Characterizing the Human Factors of Offsite Monitoring and Remote Operation for the Nuclear Domain

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ABSTRACT

The diverse range of technologies expected with advanced reactors present both opportunities and challenges for the nuclear industry. The U.S. Nuclear Regulatory Commission (NRC) anticipates novel approaches to reactor operations that enable economies of scale, such as remotely operated facilities. To prepare for the human factors review of applications proposing use of remote command and control operations, the NRC and Idaho National Laboratory (INL) initiated work to characterize the unique aspects of remote operation that arise when command and control is moved outside the site boundary. The NRC and INL research team engaged the nuclear industry in early 2024 with a workshop to understand the concepts of operations the nuclear industry is considering that may include elements of remote operation. As follow up to the workshop, this paper explores three hypothetical concepts involving elements of remote monitoring and control, begins to identify the human factors implications related to these concepts, and discusses the existing applicable NRC guidance.

Keywords: Human Factors, Remote Operations, Nuclear Safety, Advanced Reactors

1. INTRODUCTION

The staff of the U.S. Nuclear Regulatory Commission (NRC) is responsible for reviewing and determining the acceptability of new reactor designs to ensure they support safe plant operations. Advanced reactors present new challenges for NRC licensing reviews as they incorporate a diverse range of technologies, sizes, and operating philosophies. Novel approaches to reactor operations that enable economies of scale may include remotely operated facilities, and the NRC must be prepared to review such designs. To prepare for the human factors review of applications proposing use of remote operations, the NRC and Idaho National Laboratory (INL) initiated work to characterize the unique aspects of remote operation that arise when command and control is moved outside the site boundary.

In order to develop guidance for the review of such facilities, there is a need to first understand what remote operation means in terms of the different approaches to how remote concepts might be implemented and how the various implementations are unique from traditional large light water reactor (LLWR) operations. Then the NRC staff must determine whether any of the unique aspects of remote operation carry implications for human performance, and whether those unique considerations are addressed by current review guidance.

The NRC and INL research team engaged the nuclear industry beginning in early 2024 with a workshop [1] to understand the concepts of operations (ConOps) the nuclear industry is considering that may include elements of remote operation and monitoring. A facility's ConOps *"refers to the high-level*

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facility missions and goals and the functions and operational practices needed to manage both normal and off-normal situations, the expectations related to human performance, and the interactions of personnel with a facility that helps ensure that safety systems will function correctly when needed" [2]. A key takeaway was that reactor developers are considering a range of strategies for the use of remote operations, ranging from no remote operations to remote monitoring of near-autonomous operations. In addition, the anticipated use of remote operation may have significant impacts on the roles and responsibilities of personnel and may affect human performance. As follow up to the workshop, this paper will explore three hypothetical concepts involving elements of remote operation and monitoring and begin to identify the human factors implications related to these concepts.

2. CHARACTERIZING REMOTE OPERATIONS

The NRC glossary defines a control room as *"the area in a nuclear power plant from which most of the plant's power production and emergency safety equipment can be operated by remote control"* [3]. Operators in the main control room (MCR) interact with field operators to coordinate actions between the MCR and local equipment. In this sense, the MCR is already implementing some level of "remote control" over a reactor. We distinguish "remote operation" from traditional MCR operation using a definition adapted[1] from the NRC's, "Ground Rules for Regulatory Feasibility of Remote Operations of Nuclear Power Plants" [4]. For the purposes of this work, remote operation is defined as the *"command and control of the reactor from a location outside of the reactor site boundary."* Thus, remote operation is characterized by active command and control of a reactor—human operators receive plant information and send control signals from outside the physical boundary of the reactor site.

Oftentimes the terms "remote operations" and "remote monitoring" are used interchangeably, however there are some critical distinctions. If "remote" is defined as being outside of the plant boundary, then "operations" involves *command and control actions*, whereas "monitoring" refers to the *collection and observation* of plant data. By these definitions, a remote operations concept would necessarily include remote monitoring; however, a remote monitoring concept would not include remote operations due to the absence of command and control actions.

Fig. 1 illustrates four different control room configurations to aid in distinguishing remote operation from other operational concepts. Concept A represents the configuration that is seen in existing LLWRs; both the reactor and MCR are within the site boundary, and so all command and control is performed locally. Concept A is included for comparison only. Concept B represents a traditional control room with the addition of a remote monitoring facility. Concepts A and B are not considered remote operations, as characterized by the definitions used for this research.

