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Human Factors Aspects of Operating Small Reactors

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Human Factors Aspects of Operating Small Modular Reactors

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ABSTRACT

The nuclear-power community has reached the stage of proposing advanced reactor designs to support power generation for decades to come. They are considering small modular reactors (SMRs) as one approach to meet these energy needs. While the power output of individual reactor modules is relatively small, they can be grouped to produce reactor sites with different outputs. Also, they can be designed to generate hydrogen, or to process heat. Many characteristics of SMRs are quite different from those of current plants, and so may require a concept of operations (ConOps) that also is different. The U.S. Nuclear Regulatory Commission (NRC) has begun examining the human factors engineering- (HFE) and ConOps- aspects of SMRs; if needed, they will formulate guidance to support SMR licensing reviews. We developed a ConOps model, consisting of the following dimensions: Plant mission; roles and responsibilities of all agents; staffing, qualifications, and training; management of normal operations; management of off-normal conditions and emergencies; and, management of maintenance and modifications. We are reviewing information on SMR design to obtain data about each of these dimensions, and have identified several preliminary issues. In addition, we are obtaining operations-related information from other types of multi-module systems, such as refineries, to identify lessons learned from their experience. Here, we describe the project's methodology and our preliminary findings.

Key Words: human factors engineering, small modular reactors, safety reviews

1 INTRODUCTION

The nuclear power community is at the stage of proposing advanced reactor designs to support power generation for future decades. Small modular reactors (SMRs) are one category of new designs. While there is no industry-wide definition of an SMR, most such reactors have small outputs, generating 350 megawatts electric (MWe) or less. SMRs are considered scalable, that is, multiple modules can be grouped at a site to meet a utility's specific power needs; such groupings yields various power outputs, as required. Some SMRs serve purposes other than power generation, e.g., hydrogen production or process-heat applications. Furthermore, in some SMR designs, the modules share common infrastructural support systems. Hence, with multiple SMRs operating from a single control room and at a given site, the individual reactors may be in a variety of states (e.g., shutdown, startup, or refueling and various types of maintenance and testing) and running at various power levels. These characteristics distinguish SMRs from current plants and so they may require a concept of operations (ConOps) that is different.

Research is needed to provide a better understanding of the human performance implications associated with the ConOps for SMRs. Accordingly, the U.S. Nuclear Regulatory Commission (NRC) initiated work to examine the human factors engineering (HFE) and ConOps aspects of SMRs; if needed, they will develop guidance to support SMR licensing reviews. This paper describes the project's methodology and our preliminary findings.

2 METHODOLOGY

The research methodology encompasses several tasks, each of which is described below.

2.1 Develop a Model of Concept of Operations

To examine the HFE aspects of SMRs, we first need precisely to define ConOps. Therefore, our initial step was to develop a ConOps model. Thereafter, we can use the model to identify the needed information and subsequently to structure its organization. This task is completed; we discuss the development of the model in Section 3.1.

2.2 Identify Issues Related to Multi-module Operations

Using the ConOps model, we evaluated information about SMR design and operations to identify the human-performance issues related to multi-module operations. In addition, we visited the sites of selected vendors to get a better understanding of their anticipated ConOps and operational challenges. We note that many SMRs are not designed fully, and there is little information on how the plants will be operated. Where such data are available, the ConOps are incomplete. In addition, there is little operating experience to evaluate since SMRs are a new concept for commercial plant development, and there are few predecessor plants.

Thus, to gain a more complete understanding of potential HFE issues at SMRs, we sought to learn from experience in surrogate systems, i.e., ones whose operations make similar demands of human performance. Undoubtedly, while there are important differences between other industrial domains and nuclear power, there are similarities that afford an opportunity for learning. We are examining that experience for the following systems: Nuclear naval vessels, refineries, offshore oil platforms, unmanned vehicles, and remote intensive-care centers. To support our data collection and understanding, we are making visits to selected facilities to observe and discuss multi-unit operational challenges with the staff.

