INL/CON-23-71443-Revision-0

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July 2023

Changing the World's Energy Future

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http://www.inl.gov

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

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ABSTRACT

Existing light water reactors in the U.S. are primarily large baseload electricity generating facilities. The concept of operations for these plants remains largely unchanged since the advent of commercial nuclear power—the main control room serves as the hub of plant activities and is staffed with multiple licensed operators who work in tandem under the shift supervisor, and staff such as field workers support the control room remotely. While newer plants have brought the advent of digital human-machine interfaces to replace earlier analog and mechanical instrumentation and controls, much of the control process remains unchanged and manual. It is simply a newer version of legacy concepts. Advanced reactors potentially bring considerable changes to the size, fuel type, automation, and staffing of nuclear power plants, necessitating a fundamental shift not just from analog to digital, but further from human to automation, from onsite to remote, from control to monitoring, and from many to few operators. Despite this multitude of parallel evolutions in reactor designs, many of the vendors developing the next generation of reactors represent smaller research and development enterprises. It is therefore not feasible to address all aspects of plant design at the same time. In particular, the competing design aspects of new reactors present a significant challenge to the development of robust and human factored systems at the plant. As vendors develop new reactor designs, much of the early focus is naturally on the fuel and reactor system technology. Looming behind these early advances is the daunting prospect of first-of-a-kind control concepts that have not yet been developed or validated. A failure to address the human element of reactor design early will lead to missed opportunities. The quickest development process is the replication of existing concepts of operations at legacy plants, even when such systems were long ago surpassed by better human-machine technologies outside the nuclear industry. Conversely, attempting to undertake novel concepts of operations late in the design life cycle of a plant could result in protracted development efforts and delays in licensing and deployment. This does not have to happen, and it is imperative that human factors be considered now, early in the design of new reactors.

Keywords: Advanced Reactors, Nuclear Power Plant, Human Factors

INTRODUCTION

The Watts Bar Nuclear Power Plant in Rhea County, Tennessee, is a two-unit commercial pressurized water reactor with a combined electrical generating capacity of 2,332 MWe. Watts Bar tells an important story of the U.S. commercial nuclear industry (Blau, 2016). Construction began in 1973 but was halted in 1985 due to projected decrease in power demand in the area and construction issues. At the same time, following the high-profile events at the Three Mile Island and Chernobyl nuclear generating stations in 1979 and 1986, respectively, public support for nuclear power was waning and likely played a role in discontinuing many nuclear power construction efforts internationally. Watts Bar Unit 1 resumed construction in 1992 and began operation on May 5, 1996—fully 23 years after construction began. Construction on Unit 2 continued in 2007, was delayed in 2011 due to design modifications in the wake of the Fukushima Daiichi event, and began operation on October 19, 2016. The beginning of construction for Unit 1 and the beginning of operations for Unit 2 represented a 43-year lapse. No commercial power plants went online between Unit 1's first operation in 1996 and Unit 2's first operation in 2016, marking a 20-year gap in new nuclear power plants in the U.S. Moreover, these newly constructed reactors represented designs dating back more than 50 years and are considered legacy projects. The first newly designed and constructed nuclear power plants in the U.S., Plant Vogtle Units 3 and 4, are drawing to completion but have not, at the time of this writing, started generating electricity (Conrad, 2023). Vogtle Units 3 and 4 represent the first new license for a nuclear power plant in the U.S. since Three Mile Island, marking a 44-year gap in new nuclear in the U.S.

High demand for electricity, especially from carbon neutral sources like renewables and nuclear power, proved a compelling reason to sustain the fleet of nuclear power plants in the U.S. Even though no new plants were constructed, nuclear power provided over 20% of electricity in the U.S. The U.S. Nuclear Regulatory Commission licenses nuclear power plants for 40 years of operation. In the early 2000s and into the 2010s, original plant licenses started to near expiration, but the useful life of the plants proved to be much longer. Thus, U.S. utilities began requesting license extensions for another 20 or 40 years of operation. Extensive prescribed maintenance and refurbishment of plants as part of the nuclear refueling process (typically every 18 months), ensured the safe continued operation of aging plants.

In conjunction with life extensions, plants invested heavily in modernization and upgrades. For example, in many cases, technological advances allowed plants to uprate their electrical generation capacity through upgrades in the generators and control systems. Some technologies had reached obsolescence and required extensive modernization to upgrade. For example, plant control systems were originally tied to 1970s and 1980s analog technology, which had not anticipated the technological shift brought about by the digital revolution. Many plants had stockpiled replacement parts suitable for a 40-year operating life, but the extension beyond 40 years necessitated a shift to digital control technologies. U.S. Government programs like the U.S. Department of Energy's Light Water Reactor Sustainability Program were implemented to help with such transitions, and Idaho National Laboratory became involved in control room modernization to ensure the successful transition to digital control rooms while also ensuring that advances in human factors resulted in improvements to human-machine interfaces rather than simple like-for-like analog-for-digital replacements (Boring et al., 2019).

