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NRC Reviewer Aid for Evaluating the Human Factors Engineering Aspects of Small Modular Reactors

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NRC Reviewer Aid for Evaluating the Human Factors Engineering Aspects of Small Modular Reactors

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Abstract

Small modular reactors (SMRs) are a promising approach to meeting future energy needs. Although the electrical output of an individual SMR is relatively small compared to that of typical commercial nuclear plants, they can be grouped to produce as much energy as a utility demands. Furthermore, SMRs can be used for other purposes, such as producing hydrogen and generating process heat. The design characteristics of many SMRs differ from those of current conventional plants and may require a distinct concept of operations (ConOps). The U.S. Nuclear Regulatory Commission (NRC) conducted research to examine the human factors engineering (HFE) and the operational aspects of SMRs. The research identified thirty potential human-performance issues that should be considered in the NRC's reviews of SMR designs and in future research activities. The purpose of this report is to support NRC HFE reviewers of SMR applications by identifying some of the questions that can be asked of applicants whose designs have characteristics identified in the issues. The questions for each issue were identified and organized based on the review elements and guidance contained in Chapter 18 of the Standard Review Plan (NUREG-0800), and the Human Factors Engineering Program Review Model (NUREG-0711).

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1 Introduction

Small modular reactors (SMRs) are a promising approach to meeting future energy needs. Although the electrical output of an individual SMR is relatively small compared to that of typical commercial nuclear plants (NPPs), they can be grouped to produce as much energy as a utility demands. Furthermore, SMRs can be used for other purposes, such as producing hydrogen and generating process heat. While much information on concept of operations (ConOps) aspects of SMRs is in the preliminary stages, there are key differences between SMRs and current NPPs that have the potential to impact human performance.

To address these differences, the U.S. Nuclear Regulatory Commission (NRC) is conducting research to examine the human factors engineering (HFE) aspects of SMRs. The main objective was to identify potential issues in human performance related to the design and operations of SMRs. We identified a set of 30 potential human-performance issues to be considered in research and regulatory reviews of SMRs (O'Hara, Higgins, & Pena, in 2012). Since individual SMR designs differ from each other, not all issues described below pertain to all designs. Also, some of the issues identified are not solely related to SMRs, such as passive systems, and non-LWR technology. We were included because they will have to be addressed in SMR licensing reviews, even though they are not strictly limited to SMRs.

One general conclusion from the research was that the issues have implications for the NRC's HFE regulations and design review guidance. Modifications to some HFE regulations and review guidance are likely to be needed to address SMR licensing reviews. For example, the HFE review guidance for integrated system validation may need to be modified to address SMRs by including multi-unit simulation. Until additional guidance is available, HFE reviews can use information about the potential human-performance issues to support their safety evaluations.

The staff's HFE reviews are guided by the following documents:

- Chapter 18, HFE, of the Standard Review Plan (SRP), NUREG-0800 (NRC, 2007)
- Human Factors Engineering Program Review Model , NUREG-0711, Rev 2 (O'Hara et al., 2004) (Note Rev 3 of this document will soon be published)
- Human-system Interface Design Review Guidelines, NUREG-0700, Rev 2(O'Hara et al., 2002)

The review process can accommodate the review of novel technology and new operational approaches using a variety of strategies until more complete, comprehensive review guidance becomes available. Knowledge of key issues provides reviewers with information about what questions to ask SMR design applicants. Knowing what questions to ask is a vital aspect of conducting a design review. This is typically guided by the documents listed above. However, lacking such guidance, knowledge of important aspects of the design that might impact performance provides a basis for seeking information about it. The human-performance identified in the NRC research provides some of these information needs.

The information provided by applicants in response to the NRC staff's questions can be evaluated by:

• adapting existing criteria, e.g., from NUREG-0711 and NUREG-0700

- extrapolating best practices from general HFE principles, such as are presented in 0700, Appendix A
- examining an applicant's tests and evaluations (T&E) that demonstrate the acceptability of a new technology or operational approach (T&E is built into the NUREG-0711 HFE review process; test results can be a good substitute for deterministic review criteria.)
- ensuring the ISV addresses all issues for which limited guidance is available, so they are evaluated in an integrated-systems manner using comprehensive performance measurement

The purpose of this report is to support NRC HFE reviewers of SMR applications by identifying some of the questions that can be asked of applicants whose designs have characteristics identified in the issues.

2 Addressing Potential Human-performance Issues During Safety Reviews

In this section, each of the issues is described, followed by its implication for HFE safety reviews using NUREG-0711. The issue descriptions come directly from the NUREG/CR, with some slight modifications to better suit the purpose of this report.

Then for each issue, we identify the NUREG-0711 elements impacted; and, where possible, suggest the questions and information needed to better understand how the applicant's design addresses the issue. We identified questions for the following NUREG-0711 elements:

- Operating Experience Review (OER)
- Functional Requirements Analysis and Function Allocation (FRA/FA)
- Task Analysis (TA)
- Staffing and Qualifications (S&Q)
- Treatment of Important Human Actions (IHA)
- Human-system Interface Design (HSI)
- Procedure Development (PD)
- Training Program Development (TPD)
- Human Factors Verification and Validation (V&V)

These elements address considerations that the SMR issues relate to. Note that no specific questions were identified for the HFE Program Management element. This element addresses overall program management and, therefore, is not technology specific. Thus it applies to SMRs just as it would to any other application. There are also no question for the elements of Design Implementation and Human Performance Monitoring. These elements address considerations once the design is completed and transitioning to operations. The guidance applies to SMRs, just like it would to any other plant.

Table 2-1 provides an overview of the relationship between the potential SMR human-performance issues and these NUREG-0711 elements. A checkmark indicates that there are questions pertaining to an SMR issue of the NUREG-0711 element identified in the column. We identified questions for the main aspects of the issues as described. We could have generated questions for each review element for many, if not most, of these issues. For example, for the issue of New Hazards, one can ask what the operating experience relative to that hazard is, how the tasks for the hazard, what new qualification (if any) are needed to deal with the hazard, etc. We felt many of these types of question would be routinely picked up in the HFE review. Thus, we instead focused on the key aspects of the issues and identified questions accordingly.

We note that the issues vary in their degree of abstraction. Some, like New Missions, are higher-level. These types of issue tend to be cross-cutting and impact many NUREG-0711 review elements. Others, such as Safety Function Monitoring, are more specifically focused on a detailed aspect of the design. Such issues tend to impact fewer elements.

There are also recurring themes in the questions when one looks across the issues, such as the need to address an issue in validation. Thus there is some redundancy in the questions.

Table 2-1 NUREG-0711 Elements Impacted by Potential SMR Issues

NUREG-0-711 Element	OER	FRA/FA	TA	S&Q	IHA	HSI	PD	TPD	V&V
SMR Issue									
New Missions	✓	✓	✓	✓	✓	✓	✓	✓	
Novel Designs and Limited OE	✓								
Multi-unit Operations and Teamwork	✓			✓		✓	✓		✓
High Levels of Automation		✓	✓			✓			✓
Function Allocation Methodology		✓							
New Staffing Positions				✓				✓	
Staffing Models				✓					✓
Staffing Levels				✓					✓
Different Unit States of Operation				✓		✓	✓	✓	
Unit Design Differences						✓	✓	✓	
Control Systems for Shared Aspects of SMRs						✓	✓		
Impact of Adding New Units on Ops						✓	✓		
Non-LWR Processes and Reactivity Effects		✓				✓	✓	✓	✓
Load-following Operations		✓		✓	✓	✓	✓	✓	✓
Novel Refueling Methods		✓		✓	✓	✓	✓	✓	✓
Control Room Configuration & Workstation Design						✓			✓
HSI Design for Multi-unit Monitoring and Control						✓			✓
HSIs for New Missions						✓			✓
Safety Function Monitoring						✓			✓
Unplanned Shutdowns and Degraded Cond.				✓		✓	✓	✓	✓
Handling Off-Normal Conditions at Multiple Units				✓		✓	✓	✓	✓
Design of EOPs for Multi-Unit Disturbances							✓		✓
New Hazards			✓			✓	✓	✓	✓
Passive Safety Systems			✓			✓	✓	✓	✓
Loss of HSIs and Control Room						✓	✓	✓	✓
PRA Evaluation of Site-wide Risk					✓				
Identification of RIHAs					✓	✓	✓	✓	✓
Modular Construction and Replacement								✓	
New Maintenance Operations					✓	✓	✓	✓	✓
Managing Novel Maintenance Hazards									

While this section presents the questions organized by SMR issue, all of the questions are reorganized by NUREG-0711 element in Appendix A. Since HFE reviews are organized by the NUREG-0711 elements, we think the appendix will be more useful to reviewers than the issue organization presented in this Section. The appendix cross references the SMR issue associated with each question should the reviewer need additional information.

The questions are intended to support NRC HFE reviewers in applying the information gained from the research. It is not intended to be comprehensive, e.g., an issue may have implications for a NUREG-011 element that is not identified. Further, it is possible that an implication we identify is not applicable to a specific design due to its unique characteristics. Thus the reviewer should use this information with these caveats in mind.

Further, we emphasize that this document does *not* contain HFE review guidance. Where we suggest that information be obtained in connection with a specific NUREG-0711 review criterion, it is only a suggestion and should not be interpreted as a proposed modification of the criterion.

2.1 New Missions

Issue Description

The primary mission of current U.S. NPPs is to safely generate of electrical power. Some SMRs are designed to accomplish additional missions, such as producing hydrogen and steam for industrial applications, e.g., heating or manufacturing. Demick (2010) describes these new missions for high-temperature, gas reactors (HTGRs) as follows:

> These applications include supplying process heat and energy in the forms of steam, electricity and high temperature gas to a wide variety of industrial processes including, for example, petro-chemical and chemical processing, fertilizer production, and crude oil refining. In addition to supplying process heat and energy the HTGR [high-temperature gas reactor] can be used to produce hydrogen and oxygen which can be used in combination with steam and electricity from the HTGR plant to produce, for example, synthetic transportation fuels, chemical feedstock, ammonia, from coal and natural gas.)

Achieving these missions will necessitate having new systems and personnel tasks, and possibly, added workload.

Currently, the NRC staff reviews hazards of nearby facilities, such as natural gas. For SMR licensing reviews, these may be onsite and be a mission of the plant. Also, the operators must deal with these new hazards along with reactor-related hazards.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of most HFE elements, including an applicant's operating experience review (OER), functional requirements analysis and function allocation, task analysis, staffing and qualifications, treatment of important human actions, human-system interface (HSI) design, procedure development, training program development, and verification and validation (V&V). Information about how an applicant has considered this issue can be obtained using the following questions.

Operating Experience Review

What operating experience is available for predecessor systems associated with the new missions?

Functional Requirements Analysis and Function Allocation

How are functions associated with new missions addressed in the functional requirements analysis and function allocation?

If pertinent, do the functions and systems associated with new missions interact with those associated with the safe generation of electrical power?

Are systems shared between the various missions that may be implemented at the site?

Describe the level of automation associated with new missions and the personnel roles and responsibilities for them?

If process-heat applications are envisioned for multi-unit sites, are different ones allowed at the same facility, e. g., hydrogen production, steam production, desalination, refining, and electricity production?

Will the new processes associated with these missions create new hazards and safety issues, such as fires and explosions from hydrogen, methane, or natural gas?

