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Important Human Actions for Advanced Reactors: Implications for Risk Analysis

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ABSTRACT

Advances in technology have led to development of new reactor designs and significant changes in human-system interfaces used by operators to monitor and control commercial nuclear power plants (NPPs). These advances have led the way to novel concepts of operations (ConOps) that are very different from those used in operations for traditional NPPs, i.e., large light water reactors. Accordingly, in collaboration with Idaho National Laboratory (INL), the U.S. Nuclear Regulatory Commission (NRC) started multiple projects to support the NRC's guidance for human factors engineering (HFE) reviews of advanced reactor applications. As a part of these efforts, INL staff members are currently working on a project to risk-inform the scope of HFE reviews when there are changes to important human actions (IHAs). Specifically, the purpose of the project is to capture specific regulatory aspects of these novel ConOps proposals and risk-inform HFE reviews related to IHAs.

Keywords: Nuclear power plants, Advanced reactor, Human factors engineering, Important human action, Risk assessment

INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) uses NUREG-0711, "Human Factors Engineering Program Review Model" (O'Hara, Higgins, Fleger, & Pieringer, 2012), to review the human factors engineering (HFE) programs of applicants for construction permits, operating licenses, standard design certifications, combined operating licenses, and license amendments. The review model aims to verify whether the applicant's HFE program embraces HFE practices and guidelines accepted by NRC staff. NUREG-0711 proposes to review twelve elements of an HFE program: (1) HFE Program Management, (2) Operating Experience Review, (3) Functional Requirements Analysis and Function Allocation, (4) Task Analysis, (5) Staffing and Qualifications, (6) Treatment of Important Human Actions [IHA], (7) Human-System Interface [HSI] Design, (8) Procedure Development, (9) Training Program Development, (10) Human Factors Verification and Validation, (11) Design Implementation, and (12) Human Performance Monitoring. These are characterized along four general phases: Planning and Analysis (Elements 1–6), Design (Elements 7–9), Verification and Validation (Element 10), and Implementation and Operation (Elements 11–12).

Among the twelve NUREG-0711 elements, the sixth one identifies IHAs and considers them in designing the HFE aspects of the plant to minimize the likelihood of plant personnel error, and to help ensure that plant personnel can detect and recover from any errors that occur. Another NRC document regarding IHAs is NUREG-1764, "Guidance for the Review of Changes to Human Actions" (Higgins et al., 2004), which provides guidance on reviewing modifications of human actions. Changes in credited human actions may result from a variety of plant activities such as plant modifications, procedure changes, equipment failures, justifications for continued operations, and identified discrepancies in equipment performance or safety analyses.

Advances in technology have led to the development of new reactor designs and significant changes in the HSIs used by operators to monitor and control commercial nuclear power plants (NPPs). These advances have led the way to novel concepts of operations (ConOps) that are very different from those used in operations for traditional NPPs, i.e., large light water reactors. Representatively, many advanced reactors or small modular reactors are considering adopting a main control room (MCR) type that operates multiple reactor modules, while MCRs in conventional NPPs operate one reactor unit only. An emerging ConOps is a smaller staffing level, e.g., a single operator crew controlling multiple modules in parallel. A reduced crew operating multiple modules will likely require higher levels of automation and a greater number of passive systems.

Current regulatory guidance is still anchored in existing ConOps for traditional NPPs. New and updated guidance for the new reactor technologies and designs is being developed by the NRC for use in reviewing HFE programs for emerging advanced reactor ConOps. Accordingly, in collaboration with Idaho National Laboratory (INL), the NRC has started multiple projects to support the NRC's guidance for HFE reviews of advanced reactor applications. As a part of these efforts, INL staff members are currently working on a project to risk-inform the scope of HFE reviews when there are changes to IHAs. Specifically, the purpose of the project is to identify relevant risk assessment methodologies and develop the technical basis to support determining an appropriate scope of HFE review for advanced reactor designs.

