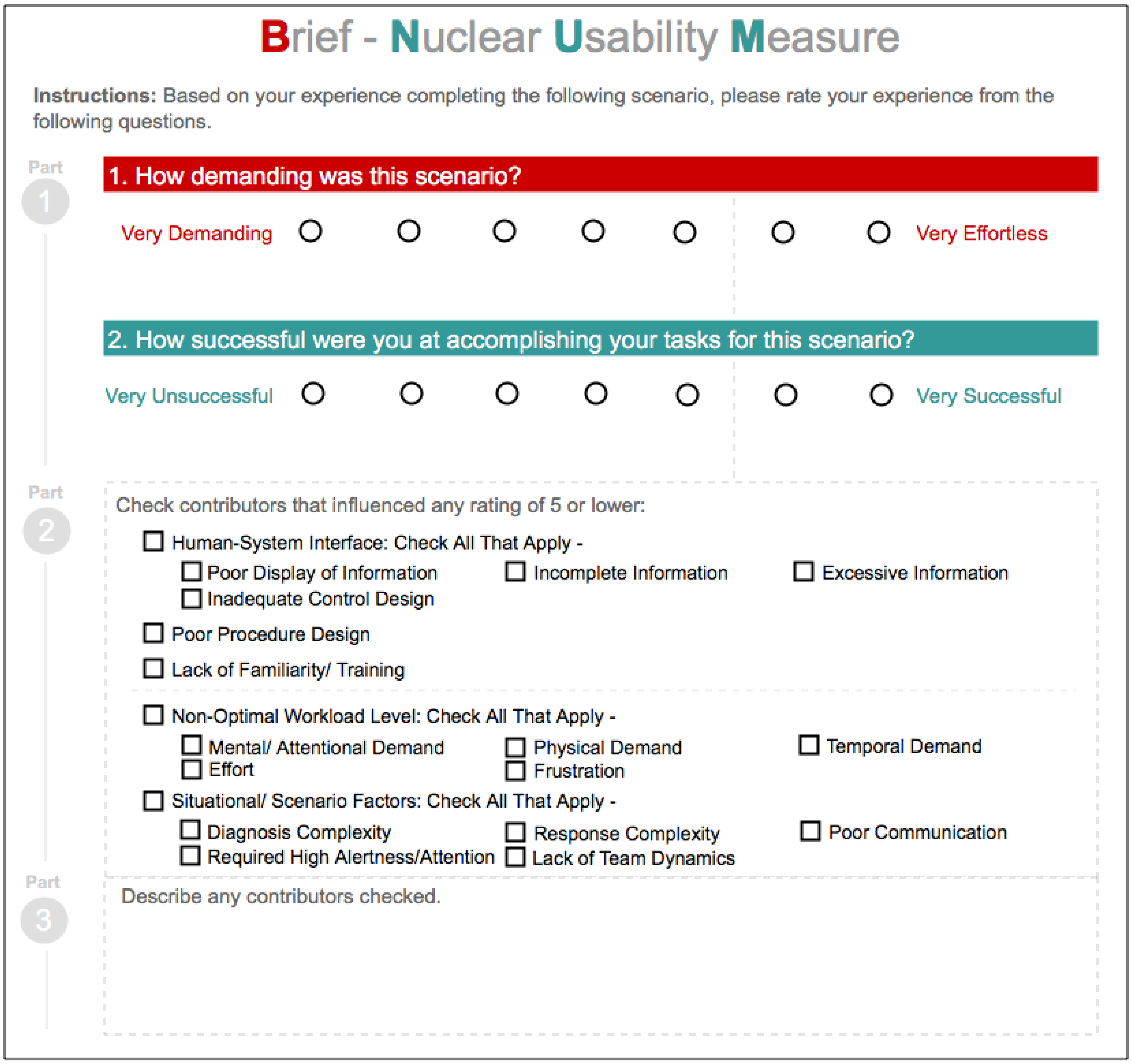
Familiarity with Situation
How familiar are you with the situation? Do you have a great deal of relevant experience (High) or is it a new situation (Low)?

1 = Low	2	3	4	5	6	7 = High

Figure 27. SART standardized survey instrument.

Brief – Nuclear Usability Measure

Finally, the electronic surveys included the B-NUM, a recently developed survey tool (Kovesdi & Joe, 2019). Figure 28 presents an example of the B-NUM; 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 to the two questions. 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 in more detail the specific attributes of these contributors 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 28. B-NUM standardized survey instrument (adapted from Kovesdi and Joe, 2019).

Perform Post-Scenario Discussion

After completion of the surveys, human factors staff prepared to video record. There was a primary notetaker during the debrief. The utility first performed a crew debrief following the scenario. A three-dimensional (3D) model, showing the modifications, was used to focus on the discussion. After the crew utility debrief, human factors staff facilitated additional discussion, using the workflow below as a template (Figure 29). Additional questions were asked by others as needed, particularly with any observed difficulties.

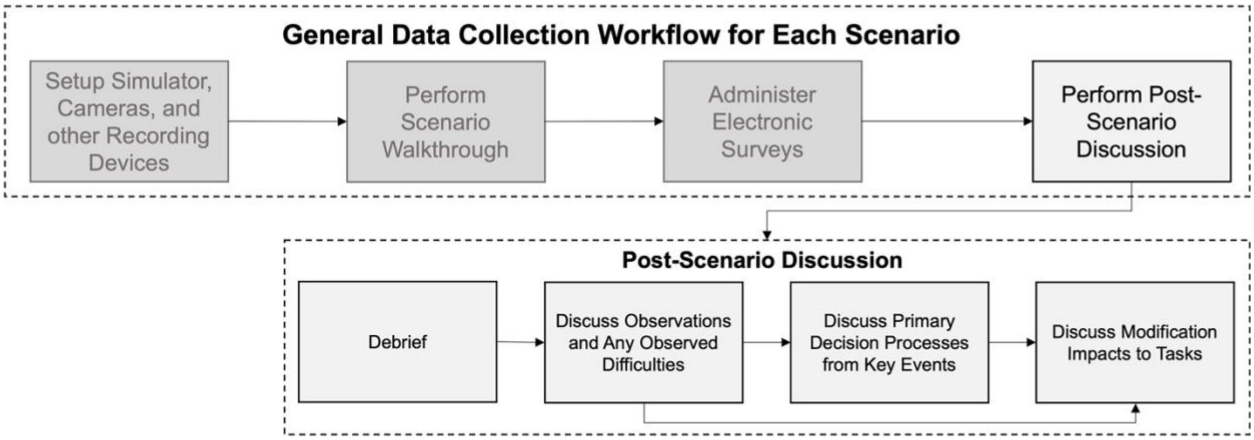


Figure 29. Post-scenario discussion workflow for FA&A Workshop.

Crew Debrief

The utility crew members performed a debrief to initiate the post-scenario discussion. The crew each discussed what primary tasks they performed, what went well, and where they had notable challenges. Human factors staff collected notes and contributed to this discussion.

Discuss Observations and Observed Difficulties

Any observed difficulties collected during the scenario covered in the crew debrief were discussed next. Difficulties were reviewed within the context of contributors including HSI design, procedure design, training, and simulator artifacts (Figure 30).

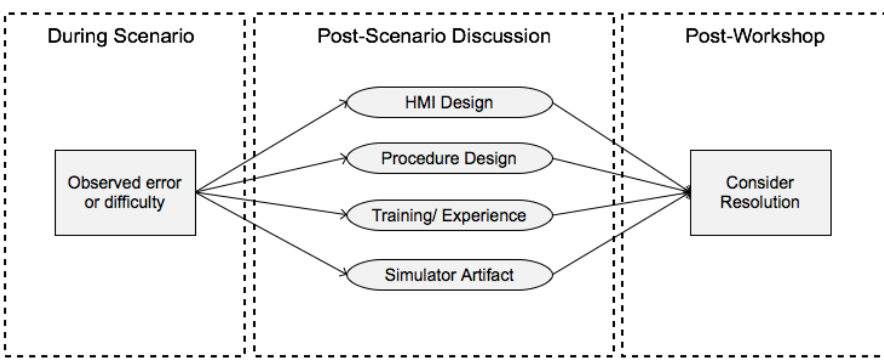


Figure 30. Contributors to observational difficulties.

If there are no observed difficulties, the questions, such as the following, were administered by human factors staff members:

- Was there anything about the existing indications and controls that made this scenario difficult to perform?

- Were there difficulties accessing information to enable you to effectively monitor the plant, diagnose faults, and maintain situation awareness? How might this be improved?
- Were there difficulties taking control actions with the existing controls? Tedious actions? Difficult actions?
- Are there tasks that should be automated (e.g., tedious tasks, instances of multi-tasking, tasks required communication outside the MCR, etc.)? What tasks? Why?

Discuss Primary Decisions Processes from Key Events

Based on the OER, certain tasks were identified as being problematic due to an increased level of uncertainty in information provided in the MCR. Questions such as those listed in Figure 31 were used during the discussion of the primary decision processes by human factors staff to understand the cognitive activities required to bring the plant to a safe state. These questions were developed as general guides to facilitate discussion around key decision processes made by the crew, inspired by using decision ladders from the control tasks analysis phase of CWA (Stanton et al., 2017). Figure 31 below illustrates specific probe questions used that were derived from the CWA decision ladder.

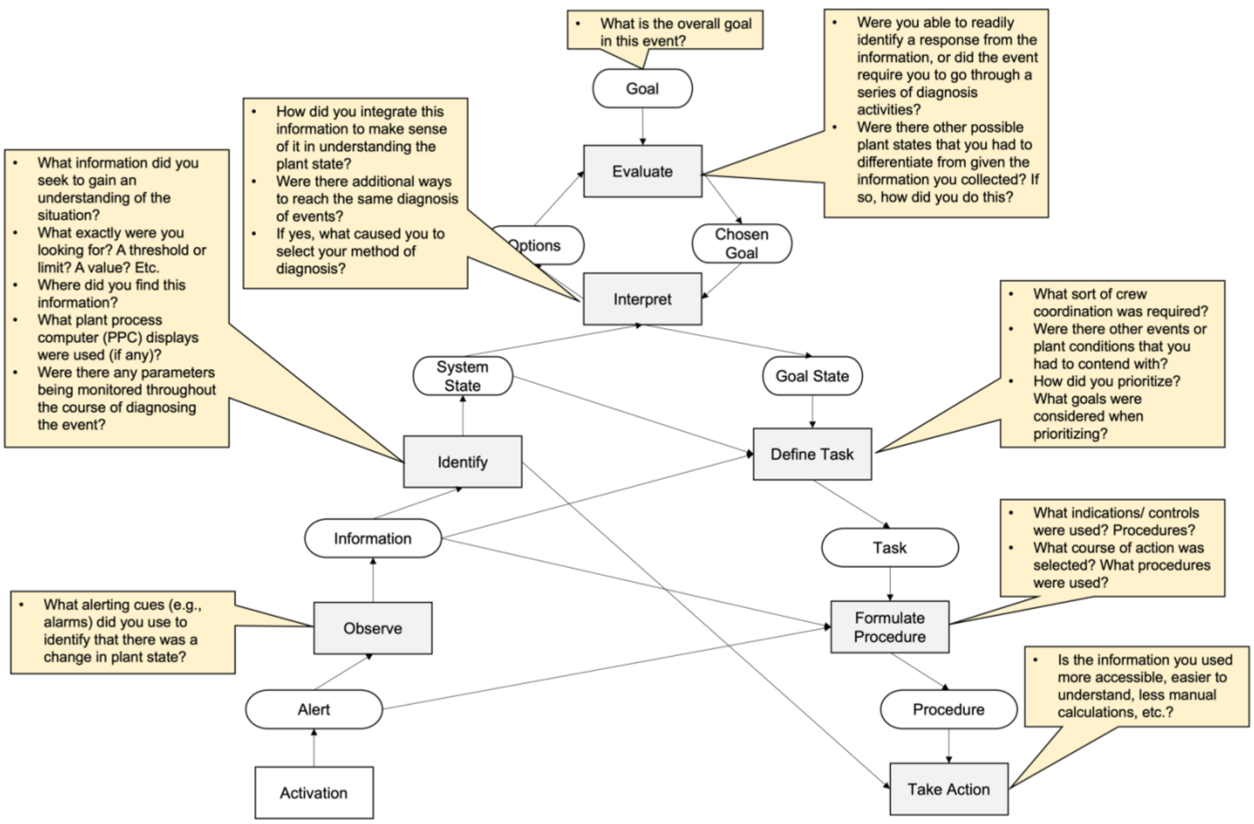


Figure 31. Post-scenario questions informed from decision ladder framework of CWA.

