INL/CON-23-71488-Revision-0

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Changing the World's Energy Future

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July 2023

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Safety-Related Instrumentation and Control Upgrade Pilot Project: NUREG-0711 Process Development, Planning and Analysis Activities, and Lessons Learned

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ABSTRACT

Constellation Energy and the United States Department of Energy (DOE) have established a public/private partnership to implement a pilot digital upgrade to replace legacy analog, safety-related reactor protection and emergency safety feature actuation systems (RPS/ESFAS) with modern digital systems. This effort is occurring at Constellation's Limerick Generating Station. This project is being performed in accordance with industry processes that have been adapted to better support digital upgrades. These processes include IP-ENG-001, Standard Design Process, NISP-EN-04, Standard Digital Engineering Process and Electric Power Research Institute Report 3002011816, Digital Engineering Guide. The Light Water Reactor Sustainability (LWRS) Program at the Idaho National Laboratory (INL) has been supporting this effort. Latest INL HFE efforts in support of this project have focused on definition and implementation of the Human Factors Engineering (HFE) Program in support of Constellation design and related licensing efforts. This paper presents the development execution of the HFE Program through completion of the Planning and Analysis Phase as defined by NUREG-0711 as well as HFE lessons learned.

Key Words: safety-related instrumentation and control upgrade, human factors engineering

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 [1]. 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. Specifically in this work, the U.S. DOE LWRS Program has established a public/private partnership with Constellation Energy Generation (CEG) in the implementation of a pilot digital I&C upgrade (herein referred to as the Pilot Project) that will replace legacy analog, safety-related reactor protection and emergency safety feature actuation systems (RPS and ESFAS) with modern digital I&C systems.

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The business driver for implementing digital technology to replace existing safety-related analog I&C systems is to address aging and obsolescence considerations with decades-old technology [2]. For instance, replacement parts for current analog systems are becoming more difficult and costly to attain. Further, specialized expertise is needed to maintain at nuclear power plant sites for the support and maintenance of these existing vintage systems. From an operational standpoint, these legacy I&C systems are highly analog, costly to operate and maintain, and demand high levels of cognitive and physical workload from plant staff (i.e., the licensed operators using these systems). 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:

- Transitioning 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 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.

The Pilot Project is addressing Human-technology integration and HFE considerations associated with the integration of digital I&C technology into the main control room of the Pilot Project nuclear power plant facility. Following a systems engineering approach as described in IP-ENG-001 [3], Standard Design Process, NISP-EN-04 [4], Standard Digital Engineering Process and Electric Power Research Institute Report (EPRI) 3002011816, Digital Engineering Guide (DEG) [5], HFE has been integrated throughout the lifespan of the Project and the scope of HFE is informed through several HFE process standards and guidance documents, including:

- NUREG-0800 Chapter 18, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants - Human Factors Engineering, (2016) [6]
- NUREG-0711, Human Factors Engineering Program Review Model, (2012) [7]
- Institute for Electrical and Electronics Engineers (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) [8]
- 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) [9]
- INL/EXT-21-64320, Development of an Assessment Methodology That Enables the Nuclear Industry to Evaluate Adoption of Advanced Automation, (2021) [10]

These HFE standards and guidelines were applied in part of following the recently revised *Digital Instrumentation and Control Interim Staff Guidance* (DI&C-ISG-06) *Licensing Process*, Revision 2, (2018) [11]. DI&C-ISG-06 as revised now provides both the Tier 1, 2, and 3 review process (the "Standard Process f or Licensing Reviews" (Section C.1) and the new "Alternate Review Process" (Section C.2). 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).

In following the Alternative Review Process, HFE is referenced in DI&C-ISG-06 as an element to be addressed. Specific standards that apply to HFE in DI&C-ISG-06 can be traced to IEEE 603 (2018) [12] and IEEE 1023 (2020) [8]. 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) [6]. NUREG-0800 Chapter 18, Human Factors Engineering, references NUREG-0711 (2012) [7] and NUREG-1764 (2007) [13] 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 [9]). 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 [8]).