We also are assessing the implications of the data for human reliability analysis (HRA). Since SMR operations will differ considerably from those in traditional nuclear plants, we seek insights into the aspects of modular operation that impact human reliability and how they must be addressed in HRAs.

Our preliminary findings from this current task are detailed in Section 3.2.

2.3 Evaluate Current NRC Regulation and Guidance

In this task, not yet begun, we will evaluate the NRC's HFE regulations and regulatory review guidance to determine the following: (1) Whether they are suitable to address issues of human performance in SMRs; (2) what aspects of the regulations and guidance may need modification; and, (3) which issues will necessitate developing new HFE guidance to support SMR licensing reviews.

2.4 Develop Draft HFE Review Guidance

Having identified the issues and guidance needs, we will formulate draft HFE review guidance via the NRC’s HFE guidance development methodology (O’Hara, 2008a).

2.5 Implementation of the Methodology

A simple example can illustrate our overall methodology. Using the ConOps model, we obtain information about the SMR designs for each dimension. We note differences between the staffing approaches to many SMR designs and staffing levels in current reactors; thus, an HFE issue is identified. By examining current regulations, we may find that the proposed SMR staffing does not meet the 10CFR 50.54m requirement on staffing level. Thus, we may need a change in the regulations, or additional HFE review guidance to evaluate exceptions to the regulations.

3 PRELIMINARY RESULTS

3.1 Model of Concept of Operations

ConOps plays a major role in the NRC's review of the human-factors aspects of NPPs. NUREG-0711(O'Hara et al., 2004) defines it in Section 8.4.2, Concept of Operations. Criterion 1 states that

> A concept of operations should be developed indicating crew composition and the roles and responsibilities of individual crew members based on anticipated staffing levels. The concept of operations should:
>
> - Identify the relationship between personnel and plant automation by specifying the responsibilities of the crew for monitoring, interacting, and overriding automatic systems and for interacting with computer-based procedure systems and other computerized operator support systems.
> - Provide a high-level description of how personnel will work with HSI [human-system interface] resources. Examples of the types of information that should be identified is the allocation of tasks to the main control room or local control stations, whether personnel will work at a single large workstation or individual workstations, what types of information each crew member will have access to, and what types of information should be displayed to the entire crew.
> - Address the coordination of crew member activities, such as the interaction with auxiliary operators and coordination of maintenance and operations.

While ConOps is used in NRC HFE review guidance, industry standards define ConOps in a slightly broader way. For example, IEEE Standard 1362 (IEEE, 2007) states that a concept of operations

> … describes system characteristics of the to-be-delivered system from the user's viewpoint. The ConOps document is used to communicate overall quantitative and qualitative system characteristics to the user, buyer, developer, and other organizational elements (e.g., training, facilities, staffing, and maintenance). It describes the user organization(s), mission(s), and organizational objectives from an integrated systems point of view.

Accordingly, ConOps is a fundamental component of the systems-engineering process for any complex system (Fairley & Thayer, 1977). Design guidance suggests using a "concept of operations" document to guide the development of requirements, the detailed design, and the system's evaluation. In addition, more and more industries are employing a system ConOps to assure their vision of how personnel are integrated into a new system design or major modification. Employing a ConOps especially is appropriate in the early stages of design to identify design goals and expectations relative to human performance (Pew & Mavor, 2007). Since a ConOps covers all facets of personnel's interactions with a complex system, it offers a good organizational framework for defining the inputs to system development and the categories of requirements that must be set out.

Military projects usually require documented ConOps (DoD, 1995); and it is recommended practice in the aerospace industry (AIAA, 1992). The IEEE (2007) considers identifying a ConOps for system design in industry standards. Examples of the use of ConOps documents include the Federal Highway Administration's ConOps for transportation management systems (DOT, 2004) and the FAA's next-generation air-traffic-control system (FAA, 2007).