Discuss Modifications Impacts

A conceptual 3D model was produced by human factors staff based upon initial design concepts communicated by the utility. Based on their experience when executing the FA&A scenarios, human factors staff administered the questions in the following subsections to the utility workshop participants.

General and Task Information Requirements

- Based on the scenario you've performed, what are your impressions with the proposed modifications in terms of how you believe it may support or not support the tasks you performed here?
- How might you envision the large screen overview displays being used?
- From the scenario, what specific displays would be likely used for monitoring?
- Are there specific parameters or information you would want to see on these overviews?
- Are there specific plant process computer displays that were used that you wished were located on these?
- What information from these displays is most critical?
- What is the preferred format of this information?

Task Information Requirements and Anthropometrics

- From a supervisor point of view, do you have any concerns with the viewability of information?
- Do the safety system displays occlude the non-safety system displays for monitoring?
- Based on the task flow from the operators during this scenario, would there be any concerns or distractions from using the overview displays?
- From a reactor operator point of view, do you have any concerns with the viewability of information?

Automation

- How might the automated operator aids support you with this scenario?
- What are the specific benefits of these aids in this scenario?
- What specific human error trap(s) does it mitigate?
- What information would be important for you to understand whether [*particular aid*] is operating correctly?
    - Logic drill-down?
    - Mimic overview with embedded process data?
    - Both? Other?
- Are there specific concerns you have with the proposed automation in this scenario?
- Are there any other enhancements (e.g., additional features and functions) you can think of?

Final Discussion

The final wrap-up discussion was facilitated and recorded to:

- Verify information collected during the walkthroughs is accurate and complete
- Collect any additional impacts to the physical layout identified from the scenarios is captured
- Identify and confirm representative displays (e.g., using plant process computer) for the common scenarios to prepare for the task analysis workshop
- Confirm a set of representative scenarios for the task analysis workshop, including training guides, procedures, and representative plant process computer displays used currently for these scenarios
- Identify action items

- Open discussion (i.e., items not previously covered before workshop close out).

5.2.5 Step 4 – Documentation and Use of Results

The results from the FA&A workshop were documented in an RSR and provided to the utility. The results from the workshop broadly provided an understanding of how operators take action (i.e., respond to transients and casualties) in their current MCR. HFE researchers gained insight into how the crew use existing indications and controls for monitoring, situation assessment, response planning, and execution. These insights covered both positive attributes and negative attributes of the MCR and current technology. These results served as inputs into the task analysis workshop described next.

5.3 Task Analysis

Task analysis is a collection of different data collection, visualization, and analysis techniques that all have a common purpose. Within the context of nuclear power plant modernization, task analysis is the analysis of functions that have been assigned to plant personnel to satisfy the requirements for successful performance. The actions personnel must do to accomplish functions assigned to them are called "tasks." Generally, the term "task" refers to a group of activities that have a common purpose. The fundamental basis of task analysis is a decomposition of tasks into their constituent activities performed to accomplish a goal. The degree of decomposition varies dependent on the purpose of the task analysis. Figure 32 shows the decomposition of tasks as demonstrated by task analysis.

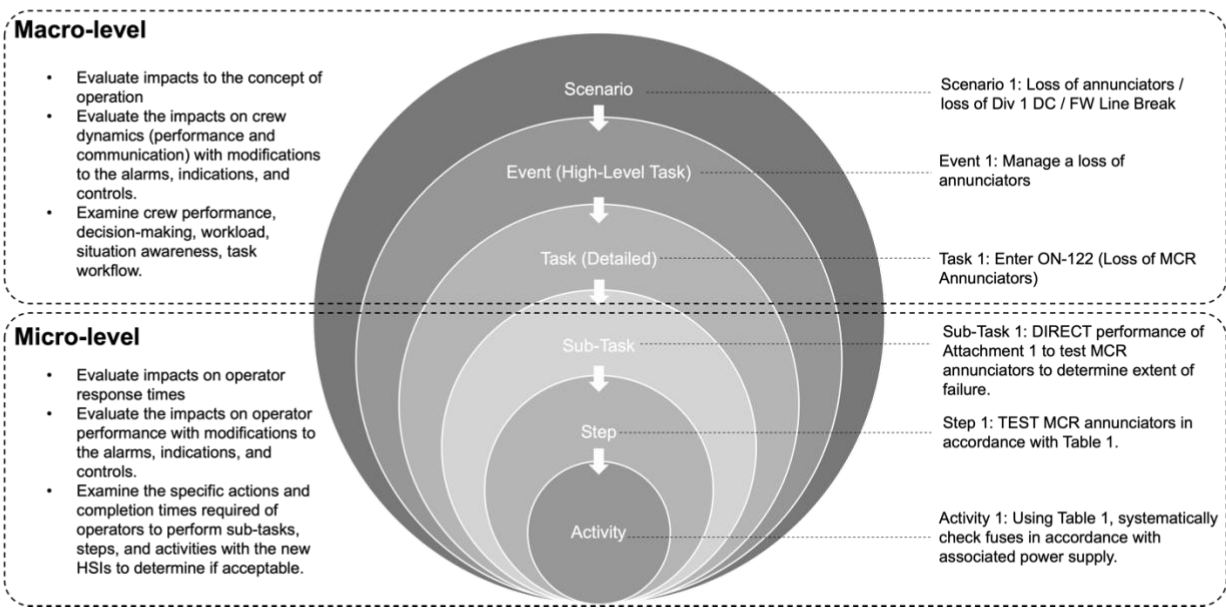


Figure 32. Decomposition of tasks for performing task analysis.

As seen in Figure 32, a top-down approach is taken by developing scenarios that comprise one or more events (i.e., high-level tasks), which are logically grouped in terms of accomplishing a goal. The individual tasks are contained within a scenario and event to accomplish these goals. The benefit of performing task analysis in this way is that tasks can be evaluated naturalistically. The influence of other tasks being performed in succession or in parallel can be properly analyzed in this manner. Further, by analyzing tasks from scenarios and events, the human factors engineer can understand how modifications to the HSIs needed to perform these tasks can influence "macro-level" HFE considerations, such as how the specific modifications impact crew performance and decision-making, situation awareness, workload, and overall task workflow. Put differently, these macro-level HFE considerations are important when understanding how the modifications impact the concept of operations.

As the design matures and specific HSIs and design features are identified, the task analysis can be iterated upon and the scenarios, high-level tasks, and tasks can be further decomposed and analyzed to understand the impacts to "micro-level" HFE considerations that are concerned with the interaction with specific design features from the HSIs. It is here where the task analysis can examine the time required to perform specific tasks, sub-tasks, steps, and activities tied to important HAs with the defined HSIs via OSAs and OSDs, as described in:

- NUREG-0800, Chapter 18, Attachment A, "Guidance for Evaluating Credited Manual Operator Actions" (2016)
- NUREG-1764 (2007)
- NUREG-1852, "Demonstrating the Feasibility and Reliability of Operator Manual Actions in Response to Fire" (2007).

Task analysis began with macro-level considerations impacting the concept of operations and resulting impacts to the alarms, indications, decision processes, control actions, communication, workload, and interaction of tasks in addressing specific events. While some micro-level task analysis methods such as cognitive modeling have been used to analyze interactions with the new HSIs, it was expected that the task analysis will be iterated upon in later HFE activities in HSI Design and V&V. Collectively, the requirements developed in task analysis were a primary consideration in designing the HSIs, procedures, and training that are provided to plant personnel.

The methodology followed here for performing task analysis was based on NUREG-0711 (2012) and EPRI 3002004310 (2015). The major activities are shown in Figure 33. The primary activities shown in this methodology are summarized next.

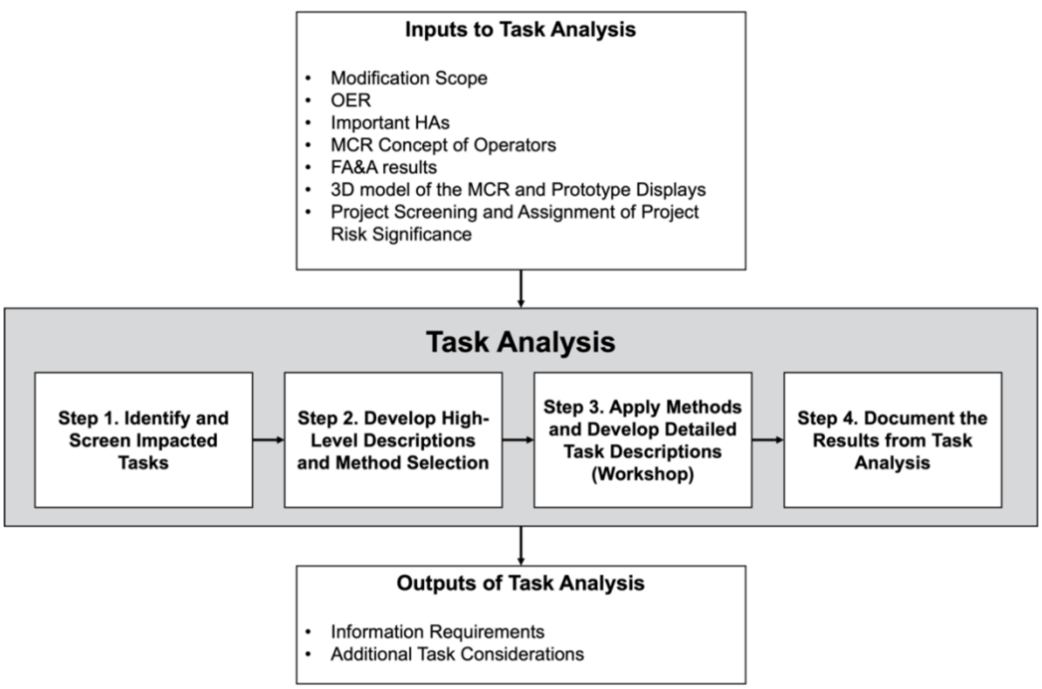


Figure 33. Overview of task analysis.

5.3.1 Inputs to Task Analysis

5.3.1.1 Task Analysis Inputs from Earlier Human Factors Engineering and Other Activities

Necessary task analysis inputs flowing from earlier HFE efforts as well as those identified from I&C system analyses included:

- The SR I&C upgrade modification scope
- Results from OER
- Results from FA&A
- The MCR concept of operations
- Important HAs identified from the PRA, D3 analysis, and UFSAR.

These inputs collectively provided information about impacted tasks, which of these tasks were problematic, and where there is significant opportunity for improvements with the new HSIs.