Task Analysis

What tasks do personnel have to perform for the new missions?

How do the new mission tasks related to those performed for the safe generation of electrical power?

Staffing and Qualifications

Will new process applications use the same or different operators as the safe generation of electrical power?

Will new staffing positions be created?

How do new missions impact overall staffing?

Treatment of Important Human Actions

Are there important human actions associated with the new missions?

How will important human actions for new missions be identified?

Human-system Interface Design

The impact of new mission on HSI design has been identified as its own issue; see Section 2.18, HSIs for New Missions.

Procedure Development

What procedures will govern new missions?

How do these procedures relate to those used for the safe generation of electrical power mission; will there be integrated procedures addressing tasks for multiple missions?

Training Program Development

Describe the training requirements and demands for new missions?

Will plant operators be trained in dealing with upset conditions in process-heat applications, and other interfacing requirements?

Depending on number of process applications the nuclear facility services, how will these new responsibilities complicate operator training since they must be familiar with all application interfaces?

2.2 Novel Designs and Limited Operating Experience from Predecessor Systems

Issue Description

Commercial NPPs evolved gradually, with new designs improving upon prior ones. Using operating experience from predecessor plants has been an important aspect of plant design, licensing reviews, and operational improvements for years. By contrast, SMRs represent a new category of plant design, and consequently, for many, there is little operating experience; such that that exists may be for research- and demonstration-plants operated as a single unit designed using old technology. For example, in examining the operating experience of a demonstration plant, Beck et al. (2010) and Copinger and Moses (2004) gained only limited insights for HFE. We may have to address and assess the need for operating experience by considering the experience of similar designs and non-nuclear systems. The impact of this information gap and compensatory approaches should be evaluated.

There are two general implications for HFE reviews of this issue. The first implication of this issue is that modifications of the staff's review guidance on operating experience are needed to accommodate a greater diversity of experiences at predecessor plant that likely will contribute to SMR design more than the traditional new-plant designs reviewed to date. Current guidance is based on the way large LWR were designed, viz., small evolutionary changes from specific predecessor plants.

The second implication is that operating experience may be lacking for predecessor designs in comparison with those new reactors that underwent design-certification reviews. Addressing and evaluating this dearth of information should be of the HFE program, e.g., will additional test and evaluations be needed in lieu of operational experience; here, input from SMR vendors may be a valuable source of information.

NUREG-0711 Implications and Questions for Applicants and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's OER. The impact of new missions was identified in Section 2.2 above. Additional information about how an applicant has considered this issue can be obtained using the following questions.

> What are the sources of operating experience contributing to the design of the SMR? Applicants should describe all relevant sources, even those that may come from non-nuclear systems.
>
> What information will be used as a substitute for operating experience for those aspects of the design for which operating experience is unavailable?
>
> How has this operating experience been used in the design?

2.3 Multi-unit Operations and Teamwork

Issue Description

For many designs we examined, a single crew/operator simultaneously monitored and controlled multiple units from one control room. Key issues in effectively and reliably accomplishing this task will be teamwork, situation awareness (SA), control room and HSI design, and the operator's workload. Maintaining sufficient awareness of the status of multiple

SMRs may tax crews and individual operators. For example, unmanned aerial vehicle (UAV) studies found that operators sometimes focus on a particular unit and may neglect others, or fail to notice important changes to them (change blindness).

When operators are focused on a particular problem in current plants, other operators undertake their tasks. Such cooperation may be problematic when each operator is responsible for multiple units. In the oil refinery facility, this situation was resolved augmenting the crew with additional staff during times of high workload or special evolutions. This is a different operational practice than that in present-day control rooms where the on-shift crew manages all aspects of the plant's condition (except accidents).

Maintaining SA may be further challenged when other situational factors intervene (separately identified as issues below):

- individual units can be at different operating states, e.g. different power levels or different states such as shutdown, startup, transients, accidents, refueling and various types of maintenance and testing (see Section 2.9)
- unit design differences often exist (see Section 2.10)

Shift turnovers occur two to three times a day when a new crew relieves the old crew. An effective way is needed to convey the status of each plant, ongoing maintenance, and trends in operation from one crew to another, particularly because more than one plant is involved, and one operator will be operating multiple plants.

An understanding the contribution of situational factors such as these to multi-unit monitoring and control tasks will be important in safety reviews.

Multi-unit monitoring and control is a new type of operation in the commercial nuclear-power industry, with a limited technical basis for developing review guidance for multi-unit operations. Therefore, research is needed to address the issue and identify the considerations that must be accounted for in evaluating applicant submittals for multi-unit operations. We recommend that this research include an extended in-depth study of multi-unit operations in other industries, similar to our use of surrogate systems. Since there is a limited literature to draw on in many industries, site visits may be the best way to obtain data. Having a fuller technical basis rests on identifying the enabling technologies, operational strategies for both normal and off-normal situations, control room and HSI design, and lessons learned; evaluations will demonstrate if the latter can be generalized to NPP operations. In addition, the findings should be compared with NPP specific research to verify that their technical basis is appropriate for resolving NPP-specific issues.

Revisions may be needed, for example, to portions of the regulations in 10 CFR: 50.34(f)(2)(i) on simulators; 50.54(i) - (m) on staffing; and Appendix A, General Design Criterion (GDC), Criterion 19 on control room design. Regulatory guidance may need updating: RG 1.114, guidance to operators at the controls; RG 1.149 and the related ANS 3.5 on simulators; the SRP NUREG-0800 Chapters 13 and 18; and NUREG-1791, guidance for staffing exemptions. Like many issues discussed in this section, the guidance developed likely will impact NUREG-0711 and NUREG-0700.

Related issues are discussed below in Sections 2.7, Staffing Models, and 2.21, Handling of Off-normal Conditions at Multiple Units.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's OER, HSI design, procedure development, training program development, and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Operating Experience Review

What operating experience for multi-unit operations has been collected?

Staffing and Qualifications

How will multi-unit responsibly be assigned to staff?

How will teamwork be assured for multi-unit operations?

Human-system Interface Design

The impact of multi-unit operations on HSI design has been identified as its own issue; see Section 2.17, HSI Design for Multi-unit Monitoring and Control.

Procedure Development

What impact does multi-unit operations have on overall procedure structure and the design of individual procedures?

See also Section 2.22, Design of EOPs for Multi-unit Disturbances.

Human Factors Verification and Validation

How will integrated system validation methodology validate multi-unit operations?

2.4 High Levels of Automation for All Operations and its Implementation

Issue Description

The findings from our surrogate systems emphasized automation as key enabling technology for multi-unit operations. As crews are assigned more units to manage, automation must undertake tasks traditionally performed by operators. SMRs are no exception, and their degree of automation will be high as both normal and safety operations will be automated. The "automate all you can automate" philosophy often dominates programs for developing advanced reactors to improve their performance and decrease operational costs. However, as we noted earlier, there is a complex relationship between automation and human performance, which often fails to confirm common-sense expectations. For example, expectedly high levels of automation will lower workload; instead, it shifts workload and creates other human-performance difficulties, including (O'Hara & Higgins, 2010):

- change in the overall role of personnel that does not support human performance
- difficulty understanding automation
- low workload, loss of vigilance, and complacency

- out-of-the-loop unfamiliarity, and degraded situation-awareness
- difficult workload transitions when operators must assume control when automation fails
- loss of skills since automated tasks seldom are performed
- new types of human error, such as "mode" error[1]

The design of SMRs and their operations must address these potential problems.

Concerns about these negative effects of over-automation increased the usage of more interactive automation implemented at different levels (see Table 2-2). In addition, flexible approaches to using different levels of automation in a single system are being explored. In adaptive automation, its level is dynamic and changes with the needs of personnel and plant conditions. Therefore, this approach may assist operators in managing changing attentional- and workload demands in supervising multiple plants.

Table 2-2 Levels of Automation

Level	Automation Functions	Human Functions
1. Manual Operation	No automation	Operators manually perform all functions and tasks
2. Shared Operation	Automatic performance of some functions/tasks	Manual performance of some functions/task
3. Operation by Consent	Automatic performance when directed by operators to do so, under close monitoring and supervision	Operators monitor closely, approve actions, and may intervene with supervisory commands that automation follows
4. Operation by Exception	Essentially autonomous operation unless specific situations or circumstances are encountered	Operators must approve of critical decisions and may intervene
5. Autonomous Operation	Fully autonomous operation. System or function not normally able to be disabled, but may be manually started	Operators monitor performance and perform backup if necessary, feasible, and permitted

Note: Adapted from O'Hara & Higgins, 2010, Table 3-3.

The reliability of automation also is an important consideration in using it. As automation's reliability declines, operator's performance and trust in the automation is degraded

SMR designs must find the right balance between automation and human involvement to assure plant safety, by determining the right levels of automation and flexibility to support operators in maintaining multi-unit SA and managing workload- demands. In addition, the design of SMR automation should mitigate the types of human performance issues that are associated with high-levels of automation. Licensing reviews of SMRs must determine whether the applicant has reasonably assured the effective integration of automation and operators, and the design supports safe operations.

The pitfalls of high-levels of automation for human performance are well known, as are some of the design characteristics that generate them. The NRC published guidance (O'Hara & Higgins, 2010) on human-automation interactions that should support HFE reviewers in addressing

[1] Automated systems often have a variety of modes in which the inputs used and output provided differ. Operator inputs might have different effects, depending upon each mode's characteristics. Errors result when operators make inputs thinking the system is in one mode when it is in another.

automation in SMR designs. The guidance is being incorporated into NUREGs-0711 and -0700.

While this guidance significantly enhances the staff's reviews, additional research is needed in some areas (O'Hara and Higgins, 2010 detail the research needs listed below):

- models of human-automation teamwork
- reliability
- processes used by automation
- isolation of the effects of automation's dimensions
- triggering mechanisms for adaptive automation
- HSI design

In addition, a lesson learned from the DoD's experience is the difficulty in automating high-level, unmanned-vehicle functions. The NRC's HFE reviewers should pay special attention to applications of SMR automation that extend beyond those typically used in new reactors, since there is little experience with them.

See also the related issues in Section 2.5, Function Allocation Methodology to Support Automation Decisions; and Section 2.11, Operational Impact of Control Systems for Shared Aspects of SMRs.

<u>NUREG-0711 Implications and Questions for Applicants</u>

This issue mainly impacts the NRC staff's evaluation of an applicant's Functional Requirements Analysis and Function Allocation, Task Analysis, and Human-system Interface Design. Information about how an applicant has considered this issue can be obtained using the following questions.

Functional Requirements Analysis and Function Allocation

> How has the applicant's HFE program addressed the human performance issues associated with high-levels of automation?

Task Analysis

> How were personnel tasks identified and analyzed for personnel responsibilities with regard to automatic functions?

Human-system Interface Design

> How are HSIs designed to support the performance of personnel tasks associated their responsibilities for interacting with automatic systems?

Human Factors Verification and Validation

> How is the level of automation and the associated personnel tasks validated to ensure successful performance and to ensure that the human performance concerns associated with high-levels of automation are addressed?

