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Human-Performance Issues Related to the Design and Operation 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). In this U.S. Nuclear Regulatory Commission (NRC) research project, we examined the human factors engineering (HFE) and the operational aspects of SMRs. Our main objective was to identify potential issues in human performance related to the design and operations of SMRs. For our purposes, the term “issue” refers to (1) an aspect of SMR development or design for which information suggests a negative impact on human performance; (2) an aspect of SMR development or design that may degrade human performance, but additional research and/or analysis is needed to better understand and quantify the effect; and (3) a technology or technique that will be used in designing new plants or implementing them for which there is little or no review guidance. To accomplish this objective, we first developed a six-dimensional ConOps model that we then used to obtain information about SMRs. Since there is little detailed information about the operational and HFE aspects of SMRs, we also examined several “surrogate facilities,” such as petroleum refineries, wherein operators manage multiple units in a manner similar to what might be expected of SMR operators. We used this information to identify a set of potential human-performance issues that might be considered in the NRC’s reviews of SMR designs and future research activities.

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LIST OF ACRONYMS

Abbreviation/ Acronym	Definition
AA	adaptive automation
ABWR	Advanced Boiling Water Reactor
ADAMS	Agency Wide Document Access and Management Systems
ADS	automatic depressurization system
AIAA	American Institute of Aeronautics and Astronautics
ANS	American Nuclear Society
AP 1000	Advanced Plant 1000
AP 600	Advanced Plant 600
ARL	Army Research Laboratory
ARP	alarm response procedure
ATR	automation target recognition
ATWS	anticipated transient without scram
BNL	Brookhaven National Laboratory
BOP	balance of plant
CBP	computer based procedure
CCR	centralized control room
CFR	Code of Federal Regulations
CNSG	consolidated nuclear steam generator
CONOPS	concept of operations
CV	containment vessel
CVCS	chemical and volume control system
DCD	design control document
DCS	distributed control system
DOE	Department of Energy
DOT	Department of Transportation
EBR	Experimental Breeder Reactor
ECCS	emergency core cooling system
EM	Electromagnetic
EOF	emergency offsite facility
EOP	emergency operating procedures
FAA	Federal Aviation Administration
FCC	fluid catalytic cracker
FFTF	Fast Flux Test Reactor
GDC	General Design Criteria
GE	General Electric
GO	gas oil
GT-MHR	Gas Turbine-Modular Helium Reactor
iPWR	integrated pressurized water reactors
HFAT	Human Factors Assessment Tool
HFE	human factors engineering
HP	human performance
HPM	Hyperion Power Module
HRA	human reliability analysis
HSI	human-system interface
HTGR	High-temperature Gas-cooled Reactor
HVAC	heating, ventilating, and air conditioning

Abbreviation/ Acronym	Definition
IAEA	International Atomic Energy Agency
IAI	intelligent adaptive interfaces
ICU	intensive care unit
IEEE	Institute of Electrical and Electronics Engineers
IHTS	intermediate heat transport system
IHX	intermediate heat exchanger
IMPRINT	Improved Performance Research Integration Tool
INL	Idaho National Laboratory
IRIS	International Reactor Innovative and Secure
ISI	in-service inspection
IST	in-service testing
LFR	Lead-cooled Fast Reactor
LMR	liquid-metal reactor
LOA	levels of automation
LOCA	loss of coolant accident
LOOP	loss of offsite power
LWR	light water reactor
MASLWR	Multi-application Small Light Water Reactor
MCR	main control room
MHR	Modular Helium Reactor
MO	main operator
MWe	megawatts electric
MWt	megawatts thermal
NAS	National Academy of Sciences
NERI	Nuclear Energy Research Initiative
NGNP	Next Generation Nuclear Plant
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NSSS	nuclear steam supply system
OBC	operation by consent
OBE	operation by exception
OM	operation and maintenance
OJT	on-the-job training
OPAS	Operator Performance Assessment System
OSU	Oregon State University
PBMR	Pebble Bed Modular Reactor
PCS	power control system
PL	process lead
PORV	power-operated relief valve
PPE	personal protective equipment
PRA	probabilistic risk assessment
PRISM	Power Reactor Innovative Small Module
PS	production specialists
PWR	pressurized water reactors
RB	refueling bridge
RCCS	reactor cavity cooling system
RCP	reactor coolant pumps
RG	regulatory guides
RO	reactor operator

Abbreviation/ Acronym	Definition
RPS	reactor protection system
RPV	reactor pressure vessel
RSF	remote shutdown facility
SA	situational awareness
SG	steam generators
SMR	small modular reactor
SRO	senior reactor operator
STA	shift technical advisor
THTR	Thorium High-Temperature Reactor
TLX	Task Load Index
TOO	target of opportunity
TR	technical report
TSC	technical support center
UAS	unmanned aircraft systems
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicle
UPS	uninterruptable power supply
UV	unmanned vehicle

1 INTRODUCTION

1.1 Background

The designs of commercial nuclear power plants (NPPs) have evolved over several generations (Figure 1-1). Following the experience gained from early prototype reactors, the first reactors for the commercial production of energy were developed, viz., the Generation II plants that include the NPPs currently operating in the United States. The state-of-the-art commercial nuclear plant today is referred to as a Generation III plant. These plants combine decades-old reactor technology with simplified or passive safety-features, digital instrumentation and control (I&C) systems, and computer-based control rooms.

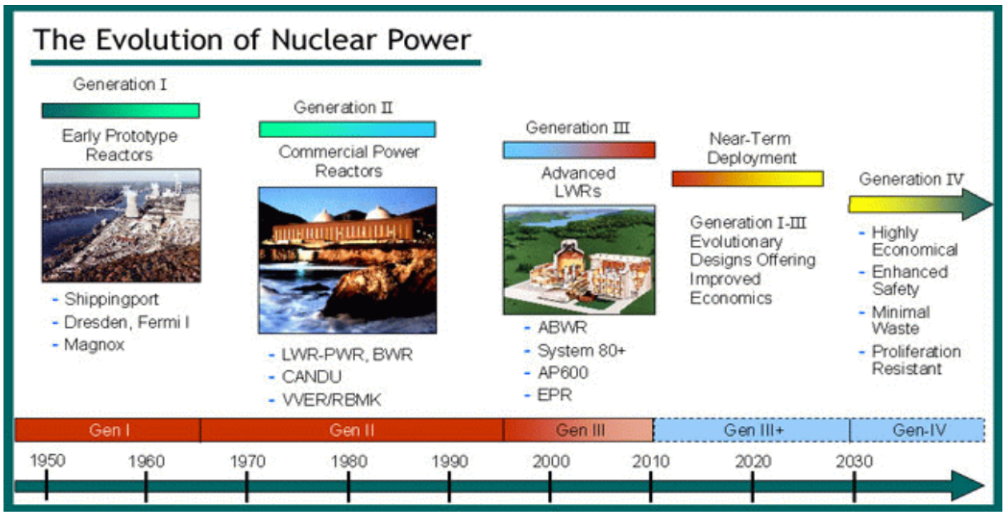

Figure 1-1 Evolution of nuclear-power technology
(source: U.S. Department of Energy – http://nuclear.energy.gov/genIV/neGenIV1.html)

Looking to the longer-term, the United States participated in the International Generation IV reactor initiative[1] (DOE, 2002, 2003) to identify and develop the next generation of commercial nuclear power plants, and also through the U.S. Department of Energy's (DOE) Nuclear Energy Research Initiative (NERI). NERI was established to address and help overcome the principal technical- and scientific-issues affecting the future use of nuclear energy.[2]

Small modular reactors (SMRs) are one category of the new designs. They are smaller than typical current U.S. nuclear plants that may generate over 1000 megawatts electricity (MWe). By contrast, SMRs generate far fewer MWes per unit, many producing less than 100 MWe. According to the classification adopted by the International Atomic Energy Agency (IAEA), a "small reactor" is one with a total possible electrical power of 300 MWe or less; those delivering between 300-700 MWe are called "medium sized reactors" (IAEA, 2005, 2006).[3]

[1] Current information about DOE's Generation IV Program can be found at: http://www.ne.doe.gov/geniv/neGenIV7.html; retrieved March 31, 2011.
[2] Current information about DOE's NERI Program can be found at: http://nuclear.energy.gov/neri/neNERIresearch.html; retrieved March 31, 2011.
[3] The IAEA uses the abbreviation "SMR" to mean small and medium reactors.

Thus, while SMRs are small compared to typical plants operating in the United States today, they are “scalable;” that is, multiple SMR units can be grouped at a site to meet a utility’s specific power-needs. For example, if an SMR produces 100 MWe, a utility needing 200 MWe can install two units at a site, while a second one needing 400 MWe can install four, and so on. As future electrical demands change, additional units can be added as needed, thereby scaling their number to meet the needs of different communities. Another characteristic separating SMRs from current U.S. plants is that they can serve purposes other than power generation, e.g., hydrogen production.

SMRs are “modular.” They can be fabricated in a factory and transported to the plant site for assembly. (We compare SMRs and current reactors more thoroughly in Section 3.)

Thus, SMRs are quite different to current plants. Accordingly, the U.S. Nuclear Regulatory Commission (NRC) initiated research to examine the human-factors aspects of SMR designs and operations to better understand the potential effects on human performance and the need for enhanced guidance to support human factors engineering (HFE) safety reviews.

1.2 Objective

The main objective of our research was to delineate how the design and operations of SMRs differ from current plants and to identify potential human-performance issues. In this report, the term “issue” refers to the following:

- an aspect of the SMR development or design for which information suggests that it may negatively impact human performance
- an aspect of SMR development or design that may degrade human performance, but additional research and/or analysis is needed to better understand and quantify the effect
- a technology or technique that may be used for a plant’s design or implementation for which there is little or no review guidance

The information and insights developed in this report will provide NRC reviewers with a technical basis for better understanding the human performance, and hence, the safety implications of SMR designs for licensing reviews.

1.3 Methodology

Our methodology consisted of the following activities.

Develop a Model of Concept of Operations

According to the Institute of Electrical and Electronics Engineers (IEEE), a “concept of operations” (ConOps):

> …describes system characteristics of the to-be-delivered system from the user’s viewpoint. The ConOps document is used to communicate overall quantitative and qualitative system characteristics to the user, buyer, developer, and other organizational elements (e.g., training, facilities, staffing, and maintenance). It describes the user organization(s), mission(s), and organizational objectives from an integrated systems point of view. (IEEE, 2007, p. 1)

While this is a good definition, we developed it further into a ConOps model that delineated key ConOps dimension. The model was used to collect information about various SMR designs. To facilitate the model's use, we developed a set of questions pertaining to each dimension of the model.

Identify Potential Issues Related to Multi-unit Operations

Using the ConOps model, we evaluated information about SMR designs and operations to identify potential human-performance issues. The design of many SMRs is incomplete and, therefore, information is limited on how the plants will be operated. In addition, there is a lack of operating experience for SMRs. To supplement our knowledge of design, we visited the site of one SMR vendor to better understand the anticipated ConOps and operational challenges. In this report we described the SMR designs as they were when we were conducting the work. Some of this information will be out-of-date after the report is published.

In view of the scarcity of this information, we considered experience with "surrogate facilities" to gain a more thorough knowledge of potential human-performance issues at SMRs. We considered as surrogate facilities ones in which operators manage multiple units in a manner similar to what we might expect from SMR operators. The systems we examined were unmanned vehicles, petroleum refineries, and remote intensive-care medical centers. Although there are important differences between SMRs and these surrogates, there are similarities that afforded us an opportunity to learn about the design and operations of multiple units, and the resulting demands on human performance. We also visited selected facilities to observe and discuss with their staff the challenges of multi-unit operations.

We assessed the implications of the SMR human-performance issues identified by human reliability analysis (HRA). Because SMR operations likely will differ from those in traditional nuclear plants, we sought insights into the aspects of modular operation that impact human reliability, and how the HRA might address them.

From our information on SMRs and surrogate facilities, we identified a set of possible human-performance issues to include in research and regulatory reviews of SMRs. Because our different sources of information often identified the same issues, there is some redundancy in the various sections of this report. Nevertheless, it increases our confidence in the validity of the potential issues we identified.