5.3.1.2 Additional Inputs Created to Support the Task Analysis

Three-Dimensional Main Control Room Modeling

3D MCR models supported FA&A and task analysis. That is, when performing knowledge elicitation activities, the models served as a visual reference to the MCR to enrich the discussion, identify human error traps, and drive development of the optimal placement of HSIs for the upgrade.

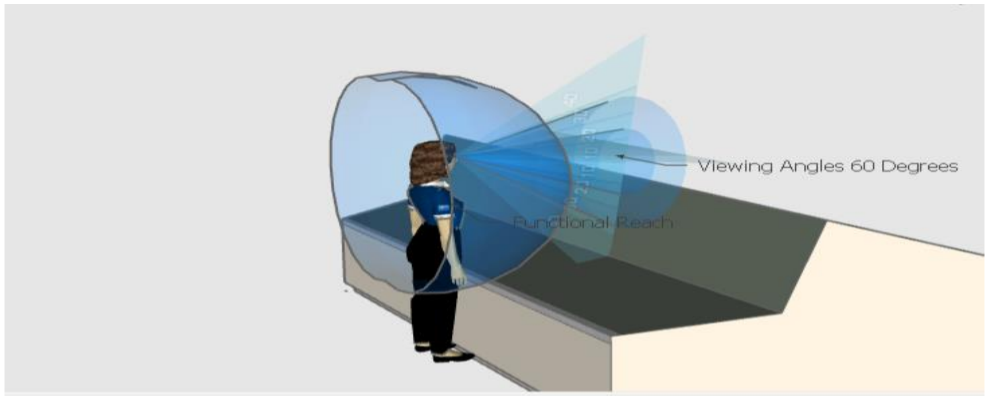
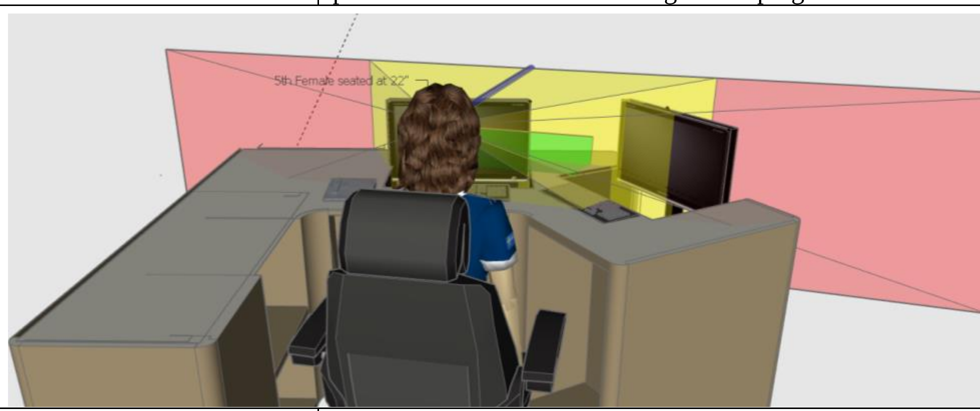
Refinements to the 3D model (genericized example shown in Figure 34) were performed based upon utility operations and engineering input during the FA&A workshop and in the lead up to the task analysis workshop. The resultant 3D model arrangement used as an input to the task analysis workshop is presented in Figure 34 below.

Figure 34. 3D model showing pre-task analysis modifications and 5th percentile female reach envelope.

Anthropometrically correct digital human models were added to the 3D environment as shown in Figure 34 to evaluate the placement of VDUs and controls. This ensured adequate sightlines, reach, and overall placement, following guidance from NUREG-0700, “Human-System Interface Design Review Guidelines” (2002).

The 3D model was used (and will continue to be used in the future) to support analysis from NUREG-0700 Revision 2 Chapter 1 (Information Display) and Chapter 11 (Workstation Design) by identifying ergonomic and anthropometric data (see Table 6 below).

Table 6. Applicable HFE design guidance from NUREG-0700 Revision 2 (2002).

Criteria	Guideline	Description
Functional Reach		
	11.1.1-2 (Control Height)	The highest control on a stand-up console should be within the highest reach of the 5th percentile female without stretching or using a stool or ladder, while the lowest controls should be within the lowest reach of the 95th percentile male without bending or stooping.
Viewing Angle		
	11.1.1-6 (Display Height and Orientation)	All displays, including alarm indicators, should be within the upper limit of the visual field (75 degrees above the horizontal line of sight) of the 5th percentile female, and should be mounted so that the interior angle between the line of sight and the display face is 45 degrees or greater.
	11.1.1-7 (Location of Frequently Monitored Displays)	Displays that require frequent or continuous monitoring, or that may display important (e.g., alarm) information, should be located not more than 35 degrees to the left or right of the user's straight-ahead line-of-sight, and not more than 35 degrees above and 25 degrees below the user's horizontal line-of-sight, measured from the normal workstation.
Legibility	1.3.1-4 (Character Size for Text Readability)	The height of characters in displayed text or labels should be at least 16 minutes of arc and the maximum character height should be 24 minutes of arc.

Data from functional reach, viewing angles, legibility, HSI designs, and workplace design layouts is identified when using 3D 5th percentile female and 95th percentile male digital human models in the 3D models to measure the functional reach of controls or viewing angles of HSI screens. The results were used to inform engineering and operations on the placement of equipment and controls.

Use of the Human-Systems Simulation Laboratory

To provide the most realistic environment possible to perform the task analysis, the researchers decided to leverage the INL Human-Systems Simulation Laboratory (HSSL). The HSSL provides a capability to emulate MCR functionality through a configurable set of digital bays, each of which presents three 55" touch screen, flat panel VDUs. These can be configured to approximate existing MCR layouts as well as to provide a "canvas" to present conceptual MCR modifications.

The 3D model shown in Figure 34 was used as a guide to establish the HSI layout in the HSSL. The objective of this effort was to provide a realistic approximation of the location and functionality of the new VDUs in the HSSL for the task analysis workshop to obtain operator feedback on the latest notional MCR layout. The 3D model from Figure 34 was presented on a large monitor in the HSSL during the task analysis scenario walkthrough analyses to communicate concepts and placements of controls and HSI screens for operations and engineering reviews. This enabled quick reviews for measuring maneuverability in the MCR and other workplace designs needing to be reviewed by operations and engineering at the time of the workshop.

Prototype Displays and Navigation Strategy

Prototype HSI displays for both the safety and non-safety platforms were created by INL along with a notional navigation strategy. These displays and the navigation strategy were developed based upon direct input from engineering, operations, and training personnel from the utility to reflect the latest HSI design concepts. Based upon the revision of the concept of operations, the conceptual safety and non-safety system displays were designed to maximize the use of available VDU space provided by both systems and to support, augment, and improve the current way operators use indications and controls in the MCR.

The result of these efforts was then loaded on the HSSL. The HSSL provided operators the ability to view the notional displays and exercise the navigation strategies on representative VDUs. For the workshop, a mix of computer workstations and simulator glasstop bays was employed to represent the new HSI displays. The layout of the upgrade VDUs from the 3D model (refer to Figure 34) and the prototype display functionality presented on them (Figure 35) was reflected in the HSSL configuration for the task analysis workshop.

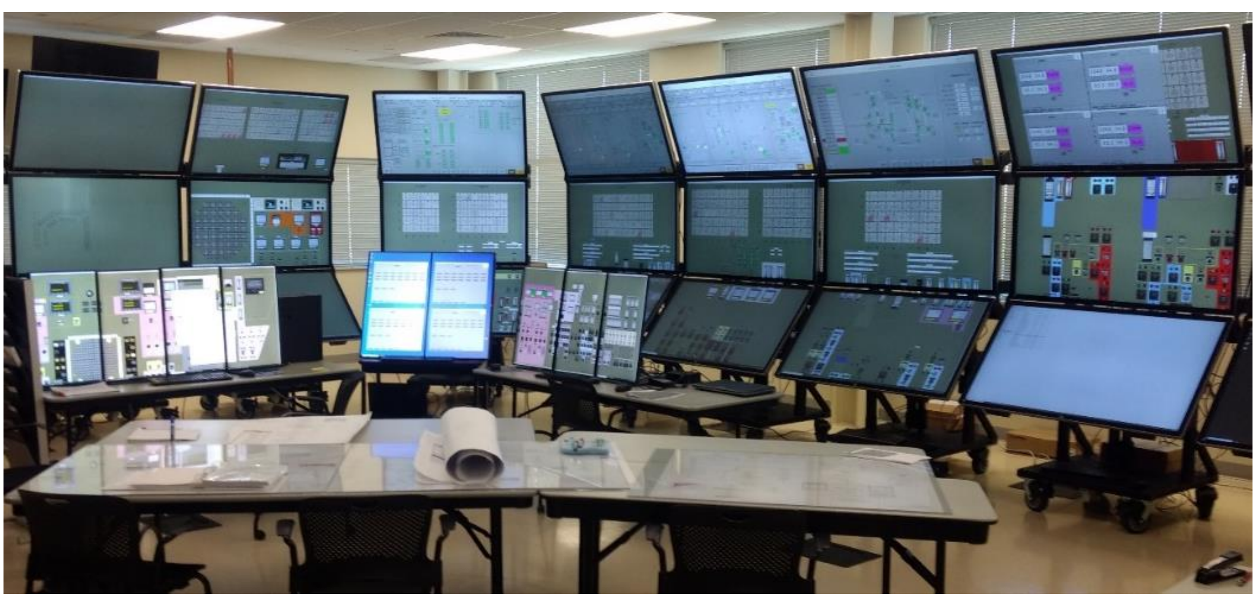


Figure 35. Configuration of Human-Systems Simulation Laboratory for the Task Analysis Workshop.

The prototype displays developed and used in the task analysis were developed in the C# programming language using the Windows Presentation Foundation, a subset of Microsoft's.NET framework, which uses the Extensible Application Markup Language. Windows Presentation Foundation comes equipped with a broad set of development features, resources, controls, graphics, layout, data binding and other characteristics that can lend themselves well to the quick prototyping required for this workshop.

An executable program was compiled for each prototype display used in the workshop and placed in a directory of its same name along with the required dynamic link libraries for executing that program. These were placed on the same drive the simulator was mapped to so that they could be run from any bay or computer on the local network. INL was able to import and run the operating simulator model from the utility training simulator on the HSSL as well. The objective of this effort is to provide an interactive display prototyping capability during initial HSI development and subsequent refinement prior to rendering the displays in safety systems and non-safety systems.

Overview displays were built to be dynamic displays, pulling live values from the simulator, and responding to those state changes in real time. The top-most, horizontal indicators displayed live values of variables that plant operators find useful to monitor. Other useful live values were displayed throughout the overviews as numerical display readouts. Pump and valve widgets were also displayed in these overviews and were built to dynamically change color according to their status.

Conceptual navigation features were presented and discussed during scenario walkthroughs. Sufficient real estate existed on the HSSL glasstop bays to present the current and fully functional HSIs from the simulator in digital form while at the same time presenting the DCS overview displays created for the workshop. This allowed the operator subjects participating in the workshop to cross- reference data produced from the simulator and presented on the current HSIs to the way this data is being packaged on the DCS overview displays.

5.3.2 Methodology and Procedure

5.3.2.1 Step 1. Identify and Screen Impacted Tasks

Initial HFE Project Screening and Assignment of Project Risk Significance

The project was initially screened to determine the extent of potential HFE impacts. Changes considered in project screening included those that impacted operator HSIs. Changes that did not modify HSIs but could have other potential impact on operator tasks were also considered. The project screening process followed was based on guidance given in NUREG-0800, Chapter 18 Sections II.B and II.C (2016) and EPRI 3002004310 (2015). Figure 36, which depicts this process from EPRI 3002004310, is repeated and updated below for convenience.