Concept C and Concept D (highlighted in red) both refer to remote operations.[2] Concept C represents a configuration in which primary command and control is performed from a remote facility with the availability of a local control room. Concept D also represents a remote control configuration, but *without* a local control room. The concepts described in this paper are illustrative in nature and not exhaustive. There may be a continuum between Concept C and Concept D, such as the extent to which command and control may shift between the remote facility and local control room under varying conditions or operational states, the availability of indications and controls at each location, or the extent to which operations personnel are available onsite. The present work is intended to provide examples of potential

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[1] For this paper we adapted the definition to use the term 'reactor' in place of the term 'plant' because the term 'reactor' may not be applicable to some advanced reactors designs (e.g., microreactors)

[2] The concepts presented in this paper are for research and discussion purposes only; they do not constitute NRC endorsement or a determination of regulatory acceptability of any particular operating strategy.

use cases as a means to explore the human performance implications of such concepts and inform future human factors reviews.

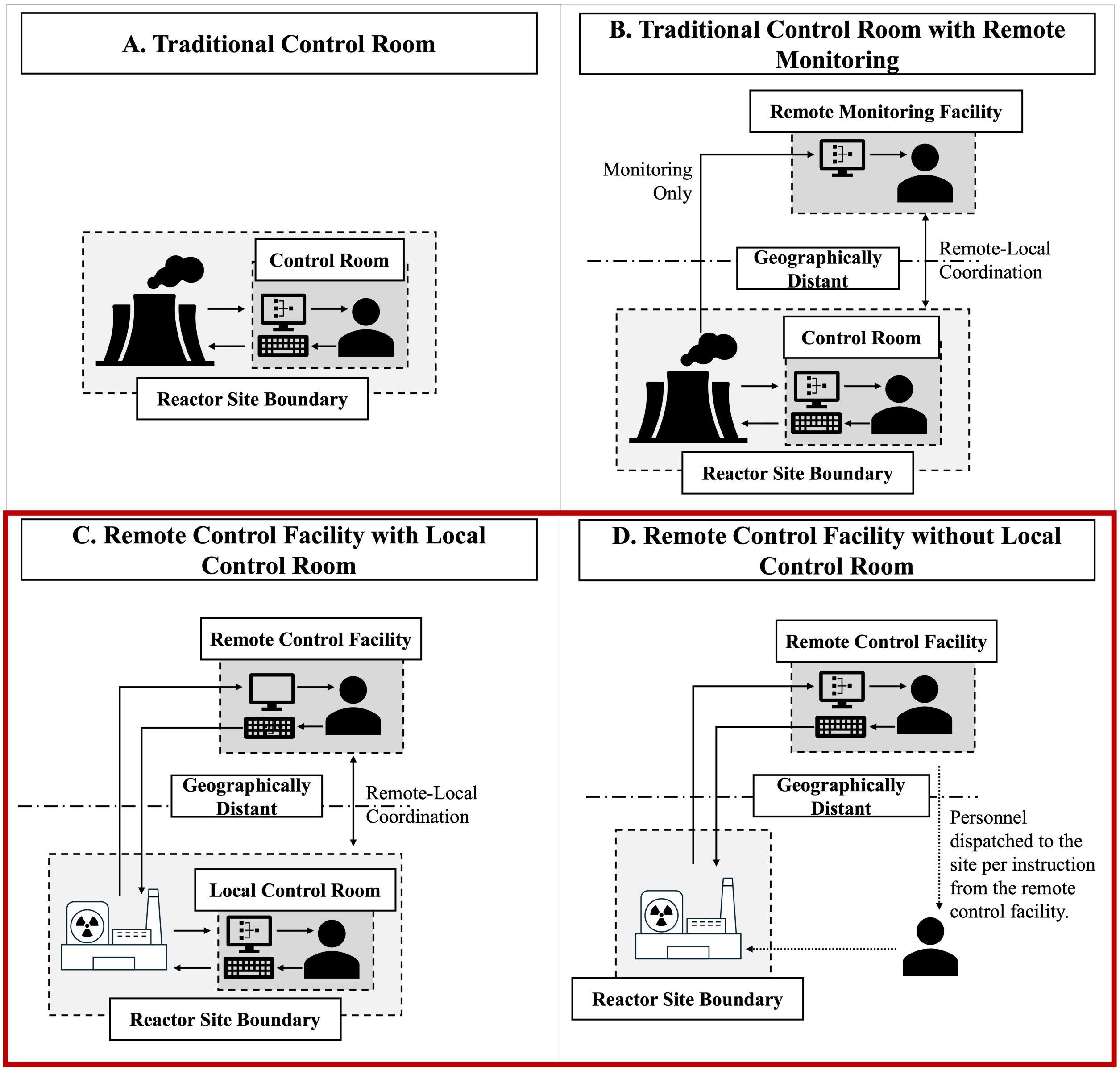

Figure 1 Conceptual illustration of different control room configurations

2.1. Traditional Control Room with Remote Monitoring

Concept B in Fig. 1 features a traditional control room with remote monitoring. In Concept B, command and control would be performed by operators in a control room within the site boundary, with the availability of a facility located outside of the site boundary for monitoring plant data (i.e., remote monitoring). The remote facility is for monitoring only, and thus there is no command and control expected to occur offsite. The remote facility could provide support with engineering expertise[3], plant health monitoring, or other administrative functions. Concept B is not considered remote operation because there is no command or control occurring outside the site boundary, only monitoring of plant data. However, some variations in this concept could involve staff at the remote monitoring facility providing recommendations for action to licensed operators in the local control room (e.g., cycling a valve for testing), or supervisory personnel directing action (e.g., raise power). The boundary between monitoring and operation may depend on who is responsible for decision making and direct manipulation of reactor controls.

2.2. Remote Control Facility with Local Control Room

Concept C in Fig. 1 is an offsite remote control facility with local control available. In Concept C primary command and control would be accomplished from a facility that is outside of the reactor site's boundary. This concept could include remote operation of more than one reactor unit at more than one site from a centralized facility. Concept C also includes a local control room that is within the site boundary with operations personnel available locally to assume control of the reactor if needed. In this concept the local control room would be expected to have a full complement of indications and controls to operate the reactor. Transfer of command and control would be established by coordinating with the offsite remote control facility.

