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Exploring Human Factors Considerations Of Remote And Automated Operations For The Nuclear Domain

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Advanced nuclear reactor technologies present new opportunities and new challenges for regulators like the U.S. Nuclear Regulatory Commission (NRC) and the nuclear industry worldwide. Operating costs are a driving consideration for advanced reactor designers. The NRC staff anticipates that reactor developers will propose novel approaches to reactor operations as a means of minimizing costs. These novel approaches may include remotely operated facilities and increased reliance on automated operations for safety-significant systems, structures, and components (SSCs). The operation of first-of-a-kind technologies can be challenging due to a lack of operating experience and potential for significant changes to traditional operational concepts (Blackett, Eitrheim and Bye, 2022). Proposals that include novel design concepts may also have implications for the NRC's safety reviews, including human factors engineering (HFE) areas like human-system interfaces (HSI), staffing, training, qualifications, and operator actions. The NRC is undertaking research to develop the technical basis for guidance supporting human factors reviews of advanced reactor license applications that include novel concepts, such as remote and highly automated operations.

Advanced reactors represent a more diverse range of technologies than the large light-water reactors that characterize the current fleet of commercial nuclear reactors in the United States. Advanced reactor concepts include:

- all designs that are not light-water reactors (LWRs), regardless of size;
- all small modular reactor designs;
- microreactors;
- fusion reactor systems (per the Staff Requirements Memorandum (SRM) to SECY-20-0032 (NRC, 2020).

This diversity in advanced reactor technologies is reflected in many design and operational characteristics:

- some rely on simpler designs, involving fewer systems and moving parts;
- some rely on design features that make them inherently safe, such as natural physical processes that do not require automatic or human intervention;
- some are highly automated, including some that may operate in a fully autonomous mode, and may not require much, if any, human monitoring, control, and intervention;
- some may not have a control room in the traditional sense; reactor monitoring, and control may be accomplished from simple panels either locally or remotely.

Some of the design characteristics described above may provide an opportunity to leverage remotely operated nuclear facilities. Remote operations could allow fleets of small, advanced reactors to consolidate their workforce at a single central location and thereby reduce operating costs. However, operating a reactor from an off-site control room can present new and unique human factors challenges. For instance, it may no longer be practical to dispatch an operator on site to gather additional information about plant status. Additional information would need to be available through some other means and may require new human-system interfaces (HSIs). Further,

some of the economic drivers for remote operation include the opportunity to manage multiple units from a single control room. Multi-unit, remote operational concepts introduce human factors complexities including those related to the role of the operator, communication, teamwork, and situational awareness (Blackett, Eitrheim, McDonald and Bloch, 2022; Blackett, Skraaning, Kaarstad and Eitrheim, 2023).

The NRC initially explored the topic of remote operations of nuclear facilities by identifying 11 ground rules for regulatory feasibility (NRC, 2021). The report explores considerations and key attributes that will likely be crucial to make remote operations feasible from both a developmental and decision-making perspective. Most of these ground rules include human factors considerations or have HFE implications. Ground rule 7 acknowledges that the responsibility of remote reactor operators should be based on the level of automation; the reliance on human actions to meet safety needs and the technology's "minimal risk conditions"; and the time in which such human actions need to be completed.

The use of automation necessarily changes the human role and may enable remote concepts of operation. However, remote operation should not be conflated with autonomous operation. Remote operation means "command and control of the plant from a location outside the nuclear reactor site boundary" (NRC, 2021), but may still require human monitoring, supervision, and control. Autonomous systems are "able to perform their task and achieve their functions independently (of the human operator)" for most, if not all normal and safety operations (NRC, 2024). Autonomous operation may be broadly defined to represent a spectrum of automation capabilities, with autonomously controlled reactivity being at the extreme end of that spectrum.

While remote and autonomous concepts should not be conflated, they are necessarily interrelated and are therefore examined in parallel and in relation to each other. The focus of the present research is to:

- understand the range of remote and autonomous concepts anticipated for advanced reactors;
- identify the human factors considerations and implications across the range of remote and autonomous concepts;
- gather research findings and lessons from experience in other high-risk domains that may serve as surrogates for similar concepts anticipated in nuclear (e.g., oil and gas, maritime, aviation, and aerospace);
- develop a taxonomy to elucidate the human factors considerations that are important to ensuring safe operation of advanced reactors.

Preliminary work indicates a number of human factors areas that may require further exploration in order to address advanced reactor concepts including how functions are assigned to humans or automation, multi-unit monitoring and control, communications between reactor and remote operations facilities, and the design of local and remote monitoring and control interfaces.

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