2.5 Function Allocation Methodology to Support Automation Decisions

Issue Description

Under the issue of "High Levels of Automation for All Operations and its Implementation," we discussed establishing various levels of automation and their flexible use by operators. Making design decisions on these two parameters generally is called allocation. An issue facing designers and reviewers is that current allocation methods do not offer specific analytic tools for deciding when and how to apply new types of automation. SMR designers also noted this problem. In discussing automation for the PBMR, Hugo and Engela (2005) observed that most methods of function allocation are "…subjective and prone to error and in projects where human and environmental safety is a concern, it is necessary to use more rigorous methods."

NUREG-0711 gives general guidance for reviewing function allocation in Section 4, Functional Requirements Analysis and Function Allocation. However, modern applications of automation have much flexibility, so that operators face many different types of tasks and interactions (as discussed earlier). The NRC's characterization of automation identified six dimensions: functions, processes, modes, levels, adaptability, and reliability (O'Hara and Higgins, 2010). These dimensions can be combined to design automation for a specific application. However, designers lack methodologies to back-up their decisions as to what combinations are appropriate, i.e., current function-allocation methods do not address such choices; and reviewers lack guidance to evaluate them. Additional research is needed on function allocation; that is, selecting the types of automation and levels of operator involvement to implement for specific applications; the resulting guidance should be included in NUREG-0711.

See also the related issue in Section 2.4, High Levels of Automation for All Operations and its Implementation.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Functional Requirements Analysis and Function Allocation. Information about how an applicant has considered this issue can be obtained using the following question:

> What function allocation methodology, rules, or criteria were used to determine the appropriate level of automation for SMR functions?

2.6 New Staffing Positions

Issue Description

In discussing "New Missions" above, we noted that the industry identified SMR missions beyond safe production of electricity; hence, management may require new staffing positions over current NPPs staffing. As well as the new missions, new positions may be needed to manage design differences between current plants and SMRs, such as reactor transfer and on-line refueling.

The allocation of responsibilities for new missions and new operational activities to shift crew members, either in terms of new positions or new personnel responsibilities must be a part of staffing and qualifications analyses, training program development, and regulatory reviews to determine their potential impact on safety.
This issue has potential impact on 10 CFR 50.54, Staffing, and 50.120, Training.

See also the related issues in Section 2.7, Staffing Models, and Section 2.8, Staffing Levels.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Staffing and Qualifications, and Training Program Development,. Information about how an applicant has considered this issue can be obtained using the following questions.

Staffing and Qualifications

What staffing positions will be responsible to perform tasks associated with new missions (insert specific new SMR mission relevant to the review) and new operational activities (insert new activities relevant to the review)?

Training Program Development

How are the new mission and operational responsibilities addressed in the training program?

2.7 Staffing Models

Issue Description

The concept of "staffing model" addresses the general approaches to fulfilling the organizational functions necessary to operate a NPP, including operations, maintenance, engineering, administration, and security (O'Hara et al., 2008).[2] To meet these responsibilities, utilities employ a combination of on-site staff and off-site personnel. The staffing model chosen is a very significant design decision as it drives many other aspects of the plant's design, including degree of automation, the HSI design, and personnel training.

Current U.S. NPPs have many on-site personnel organized into functional groups. Operations are performed by shifts of reactor operators who the NRC licenses to manage reactor and balance of plant systems. Each shift is expected to manage all phases of plant operations including normal- (e.g., startup, changing power levels, and shutdown) and off-normal-conditions (e.g., equipment failures, transients, and accidents). In certain emergencies, additional staff is brought in to assist. While day-to-day maintenance is handled by on-site staff, outside organizations often come on-site during outages to undertake major maintenance.

[2] Our use of the term "staffing models" should not be confused with "human performance models." The latter refers to models that are (1) mathematical, programmable, and executable rather than purely explanatory; and, (2) applied in the engineering design and evaluation of complex systems.

However, the same model is not employed worldwide. For example, in many European NPPs, the operations shift crew divides responsibilities between a reactor operator who manages the reactor systems, and the balance-of-plant operator who manages the rest of the plant, an approach analogous to the UAV- and refinery-operations we examined. UAV crews split duties between flying/navigating the vehicle, and payload operations. In the refinery, four units were managed, with each operator being responsible for a part of the process and monitored all four units for it.

Definition of staffing models needed for SMRs; they may differ from those in currently operating plants. For example, we noted in our discussion in Section 2.3, Multi-unit Operations and Teamwork, that the crews in some of our surrogate systems where operators monitor multiple units, are augmented with additional staff when dealing with units under high-workload situations (such as during startup or emergencies). Crew flexibility is a key to managing off-normal situations. Thus, at refineries and tele-intensive care units (ICUs), significant organizational changes are needed to manage these situations. In both, additional staff is brought in for off-normal units, and during transitions at the refinery (unit startup or shutdown). Being able to transfer responsibilities for reactors in off-normal states to a person or team specialized in dealing with them may benefit SMR operations.

After defining personnel responsibilities for a particular SMR design, the associated tasks must be assigned to specific staff positions for both normal operations and off-normal/emergency conditions. Depending on the use of automation, these tasks may include the monitoring and control of multiple individual units, shared systems, reactor transfer, online refueling, new missions, and monitoring and backing-up the automation. SMR designers will have to determine the allocations of operator role hat best support overall system performance and safety, and consider the impact on teamwork, e.g., on the peer-checking process.

Changes to staffing models that deviate from current practices are likely to have implications for 10 CFR 50.54 and the various staffing guidance documents, including NUREG-0711, as we further discussed next in Section 2.8, Staffing Levels.

See also the related issues in Section 2.6, New Staffing Positions, and Section 2.8, Staffing Levels.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Staffing and Qualifications and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Staffing and Qualifications

> Will staffing models (general approaches to fulfilling the organizational functions necessary to operate a NPP, including operations, maintenance, engineering, administration, and security) be employed that deviate from current practice?

Human Factors Verification and Validation

> How will integrated system validation methodology validate the new staffing model?

2.8 Staffing Levels

Issue Description

10 CFR 50.54m governs the minimum staffing levels for licensed operators in current plants; it has a table establishing the numbers of operators for one-, two- and three-unit sites. For a one-unit site, one senior reactor operator (SRO), two reactor operators (ROs), and a shift supervisor (second SRO) are required for an operating reactor. For a two-unit site, two SROs and three ROs are needed. A three-unit site needs three SROs and five ROs. The table does not cover sites with more than three units.

Most SMRs for which staffing information is available, propose staffing levels below these requirements and, therefore, an exemption from this staffing regulation is needed. For example, one SMR design anticipates assigning one reactor operator to monitor and control four units, each consisting of a fully integrated reactor and turbine generator. Drivers supporting this approach include the reactor's small size, it's simple, design, high-degree of automation, modern HSIs, and it's slow response to transients. Control-room staffing for the baseline configuration of one SMR design consisting of 12 units encompasses three ROs, one SRO control-room supervisor, one SRO shift manager, and one shift technical advisor (STA). Thus, the staffing levels needed to safely and reliably monitor and control SMR units must be determined and reviewed, possibly addressing new positions and staffing models, as described above.

Staffing levels are identified in 10 CFR 50.54(m); hence, a change in this regulation or an exemption is needed to permit SMRs to deviate from the minimum established. SMR staffing levels was recognized in Issue 4.1, *Appropriate Requirements for Operator Staffing for Small or Multi-Module Facilities* of SECY-10-0034 (NRC, 2010) "…as a potential policy issue that may require changes to existing regulations." Also, staffing levels must be considered in the broader context of new staffing positions and models that might different than those used in currently operating plants and must be reflected in NRC regulations and review guidance.

Until such regulatory changes are made, NUREG-1791 (Persensky, et. al, 2005) provides guidance for reviewing staffing exemptions. The guidance therein reflects the NUREG-0711 HFE review process, and addresses multi-unit operations. So far, the guidance has not been tested or used to evaluate an exemption request. Additional research is warranted aimed at verifying its approach and updating it. If necessary, it should better address the SMR staffing issues in light of the design developments and human-performance considerations since its publication.

See also the related issues in Section 2.5, Staffing Models, and Section 2.6, New Staffing Positions.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Staffing and Qualifications and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Staffing and Qualifications

Will staffing levels will be employed that deviate from current practice?

Human Factors Verification and Validation

How will integrated system validation methodology validate the staffing levels?

2.9 Different Unit States of Operation

Issue Description

Individual SMR units may be in different operating conditions, e.g., different power levels or different states, such as shutdown, startup, transients, accidents, refueling and various types of maintenance and testing. Depending on the staffing model used and the allocation of SMR units to individual operators, the effects must be evaluated of these differences on the operators' workloads and their operators to maintain SA.

See also the related issues in Section 6.20, Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units, and Section 2.21, Handling Off-normal Conditions at Multiple Units.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Staffing and Qualifications, HSI Design, Procedure Development, and Training Program Development. Information about how an applicant has considered this issue can be obtained using the following questions.

Staffing and Qualifications

As a team, how will crews manage units in different states, e.g., will one operator continue to monitor multiple units in different states, or will units in states other than at-power be transferred to a different operator or crew?

What analysis or data are available to demonstrate that operators and crews maintain situation awareness of units in different states and that they will properly respond to unplanned changes in a unit's state and to off-normal conditions?

Human-system Interface Design

How will the HSI be designed to ensure operator awareness of each unit's status?

Procedure Development

How will different unit states be addressed in procedures?

Training Program Development

How are unit differences addressed in operator training?

2.10 Unit Design Differences

Issue Description

The effect of SMR unit differences (heterogeneity) is unresolved. Every surrogate-system organization we contacted deals with unit differences, some of which were significant. At the refinery, these differences aided monitoring by helping operators to distinguish between the units, but for tele-ICU- and UAV-operators, differences complicate operations. There may be differences between the individual units at a given site, between units at different sites, or both.

Since many SMRs are designed to be scalable, units can be added while other units of the plant are operating. Whilst a licensee may plan to have all identical units at a particular site, this may not be achievable due to changes made to improve reliability, lower cost, or deal with obsolescence issues, so impacting, crew and operator reliability. Thus, we need to understand and address the effect of unit differences on SMRs operations.

The research questions stemming from this issue may be qualifying the extent to which differences impact performance, and identifying which aspect of performance affected. Unit differences may support the operator's ability to distinguish between them when monitoring workstation displays; yet, the difference may make situational assessment and response planning more difficult. For example, if the disparities in the units lead to a different interpretation of their status based on parameter displays, it may impair the operator's recognition of performance that deviates from what it should be. Further, if the differences between units lead to the need for different responses, then they may compromise the operator's response and opening an opportunity for operator error; for example, the operator may respond to a disturbance in Unit 2 is appropriate to Unit 1, but inappropriate to Unit 2. The results of research addressing this issue affect the review of procedures as well as HSIs.

For HSIs, we need guidance on whether and how these differences should be depicted in control room HSIs. NUREG-0700 lacks guidance on this issue. Depicting differences with no import on operator's performance could needlessly complicate displays; failing to depict those that impact operator performance may engender difficulty in situation assessment, and operator error.

Furthermore, once the effects on performance of unit differences are determined, the results may help resolve the needs for standardization, for evaluating unit differences using the 50.59 process, or for ways to address it, such as specific HSI design techniques. There are implications also in how to address these unit differences in procedures and training. Should the procedures be common for all units with the differences noted in the appropriate places, or should the procedures be completely separate and different for each unit? Operators must be thoroughly trained in recognizing the differences between units.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's HSI Design. Information about how an applicant has considered this issue can be obtained using the following questions.