Evaluate Current NRC Regulation and Guidance

We used the information about SMR design and operations, and human- performance issues, to evaluate the NRC's HFE regulations and regulatory-review guidance to determine the following: (1) Whether they suitably address issues of human performance in SMRs; (2) what modifications of the regulations and guidance might be needed; and (3) which issues will necessitate developing new HFE guidance to support SMR licensing reviews. We detailed our findings in an earlier report (Higgins & O'Hara, 2010).

1.4 Organization of This Report

In Section 2, we describe the multi-dimensional ConOps model and its development, and discuss its role in systems engineering, and in the NRC's HFE review process.

Section 3 describes the design and operation of selected SMRs. We obtained information on them from the following categories of reactor designs: Integral pressurized water reactors; gas-cooled reactors; and liquid-metal reactors. We then evaluated the information for each type of reactor and identified pertinent issues. In contrast to the focus on specific designs in Section 3, in Section 4 we reviewed the general literature pertaining to SMRs.

We present the results of our evaluations of the surrogate facilities in Section 5, viz., the unmanned vehicles, petroleum refineries, and remote intensive-care centers. For each system, we discuss the operational considerations that pertain to SMR operations.

In Section 6, we integrated the issues identified in Sections 3, 4, and 5 into a set of potential human-performance issues, and then organized them according to the dimensions of our ConOps model. Section 7 offers our insights for reviewing the HFE aspects of SMRs.

All cited references are listed in Section 8.

The report has an appendix that lists the questions developed to obtain ConOps information.

2 MODEL OF A CONCEPT OF OPERATIONS

In this section, we discuss the use of ConOps in systems engineering, and in the NRC's review of an applicant's HFE program. We then propose a new HFE-focused ConOps model that we used to support our acquisition and structuring of information for this project.

2.1 Use of Concept of Operations in Systems Engineering

Developing a ConOps is a fundamental component of the systems engineering process for any complex system (Fairley & Thayer, 1977; IEEE, 2007). It is recommended practice in the aerospace industry (AIAA, 1992) and military projects (DoD, 1995, 2000). Examples of the use of ConOps documents include the Federal Highway Administration's ConOps for transportation management systems (DOT, 2004), and the FAA's next-generation air-traffic-control system (FAA, 2007).

The definition of the ConOps for a new system begins before the design work starts, and often is used in the early design stages to identify goals and expectations relative to human performance (Pew & Mavor, 2007). A ConOps covers all facets of the interactions of personnel with a complex system, so affording a good organizational framework for defining the inputs to system development. A ConOps established early in system development will be stated in high-level terms that can be made more specific and detailed as the system is refined. Design guidance recommends using a ConOps document to guide the formulation of requirements, the details of design, and the evaluation of the system. Increasingly, industries are employing a system ConOps to assure their vision of how personnel are integrated into a new system design or major modification (Thronesbery et al., 2009).

Figure 2-1 illustrates the relationship between a ConOps and system design. Design organizations refine and more precisely define the ConOps through analyses, specifying requirements, and evaluations.

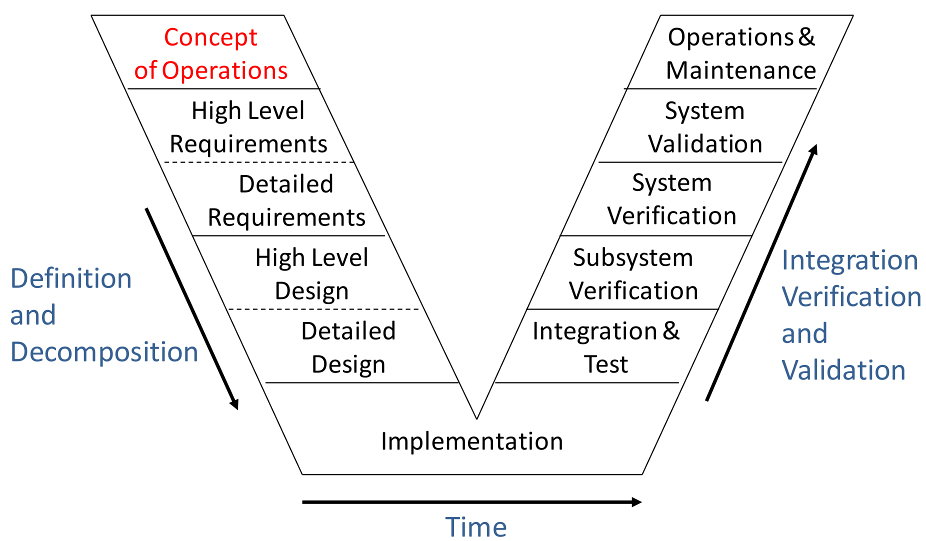

Figure 2-1 Concept of operations in systems engineering
(adapted from DOT, 2009)

2.2 Concept of Operations in NRC HFE Regulatory Reviews

A ConOps document plays an important role in the NRC's review of the HFE aspects of NPPs. Persensky et al. (2005) defined ConOps as a "…description of how the design, systems, and operational characteristics of a plant, such as an advanced reactor, relate to a licensee's or applicant's organizational structure, staffing, and management framework." Although ConOps documents are employed by design organizations for developing systems, the NRC uses them as an information source for reasonably assuring that the intended human-system integration can properly support safe operations.

NUREG-0711 contains detailed HFE review guidance for an applicant's HFE program (O'Hara et al., 2004). Review criterion 1 of Section 8.4.2, Concept of Operations, states:

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

Using the IEEE definition of ConOps (see Section 1.3) as a start, we expanded the use of ConOps in 2008 in support of research addressing HFE issues associated with new and emerging technology (O'Hara et al., 2008). In this project, we further extend the 2008 ConOps model to encompass SMR design and operational considerations.

With the new model (described below), we obtained and structured information on the HFE-relevant aspects of SMR operations. The model also allowed us to organize the human-performance issues and ensure that all important topics were addressed.

2.3 Model Dimensions

We developed an HFE-focused ConOps model to identify all information needed to understand SMR ConOps. The model has six dimensions:

- Plant Mission
- Agents' Roles and Responsibilities
- Staffing, Qualifications, and Training
- Management of Normal Operations
- Management of Off-normal Conditions and Emergencies
- Management of Maintenance and Modifications

Each dimension is described below. We developed the questions, set out in the Appendix, for each dimension to support data collection.

Plant Mission

A ConOps reflects top-down and bottom-up design considerations (Figure 2-2). From the top, ConOps reflects the plant's mission and the high-level goals. From the bottom, it reflects the technological infrastructure needed to support the mission and those goals.

Figure 2-2 Top-down and bottom-up design considerations

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

- *Goals and objectives* - The purposes for which the plant was designed, e.g., for current NPPs, electrical generation and safety.
- *Evolutionary context* – The design of the predecessor plant(s) and the operating experience that set the foundation for the new design, as well as the technological- and operational-changes and improvements that the new plant seeks to achieve.
- *High-level functions* – The functions, e.g., reactivity control, that must be undertaken (regardless of the performing agent) to achieve the plant's goals and objectives.
- *Boundary conditions* – The conditions that clearly identify the operating envelope of the design, i.e., the general performance characteristics within which the design is expected to operate, such temperature and pressure limits. Clearly identifying boundary conditions helps define the design's scope and interface requirements.
- *Constraints* – A constraint is an aspect of the design, e.g., a specific staffing plan or the use of specific technology. These constraints influence the design.[4]

Agents' Roles and Responsibilities

This dimension clarifies the relative roles, responsibilities, and relationship of a system's agents, namely, personnel and automation. Modern approaches to automation emphasize the value of multi-agent teams of human-, software-, and hardware-elements monitoring and controlling

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[4] NUREG-0711 recognizes the importance of identifying constraints in the HFE Program Management review, Section 2.4.1, General HFE Program Goals and Scope, Review Criterion 2.

complex systems (O'Hara & Higgins, 2010). The teams share and shift responsibilities to assure the plant's overall production and safety goals. Here, the term "agents" generically refers to who or what is performing an activity; i.e., agents are entities that perform functions. An agent will monitor the system to detect conditions indicating that a function or task must be performed. An agent will assess the situation and plan a response, and having established the response plan, will implement it. The agent will monitor the activity to assure that the function is being accomplished, and to plan again if it is not. Finally, the agent must decide when the function is completed satisfactorily. Human or machine agents can undertake any one or all of these roles.

Defining human roles and responsibilities is the first step toward integrating humans and systems, from which should flow all other aspects of the ConOps and design. This dimension usually is specified to some level before beginning design work, based on the operating experience from earlier systems, and the goals for developing the new one. These roles then are refined though the HFE program.

Staffing, Qualifications, and Training

This dimension addresses the number and capabilities of staff needed to accomplish the human roles and responsibilities. Staffing should consider organizational functions, including operations, maintenance, and security. Staff positions and the qualifications necessary for each should be defined. The ways must be identified in which teams will be structured and the types and means of interaction between their members and other organizational functions identified, including the coordination of crew member activities, how peer-checks and supervision are accomplished, and how the control-room crews coordinate work with other plant personnel.

The training needed to meet qualification requirements and to perform the human roles and responsibilities should be specified.

Management of Normal Operations

This dimension encompassed three main considerations: Identifying key scenarios; identifying the tasks needed to perform them; and establishing the HSIs and procedures essential to supporting the tasks.

Key scenarios herein include those reflecting the plant's normal evolutions, such as start-up, low power, full power, refueling, and shutdown. For each one, the tasks personnel must accomplish to fulfill their roles and responsibilities are identified, as are the ways in which personnel interact with the plant's functions, systems, and components to complete them, along with the support of automation in monitoring and controlling the plant through these evolutions. Also included is job design, i.e., the integration of tasks into jobs that specific crew members undertake.

The design of HSIs and procedures should support personnel with their task and job assignments. For example, the following concepts for how personnel interact with HSI resources may be specified:

- information distribution, e.g., the types of information that individual crew member access, and the types that are displayed to the entire crew
- the determination of the location of particular HSIs, either in the main control room or at local control stations

- configuration of personnel workplaces, such as a single large workstation, individual ones, or large overview displays

Management of Off-normal Conditions and Emergencies

This dimension addresses many of the same considerations (key scenarios, tasks, and supporting HSI resources) as does normal operations, except the conditions are atypical. Considerations include:

- degraded I&C and HSI conditions (such as a faulty sensor, loss of an aspect of automation, or degradation of a workstation)[5]
- failed equipment, such as pumps and valves
- loss of plant systems for which compensation is needed , such as the failure of a cooling-water system
- emergencies that may impact safety, such as a loss of coolant accident (LOCA)

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

Management of Maintenance and Modifications

This dimension looks at the concepts underlying the installation of new systems, plant upgrades, maintenance, and configuration management. Like the previous two dimensions, the staff's tasks and how the HSIs and procedures support their work must be considered. For example, much of the maintenance of advanced systems typically occurs at a workstation through changes in software. Such activities will be more extensive in new reactor designs relying heavily on digital systems and automation.

2.4 Concept of Operations Questionnaire

We developed the questionnaire in the Appendix to gather information about a facility's ConOps, and tailored the questions to fit each type of facility surveyed.

[5] Digital I&C systems and automation support operators in their monitoring, decision making, and control tasks. Even though digital systems typically are highly reliable, their potential for degradation or failure significantly could affect the operators' performance and, consequently, jeopardize system safety. I&C degradations may affect the user interfaces. For example, deterioration of sensors can complicate the operators' interpretation of displays, and sometimes may mislead them by making it appear that an actual emergency has occurred (O'Hara, Gunther & Martinez-Guridi 2010).

2.5 Conclusions

Developing a ConOps for a new system or system modification is an accepted and recommended practice in systems engineering. Evaluating an applicant's ConOps is an important aspect of the NRC's safety review of an applicant's HFE program for new and advanced reactors. We noted that ConOps documents often are especially useful in the early stages of new system development by forcing consideration of aspects of system design, staffing, and operations.