We developed a ConOps model consisting of a description of the plant mission, and five supporting dimensions (Figure 3-1), each of which we discuss next.

<u>Plant Mission</u>

A ConOps reflects top-down and bottom-up considerations. From the top, the concept reflects the plant's missions and the high-level goals the system expectedly will achieve. From the bottom, the concept rests on the technological infrastructure needed to support it.

The plant mission can be described in terms of the following parameters:

- Goals and objectives - Electrical generation and safety for current NPPs.

- High-level functions – The functions that must be undertaken (regardless of the performing agent) to achieve the plant's goals and objectives.
- Boundary conditions – These conditions clearly identify the operating envelope of the current design. Clearly identifying the boundary conditions helps define the design's scope and interface requirements.
- Constraints – A constraint is an aspect of the design, such as a specific staffing plan, or the use of specific technology. These constraints are design drivers.

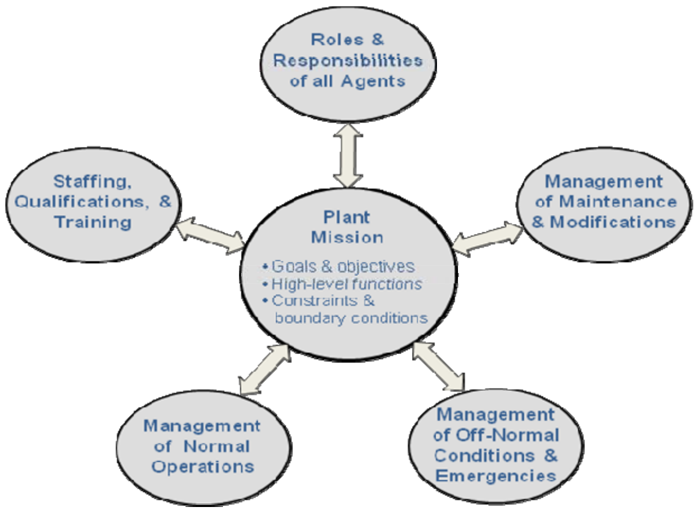

Figure 3-1 Concept of operations dimensions

Roles and Responsibilities of All Agents

This dimension clarifies the relative roles and responsibilities of system's agents, viz., personnel and automation, and their relationship. Modern approaches to automation emphasize the value of multi-agent teams monitoring and controlling complex systems. The teams, consisting of human-, software-, and hardware-elements, work together, sharing and shifting responsibilities to support the plant's overall missions of production and safety. Here, the term "agents" generically refers to who/what is performing an activity; i.e., agents are entities that do things. An agent will monitor the system to detect conditions indicating that a function or task must be performed. An agent will assess the situation and plan a response, and having established the response plan, will implement it. The agent will monitor the activity continuously to assure that the function is being accomplished, and to plan again if it is not. Finally, the agent must decide when the function is completed satisfactorily. Human- or machine-agents can undertake any one or all of these activities.

The definition of human roles and responsibilities is the first step toward human-system integration, from which all other aspects of the ConOps and system design flow. This dimension usually is specified to some level before beginning design work, based on the operating experience of predecessor systems and the goals for developing the new system. These roles then are refined though the HFE program.

Staffing, Qualifications, and Training

This dimension addresses approaches to staffing required to meet human roles (defined in the roles and responsibilities section above) in system operation and maintenance, including staffing positions and levels, and personnel's qualifications. In addition, this dimension includes the ways in which teams will be structured and the types and means of interaction between their members and other people, such as the coordination of crewmember activities, and how peer checks and supervision are accomplished. The training needed to achieve these roles and responsibilities also is addressed.

