# TECHNOLOGY-INCLUSIVE HUMAN-SYSTEM CONSIDERATIONS FOR ADVANCED REACTORS

J.L. SEYMOUR, D.R. DESAULNIERS, B.D. GREEN

U.S. Nuclear Regulatory Commission, Rockville, Maryland, United States of America

**Abstract**

It is anticipated that developers of advanced reactor technologies will propose novel approaches to reactor operations. Existing U.S Nuclear Regulatory Commission (NRC) requirements for human factors engineering (HFE), staffing, and personnel qualifications were developed for large light water reactors and may not be appropriate for other nuclear technologies. Therefore, the NRC is developing a new risk-informed, performance-based, and technology-inclusive regulatory framework for licensing new technologies. The new framework takes an integrated approach to human-system interactions and achieves being technology-inclusive by linking requirements for HFE, staffing, and operator qualifications to design-specific plant safety functions and their fulfillment. Within this framework, HFE is required for settings where HFE is needed to support plant and public safety, versus limiting its application to the main control room. Operator staffing requirements are based on analyses that demonstrate minimum staffing is adequate to support safety function fulfilment, versus a prescribed number of operators. Finally, the fundamental role of reactor operators and senior operators is centered around the management and fulfilment of safety functions, with personnel qualification requirements being performance-based and applying an examination process that is tailored to the facility. This paper will discuss the method the NRC is using to develop technology-inclusive, performance-based, and risk-informed proposed requirements for HFE, staffing, and plant personnel qualifications.

## 1.0 INTRODUCTION

It is anticipated that advanced nuclear reactor technologies will provide new opportunities and challenges for nuclear developers, utilities, and regulatory bodies alike. In light of this, the U.S. Nuclear Regulatory Commission (NRC) recognized the need for a new regulatory framework that will be capable of addressing the full range of operational characteristics and considerations associated with advanced reactor facilities. Examples of the diverse characteristics that warrant consideration include high degrees of automation, reduced reliance on human action for assuring safety, non-traditional personnel staffing and qualification needs, variations in the design and operation of the main control room, and new facility missions (e.g., hydrogen production). In particular, the Concept of Operations (ConOps) (discussed in greater detail in the following section) for an advanced reactor facility is expected to differ significantly from that of large light-water reactor (LLWR) facilities. Existing NRC requirements that address such design and operational characteristics were developed for LLWRs and may not, in many instances, be appropriate within the context of advanced nuclear facilities [8]. The authors were among the principal staff members who worked to analyze the issues described above and to develop the regulatory approach to human-system interactions that is described within the paper.[1]

Consistent with the provisions of the Nuclear Energy Innovation and Modernization Act (NEIMA), the NRC staff are developing a modern regulatory framework that can be applied to a wide range of advanced reactor technologies. This framework is intended to facilitate sound conclusions regarding whether proposed designs and operational approaches will satisfy the overall objective of providing reasonable assurance of adequate protection. At the same time, it is also desired to provide a regulatory framework that will yield predictable outcomes for designers. Furthermore, the NRC staff have a statutory mandate to ensure that this regulatory framework achieves the overarching objectives of being performance-based, technology-inclusive, flexible, and risk-informed [8]. Thus, from a standpoint of the regulatory approach towards human roles at advanced reactor facilities, it has been recognized that the appropriate path forward must incorporate risk-informed, performance-based, and technology-inclusive regulations that appropriately consider the role of humans and human-system integration in the operational safety of advanced reactors. The subsequent sections of the paper will discuss the ways in which this new regulatory framework takes an integrated approach to human-system interactions and how it simultaneously achieves being technology-inclusive by means of linking

[1] The views expressed herein are those of the authors and do not necessarily represent an official position of the U.S. Nuclear Regulatory Commission. 

requirements for HFE, staffing, and operator qualifications to design-specific plant safety functions and their fulfillment.