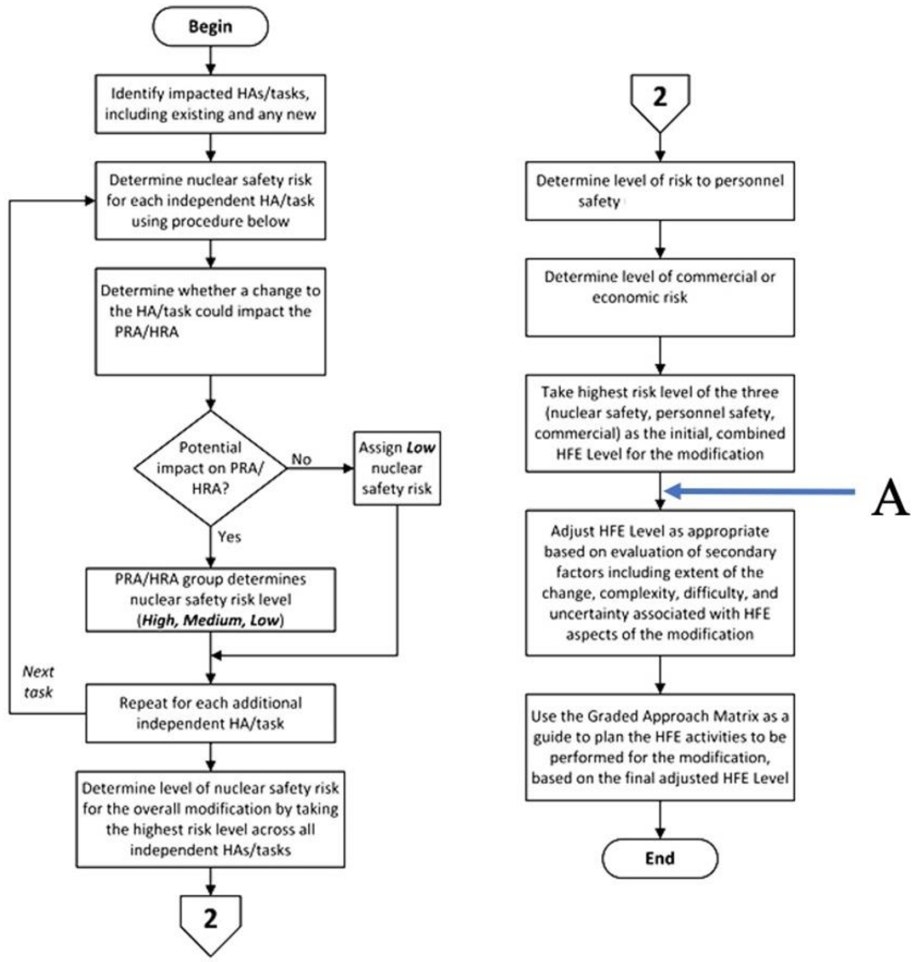
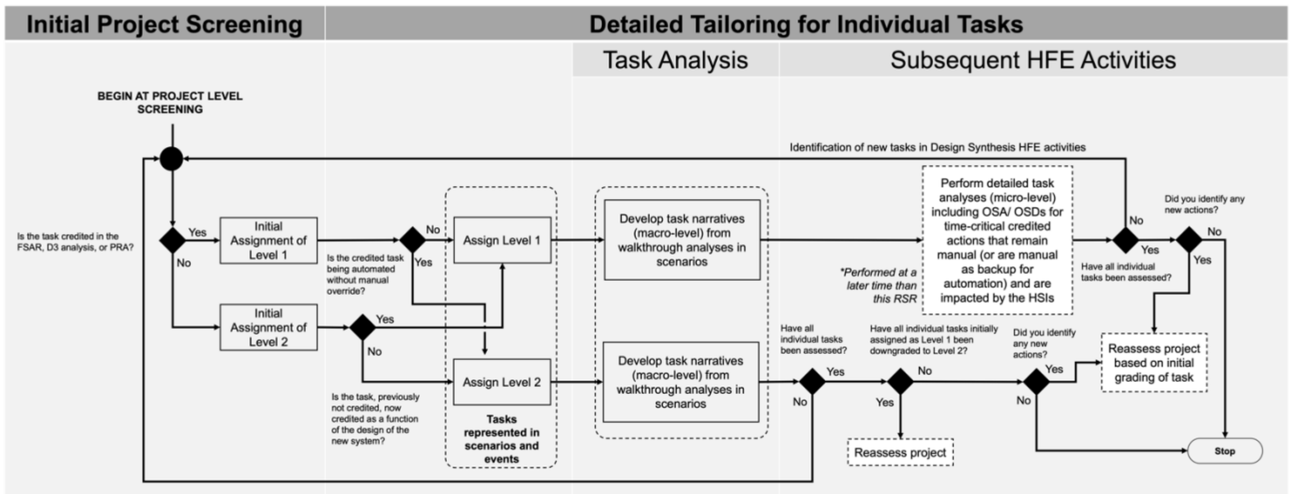


Figure 36. Process for determining HFE level of activity through project screening (adapted from EPRI 3002004310, 2015).

This process first determined if any important HAs related to nuclear safety (i.e., identified from the utility UFSAR, D3 analysis, and PRA) may be impacted by the modification as an input to the initial screening. The initial screening also considered personnel safety, and risk to commercial operation. This executed the process shown in Figure 36 (up to point "A"). Screening was accomplished using an analysis tool developed as part of the EPRI 3002004310 (2015) guidance. This screening approach first accounted for potential risk to nuclear safety and economic risk, followed by an assessment of secondary factors. The secondary factors were based on the EPRI 3002004310 (2015) guidance, as well as NUREG-1764 (2007). This screening provided a project-level assignment of project risk significance.

Detailed Tailoring of Specific, Individual Tasks in the HSI Design Phase

Figure 37 illustrates the process for specific task identification and tailoring the task analysis following a graded approach.



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

Figure 37. Task screening and tailoring process for task analysis.

The first step was to identify the specific tasks impacted by the modification. The task identification and screening process was accomplished by engaging with utility training SMEs who identified all the known tasks performed inside and outside the MCR from an Institute of Nuclear Plant Operations required methodology. This methodology produced specific utility tasks and DIF scores. Screening of these specific tasks was based on whether these tasks were impacted by the upgrade using criteria such as:

- Impacts to the operator HSIs inside the MCR
- Changes to workplaces where operators use HSIs, if the changes could impact human performance
- Changes that do not modify HSIs but could have other potential impact on operator tasks (e.g., system changes that reduce the amount of time available for an operator to perform a task).

Next, tailoring the graded approach was performed at the individual task level. Tasks that were not impacted per criteria above were considered a Level 3 and were not considered in subsequent task analysis walkthroughs. Screened-in tasks were evaluated in the task analysis cognitive walkthrough analysis and further determined as being important (Level 1) or of lower significance (Level 2) based on whether the tasks were credited in the utility UFSAR, D3 analysis, or PRA. That is, if the screened-in task was credited, it was initially assigned Level 1. If not, it was initially assigned a Level 2.

Uncredited tasks (Level 2) or any new tasks that could, because of this upgrade, rise to a level where they were identified as safety-significant (in the USFAR, D3 analysis, or PRA) would be tailored up to or established as Level 1 tasks. Likewise, previously credited tasks that would be completely automated without any manual intervention would be assigned Level 2. As of the writing of this report, no existing tasks have been upgraded and no new tasks have been identified that are Level 1. No previously identified Level 1 manual tasks have been automated and downgraded to Level 2.

The final assignment of Level 1 or 2 determined the level of rigor in applying task analysis. All Level 1 and 2 tasks were evaluated at a macro-level through the cognitive walkthroughs. The identified credited manual tasks, assigned Level 1, were further tabulated for subsequent HFE analyses (i.e., subsequent micro-level analysis). While time available was qualitatively assessed, the Level 1 tasks were prioritized for subsequent HFE activities in later phases to apply OSA and OSDs following guidance described in Attachment A of NUREG-0800 (2016).

5.3.2.2 Step 2. Develop High-Level Task Descriptions and Select Method

A common approach to task analysis is to develop high-level task descriptions that can be further decomposed to the level of detail necessary to identify task performance requirements (EPRI 3002004310, 2015); this decomposition is reflected in Figure 32, as previously described. Task analysis is generally considered to extend from the results documented in FA&A. Thus, the task identification and risk significance assignment were used to develop and refine scenarios. Each scenario contained higher level tasks (i.e., managing specific plant events) in which the specific tasks were grouped in a logical manner by utility operations and training SMEs to ensure the context to which each task was considered. The higher level tasks and scenarios were documented in simulator guides and served as the basis for the detailed task analysis.

These higher level tasks served as a goal-oriented approach in managing the plant in a way that required performing specific tasks. The benefit of this approach was added contextual accuracy in which the tasks were observed. That is, tasks are often not performed in isolation, but are generally performed to accomplish a specific goal that can be characterized through events and scenarios. A group of related tasks used to accomplish a goal (high-level task) is considered an event. Related events can be further grouped into scenarios. Furthermore, the scenario-based approach allowed the team to sample tasks based on their uniqueness and level of impact by the modification. For example, while there may be several different tasks associated with maintenance testing, it is possible to sample a single task that is representative of the entirety of maintenance tasks.

The primary task analysis methods selected are documented in Table 7 below. All Level 1 and 2 tasks were grouped into specific scenarios that contained individual higher level tasks, or events. This composition of tasks and events were documented in simulator guides to which the hierarchical relationship was clearly defined through a tabulated hierarchical task analysis format. Cognitive walkthroughs were performed at the HSSL with two licensed operators and facilitated by human factors engineers. The specific methodology is described in the next section. Level 1 tasks were positioned to be analyzed in later HFE activities using OSA and OSDs when the design is matured.

Table 7. Task Analysis method selection.

Level 3 Task	Level 2 Task	Level 1 Task
Primary Task Analysis Methods		
• Expert evaluation	• Hierarchical task analysis (Grouping tasks by events and scenarios in simulator guides) • Cognitive walkthrough	• Hierarchical task analysis (Grouping tasks by events and scenarios in simulator guides) • Cognitive walkthrough • *OSA and OSD
Primary Task Analysis Activities		
• Screened out of simulator guides • Review of previous task analysis	• Screened into simulator guides and evaluated via cognitive walkthroughs with scenarios • Develop task narratives to address macro-level task impacts	• Screened into simulator guides and evaluated via cognitive walkthroughs with scenarios • Develop task narratives to address macro-level task impacts • Identify credited manual tasks from UFSAR, D3 analysis, and PRA • *Evaluate credited tasks in later HFE activities to address micro-level considerations, such as time required and time available to perform tasks
Primary Task Analysis Outputs		
• No formal task analysis outputs	• Task narratives	• Task narratives • List of important HA • *OSA and OSDs for credited tasks
Note: * indicates that method will be performed in later HFE activities.		

5.3.2.3 Step 3. Apply Methods and Develop Detailed Task Descriptions

The primary task analysis method was a series of cognitive walkthroughs from the developed scenarios in the HSSL glasstop simulator testbed. A cognitive walkthrough is a knowledge elicitation technique where domain experts (i.e., also referred to as SMEs) demonstrate a set of tasks (i.e., often using procedures) to describe it, highlighting potential issues or identifying the important actions (Kovesdi, Joe, & Boring, 2018.). As seen in Figure 38 in purple, the talkthroughs and walkthroughs used in the task analysis were selected to collect rich qualitative data related to design input. This type of data is particularly useful in early, formative HFE efforts, such as those seen in the Planning and Analysis of NUREG-0711 (2012).