This work demonstrates the first-of-a-kind use of the human-technology integration and HFE following the Alternate Review Process provided in DI&C-ISG-06. The HFE activities followed guidance from INL/EXT-21-64320 [10], IEEE 1023 [8], and NUREG-0711 [7]. Table I 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 first and second phases of the human-technology integration methodology described in INL/EXT-21-64320 [10], which is highlighted in light gray. The correspondence of the scope of the work in terms of application to NUREG-0711 [7] refers to the 'Planning and Analysis' phase and refers to the 'Planning' and the 'Analysis' phases of the IEEE 1023 Star Model [8].

Table I. Crosswalk Between Primary HFE Processes Used

INL/EXT-21-64320	NUREG-0711	IEEE 1023
Develop the Vision and New Concept of Operation	**Planning and Analysis**	**Planning**
Develop Human-Technology Integration Requirements		**Analysis**
Design Synthesis	Design	Specification
Verification and Validation	Verification and Validation	Testing and Evaluation
HFE Monitoring	Implementation and Operation	Operations and Maintenance

2 COMPLETED PLANNING AND ANALYSIS ACTIVITES

2.1 HFE Program Plan Development and Management

The HFE Program Plan was developed to ensure safe, efficient, and reliable operation, maintenance, testing, inspection, and surveillance of the plant with the new digital I&C. The HFE Program Plan encompassed the entire Project lifecycle by providing a systematic method for integrating HFE into the analysis, design, evaluation, and implementation of the digital upgrades. The HFE Program Plan leveraged guidance from NUREG-0711 Section 2 [7] and included pertinent sections such as team composition and responsibilities, Project grading of HFE activities, the planning and execution of HFE technical activities (e.g., such as those seen in NUREG-0711 [7]) to support the Project, as well as HFE issue tracking to record and track issues throughout the lifecycle of the Project. The HFE Program Plan considered HFE as part of the broader modernization process, using the EPRI DEG [5], as a systems engineering framework to integrate HFE in the broader Project. The emphasis of a multidisciplinary team was central to the HFE Program Plan to ensure the correct domain knowledge was accounted for at each HFE activity. This aspect was critical in the development of requirements, design specifications, and to address engineering tradeoffs for timely support of the LAR following the Alternative Review Process.

2.2 Development of a New State Vision and Concept of Operations

2.2.1 New State Vision Definition

CEG is planning future digital upgrades and associated main control room upgrades to address obsolescence and improve plant and human performance, while lowering plant total ownership costs. To support both near- and long-term objectives, the Pilot Project was performed in such a way that it stood alone so that when the digital I&C upgrade is complete, it functions with the plant and control room at that point in time. Further, both near- and long-term objectives were considered as such that the upgrades within the scope of the Pilot Project can be leveraged with no or minor additional modifications (i.e., to avoid unnecessary rework). For instance, the placement of the safety-related workstations would not impact future modifications in the main control room in terms of workplace design, anthropometrics, or accessibility to equipment. The vision was defined using state-of-the-art HFE tools such as three-dimensional (3D) modeling software to depict the main control room and show the changes to the facility resulting from the upgrade. Specific details of the use of 3D modeling is discussed in the companion paper to this work.

2.2.2 Concept of Operations

Complementary to the vision, the concept of operations defines the desired role of the personnel. The concept of operations describes the vision, goals, and expectations for the new system from the lens of the users (NUREG-0711, 2012 [7]). For a major modification to an existing plant, it may be useful to understand what impacts the new digital technology will have on the way operators perform their work. Thus, key inputs into defining a new concept of operations includes scope of the modification of design (i.e., including the available characteristics of the selected vendor platform), results from the operating experience review (OER), and the new state vision. The concept of operations addresses how the role of automation will be used to support staff in performing their desired functions/ tasks. The use of other advanced control room features such as overview displays, digital human-system interfaces (HSIs), or changes in the way procedures and/or training is executed are additional considerations. For the Pilot Project, the concept of operations was initially defined, but later refined through subsequent HFE activities, including OER, Functional Requirements Analysis and Function Allocation (FRA & FA), and Task Analysis (TA).