## 2.0 IMPLICATIONS OF ADVANCED REACTOR TECHNOLOGIES

There are certain, key attributes of advanced reactor technologies that serve to shape the approach selected for the treatment of human-system interactions under the new regulatory framework. Notably, these attributes include design elements such as passive safety features, modular reactor units, and non-light-water reactor technologies (including those associated with fusion technologies). These design attributes represent a departure from traditional LLWR approaches and warrant careful consideration as part of crafting a technology-inclusive framework [8]. Two potential attributes of advanced reactor designs that are significant in this regard are smaller source terms and the incorporation of inherent safety characteristics.

Variations in advanced reactor designs will likely have broad implications for accident source terms and radiological consequences. Source term sizes and accident consequences are considerations that inform the characterization of the degree of hazard posed by a reactor facility and, in the case of advanced reactors, represent potential points of difference from LLWR designs [8]. The implications of this have been identified previously, such as in SECY-10-0034, "Potential Policy, Licensing, and Key Technical Issues for Small Modular Nuclear Reactor Designs," where the NRC staff observed the following:

> Accident source terms are used for the assessment of the effectiveness of the containment and plant mitigation features, site suitability, and emergency planning. Other radiological source terms are used to show compliance with regulations on dose to workers and the public. Design and license applicants and the NRC will need to establish appropriate bounding source terms for high-temperature gas-cooled reactors and other SMRs. [7, p. 4]

In its 2020 report on "Human Factors Considerations for Automating Microreactors," Sandia National Laboratory evaluated a variety of potential issues associated with the role of personnel at microreactors. For example, the report observed that microreactor designers may elect to incorporate more extensive automation than what has historically been observed at LLWR facilities. Additionally, it was identified that the incorporation of passive safety features and inherent safety characteristics may have significant implications in the design and operations of microreactor facilities [3]. Illustrating this point, this report observed that passive safety systems "…would not require significant human or automation intervention to maintain a safe state. Thus, human and/or automated tasks may serve as a secondary safety check rather than a primary function to operate the reactor" [3, p. 10]. A key takeaway from such considerations is the principle that technological factors tend to shape and recharacterize human roles in maintaining safety at nuclear facilities.

As alluded to earlier, in addition to the use of passive safety features, the incorporation of inherent safety characteristics in advanced reactor designs can have far-reaching implications for human-systems considerations. In contemplating the influence of inherent safety characteristics in this regard, the NRC staff considered the definitions historically used within this area. The International Atomic Energy Agency (IAEA) observed in a 1991 publication that safety related terms such as passive and inherent safety have been widely used, particularly with respect to advanced nuclear plants, generally without definition and sometimes with definitions inconsistent with each other" [2, p. 7]. In addressing this, the IAEA went on to describe an inherent safety characteristic as being "…a fundamental property of a design concept that results from the basic choices in the materials used or in other aspects of the design which assures that a particular potential hazard can not become a safety concern in any way" [2, p. 10]. In considering this approach to inherent safety characteristics, NRC staff recognized that a hierarchy exists where inherent safety characteristics possess a greater degree of reliability than passive safety features which, themselves, are expected to be comparatively more reliable than active safety features. These comparative differences in reliability across safety features and characteristics shape the human role needed to achieve and maintain safety during the full range of facility operating and accident conditions.

As mentioned earlier, the facility ConOps is an important area of consideration for advanced reactors. According to NUREG-0711, "Human Factors Engineering Program Review Model," a ConOps "…defines the goals and expectations for the new system from the perspective of users and other stakeholders and defines the high-level considerations to address as the detailed design evolves" [6, p. 113]. Building upon this, it is further described that an HFE-focused ConOps will address the following six dimensions:

- Plant Goals (or Missions)

- Agents' Roles and Responsibilities ["agents" refers to the person or automation (or any combination thereof) that are responsible for completing a plant function]
- Staffing, Qualifications, and Training
- Management of Normal Operations
- Management of Off-normal Conditions and Emergencies
- Management of Maintenance and Modifications [6, p. 113]