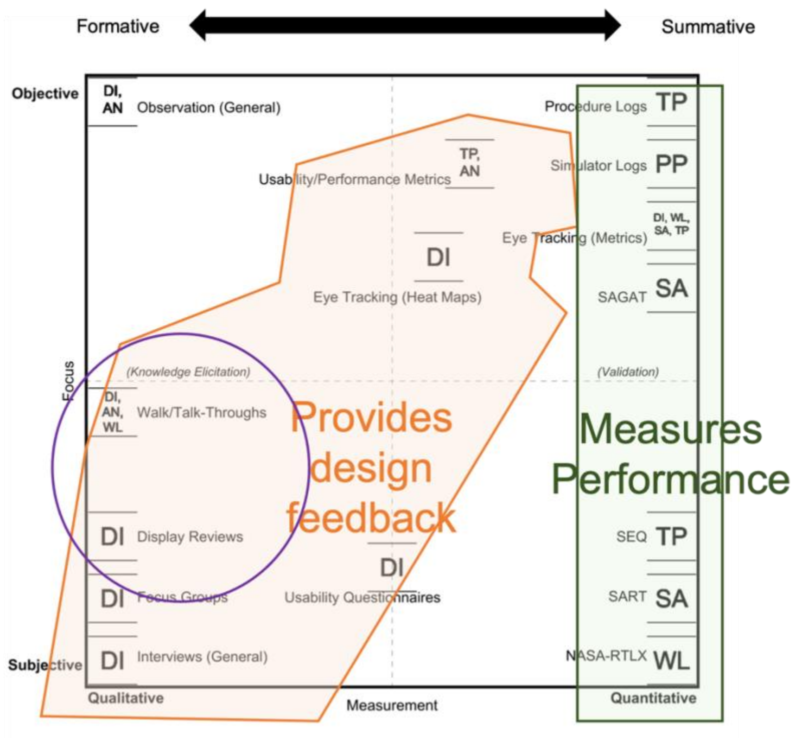


Figure 38. Landscape of HFE methods and measures for nuclear power plant modernization (adapted and enhanced from Kovesdi, Joe, & Boring, 2018).

The walkthroughs were performed by operators and facilitated by both a human factors engineer and a training SME. Additionally, there were several other key staff available from the utility (i.e., training and engineering), as well as the vendor.

The walkthroughs were facilitated by presenting the key impacted tasks, including important HA, to operators and having the training SME facilitate the key events from the scenarios in which the impacted tasks would be performed. Operators demonstrated and discussed what specific tasks they would need to perform to address each event (e.g., managing a loss of offsite power) with both the existing state and new state MCR (Figure 39). The simulator was configured to present both the current boards and new HSIs to allow operators to discuss the impacts of changing the HSIs in performing the identified tasks. The crew also had access to their procedures as hard copies.

Figure 39. Crew procedure use during Task Analysis Workshop.

The training SME was able to run aspects of the scenario and pause to add additional context to the data collection. Further, a large screen monitor positioned adjacent to the MCR layout presented the anthropometrically accurate 3D model of the MCR (see Figure 34) to aid in the discussion related to positioning of VDUs and anthropometric considerations with the modifications. The model contains ergonomic digital human models that could reflect 5^{th} percentile female and 95^{th} percentile male engineering design characteristics to evaluate sightlines and reach using NUREG-0700 (2002).

Task Analysis Workshop Objectives

The primary focus of this task analysis workshop was to:

- Present prototype HSIs (VDUs and hosted displays)
- Evaluate the use of these displays and how they are presented to the operators (relative physical arrangement, navigation, etc.) so that they can be used to accomplish their tasks with the new systems
- Evaluate the current conceptual arrangement of the new HSIs
- Obtain interactive feedback from operators.

The output was intended to support additional workshops and directly drive the vendor-development of displays hosted on VDUs, aid in placing MCR VDUs to promote optimal use, identify any sizing issues, etc.

Design Team

The design team consisted of a combination of human factors engineers, vendor SMEs, and utility operations, training, and engineering SMEs.

Detailed Methods

Introductions, Overview, Agenda, and Objectives

The workshop began with introductions and a safety brief of the facility. The overall agenda and objectives of the workshop were provided to ensure team alignment. Next, key findings from the FA&A workshop were summarized and presented to ensure that these topics were addressed in walkthrough analyses covering the nine scenarios. The goals of task analysis and this workshop were covered by INL, and an overview of the task analysis methodology was provided. The team was reminded that the workshop was intended to evaluate the impacts of technology on the tasks and not to evaluate the crew specifically. All data was anonymized through participant IDs and data aggregation where possible.

Perform Walkthrough Analysis

Figure 40 illustrates the workflow performed for the walkthrough analysis.

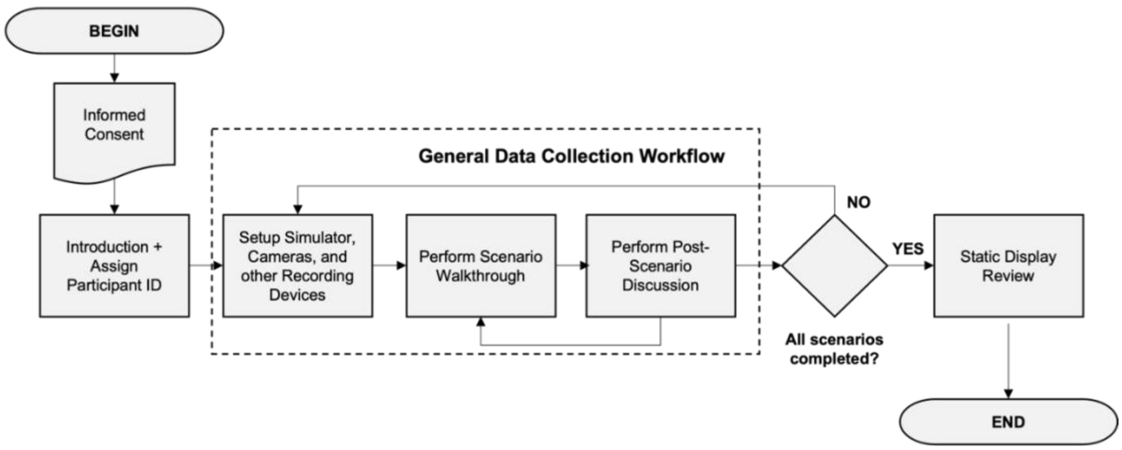


Figure 40. Walkthrough analysis general workflow for the Task Analysis Workshop.

Informed Consent

Informed consent was verbally administered to the crew prior to the walkthrough analysis.

Introduction and Participant ID Assignment

Data collection was anonymized and aggregated throughout. Operators were instructed to perform a think aloud approach (i.e., verbalize their thoughts) regarding their experience using the existing and new indications and controls during the scenario. Operators were reminded that:

- Their participation was being requested because of their knowledge and expertise and that the information they provide will be used to guide the HSI design.
- Their opinions would guide preferences and requirements for the new designs.
- The information being collected was being used to design or evaluate the HFE aspects of the HSIs, and NOT to evaluate their performance.
- The anonymity of personnel was maintained, their comments were treated as anonymous, and the comments were coded using a participant ID scheme.

During this time, SMEs from the utility provided supporting details to help operators align to the objectives of these walkthroughs and expectations when performing these scenarios. While these introductions were performed once, reminders were given as often as necessary to ensure operators were aligned with the goals of this workshop.

Simulator and Data Collection Setup

The simulator specialist prepared the simulator for each scenario by setting up initial conditions and other tasks (e.g., preparing the simulator guides) necessary to run the scenario and enable video recording. The simulator specialist provided a cue when the scenario began and ended. Human factors staff prepared data collection tools, printed procedures, and cameras as the primary recording device. Each human factors staff was assigned different primary roles for collecting notes.

Perform Walkthroughs

During the walkthrough, the simulator was stopped at steps in the procedure where new functions were added, eliminated, or changed. The operators and others in attendance were asked to discuss these possible changes from existing practices. The human factors staff collected verbal and observational data while also facilitating the think aloud technique per scenario. Figure 41 presents a photograph taken during one of the scenarios performed for the walkthrough analysis. As seen, operators walked through key tasks within the defined events and scenarios from the simulator guides. The arrangement of the MCR was faithfully represented to match the board configuration of the actual MCR. Both the existing and new states were presented to allow operators to discuss how they perform tasks now and how the upgrades will impact these tasks. Human factors staff collected observational and self-report data from the walkthroughs using a combination of recording devices.

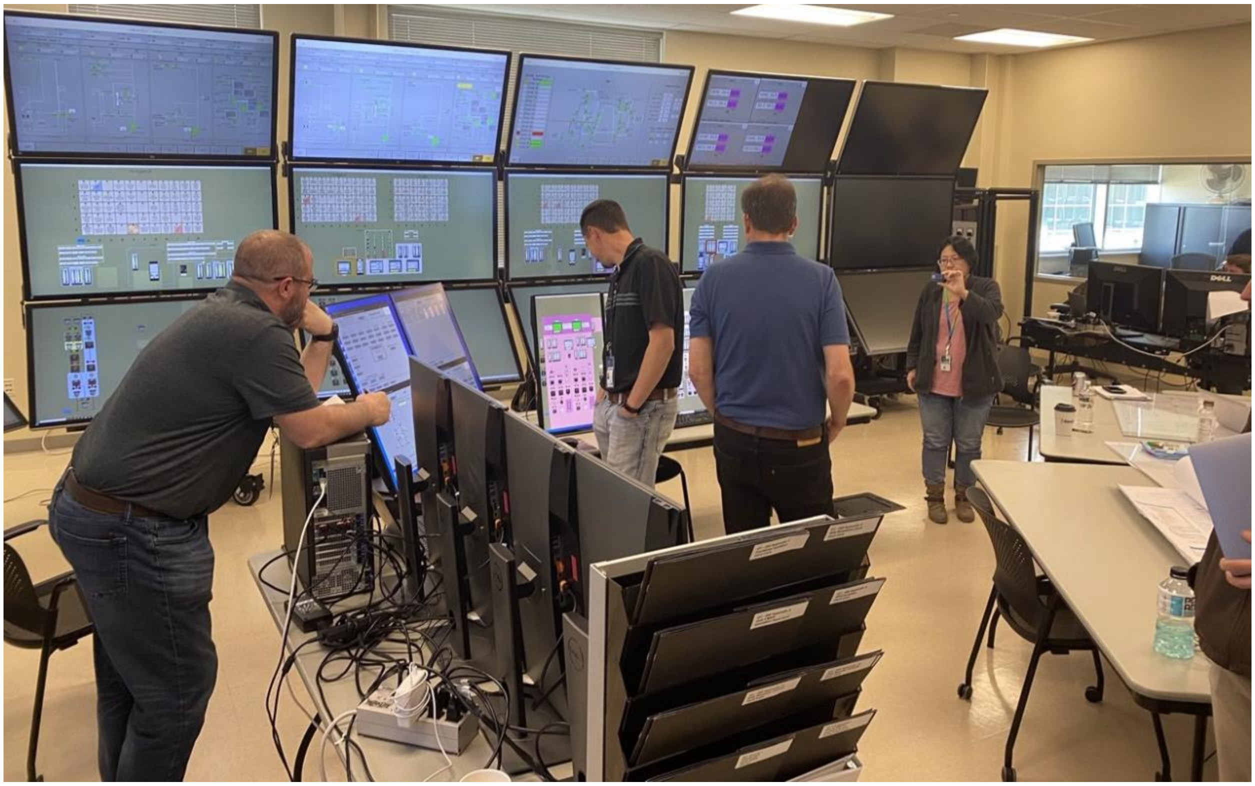


Figure 41. Photograph of the Task Analysis Workshop walkthrough analysis.