Human-system Interface Design

Are there unit differences that can impact operator performance? If so, how are they depicted on the HSIs used by operators?

How was it determined what unit differences should be depicted in plant HSIs?

Procedure Development

How are unit differences addressed in plant procedures?

Training Program Development

How are unit differences addressed in operator training?

2.11 Operational Impact of Control Systems for Shared Aspects of SMRs

Issue Description

In today's typical plants, the control systems manage a single unit. For SMRs, the control systems may manage multiple units in an integrated fashion. This could include systems that the units share in common, such as for circulating water, for the ultimate heat sink for removing decay heat, and systems for instrument air, service-water cooling and AC and DC electric power. It may also include common control of systems that are similar but not shared between units, such as balance-of-plant (BOP) systems. Clayton and Wood (2010) noted that "Multi-unit control with significant system integration and reconfigurable product streams has never before been accomplished for nuclear power, and this has profound implications for system design, construction, regulation, and operations" (p. 146). The integrated control of multiple SMRs and their shared systems can be an operational challenge, as well as an I&C one. The challenge to operators lies in monitoring such a control system to confirm that individual units and shared system are performing properly, and that there are not degradations of the I&C system.

A few additional considerations enhance the challenge. The first is that SMR scalability can make multi-unit operations even more complex as new units are added to the control system. Wood et al. (2003) noted that "…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" (p. 59).

The second is that SMRs may serve multiple missions. That is, systems must be flexibly reconfigured to meet electricity production and other objectives, such as hydrogen production. For example, the operators may need to change the SMR units driving a turbine to produce electricity so they generate hydrogen. Designing operational practices and control rooms to effectively support operators is an important issue to address in design and licensing multi-unit SMRs.

The HFE implications of this issue pertain mainly to HSI design. While NUREG-0700 has guidance on controls, it does not consider how multi-unit and shared system controls should be implemented at operator's workstations. Furthermore, from an HSI design perspective is how to address controls for shared systems when different operators at different workstations monitor the units sharing those systems. There may also be increased opportunities for wrong-unit/wrong-train types of error that need resolution.

Additional implications are the outcomes of degradation of the control system on the operator's detection of malfunctions and SA of the status of units and shared systems.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's HSI Design and Procedure Development. Information about how an applicant has considered this issue can be obtained using the following questions.

HSI Design

> How will shared systems be depicted in the HSIs and how do operators determine that they are performing properly?
>
> How do operators identify degradations of the I&C system; how are they identified in the HSIs?
>
> Will different operators be able to control systems shared between units; if so, how is the control managed?

Procedure Development

> What procedures will be available to support operators in the management of degraded I&C conditions?
>
> How do operators interact with the control systems for shared systems for plant configurations for different missions?

2.12 Impact of Adding New Units While Other Units are Operating

Issue Description

Most SMRs are scalable; that is, multiple units can be grouped at a site to meet a utility's specific power needs. Current construction plans are to have ongoing installation of additional units while earlier units operate at power, in contrast to current practices at multi-unit sites where a Unit 2 under construction is clearly separated from operating Unit 1. The impact of adding new units on a site with existing units must be addressed.

Another consideration is the need to add workstations to a control room to accommodate new units. For current plants, the practice is to erect a stout wall between the operating control room and the control room being built. The wall controls access to the new unit, and limits noise, interruptions, fumes, dust, the potential for construction-related fires and electromagnetic interference from radios, along with other construction work and tests. The shared or common systems typically are included in the operating control room's boundaries.

If construction activities on subsequent units cannot be completely separated from operating units, they might distract operators. Even if separated, there likely will be mechanical and I&C tie-in activities that could cause trips or other operational problems for the operating units. This may be a particular issue in designing the workstation and HSI displays that will be used to monitor and control existing operating units and the new ones under construction.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's HSI Design and Procedure Development. Information about how an applicant has considered this issue can be obtained using the following questions.

Human-system Interface Design

Will any changes be needed to HSIs during the time period when new units are added to the plant?

How will a new unit's HSIs be added to an existing workstation that is being used to monitor and control other units?

How will new workstations that support the operation of new units be introduced in a manner that does not distract or disrupt the monitoring and control of existing units?

Procedure Development

How will the installation of new units impact procedures? Will separate procedures be used during this time?

2.13 Managing Non-LWR Processes and Reactivity Effects

Issue Description

Non-LWR SMR designs incorporate the unique systems and features of their processes, and may have reactivity effects that differ from LWRs. For example, the presence of lead in the core area of HPM, a lead-cooled fast reactor, will involve different reactivity effects from those in light-water reactors. It will exhibit little neutron thermalization, have lower Doppler effects, the temperature coefficient of reactivity will be less negative, and the neutron lifetime shorter. These features all quicken the dynamics of core power and transient operations. The operator's control of both reactivity effects and overall reactor safety depends on their understanding of these effects.

To understand these differences, operators familiar only with LWRs, but transitioning to non-LWR plants, will require special training both in the classroom and on simulators. In addition, the design of the HSI and procedures should particularly aim to supporting the operator's performance. The acceptability of the operator's performance must be specifically tested as part of a thorough an integrated system validation program.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Functional Requirements Analysis and Function Allocation, HSI Design, Procedure Development, Training Program Development, and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Functional Requirements Analysis and Function Allocation

What are the non-LWR processes and systems and what missions do they support?

What is the operator's role in controlling reactivity effects?

Human-system Interface Design

What HSIs are available for reactivity monitoring and control of non-LWRs?

Procedure Development

How is reactivity monitoring and control for non-LWRs addressed in plant procedures?

Training Program Development

How are non-LWR processes addressed in operator training?

How is the control of reactivity effects addressed in operator training?

Human Factors Verification and Validation

How will the performance of non-LWR tasks incorporated into Human Factor V&V?

How will reactivity control performance be validated?

2.14 Load-following Operations

Issue Description

Current day NPPs typically operate at 100% power and provide a base load to the utility's electrical distribution system, i.e., the plants produce electricity for the grid and other producers of electricity compensate for changes in demand. Clayton and Wood (2010) suggested that a base-load mode of operation may not suffice for SMRs that may have to cooperate with other sources of renewable energy whose production is variable because they depend on sun and wind.

Load following is an operating procedure that allows the power output generated by the NPP to vary up or down as determined by the load demanded by the distribution system. It entails more transients, so the plant can increase or decrease both reactor- and turbine-power in response to the external demand. In turn, this requires more actions from operators, and increased monitoring of the response of the automatic systems. In addition, for a multi-unit site, load following may entail the startup and shutdown of units to meet large changes in load demand. Hence, there is more opportunity for equipment failures and operator errors.

Vendors and plant owners, in conjunction with the NRC, will need to decide on the method to implement load following, e.g.:

Method A – A load dispatcher contacts the NPP's shift supervisor for all changes.

Method B – A load dispatcher dials in requested change, and the NPP automatically responds, while the load dispatcher and RO/SRO monitor for the proper response.

Each of the two approaches has its own issues. Method A creates a greater workload and more distractions for the operators. While manual control of a single unit is well within an operator's capability, simultaneously controlling several may be much more difficult and lead to errors.

Method B permits a person not trained in NPP systems and not licensed to change reactivity and power level in the reactor to do so. The NRC has not permitted plants to be operated by an automatic load-following scheme.

Once an acceptable approach is determined, designers will need to define the needed operator tasks to properly manage load-following operations, and to provide HSIs, procedures and training to support them.

Such a change in operating methods might increase risk due to a higher frequency of transients, and should be evaluated via probabilistic risk assessment (PRA) techniques.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Functional Requirements Analysis and Function Allocation, Staffing and Qualifications, Treatment of Important Human Actions, HSI Design, Procedure Development, Training Program Development, and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Functional Requirements Analysis and Function Allocation

> How is load following accomplished and what are the relative roles of NPP personnel; non-plant personnel, such as an external load dispatcher; and automation?

Staffing and Qualifications

> How are load-following operations staffed and what qualifications are needed?
>
> How do load-following duties impact other personnel duties?

Treatment of Important Human Actions

> Are load-following failures modeled in the PRA and are human actions contained in the model?

Human-system Interface Design

> What HSIs are needed for load-following operations and how are they integrated into the overall control room design?

Procedure Development

> What procedures are needed for load-following operations and how are they implemented in the control room? Will there be procedures for off-site load dispatchers?

Training Program Development

What training is necessary for operators to perform load-following operations? Will load dispatchers be trained together with plant operators?

Human Factors Verification and Validation

How will the design of the integrated system for load-following operations be validated?

2.15 Novel Refueling Methods

Issue Description

Several SMR designs refuel the reactor on-line or continuously. While there is international experience with such refueling operations, it will represent a new practice in the United States. Further, in some circumstances, specific approaches to refueling will be novel. Based on information we obtained about the current NuScale refueling concept, there will be online refueling operations where the reactor to be refueled is detached from its mounting position and connected to a crane. The crane then moves the reactor to a refueling bay for disassembly and refueling. The reactor instrumentation is monitored through the entire process. There are four channels of instrumentation and control (I&C). When preparing to move the reactor, first one channel's cable connector is removed from the reactor and attached to the refueling bridge (RB). When the channel on the RB is verified to be reading properly, the second I&C channel is similarly transferred, and then in turn the 3rd and 4th channels are transferred. Control of this reactor is the responsibility of an SRO in the refueling area, not the main control room. One concept under consideration is having a 13th reactor, which would then be moved to replace the one being refueled. Then the reactor could be refueled while the other 12 are still maintaining the full power output of the station.

It is likely that a refueling crew will manage this operation. However, there still are interfaces with the operators of the primary reactor that should be considered, as well as the operations of the refueling crews. The effects of such novel approaches on human performance and plant safety need to be assessed.

Vendors will have to define the methods by which reactors will be refueled, and their impacts on operator performance assessed through HFE analysis and research, particularly by operators responsible for other operating units at the same time. A key policy question here is whether the NRC will allow one operator simultaneously to control both an operating unit and one undergoing refueling.

Depending on the effects of refueling on the operator's performance, additional review guidance may be needed to the review the associated HSIs, procedures, and training. See also, the discussion in Section 2.9, Different Unit States of Operation.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Functional Requirements Analysis and Function Allocation, Staffing and Qualifications, Treatment of Important Human Actions, HSI Design, Procedure Development, Training Program Development, and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Functional Requirements Analysis and Function Allocation

How is refueling accomplished and what are the relative roles of NPP personnel and automation?

Staffing and Qualifications

How are refueling operations staffed and what qualifications are needed?

How do refueling duties impact other personnel duties?

Treatment of Important Human Actions

Are refueling failures modeled in the PRA and are human actions contained in the model?

Human-system Interface Design

What HSIs are needed for refueling operations and how are they integrated into the overall control room design?

Procedure Development

What procedures are needed for refueling operations and how are they implemented in the control room?

Training Program Development

What training is necessary for operators to perform refueling operations?

Human Factors Verification and Validation

How will the design of the integrated system for refueling operations be validated?