In designing a new plant such as an SMR, elaborating a ConOps will help define the goals and expectations for the new system, the role personnel will play, and the staffing required. Once the roles of personnel roles are understood, designers can develop concepts for how the HSIs, procedures, and training will support them in performing their tasks. The ConOps also forces debate on how to manage off-normal conditions and system degradations, and to upgrade and improve systems. Thus, the ConOps will begin to define high-level considerations to address as the detailed design evolves.

The six-dimensional ConOps model we developed allowed us to obtain and organize information in the project activities described in the rest of this report.

3 DESIGN AND OPERATIONS OF SMALL MODULAR REACTORS

We earlier noted that SMRs are small relative to typical U.S. plants, modular, scalable and may serve purposes in addition to generating electricity. In this section, we take a closer look at the general design and operational characteristics of SMR comparing their characteristics with those of current U.S. plants, and identifying key differences between them. In addition, we will identify their potential human-performance issues.

The IAEA estimated that more than 45 SMR designs are being developed (IAEA, 2009). Thus, we selected a sample of designs representative of the major SMR technology classes:

- integral pressurized water reactors (iPWRs)
- high-temperature, gas-cooled reactors (HTGRs)
- liquid-metal reactors (LMRs)

Table 3-1 depicts the specific SMR designs included within each class. One consideration in our choosing the specific designs to examine was our expectation of NRC licensing activities over the next decade. However, based on economic factors and others , the SMR landscape is changing rapidly; already, there have been some changes in the NRC’s long-range planning from the time our study began. We have noted these changes where appropriate in the discussion.

Table 3-1 SMR Reactor Class and Designs

Reactor Class and Design	Size, MWe	Vendor
Integral PWRs (iPWRs)		
NuScale	45	NuScale Power, Inc.
International Reactor Innovative and Secure (IRIS)	335	Westinghouse Electric Corp.
mPower	125	Babcock & Wilcox
High-temperature, Gas-Cooled Reactors (HTGRs)		
Gas Turbine-Modular Helium Reactor (GT-MHR)	300	General Atomics
Pebble Bed Modular Reactor (PBMR)	165	PBMR (Pty.), Ltd.
Liquid-Metal Reactors (LMRs)		
4S (super-safe, small and simple) Reactor	10	Toshiba Corp.
Hyperion Power Module (HPM)	25	Hyperion Power Generation, Inc.
Power Reactor Innovative Small Module (PRISM)	415	GE Hitachi Nuclear Energy

In this section, we briefly describe each class of SMRs, giving publicly available information about their specific designs. We sought information for each SMR class pertaining to the ConOps dimensions discussed in Section 2 of this report. Much of the detailed information about the SMRs came from the following reports:

- NRC Advanced Reactors: iPWRs (Belles et al., 2010)
- NRC Advanced Reactors: Modular HTGRs (Ball et al., 2010)
- NRC Advanced Reactors: LMRs (Flanagan et al., 2010)

Other information sources were used and are noted. In addition to reviewing documentation, we visited the site of one SMR design organization to discuss their plans for ConOps. This information discussed in this section was gathered in 2010 and early 2011. Most designs and operations characteristics of these SMRs still were under development and may change as the design process continues. Accordingly, we note that information on our ConOps dimensions generally is in its preliminary stages.

The information on iPWRs, HTGRs, and LMRs, respectively, is discussed in Sections 3.1, 3.2, and 3.3. Section 3.4 presents our assessment of the potential human-performance issues gained from the information we obtained about SMR design and operations.

3.1 Integral Pressurized Water Reactors

The iPWRs are moderated and cooled with light water. They are typical somewhat of PWR technology, e.g., the fuel is similar to that used in present day LWRs. An exception is that their design eliminates external primary piping and components, thereby reducing the size of the containment and overall plant and also most of the piping that is susceptible to a LOCA. The nuclear steam- supply system (NSSS) includes the reactor core, steam generators (SGs), and a pressurizer inside one large reactor pressure vessel (RPV). Reactor coolant circulation may be via reactor coolant pumps (RCPs), also inside the RPV, or via natural circulation.

We examined three iPWR designs:

- NuScale Power's NuScale SMR
- Westinghouse's International Reactor Innovative and Secure (IRIS) SMR
- Babcock & Wilcox's mPower SMR

NuScale

Each NuScale unit comprises a reactor and balance-of-plant (BOP) systems able to generate 45 MWe. In its baseline configuration, a NuScale site will consist of up to 12 units in a common reactor pool. The pool has a three-day passive cooling capacity during a reactor accident before operators must act. The reactor is cooled via natural circulation to two SGs located inside the RPV. The design employs passive safety-features such as natural circulation to prevent fuel damage for postulated accidents. The NSSS is fabricated offsite and will be shipped by rail, truck, or barge to the plant site.

The NuScale concept initially was developed as the Multi-application Small Light Water Reactor between 2000 and 2003 under the DOE's Nuclear Energy Research Initiative (NERI) program. Oregon State University (OSU) improved the design thereafter, and filed concept patents in 2007. OSU built a non-nuclear prototype plant that was used for experiments on, and testing of design concepts.

IRIS[6]

The IRIS SMR has a 335 MWe capacity, although it can be scaled down to approximately 100 MWe. It has an integral primary coolant system and forced circulation using eight in-vessel RCPs, and internal SGs. Passive safety features prevent fuel damage for postulated accident scenarios. It does not have a pressurizer power-operated relief valve (PORV) nor a spray valve for controlling the reactor vessel's pressure, although the non-safety chemical and volume control system (CVCS) offers an auxiliary spray capability.

[6] In February 2011, Westinghouse announced a new SMR design based on the AP1000 plant: http://www.westinghousenuclear.com/smr/index.htm; retrieved March 1, 2011.

The original IRIS design was conceived in the early 1990s, as part of the DOE's NERI program, by an international consortium led by Westinghouse Electric Co.

mPower

A B&W mPower SMR generates 125 MWe per reactor. This SMR basically is a PWR with an integral primary coolant system and forced circulation afforded by up to 12 in-vessel RCPs feeding a single once-through internal steam generator. The reactor core uses 17x17 pin array fuel assemblies with UO_2 pellet fuel. The fuel, clad in zircoloy, is less than 5% enriched. Two feedwater and two steam lines penetrate the reactor vessel. The pressurizer is integrated into the upper head of the reactor vessel with heater rods and a surge path. Normal pressurizer spray, driven by the PCP pressure, is provided through piping with a valve. The charging system provides auxiliary spray. Automatic depressurization system (ADS) valves are connected to the pressurizer, but there is no manual PORV function. The reactor is shut down safely by multiple control-rod assemblies. No boron is used in the primary coolant for reactivity control during normal operations. The containment is a tall cylinder with a domed top located entirely below grade. Equipment access is through a hatch in the containment dome. A polar crane and the refueling water-storage tank are located within containment. The NSSS is designed for offsite fabrication and shipping by rail, truck, or barge to the plant site.

The mPower concept has its roots in a Babcock & Wilcox (B&W) design of a small reactor for the NSSS on the commercial ship NS Savannah, launched in 1959. The NS Savannah NSSS was funded by the U.S. government as a demonstration project for the "Atoms for Peace" initiative. After designing the Savannah reactor, B&W began developing a design for a consolidated nuclear steam generator (CNSG). Its first iteration, including a helical coil SG, was used in the German ship Otto Hahn from 1968 until 1979. The CNSG design was revised several times and the current mPower design evolved from this concept.

Plant Mission

The primary mission of all three iPWR designs is producing electricity. The multi-unit IRIS configuration can provide process heat for industrial applications, such as hydrogen generation or the production of synthetic fuels. It is unclear from the documentation whether a process-heat application would be used in a single-unit configuration.

While the NuScale baseline configuration does not include additional missions, their website[7] discusses secondary uses, such as steam for industrial applications or district heating for communities and large facilities, or for use producing synthetic fuels. The site indicates that "It's also possible to configure a NuScale system to produce steam as its primary purpose with the option of switching to electricity generation in an emergency, and used for a range of low temperature, low pressure applications requiring heated water."

There is no reference to additional missions in the mPower literature.

Agents' Roles and Responsibilities

The high-level functions for iPWRs largely are the same as those for current PWRs. All three designs will be highly automated, but precise details are undetermined. Westinghouse's goal

[7] Information about NuScale applications appears in http://www.nuscalepower.com/ot-Applications-For-Scalable-Nuclear-Technologies.php; retrieved June 29, 2011.

for the IRIS is that reactor startup and shutdown largely will be automated, requiring only minor manual actions by the operator. Other operational tasks, such as surveillances, likely will be automated.

Similarly, NuScale's designers intend to support many operational tasks, such as using partial automation during startup, shutdown, and reactivity control to keep operators aware of the reactor's status. For example, the startup process is divided into several sequences with a checkpoint at the end of each for the operator to verify that it was performed correctly and startup is progressing normally. When it is, the operator initiates the next sequence until the next checkpoint. Thus, both automation and operators have a role in the partially automated process.

In light of NuScale's high levels of automation, Weaver, Harris, and Blomgren (2010, p. 351) identified the following main tasks of the operators:

- initiate unit start-up
- initiate unit shutdown
- provide oversight and permission for automatic controls (e.g., reactivity manipulations) to continue past predefined hold-points
- set or correct process-control parameters to control operating state or plant functions
- initiate corrective action if plant systems fail to operate properly

Most of these actions involve supervising automatic systems; very few human actions will be associated with normal plant operations. Thus, NuScale is investigating potential issues of operators' low workload (discussed in effects on human performance of high levels of automation, Section 3.4, Conclusions).

<u>Staffing, Qualifications, and Training</u>

NuScale anticipates that for a twelve-unit site, the staff will comprise three reactor operators (ROs), a control room supervisor (senior RO), a shift manager, and a shift technical advisor (STA); a profile that will require a staffing exemption request from Title 10, Section 50.54(m), of the *Code of Federal Regulations* (10 CFR 50.54(m)). NuScale plans to follow the methods described in NUREG-1791 (Persensky et al., 2005) and NUREG/CR-6838 (Plott et al., 2004) to detail the technical basis to support the exemption request (NuScale, 2010). They determined that their approach is justifiable because (1) NuScale systems are slow-acting in transients, so operators have time to gain situation awareness (SA) and no rapid actions are needed; and (2) automation will be used extensively.

NuScale designers currently are studying the operator's workload. To determine the maximum- and minimum-values, they are exploring the best ways to measure workload. The methodology will include simulator testing of staffing concepts.

All shifts will include auxiliary operators, and personnel for maintenance, health physics (HP), and chemistry, but their numbers have yet to be determined. In addition, there will be a refueling crew.

At present, NuScale designers expect personnel qualifications to be based on current NPPs. However, some new considerations may have to be made for new missions and novel operations, such as the way a NuScale reactor is refueled (discussed in the “Normal Operations” subsection).

Training requirements have yet to be determined.

Management of Normal Operations

In their multi-unit configurations, all three iPWR SMRs will be monitored and controlled from one control room. NuScale operations will cover up to 12 units. Each RO will manage multiple units from a workstation (discussed below); a significant departure from current practice of assigning a shift crew to each reactor. The high level of automation is one basis for this change. There are times when a second operator will be needed, e.g., when one unit is being started up or shut down; then, one RO will monitor the unaffected units, while the other RO will manage the startup/shutdown operation. Both will work at the workstation.

Because the iPWR SMR designs are scalable, new units can be added while others are continuing operating; so far, this arrangement has not been designed.

A consequence of having a multi-unit site where modules are added over time is that the units are likely to differ; the differences will have to be addressed by personnel.

Refueling a NuScale reactor entails detaching it from its mounting position and connecting it after manually unbolting four large diameter pipes (two steam and two feedwater lines) from the containment vessel. Because the turbine is above the reactor, the steam and feedwater lines will contain water. So far, it is unclear how or to where these pipes will be drained before they are unbolted. NuScale noted that these details will be part of the design for these systems. The crane then moves the reactor to a refueling bay for disassembly and refueling. Operators monitor the reactor’s instrumentation through the entire process. There are four channels of I&C. When preparing to move the reactor, operators first remove one channel’s cable connector from the reactor and attached it to the refueling bridge (RB); after verifying that it is reading properly, the second I&C channel similarly is transferred. NuScale designers have not yet determined whether two or four channels will be transferred to the RB. Control of this reactor is the responsibility of an SRO. One concept NuScale is considering is having a 13th reactor that then would be moved to replace the one being refueled. Meanwhile, the other 12 still would maintain the station’s full power output.