2.2.3 Human-System Interface Style Guide

The HSI style guide was developed with leveraging the native capabilities of the graphics packages of the selected platforms in mind. The style guide focused on maximizing the selected vendor’s native capabilities to the extent practical. Its purpose was multifaceted. First, it ensured that consistency was applied across the HSIs between the safety- and non-safety platforms to ensure familiarity and minimize unnecessary training burden. The style guide also accounted for the consideration of existing plant conventions including the current uses of color, labeling, and grouping of indications/ controls. HFE design principles, such as those described in NUREG-0700 ([14]) were used to address design considerations related to the HSIs and their location and placement in the control room. For instance, NUREG-0700 guidance specific to minimum font size and color contrast for legibility were applied to HSI design convention. Placement of the visual display units (VDUs) regarding ergonomic and anthropometric considerations was considered in combination with using 3D modeling and digital human modeling tools for HFE evaluations. A final consider ation was that the style guide balanced these considerations with the native capabilities of the selected platforms. This ensured that the design guidance presented in the style guide was practical, consistent with current plant conventions, and considered state-of-the-art HFE principles.

2.3 Operating Experience Review

The objective of OER was to identify HFE-related safety and availability issues and lessons learned that could be applied in designing, analyzing, and evaluating the modification. The OER followed guidance described in NUREG-0711 [7] and ERPI 3002004310 [9] to review relevant industry experience related to the upgrades, as well as to review design-specific operating experience (OE) at the site. Thus, the OER combined the results of reviewing several related databases (e.g., such as from Institute of Nuclear Plant Operations and the NRC Licensee Event Reports) with interviewing operations, training, and engineering staff at the site. The results of this work generated a list of OE in a result summary report (RSR) to be used as input into later HFE activities. In addition, a set of scenarios/ use cases were identified that were notably impacted by the modifications. These scenarios served as inputs into FRA & FA and TA, later described.

2.4 Functional Requirements Analysis and Function Allocation

FRA & FA aimed to identify and allocate responsibilities for new and changed control to improve safety and availability while accounting for the strengths and limitations of both human operators and automation. The FRA sets the objectives, performance requirements, and constraints for the HSI design and defined the role of personnel and automation. FA was then performed to allocate functions between manual, automated, and shared control to ensure safety and performance and by reducing human errors and inappropriate actions. FRA and FA was accomplished through a workshop hosted at the plant's qualified training simulator. Human factors engineers used the inputs from OER and worked with the site's training staff to identify tasks being impacted by the upgrades. These tasks were then prioritized based on their level of difficulty, importance, and frequency as described by the training program. Impacted tasks that were part of the licensing basis or referenced in the final safety analysis report (FSAR), defense in depth (D3), or probabilistic risk assessment (PRA) were further prioritized (i.e., see Section 2.6). Scenarios were developed around the identified and prioritized impacted tasks to enable licensed plant operators to perform these tasks in the qualified simulator at the workshop. The human factors team could then observe performance but also facilitate focused discussions on how the use of the digital upgrades could better facilitate crew performance and reduce human error traps.

2.5 Task Analysis

Functions to be allocated to people in the upgrade were further analyzed in TA, using the results from FRA & FA. Specifically, key findings that came out of the FRA and FA workshop was a refined understanding of the plant's current concept of operations as a boiling water reactor (BWR) and specific automation enhancements to improve efficiencies, reduce workload, and improve overall situation awareness. These findings culminated into a set of conceptual HSI display concepts that reflected the upgraded HSIs that would be used in facilitating a TA workshop in the Human System Simulation Laboratory (HSSL) at Idaho National Laboratory. The TA workshop used talk-through/ walk-through analyses in which licensed operators were presented the conceptual HSIs in static form and asked to verbalize the goals, key decisions, and actions taken in performing the tasks from the identified scenarios. The operators were also presented their existing configuration in tandem to generate rich discussion of the task and information requirements of the new HSIs and modifications to the impacted procedures. The tasks were evaluated at a macrolevel across the scenarios, concerning how the new HSIs and modified procedures impact global crew performance, situation awareness, communication, and teamwork. Specific tasks important to safety were identified and considered for more detailed TA in later HFE activities; these tasks would be specifically analyzed in terms of whether the upgrades provide timely execution of these tasks within the times available to perform these actions using timeline analyses and operational sequence diagrams.