2.3. Remote Control Facility without Local Control Room

Concept D in Fig. 1 represents an offsite remote control facility without a local control room. Like with Concept C, this concept could include operation of more than one reactor unit at more than one site from a centralized facility. Concept D is distinct from Concept C in that it does not include a full complement of indications or controls at the site of the reactor. Although it would be expected that some control actions could be accomplished locally, they would only be used in off-normal situations. For instance, there may be a limited set of indications and controls accessible on site, such as those described in Regulatory Guide 1.97 [9], that personnel would use to shut down the reactor in emergency conditions. Rather than use of a remote shutdown panel as is common in LLWRs as a backup to the main control room, this concept might include a local shutdown panel as a backup to the remote control facility. Onsite personnel may also be limited in this concept—personnel may be dispatched to the reactor site on an as-needed basis as opposed to the site being continuously staffed.

2.4. Distinguishing between Overlapping Concepts

In each of the remote concepts, there is an interplay between remote operation, use of autonomy, and control of multiple units or sites. Although not necessarily unique to remote operations, this paper explores how these features may interact and their implications for human performance.

2.4.1 Relation and Distinction of Remote Operations to Multi-site Operation

The concept of *multiunit* and *multisite* should be defined. We refer to *multiunit*[4] operation in terms of the command and control of more than one reactor from a common control room, irrespective of location. In a multiunit design, the reactors may or may not be collocated on a single reactor site. *Multisite* means

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[3] The proposed 10 CFR Part 53 rulemaking and associated guidance documents introduce an alternative to the traditional Shift Technical Advisor role, whereby an individual with the requisite education and training can provide engineering expertise to operating crews from a remote location (potentially to multiple facilities concurrently).
[4] The term *multiunit* used here is analogous to the term *multi-unit, common control room* used in DRO-ISG-2023-03.

"the command and control of more than one reactor from a common control room where the reactors are located at two or more different sites." Thus, multiunit operation may entail operation of two or more reactors within a single site or across two or more sites with the latter referring to multiunit/ multisite operation. Finally, for multisite operation, the control room may be located onsite of one unit or be completely outside the site boundary for all reactors.