Some information was available on IRIS refueling. The containment is an 82-ft diameter sphere with a top hat allowing access to the reactor vessel; this part of the containment and the reactor vessel’s head are removed during refueling. The refueling cavity is located above containment. The gap between the cavity floor and reactor vessel flange must be sealed during refueling.

The mPower design has the core below the SG, so that the SG must be removed for refueling. The containment portion of the plant is fully below grade.

The NuScale main control room (MCR) will have three RO workstations, a control room supervisor workstation, and a workstation for an STA, (who will be an SRO). Each RO workstation contains the HSIs for each of the multiple reactors being monitored and controlled. NuScale’s current concept is that the information presented will not be integrated across reactors; each reactor will have its own set of monitors. The preliminary estimate is that each reactor will require eight monitors to display its alarms, displays, and controls. NuScale still is uncertain about using a large overview display. Operating procedures have not been developed yet.

NuScale described the process that will be used to design the NuScale control room and HSI (Weaver, Harris, & Blomgren, 2010). Specifically, a work-domain analysis (Vicente, 1999) will be completed to allocate functions and identify task requirements. Tests and evaluations using a simulator will support their staffing plan and HSI design. Weaver et al. noted:

> An HSI will be designed and verified to allow the operator to monitor more than one unit. It is expected that this operational strategy will require a high level of automation and a proven method for transfer between operators of monitoring and control of affected modules during off-normal or accident conditions. (p. 349)

Little information is available on normal operations, control room design, or HSI design for the IRIS and mPower designs.

<u>Management of Off-normal Conditions and Emergencies</u>

NuScale units are designed such that they do not need an operator to respond rapidly to transients and accidents. Instead, the design relies on passive safety systems that require an automatic valve alignment to function. The passive features rely on the reactor pool for cooling; it can function for three days without an operator's action. In response to an event, initially operators will observe the unit's status, and will be unable to take control actions to affect the circulation of coolant. The design also requires each operator to implement and monitor the safe shutdown of multiple units.

NuScale's current plan for handling an event (transient/accident) at one unit is for one RO to monitor the normally operating units, while another RO monitors the affected unit at one control station. However, their designers will establish and verify the capability to transfer control of one unit to another operator if necessary. The supervisor will manage the use of the emergency operating procedures (EOPs).

As we noted earlier, one NuScale unit is designed for a power output of 45 Mwe. About 20- to 25-Mwe will be needed for house loads at a 12-unit station; thus, one unit has the capacity to supply the entire site. Current nuclear plants often operate with house loads supplied from offsite power feeds; NuScale likely will follow the same practice. A loss of offsite power transient will affect all 12 units, but then, a unit can operate in an "island mode," with the reactor/turbine generator supplying in house loads for the site. Additionally, each reactor is designed for 100% steam bypass without a scram, thereby allowing a unit to continue operation during a loss of off-site power event.

The overall plant design basis is for only one "accident" (e. g., LOCA) per site, i.e., the NuScale design-basis accident analysis assumes an accident affecting only one unit.

All mPower ECCS functions are passive in the current concept, and no operator actions are required to mitigate design-basis accidents. mPower has two emergency boron injection tanks that force borated water into the core, driven by pressurizer steam; the purpose of these tanks is mitigating an ATWS. Since vessel/core injection time depends on the in-vessel pressure, and most ATWS events involve high pressure in the reactor vessel, it is unclear whether sufficient boron will enter the core to mitigate the ATWS-generated reactivity insertion in a timely fashion, based on pressurizer steam pressure alone. Hence, ATWS mitigation may require operators to ensure there is a sufficient driving pressure available to these injection tanks.

The documentation we examined indicated that steam from multiple reactors may go to a single turbine. This may complicate an operator's diagnosis of potential BOP-induced upset conditions in a particular reactor.

Little information is available on IRIS operations during off-normal conditions. However, on loss of AC power, the MCR heating, ventilating, and air conditioning (HVAC) will shut down. The habitability of the control room must rely on a three-day supply of compressed air. Because the control room's HVAC also cools the battery and DC equipment rooms needed to monitor safe shutdown of the plant, it is unclear if the planned three-day compressed air supply is sufficient to cool these rooms as well.

Management of Maintenance and Modifications

As the design of the iPWRs is incomplete, information on maintenance and modification practices was sparse.

We noted the NuScale refueling operation of moving the reactor to a refueling bay, an operation also used to maintain the reactor. NuScale is looking into remote maintenance, for example, trouble-shooting by experts not physically located at the plant's site.

The IRIS design has eight in-vessel RCPs and SGs. Pump seal replacement and SG maintenance/repair will be performed in-vessel.

3.2 High-temperature, Gas-cooled Reactors

HTGRs use helium as the coolant, and graphite as the neutron reflector and moderator. The fuel has a ceramic cladding, supporting very high-temperature operation and serving as a primary barrier against the release of radionuclides from the fuel. These reactors have an increased thermal efficiency because the primary coolant, Helium, operates at very high temperatures (~1000° Celsius). These reactors have passive safety characteristics, an inherently slow response to transients, and large safety margins.

The DOE selected a gas-cooled reactor as the Next Generation Nuclear Plant (NGNP).[8] The NGNP reactor has two potential designs, the prismatic type, and the pebble bed type. We examined one of each type:

- General Atomics' Gas Turbine Modular Helium Reactor (GT-MHR) (a prismatic-type reactor)
- PBMR Ltd's Pebble Bed Modular Reactor (PBMR)

We briefly describe each below, before discussing our ConOps dimensions.

GT-MHR

The GT-MHR is a helium-cooled, graphite-moderated, prismatic core, high-temperature reactor that produces 300 MWe. As a commercial power reactor, this design uses uranium dioxide

[8] For information on DOE's NGNP program see http://www.nextgenerationnuclearplant.com/; retrieved March 8, 2011.

(UO_2) particles, enriched to a 19.9% uranium-235 (U-235) content, and are encased in graphite to form a fuel rod. The energy in the heated helium coolant is converted directly into electricity in a gas turbine.

The GT-MHR's low power density and geometry assures the passive dissipation of decay heat by conduction and radiation; it will never reach a temperature that can threaten the integrity of the ceramic-coated fuel particles, even with a total loss of coolant. Using a direct cycle and advanced gas-turbine technology will improve thermal efficiency from the mid 30 percent of current NPPs, to nearly 50 percent.

Both the reactor and the BOP are designed to be located below grade level. The GT-MHR has two active diverse heat-removal systems: the power conversion system, and a shutdown cooling system. Should neither of these active systems be available, an independent passive means removes core decay heat. The reactor-cavity cooling system (RCCS) surrounding the reactor vessel affords sufficient cooling to contain the radionuclides within the coated fuel-particles without needing active safety systems or operator intervention.

The design is based on the standard General Atomics reactor built and operated at Peach Bottom Unit 1 (1967–1974) and at Fort St. Vrain (1976–1989); both were helium-cooled demonstration plants with graphite block fuel (DOE, 2010).

PBMR

The PBMR is a helium-cooled, graphite-moderated high-temperature reactor generating 165 MWe. It consists of a vertical steel pressure-vessel, lined with a layer of graphite bricks that serves as an outer reflector for the neutrons generated in the nuclear reaction, and as a passive-heat transfer medium. This graphite reflector encloses the reactor core. A fully loaded core would contain a bed of 456,000 fuel spheres (pebbles). Each sphere consists of ceramic-coated, low-enriched (less than 20%) UO_2 particles, encased in graphite to form a 60-mm diameter fuel sphere (about the size of a tennis ball). The geometry of the fuel region is annular (ring shaped) and located around a central graphite column that serves as an additional nuclear reflector. The nuclear reaction takes place in this fuel annulus or "pebble bed." Helium flowing through the pebble- bed core removes the heat generated by the nuclear reaction. This helium then is cycled through a power-conversion unit to directly produce electricity via a gas turbine. or indirectly through an external SG, which drives a steam turbine.

The graphite in the fuel sphere and the silicon-carbide coating on the fuel particles form the main barrier preventing the release of radioactivity from the fuel. Due to the vendor's high degree of confidence in the fuel-fabrication process, a pressure-retaining containment may not be required; similarly, because there is no change of phase in the coolant to produce large pressure spikes, high-pressure-engineered safety features are unnecessary. The documentation we reviewed stated no physical process in the reactor's design can produce a radiation hazard outside the site's boundary mainly due to the reactor's low power- density, and the graphite's large heat capacity. Core cooling is maintained even in a loss of all forced convective cooling. Therefore, the PBMR does not require any of the traditional nuclear-safety systems that actively protect the current generation of reactors against a radiation release.

The pebble-bed reactor is based on a previous German test reactor, the Advanced Burner Reactor (ABR), and the Thorium High-temperature Reactor (THTR) (DOE, 2010).

Plant Mission

In addition to generating electricity, the NGNP program identified other missions (Figure 3-1). Demick (2010) recently discussed them in a report on the U.S. energy infrastructure:

> Because it [a high-temperature gas-cooled reactor] operates at a much higher temperature than an LWR (typically operating temperatures of a light water reactor (LWR) are in the range of 300^{o}C), it can be used in commercial applications other than for generation of electricity; the principal application of LWRs to-date. 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 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. Studies performed to the date of this writing and discussions with potential end users have investigated the characteristics of the HTGR that best fit these applications. These studies have concluded that reactor module sizes in the range 200 to 600 MWt operating in the temperature range of 700 to 800^{o}C can satisfy most of the energy needs of these applications. (p. 26).

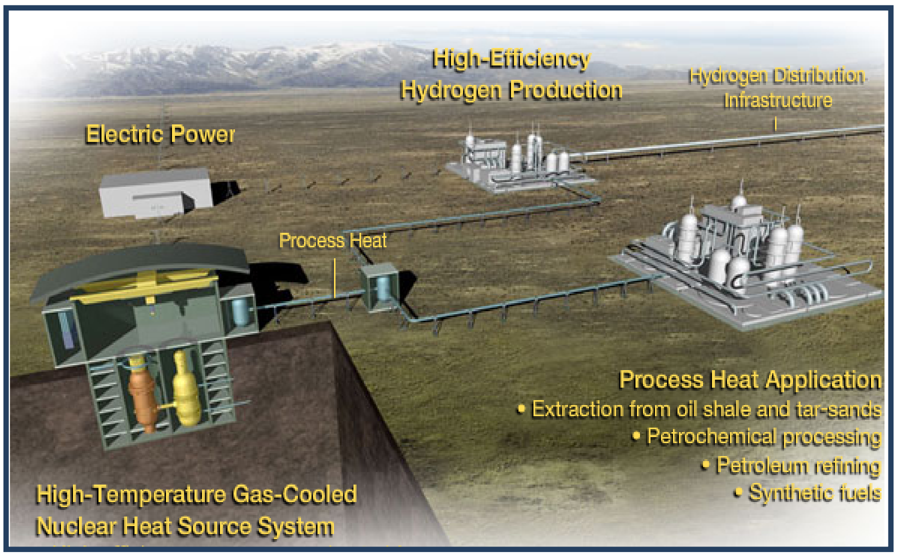

Figure 3-1 Multiple SMR missions
(Illustration courtesy of Idaho National Laboratory)

Agents' Roles and Responsibilities

The HTGR SMRs will be highly automated; details about the level of automation are yet undetermined.

Staffing, Qualifications, and Training

A preliminary estimate of the requirements for operations and maintenance staffing for the PBMR is approximately 150 for a 10-unit site (Kadak, 2000); however, staffing in the MCR may be impacted when installing new units. Staffing requirements for the GT-MHR were not discussed in the information we reviewed.

Management of Normal Operations

The GT-MHR design can have up to 10 units located in underground silos with a common control room. The PBMR's current concept is to have a 10-unit configuration. Multiple units will be monitored and controlled from one control room. As yet, no detailed information about the design of the control room is available.