The nascence of carbon neutral energy solutions has increased the demand for nuclear power. A large focus of current domestic energy policy is on strengthening renewable energy sources like wind and solar. Hydroelectricity remains an unpopular area for future expansion because of the environmental impact due to damming. The intermittent nature of these remaining renewable energy sources coupled with the immaturity of cost-effective energy storage systems paves the way for nuclear energy to play a complementary role to renewables. A challenge with existing nuclear power plants is they do not load follow very well, meaning they are not designed to ramp electricity production up and down to match the availability of renewable sources. Recent research on secondary uses of nuclear power plants such as thermal power extraction for hydrogen production allow the use of nuclear power as a heat source that can alternate between electricity and steam-heat production for secondary applications (Ulrich et al., 2019). The plant can be operated in a continuous manner without ramping up or down and decreasing the lifespan of the plant.

In addition to increased uses for existing reactors, novel designs have opened a strong interest in advanced reactors. The Nuclear Renaissance originally envisioned in the first decade of the 2000s (Boring et al., 2008) is delayed, but it is coming in a new form. In particular, smaller reactors like small modular reactors, microreactors, and fission batteries feature a smaller size and electrical output. The smaller size provides the opportunity for more offsite assembly, thereby significantly reducing the cost of reactors. Smaller reactors allow placement in less populous areas, eliminating significant fuel transportation costs compared to traditional fossil fueled electric generating facilities. Additionally, newer reactor designs feature new safety features like passive cooling systems or pebble-sized fuels. The NuScale Power small modular reactor, for example, demonstrates the potential for highly automated control systems, thereby significantly reducing the staffing requirements for plants (Cho, 2019). Dozens of other small reactor designs are being developed (International Atomic Energy Agency, 2020), unveiling reactor designs that promise shorter development times, licensing times, and build times. Most of these designs address shortcomings of existing reactors by being able to load follow, setting the stage for advanced reactors to become part of a modernized national electricity generating capability that seamlessly mixes renewables with nuclear power to maximize electricity generation and grid reliability.

While there is much energy industry excitement at having so many new reactor designs emerging, the underlying vendors sometimes have limited resources, especially since many are startup companies. Much of the focus of their development activities is rightfully on core reactor technologies. Many of these vendors may assume that the advanced control room design challenges were solved with the recent license approval of NuScale Power’s reactor. Or, they may assume a focus on the control room is unnecessary, because control functions will be automated. In reality, the successful control room design by NuScale Power with reduced staffing remains a proprietary solution that cannot easily be generalized to other plant designs. Additionally, licensing an automated control system with the U.S. Nuclear Regulatory Commission is subject to no less rigorous scrutiny than would be a conventional, fully staffed control room. There is a need for human factors to support the development of advanced reactors. To date, most vendors of new reactor designs have not adequately considered the human-technology interactions of these designs.

CHANGES IN HUMAN-TECHNOLOGY INTERACTIONS WITH ADVANCED REACTORS

The current fleet of commercial nuclear power plants in the U.S. are pressurized or boiling water reactors, which use normal water for cooling. These light water reactors have been scaled to operate in the one-gigawatt-plus electricity generating range. Currently, 93 such reactors generate about 20% of the U.S. electric supply (U.S. Energy Information Agency, 2023). These reactors are baseload power sources that form an essential backbone of the power grid. Owing to the average 40-year vintage of the plants, they feature conventional control rooms, consisting of analog instrumentation and control with multiple reactor operators monitoring and controlling the plant. Because of the large size of the plants, they form a sizeable footprint, with infrastructure to support large cooling demands (including backup cooling reservoirs) and to connect to high voltage transmission lines. A high standard of defense-in-depth safety coupled with a lack of automation require several hundred onsite staff during operations and many more onsite people during maintenance and refueling outages.

In contrast, advanced reactors may feature light water reactor technology, but many designs consider higher temperatures and alternate cooling methods for greater efficiency, potentially in a smaller form factor. Instead of a sole focus on baseload power generation, advanced reactors are more likely to have mixed load applications such as industrial heat applications that can alternate with electricity generation. Of particular interest to this paper is the shift in the concept of operations, from a highly manual monitoring and operations approach in the current fleet to one involving higher levels of automation, including the potential for remote monitoring.

Table 1. Operational shifts from current to advanced reactors.