Management of Normal Operations

This dimension covers the concept of how personnel will operate the plant to assure all functions for normal operations (e.g., to follow its normal evolutions, such as start-up, low power, full power, and shutdown). Specifically, the concept concerns how personnel will interact with the plant's functions, systems, and components to accomplish their main tasks of monitoring and controlling the plant through these evolutions. Also included is job design, viz., the integration of tasks into jobs that specific crewmembers undertake. This dimension addresses concepts about the HSI resources are designed and organized to support personnel task performance.

Management of Off-normal Conditions and Emergencies

This dimension addresses many of the same considerations as do normal operations, except the conditions are off-normal. That is, the dimension encompasses the operators' tasks, and how the HSIs and procedures support their performance. Considerations include

- degraded I&C and HSI conditions (such as a faulty sensor, loss of an aspect of automation, or of electronic communication, or a workstation)
- failed equipment, such as pumps and valves
- loss of plant systems that must be compensated for, such as the failure of cooling water
- emergencies that may impact safety, such as a loss of coolant accident (LOCA)

Identifying such conditions and developing ways to resolve them during operations are very significant considerations that affect the planning and design of operations. For example, if a major digital I&C failure should cause a loss of the control room's HSIs, designers must decide whether personnel should (1) shut the plant down until the condition is fixed, (2) maintain the plant in its current state, or, (3) do something else. Their decisions will significantly influence the types of backup resources that must be provided, the procedures that must be written, and the training that personnel must receive. Handling off-normal conditions often requires crews to transition to a ConOps that differs from that of normal operations (O'Hara et al., 2010a).

Management of Maintenance and Modifications

This dimension looks at the concepts for installing new systems (or, for SMRs, new units), plant upgrades, maintenance, and configuration management. Like the previous two dimensions, considerations involve the tasks that personnel accomplish, and how their performance is supported by HSIs and procedures. For example, much of the maintenance of advanced systems typically occurs at a workstation through changes in software. This approach to maintenance is very different from current practices. Another example is the management and control of operator-initiated changes. New software systems usually have features enabling a user to make changes: again, it is a marked departure from today's practices wherein engineering change procedures control all modifications.

We are using this ConOps model to support our data collection for the next task.

3.2 Issues Related to Multi-module Operations

SMRs fall into three major classes: Integral pressurized water reactors (iPWRs); liquid-metal cooled reactors (LMRs); and, gas-cooled reactors. Each is described briefly below. Table 3-1 lists the specific reactor designs we examined within each class. Sections 5.2.1 through 5.2.6 discuss the key issues in human performance that we identified.

Table 3-1 SMR Reactor Designs

Reactor	Size, MWe	Vendor
Integral PWRs (iPWRs)		
International Reactor Innovative and Secure (IRIS)	335	Westinghouse Electric Corp
NuScale	45	NuScale Power, Inc.
mPower	125	Babcock & Wilcox
Gas-cooled Reactors		
Gas Turbine-Modular Helium Reactor (GT-MHR)*	285	General Atomics
Pebble Bed Modular Reactor (PBMR)* 175		Westinghouse Electric Corp.
Liquid-metal Reactors (LMRs)		
Super-Safe, Small and Simple (4S)	10	Toshiba Corp.
Hyperion Power Module (HPM)	25	Hyperion Power Generation, Inc.
Power Reactor Innovative Small Module (PRISM)	311	GE Hitachi Nuclear Energy

* This design is included in DOE's NGNP Program.

The iPWRs are light water cooled and moderated. They are somewhat typical of PWR technology but their key feature is the elimination of external primary piping and its components. This removal reduces the size of the containment and the overall plant, and eradicates most of the piping that might be susceptible to a LOCA. Thus, the nuclear steam supply system (NSSS) includes the reactor core, steam generators (SGs), and a pressurizer inside one large reactor-pressure vessel (RPV). The reactor coolant may circulate via the reactor coolant pumps (RCPs), also inside the RPV, or typically, they may employ passive safety features, such as natural circulation.