The GT-MHR will be refueled on site every 250 days. The PBMR reactor will be refueled continuously thus, plant availability is higher than LWRs. Furthermore, continuous refueling precludes there being a large amount of excess reactivity within the core. Refueling operations will be completely automated, with an automated pneumatic system continuously handling the fuel.

Accordingly, only 30 days of outage is envisaged every six years. This plan demands greater emphasis on controlling plant configuration because most routine maintenance repairs and in-service inspections likely will likely be done at power. Additionally, to compensate for any small helium leakages, helium will be added to the reactor's coolant system.

The PBMR also is designed for load-following operation within specified limits, meaning that the amount of electrical power output can be varied to match the existing power demand. This is very different from the typical base-load NPP. Additionally, the PBMR will withstand a 100% load rejection without a reactor trip.

Management of Off-normal Conditions and Emergencies

There was little information about handling off-normal conditions and emergencies in the documentation for either design. However, their low excess reactivity lowers the safety significance of reactivity control and reactor shutdown systems compared with typical NPPs.

Although the reactor protection system will bring the reactor into a hot shutdown during a normal shutdown, the decay of xenon (Xe^{135}) might cause the core to become re-critical after one or two days. Then, the operator might have to actuate additional reserve shutdown systems to reach cold shutdown. In a depressurization accident, rapid cooling could produce a similar reactivity effect.

Management of Maintenance and Modifications

No information was available.

3.3 Liquid-metal Reactors

The LMRs are liquid-metal-cooled using either sodium or lead-bismuth as a primary coolant: hence, they have high thermal-conductivity and high boiling-points. The primary system uses electromagnetic (EM) pumps or natural circulation to circulate the liquid-metal. An intermediate cooling system is employed between the primary-coolant system and the SGs. The LMRs are fast neutron-reactors (rather than thermal) and therefore do not need a neutron moderator. They are designed to use the full energy-potential of uranium, rather than the approximately one percent used by conventional power reactors. They operate at or near atmospheric pressure, thereby greatly reducing the need for active safety features.

We examined three LMR designs, each of which we describe below, with a discussion of our ConOps dimensions:

- Toshiba's 4S (super-safe, small, and simple) SMR
- Hyperion Power Generation's Hyperion Power Module (HPM) SMR
- GE's Power Reactor Innovative Small Module (PRISM) SMR

4S Reactor

This small, liquid-sodium-cooled 4S reactor, with a thirty-year lifespan, produces 10MWe. The 4S NSSS is designed for offsite fabrication and shipping by rail, truck, or barge to the plant site. The entire NSSS, comprising a reactor vessel, containment guard vessel, SG, and equipment compartments or cells, is located below grade.

Inside the reactor vessel are the core, a single control rod, two 50% capacity electromagnetic-pumps, an intermediate heat exchanger, and movable radial reflector. The reflectors control reactivity and power of the plant by moving vertically. The core consists of 18 hexagonal metal-fuel assemblies made up of U-10%Zr Alloy rods enriched with 19.9% U-235. The SG, part of the secondary sodium loop, is separate from the reactor vessel and connected to it by a below-grade pipe way. Its own electromagnetic pump circulates liquid sodium between the in-vessel intermediate heat exchanger (IHX) and the shell side of the SG. Steam is on the tube side of the SG, which flows to the turbine. A sodium dump-tank containing argon cover-gas is connected to the shell side of the SG to drain liquid sodium from it should the pressure increase from water/sodium interacting (due to a SG tube leak). The BOP equipment (turbine, generator, and steam-cycle support equipment) is located above grade.

The designs of the 4S and PRISM SMR (discussed below) are based on older LMRs, such as the French-designed Phenix and Super Phenix plants. Their design also is influenced by the experience gained from the U.S. test reactors, viz., the Experimental Breeder Reactor (EBR) 1, EBR 2, and the Fast Flux Test Reactor (FFT).

HPM

The HPM is a small, lead/bismuth eutectic-cooled reactor producing 25MWe. The HPM NSSS is designed for offsite fabrication and shipping to the plant site by rail, truck, or barge. The entire NSSS is located below grade, and consists of a reactor vessel, a superheater, evaporator, pre-heater, and equipment cells. Internal to the reactor vessel are the core, two boron carbide (B_4C) control rods, and a quartz radial reflector. The core, of stainless-steel-clad uranium hydride (UH_3) fuel rods, has less than a 20% U-235 enrichment. The BOP equipment (turbine, generator, and steam-cycle support equipment) is located above grade.

The Hyperion SMR design uses nitride fuel, with which the industry has very little experience. Also, it uses lead-bismuth cooling which is new and different; thus, experience with it is sparse. However, there is a Pb-Bi test loop at Los Alamos National Laboratory, and the reactors in Soviet submarines were Pb-cooled.

PRISM

The PRISM reactor is a small, sodium-cooled reactor. The standard plant design consists of three identical "power blocks", each of 415 MWe, and with three reactors. Each reactor is located in its own below-grade silo, and is connected to its own intermediate heat-transport system (IHTS) and SG system. The SG and secondary-system hardware sited in a separate building are connected by a below-grade pipe way. Each power block shares a sodium-service vault containing sodium-purification-process equipment. Each reactor has its own SG, combined with the two others in each power block by a common header to feed a single turbine generator. All the reactors on the site share a common control center, reactor maintenance facility, remote shutdown and radwaste facility, and assembly facility.

The reactor enclosure consists of the reactor vessel, the containment vessel, and the reactor-closure head. There is a diametrical gap filled with argon gas between the reactor vessel and the containment vessel; it is designed to permit in-service inspection (ISI) and contain a primary-coolant leak without uncovering the core. The reactor's closure head is common to the reactor and containment vessels. Its head has a rotatable plug for refueling and penetrations for the primary coolant pumps, piping to the intermediate heat exchanger system, instrumentation and other hardware. All containment penetrations pass only through the closure head.

The PRISM core is designed to use metallic rather than oxide fuel. Six control rods modulate reactivity and power. An ultimate shutdown system in the center of the core offers the ability to reach cold shutdown if the control rods cannot be inserted.

Four EM pumps, powered by non-1E[9] power supplies, force primary coolant through the core. However, four motor-generator sets supply power to coast down the EM pumps. Heat from the core is transferred to an intermediate sodium loop heat exchanger, then to a sodium/steam heat-exchanger, and finally a steam turbine.

Each of the nine reactors has an independent reactor protection system (RPS) located in the reactor vault, but isolated from the reactor. The RPS, a quad-redundant protection system, is a digital system entirely independent from the power control system (PCS).

As mentioned above, the predecessors to the PRISM and 4S are based on older LMRs, such as the French-designed Phenix and Super Phenix plants. Their design also is influenced by the experience gained from the U.S. test reactors, viz., the Experimental Breeder Reactor (EBR) 1, EBR 2, and the Fast Flux Test Reactor (FFT).

Plant Mission

The primary mission of these designs is producing electricity. The missions of the 4S and HPM additionally consider district heating; although this capability will entail design modifications, the documentation did not specify what they are. Additional missions for the PRISM design were not discussed in the literature.

Agents' Roles and Responsibilities

The documentation provided little information on agents' roles and responsibilities. All three designs will be highly automated, but the precise levels are undetermined as yet.

The 4S documentation stated that the plant's computer will automatically sequence normal startup and shutdown, with predetermined hold points where the operator's permission is

[9] The safety classification of the electrical equipment and systems that are essential to emergency reactor shutdown.

needed to continue the sequence. This arrangement is similar to NuScale's partial automation approach described earlier.

PRISM operations from 0 to 25% power are partially automated; but between 25 to 100% power, they are fully automated, although operators can intervene.

Staffing, Qualifications, and Training

The designs of the 4S and HPM SMRs did not discuss staffing, qualifications, and training requirements. The PRISM design can be expanded up to three power blocks (nine reactors). For this configuration, the common main control room is expected to have four licensed operators (one SRO, and three ROs).

Management of Normal Operations

All three HTGR designs can be organized in a multi-unit configuration and monitored and controlled from one control room. As noted above, as many as nine PRISM reactors may be operated at a site. Then, each RO would control three reactors. However, the documentation we reviewed for the 4S and HPM designs lacked information on the design of the control room.

The HPM is designed to operate for 7- to 10-years, at which time the entire reactor is removed from service and returned to the factory, eliminating the need for on-site refueling.

The 4S is designed to operate for 30 years with no refueling. The PRISM design requires 198 days of refueling in a year for the maximum plant configuration of nine reactor units. However, it is unclear who operates the refueling machine, and how; similarly, this is not stated for the auxiliary liquid-metal processing systems, (e.g., the Primary Sodium Processing Subsystem) in each plant.

Management of Off-normal Conditions and Emergencies

The 4S reflectors provide the main shutdown reactivity and, on a scam, are dropped below the core. The one control rod is for backup shutdown only. Cooling is by natural convection on loss of pumping power.

PRISM has a remote shutdown facility (RSF), and the RPS vaults contain safety-related instrumentation powered by a Class 1E source. For emergencies involving toxic gases or smoke, it is not clear how the PRISM operators will access the RSF or RPS vaults.

The fire brigades of the PRISM and 4S reactors are of particularly importance because of the potential therein for sodium/water fires. Thus, the personnel manning the brigade need specialized training. Also, staffing the fire brigade may impact overall shift staffing levels.

Management of Maintenance and Modifications

HPM's and PRISM's primary coolant is sodium; hence, any maintenance on the SGs is hazardous. Furthermore, the HPM's primary coolant is lead/bismuth, so that maintenance on any external equipment containing the primary coolant can also be precarious. Work must be done in an inert atmosphere, thus, necessitating specialized training (in hazards associated with liquid sodium), and specialized personal protective equipment (PPE).

When a reactor is removed from service in a multi-unit HPM configuration to be returned to the factory, its instrumentation is disconnected from the main control room. Additionally, any piping containing liquid lead/bismuth is disconnected. The potential impact on other operating units remains to be determined.

The documentation did not address the handling of any of the residual liquid-metal from the operational maintenance of 4Ss and HPMs, or from the disconnected primary coolant pipes when the reactor is to be shipped back to the factory for refueling.

Because the 4S and HPM reactors come sealed from the factory and there is no design provision for opening the reactor vessel, it is uncertain how any ISI or maintenance will be performed on the radial reflector or in-core sensors.

3.4 Insights for SMR ConOps from SMR Design and Operations

Much of the information available to us on ConOps aspects of SMRs was in the preliminary stages. In this Section we described the SMR designs as they were when we were conducting the work. Some of this information will be out-of-date after the report is published.

We nonetheless can identify key design differences between SMRs and current NPPs them may be influence human performance. By current plants, we mean Generation II plants operating in the United States, and the Generation III and III+ designs that the NRC currently reviewing. Table 3-2 shows these comparisons (note that not every item listed applies to all SMR designs). We next discuss the implications of these differences.

Table 3-2 Comparison Between Current Plants and SMRs on Dimensions That May Influence Human Performance

ConOp Dimension	Current Plants	SMRs
Plant Mission	Electrical production	Electrical production and, potentially, process-heat applications
	Current designs are incremental evolutions from previous designs with extensive operating experience	Many SMR designs are based on new technology with minimal predecessor plant experience
Roles and Responsibilities	Crew responsible for electrical production	Crew may be responsible for electrical production and collateral missions. such as hydrogen production
	Crew responsible for a single unit	Crew or individual operator responsible for multiple units
	Automation, often simple, mainly applied to safety systems	Extensive use of automation, sometimes complex, for operations
Staffing	Staffing levels meet 10 CFR 50.54(m)	Staffing levels typically are below 10 CFR 50.54(m)
Normal Operations	Plants are based on LWR-technology with well-known operational requirements	Many SMR designs use non-light-water reactor technology that might pose new operational requirements
	Large plants that typically can produce 1000+ MWe	Smaller, simpler designs with electrical-generation capacity typically less than 400

ConOp Dimension	Current Plants	SMRs
		MWe
	Plants are built on-site	Modular approach to constructing plants
	Limited use of shared systems	Some SMR designs use shared systems; some are shared across many units. An example is the NuScale reactor pool used by all 12 units
	Base-load operations	Load following as well as base-load operations
	A shift crew manages a single reactor unit from a control room	A single crew or operator may manage multiple units and additional missions from a single control room
	HSIs provided for plant evolutions	HSIs provided for plant evolutions of multiple units, and also for monitoring and control or other missions
	A single reactor can be in a variety of states	Individual reactors may be in a variety of states (e.g., shutdown, startup, or refueling, and various types of maintenance and testing) and running at various power levels
	Additional reactors are introduced as separate plants	Additional units can be added when needed and while other units are operating
	Refueling is performed during outages	Novel approaches to refueling, such as on-line refueling, and relocating reactor modules to a dedicated servicing area for refueling
Off-normal Operations	Plants are based on LWR-technology with well-known hazards	Many SMR designs use non-light water reactor technology that might pose new hazards
	Currently operating plants use active safety systems; some new designs employ some passive systems	Safety systems mainly are passive
Maintenance	Major maintenance performed during outages	Novel approaches to maintenance, such as moving reactor module to a dedicated location in the plant or to the factory for servicing
	Maintenance practices and hazards are well-defined	There are many new maintenance practices and potential hazards

The differences between current U.S. plants and SMR design and operations lead to new challenges and potential human-performance issues. They are summarized below, and organized by the ConOps dimensions to which they apply.