Beyond the considerations noted thus far, the NRC staff also identified that there are several other potential design and operational attributes that must be factored into the treatment of human-system considerations for advanced reactors. Examples of these include multi-module operation, autonomous reactor operations, and load-following. In cases where multiple reactor modules will be operated as part of a larger power reactor facility, both the control room design and staffing must be conducive to the adequate implementation of supervision and control functions. The NRC staff also expect that another area of difference between current LLWRs and advanced reactors may be the possibility of autonomous operations [8]. However, in evaluating the implications of highly automated facility operations, the NRC staff noted that, even within the context of a fully autonomous design, the need might still exist for human actions under certain circumstances, such as, perhaps, for the purpose of defense-in-depth [8]. Additionally, irrespective of any degree of automation, certain important administrative functions that must be implemented by a human being (e.g., technical specification implementation, configuration control, authorizing emergency-related departures from facility license conditions, notifications to offsite authorities, etc.) would still be required at any foreseeable advanced reactor facility, thus requiring that human roles continue to be considered outside of purely operational contexts.

## 3.0 REGULATORY FRAMEWORK NEEDS

As discussed previously, the NRC staff have an overall objective of developing a risk-informed, performance-based, and technology-inclusive regulatory framework for advanced reactors. In working towards this objective, the NRC staff identified that any framework covering human-system interactions would need to appropriately consider how human action factors into the overall context of safe facility operations [8]. The central premise is that interactions between humans and plant systems in contexts that have a nexus to plant safety should be key to the regulatory approach. Accordingly, the regulatory framework for advanced reactors must appropriately consider the role of humans and human-system integration in ensuring safe nuclear operations via means that are risk-informed, performance-based, and technology-inclusive [8].

It should also be noted that, in developing this approach, the NRC staff must also comply with U.S. statutes that are applicable to certain areas covered by the proposed regulatory framework. Specifically, within the area of operator qualifications, regulations that address operator licensing must be consistent with the provisions of the Atomic Energy Act of 1954, as amended (AEA). The Nuclear Waste Policy Act of 1982, as amended (NWPA), has provisions that apply to operator licensing as well, in addition to addressing training requirements for nuclear power plant personnel more broadly. Thus, while the NRC staff have sought to provide flexibility within the proposed framework, this has been done with the understanding that certain overriding statutory requirements, in addition to those contained within NEIMA, must continue to be met.

Beyond the areas addressed thus far, an additional attribute that is an important aspect of the new framework is the use of an integrated approach to the various areas involving humans and systems. NRC's current regulatory framework for LLWRs, treats areas such as staffing, training, operator qualifications, and HFE as distinct areas, with each having requirements that are imposed in a manner that is independent of the other areas. It is recognized that the attributes of advanced reactors may concurrently influence areas such as these in a way that warrants a cohesive treatment capable of adapting to such interdependencies. Therefore, in lieu of treating the areas of staffing, operator qualifications, and human factors engineering for advanced reactors as discrete review areas, the new framework uses an integrated approach to humans, systems, and the interactions between them [8]. Thus, the approach selected for the advanced reactor regulatory framework recognizes that staffing, operator qualifications, and HFE are interrelated and interdependent, thereby necessitating an integrated approach to requirements.

## 4.0 DESIGN SPECIFIC SAFETY FUNCTIONS

As noted in the previous section, the NRC staff have identified that, as part of the overall regulatory approach to advanced reactors, it will be essential to establish a clear understanding of the interactions between

human beings and plant systems within contexts having a nexus to plant safety. However, accomplishing this objective in a manner that is technology-inclusive necessitates being able to take a wide variety of advanced reactor technologies and, for each, to identify where facility safety is dependent upon human support. The staff found that design-specific safety functions represent an effective way to achieve this goal because of the shared utility that such safety functions have within both the systems design and HFE aspects of developing an advanced reactor facility. Regulatory Guide 1.233, "Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors," provides the following insights into the important role played by safety functions in the design process:

> The design process and related development of licensing-basis information is iterative, involving assessments and decisions on key [systems, structures, and components] SSCs, operating parameters, and programmatic controls to ensure that a reactor can be deployed without posing undue risk to public health and safety. To begin the process of translating design information into a licensing application, a developer needs, at a minimum, a conceptual design that includes a reactor; a primary coolant; and a preliminary assessment of how the design will accomplish fundamental safety functions, such as reactivity and power control, heat removal, and radioactive material retention [5, p. 24].
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> Many of the basic reactor characteristics have traditionally been described in Chapters 4, 5, and 6 of safety analysis reports. These chapters address the reactor, including fuel and reactivity control systems, the reactor coolant and connecting systems, backup cooling systems, and functional barriers for retaining radionuclides within the facility. The material in these chapters largely addresses the fundamental safety functions of reactivity and power control, heat removal, and radionuclide retention. The next set of information to be provided describes the fuel or fuel system boundary and primary system in terms of the limits on operation (e.g., values or ranges of values for key parameters) to prevent failures or degradation or to remain within the bounds of testing or qualification of related SSCs. These limits on operation thus establish the safety functions needed to prevent damage to barriers to the release of radionuclides (e.g., functions to maintain integrity of fuel cladding, coatings, or other fuel system boundary) [5, p. 24].

Importantly, the safety functions identified during the design process can vary from one type of advanced reactor to another; this means that the safety functions are unique to the design. The HFE methods of Functional Requirements Analysis and Function Allocation provide a method for defining the human actions that are necessary to maintain the plant safety functions. Functional Requirements Analysis shows what features, systems, and human actions are relied upon to demonstrate safety [6]. From a human factors engineering perspective, the term 'function' can refer to high-level plant functions, such as safety functions, or to a lower-level description of the purpose of an individual piece of equipment, such as a valve or display system" [6, p. 23]. "High-level functions can be broken down into the actions that are necessary to perform that function, whether those actions are performed by personnel or automation" [6, p. 24]. A Function Allocation, in turn, then describes how safety functions are assigned to both personnel and automatic systems. The allocation of functions to personnel (i.e., human actions) provides for an initial definition of the role of personnel, with the personnel role, in effect, being the summation of the human actions associated with functions [6].

In summary, design-specific safety functions have direct relevance in understanding the human safety role for novel designs. From this basis, technology-inclusive requirements within the areas of staffing, personnel qualifications, and HFE can be appropriately informed. For example, when considering the applicability of HFE requirements, emphasis should be placed on contexts and locations where a role in fulfilling plant-specific safety functions has been allocated to humans. Proposed staffing levels must be adequate to facilitate the needed support for the fulfillment of plant safety functions. Finally, operator qualification processes must be capable of providing assurance that operators will be able to manage and fulfill plant-specific safety functions [8].

## 5.0 APPROACH TO HUMAN FACTORS ENGINEERING

From an HFE perspective, the NRC staff identified that the HFE of advanced reactors must be adequate to ensure that humans beings can understand plant status, take necessary actions to ensure safety, and perform

other required technical and administrative functions. In contrast with traditional LLWRs, in which human operators have a prominent role in controlling the plant during normal operations and implementing mitigative actions in response to off-normal events, the human contribution to safety in advanced reactor designs may differ both in degree (e.g., risk importance) and in the types of actions that are most important to ensuring safe operations. Accordingly, NRC's expectations for the HFE activities that will be necessary for the development of the design and operation of advanced nuclear reactors should reflect these changes in demand, as should the nature of the HFE reviews that the NRC conducts of applications pertaining to advanced reactor designs [8].