These types of multiunit remote operations are possible configurations for prospective ConOps. Further, while these types of multiunit remote operations may share similar human factors considerations, it is likely that multiunit/ multisite operations may contain additional considerations (e.g., site differences such as with emergency response time differences between sites) that should be accounted for. Though, a detailed review of human factors implications for multiunit/ multisite operations goes beyond the scope of this report.

2.4.2 Relation and Distinction of Remote Operations to Autonomous Operation

The Ground Rules paper also distinguishes remote operations from autonomous systems and automatic functions (i.e., automation). Autonomous systems are "*able to perform their task and achieve their functions independently (of the human operator), perform well under significant uncertainties for extended periods of time with limited or nonexistent communication, with the ability to compensate for failures, all without external intervention"* [4]. While autonomous operation seeks to eliminate the reliance of personnel in command and control, remote operation seeks to relocate personnel to a centralized location to operator reactors remotely [5].

In this paper, we focus specifically on the characteristics of remote operation, which may embody reactor designs of varying levels of autonomy or automation. Thus, it is important to note that while these concepts are distinct, they are likely interrelated in the sense that a reactor design concept with greater autonomy may be achieved through a combination of using greater levels of automation, inherent safety characteristics, and passive safety features. Specifically, to create definitional clarity between somewhat overlapping concepts, this paper refers to autonomy and automation from these definitions. Autonomy refers to a characteristic of something (e.g., a system or component) that describes its ability to bring about some end without direct human action. Autonomy is a spectrum where some systems may have high levels of autonomy (i.e., autopilot functions in aviation) and some may have less (i.e., a power drill). Automation refers to a specific artifact (i.e., a system or device) that may enable autonomy in a system.

Autonomy can be achieved by using higher levels of automation, or by inherent safety characteristics and passive safety features of the reactor. Automation can be characterized as a system or device that accomplishes a function or task. Automation may fully or partially support a function or task depending on the level of automation prescribed [6]. In some cases, particularly in simpler systems, autonomy and automation may have near identical descriptions. However, they remain distinct concepts. Therefore, specific technologies such as artificial intelligence, machine learning, automatic safety systems, or physics-based components are examples of automation that enable some degree of autonomy in performing key functions that support the facility's missions and goals.

3. HUMAN PERFORMANCE CONSIDERATIONS WITH REMOTE OPERATIONS

A number of ways in which human performance may be impacted by remote operation include situation awareness (SA), workload, human-system interface (HSI) interactions, communication and coordination, vigilance, sensation and perception, decision making, and procedure use and adherence. For brevity, this paper will highlight a selection of these considerations. A more comprehensive report is forthcoming.

3.1. Situation Awareness Considerations

SA is an important consideration during the design process of an effective human factors engineering program in nuclear reactors in general [7] and will be an important concept to understand for safety reviews of facilities incorporating remote operations. The three primary components of SA are perception, understanding, and projection [8]. Fundamentally, an operator must perceive the environment, understand the environment, and then anticipate (i.e., predict) how the environment may adjust in the future based on different phenomena or their own actions.

There are several key challenges to SA for remote operations. Maintaining SA may be more challenged when personnel are distant from the environment they are perceiving, understanding, and anticipating. Challenges with maintaining SA from a remote location may be compounded when operators are responsible for more than one reactor unit at more than one site. In Concept C, the potential for transfers of control between local and remote facilities may carry implications for SA. In Concept D, there may not be personnel readily available at the local site to assist remote operators with perceiving and understanding the environment.

When remote, the operator cannot perceive the environment directly as they are not physically present in the environment they are controlling. Many designs for remotely operated environments try to solve this with video feeds of the environment or an increased number of sensors that can attempt to give the operator more insight into the system or component's performance. In contrast, the sense of understanding is more nuanced because there are critical components in sensory processing that enable understanding the environment. As the sensory aspect is not directly present in a remote operations concept, the stand-ins, video feeds, and additional sensor data will be needed to enable understanding to yield a similar level of success. Likewise, projecting future environmental states may also change when operation is accomplished remotely. Rather than relying on sensory information (e.g., visual information about the trajectory of a plane at an airport), this may rely heavily on training and the strength of the inherent mental model of the operator in the situation. All these changes may not result in a decreased level of SA but may result in modified SA that should be considered in the design, review and evaluation of these systems.