Plant Mission

1. New missions create new systems, personnel tasks, and workload. Questions that may be associated with the multi-mission operations include the following:

    - If process heat applications, viz., hydrogen production, desalination, and refining are envisioned for multi-unit sites, will different ones be allowed at the same facility generating electricity?

- If so, must plant operators be trained in dealing with upset conditions in process heat applications and other interfacing requirements.
- Will this complicate the operator's training because they will have to know all application interfaces?

2. Commercial NPPs evolved slowly, with new designs improving upon prior ones. Through the years, using operating experience from predecessor plants has been an important aspect of plant design, licensing reviews, and operational improvements. SMRs are a new category of plant design, and consequently, there are few or no predecessor plants affording operating experience. Some operating experience may be available from the experience of similar designs and non-nuclear systems. However, less operating experience can mean that design problems have not been worked out and may cause operational problems, events, or accidents. Vendors and regulators will have to address the impact of this information gap on design and licensing of plants.

Agents' Roles and Responsibilities

3. SMRs will be highly automated. High levels of automation were associated with difficulties in human performance in many types of complex systems (O'Hara & Higgins, 2010). Some of these issues include:

   - 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[10]

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

Staffing, Qualifications, and Training

4. 10 CFR 50.54(m) governs staffing levels in current plants, requiring one SRO, two ROs, and a shift supervisor (second SRO) per reactor. In those SMRs with staffing information, levels were below this; therefore, an evaluation of, and exemption from the staffing regulation will be needed.

5. After defining human responsibilities, the tasks associated with them 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 monitoring and controlling multiple individual units, shared systems, new missions, and monitoring and backing up the automation. SMR designers must determine the allocations that best support overall

[10] 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.

system-performance and safety, and consider the impact on teamwork, e.g., such as the effect on supervision and the peer-checking process.

6. SMR operating crews have the added responsibility of monitoring and controlling multiple units. Situational awareness and workload are key considerations in assessing the ability to effectively and reliably accomplish these tasks: Maintaining sufficient awareness of the status of multiple SMRs may tax crews and individual operators. Maintaining SA may be further challenged when individual units are at different operating power levels and different states (e.g., shutdown, startup, transients, accidents, refueling, and maintenance and testing).

7. While the training requirements for SMRs are yet undetermined, there will be new considerations. For example, in current PWRs, a PORV or the pressurizer spray are the mitigation function to primary system pressure spikes. Because the NuScale and IRIS SMRs do not have either, the design will require a change in operator training on controlling the primary system's pressure for various upset conditions. Also, chemical shim (boron) is used to make operational adjustments for reactivity control for fuel burn-up. Because mPower controls reactivity via a control rod movement only, this design will require changing the training for operational reactivity control.

<u>Management of Normal Operations</u>

8. Some designs incorporate unique features entailing reactivity effects that differ from those in light-water reactors. For example, the HPM is a lead-cooled fast reactor, and the presence of lead in the core involves different reactivity effects from those in light-water reactors; it exhibits little neutron thermalization and has lower Doppler effects. In addition, the temperature coefficient of reactivity will be less negative and the neutron lifetime shorter. These features all tend to quicken the dynamics of core power and transient operations. The operators' control of reactivity effects and overall reactor safety depends on their understanding of them; an incomplete understanding by operators may lead to incorrect actions, particularly during upsets.

9. Current-day NPPs typically operate at 100% power and provide a base load to the utility's electrical distribution system. Load following is an operational method that allows the NPP's power output to vary up or down as determined by the load demanded by the distribution system. Thus, both the reactor and turbine power change in response to the external demand; raising the demand on operators to monitor the automation and plant response, and to take any needed actions. In addition, for a multi-unit site, load following may engender the startup and shutdown of multiple units in response to large changes in load demanded, affording additional opportunity for equipment to fail. Further, load following will create new tasks that are not currently undertaken in U.S. plants and they will open new chances for personnel errors.

10. Refueling operations for some SMRs are different from current practices in the United States, for example, several designs refuel the reactor on-line or continuously. Multi-unit plants may encompass units undergoing refueling while others are in shutdown or operation. The need to manage this concurrent activity while the plant is operating must be included as part of the operator's tasks. As another example, every 250 days, the GT-MHR is refueled on-site; hence greater emphasis must be placed on controlling overall plant configuration because of possible overlaps in refueling operations at a multi-unit reactor site. Since coolant pressure varies with power level in the GT-MHR, a single operator monitoring

multiple reactors may have to make different compensating manual adjustments to the reactivity control system, which might lead to potential errors. Additionally, since any small helium leakages must be compensated for by adding helium to the reactor-coolant system, such adjustments to the coolant pressure/power level will be complicated further. In the literature we reviewed, it was unclear whether this would be a manual or automated function.

11. Most SMRs are scalable; that is, multiple units can be grouped at a site to meet a utility's specific power needs, yielding various power outputs. Also, units share common support systems in some designs. Construction and installation of 2nd, 3rd, or later units may be ongoing while earlier ones operate at power, a very different situation from the current practice wherein a second unit under construction is clearly separated from operating units. Ongoing construction might distraction the operators of working units.

12. The effect on personnel of differences in SMR units is unknown. While a licensee may plan to have identical units at a particular site, this may not be achievable due to modifications that improve reliability, reduce cost, or deal with problems of obsolescence, thereby impacting the reliability of the crew and operator. For example, should the units' differences lead to a different interpretation of status based on parameter displays, it may impair the operator's recognition of deviant performance. Further, if the unit differences necessitate distinct responses, such differences may complicate the operator's response; this might entail operator error when, for example, operators respond to a disturbance in Unit 2 in a way that is appropriate for Unit 1 but inappropriate for Unit 2. Unit differences will affect the review of procedures as well as HSIs. Thus, the effect of unit differences on SMRs operations must be understood and addressed.

13. The design of the control room is very important. 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. The plan is managed by a crew of three or more people. The principal question centers round the design of the control room to support SMR operations when a single control room serves multiple reactors, and a single operator may be responsible for the reactor and secondary systems of up to four complete units. The answer partly depends on the allocation of the crew's responsibilities. Nevertheless, it might be challenging to develop a single workstation to monitor even one reactor in light of the HSIs presently needed for control room monitoring of a single reactor; expanding that know-how to four units may prove difficult.

    One SMR designer's preliminary concept suggested that eight monitors are needed to show the alarms, displays, procedures, and controls for a single unit; thus, 32 monitors would be needed for four units. The ability of a single operator to monitor so much information may be problematic, and, compared with current NPPs; the likelihood of missing important information might well increase.

    In addition to considering multi-unit operations, some designers will need to accommodate new tasks in the HSIs, such as moving reactors for refueling, and new missions, such as hydrogen production. These could increase the operator's workload and complicate navigation through the information screens.

14. A vital aspect is assuring the optimum design of controls, displays, and alarms such that a single operator effectively can manage one or more SMRs. Thus, should separate HSIs be

associated with each unit, or should an integrated representation be used to help operators maintain high-level awareness of the status of all units for which they are responsible. If the units are separately displayed, and the operator is focusing on one of them, then he/she might lose awareness of the status of the others. However, with an integrated display of multiple units, it might be challenging to ensure that operators do not confuse information about one, with that about the others. Furthermore, there is the problem of unit differences (discussed earlier) and how to resolve this in HSI design.

Management of Off-normal Conditions and Emergencies

15. One of the NRC's actions 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 SPDSs in NUREG-0835, NUREG-1342, NUREG-0737 (Supplement 1), and NUREG-0700, Section 5. The specific safety functions and parameters identified in these documents are based on conventional LWRs. SMR designs may require different safety functions and parameters, especially for HTGRs and LMRs, to support operating crews in effectively monitoring plant safety.

16. Two of the classes of SMR designs are based on non-light water technology: Gas-cooled; and liquid-metal ones. In contrast to LWR designs, these classes of designs encompass new hazards associated with the reactor's technology. These include hydrogen, helium, liquid-metal (such as sodium and lead), and much higher operating temperatures/pressures, along with the use of high-temperature gas, and graphite in the core. Sometimes, graphite cores are flammable and could create radiologically hazardous fumes. Such hazards must be understood and addressed in the safety systems used to monitor and mitigate the hazards, in the HSIs through which staff monitor the plant, in the procedures they use to resolve hazards, and in operator training.

Management of Maintenance and Modifications

17. Many SMRs are designed for modular construction and maintenance consists of replacement of modular components.[11] Previously, plant personnel participated in the on-site construction, component-level testing of installed components, and pre-operational testing; hence, they were thoroughly knowledgeable of plant structures, systems, and components. Therefore, fabricating plants in factories rather than on the site demands changes in how plant personnel gain a comprehensive knowledge of systems and components since they may well have less understanding of the plant and equipment.

18. During our review, we noted several new maintenance operations with potential safety implications:

    - The NuScale design has only one bay that is used for refueling and maintenance. Hence, one reactor may be refueling when another develops a problem requiring in-vessel access. It is unclear how operators will manage this situation because the reactor pool is the ultimate heat sink for the operating reactors and cannot be drained.

[11] For describing maintenance, a module is an assemblage of two or more interconnected parts or components that comprise a single physical entity with a specific function. NUREG-0700, Section 13 has examples of replacing modular components in digital systems.

- mPower's core is located below the SG, so that the latter must be removed during refueling, adding extra work and complexity.
- The 4S and HPM reactor vessels are sealed; thus, it is unclear how in-vessel SI or maintenance will be undertaken.

19. During our review, we noted new potential hazards for off-normal conditions and emergencies that also might impact maintenance. Also, we identified several maintenance hazards for the various SMR designs.

    - The IRIS design has eight in-vessel 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 GT-MHR and the PBMR need extensive training on the hazards of helium leaks and their detection.
    - Sodium is the primary coolant in the 4S and PRISM designs; accordingly, maintenance on the two external SGs is hazardous, and will entail specific training because operators must wear specialized PPE and work in an inert atmosphere.
    - Lead/bismuth is the primary coolant in the HPM, so working on the external SGs may be hazardous, requiring specialized training and the use of particular PPE.

Our main conclusion is that more information is needed on the ConOps aspects of SMRs. SMR ConOps are preliminary as yet, but continue to evolve as the plants' designs are refined, and the vendors prepare for licensing activities.

From the information available, we identified significant differences between SMRs and current designs, and the potential human-performance issues that may require resolution.

4 GENERAL SMR LITERATURE

There are very few general publications about the operational and HFE aspects of SMR designs; we reviewed them below, organized by the dimensions of our ConOps model. In addition, the nuclear industry has hosted meetings between the NRC, the DOE, and SMR vendors to identify licensing and technical issues/challenges that must be addressed to support the design, design review, and licensing of SMRs. Such meetings included the NRC's Regulatory Information Conference, Commission Briefing on Reactor Issues - Design Certifications, and the Workshop on Small- and Medium-sized Nuclear Reactors. At them, several presentations covered HFE and operational considerations (Kinsey, 2010; Mallett, 2010; Mays & Williams, 2010; Reckley, 2009; Smith, 2009).[12] However, while these presentations identified human-performance challenges, they were not described in detail. In Table 4-1, we summarize those challenges, organizing them by the dimensions in our ConOps model presented in Section 4.7.