This paper briefly summarizes INL's efforts to characterize the treatment of IHAs in advanced reactors. To date, the technical basis review in terms of risk analysis has been carried out via literature survey. In this paper we briefly introduce: (1) the existing processes for identifying IHAs and their challenges and (2) characteristics of advanced reactors and issues on HFE and risk assessment.

THE EXISTING PROCESSES FOR IDENTIFYING IMPORTANT HUMAN ACTIONS AND THEIR CHALLENGES

Treatment of IHAs (NUREG-0711)

Treatment of IHAs is introduced in Chapter 7 of NUREG-0711 (O'Hara, Higgins, Fleger, & Pieringer, 2012). According to this chapter, license applicants identify human actions most important to safety via a combination of probabilistic risk assessment (PRA), human reliability analysis (HRA) and deterministic analysis, and then address them when conducting the HFE program. The PRA and HRA techniques are used for identifying risk-important human actions. These analyses begin early in the design process to provide insights and guidance for both systems design and for HFE purposes. Specifically, HRA evaluates mechanisms of human error that might affect plant safety and quantifies the human error possibility. It is an essential feature in assuring the HFE program goal of generating a design to minimize human errors, support their detection, and ensure recovery capability. The deterministic analysis is related to instrumentation and controls (I&C) design and transient and accident analyses. IHAs that are (1) necessary for accomplishing required safety functions using backup systems added in preparation for common cause failures of digital I&C or (2) required for mitigating from transients or accidents can be credited via the deterministic analysis. The outputs of the IHA process in Chapter 7 of NUREG-0711 are the final list of IHAs and a description of methods employed to identify and determine IHAs. For the list of IHAs, it is transferred to the other pertinent HFE elements. The IHAs are specifically addressed in many HFE elements as shown in Figure 1.

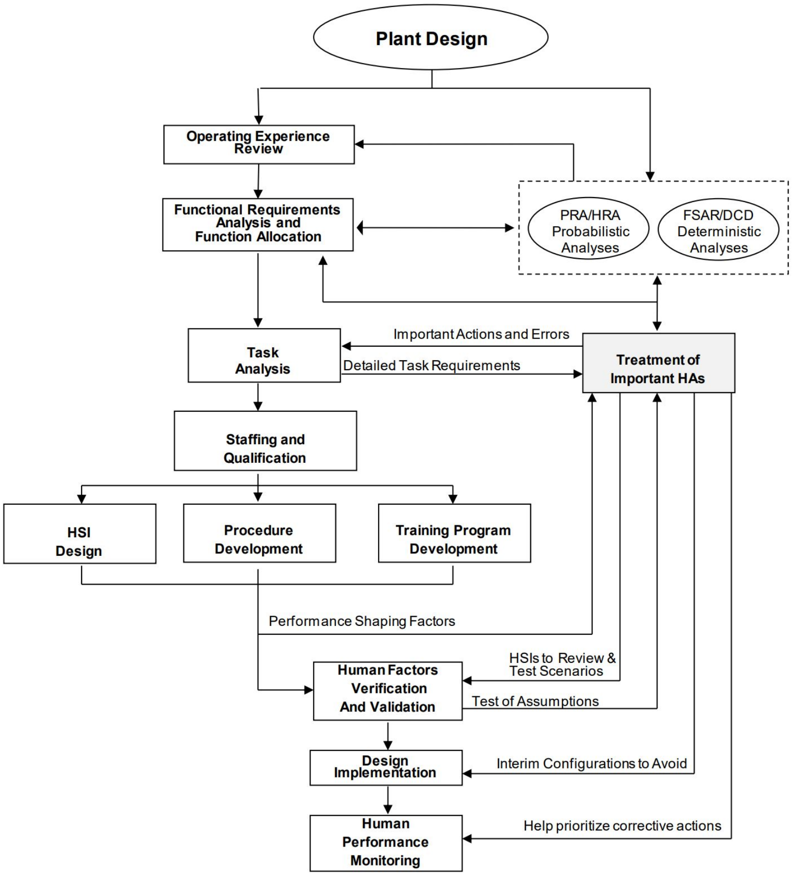

Figure 1: The role of IHAs in the HFE program proposed in NUREG-0711 (O'Hara, Higgins, Fleger, & Pieringer, 2012).