2.16 Control Room Configuration and Workstation Design for Multi-unit Teams

This section and the next several address HSI design. In this section, we address the overall layout and design of the control room and its workstations. In subsequent sections other issues pertaining to details of HSI design are identified:

- Section 2.17, HSI Design for Multi-unit Monitoring and Control
- Section 2.18, HSIs for New Missions
- Section 2.19, Safety Function Monitoring

<u>Issue Description</u>

The control room's design, from where three or more people manage the plant, is an important issue. 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. The question is how to design a single control room to support SMR operations encompassing multiple reactors, and where a single person may be responsible for a reactor and its secondary systems for up to four complete units. The answers partly depend on the allocation of the crew's responsibilities. Nevertheless, it may be demanding to design a single workstation to monitor one unit alone in light of the HSI resources needed for today's control room that monitors a single unit; expanding that to four units may prove more challenging.

One SMR designer's very preliminary concept suggested that eight monitors are needed to display the alarms, displays, procedures, and controls for a single unit. Thus, for four units would necessitate 32 monitors. It is unclear whether a single operator could monitor such a large amount of information, and, the chances of missing important data might well increase.

As well as considering multi-unit operations, the design will need to accommodate new tasks, such as moving reactors for refueling, as well as new missions, such as hydrogen production.

Another question is whether the individual unit control stations should be located in one room or in different ones close together. In a single control room, situational factors associated with a single unit, such as alarms and using emergency procedures, may impact the operators monitoring other units. However, accommodating operational staff in one room, allows them to help each other more easily, and they will be easier to supervise. If individual unit-control stations are in separate control rooms, overall supervision, teamwork, and the transitions needed in high workload situations may be more difficult to manage. Also, operations at each unit will be undisturbed by what happens at the others.

Operating multiple units from a single control room is a new practice and research into the workstation and control room configuration is needed to determine appropriate approach to ensure its support of situation awareness and teamwork. As noted earlier, one aspect of this research is to gather experience from other industries on multi-unit operation. In our research to date, we observed both single control rooms and multiple ones.

See also the sections identified at the beginning of this section and Section 2.3, Multi-unit Operations and Teamwork.

<u>NUREG-0711 Implications and Questions for Applicants</u>

This issue mainly impacts the NRC staff's evaluation of an applicant's HSI Design and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Human-system Interface Design

Explain how is the overall control room layout supports:

- multi-unit operations, including reactor operations, BOP systems, shared systems, refueling, etc.
- other personnel responsibilities, for new missions, such as hydrogen production
- maintenance activities performed from the control room

Where are the staff located for minimal, nominal, and maximum staffing levels?

How does the design of the control room support teamwork and supervision tasks?

How are workstations designed/configured to support the responsibilities of individual operators?

Human Factors Verification and Validation

How will the design of the control room and workstations for multi-unit teams be validated?

2.17 HSI Design for Multi-unit Monitoring and Control

Issue Description

The detailed design of HSIs (alarms, displays, and controls) to enable a single operator to effectively manage one or more SMRs is an important feature. HSIs must enable monitoring the overall status of multi-units, as well as easy retrieval of detailed information on an individual unit. This need raises several questions. For example, should the HSIs for with each unit be separate from those of other units, or should they be integrated to help operators maintain high-level awareness of the status of all units for which they are responsible. If the units are separated, and an operator is focusing on one of them, awareness of the status of the other units may be lost. If the information is integrated, it might be a challenge to ensure that operators do not confuse information about one unit with that about the others. Related to this is the problem of how to address unit differences in designing HSIs, as discussed earlier in Section 2.10, Unit Design Differences.

Alarm design is especially important in ensuring that operators are aware of important disturbances, so minimizing the effects of change blindness and neglect.

SMR personnel may also require more advanced I&C and HSI capabilities to support their tasks. For example, systems that provide diagnostics and prognostics support to monitoring and situation assessment activities may be available. How personnel manage and understand these capabilities is an important consideration in overall personnel- and plant-performance.

The organization of information in supporting teamwork is another important HSI factor e.g., deciding what information crew members need to have access to individually, and as a crew, to promote teamwork. A key aspect to be researched is employing a large overview display in a control room with multiple operators, each controlling more than one unit. Its value here may not be so clear-cut and obvious as it is for a single unit's control room.

Another problem is the HSIs needed for shifting control for one unit from one operator to another.

Research should be undertaken to more define the requirements imposed by multi-unit monitoring and control on all HSI resources, and to delineate how they should be integrated into workstation, overview displays, and control room layouts to support multi-unit control rooms.

See also the sections identified at the beginning of Section 2.16, Control Room Configuration and Workstation Design for Multi-unit Teams, and Section 2.3, Multi-unit Operations and Teamwork.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's HSI Design and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Human-system Interface Design

Describe the concept of use and provide an HSI overview for the HSIs for multi-unit operations?

How are the alarms for multiple units presented in the control room and on the workstations? How are alarms presented and how is operator awareness of all high-priority alarms assured?

What HSI features are used to support SA of all units assigned to a single operator or crew accomplished?

How are controls designed for operators to interact with different units from a single workstation?

What design features are implemented to minimize wrong unit errors?

From an HSI standpoint, how is control for one unit transferred from one operator to another?

Human Factors Verification and Validation

How will the HSI design for multi-unit monitoring and control be validated?

2.18 HSIs for New Missions

Issue Description

HSIs are needed to help monitoring and controlling new missions, such as hydrogen production, or the industrial use of steam, so that the question of how to design and integrate them into the control room needs to be addressed.

Note that the NRC design review of the new HSIs themselves likely can use the guidance in NUREG-0700, but it may need to be expanded to guide the interplay between these new functions and the reactor controls. Before researching this issue, more detailed data are needed from SMR designers on how personnel manage new missions, and how their operations are staffed and integrated into the rest of SMR operations.

See also the sections identified at the beginning of Section 2.16, Control Room Configuration and Workstation Design for Multi-unit Teams, and Section 2.3, Multi-unit Operations and Teamwork.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's HSI Design and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Human-system Interface Design

Will HSIs for new missions be available in the main control room; if so, how are they related to the HSIs for the safe generation of electrical power?

Describe the concept of use and provide an HSI overview for the HSIs for new missions?

How will alarms, displays, and control for new missions be integrated with those for reactor and BOP operations?

Human Factors Verification and Validation

How will the HSI design for new missions be validated?

2.19 Safety Function Monitoring

Issue Description

One action taken by the NRC after the accident at the Three-Mile Island NPP was to improve the operating crews' ability to monitor critical safety functions by requiring each plant to install a safety-parameter display system (SPDS) through 10 CFR 50.34(f)(2)(iv). The NRC also published guidance on the characteristics of SPDS in NUREG-0835 (NRC, 1981)), NUREG-1342 (Lapinsky et al., 1989), NUREG-0737 (Supplement 1) (NRC, 1983), and NUREG-0700, Section 5). The specific safety functions and parameters identified in these documents are based on conventional LWRs. However, SMR designs, using HTGRs and LMRs, may require different safety functions and parameters to help operating crews to effectively monitor the plant's safety.

Improving safety-function monitoring is a post-TMI item required by 10 CFR 50.34(f)(2)(iv). A change in this regulation is needed for some SMRs, such as HTGR and LMRs, to address the identification both of the safety functions appropriate for these designs and the important safety parameters that operators will use to monitor them. The new guidance will affect both NUREG-0711 and NUREG-0700. While the guidance must be updated, new research is unlikely to needed to support the formulation of new guidance.

See also the sections identified at the beginning of Section 2.16, Control Room Configuration and Workstation Design for Multi-unit Teams, and Section 2.3, Multi-unit Operations and Teamwork.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's HSI Design and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Human-system Interface Design

What are the critical safety functions and what parameters do operators monitor to determine their status?

How is the critical safety function information presented in the control room?

If operators monitor the safety functions for multiple units, how is the information for individual units presented in the control room and how is operator awareness of each unit assured?

Human Factors Verification and Validation

How will the HSI design for safety function monitoring be validated?

2.20 Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units

Issue Description

Unplanned shutdowns or degraded conditions of one unit may affect other units, especially those sharing systems. Operators must be able to detect and assess these impacts; therefore, HSIs are needed to support their managing the situation. Clear criteria should signal the conditions under which additional personnel must be brought in or the affected unit is transferred to another operator or crew. Further, the design of the main control room (MCR) and the HSI must support the effective transfer of a unit to other operators.

While this is clearly a broad safety issue of interest to many NRC technical disciplines, more research is needed on the operator's tasks, HSIs, procedures, and training essential to successfully manage such situations. The research should reflect approaches proposed by SMR applicants. Guidance is needed for HFE reviews of proposed approach to handle unplanned shutdowns and degraded conditions.

See also the related issues in Section 2.9, Different Unit States of Operation, and Section 2.21, Handling Off-normal Conditions at Multiple Units.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Staffing and Qualifications, HSI Design, Procedure Development, Training Program Development, and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Staffing and Qualifications

Will there be a change in the staff members responsible for the affected unit?

Human-system Interface Design

How will operators detect and monitor the unplanned shutdowns or degraded conditions of one unit while monitoring multiple units?

Procedure Development

How will operating crews handle unplanned shutdowns or degraded conditions of one unit while the others are operating normally?

How will the units operating normally be affected if one unit shutdown or degrades?

Training Program Development

How will the handling of unplanned shutdowns or degraded conditions of one unit while the others are operating normally be addressed in training?

Human Factors Verification and Validation

How will the management of unplanned shutdowns or degraded conditions of one unit while the others are operating normally be validated?

2.21 Handling Off-normal Conditions at Multiple Units

Issue Description

Evaluations are needed of the crew's ability to handle off-normal conditions and emergencies[3] in a control room with multiple units, as we commented on earlier in Sections 2.3 and 2.7. The evaluations should consider the potential for common-cause initiating events that could affect multiple onsite units, or even all of them. Examples are a loss of off-site power and "external events" such as fire, flood, and earthquakes.

As with current plants, changes in the crew, including their augmentation, may be needed to handle off-normal situations. Most SMRs propose having operators/crews monitoring and controlling multiple units. Then, the following questions about off-normal conditions arise.

This issue affects 10 CFR's staffing and emergency-planning regulations and guidance. SMR vendors stated that emergency planning zones might be reduced, potentially lowering the staffing requirements for EP crews.

The resolution of this issue can have a significant impact on staffing, since any increase per SMR unit is multiplied by the number of reactors on site.

See also the related issues in Section 2.9, Different Unit States of Operation, and Section 6.20, Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Staffing and Qualifications, HSI Design, Procedure Development, Training Program Development, and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

[3] Transients occur more frequently than accidents, and are less severe. Examples of transients are reactor or turbine trips, and loss of offsite power, while those of accidents are a stuck-open primary relief valve, and a loss of coolant accident.

Staffing and Qualifications

Will there be a change in the staff members responsible for the affected units?

- With operators controlling multiple reactors, do they need relief if a transient occurs in one of their units? If so, how will it be provided, on-shift or on-call?
- Will the designated transient relief be for the site or per unit?
- Will this relief be an operator or a crew?

How is the number of EP staff determined for off-normal conditions at multiple units?

- Is the number of on-shift EP staff at current plants, adequate for multi-SMR plants?
- Will it apply to the site or does each unit need a designated emergency crew?

Human-system Interface Design

How will operators detect and monitor the handling of off-normal conditions at multiple units?

Will the off-normal units be handled at the same workstation as the normally operating units and with the same or different staff?