4.1 Plant Mission

Several SMR plant designs envision additional missions beyond electrical generation, including co-generation, hydrogen production, industrial-heat production, district heating, desalination, oil extraction, and vessel propulsion (Clayton & Wood, 2010; IAEA, 2001). A study by the National Academy of Sciences (NAS, 2008) of NGNP technology reached the following conclusions:

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

Also, the topic was identified as Issue 4.4, *Industrial Facilities Using Nuclear-Generated Process Heat*, in SECY-10-0034 (NRC, 2010):

> The NRC staff has identified potential policy and licensing issues for those facilities used to provide process heat for industrial applications. The close coupling of the nuclear and process facilities raises concerns involving interface requirements and regulatory jurisdiction issues. Effects of the reactor on the commercial product of the industrial facility during normal operation must also be considered. For example, tritium could migrate to a hydrogen production facility and become a byproduct component of the hydrogen product. (p. 15)

This concern applies to all SMRs with multiple purposes.

4.2 Agents' Roles and Responsibilities

As we discussed in Section 3, SMRs are expected to be highly automated plants. Clayton and Wood (2010) suggested that automation likely will manage all aspects of operations, from startup to shutdown, and responses to anticipated events. Innovative technologies, such as intelligent automation and prognostics, must accompany the reduced staffing of SMRs. According to Clayton and Wood, "Highly automated intelligent control involves more than simple automation of routine functions. It implies the detection of conditions and events, determination of appropriate response based on situational awareness, adaptation to unanticipated events or

[12] The NRC hosts many meeting to discuss SMR issues that include presentations from the NRC, the DOE, industry groups such as the NEI, and vendors. The presentations are at http://www.nrc.gov/reactors/advanced/public-meetings.html; retrieved April 26, 2011.

degraded/failed components, and reevaluation of operational goals" (p. 149). They further emphasize that these types of controls were not tested in the nuclear plants, and there is limited experience from other industries.

Tran et al. (2007) identified the high level of SMR automation as a potential HFE concern. This is supported by the NRC's research on the effects of high levels of automation on operator performance (O'Hara & Higgins, 2010), including the following:

- change in the overall role of personnel that does not support satisfactory human performance
- difficulty understanding automation
- monitoring failures, loss of vigilance, and complacency
- out-of-the-loop unfamiliarity, and degraded SA
- difficult workload transitions when operators assume control on loss of automation
- loss of skills since automated tasks seldom are performed manually
- new types of human error

Passive safety systems are one type of automation employed in SMR design. The IAEA identified the following potential concerns related to passive systems based on the limited experience available (IAEA, 2009):

- The reliability of passive safety systems may not be understood as well as that of active ones.
- There may be a potential for undesired interactions between active- and passive-safety systems; for example, injection by an active pump easily will overwhelm passive natural circulation.
- 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 the target safety goals; the supporting regulatory requirements must be formulated and established.

These IAEA concerns and their associated uncertainties may challenge operators of plants utilizing passive systems.

4.3 Staffing, Qualifications, and Training

Plant staffing seemingly is the most frequently identified HFE issue in SMR design. Staffing levels in U.S. plants are governed by regulations in 10 CFR 50.54(m); the NRC recognized that SMR staffing levels might deviate from them. Issue 4.1, *Appropriate Requirements for Operator Staffing for Small or Multi-Module Facilities*, in SECY-10-0034 (NRC, 2010) identified staffing "…as a potential policy issue that may require changes to existing regulations." The NRC has written general guidance for reviewing staffing exemptions in NUREG-1791 (Persensky, et. al, 2005); however, this guidance has not been applied yet.

In 2001, the IAEA published the staffing requirements for small- and medium-reactors, defined as 700 MWe or less (IAEA, 2001). As noted earlier, IAEA defines small reactors as 300 MWe or less (IAEA, 2005). While not addressing multi-unit, modular reactors, the IAEA recognized that the staffing demands in small plants may differ from those in larger plants. Developing countries favor small plants; staffing is the most costly component of their operation and maintenance. Thus, reducing staffing costs offers economic advantages in these countries and elsewhere. The IAEA convened a workshop for operators of small plants, at which it was concluded that while staffing levels for current small plants is similar to those of larger ones, the designs of new small plants will incorporate features likely to reduce staffing demands. These features include simplified design, simplified maintenance, use of computerized support systems for personnel tasks, and increased control room functionality. The latter covers greater employment of automation for routine tasks, and HSIs that will lower the workload of plant operations. The IAEA study considered that specific staffing requirements will reflect the plant's design and its intended use, which may include co-generation. A limitation of this study for our present purposes is that it does not consider staffing in multi-unit plants.

A special committee of the American Nuclear Society (ANS, 2010) evaluated the staffing of SMRs. Grenci and Haemer (2010) assessing these needs for SMRs concluded that staffing levels can be reduced below current regulations. In addition, they determined that the collateral duties of operators can be increased. Their analysis was not based on any single SMR design; rather it considered generic SMR design features. Compared to typical operating U.S. LWRs, SMRs have a smaller core inventory, and the plants have a smaller, simpler design that incorporates advances, such as passive safety-systems. Consequently, they should experience less core damage and release frequencies, and longer times to release. In addition, since SMR designs incorporate greater levels of automated operations, the operators' workloads will be "significantly reduced." Nevertheless, we particularly are concerned that such an analysis often fails to consider that increasing automation does not simply mean fewer tasks for the operators. Rather, increases in automation shift the operator's work to supervisory control, thereby increasing the monitoring workload, a shift that can be very challenging (O'Hara & Higgins, 2010).

Grenci and Haemer (2010) conclude that these differences from current designs lead to fewer needed human actions and increased time availability. Thus, fewer staff are needed, collateral duties can be increased, and operators will be able to monitor and control more than one reactor. Should additional staff be needed, the longer times to damage or release should suffice, in most cases, to get them on-site. Supporting their argument, these authors considered the experience in other industries, wherein increases in automation led to reductions in staffing; they offered, as an example, the reduction in flight-deck crew from three to two in modern airliners. Grenci and Haemer (2010) noted that their general conclusions need to be confirmed for individual designs.

Some support for staffing reductions stemming from applying improvements in plant design comes from an NRC-funded study at the Halden Reactor Project (Hallbert et al., 2000). It examined the crew's performance in normal- and minimum-staffing configurations while operating either a conventional plant or an advanced plant with passive safety features. This study did not look at multiple units. The control rooms for each plant design differed, and were representative of conventional- and advanced-plants. The former met the requirements of 10 CFR 50.54(m) while the latter had fewer operators. Eight crews of professional operators, four for each plant type, managed five scenarios: (1) SG tube rupture, with a stuck-open SG safety relief valve in the affected SG, followed by a fire in the turbine hall; (2) interfacing systems LOCA compounded by instrument failures; (3) sustained total loss of feedwater; (4) loss of offsite power with a single SG safety relief valve stuck-open; and (5) SG overfill. A wide range of performance measures were used including plant performance, team performance, SA, and workload.

The results across the measures were not completely consistent, but the general finding was of a correspondence between crew size and plant type: The conventional staffing configuration performed better in the conventional plant than the reduced staffing configuration, while, for the advanced plant, the smaller crew performed better than did conventional staffing. The authors partly attributed the results to the relationship of the plant and control room design, and the allocation of functions and tasks between the two different designs.

Several nuclear plant sites in Canada operate four-reactor units from a single control room (Lane & Davey, 2007). Each individual reactor has its own control boards and there are additional ones for common services such as fire protection, instrument air, heating and ventilation, and on-line refueling.[13] The crew is structured with teams of approximately three for each reactor, along with a shift supervisor and shift manager. Separate operators are used for common services and refueling. Thus, during normal operations, each reactor has its own crew and its own control area. During unit upsets, shift assignments change; the shift supervisor focuses on the upset unit, and operators from unaffected units are reassigned to work with the crew of the upset reactors. The shift manager oversees the other three units and they are put in a “quiet mode”, viz., any evolutions are stopped and nonessential activity is ceased, so minimizing the likelihood of another unit upset. Thus, a significant transition occurs in the operation of all units, and in operator roles and responsibilities to manage the upset unit. The transitions are marked by “turnovers” at each unit to bring “new staff” up-to-date on the unit’s current condition and coordinate the activities of individual staff members. Lane and Davey emphasize the importance of the design of the control center in supporting normal operations and unit upsets when staffing transitions occur, and the latter has additional staff relative to normal operations.

Tran et al. (2007) identified a staffing model as a key HFE issue for SMRs, noting that increasing automation is likely to reduce staffing size and may lead to new staffing models. The NRC’s research on emerging technologies identified the concept of alternative “functional staffing models” (O’Hara et al., 2008). Current plants have a large number of on-site personnel organized into functional groups including operations, maintenance, engineering, administration, and security. Many designs slated for near-term deployment in the United States do not involve fundamentally different plant-staffing concepts; accordingly, changes to the current approaches to staffing are not anticipated. However, SMR designs and the longer-term goals for economy and safety for Generation IV plants[14] (DOE, 2002) likely will entail a trend toward different operating concepts and different approaches to staffing. In anticipating such new approaches, we use the term "functional staffing models" to refer to general approaches to fulfilling these human roles.

Some staffing models depart from those typically used in current plants; for example, one with a decentralized functional groups may be considered. In this model, SMRs may be staffed with a very few on-site personnel. The on-site crew is made up of technicians who oversee the highly

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[13] Personnel refuel the CANDU plants while they are operating.

[14] The international nuclear-community is cooperating in developing new reactor design- concepts to meet energy needs thirty years from now and beyond under the so-called Generation IV initiative. The vision for Generation IV plant designs includes ambitious goals for sustainability, economics, safety and reliability, and physical protection (DOE, 2002).

automated operation and occasionally undertake minor operations and maintenance tasks. Off-site specialists are responsible for other activities, and either come to the site when needed (such as for maintenance) or perform their tasks remotely. Highly trained crisis- management teams may handle significant disturbances; since they handle only crises, their level of expertise would be superior to what is attained when a single crew is responsible for normal- and emergency-operations (today's model). Due to the low probability of such an accident, the teams are available to resolve emergencies at many sites, a role that will be supported by increased plant standardization. This is one example; many alternatives models can be proposed.

The staffing model chosen is a very significant design decision that will drive many other aspects of the plant design, including degree of automation, HSI design, and personnel training.

Eitrheim et al. (2010) examined the operation of more than one reactor by an NPP crew, exploring the effects on performance when three-operator crews simultaneously controlled two nuclear units compared to one. The simulated plants were highly automated BWRs with advanced HSIs. The one-unit configuration had standard staffing, consisting of a reactor operator, a BOP operator, and a supervisor. In the two-unit configuration, a main operator (MO) monitored Unit A (reactor and balance of plant systems) from one control room, and a second assistant operator monitored Unit B from another control room adjacent to the first one. A work manager supervised both operators. When Unit A was in an upset condition, the assistant operator from Unit B came to assist the MO under the direction of the work manager. Meanwhile, the Unit B simulator was put in a frozen state.

Nine professional crews participated in eight scenarios, all involving Unit A and the transition from start-up to 50% power. Performance measures included the following: Operators' task performance as measured by the Operator Performance Assessment System (OPAS); SA based on operators' reports on the state of specific parameters while the parameters were not in view; operators' self-assessment of performance using a rating scale; and workload using a version of the NASA's Task Load Index (TLX) and a subjective task complexity scale.

We found the findings difficult to interpret. Both groups demonstrated similar task performance during easy periods of the scenarios. However, while the performance of all crews fell when the scenario became difficult, that of the two-unit crews dropped significantly more than the one-unit crews. There were no differences between one- and two-unit crews in their self assessments of performance. However, although there were no workload differences between the groups, the two-unit crews achieved better SA than the other crew. The study's authors suggested that the results tend to favor the more traditional, one-unit staffing approach, concluding that "Reduced staffing levels might be sufficient during normal operation, but specialized support teams and roles may be necessary to handle disturbances and upset situations." However, generalizations are hard to make due to inconsistencies in the results. Another aspect of this study limiting generalizations is that when the assistant operator left Unit B to assist the MO in Unit A, Unit B was put in a frozen state and left unattended; this would not happen in actual NPPs.