Domain	Current Reactors	Advanced Reactors
Technology	Analog	Digital
Procedures	Paper Procedures	Computerized Procedures
Control	Human	Automation
Operator Training	Years	Months
Operator Role	Monitoring + Control	Monitoring
Monitoring Type	Deductive	Inferential
Operator Span	Single Unit	Multiple Units
Control Station	Control Room	Workstation
Operations Location	Local	Remote
Number of Operators	Crew	Individual
Communications	Oral	Digital

The shift in concept of operations covers many dimensions as depicted in Table 1. These shifts are elaborated below:

- *Analog to digital:* As noted, control rooms are undergoing a shift from analog to digital technology due to obsolescence of analog instrumentation and controls. The most tangible artifact of this change is the use of digital displays instead of individual, hard-wired indicators. Digital controls may still be standalone, but it is typical to use some form of input device like a keyboard, mouse, trackpad, or touchscreen linked to the displays (Ulrich, Boring & Lew, 2015). Digital technology also introduces the concept of a thin client, meaning displays and input devices need not be in a fixed position, and it is possible to have the same controls at multiple locations.

- *Paper procedures to computer-based procedures:* Existing reactors in the U.S. use paper-based procedures, but advanced reactors will make use of computer-based procedures, which feature automated placekeeping, integration of relevant plant indications into the procedures, embedded soft controls, and control automation in some cases (Institute of Electrical and Electronics Engineers., 2022).
- *Human control to automation:* While existing plants feature a cadre of human operators performing manual actions, advanced reactors will see opportunities for more automated tasks, resulting in fewer required manual actions and fewer required reactor operators (Boring, Ulrich, & Mortenson, 2019).
- *Years to months of training:* Current reactor operators have a multi-year operator training regime culminating in comprehensive license to control the plant. Emerging guidance (U.S. Nuclear Regulatory Commission, 2022) suggests as the complexity of manually operating the plant decreases with increases in automation, the operator licensing requirements will decrease in a commensurate manner.
- *Control to monitoring:* Reactor operators currently alternate between monitoring plant states and taking control actions to maintain the steady state or trigger a desired change to the plant. With advanced reactors, many or all of these control actions will become the purview of the plant automation systems, leaving the operators primarily in a monitoring role. In the design of control rooms, there may be a general shift from a concept of operations (ConOps) to a concept of monitoring (ConMon—not to be confused with *condition* or *continuous* monitoring).
- *Deductive to inferential monitoring:* The importance of presenting information effectively to operators does not diminish even as operators' roles shifts from active control to monitoring. Information automation—the consolidation of plant parameter information including inferred prognostic information—will become an important part of plant operations (International Atomic Energy Agency, 2013). Smart integration of sensor information, including the use of machine learning for predictive monitoring and predictive maintenance, plus the use of digital twins to monitor anomalies will provide operators with increased abilities to anticipate future plant states and take preemptive actions beyond routinized automations.
- *Single to multiple unit:* Current nuclear power plants exist in either single- or multi-unit configurations, but to date, each unit maintains a separate crew of operators. In some multi-unit configurations, additional crew members may rotate between different units to support activities as needed, but there is no integrated operations across reactors. This ConOps changed with the NuScale Power multiunit design, where a single crew operates multiple reactors in parallel. With the advent of smaller scale reactors, there is the

ability to chain reactors together at a single site to produce cumulative power similar to a larger reactor. The poor economics of maintaining separate crews for smaller reactors point toward increased span of control by crews, such that one crew is likely to operate multiple reactors in the future.

- *Control rooms to workstations:* Legacy reactors rely heavily on stand-at-the-boards controls, with a top-to-bottom delineation of control panels into alarms, indicators, and controls. This arrangement allowed room for sometimes bulky instrumentation and controls behind the boards and provided a common view of plant status across multiple operators. With the transition to digital technology, all functionality of the boards can be brought into displays with input devices, typically on a desk proximate to the operator. Digital navigation between windows and screens eliminates the need for going to different locations in the control room. These displays can be mirrored at multiple locations, e.g., the control room supervisor can monitor what a reactor operator is doing by seeing the same screen locally. With the reduction in crew sizes, the need for shared space may be eliminated, which brings into question the necessity of dedicated multi-person control rooms.
- *Local operations to remote operations:* There remain cybersecurity and regulatory hurdles to operating reactors remotely, but the concept becomes more tenable with the advent of smaller reactors with greater autonomy. Remote operations could overlap with the transition to more of a monitoring role for operators, but it could also avail itself of integrated operations, whereby expertise is concentrated at single locations, especially when that expertise is not required full time for a single unit (Stevens et al., 2023). One possible scenario is one crew enlisted for multiple reactors at different locations, thereby sharing reactor operations expertise across multiple sites.
- *Crew to individual:* Related to the shift from control rooms to workstations, there is the possibility that individuals will play a larger role in controlling plants. The NuScale Power configuration of one crew across multiple units is groundbreaking. Multiple reactor operators are maintained to have redundancy if needed, and regulatory requirements prescribe a control room supervisor to oversee the reactor operators. With increases in automation and the shifting in roles of operators to a monitoring responsibility, it is entirely possible that the need for redundant operators or supervisory roles is eliminated.
- *Oral to digital communications:* Current control room ConOps feature threeway communications, in which the control room supervisor acts as the procedure reader and guides activities of the operator at the controls and the balance-of-plant operator, plus any additional control room staff. The control room supervisor utters the required action from the procedure, the operator repeats back, and the control room supervisor acknowledges that the operator has understood the instruction correctly. If a reactor operator shares important information, the control room supervisor repeats the information back, and the operator in turn acknowledges that the information was correct. As computer-based procedures become embedded in the workstations of the individual operators, the need for oral exchanges