Guidance for the Review of Changes to Human Actions (NUREG-1764)

NUREG-1764 (Higgins et al., 2004) mainly describes how to review changes to plants that affect human actions, to determine whether the proposed human actions can be reliably performed when needed. Changes in credited human actions may result from a variety of plant activities such as plant modifications, procedure changes, equipment failures, justifications for continued operations, and identified discrepancies in equipment performance or safety analyses. NUREG-1764 provides guidance for reviewing those changes.

The guidance proposed in NUREG-1764 consists of two phases. The first phase is a risk-informed screening process to determine the level of HFE review. In this phase, risk calculations (i.e., core damage frequency and large early release frequency) and risk-importance measures (i.e., risk achievement worth and Fussell-Vesely value) are employed to determine the risk-significance of human actions. This phase also considers factors that the PRA model cannot quantitatively account for, such as personnel functions and tasks, design support for task performance, and performance shaping factors (PSFs). The second phase is an HFE review of human actions that are found to be risk-important in the first phase. In this phase, the NRC staff reviews the proposed changes to human actions to ensure the appropriate conditions are in place so that the change in human action does not significantly increase the potential for risk.

Challenges of Existing Processes for Identifying IHAs

Both NUREG-0711 and NUREG-1764 provide key insights into IHAs and have been used effectively to support regulatory review of plant licensing and licensing amendments. However, there are several areas where revised guidance can ensure the consistency and completeness of IHA characterization.

NUREG-1764 has four risk assessment methods used for scaling the human factors reviews of changes to operator manual actions. These methods have been criticized as overly conservative, which is not consistent with the PRA policy that best estimates should be used. During a pilot of the Risk-Informed Process for Evaluations (RIPE) process (Zoulis, 2022) (an accelerated license amendment review process used for amendments that are known to have very low risk), the output of NUREG-1764 was far more conservative than other risk assessments used.

NUREG-1764 employs most PRA techniques such as core damage frequency or risk achievement worth but rarely investigates HRA outputs (e.g., human error probabilities [HEPs] or PSFs) in the review process. It may miss human actions that are critical to safety but have low frequency or importance values. Pre-initiators such as returning valves after testing and maintenance or calibration tasks are good examples.

There is little guidance for the review of operator actions for advanced reactors that is equivalent to NUREG-1764. The strategy for assessing operator actions laid out in NUREG-1764 may not work in a technology neutral review. Such guidance will be needed to assess the adequacy of HFE principles applied to human actions performed outside of the control room. The NRC's proposed Part 53 rule for more flexible licensing for advanced reactors has an increased focus on assessing important operator actions wherever they occur (as opposed to existing 10 Code of Federal Regulations Part 50, which focuses on actions in the MCR). Actions outside a typical control room may have increased importance for advanced reactors due to new concepts of operations, limited range of activities conducted in a control room, and potential for remote monitoring and/or operation.

CHARACTERISTICS OF ADVANCED REACTORS AND ISSUES ON HUMAN FACTORS ENGINEERING AND RISK ASSESSMENT

O'Hara et al. (2021) (O'Hara et al., 2021) characterized ConOps for advanced reactors by reviewing eight advanced reactor designs under development at the time. The eight advanced reactors investigated in (O'Hara et al., 2021) are:

- General Atomics Helium-Cooled Fast Reactor
- X-Energy LLC XE-100 Modular High Temperature Gas-Cooled Reactor
- Kairos Power Fluoride Salt-Cooled, High Temperature Reactor (KP-FHR)
- Terrestrial Energy Integral Molten Salt Reactor (IMSR)
- TerraPower, LLC Molten Chloride Fast Reactor (MCFR)
- Westinghouse Electric Company eVinci Micro Reactor
- Los Alamos National Laboratory MegaPower Reactor
- OKLO Power Aurora Reactor.