3.2. Workload Considerations

Workload is characterized as, "the physical, cognitive, and other demands that tasks place on plant personnel" [9]. There are some notable concerns identified from surrogate industries with respect to workload for operators and the importance of workload management to the feasibility of remote operations [10, 11]. Consider the operation of multiple units at multiple sites, such as might be envisioned with Concept C and Concept D. Workload research for remote air traffic control centers [12] and maritime operations [10] demonstrated significant challenges for operators of multiple locations at a single time. A similar impact on nuclear reactor operators in a remote situation is possible as well.

One particular aspect of note for nuclear power is that the status quo is extremely well-defined through strong precedent and managed to ensure safety. Nuclear reactors have well developed programs for training, re-training, procedure use, fatigue management, and other operational aspects which help achieve high levels of reliability and safety. However, many of these programs have come about after decades of lessons learned. Remote operations concepts, like Concept C and Concept D, may not have the benefit of these well-worn paths and therefore there are some significant open questions on the nature of workload in these remote situations to ensure a safe and reliable system is implemented.

3.3. Human-System Interface Interaction Considerations

A critical component of the design and implementation of a control system is the HSI, and this importance is noted in multiple NRC guidance documents and standards [e.g., 6, 7, 13]. As advanced reactor platforms will make use of digital control system technologies in their control rooms, either local or remote, the need for a robust and well-designed digital system, including the HSIs, will only become more important.

There are not immediately obvious HSI challenges that will merit a novel approach for remote operations and the guidelines in NUREG-0700 [6] will likely be sufficient in many cases. However, both DRO-ISG-2023-03 [2] and Fleming, Nyre-Yu, & Luxat [14] note there may be unique considerations that arise from the use of remote operations and autonomous systems. The inclusion of high levels of automation or autonomous systems are not necessarily required for remote operations, but may be more likely in designs that employ remote operation or monitoring, like Concept B, Concept C, and Concept D. Novel interactions between remote operators and highly automated systems may present significant challenges and problems to solve from an HSI use perspective. Therefore, HSI design will be an important vector for design, analysis, and review of ConOps with remote operations.

In remote operation of multiple units, there may be risk of unit confusion or incorrect mental model about state of individual units under command and control. HSI and interaction design may have an important role in helping the user in distinguishing key differences between units under supervision and therefore realigning one's mental model for the command and control of each unit.

Indeed, consistency of HSIs across remote operating facilities will be required to ensure the operational safety of the reactor. Reflecting on Concept C, the effective and efficient transfer of command and control from the remote facility to local facility may be impacted by the design of HSIs used by personnel at each site. That is, the handoff of control requires coordination of personnel in determining the state of the reactor. Subtle differences between HSI conventions (e.g., use of colors, terminology, conveying plant equipment state, display page navigation) could result in an inaccurate mental model of the plant.

3.4. Communication and Coordination Considerations

Current control room operations involve high levels of communication and coordination of activities between MCR and field personnel to synchronize tasks requiring human action. Field personnel are sent out into the plant in different areas and use radios or other communication devices to communicate back to the control room that tasks have been completed. The NRC Ground Rule #6 considers data and voice communication infrastructure as crucial to the feasibility of remote operations and needs to be considered early in the design [4]. For reactor designs that are considering use of a remote control facility, new considerations for teamwork and coordination must be developed with good HFE practices to ensure safe, reliable human performance, and that tasks can be completed during normal and emergency conditions. It is possible that with Concept C there will be a regular need for communication and coordination between the remote facility and local site during normal and off-normal situations. Transfer of command and control from the remote control facility to the local control room in Concept C will require reliable communication methods and a means to establish and verify who has control of the reactor. For Concept D, communication and coordination activities may be limited to off-normal or emergency situations, at which point the remote control facility will need to reliably communicate and coordinate with the local site, such as to direct use of the local shutdown panel.