Perform Post-Scenario Discussions

The post-scenario discussion was performed in concert with the walkthrough analysis; this is reflected in Figure 40 from the small iterative loop between performing the scenario walkthrough and performing the post-scenario discussion. During the post-scenario discussion, the human factors staff facilitated a semi-structured set of questions. The 3D model was also used and presented on a large monitor, showing the planned modifications, to focus on the discussion where needed. General questions were used as probes to facilitate discussion. These questions are presented in Table 8.

Table 8. General questions for the task analysis post-scenario discussion.

The plant is highly dynamic and operator actions often occur in parallel (particularly during casualty events).

1. Do the new upgrades disrupt the operators' ability to perform parallel processing?
2. Do the new upgrades disrupt the operators' ability to perform teamwork diagnosis and response execution?
3. How do the proposed modifications alter individual and team situation awareness concerning parallel processing?
    - Do the overviews provide the right level of information to enable team situation awareness? Is additional information needed?
    - Is the location of the new safety system displays adequate or not?
    - Will the automation enhancements enable improved situation awareness or not?
    - Are there human error traps associated with these upgrades that may limit team awareness?

In many situations, operators can achieve successful plant safety and operational outcomes in more than one way when following the same set of procedures.

4. Do the new upgrades prevent operators from following specific actions and procedures where more than one path is permissible?
    - Is the navigation appropriate or not appropriate for safety system?
    - How should the navigation structure for non-safety system control displays be designed?

Operators leverage the existing "flat topology" of indications and controls to enable parallel processing and multi-path diagnosis.

5. Do the proposed modifications support or disrupt the "flat topology" attributes of the existing control room used for diagnosis? If so, how?
6. Any additional trending capabilities to include?

There are highly manual tasks where operators are required to remain in a particular location at the control board.

7. Is SA improved or inhibited by the reduction of "ping-ponging" around the MCR?
8. Do the automation enhancements support or not support workload management previously challenged by highly manual tasks?
9. What actions and processes have been improved with the proposed modifications?

Additionally, human factors staff facilitated discussion on the impacts to specific important HA tasks from the modification (i.e., Level 1 tasks). This discussion was based on the identified impacted important tasks from the UFSAR, D3 analysis, as well as PRA. These tasks were reviewed in terms of their impacts to the:

- Alarms
- Decision-making
- Information and controls
- Communication and teamwork
- Workload and time requirements
- Impacts to other tasks (i.e., any interdependences).

Operators self-reported on these topics above regarding how the existing MCR configuration facilitates task completion and then discussed the impacts of the upgrades along these topics.

Static Display Review

After the scenario walkthroughs were completed, a static display review was completed. The display review focused on the overview non-safety system displays and safety system displays presented in the workshop. The display review was facilitated by the human factors staff where each display was presented on a large monitor and operators provided comments, based on their experience in the walkthroughs, regarding the completeness, format, and overall usability of the displays. Vendor SMEs were available to provide feedback on the design characteristics of these platforms.

Identify Task Requirements and Additional Considerations

The results of the walkthrough analyses for the scenarios created task narratives for each of the primary events. Figure 42 presents the format used, which is based on Figure 5-1 in NUREG-0711 (2012). One of the key differences with the narrative tables used here was that the task narratives described not only a summary of current task requirements, but also the impacts of these task requirements based on the modifications. The left column in Figure 42 describes existing task considerations whereas the right column describes the impacts of these task considerations from the modifications. The intent of these tables was to understand the task requirements at a macro-level, specifically in understanding how the modifications to alarms, HSIs, and controls will impact crew performance, situation awareness, communication, and workload.

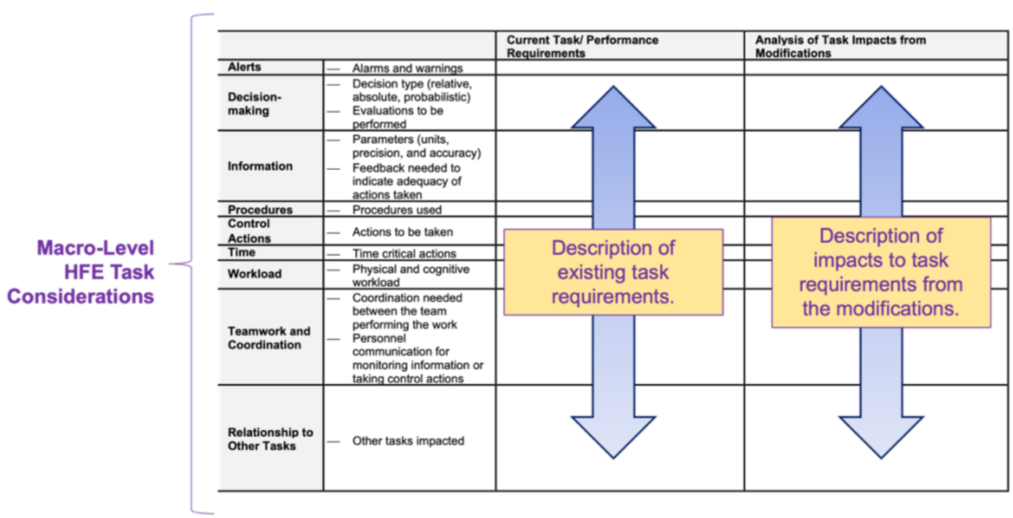


Figure 42. Task description tables.

5.3.2.4 Cognitive Modeling Software

Cognitive (i.e., keystroke-level modeling) modeling software was used to support specific user interactions with the safety system displays. Cogulator is an open-source script-based program that uses Goals, Operators, Methods, and Selection Rules based primitives to generate predicted task times (Estes, 2017). Cogulator provided a means to estimate the time required to perform specific actions within the safety system, such as navigation and operating soft controls.

5.4 Use of Results

The combined results from FA&A and task analysis provided inputs into remaining NUREG-0711 (2012) Planning and Analysis activities, such as the treatment of important HAs and staffing and qualifications. For instance, the identification and analysis of impacted important HAs directly addressed the treatment of important HAs by:

- Identifying these tasks deterministically via UFSAR and D3 analysis and probabilistically via PRA
- Considering these tasks in designing HFE aspects of the plant that were impacted by the SR I&C upgrades.

The results coming out of task analysis evaluated these impacted tasks and identified information requirements and task considerations related to impacts to operators' required knowledge and abilities, workload, situation awareness, teamwork, and coordination. The results from this were able to verify whether there were any impacts on staffing and qualifications.

The results from task analysis also informed NUREG-0711 design activities, including HSI design, procedure impacts, and training. Specifically, the impacts on existing tasks, procedures, and associated HSIs were evaluated through the cognitive walkthroughs to directly inform:

- Design requirements for both the safety and non-safety HSIs, including addressing previous design tradeoffs (HSI design)
- Workstation design and placement for supporting both the safety and non-safety platforms to support the overall concept of operations of the entire crew (HSI design)
- Potential impacts to existing procedures (procedures) and training (training).

As described in the human-technology integration methodology (Kovesdi et al., 2021) and specifically to this project, it was expected that lessons learned, and input collected from these planning and analysis activities are iterative in nature. That is, design input collected in subsequent HFE activities seen in the design phase will build on the findings from the FA&A and task analysis activities to support the larger project schedule, such as by significantly reducing cost through addressing HFE considerations early in the project lifecycle. From a licensing standpoint, a key product of this work served as technical input into supporting HFE aspects of the LAR, following DI&C-ISG-06. Lessons learned are presented in the next section, following into conclusions.

6. LESSONS LEARNED

This section presents lessons learned in demonstrating the human-technology integration methodology and function allocation described in Section 4 in a major safety-related upgrade following DI&C-ISG-06 described in Section 5. The lessons learned and resulting guidance is presented across three general categories:

- **HFE insights in planning** for human-technology integration requirements activities
- **HFE insights in execution** of human-technology integration requirements activities
- **Licensing** insights as applied to the planning and execution of human-technology integration requirements activities.

6.1 HFE Planning

6.1.1 Team Composition and Dynamics

Lesson #1.	Early involvement and regular communication between operations, training, and HFE is critical in planning and coordinating HFE activities.

The early involvement of the multidisciplinary team benefits the effective identification of scenarios, designing early concepts, and identifying key considerations to address, as well as logistical considerations with simulator integration and general workshop planning. Regular communication between the team should be established. This is especially important in managing some of the challenges described in Lesson #12.

Lesson #2.	A clear division of responsibility between parties is important for effective collaboration.

Having a division of responsibility is pertinent for the entire design team. In the SR I&C upgrade project, parties included operations and training, engineering, vendor, and HFE. Having well defined roles for each discipline ensures that planning activities are completed efficiently and that each team member can effectively contribute using their domain expertise. Having a "team lead" across each area if there are multiple staff in a single disciplinary can be useful when coordinating between organizations.

This guidance can be given to the planning of specific HFE-related activities as well. For instance, having clear roles for HFE staff can support workshop planning, which involves scheduling, team coordination, protocol and tool development, scenario development, simulator integration, management of facility security protocols, among other administrative tasks.

6.1.2 Methodological Considerations

Lesson #3.	A risk-driven scenario-based approach to evaluating impacted functions and tasks provides an effective way to evaluate the impacts to tasks naturalistically and capture task interdependencies for the most critical impacted HAs.

A scenario-based approach allows evaluating macro-level (e.g., concept of operations) and micro-level (e.g., specific interactions with HSIs) task considerations. As discussed in Section 5.3, the use of scenarios allowed the HFE team to evaluate impacted tasks in a naturalistic manner to which their interdependencies could be effectively addressed by added context of use. As such, macro-level considerations, such as impacts on teamwork, communication, and overall crew performance, could be examined with the proposed modifications, compared to the existing MCR concept of operations. The scenario-based approach really enabled additional benefits captured in Lesson #4–Lesson #11. Moreover, the scenarios can be reused in later HFE activities like V&V for ISV. As such, a key lesson learned is to identify scenarios (key use cases), driven by a graded approach (i.e., view risk analyses), early so that the impacted tasks can be evaluated in planning and analysis HFE activities when design input can be best leveraged.

Lesson #4.	Applying a “baseline” evaluation of the existing state offers value in benchmarking human-system performance and can be used as reference in future HFE activities.

This work performed benchmark testing of the existing MCR configuration at the utility’s training simulator. The benefit to this, beyond capturing observational data of existing challenges, was the collection of baseline performance, workload, and situation awareness data. These measures can be compared to the later iterations of the new configuration to provide a data-driven approach in ensuring that these HFE considerations are not being negatively impacted. These results agree with earlier guidance from Boring and colleagues (2015) that identified potential activities supplementing the existing HFE activities described in NUREG-0711 (2012) to better support modifications at existing nuclear power plants. One of these added elements in planning and analysis is the benchmark test.

Lesson #5.	Having access to a digital glasstop simulator is instrumental in collecting early feedback during planning and analysis activities like task analysis.

Without a glasstop simulator, human-in-the-loop simulation and rapid prototyping of HSI concepts cannot be faithfully represented and evaluated. The use of a glasstop simulator is simply instrumental in applying an empirical approach to HFE evaluation, especially early in the project lifecycle. Facilities like the HSSL at INL can enable early testing through rapid prototyping to collect early design feedback. A facility like the HSSL, or an equivalent, is recommended when embarking on any major digital modification. This guidance is necessary to enable Lesson #3 and evaluate scenarios and impacted tasks in a naturalistic way.

Lesson #6.	Focus on knowledge elicitation via qualitative measures is pertinent to the success of addressing human-technology integration requirements.