Table 1 lists characteristics of ConOps for advanced reactors as defined in (O'Hara et al., 2021). As shown in the table, there are fourteen characteristics that would be different from existing large light water reactors.

Table 1: Characteristics of ConOps for advanced reactors (O'Hara et al., 2021).

Characteristics	Details
Modular Construction	Reactors are constructed in a factory and transported to the needed site via general transportation such as truck, rail, etc.
Simpler and Smaller Design	Reactors rely on simpler and smaller designs. Also, they include fewer systems and moving parts.
Simple Maintenance	When maintenance is needed, modules can be replaced.
Lifetime Operation	Reactors are designed to operate for many years without shutting down, being refueled, or maintained.
Inherent Safety Characteristics	Reactors rely on design features that make them inherently safe, such as natural physical processes that do not require automatic or human intervention.
More Passive Safety Systems	Reactors may have more passive safety systems than traditional NPPs.

Continued

Table 1: Continued

Characteristics	Details
Limit Public Exposure	Reactors produce public exposure to postulated accidents that is much lower than traditional large light water reactors.
New Missions	Reactors may operate at higher temperatures than large light water reactors and thus can support new missions, e.g., the production of multiple products in addition to electricity, such as industrial process heat.
New Operating Modes	Reactors can be operated in load-following mode.
Small Modular Reactor Configuration	Reactors can be operated in a small modular reactor configuration and therefore scalable to meet energy demands. For example, reactor modules can be added or moved for maintenance.
High Levels of Automation	Reactors are highly automated, including some that may operate in a fully autonomous mode, and may not require human monitoring, control, and intervention.
No Centralized Main Control Room	Reactors may not have a control room. Reactor monitoring and control may be accomplished from simple panels either locally or remotely.
Less Number of Staff	Reactors may be staffed by few or no onsite personnel.
Organizational Structure	Staffing organizational structures may be different than those described in current regulations.

Based on the characteristics of ConOps for advanced reactors, O'Hara et al. also investigated potential HFE technical issues of ConOps for advanced reactors, as shown in Table 2. The table includes four HFE issues and corresponding considerations. The issue details are described in (O'Hara et al., 2021).

Table 2: HFE issues and considerations regarding ConOps for advanced reactors (O'Hara et al., 2021).

HFE Issues	Considerations
Identification of IHAs	• Use of non-traditional risk analysis methods • Lack of supporting analyses used to identify human tasks • Human role in safety function management
Autonomous Operations	• Allocation of function decisions • Identification of human actions needed to support autonomy • Management of degraded conditions and automation failures • Staffing decisions related to autonomous operations • HSI designs to support automation-related human actions

Continued

Table 2: Continued

HFE Issues	Considerations
Approaches to Staffing	• Alternative staffing approaches • Training and qualification • Beyond control room staffing
HSIs for Monitoring and Controlling the Reactor and Interfacing Systems (This Issue Includes Remote Operations)	• No HSIs • Simplified HSIs providing limited displays and controls • Portable or wearable HSIs that are not tied to a specific location • HSIs located at a location remote from the facility

Table 3 summarizes HRA and PRA issues of ConOps for advanced reactors. These issues were derived based on characteristics and HFE issues of ConOps for advanced reactors described in Table 1 and Table 2.

Table 3: Risk assessment issues on ConOps for advanced reactors.