is lessoned. Additionally, as crew sizes are minimized, same-room oral exchanges become less likely. Instead, communications may be dispatched via computer between physically separated individuals. This can be between field operators and reactor operators or even between distal reactor operators.

This list of changes is not exhaustive. No particular shift described above is inevitable, beyond the already in-motion transition from analog to digital instrumentation and controls. Nonetheless, this necessarily speculative list covers many of the shifts that are likely to happen with the emergence of advanced reactors, should technological solutions and regulatory guidance align to enable these evolutions. Many of these transitions have already occurred in process control industries outside nuclear power.

THE HUMAN FACTORS IMPERATIVE FOR ADVANCED REACTORS

The technology to support the afore-mentioned transition in human operational roles exists. The reality is that no level of automation is likely to override the need for humans in a monitoring or supervisory role. Humans are required in our current regulatory framework. In the U.S., a rigorous human factors design process must be documented in the Chapter 18 of NUREG-0800, *Standard Review Plan for the Review of Safety Analysis Reports,* that nuclear licensees submit to the U.S. Nuclear Regulatory Commission (2016). There is no ready, reusable demonstration of human-less control scheme, and this remains uncharted territory. Instead, automation will likely augment human capabilities to ensure continued safe yet more efficient operation of advanced reactors. Human factors research and development work is not currently being undertaken with sufficient urgency to ensure the timely licensing of advanced control systems to support advanced reactors.

A failure to address human factors needs in the development of advanced reactors likely would result in one of two undesirable outcomes:

- *Outcome 1—Licensing and Deployment are Delayed:* By not addressing human factors considerations early in the design of the reactor, this can result in years of catchup. This process could break an otherwise lean development effort and pose significant challenges to the financial viability of the advanced reactor program.
- *Outcome 2—A More Conventional Control Room is Adopted:* In the absence of sufficient time to license innovative control schemes, a vendor may resign themselves to more conventional control room ConOps. Adopting tried and true control room designs may fail to take advantage of new technologies that enhance safety while reducing staffing. In other words, reverting to existing ConOps may take away some of the economic assumptions that make advanced reactors viable.

As noted in Boring (2022), vendors are rapidly accelerating the Technology Readiness Level of advanced reactors but not in parallel advancing the Human Readiness Level (Human Factors and Ergonomics Society, 2021) of the control systems for those reactors. This mismatch between the technology of the reactor and the technology of the human interface presents a hurdle to success of advanced reactors.

DISCUSSION

A better option is to address human factors formatively as part of the design of the advanced reactor (Boring et al., 2014). Integration of human-technology interface considerations in parallel with the engineering efforts will ensure efficiencies are made that guarantee the economic viability of the advanced reactor. Additionally, addressing human factors early in the design will help ensure successful licensing of the integrated plant and control systems.

Dedicated efforts are required to help advanced reactor vendors address human factors needs. These include:

- Industry education on human factors methods and benefits of their application to the engineering lifecycle of nuclear systems.
- Development of roadmaps and requirements for control rooms for advanced reactors.
- Funding for fundamental research to validate technological shifts in human-technology interactions in advanced reactors.
- Research and development to serve as pilot projects for reuse across the nuclear industry.
- Development of agile prototyping capabilities like the Rancor Microworld Simulator (Lew et al., 2017) to allow design exploration and human-in-the-loop testing of control room concepts early in the engineering process.
- Support of universities to build a pipeline of human factors researchers and practitioners in nuclear energy.

Human factors has the opportunity to help advanced reactor deployment be successful. However, much work remains to be done to establish usable control technologies and modern ConOps suitable for advanced reactors. With aggressive development timelines, the time is now to address human factors for advanced reactors!

ACKNOWLEDGMENT

This work of authorship was prepared as an account of work sponsored by Idaho National Laboratory, 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. Idaho National Laboratory is a multi-program laboratory operated by Battelle Energy Alliance LLC, for the United States Department of Energy under Contract DE-AC07-05ID14517.

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