Gas-cooled reactors use helium as the coolant, and graphite as the neutron reflector and moderator. The fuel has very high integrity, and is the primary barrier to the release of radioactivity. These reactors have passive safety characteristics, inherently slow responses to transients, and large safety margins. The US Department of Energy (DOE) selected a gas-cooled reactor as the prototype to be built at Idaho National Laboratory for their Next Generation Nuclear Plant (NGNP). The possibility of producing helium at much higher temperature (~1000° Celsius) confers on these reactors the potential for much greater thermal efficiency.

The LMRs are liquid-metal cooled reactors, using either sodium or lead-bismuth that have a high thermal-conductivity and boiling point. In the primary system, the liquid metal circulates naturally, or electro-magnetic pumps are used. They employ an intermediate cooling system between the primary coolant system and the steam generators. These are fast neutron reactors, rather than thermal ones, and hence, do not need a neutron moderator. Their design assures their use of the full energy potential of uranium, rather than about one percent used by conventional power reactors. They operate at or near atmospheric pressure and have passive safety features (e. g., natural circulation of the primary coolant).

3.2.1 Plant mission

<u>New Goals, Objectives, and Functions</u>

The primary goals of current plants in the United States are producing electricity and operating safely. The plants' systems are designed to meet these goals. While safety invariably is a primary objective of all nuclear plants, using SMRs to provide additional (or alternative) functions beyond electrical production, is being considered. For example, in addition to generating electricity, the steam produced may be used for other industrial applications, such as heating or manufacturing. SMRs may serve other purposes, such as hydrogen production.

These additional plant functions may entail additional responsibilities for personnel, and further requirements for monitoring and control. These new functions may also create new safety issues, such as new hazards. For example, a National Academy of Sciences study (NAS, 2008) of NGNP technology reached the following conclusions:

> The potential need to couple two diverse processes (electric power generation and hydrogen production) complicates the mission of the NGNP. Differing dynamic responses of the reactor to the hydrogen production plant or an electricity generating plant must be carefully assessed for NGNP's single mission project. Design and analytical studies are needed to investigate possible configurations and control schemes. (p. 38)

<u>Lack of Predecessor Plants and Operating Experience</u>

Commercial plants evolved slowly, with new designs improving upon prior ones. Using the operating experience from predecessor plants has been an important aspect of plant design, licensing reviews, and operational improvements through the years. SMRs represent a new category of plant design, and consequently, for many, there are no earlier ones affording operating experience (May & Williams, 2010). The impact of this information gap must be assessed.

3.2.2 Roles and responsibilities of all agents

<u>Degree of Automation</u>

Expectedly, the degree of automation in SMRs will be high and may pose difficulties for operations (Tuan et al., 2007). The "automate all you can automate" philosophy often dominates programs for developing advanced reactors in order to improve performance and decrease operational costs. However, high and low degrees of automation entail human performance issues (O'Hara et al., 2010b).

The right balance must be found between automation and human involvement to assure plant safety. This need lends itself to some new approaches to automation, such as adaptive automation (wherein the degree of automation is dynamic, and changes based on personnel's needs and plant conditions). Automation that is more flexible can better integrate human-automation teams. Thus, the appropriate degree of automation must be identified.

<u>Function Allocation</u>

Allocating functions to human and machine agents is a technical issue that has to be addressed as part of automation. Current methods do not offer specific analytic tools for designers or regulators to decide when to apply new types of automation.

3.2.3 Staffing, qualifications, and training

Perhaps the most readily identified issues to be addressed in SMR licensing are related to plant staffing (Kinsey 2010; Mallett, 2010; May & Williams, 2010; Smith, 2009; Tuan et al., 2007). NRC SECY-10-0034 (NRC, 2010) identifies "Appropriate Requirements for Operator Staffing for Small or Multi-Module Facilities as a potential policy issue that may require changes to existing regulations. Plant staffing can be subdivided into two issues: staffing levels and designated roles and responsibilities of human agents.