Methodologically, early HFE activities benefit significantly by implementing qualitative approaches that focus on knowledge elicitation in understanding operators’ rationale (i.e., the “why”) when performing actions, making decisions, and coordinating as a team. Applying observational and interview techniques enables a balance between objective and knowledge elicitation. This recommendation falls on the premise that design decisions should go beyond asking operator opinion. While preference data is important, understanding the rationale and bases to which operators act on the information they receive in the MCR is pertinent in designing new digital systems; the use of qualitative measures simply addresses this need.

Lesson #7.	Advanced frameworks can complement simulation and modeling techniques applied to FA&A and task analysis.

The frameworks included using decision ladders from CWA and CTA techniques (cognitive walkthroughs). These approaches allow an evaluation of the cognitive processes required of the crew and individual operators when performing the impacted tasks. It is recommended that someone experienced in HFE and with a background in cognitive science facilitate the use of these methods (e.g., see NUREG-0711 (2012) Appendix – Composition of the HFE Team). Guidance from INL/EXT-21-64320, EPRI 3002004310 (2015), and associated references listed in these documents can be used in applying such approaches.

6.2 HFE Execution

Lesson #8.	A multidisciplinary team, including operations, training, simulator SMEs, engineering, vendor, and HFE personnel should be embedded in the execution of HFE workshop activities.

As mentioned in Lesson #1 for HFE planning, a multidisciplinary team is needed in the execution of HFE activities. A level of team building and synergy that is difficult to quantify is needed for effective decision-making. Having the right people available allows the team to efficiently address design tradeoffs to make effective decisions. For example, during the operator walkthroughs, questions would be elicited by operators during discussion with human factors engineers in which only engineering personnel or the vendor could answer. Having this real-time coordination allows for quicker and more complete design decisions. This directly addresses challenges observed in Lesson #12.

The ability of the multidisciplinary team to dynamically interact to identify issues and proposed solutions is paramount when developing and refining HFE concepts and associated designs. This allows ideas to be proposed, vetted, and dispositioned much more rapidly (orders of magnitude faster) than following a document-driven, linear process of concept and requirement development, rendering of HSIs based upon those written “requirements,” written comment creation and aggregation, and then written dispositions of comments and associated “requirement” updates.

The interactive dynamics associated with bringing the multidisciplinary team together and working together as a team to converge ideas and concepts into workable solutions where team consensus is achieved was best executed during face-to-face team activities via FA&A and task analysis workshops. When geographical separation prevented true face-to-face interactions, bringing the team together via electronic means was leveraged. While this medium provided a somewhat diminished capability to create the “full experience” of true face-to-face meetings, it was still much more effective than exchanging asynchronous emails for communication.

Lesson #9.	Real-time 3D and digital human modeling can significantly improve design team decision-making.

The use of 3D models in combination with digital human models can be used to support effective team decision-making. The models can present design changes to the MCR to help align stakeholders in which changes can be made based on engineering and operations feedback in near real time. These models can then be further leveraged to evaluate HFE considerations, such as those in NUREG-0700 (2002), using digital human models. The use of the 3D models was successfully applied through the key HFE activities described in this report to make iterative changes and come to a rapid consensus on the placement and location of safety and non-safety VDUs and workstations. Feedback provided by stakeholders (i.e., engineering and operators) was collected in a combination of a series of workshops and virtual meetings. HFE principles were then applied to the feedback to verify acceptability of proposed changes to the MCR.

Lesson #10.	Using a think aloud protocol during scenario walkthroughs enables deeper knowledge elicitation and real-time design feedback that drive design decisions.

Applying a think aloud protocol allows for collection of verbal responses associated with design insights regarding decisions, workload consideration, and other cognitive considerations. This guidance correlates with Lesson #6 in which think aloud can be used to elicit knowledge during the scenario walkthroughs to capture knowledge and design input. The think aloud protocol is a technique well-known in the HFE and usability engineering literature (e.g., Nielson, 1994). This approach is commonly used in early HFE activities that demand knowledge capture. Later staged efforts like ISV should not take on the think aloud protocol.

Lesson #11.	There is a benefit in presenting conceptual displays in tandem with the current boards to enrich design feedback.

By using a glasstop simulator (see Lesson #5), HFE staff were able to present both the existing state and the conceptual new state at once when performing the walkthroughs. This feature allowed the operators to provide targeted feedback on the specific indications presented on the HSI display concepts. Such feedback would be arguably more difficult to collect if not collected in tandem. This tandem approach offers a useful way of collecting data and is particularly beneficial in early HFE activities where knowledge elicitation is the focus (Lesson #6) and a think aloud protocol (Lesson #10) is used.

6.3 Licensing

Lesson #12.	The I&C-ISG-06 process places unique challenges in executing HFE. Lessons learned described above must be considered to address scheduling challenges.

A notable challenge that was encountered in this effort dealt with scheduling constraints of the larger project and implementing the HFE activities (i.e., FA&A and task analysis) within these constraints. One contributor of this challenge may be due to the application of the DI&C-ISG-06 Alternate Review Process for LAR submittal and approval. The Alternate Review as enabled by using a safety platform with a generic SER creates efficiencies and reduces schedule, licensing, technical, and project cost risks from an I&C perspective. The expectations for HFE are the same as the Standard Review Process. This is clearly communicated in Section B.1.4, "Review Areas Outside the Scope of this Interim Staff Guidance" of DI&C-I&C-06, Revision 2. That section states:

> *A modification described in an LAR may also impact other review areas. The NRC staff should review the information necessary to make a safety determination using the review criteria found in the SRP for all relevant review areas.*
>
> *For example, some DI&C equipment modifications may involve human factors engineering (HFE) considerations (e.g., HFE analyses and design processes). In these cases, an HFE safety evaluation should be performed in accordance with SRP Chapter 18, "Human Factors Engineering"; NUREG-0711, "Human Factors Engineering Program Review Model"; and NUREG-1764, "Guidance for the Review of Changes to Human Actions," with close coordination with the DI&C evaluation under SRP Chapter 7.*

This communicates that HFE efforts are expected follow the normal progression described in NUREG-0711. The "design verification" and "ISV" activities for HSIs as described in NUREG-0711 are in a sense the FAT testing of the HSIs. So, while the Alternate Review Process enables the early submittal and approval of a LAR for the I&C aspects of the design (before FAT), there is a challenge when trying to complete of NUREG-0711 HFE activities within the compressed schedule project schedule otherwise enabled by the Alternate Review Process. This also creates associated workload challenges. The NRC staff is aware of this and has been working with industry to find ways to address the NUREG-0711 process compression to support timely and complete LAR submittals and subsequent SER issuance. This is a "first-of-a-kind" HFE effort that is running in parallel to support the "first-of-a-kind" implementation of the ISG-06 Rev. 2 Alternate Review Process.

Figure 43 shows this constraint in more detail over a typical HFE schedule (e.g., EPRI 3002004310, 2015). Primary HFE activities as described by NUREG-0711 can be executed from initial scoping through implementing and testing (i.e., including FAT). The Standard Review Process approach allows for completion of HFE activities leading through V&V, such as ISV. In the Alternate Review Process, the issuance of a license amendment comes before implementation and testing. HFE expectations are similar to that of Standard Review Process and therefore constrains the schedule, particularly in the planning and execution of V&V activities. The importance of early human-technology integration activities is therefore emphasized as being critical to address HFE issues well before execution of V&V. The lessons learned described above hence are integral in the sense of their importance in addressing this licensing consideration.

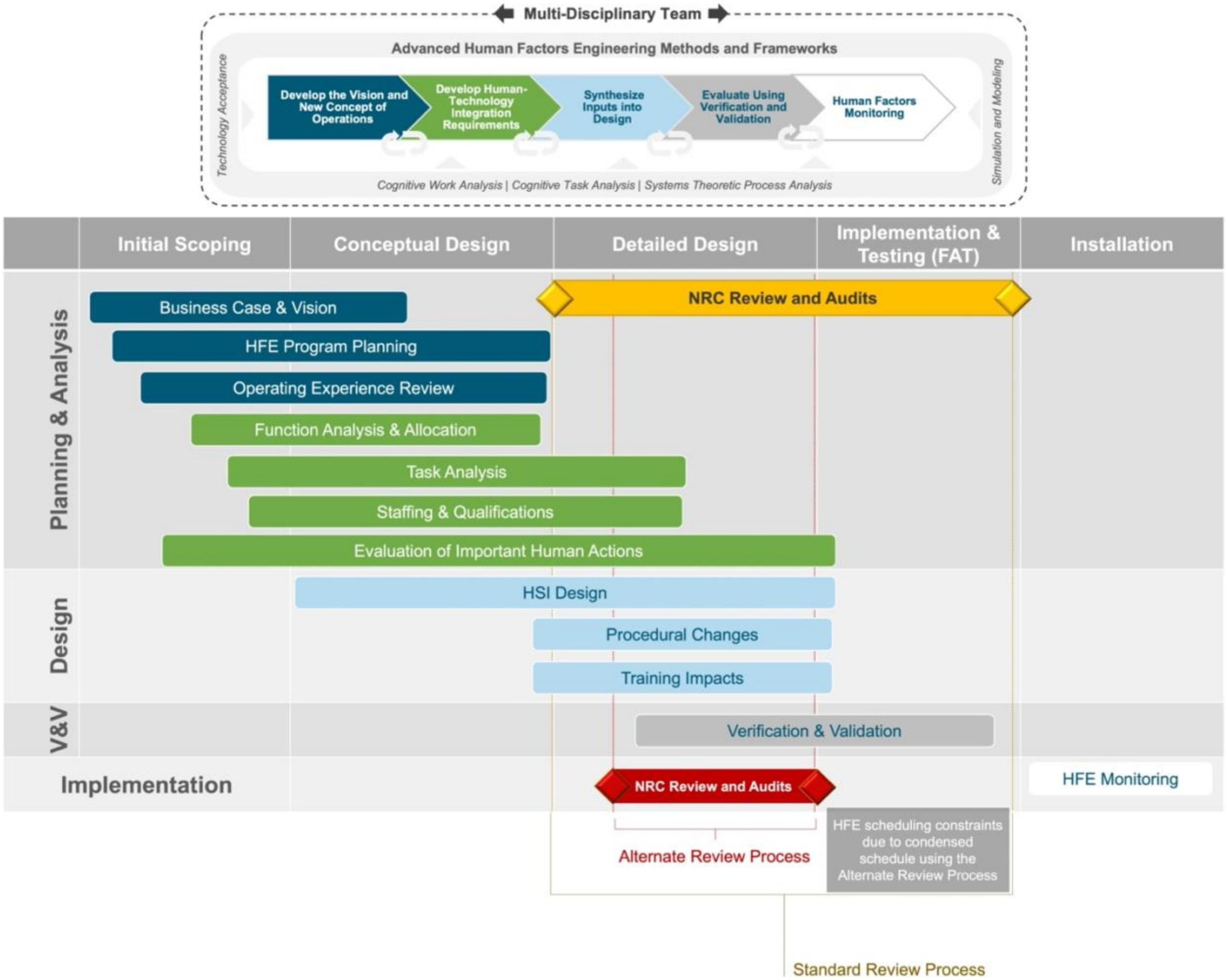


Figure 43. Typical HFE schedule overlaid with the Standard Review and Alternate Review Processes.

7. CONCLUSIONS

As the single largest contributor for non-greenhouse-gas-emitting electric power generation, the existing LWRs in the U.S. are valuable assets in support of the nation's electricity needs and have a significant role in mitigating climate change. These plants are currently being challenged economically due to changes in the energy market combined with managing aging and obsolescence (Remer et al., 2021). Digital capabilities are necessary in ensuring the continued operation of the existing LWR fleet. These capabilities must address business needs by identifying ways in which work can be fundamentally changed through the use of advanced features and automation. To ensure that these new capabilities are integrated in a way that affords continued safe and reliable operation, the human-technology integration element must be considered. Fundamentally evaluating the integration of new technology in a way that accounts for the capabilities of both people and automation is pertinent for these digital modifications.