Current HFE-related regulatory requirements are largely limited in their scope and applicability to the design of the facility control room. However, the NRC staff have identified that, for advanced reactors, important tasks such as maintaining and fulfilling safety functions may not necessarily be performed only in a traditional control room [8]. In recognition of this, the new framework aims to require advanced reactor applications to address the incorporation of state-of-the-art human factor principles in all settings and locations where humans will act to maintain plant safety functions. Stated differently, an advanced reactor HFE program should ensure that humans beings can operate the plant in a safe manner and perform all the tasks needed to ensure the fulfillment of safety functions. In some instances, this may extend beyond those tasks only associated with plant operations and might also encompass maintenance, testing, and inspection-related activities as well [8]. While the nature of this new requirement is such that HFE could be required in a wide range of possible locations throughout a facility, it is important to note that this is not synonymous with requiring HFE to be applied across an entire facility in a blanket manner. Rather, HFE is only required in locations where safety considerations warrant it and is not required beyond that scope. Thus, while this new requirement does imply an expansion of scope for the required application of HFE in comparison with existing requirements for LLWRs, it is believed by the NRC staff that any potential increase in burden beyond that of existing requirements will be tempered by the focused nature of the new requirement's applicability.

The approach to HFE requirements discussed above is performance-based in nature and focuses on locations where human activities serve to fulfill design-specific safety functions. While this approach establishes the objective that must be met for the designer, the staff is developing a new HFE review process to function in tandem with this requirement. Specifically, the performance-based HFE requirement will be evaluated using a scalable HFE review process. Plans for conducting scaled HFE reviews will be established in four distinct stages: characterization[2], targeting, screening, and grading. While new, this approach has a basis in existing practices. In general, the characterization stage entails the reviewer gaining an integrated view of the design and the human role in ensuring plant operational safety to identify characteristics important to the HFE of the design. In the targeting stage, the reviewer begins to focus the review plan by selecting candidate characteristics for review considering the safety/risk insights that are gained during the facility characterization. In the screening stage, the reviewer selects HFE activities to review that are important to the design and implementation of each targeted characteristic. This is followed by grading, in which appropriate acceptance criteria are identified from suitable guidance documents and standards [1]. The result is an HFE review plan that is appropriately scoped and graded according to the design-specific human role in facility safety. The HFE review plan will then be used to guide the technical review of a particular design.

## 6.0 APPROACH TO OPERATOR STAFFING

Due to the wide variety of design considerations and operational approaches associated with advanced reactors, the NRC staff concluded that the prescriptive staffing requirements historically used for LLWRs would not be appropriate for use within the new framework. Instead, it was determined that it would be appropriate for applicants to propose staffing plans in which the numbers and qualifications of operations personnel could be determined based upon design-specific needs and the ConOps. However, to implement such an approach, it was also identified that such staffing plans would also need to be supported by an HFE-based staffing analysis of sufficient scope and depth to allow for the NRC staff to evaluate the acceptability of the proposed staffing levels. It is expected that these HFE-based analyses and assessments will generally require the use of a simulation facility to facilitate the conduct of performance-based testing [4]. A central consideration in the evaluation of any staffing plan will be whether the proposed numbers and qualifications of operators will be adequate to provide assurance that design-specific safety functions can be reliably fulfilled.

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[2] It is also anticipated that the facility characterization that is developed as part of this process, and which catalogues those characteristics of the facility and its operation important to understanding the human role in ensuring safe operation of the facility, will be used as a common point of reference to facilitate the integration of HFE, operator staffing, and operator licensing reviews.

The NRC staff have identified that the development and justification of alternative staffing models by advanced reactor applicants can be informed by a process like that described within NUREG-1791, "Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)" [8]. In general, the review of flexible staffing plans to evaluate their adequacy can be guided by the general framework of NUREG-1791, which includes, in part, review of the following elements:

- Concept of Operations
- Operational Conditions
- Operating Experience
- Functional Requirements Analysis and Function Allocation
- Task Analysis
- Job Definitions
- Staffing Plan Validation [4, pp. xi-xiii]

In summary, flexible staffing requirements can be derived from an assessment of the number, qualifications, and roles of individuals needed to both fulfil safety functions and carry out other necessary operational tasks. This process can be implemented via the development of staffing plans that evolve from, and evaluated using, the results of HFE-based analyses and assessments. Ultimately, it is envisioned that performance-based testing will serve as a key evaluative measure in assessing the adequacy of proposed staffing plans.