<u>Staffing Levels</u>

SMRs are designed to be operated with fewer staff than current plants. For example, one SMR design anticipates assigning one operator to monitor and control four reactor modules, each consisting of a fully integrated reactor and turbine generator. Drivers supporting this approach include the small size of the reactor, its simplicity, high-degrees of automation, modern HSIs, and its slow response to transients. The control room staffing for the baseline configuration of 12 reactor modules encompasses three reactor operators (ROs), one senior reactor operator (SRO) control-room supervisor, one SRO shift manager, and one shift technical advisor (STA). This staffing level is considerably below the current regulations in 10 CFR 50.54M; thus, an exemption is required, as also is likely for most SMR designs. Therefore, a central issue for resolution is the staffing levels needed to safely and reliably monitor and control one or more reactors modules. Further, managing unplanned transients and emergencies might demand additional staff. Recent empirical evidence verified the importance of this issue. Eitrheim et al. (2010) evaluated the performance of three- person crews simultaneously controlling one or two reactors, and found that during difficult phases of the scenarios, task performance was significantly lower when there were two reactors rather than one.

The need for additional staff during planned evolutions, such as module startup, shutdown, refueling also should be addressed. At one refinery where single operators monitor and control multiple units, additional staff are brought in to manage units going through startup and shutdown.

Designated Roles and Responsibilities of Human Agents

An issue closely coupled with staffing levels is assigning crewmember's roles and responsibilities in a control room where multiple reactors are monitored and controlled. The same model is not employed to operate nuclear power plants worldwide. For example, in the United States, plants authorize licensed personnel to operate both the reactor and the balance-of-plant (BOP) systems. In many European plants, the operator's responsibilities and interactions are confined to one or the other. Alternative approaches are also possible (O'Hara et al., 2008b).

Identifying an appropriate model for SMRs must be addressed, as must adding tasks associated with on-line refueling and management of secondary functions.

3.2.4 Management of normal operations

Different Reactivity Effects

Some of the designs incorporate unique features. The HPM is a lead-cooled fast reactor (LFR), and the presence of lead in the core area may entail reactivity effects that differ from those in light-water reactors. For example, a LFR will exhibit little neutron thermalization and have lower Doppler effects. In addition, the temperature coefficient of reactivity will be less negative and neutron lifetime shorter. These features all tend to quicken the dynamics related to core power and transient operations. The operator's control of both reactivity effects, and of overall reactor safety depends on their understanding of them. Generally, complex physical interactions or dynamic behavior in principal processes place added demands on human performance (Papin, 2002). Thus, designs incorporating innovative reactor technologies should include features aimed at mitigating new/additional challenges (e.g., training, automation, design of I&C systems, and controls and displays). The safety impact of these effects and features may require clarification.

Multi-module Control System Architectures for Shared Aspects of SMRs

The integrated control of SMRs and shared systems can be an operational and I&C challenge (Mays & Williams, 2010; Smith, 2009). Discussing the control of modular units, Wood et al. (2003) noted:

> The challenge is to address operability issues of the shared and common systems when the first module is declared operational and the follow-on modules are still under construction. Because of the advances in I&C technology, common data networks that transmit and utilize large amounts of information will serve as integrated data links rather than the traditional direct point-to-point wiring. Thus, the control and monitoring operations of these modules must be fully operational and not susceptible to interference from construction and testing activities in the non-operational modules. Research is needed to address basic guidelines that may include modifications to the data highway and control room design to optimize the construction sequencing. This may result in a control room that is less optimal for human factors at all levels than would otherwise be possible if all the modules simultaneously completed construction. In addition to licensed operation, an option to consider is the use of a dedicated commissioning room in which a module would be commissioned and then "transferred" to the shared control room. (p. 59)

Modular plants may create additional opportunities for the "wrong unit/train" errors noted persistently over the years at dual-unit NPP sites.