The U.S. DOE LWRS Program Plant Modernization Pathway conducts targeted R&D to address nuclear plant economic viability in current and future energy markets through innovation, efficiency gains, and business-model transformation through digital technologies. In this effort, human-technology integration is a key research focus, and guidance has been developed and documented in INL/EXT-21-64320. This work describes the demonstration of developing human-technology integration requirements through updated function allocation guidance in combination with known HFE methodologies like task analysis. Specifically, the demonstration described in this work is based on a first-of-a-kind digital modification using the newly developed guidance from DI&C-ISG-06. Lessons learned are captured to disseminate to industry-specific guidance in applying HFE and human-technology integration to large-scale digital modifications as such.

This research will continue in applying the guidance in INL/EXT-21-64320 in later HFE activities, such as design synthesis and V&V. Further, applying the guidance to other areas of the plant as defined by ION should be considered. That is, guidance on applying HFE should be scalable based on the specific solutions and associated risk of the given technology and work domain. Applying human-technology integration may require different levels of rigor and focus for a digital safety system compared to an application that resides on the business network. Associated "risk" may differ with safety from economic risk. These differences may require taking different approaches to addressing human-technology integration. It is possible that other approaches described in INL/EXT-21-64320 like STPA or other elements of CWA (e.g., work domain analysis) may have particular use in applications where there are fundamental changes to the work domain, as discussed in Section 3.4.5 of this report.

Another area in which future work will be considered is in the role of HFE and human-technology integration in assessing an organization's ability for embracing change. This is depicted in the salmon-colored section in Figure 44.

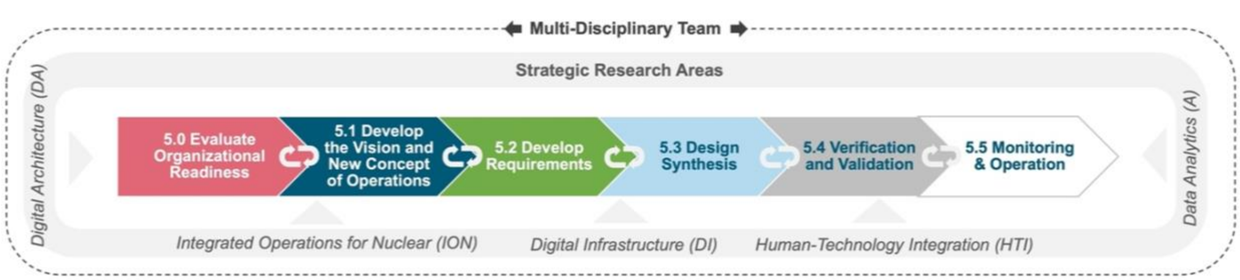


Figure 44. Extending human-technology integration in capture evaluating organizational readiness.

That is, the assessment of organizational readiness is one area that is relatively new in this specific context, and it is hypothesized to have influence on the ability to embrace change, such as embarking on large-scale digital transformation that may extend to the fleet level (i.e., requiring strategic innovation in addition to tactical innovation solutions). For instance, the extent of readiness of an organization to address HFE following the lessons learned above, such as developing a multidisciplinary team, having access to a glasstop simulator, having HFE expertise available, and employing these considerations in a way that supports the scope of the upgrades, may in part be influenced by the capabilities and characteristics of the organization. Having the proper resources within an organization to enable strategic and tactical innovation may be necessary in successfully planning and executing significant digital modifications that fundamentally change the concept of operations across the plant and fleet. As such, the characteristics that are important for an organization to embrace change should be examined in light of how they impact whether an organization is capable of successfully undertaking a significant modification.

8. REFERENCES

10 CFR 50.62. "Requirements for reduction of risk from anticipated transients without scram (ATWS) events for light-water-cooled nuclear power plants." https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0062.html.

Boring, R. L., T. A. Ulrich, J. C. Joe, and R. T. Lew. 2015. "Guideline for Operational Nuclear Usability and Knowledge Elicitation (GONUKE)." *Procedia Manufacturing* 3: 1327–1334. https://doi.org/10.1016/j.promfg.2015.07.287.

Crandall, B., G. Klein, and R. Hoffman. 2006. *Working Minds: A Practitioner's Guide to Cognitive Task Analysis*. MIT Press.

de Winter, J. C. and Dodou, D. 2014. "Why the Fitts list has persisted throughout the history of function allocation." *Cognition, Technology & Work* 16(1): 1-11. https://doi.org/10.1007/s10111-011-0188-1.

Digital Instrumentation and Controls Interim Staff Guidance #06, Revision 2, Licensing Process. Washington, DC: U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML1826/ML18269A259.pdf.

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.

Electric Power Research Institute. 2018. "Digital Engineering Guide: Decision Making Using Systems Engineering." Report 3002011816.

Estes, S. 2017. "Cogulator." The MITRE Corporation. http://cogulator.io.

Fitts, P. M., et al. 1951. *Human engineering for an effective air-navigation and traffic-control system*. Washington, DC: National Research Council.

Fuld, R. B. 1993. "The fiction of Function Allocation." *Ergonomics in Design* 1(1): 20-24. https://doi.org/10.1177%2F106480469300100107.

Hart, S. G., and L.E. Staveland, 1988. "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research." *Advances in Psychology* 52:139-183. https://doi.org/10.1016/S0166-4115(08)62386-9.

Hugo, J., D. Gertman, J. Joe, H. Medema, A. Whaley, and R. Farris. 2013. "Development of a Technical Basis and Guidance for Advanced SMR Function Allocation." INL/EXT-13-30117. Idaho National Laboratory.

Hugo, J., J. Forester, D. Gertman, J. Joe, H. Medema, J. Persensky, and A. Whaley. 2013. "Draft Function Allocation Framework and Preliminary Technical Basis for Advanced SMR Concept of Operations." INL/EXT-13-28601. Idaho National Laboratory.

Hunton, P. and R. England. 2019. "Addressing Nuclear I&C Modernization Through Application of Techniques Employed in Other Industries." INL/EXT-19-55799. Idaho National Laboratory.

Hunton, P., R. England, et al. 2020. "Safety-Related Instrumentation and Control Pilot Upgrade Initial Scoping Phase Implementation Report and Lessons Learned, INL/EXT-20-59809. Idaho National Laboratory.

Hunton, P., R. England, P. Heaney, D. Herrell, and W. Jessup. 2020. "Vendor-Independent Requirements for a Boiling Water Reactor Safety System Upgrade." INL/EXT-20-61079. Idaho National Laboratory.

Hunton. P., R. England, S. Lawrie, W. Jessup, et al. 2020. "Business Case Analysis for Digital Safety-Related Instrumentation and Control System Modernizations-as Applied to the Limerick Generating Station." INL/EXT-20-59731. Idaho National Laboratory.

IAEA. 1992. "The Role of Automation and Humans in Nuclear Power Plants." IAEA-TECDOC-668. International Atomic Energy Agency.

IAEA. 2021. "Human Factors Engineering Aspects of Instrumentation and Control System Design." NR-T-2.12. International Atomic Energy Agency.

IEC. 2000. "Nuclear Power Plants - Design of Control Rooms - Functional Analysis and Assignment." IEC 61839. International Electrotechnical Commission.

IEEE. 2018. "Standard Criteria for Safety Systems for Nuclear Power Generating Stations." IEEE-603, Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/IEEESTD.2018.8573235.

IEEE. 2020. "Recommended Practice for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations and Other Nuclear Facilities." IEEE-1023. Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/IEEESTD.2021.9361514.

Jamieson, G. A. 2003. "Bridging the Gap Between Cognitive Work Analysis and Ecological Interface Design." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting-2003* 47(3):273-277). Los Angeles, CA: SAGE Publications.

Joe, J., and C. Kovesdi, 2021. "Using Qualified On-Site Nuclear Power Plant Simulators in Human Factors Validations of Control Room Upgrades." INL/CON-21-61472, Idaho National Laboratory. https://www.osti.gov/biblio/1768753-using-qualified-site-nuclear-power-plant-simulators-humanfactors-validations-control-room-upgrades.

Joe, J., J. O'Hara, J. Hugo, and J. Oxstrand. 2015. "Function allocation for humans and automation in the context of team dynamics." *Procedia Manufacturing* 3:1225-1232. https://doi.org/10.1016/j.promfg.2015.07.204.

Johnson, M., et al. 2014. "Coactive design: Designing support for interdependence in joint activity." *Journal of Human-Robot Interaction* 3(1):43–69. http://doi.org/10.5898/JHRI.3.1.Johnson.

Kirwan, B., and L. Ainsworth. 1992. *A Guide to Task Analysis: The Task Analysis Working Group*. London: CRC Press. https://doi.org/10.1201/b16826.

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., 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., 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.

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

NEI Nuclear Industry Standard Process – Engineering (NISP-EN-04), "Standard Digital Engineering Process," Delivering the Nuclear Promise® Initiative.

Nielsen, J. 1994. *Usability Engineering*. San Francisco: Morgan Kaufmann.

Nuclear Energy Institute (NEI) IP-ENG-001, "Standard Design Process," Delivering the Nuclear Promise® Initiative.

O'Hara, J. M., and J. C. Higgins. 2010. "Human-system Interfaces to Automatic Systems: Review Guidance and Technical Basis." BNL-91017-2010, Brookhaven National Laboratory. https://doi.org/10.2172/1013461.

O'Hara, J., C. Plott, J. Milanski, A. Ronan, S. Scheff, L. Laux, and J. Bzostek. 2009. "Trends in HFE Methods and Tools and Their Applicability to Safety Reviews." BNL-90424-2009, Brookhaven National Laboratory. https://doi.org/10.2172/1013433.

Older, M. T., P. E. Waterson, and C. W. Clegg. 1997. "A Critical Assessment of Task Allocation Methods and Their Applicability." *Ergonomics*, 40(2):151–171. https://doi.org/10.1080/001401397188279.

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.

Roth, E. M., et al. 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.

Sheridan, T. B. 2002. *Humans and Automation: System Design and Research Issues*. John Wiley & Sons Inc.; Human Factors and Ergonomics Society.

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

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.

Taylor, R.M. 1990. “Situational Awareness Rating Technique (SART): The Development of a Tool for Aircrew Systems Design.” In *Situational Awareness in Aerospace Operations*, (AGARD-CP-478) 3/1-3/17.

Thomas, K. D., J. Remer, and C. Primer. 2020. “Analysis and Planning Framework for Nuclear Plant Transformation.” INL/EXT-20-59537, Idaho National Laboratory.

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

U.S. Nuclear Regulatory Commission. 1983. “Methodology for Allocating Nuclear Power Plant Control Functions to Human or Automatic Control.” NUREG/CR-3331, U.S. Nuclear Regulatory Commission.

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

U.S. Nuclear Regulatory Commission. 2007. “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. 2012a. “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. 2012b. “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.

U.S. Nuclear Regulatory Commission. 2020. “Human-System Interface Design Review Guidelines.” NUREG-0700, Rev. 3., U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML2016/ML20162A214.pdf.

Waterson, P. E., M. T. O. Gray, and C. W. Clegg. 2002. “A Sociotechnical Method for Designing Work Systems.” *Human Factors* 44:376–391. https://doi.org/10.1518/0018720024497628.

Wickens, C. D., S. E. Gordon, Y. Liu, Y., and J. Lee. 2004. *An Introduction to Human Factors Engineering*. Second Edition. Upper Saddle River, NJ: Pearson Prentice Hall.