New communication methodologies may be important for remote operations to ensure that coordination between operators can be achieved successfully from remote control facilities. An element of redundancy in communication networks may be necessary to ensure that there is not a communication loss between the remote control facility and the reactor site. Real-time exchange of information in conjunction with video teleconferencing software and data streams are some potential methods that remote personnel may use to coordinate with onsite and other offsite teams to perform procedures and tasks. An example of this is seen in some offshore collaboration centers for oil and gas facilities where the onshore center monitors and controls operations such as remote shutdown, adjustment of setpoints, and acknowledging alarms [15]. Having additional networks would help ensure that, during an emergency or off-normal conditions, communication is not lost.[5] New communication and coordination capabilities should be evaluated and tested early during the design to ensure that the new data and voice infrastructure is secure from internal and external threats such as cybersecurity threats. The data architecture must provide layers of cybersecurity to prevent any unwanted access.

A review of technology trends and operating experience across different industries suggests that handoffs between remote and local control can be a particular challenge [16]. For the maritime industry, the authors compared communication patterns during near shore conditions (i.e., considered highly complex and fast-paced) and open water conditions (i.e., considered mundane, more predictable, and slow). Remote piloting and coordination between remote and local sites were typical for open water conditions. However, when the shipping vessels were in near shore conditions, the allocation of tasks were primarily performed locally with highly skilled personnel where significant teamwork was needed to navigate the highly trafficked waters.

4. IMPLICATIONS FOR NRC GUIDANCE

Under the proposed 10 CFR Part 53 rule, human factors principles must be applied in all locations where humans are expected to support safe operation. Specifically, the proposed 10 CFR § 53.730(a) states that "the plant design must reflect state-of-the-art human factors principles for safe and reliable performance in all locations that human activities are expected for performing or supporting the continued availability of plant safety or emergency response functions" [17].

The extent to which potential human factors challenges related to remote operation could impact safe operation of the nuclear reactor may depend on the role of the human, such as whether there are any important human actions that are required for ensuring safety or providing defense-in-depth. If there are no important human actions, then human factors reviews may be more limited in scope. Whereas if there are HAs that are required for ensuring safety of the plant, then human factors reviews would be expected to include some of the unique considerations discussed in this paper, such as SA, workload, the HSIs, and communication and coordination between the remote facility and local site.

The guidance in DRO-ISG-2023-03 [2] provides a scaled approach for reviewing an applicant's human factors engineering and does not limit its scope to facilities that are within the site boundary of the nuclear reactor. Therefore, it can be expected to be sufficient for the review of human factors engineering programs for ConOps that include remote operations. Regarding the review of operating experience, there may be limited 'real world' examples of nuclear remote operations experience upon which to rely. Thus, lessons learned for remote operations in surrogate industries will be needed; this gap is being addressed as part of parallel efforts.

There are a number of other relevant interim staff guidance documents associated with the proposed 10 CFR Part 53 rule that can support human factors reviews of concepts that include remote operations [18,

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[5] Within the context of a remotely operated nuclear power plant, a loss of remote monitoring and control capability could present a safety concern, particularly in instances where required operator actions exist for mitigating certain plant events. On account of this, the appropriateness of crediting remotely implemented operator actions within plant safety analyses is currently an area of ongoing consideration by the NRC staff.

19, 20]. The guidance in DRO-ISG-2023-01 [19] provides guidance for review of an applicant's training program, which could include training for remote operators. Staffing levels are an important human factors engineering consideration in part because staffing can impact workload and distribution of work. DRO-ISG-2023-02 [20] provides a flexible review process and a set of systematic methods to evaluate a wide range of staffing plans that may be submitted under Part 53, including staffing for ConOps that include remote operation. DRO-ISG-2023-02 addresses considerations like staffing number, position, responsibility for multiunit and multi-site operation, travel and response times for maintaining safety of the nuclear reactor, and descriptions of how the nuclear reactor will be monitored from all facilities including those that are offsite.

5. CONCLUSIONS

This paper is part of a larger research effort to prepare the NRC to review license applications proposing some of these novel operational concepts (e.g., remote and autonomous operations). The NRC's research aims to 1) characterize the unique aspects of evolving reactor technologies that may have implications for human performance, 2) assess the degree to which existing NRC guidance is suitable to support reviews that include these concepts, and 3) identify gaps, if any, that must be addressed to support future human factors reviews. This paper summarizes three concepts involving aspects of offsite monitoring and control to varying degrees, characterizes the unique elements for those concepts, identifies a number of associated implications for human performance, and summarizes the available NRC guidance that could aid in a human factors review of an application proposing remote operations.

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