## 7.0 APPROACH TO OPERATOR QUALIFICATION

In the U.S., operations staff at commercial nuclear power plants include both licensed and non-licensed operators. From a standpoint of operator qualifications, operator licensing is of central importance because several important operational and administrative functions at LLWRs have historically been restricted to performance by licensed personnel. Thus far, the requirements and processes used to implement operator licensing have been prescriptive in nature, with limited opportunity for flexibilities. Certain requirements associated with operator training and licensing also have a statutory basis in either the AEA or NWPA. However, the NRC staff have recognized that advanced reactor designs and operational concepts may not align well with the existing operator licensing framework for LLWRs. In general, some of the flexibilities that may be appropriate for operator licensing programs at advanced reactors might include accommodating variations in design-specific technologies and ConOps, modifying licensing examination scope, structure, and content on a facility-specific basis, and providing reasonable alternatives to the use of full-scope, plant-referenced simulator facilities [8]. However, irrespective of the flexibilities afforded under the new framework, an overriding objective remains to ensure that licensed operators will possess the knowledge and abilities needed to reliably carry out those tasks needed to fulfil and maintain plant safety functions and, as such, this comprises a central element of the overall approach.

For the purposes of accomplishing the effective training of operations personnel, the NRC has historically found the Systems Approach to Training (SAT) to be a suitable training methodology. The basis for accepting SAT as an acceptable training process includes, in part, consideration of programmatic attributes, such as deriving training content and design from job requirements, evaluating and revising training based upon job performance, and having predictive ability regarding subsequent trainee job performance [9]. Thus, within the new framework, the NRC staff intend to require that training programs for licensed operators will be based on the SAT.

In implementing this new approach, the NRC staff have identified that advanced reactor vendors and licensees could develop an operator licensing examination program that is tailored to the specific needs of their facilities by means of a process that includes the following general components:

- A job task analysis would be an essential first step to identify the knowledge, skills, and abilities (KSAs) that are related to the purpose for which operators would be licensed (i.e., protection of public health from harmful radiation and the management of plant-specific safety functions). The vendor or licensee would perform this analysis and the NRC staff would review the product. These actions would establish what is known as the "content domain" and the amount of it that is testable.
- The training and evaluation methods to be used would be selected using a [SAT] process. This would serve to ensure that the training and evaluation settings remained

appropriate for the job the operator is being licensed to perform. …the vendor or licensee would propose a means of testing a representative sample of the important KSAs and the methods to be used (e.g., written exam, [job performance measures] JPMs, or simulator test), including recommendations on details such as how many written questions, JPMs, or simulator events would be included in the initial licensing examination.

— Initial licensing examination pass/fail criteria (e.g., the cut score for a written exam) and the basis for those criteria would be proposed by the vendor or licensee and reviewed by the staff… [8, pp. 43-44]

In summary, under the new framework, it is envisioned that the knowledge and ability requirements for licensed operators will be focused on the management and fulfilment of safety functions, in addition to other tasks needed to support safe operation. Evaluations of the required knowledge and abilities would be based upon tailorable examination programs. The licensed operator training process would occur within the structure of a SAT-based approach.

## 8.0 CONCLUSION

The paper has outlined key attributes and features of a proposed regulatory framework for addressing human-system considerations at advanced reactor facilities. This approach uses an applied understanding of design-specific safety functions as a means to provide requirements that are technology inclusive. Requirements associated with human-system interactions are integrated in a manner that reflects the interdependent and interrelated nature of operator staffing, operator qualifications, and HFE at advanced reactors. Finally, flexibilities are provided by means of requirements that are performance-based in nature.

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