2.6 Treatment of Important Human Actions

The treatment of important human action element identified important human actions impacted from the upgrades from the FSAR, D3, and PRA to screen these tasks into more detailed HFE analysis. This screening process was based on guidance given in NUREG-0800, Chapter 18 [6] and EPRI 3002004310 [9]. The results of this element enabled a risk-based graded approach to evaluating impacted functions/ tasks across the HFE activities to ensure that the appropriate level of detail was applied in a systematic manner to support timely execution of these activities.

2.7 Main Control Room Staffing and Qualifications Impact Analysis

Impacts to staffing and qualification requirements at the site were evaluated based on the results from previous HFE activities described in this paper. This included the results coming from OER, FRA & FA, and TA. These results indicated that there were no fundamental impacts to staffing and qualification requirements in the MCR. The results coming from FRA & FA, TA, treatment of important human actions, and main control room staffing, and qualification impact analysis were documented in a combined RSR.

3 PLANNING AND ANALYSIS LESSONS LEARNED

3.1 HFE Planning

3.1.1 Team Composition

The early involvement of a multidisciplinary team benefits timely execution of Planning and Analysis activities. Specifically, it enables effective identification of scenarios, designing early concepts, and identifying key design tradeoffs, as well as logistical considerations with implementing a simulator integration strategy for subsequent HFE activities. For the Project, different disciplines were included from operations and training, licensing, engineering, the vendor, and HFE.

With this, a clear division of responsibility by each team was needed. Having well defined roles for each discipline ensured that planning activities were completed efficiently and that each team member could effectively contribute using their domain expertise. The Project utilized a cross-functional team member divided into four independent teams to leverage domain expertise and minimize bias. These teams are summarized in Table II.

Table II. Team Composition

Team Name	Team Role(s)	Team Composition
HSI Design and Procedure Modification Team	— To create the HSI design concepts to produce design inputs. — To then iterate and refine the design of the HSIs to conform to those inputs and established HFE principles. — To identify and propose procedural changes to enable plant operation	Site engineering and operations personnel with significant knowledge of: — The legacy plant I&C and HSIs being upgraded. — Plant operations. — Use of existing operating procedures. Additionally, vendor staff who have

	with the new digital I&C.	significant understanding of the capabilities of the selected platforms.
HFE Process Team	— To ensure that the Project establishes and then executes the HFE activities described in the HFE Program Plan.	Staff with significant knowledge of HFE and experience applying HFE in main control room modernization.
HSI and Procedure Validation Team	— To evaluate whether the modified HSIs and procedures acceptably promote plant operation.	The ultimate 'end users' of the HSIs and procedures being developed. These include qualified and licensed operations personnel from the site.
Simulator Team	— To support integration of the simulator and HSI concepts to enable interactive capabilities in an immersive simulator environment. — To run the simulator during HFE activities and assess the ability of the operators to use the upgrades HSIs.	A combination of simulator engineering personnel and site simulator training personnel.

3.2 Methodological Considerations

One key consideration was to apply a scenario-based approach to the Planning and Analysis activities. 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, macrolevel considerations, such as impacts on teamwork, communication, and overall crew performance, could be examined with the proposed modifications. The Project also considered these scenarios to be re-used in later HFE activities (e.g., integrated system validation). Thus, a key lesson learned was to identify scenarios, driven by a graded approach, early so that the impacted tasks can be evaluated in Planning and Analysis activities when design input can be best leveraged.

A second methodological consideration was to apply a baseline evaluation of the impacted tasks performed in the current main control room. This was performed during FRA & FA. The benefit to this enabled capturing observational data of existing challenges, as well as a baseline collection of human-system performance, workload, and situation awareness. The results can serve as a reference point in subsequent HFE activities that leverage these same measures with the new system when the design is matured.