Procedure Development

How will operating crews handle off-normal conditions at multiple units?

How will the units operating normally be affected if there are off-normal conditions at multiple units?

Training Program Development

How will the handling of off-normal conditions at multiple units be addressed in training?

Human Factors Verification and Validation

How will the handling of off-normal conditions at multiple units be validated?

2.22 Design of Emergency Operating Procedures (EOPs) for Multi-unit Disturbances

<u>Issue Description</u>

The potential for disturbances at multiple units, particularly ones sharing systems, may necessitate developing emergency operating procedures (EOPs) that consider strategies for responding to multi-unit emergencies from external events, such as loss of grid, earthquakes, high winds, and floods, or from failures of shared systems, such as the ultimate cooling or the switchyard. Responses must be evaluated carefully to account for unit interactions and procedures must ensure the critical safety functions of each unit.

Most new reactor designs have computer-based procedure (CBP) systems to support crews in managing emergency conditions. Their use in managing multi-unit emergencies must ensure the operators are awareness of all units. The procedures likely will have to support use by multiple crew members. CBPs are relatively new operator-support systems in NPPs; the many new demands imposed by multi-unit EOPs will require new functionalities necessitating regulatory review.

The NRC reviews the design and content of EOPs and also their implementation as computer-based procedures under SRP Chapter 13 and 18 reviews. This guidance might need updating if EOPs are modified to cover multi-unit disturbances. In addition, NUREG-0700 contains detailed design review guidelines for CBP that also may need upgrades to address multi-unit applications.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Procedure Development and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Procedure Development

Will each unit have independent procedures or will they be integrated?

How will the execution of common procedures be managed?

Will an EOP be used by more than one crew member; if so, how it that managed?

Will EOPs be implemented as CBPs; if so, how will the CBP address multi-unit disturbances?

Human Factors Verification and Validation

How will EOPs for multi-unit disturbances be validated?

2.23 New Hazards

Issue Description

Two classes of SMR designs are based on non-light water technology: HTGRs, and LMRs. In contrast to LWR designs, they involve new technology-associated hazards, for example, hydrogen, liquid-metal (such as sodium and lead), and much higher operating temperatures and pressures, and the use of high temperature gas, and graphite in the core. Under some circumstances, graphite cores are flammable and could create radiologically hazardous fumes. The hazards must be understood, and then addressed in those safety systems that monitor and mitigate the hazards, in the HSIs that personnel employ to monitor the plant, the procedures they use to address hazards, and in operator training.

Vendors will need to address new hazards and NRC likely will review them as part of the licensing process. Review guidance will be needed for monitoring the HSIs of systems that detect hazards, the procedures identifying appropriate operator actions, and training in the overall management of hazards.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Task Analysis, HSI Design, Procedure Development, Training Program Development, and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Task Analysis

What hazards exist for non-LWR technology aspects of the design and what human actions are needed to manage them?

Human-system Interface Design

How does the HSI alert operators to the presence of (or potential for) upsets associated with each new hazard?

Procedure Development

What procedures are available for use in managing new hazards?

Training Program Development

What training is provided for managing new hazards?

Human Factors Verification and Validation

How will personnel management of new hazards be validated?

2.24 Passive Safety Systems

Issue Description

Like some new reactor designs, SMRs employ passive safety systems to respond to transients and accidents that depend on physical processes rather than active components, such as pumps. For example, should an excessively high temperature be reached, the temperature gradient increases natural circulation. Many passive systems use one or two valves to initiate the process; the valve(s) must be highly reliable.

The IAEA's (2009) expressed concerns about passive systems based on the limited experience with reactor design using such systems:

- The reliability of passive safety systems may not be understood as well as that of active ones.
- There might be undesired interaction between active and passive safety systems.
- It may be difficult to 'turn off' an activated passive safety system after it was passively actuated.
- Implications must be proven of incorporating passive safety features and systems into advanced reactor designs to achieve targeted safety goals; supporting regulatory requirements must be formulated and established.

We note that passive safety systems depending of physical processes are not as amenable to routine testing as are active ones. There are no components to easily test, e.g., no pumps to start. For passive systems with valves, operating them would not fully test the process in the absence of the physical condition that initiates it. Thus, operators may not become as familiar using them as they are with current-generation active systems, nor know from operational experience how to verify the system's proper automatic initiation and operation in a real event. For example, there may not be the same observable initiation signals to start systems. Flow rates and temperatures typically are much lower, and perhaps not as easily verified.

Operational aspects of monitoring and verifying the success of passive systems must be defined, along with any operator's actions needed to initiate or back them up should they fail to operate as designed.

Active safety systems must be tested periodically, so giving operators with the opportunity to become familiar with them. However, there may not be an equivalent opportunity with passive safety systems. Thus, higher reliance on simulators may be needed to assure the operators' familiarity with, and training on, passive safety systems.

Procedures must be written to carefully specify the operator's actions for monitoring, backing-up, and securing passive systems, and NRC's guidance updated to address these new review areas. Additionally, the control room V&V program should encompass these three aspects of operator interaction with passive systems.

<u>NUREG-0711 Implications and Questions for Applicants</u>

This issue mainly impacts the NRC staff's evaluation of an applicant's Task Analysis, HSI Design, Procedure Development, Training Program Development, and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Task Analysis

How are passive features tested?

Are any operator actions needed to initiate passive features?

Are any operator actions needed as back-up, if passive features fail to operate as designed.

Human-system Interface Design

How do operators monitor the status and verify the success of passive systems?

Procedure Development

What procedures are available to guide operator actions for monitoring, backing-up, and securing passive systems?

Training Program Development

How will training enable operators to become familiar with passive systems?

Human Factors Verification and Validation

How will operator interaction with passive systems be validated?

2.25 Loss of HSIs and Control Room

Issue Description

The design of a multi-modular SMR control room should consider the potential loss of HSIs and the entire MCR, taking into account (1) NRC I&C requirements and guidance, and (2) 10 CFR 50 Appendix A, GDC 19, Control Room, and Appendix R. Also, for the site-wide PRA (discussed in Section 2.26 below), the impact of loss of control room and HSIs might consider the following:

- potential loss of the main control room and how to use back-up facilities
- operator errors at one operator workstation may affect multiple units rather than just one
- potential loss of one operator workstation that impacts multiple units
- a site-wide initiating event that likely will impact all units similarly

Using a single MCR for multiple units has implications for various aspects of MCR requirements, guidance, and analyses, including design, PRA and failure analysis, HRA, GDC 19 compliance, MCR evacuation, Appendix R and remote shutdown.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's HSI Design and V&V. Information about how an applicant has considered this issue can be obtained using the following questions.

Human-system Interface Design

How are losses of the HSIs addressed in the HSI design, including:

- degradations or loss of the alarm system
- degradations or loss of the information system
- degradations or loss of the controls
- degradations or loss of the computer-based procedure system
- degradations or loss of an operator workstation
- degradations or loss of multiple workstations
- degradations or loss of the overview display
- loss of I&C
- degradations or loss of the entire MCR?

Procedure Development

What procedures are available to guide operator actions on loss of the HSIs and the MCR?

Training Program Development

How will training enable operators to respond to loss of the HSIs and the MCR?

Human Factors Verification and Validation

How will the response to loss of HSIs and the MCR be validated?

2.26 Probabilistic Risk Assessment Evaluation of Site-wide Risk

Issue Description

Current PRAs in the United States address two- or three-unit sites. However, SMR sites may have many more units. Therefore, modeling SMRs, especially those with shared systems, probably will require new models for PRAs. A single-unit PRA considers common or site-wide systems such as offsite power, AC power on site, the ultimate heat sink, and various cross-connections between units, such as air- and cooling-water-systems. They also cover the effect on individual of site-wide initiating events, such as loss of offsite power, station blackout, seismic events, and external floods.

PRAs may need upgrading to encompass site-wide risk for multiple units. A site-wide PRA may evaluate potential core damage (CD) at multiple units caused by site-wide initiating events and the influences of common systems and a common control room as potential common- cause failures. This site-wide PRA may result in CD at multiple units, but at a lower frequency than for a single unit. However, the PRA level 2 releases could be potentially higher due to CD at multiple units.

The overall issue of site-wide PRAs is a policy issue for the NRC. From an HFE perspective, calculating risk-important human actions (RIHAs) from a site-wide PRA may generate further actions than does a single-unit PRA. These RIHAs will be addressed as part of the applicant's HFE program to ensure they can be reliably performed by plant staff. The treatment of RIHAs is already addressed in HFE reviews via NUREG-0711, so that new guidance for the HFE reviews may be unnecessary. However, additional HRA considerations might be required to identify these RIHAs.

See the discussion in Section 2.27, Identification of RIHAs when One Operator/Crew is Managing Multiple SMRs.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Treatment of Important Human Actions. Information about how an applicant has considered this issue can be obtained using the following questions:

Does the PRA consider the risks associated with multiple units and their shared systems? If so, are there important HAs associated with the multi-unit models?

2.27 Identification of Important Human Actions when One Operator/Crew is Managing Multiple SMRs

Issue Description

An area where new techniques may be needed is the identification of important HAs. This issue originally focused on risk-important HAs (RIHAs) that are identified as part of the HRA element. Subsequent to the identification of this SMR issue, NUREG-0711 was modified to broaden the scope of the HAs considered in the HRA element to include those that are identified deterministically, as well as those identified with the PRA. The NUREG-0711 element name was changed to “Treatment of Important Human Action.” and the more general name for the actions included is “important HAs.” Thus, we discuss this issue with the broader context of important HAs.

Plant designers typically identify and address important HAs in their HFE programs. For SMRs, this is more challenging since there will be new/unfamiliar systems and hence, little or no operating experience to draw on. If the PRA is more troublesome to quantify, it will be harder accurately to identify RIHAs. Similar difficulties may be encountered when the applicant performs deterministic analyses?

Even when the units themselves are deemed independent; i.e., no shared systems and the units are separated physically, there is the potential for human error if the same operator/crew monitors them. For example, the potential for human error for one unit may increase if the operator’s attention is directed to another unit.

Modifications may be needed to deterministic analyses, as well as PRA and HRA methods, to account for these effects.

See also the discussion in Section 2.26, PRA Evaluation of Site-wide Risk.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff’s evaluation of an applicant’s Treatment of Important Human Actions. Information about how an applicant has considered this issue can be obtained using the following questions.

Do the deterministic and PRA analyses consider the effects on HAs associated with:

- operators monitoring multiple units
- new and unfamiliar systems and their potential impact on human error?

If so, are there important HAs associated with these aspects of operations?

2.28 Modular Construction and Component Replacement

Issue Description

Many SMRs are designed for modular construction and component replacement. Some SMR designs will be fabricated at the factory, transported to the plant site, and assembled there. Previously, plant personnel participated in the on-site construction, component-level testing of installed components, and pre-operational testing; hence, they gained a thorough knowledge of structures, systems, and components. Fabricating plants at factories will necessitate changing how personnel obtain knowledge of systems and components that historically was gained (at least partially) via the construction process.

The implications on safety of this approach are unknown, but should be discussed with industry and vendors to determine their plans to resolve this issue.

NUREG-0711 Implications and Questions for Applicants

This issue mainly impacts the NRC staff's evaluation of an applicant's Training Program. Information about how an applicant has considered this issue can be obtained using the following questions.