Impact of Adding Modules During the Operation of Other Modules

A new issue posed by SMRs is the impact of sequential construction, that is, the effect of adding modules during the operation of other modules (Smith, 2009). How to safely accomplish this challenge should be addressed in both staffing and HSI design.

Refueling

Several SMR designs refuel the reactor on-line or continuously. The need to manage this concurrent activity while the plant is operating must be taken into account as part of the operator's tasks (May & Williams, 2010). Multi-module plants may have some units undergoing refueling while others are in shutdown or operation.

Control Room and Workstation Design

Control room design is a priority issue (Kinsey 2010; Mays & Williams, 2010). For a single reactor and its secondary systems, modern computer-based control rooms typically have a large overview display, several operator workstations, a supervisor's workstation, and supplemental workstations for engineering and maintenance work. A crew of three or more people uses them for managing the plant. The question arises as to how the control room should be designed to support SMR operations when a single control room serves multiple reactors, and where a single operator may be responsible for a reactor and secondary systems, or perhaps of four modules. Undoubtedly, the answers partly depend on the allocation of the crew's responsibilities. Nevertheless, it may be challenging to develop a single workstation to monitor even one reactor module in light of the HSI resources available in today's control room to monitor a single reactor. Expanding that to four modules may prove more difficult.

One SMR designer's preliminary concept suggested that eight monitors are needed to display the alarms, displays, procedures, and controls for a single module. Thus, for four modules, 32 monitors would be needed, and perhaps more for shared systems and/or secondary functions. The ability of a single operator to monitor such a large amount of information may be a problem, and, compared with current NPPs, the likelihood of missing important information might well increase.

HSI Design

The detailed design of alarms, displays, etc., such that a single operator effectively can manage one or more SMRs is an important consideration (Tuan et al., 2007). Several questions arise; should the HSIs associated with each module be separate from those of other modules, or should an integrated representation be used to help operators maintain high-level awareness of the status of all modules for which they are responsible. If the modules are separated, and the operator is focusing on just one of them, then he/she might lose awareness of the status of the other modules. If modules are integrated, it might be problematic to ensure that operators do not confuse information about one module with that about the others. Related to this is the problem of unit differences and how to address them in HSI deign.

HSIs for Secondary Functions

HSIs are needed to support monitoring and controlling of secondary functions, such as hydrogen production, or the industrial use of steam. The question of how these HSIs are integrated into the control room must be addressed.

3.2.5 Management of off-normal conditions and emergencies

Passive Safety Systems

Many SMR designs have passive safety-systems to manage emergencies. These features do not rely on active components, such as pumps, but depend on physical processes. When a condition occurs, such as excessively high temperature, the temperature gradient increases natural circulation. With their dependence on physical processes, passive safety systems are not amenable to routine testing as are active systems. There is not anything to test, e.g., no pumps to start. Some passive systems use valves, but even operating them does not test the process because the condition that would initiate the process does not exist. Thus, operators may not become as familiar with their use as they are with current-generation active systems. They may not know from actual operational experience how to verify their proper automatic initiation and operation the system are required to perform in a real event. For example, there may not be the same observable initiation signals to start systems. Flow rates and temperatures may be much lower, and perhaps not easily verified. The operational aspects of monitoring and verifying the success of passive system success should be defined, along with any of the operator's actions necessary to initiate or back up the passive systems should they fail to operate as designed.

New Hazards

Two of the classes of SMR designs are based on non-light water technology: Gas-cooled designs; and, liquid-metal designs. In contrast to LWR designs, these classes of designs involve new hazards associated with the reactor's technology. They include hydrogen, liquid sodium, liquid fuel, liquid metal, and much higher operating temperatures/pressures, along with the use of high temperature gas, and graphite in the core. For example, under some circumstances, graphite cores are flammable and could create radiologically hazardous fumes. The hazards must be understood and addressed in those safety systems used to monitor and mitigate the hazard, as well as in the HSIs that personnel employ to monitor the plant, the procedures they use to address hazards, and operator training.

Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Module on Other Modules

Unplanned shutdowns or degraded conditions of one module may affect other modules, especially when they share systems (May & Williams, 2010). Operators must be able to detect and assess these impacts; therefore, HSIs are needed to support their management of the situation. A question also arises here about whether support personnel are needed for these events.

Identification of Risk-Important Human Actions (RIHAs)

Modeling SMRs, especially those with shared systems, will be a challenge for probabilistic risk assessments (PRAs) (Smith, 2009; Tuan et al., 2007). Part of that challenge will be the identification of RIHAs. Plant designers typically identify and address them in their HFE programs. This is more challenging since there will be new/unfamiliar systems and there will be little or no operating experience to draw on. If the PRA is more troublesome to quantify, it will become harder to identify RIHAs accurately.

3.2.6 Management of maintenance and modifications

Modular Construction

Many SMRs are designed for modular construction and component replacement. Previously, plant personnel participated in the onsite construction, component-level testing of installed components, and pre-operational testing; hence, they gained a thorough knowledge of plant structures, systems, and components. Fabricating plants at factory locations rather than on the site will limit the plant personnel's knowledge of systems and components. The implications on safety of this approach are unknown.

New Maintenance Practices

Some SMRs will require new maintenance practices. Table 3-2 lists some potential human-factors issues that are specific to each design. In addition, they may be associated with new operational tasks, such as "unplugging" a module and moving it to a maintenance location. Such operations should be analyzed carefully to ensure safety.

Table 3-2 Examples of Potential Maintenance-Related Issues Specific to Each SMR Design

Reactor	Example of Potential Human Performance Issues
Integral PWRs	
IRIS	• The design has eight in-vessel RCPs. Pump seal are replaced in-vessel, which likely will be considered as confined space, with work on contaminated and activated components that will be person-rem intensive. • In-vessel electrical wiring, such as to the RCPs, may require personnel with special qualifications since it will occur in a very harsh environment.
NuScale	• Any SG tube plugging or maintenance will be person-rem intensive. • The design incorporates a natural circulation reactor-coolant loop wherein steam conditions will be less-than-optimal, requiring more maintenance of the turbine blades.
mPower	• Design has the core below the SG so that the latter must be removed during refueling.
Gas-Cooled Reactors	
GT-MHR	• Operators and maintenance staff need extensive training on helium leak hazards and their detection.
PBMR	• Continuous online refueling may pose an operational issue. • Operators and maintenance staff will need extensive training on helium leak hazards and their detection.
Liquid Metal Reactors	
4S	• Sodium is the primary coolant; hence, any maintenance on the two external SGs is hazardous. This will entail specialized training because operators must wear specialized personal protective equipment (PPE). Work must be done in an inert atmosphere. • Since the reactor vessel is sealed, it is unclear how to undertake in-vessel in-service inspection (ISI) or maintenance (i.e., on the reflector electromagnetic pump).
HPM	• Lead/Bismuth is the primary coolant, so that working on two of the three external SGs is hazardous. It will require specialized training since hazards involve the use of specialized PPE. • Since the reactor vessel is sealed, it is unclear how in-vessel ISI or maintenance will be performed.
PRISM	• Sodium is the primary coolant, so that any maintenance on the two external SGs is hazardous. • Work, including refueling every two years and maintaining/replacing coolant pump seals, will have to be done in an inert atmosphere. This will require specialized training since the hazards necessitate using specialized PPE.

4 DISCUSSION

SMRs represent a new stage in the nuclear renaissance. While the development of their ConOps is beginning, it is clear there are significant differences between operating them and operating current plants. The NRC and industry are identifying these differences, and analyzing them to support licensing reviews. Our preliminary findings highlighted several such issues, but additional research undoubtedly is needed. As our research continues, we plan to refine and better define these problems. In addition, we are evaluating the NRC's current regulations and review guidance for SMRs to establish the changes needed to strengthen the licensing reviews.

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