A third important methodological consideration was having access to enabled tools like 3D models and a digital glasstop simulator (Fig. 1). The glasstop simulator was instrumental in collecting feedback very early in the design process. Facilities like the HSSL can enable early testing through rapid prototyping to collect early feedback and allow timely resolution of input into the design. A facility like the HSSL, or an equivalent, is recommended when embarking on any major digital modification. Likewise, the use of the 3D models enabled complementary analysis of physical ergonomic considerations such as placement of VDUs in the main control room.

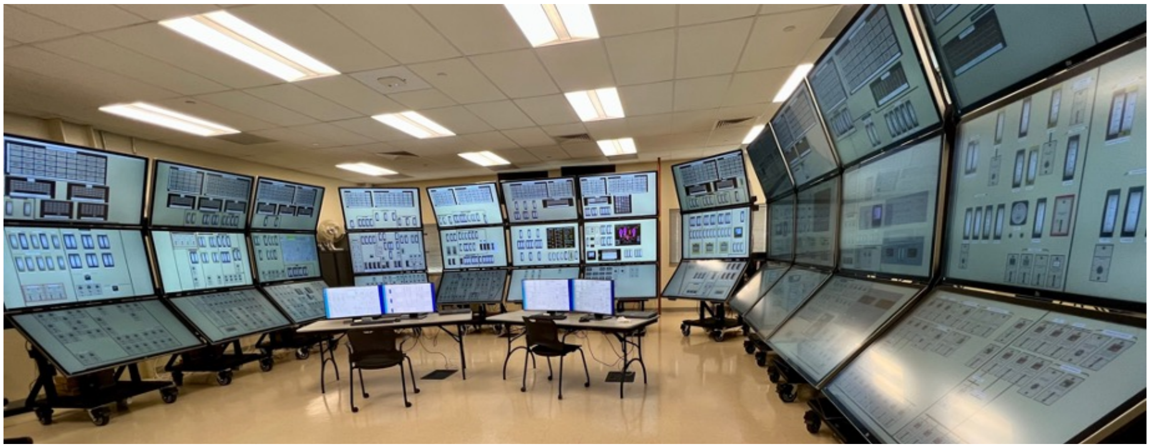

Figure 1. Photograph of the Human System Simulation Laboratory at Idaho National Laboratory.

A fourth methodological consideration was that the use of knowledge elicitation through qualitative methods, grounded in HFE theory, was pertinent throughout the Planning and Analysis phase. Qualitative methods that focus on collecting domain knowledge of the tasks being performed and their requirements (e.g., cognitive work analysis frameworks or cognitive task analysis) was central to the Planning and Analysis activities (e.g., see [10]). These approaches enabled understanding the cognitive and decision-making characteristics of the tasks being performed to gain a deeper understanding of how the new HSIs and modified procedures can support them. Qualitative methods go beyond simply asking operators their preference. 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.

3.3 HFE Execution

A pertinent lesson learned in the execution of the Planning and Analysis activities was having the cross-functional teams available, in person, at each key HFE workshop. A level of team building and synergy that is difficult to quantify is needed for effective decision-making. Having the key domain experts available enabled timely decision making, especially in addressing certain engineering tradeoffs. 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 immediately answer. Having this real-time coordination allows for quicker and more complete design decisions. The ability of the multidisciplinary team to interact in person was paramount when developing and refining HFE concepts and associated designs.