Method	Risk Assessment Issues	Details
PRA	Modeling new systems, structures, and components	Reactors may have new systems, structures, and components that are different with those used in traditional NPPs. More passive systems are employed in advanced reactors. Digital I&C systems would also be different.
	Lack of operating experience data	Operating experience data includes component type, failure mode, running hours, failure count, etc. Because there is little operating experience for advanced reactors, the data may not be enough to support quantification.
	Common-cause failure	Systems, structures and components in each module may be identical.
	Multi-unit dependencies	Multiple units may be located at a site. Multi-unit dependencies need to be considered.
	Risk matrix	Existing risk values such as core damage frequency or large early release frequency may not be applicable nor used as the major results for regulation or licensing.
HRA	New type of human actions	There are new types of human actions as advanced reactors adapt novel operational strategies such as operation with high levels of automation (e.g., autonomous operations), remote operation, load following operation and multi-module operation.

Continued

Table 3: Continued

Method	Risk Assessment Issues	Details
	Task actor	In advanced reactor operations, staffing and organizational structures may be quite different than what is described in current regulations for traditional NPPs. Also, it may include different staff positions including that there could be a reduced number of operators in MCRs.
	Task location	The proposed Part 53 rule, "Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors" (U.S. NRC, 2023), has an increased focus on assessing important operator actions wherever they occur (as opposed to Part 50, which focuses on actions in the MCR). Actions outside a typical control room may have increased importance for advanced reactors due to new concepts of operations, limited range of activities conducted in a control room, and potential for remote monitoring and/or operation.
	Human reliability data (i.e., nominal HEPs or PSF data)	Human reliability data that has been collected from traditional NPPs may not be applicable to HRA for advanced reactors. New data collection efforts may be needed.
	New set of PSFs	New set of PSFs affecting human performance in advanced reactor operations may need to be derived out.
	PSF levels and multipliers	Tasks required in advanced reactors would be much easier or much harder than those in traditional NPPs. For example, the high level of automation (e.g., autonomous control) normally eases operator tasks. However, if the automation fails during operation, operators need to understand what the automation has done, then correct problems manually. It may reduce operators' situation awareness as well as add complexity to the mitigation process. Thus, new PSF levels and multipliers may need to be investigated.

FUTURE WORK

The goal of this effort is to risk-inform the level of HFE review related to IHAs. In this paper, we introduced: (1) the existing processes for identifying IHAs and their challenges, and (2) characteristics of advanced reactors and issues on HFE and risk assessment. Table 4 shows some of the key literature being reviewed as part of the technical basis. The list includes regulatory and industry documents that should be considered in updating the HFE guidance of IHAs for advanced reactors.

Table 4: A part of literature for technical basis review.

Document	Tittle	Publisher	Reference
Part 53 (SECY-23-0021)	Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors	U.S. NRC	(U.S. NRC, 2023)
NUREG-0711	Human Factors Engineering Program Review Model	U.S. NRC	(O'Hara, Higgins, Fleger, & Pieringer, 2012)
NUREG-1764	Guidance for the Review of Changes to Human Actions	U.S. NRC	(Higgins et al., 2004)
NUREG/CR-7126	Human-Performance Issues Related to the Design and Operation of Small Modular Reactors	U.S. NRC	(O'Hara, Higgins, & Pena, 2012)
NRC Technical Letter Report No. F0028-04	Development of HFE Review Guidance for Advanced Reactors	U.S. NRC	(O'Hara et al., 2021)
DRO-ISG-2023-03	Development of Scalable Human Factors Engineering Review Plans	U.S. NRC	(U.S. NRC, 2023)
Regulatory Guide 1.174	An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis	U.S. NRC	(U.S. NRC, 2018)
Regulatory Guide 1.247	Acceptability of Probabilistic Risk Assessment Results for Non-Light Water Reactor Risk-Informed Activities	U.S. NRC	(U.S. NRC, 2022)

Continued

Table 4: Continued

Document	Tittle	Publisher	Reference
NEI 18–04	Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development	Nuclear Energy Institute	(NEI, 2019)

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