> How is personnel knowledge of plant systems impacted by modular construction and modular component replacement?
>
> How will the training program address these impacts?

2.29 New Maintenance Operations

Issue Description

Some SMRs will require new maintenance operations whose impact of safety must be assessed. They include operations such as disconnecting a reactor and moving it past other operating reactors to a maintenance location, which will involve decoupling the reactor from all the electrical and mechanical systems while continuously monitoring the reactor throughout the entire process.

In addition, current practices take on new meaning in applying them to SMRs. Current operating practices led to the increase in capacity factors from about 63% several decades ago, to the industry's current 93%. These practices include on-line maintenance. The next generation of plants similarly is likely to employ on-line maintenance practices because the same working fluids (steam and water) and equipment (pumps, motors, valves, piping, and heat exchangers) will be used. Consequently, the SMRs can be expected to be maintained on line, just like their current larger counterparts.

One outcome of continuous on-line maintenance is that the operator will be faced with several units, each in a different configuration due to normal maintenance and surveillance. Research is required to develop displays to show operators the important differences in the configurations of the units they are monitoring, and the acceptable operations. The operator requires an accurate situational awareness of each unit's status. The displays are likely to differ from the current alarm and display strategies.

Plant operators are responsible for the plant and its safe operation including establishing and maintaining it in a condition safe for maintenance personnel. Operators take a system out of service, ensure it is safely isolated during maintenance, and return it to service. The process is difficult enough with one operating crew per unit; it must be evaluated for multiple units. Systems are taken out of, and returned to service under the direction of the control room, typically through a system of locks and tags that signal to maintenance personnel and others when the component and system cannot be operated. Additional research is required into the ways by which operators can maintain safe configuration of multiple units during maintenance.

There are new operations whose impact on safety must to be evaluated. As noted above, current practices applied to SMRs at multi-unit sites may entail different implications. Additional information is needed from vendors about these planned practices, followed by research to determine their effects on performance, and how to design HSIs, procedures, and training to support their safe practice.

<u>NUREG-0711 Implications and Questions for Applicants</u>

This issue mainly impacts the NRC staff's evaluation of an applicant's Treatment of Important Human Actions, HSI Design, Procedure Development, and Training Program Development. Information about how an applicant has considered this issue can be obtained using the following questions.

Treatment of Important Human Actions

What are the impacts of maintenance of one unit on the safety of other units?

Human-system Interface Design

How are maintenance operations and their impact on safety monitored with the HSI?

Procedure Development

What procedures are available to guide personnel in the performance of maintenance operations?

Training Program Development

How will training enable operators to perform maintenance operations?

2.30 Managing Maintenance Hazards

<u>Issue Description</u>

We identified several potential challenges in human factors associated with the maintaining each specific design we examined, e.g.:

- The International Reactor Innovative and Secure (IRIS) design has eight in-vessel reactor coolant pumps (RCPs). Pump seals are replaced in-vessel, likely considered as a confined space, with work on contaminated- and activated-components that are person-rem intensive. This arrangement may increase the difficulty of maintenance and create the potential for delays in needed maintenance, for errors in completing the work, and higher exposures to workers doing it.

- IRIS's in-vessel electrical wiring, such as to the RCPs and internal control rods, may require specially qualified staff, and/or periodic testing for enhanced aging, because it will be operating in a very harsh radiation environment.
- The operations and the maintenance staffs of the Gas Turbine-Modular Helium Reactor (GT-MHR) and the Pebble Bed Modular Reactor (PBMR) need extensive training on the hazards of helium leaks and their detection.
- Sodium is the primary coolant in the Super-safe, Small and Simple (4S) reactor and the Power Reactor Innovative Small Module (PRISM) designs; accordingly, maintenance on the two external steam generators (SGs) is hazardous, and will entail specific training because operators must wear specialized personal protective equipment (PPE) and work in an inert atmosphere.
- Lead/bismuth is the primary coolant in the Hyperion Power Module (HPM), so working on the external SGs may be hazardous, requiring specialized training and the use of particular PPE.

These new maintenance practices should be analyzed carefully to ensure personnel and plant safety.

<u>NUREG-0711 Implications and Questions for Applicants</u>

This issue can most likely be addressed by industry research, and vendors' HFE programs addressing maintenance design and planning, rather than by the NRC; thus we have not identified specific questions to address it.

3 Conclusions

The purpose of this report is to support NRC HFE reviewers of SMR applications by identifying some of the questions that can be asked of applicants whose designs have characteristics identified in the potential human-performance issues pertaining to SMRs. As noted in Section 1, knowledge of key issues provides reviewers with information about what questions to ask SMR design applicants; and knowing what questions to ask is a vital aspect of conducting a design review.

Until comprehensive review guidance becomes available for these issues, the information provided by applicants in response to the NRC staff's questions can be evaluated in a number of ways, outlined in Section 1.

Flexibility is essential in a safety-review process to accommodate the applicant's design innovations that may impact safety. Review strategies, such as we described above, provide a means for an HFE reviewer to address such innovations and applications of new technologies and operational strategies.

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Appendix A - HFE Questions for SMR Applicants Organized by NUREG-0711 Element

In this appendix, the questions identified in Section 2 for each issue are reorganized by NUREG-0711 review element. Following each question, the Section 2 issue associated with the question is identified in parentheses. Reviewers needing additional information about the question should consult the originating issue in Section 2.

A.1 Operating Experience Review

What are the sources of operating experience contributing to the design of the SMR? Applicants should describe all relevant sources, even those that may come from non-nuclear systems. (Novel Designs and Limited Operating Experience from Predecessor Systems)

What operating experience is available for predecessor systems associated with the new missions? (New Missions)

What operating experience for multi-unit operations has been collected? (Multi-unit Operations and Teamwork)

What information will be used as a substitute for operating experience for those aspects of the design for which operating experience is unavailable? (Novel Designs and Limited Operating Experience from Predecessor Systems)

How has this operating experience been used in the design? (Novel Designs and Limited Operating Experience from Predecessor Systems)

A.2 Functional Requirements Analysis and Function Allocation

New Mission Considerations

How are functions associated with new missions addressed in the functional requirements analysis and function allocation? (New Missions)

If pertinent, do the functions and systems associated with new missions interact with those associated with the safe generation of electrical power?

If process-heat applications are envisioned for multi-unit sites, are different ones allowed at the same facility, e. g., hydrogen production, steam production, desalination, refining, and electricity production? (New Missions)

Are systems shared between the various missions that may be implemented at the site? (New Missions)

Describe the level of automation associated with new missions and the personnel roles and responsibilities for them? (New Missions)

Will the new processes associated with these missions create new hazards and safety issues, such as fires and explosions from hydrogen, methane, or natural gas? (New Missions)

New Operational Considerations

What are the non-LWR processes and systems and what missions do they support? (Managing Non-LWR Processes and Reactivity Effects)

What is the operator’s role in controlling reactivity effects? (Managing Non-LWR Processes and Reactivity Effects)

How is load following accomplished and what are the relative roles of NPP personnel; non-plant personnel, such as an external load dispatcher; and automation? (Load-following Operations)

How is refueling accomplished and what are the relative roles of NPP personnel and automation? (Novel Refueling Methods)

Automation Considerations

How has the applicant's HFE program addressed the human performance issues associated with high-levels of automation? (High Levels of Automation for All Operations and its Implementation)

What function allocation methodology, rules, or criteria were used to determine the appropriate level of automation for SMR functions? (Function Allocation Methodology to Support Automation Decisions)

A.3 Task Analysis

New Mission Considerations

What tasks do personnel have to perform for the new missions? (New Missions)

How do the new mission tasks related to those performed for the safe generation of electrical power? (New Missions)

New Operational Considerations

How are passive features tested? (Passive Safety Systems)

Are any operator actions needed to initiate passive features? (Passive Safety Systems)

Are any operator actions needed as back-up, if passive features fail to operate as designed. (Passive Safety Systems)

Automation Considerations

How were personnel tasks identified and analyzed for personnel responsibilities with regard to automatic functions? (High Levels of Automation for All Operations and its Implementation)

Degraded and Off-normal Conditions Considerations

What hazards exist for non-LWR technology aspects of the design and what human actions are needed to manage them? (New Hazards)

A.4 Staffing and Qualifications

New Mission Considerations

Will new process applications use the same or different operators as the safe generation of electrical power? (New Missions)

How do new missions impact overall staffing? (New Missions)

New Operational Considerations

How are load-following operations staffed and what qualifications are needed? (Load-following Operations)

How do load-following duties impact other personnel duties? (Load-following Operations)

How are refueling operations staffed and what qualifications are needed? (Novel Refueling Methods)

How do refueling duties impact other personnel duties? (Novel Refueling Methods)

Multi-Unit Considerations

As a team, how will crews manage units in different states, e.g., will one operator continue to monitor multiple units in different states, or will units in states other than at-power be transferred to a different operator or crew? (Different Unit States of Operation)

What analysis or data are available to demonstrate that operators and crews maintain situation awareness of units in different states and that they will properly respond to unplanned changes in a unit's state and to off-normal conditions? (Different Unit States of Operation)

How will multi-unit responsibly be assigned to staff? (Multi-unit Operations and Teamwork)

How will teamwork be assured for multi-unit operations? (Multi-unit Operations and Teamwork)

Staffing Considerations

What staffing positions will be responsible to perform tasks associated with new missions and new operational activities? (New Staffing Positions)

Will staffing models (general approaches to fulfilling the organizational functions necessary to operate a NPP, including operations, maintenance, engineering, administration, and security, see Section 2.7) be employed that deviate from current practice? (Staffing Models)

Will staffing levels will be employed that deviate from current practice? (Staffing Levels)

Degraded and Off-normal Conditions Considerations

Will there be a change in the staff members responsible for the affected units?

- With operators controlling multiple reactors, do they need relief if a transient occurs in one of their units? If so, how will it be provided, on-shift or on-call?
- Will the designated transient relief be for the site or per unit?
- Will this relief be an operator or a crew? (Handling Off-normal Conditions at Multiple Units and Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units)

How is the number of EP staff determined for off-normal conditions at multiple units?

- Is the number of on-shift EP staff at current plants, adequate for multi-SMR plants?
- Will it apply to the site or does each unit need a designated emergency crew? (Handling Off-normal Conditions at Multiple Units)

A.5 Treatment of Important Human Actions

New Mission Considerations

How will important human actions for new missions be identified? (New Missions)

Are there important human actions associated with the new missions? (New Missions)

New Operational Considerations

Are load-following failures modeled in the PRA and are human actions contained in the model? (Load-following Operations)

Are refueling failures modeled in the PRA and are human actions contained in the model? Novel (Refueling Methods)

What are the impacts of maintenance of one unit on the safety of other units? (New Maintenance Operations)

Multi-Unit Considerations

Does the PRA consider the risks associated with multiple units and their shared systems? If so, are there important HAs associated with the multi-unit models? (Probabilistic Risk Assessment Evaluation of Site-wide Risk)

Do the deterministic and PRA analyses consider the effects on HAs associated with:

- operators monitoring multiple units
- new and unfamiliar systems and their potential impact on human error?