3.4 Licensing

A notable challenge that was encountered in this effort dealt with scheduling constraints of the larger Project and implementing the HFE activities within these constraints. One contributor to this challenge may have been due to the application of the Alternate Review Process for LAR submittal and approval. As previously discussed, the Alternate Review Process enables the early submittal and approval of a LAR for the I&C aspects of the design. While this reduces scheduling and cost risks whereby allowing earlier approval before factory acceptance testing, the current HFE guidance such as described in NUREG-0711 [7] does not consider the Alternate Review Process. That is, the safety determination made by the NRC is based on the results of integrated system validation, following NUREG-0711. Following the Alternative Review Process, the NRC would have to make an HFE safety determination in the absence of integrated system validation results. The disparity can be seen in Fig. 2; here, the Standard Review Process shows alignment between verification and validation HFE activities and implementation and testing. In the Alternative Review Process, the safety determination can be made following detailed design. The importance of early HFE activities is therefore emphasized as being critical to support developing a safety case for the new digital I &C. A such, the lessons learned described above hence are integral in the sense of their importance in add ressing this licensing consideration.

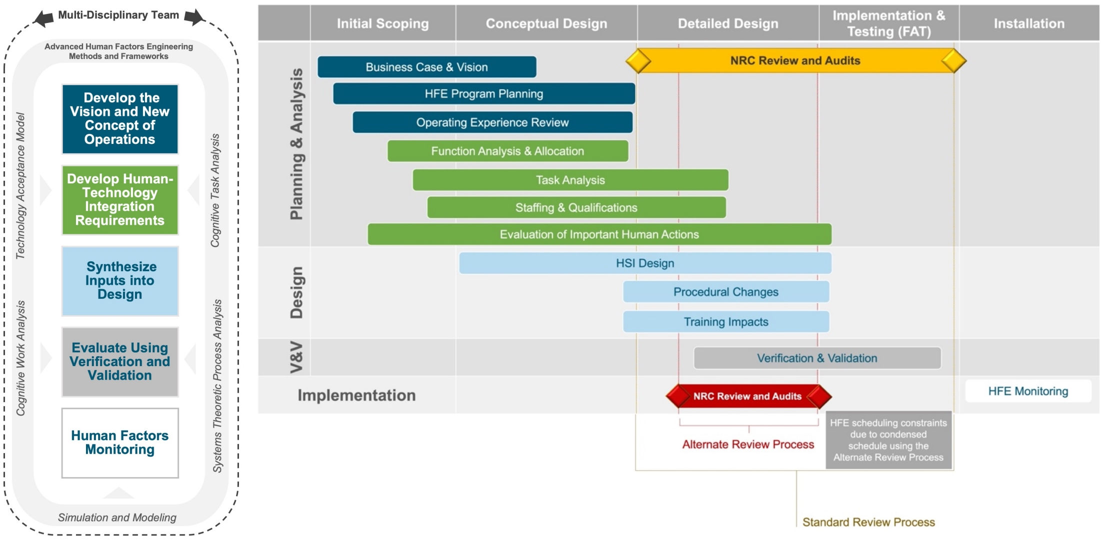

Figure 2. Typical HFE Schedule with the Standard Review Process and Alternative Review Process Overlaid.

4 FINAL REMARKS

CEG and the U.S. DOE have established a public/private partnership to implement a pilot digital upgrade to replace legacy safety-related analog with modern digital systems at Limerick Generating Station. The P roject is applying the recently revised DI&C-ISG-06 Alternative Review Process and is following a syste ms engineering approach such as the EPRI DEG [5] in performing key technical activities that encompass the lifecycle of the Project. Within this framework, the role of HFE is critical in ensuring that the HSIs, pr ocedures, and impacts to training continue to enable safe and reliable operation. The U.S. DOE LWRS Pr ogram at the INL has been supporting this effort. This paper is a companion to parallel work that focuses on project engineering, licensing, and project management activities of the Project. This paper presented t he development and execution of the HFE Program through Planning and Analysis, as well as lessons lear ned. These lessons learned are intended to provide industry guidance in the planning and execution of HF E necessary in the lifecycle of a safety-related I&C upgrade while following the recently revised DI&C-I SG-06 Alternative Review Process. As this Project continues, additional lessons learned will be provided in later phases.

5 ACKNOWLEDGMENTS

INL is a multi-program laboratory operated by Battelle Energy Alliance LLC, for the United States Department of Energy under Contract DE-AC07-05ID14517. This work of authorship was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately-owned rights. The United States Government retains, and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

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