If so, are there important HAs associated with these aspects of operations? (Identification of Important Human Actions when One Operator/Crew is Managing Multiple SMRs)

A.6 Human-system Interface Design

New Mission Considerations

Will HSIs for new missions be available in the main control room; if so, how are they related to the HSIs for the safe generation of electrical power? (HSIs for New Missions)

Describe the concept of use and provide an HSI overview for the HSIs for new missions? (HSIs for New Missions)

How will alarms, displays, and control for new missions be integrated with those for reactor and BOP operations? (HSIs for New Missions)

<u>New Operational Considerations</u>

What are the critical safety functions and what parameters do operators monitor to determine their status? (Safety Function Monitoring)

How is the critical safety function information presented in the control room? (Safety Function Monitoring)

If operators monitor the safety functions for multiple units, how is the information for individual units presented in the control room and how is operator awareness of each unit assured? (Safety Function Monitoring)

How do operators monitor the status and verify the success of passive systems? (Passive Safety Systems)

What HSIs are available for reactivity monitoring and control of non-LWR processes? (Managing Non-LWR Processes and Reactivity Effects)

What HSIs are needed for load-following operations and how are they integrated into the overall control room design? (Load-following Operations)

What HSIs are needed for refueling operations and how are they integrated into the overall control room design? (Novel Refueling Methods)

How are maintenance operations and their impact on safety monitored with the HSI? (New Maintenance Operations)

<u>Multi-unit Considerations</u>

How will the HSI be designed to ensure operator awareness of each unit's status? (Different Unit States of Operation)

Are there unit differences that can impact operator performance? If so, how are they depicted on the HSIs used by operators? (Unit Design Differences)

How was it determined what unit differences should be depicted in plant HSIs? (Unit Design Differences)

How will shared systems be depicted in the HSIs and how do operators determine that they are performing properly? (Operational Impact of Control Systems for Shared Aspects of SMRs)

How do operators identify degradations of the I&C system; how are they identified in the HSIs? (Operational Impact of Control Systems for Shared Aspects of SMRs)

Will different operators be able to control systems shared between units; if so, how is the control managed? (Operational Impact of Control Systems for Shared Aspects of SMRs)

Will any changes be needed to HSIs during the time period when new units are added to the plant? (Impact of Adding New Units While Other Units are Operating)

How will a new unit's HSIs be added to an existing workstation that is being used to monitor and control other units? (Impact of Adding New Units While Other Units are Operating)

How will new workstations that support the operation of new units be introduced in a manner that does not distract or disrupt the monitoring and control of existing units? (Impact of Adding New Units While Other Units are Operating)

Explain how the overall control room layout supports:

- multi-unit operations, including reactor operations, BOP systems, shared systems, refueling, etc.
- other personnel responsibilities for new missions, such as hydrogen production
- maintenance activities performed from the control room (Control Room Configuration and Workstation Design for Multi-unit Teams)

Where are the staff located for nominal, nominal, and maximum staffing levels? (Control Room Configuration and Workstation Design for Multi-unit Teams)

How does the design of the control room support teamwork and supervision tasks? (Control Room Configuration and Workstation Design for Multi-unit Teams)

How are workstations designed/configured to support the responsibilities of individual operators? (Control Room Configuration and Workstation Design for Multi-unit Teams)

Describe the concept of use and provide an HSI overview for the HSIs for multi-unit operations? (HSI Design for Multi-unit Monitoring and Control)

How are the alarms for multiple units presented in the control room and on the workstations?

How are alarms presented and how is operator awareness of all high-priority alarms assured? (HSI Design for Multi-unit Monitoring and Control)

What HSI features are used to support SA of all units assigned to a single operator or crew accomplished? (HSI Design for Multi-unit Monitoring and Control)

How are controls designed for operators to interact with different units from a single workstation? (HSI Design for Multi-unit Monitoring and Control)

What design features are implemented to minimize wrong unit errors? (HSI Design for Multi-unit Monitoring and Control)

From an HSI standpoint, how is control for one unit transferred from one operator to another? (HSI Design for Multi-unit Monitoring and Control)

Automation Considerations

How are HSIs designed to support the performance of personnel tasks associated their responsibilities for interacting with automatic systems? (High Levels of Automation for All Operations and its Implementation)

Degraded and Off-normal Conditions Considerations

How will operators detect and monitor the unplanned shutdowns or degraded conditions of one unit while monitoring multiple units? (Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Unit)

How will operators detect and monitor the handling of off-normal conditions at multiple units? (Handling Off-normal Conditions at Multiple Units)

Will the off-normal units be handled at the same workstation as the normally operating units and with the same or different operators? (Handling Off-normal Conditions at Multiple Units)

How does the HSI alert operators to the presence of (or potential for) upsets associated with each new hazard? (New Hazards)

How are loss of the HSIs and the MCR addressed in the HSI design, including:

- degradations or loss of the alarm system
- degradations or loss of the information system
- degradations or loss of the controls
- degradations or loss of the computer-based procedure system
- degradations or loss of an operator workstation
- degradations or loss of multiple workstations
- degradations or loss of the overview display
- loss of the I&C system
- degradations or loss of the entire MCR? (Loss of HSIs and Control Room)

A.7 Procedure Development

New Mission Considerations

What procedures will govern new missions? (New Missions)

How do these procedures relate to those used for the safe generation of electrical power mission; will there be integrated procedures addressing tasks for multiple missions? (New Missions)

New Operational Considerations

What procedures are available to guide operator actions for monitoring, backing-up, and securing passive systems? (Passive Safety Systems)

How is reactivity monitoring and control for non-LWRs addressed in plant procedures? (Managing Non-LWR Processes and Reactivity Effects)

What procedures are needed for load-following operations and how are they implemented in the control room? Will there be procedures for off-site load dispatchers? (Load-following Operations)

What procedures are needed for refueling operations and how are they implemented in the control room? (Novel Refueling Methods)

What procedures are available to guide personnel in the performance of maintenance operations? (New Maintenance Operations)

Multi-unit Considerations

How will the installation of new units impact procedures? Will separate procedures be used during this time? (Impact of Adding New Units While Other Units are Operating)

What impact does multi-unit operations have on overall procedure structure and the design of individual procedures? (Multi-unit Operations and Teamwork)

How will different unit states be addressed in procedures? (Different Unit States of Operation)

How are unit differences addressed in plant procedures? (Unit Design Differences)

How do operators interact with the control systems for shared systems for plant configurations for different missions? (Operational Impact of Control Systems for Shared Aspects of SMRs)

Degraded and Off-normal Conditions Considerations

Will each unit have independent EOPs or will they be integrated? (Design of Emergency Operating Procedures (EOPs) for Multi-unit Disturbances)

How will the execution of common EOPs be managed? (Design of Emergency Operating Procedures (EOPs) for Multi-unit Disturbances)

Will an EOP be used by more than one crew member; if so, how it that managed? (Design of Emergency Operating Procedures (EOPs) for Multi-unit Disturbances)

Will EOPs be implemented as CBPs; if so, how will the CBP address multi-unit disturbances? (Design of Emergency Operating Procedures (EOPs) for Multi-unit Disturbances)

How will operating crews handle unplanned shutdowns or degraded conditions of one unit while the others are operating normally? (Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units)

How will the units operating normally be affected if one unit shutdown or degrades? (Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units)

How will operating crews handle off-normal conditions at multiple units? (Handling Off-normal Conditions at Multiple Units)

How will the units operating normally be affected if there are off-normal conditions at multiple units? (Handling Off-normal Conditions at Multiple Units)

What procedures are available for use in managing new hazards? (New Hazards)

What procedures will be available to support operators in the management of degraded I&C conditions? (Operational Impact of Control Systems for Shared Aspects of SMRs)

What procedures are available to guide operator actions on loss of the HSIs and the MCR? (Loss of HSIs and Control Room)

A.8 Training Program Development

New Mission Considerations

Describe the training requirements and demands for new missions? (New Missions)

Will plant operators be trained in dealing with upset conditions in process-heat applications, and other interfacing requirements? (New Missions)

Depending on number of process applications the nuclear facility services, how will these new responsibilities complicate operator training since they must be familiar with all application interfaces? (New Missions)

New Operational Considerations

How will training enable operators to become familiar with passive systems? (Passive Safety Systems)

How are non-LWR processes addressed in operator training? (Managing Non-LWR Processes and Reactivity Effects)

How is the control of reactivity effects addressed in operator training? (Managing Non-LWR Processes and Reactivity Effects)

What training is necessary for operators to perform load-following operations? (Load-following Operations)

What training is necessary for operators to perform refueling operations? Will load dispatchers be trained together with plant operators? (Novel Refueling Methods)

How will training enable operators to perform maintenance operations? (New Maintenance Operations)

How is personnel knowledge of plant systems impacted by modular construction and modular component replacement? (Modular Construction and Component Replacement)

How will the training program address these impacts? (Modular Construction and Component Replacement)

Multi-unit Considerations

How are unit differences addressed in operator training? (Different Unit States of Operation and Unit Design Differences)

Degraded and Off-normal Conditions Considerations

How will the handling of unplanned shutdowns or degraded conditions of one unit while the others are operating normally be addressed in training? (Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units)

How will the handling of off-normal conditions at multiple units be addressed in training? (Handling Off-normal Conditions at Multiple Units)

What training is provided for managing new hazards? (New Hazards)

How will training enable operators to respond to loss of the HSIs and the MCR? (Loss of HSIs and Control Room)

Staffing Considerations

How are the new mission and operational responsibilities addressed in the training program? (New Staffing Positions)

A.9 Human Factors Verification and Validation

New Mission Considerations

How will the HSI design for new missions be validated? (HSIs for New Missions)

New Operational Considerations

How will operator interaction with passive systems be validated? (Passive Safety Systems)

How will the performance of non-LWR tasks incorporated into Human Factor V&V? (Managing Non-LWR Processes and Reactivity Effects)

How will reactivity control performance be validated? (Managing Non-LWR Processes and Reactivity Effects)

How will the design of the integrated system for load-following operations be validated? (Load-following Operations)

How will the design of the integrated system for refueling operations be validated? (Novel Refueling Methods)

How will the HSI design for safety function monitoring be validated? (Safety Function Monitoring)

Multi-unit Considerations

How will integrated system validation methodology validate multi-unit operations? (Multi-unit Operations and Teamwork)

How will the design of the control room and workstations for multi-unit teams be validated? (Control Room Configuration and Workstation Design for Multi-unit Teams)

How will the HSI design for multi-unit monitoring and control be validated? (HSI Design for Multi-unit Monitoring and Control)

How will EOPs for multi-unit disturbances be validated? (Design of Emergency Operating Procedures (EOPs) for Multi-unit Disturbances)

Automation Considerations

How is the level of automation and the associated personnel tasks validated to ensure successful performance and to ensure that the human performance concerns associated with high-levels of automation are addressed? (High Levels of Automation for All Operations and its Implementation)

Staffing Considerations

How will integrated system validation methodology validate the new staffing model? (Staffing Models)

How will integrated system validation methodology validate the staffing levels? (Staffing Levels)

Degraded and Off-normal Conditions Considerations

How will the management of unplanned shutdowns or degraded conditions of one unit while the others are operating normally be validated? (Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units)

How will the handling of off-normal conditions at multiple units be validated? (Handling Off-normal Conditions at Multiple Units)

How will personnel management of new hazards be validated? (New Hazards)

How will the response to loss of HSIs and the MCR be validated? (Loss of HSIs and Control Room)