4.4 Management of Normal Operations

Several authors identified the demands of monitoring and controlling multiple units, each in a different operating mode, as a potential problem in plant design and operations (Clayton & Wood, 2010; O'Hara et al., 2008; Tran et al., 2007; Wood et al., 2003). Also, the NRC denoted this topic as Issue 4.3, *Installation of Reactor Modules during Operation for Multi-Module Facilities*, in SECY-10-0034 (NRC, 2010).

SMR plant scalability and the possibility of shared systems can make multi-unit operations more complex than current plant operations, as Wood et al. (2003) stated:

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

In addition to multiple units complicating control, the need to serve multiple missions also must be considered. That is, there is a need to flexibly reconfigure the secondary portion of the plant to meet electricity production and other objectives (Clayton & Wood, 2010). For example, operators may have to change the SMR units driving a turbine to produce electricity so they can generate hydrogen.

Clayton and Wood (2010) suggest that SMR operations will require a “new paradigm” in reactor controls. In the United States, nuclear plants are operated in base-load mode. The plants produce electricity for the grid, and other producers of electricity compensate for changes in demand. The authors believe that a base-load mode may be insufficient for SMRs that may have to cooperate with, and compensate for variability from other sources of renewable energy whose production depends on the vicissitudes of factors, such as sun and wind for which SMRs may have to compensate.

Considering the challenge of controlling multiple units (in various states), shared systems, multiple missions, and grid needs, Clayton and Wood 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). Research is underway to develop control strategies to meet these situations (Perillo & Upadhyaya, 2010).

These challenges carry significant implications for personnel who will monitor and supervise these operations. Tran et al. (2007) identified as a potential HFE concern the stress imposed on single crews in monitoring multiple plants. Included in this issue is HSI design, i.e., how they should be contrived to support multi-unit monitoring and control, including monitoring of the SMR automation. Crews watching multiple units may encounter additional occasions to make the "wrong unit/train" errors that persistently were noted over the years at dual-unit NPP sites (O’Hara et al., 2008).

4.5 Management of Off-normal Conditions and Emergencies

The way in which a particular plant with a unique design manages off–normal conditions and emergencies is assessed using risk analysis. Risk analysis was identified as a potential SMR HFE issue (Tran et al., 2007) because the complexity of a multi-unit plant may encumber the identification of human contributions to risk. These authors consider that in a complex system it is difficult to determine all the ways systems interact, so "…solving one problem may introduce another somewhere else." They suggest that standard approaches to human reliability analysis (HRA) may not be fully suitable for risk analyses of SMR plants.

This issue takes on even greater importance in light of the Memorandum from Commissioners Apostolakis and Jaczko (2010) entitled, "*Use of Risk Insights to Enhance Safety Focus of Small Modular Reactor Reviews*" that encourages the increased use of risk information in design reviews. The use of probabilistic risk assessment (PRA) was also identified as Issue 3.2, *Use of Probabilistic Risk Assessment in the Licensing Process for SMRs*, in SECY-10-0034 (NRC, 2010).

4.6 Management of Maintenance and Modifications

Reduced numbers of maintenance staff may cause the transition of maintenance practices from preventative/periodic maintenance to predictive/condition-based maintenance, encompassing the usage of more advanced diagnostic- and prognostic-systems than at present (Clayton & Wood, 2010).

4.7 Insights for SMR ConOps from General SMR Literature

From our reviewing the general SMR literature, we identified the following new challenges and potential human-performance issues.

1. The HFE and operational characteristics of SMRs are influenced by the smallness of the plants (relative to most reactors now operating in the United States), their possible groupings, and their use of advanced technologies, such as passive systems, digital I&C, and computer-based HSIs and support systems. Some challenges emerging from this type of ConOps include:

    - simultaneously monitoring and controlling multiple reactor units via a single crew from one control room, which may require formulating new staffing models
    - coping with scalability, i.e., operating with new units coming online
    - managing non-LWR processes, e.g., liquid-metal and high-temperature gas-cooled designs
    - integrating electrical production with the other missions, e.g., hydrogen production
    - managing individual units that simultaneously are in various operating modes, such as starting up, full power, and shutdown
    - handling additional responsibilities, such as online refueling
    - managing units that share secondary and/or support systems
    - coping with transients or emergencies in one unit while other units are operational

2. Control room and HSI design is another important consideration. For example, should all the individual unit-control stations be located in one room or in different, closely located ones? Thus, in a single control room, an operator's activities related to one unit, such as responding to alarms and using emergency procedures, may affect operators monitoring other units. However, one room physically encompassing all operations staff increases the ease with which they can help each other, and facilitates their supervision. If individual units' control stations are in separate control rooms, then overall supervision, teamwork, and the transitions demanded in high workload situations all become more unmanageable. However, operations at each unit will be undisturbed by what happens at others.

   The HSI will have new capabilities, such as systems that support diagnostics and prognostics. Knowing how people manage and understand these advanced I&C and HSI capabilities is an important consideration in overall personnel- and plant-performance.

3. As noted in the introduction to this section, the nuclear industry hosted meetings to encourage dialog between the NRC, the DOE, and SMR vendors to identify licensing and technical issues/challenges that must be resolved to support SMR design, design reviews, and licensing. Table 4-1 summarizes the challenges highlighted in these meetings. We organized them by the dimensions of our ConOps model.

Table 4-1 SMR Licensing and Technical Challenges Identified in Recent Industry Meetings

ConOps Dimension	Licensing and Technical Challenges	Ref
Plant Mission	How can the limited operating experience for some SMR designs be addressed?	3, 4
	How will other shared facilities affect operations?	5
Agents' Roles and Responsibilities	What is the effect of the extent to which control is automated?	3
	What is the potential impact of the increased range of responsibilities, including online refueling or the installation and maintenance of other units?	3, 5
Staffing, Qualifications, and Training	What are the operator staffing requirements and the potential impact of a smaller sized staff?	2, 3, 5
	How many operators are needed on a per-unit basis?	5
	What are the requirements for supervision and reserve staff (staff available on-call)?	5
	What is the effect of shared staffing with other connected industrial facilities?	5
	What are the training/simulator requirements for SMR personnel	3, 5
Management of Normal Operations	How many units may be simultaneously operated at a single control station?	2, 3, 5
	Can an operator reliably and safely control multiple units?	5
	What is the effect of site expandability (scalability); e.g., the construction or removal of units on other currently operating units?	2, 3, 5
	How are cross-cutting responsibilities coordinated with other facilities to which the units provide process heat?	5
	How are shared resources managed, e.g., what difficulties arise with two or more modules tied to a common turbine or energy output?	5
	How will control system architectures be implemented for multiple units and secondary facilities?	3
	How will digital I&C, diagnostics and prognostics be used in SMR designs?	3
	How will digital I&C for advanced multi-unit control rooms affect operator reliability?	5
	How will the control room be configured, designed, and laid out for SMR operations?	1, 3
Management of Off-normal Conditions and Emergencies	What are the impacts of unplanned shutdowns on the other units?	3
Management of Maintenance & Mods	How will operational programs be impacted by SMR designs, e.g., in-service inspection (ISI) and in-service testing (IST) of systems and components?	5

Sources: 1=Kinsey (2010), 2=Mallett, (2010), 3=Mays & Williams (2010), 4=Reckley (2009), 5=Smith (2009)

5 MULTI-UNIT OPERATIONS IN SURROGATE FACILITIES

In this section, we will review the lessons learned from surrogate facilities to gain a fuller understanding of potential HFE issues related to SMRs. A surrogate facility is one whose operation involves managing multiple units that make similar demands on human performance. Although there are important differences between SMRs and these surrogates, their similarities afford us an opportunity to learn from their design, operations, and experience.

Accordingly, we examined unmanned aircraft systems, petroleum refineries, and remote intensive-care centers. Information about the surrogates came from a variety of sources including published literature, site visits, and conference calls. We identify the specific sources of information for each surrogate facility within their discussions.

5.1 Unmanned Aircraft Systems

5.1.1 Introduction

Unmanned aircraft systems (UASs) consist of an unmanned aerial vehicle (UAV) and the operators located in a remote control room to undertake meeting the goals of flight and mission operations. Perhaps the best known UAS to the general public is the Predator (Figure 5-1) used in recent military activities. The first modern UASs were flown during the Vietnam War, equipped with small night-vision cameras and sensors. During the Gulf War, the Predator was introduced, beginning the modern era of UASs usage. The Predator, equipped with various sensors and payloads, is used extensively in military operations.

Many different types of UASs can serve a variety of missions, as detailed in the U.S. Department of Defense (DoD) roadmaps for future UAS systems (DoD, 2005 & 2009). UASs are members of a broader class of teleoperated (remotely operated) robotic systems employed for a spectrum of purposes.

Although some UASs are fully autonomous (flown without human intervention), most of them are flown remotely by crews of varying sizes from control rooms where the vehicle is monitored and controlled at workstations (Figure 5-1) that support mission planning, navigation, aircraft control, and manage systems. A two-person crew operates the Predator.

The numerous benefits of unmanned operations include:

- crew safety
- more flexible manning compared with manned aircraft (crew members are only needed when their tasks must be performed)
- use of smaller, lighter, and more economical aircraft

UASs can conduct missions that human crews could not do, such as remaining in environmentally dangerous areas for extended times. For example, a variety of UAVs flown around the Fukushima Daiichi Nuclear Plant took videos, high-resolution photos, and sensor readings.

Figure 5-1 Unmanned aircraft system (UAS) - Predator UAV and control station
(Aircraft source is http://www.links999.net/robotics/robots/robots_introduction.html)
(Control Station source is http://www.google.com/images)

In 2005, the DoD published a UAS Roadmap (DoD, 2005) offering their vision of UAS operations over the next 25 years; the overall goal is to expand their use to new missions and identify the capability infrastructure needed to accomplish them. One such future direction therein is “multi-vehicle control.” Thus, the goal for future UASs is to change the ratio of crew members to vehicles from many-to-one to that of a single person controlling multiple aircraft (one-to-many). The DoD (2009) generalized this staffing goal to all unmanned systems (air, ground, and marine):

> Performance should evolve from today’s controller to platform ratio of many to one or at best one to one, to a single controller being able to monitor multiple unmanned systems performing across domains as collaborating teams. (p. 28)

The Roadmap (DoD, 2009) notes that accomplishing this change in crew staffing “…would migrate operational responsibility for tasks from the ground station to the aircraft, the aircraft gaining greater autonomy and authority, the humans moving from operators to supervisors, increasing their span of control while decreasing the manpower requirements to operate the UAS” (DoD, 2005). In addition to increased automation and aircraft autonomy, the Roadmap emphasizes the importance of the HSI in accomplishing this goal via communicating the UA’s “intent” and the decision logic underlying it, so to develop the operator’s trust. Trust is important to an operator’s appropriate use of automation (O’Hara & Higgins, 2010). When operators lack it, they are reluctant to use automation; when they do, they spend too much time verifying its performance. When operator’s trust in automation is excessive, they may overly rely on it in situations for which it is unsuited and not monitor it sufficiently to verify its performance.

In general, the DoD’s goals for UASs, and unmanned systems is analogous to those of SMR designers: To reduce staffing requirements, in part, through increased automation. The DoD initiated a research program to address the technological developments needed to change the operator-vehicle ratio, and to detail its impact on mission and human performance. The approach being taken to meet this goal may offer lessons-learned for SMR operations.

5.1.2 Method

We reviewed the UAS literature, concentrating on the DoD's efforts to achieve their vision for UASs. Although UASs were our primary focus, we included some papers related to unmanned ground vehicles (UGVs). The UAS literature is extensive; therefore, our review is not exhaustive. Rather, it centered on highlighting issues and findings pertinent to SMR operations, especially the operator-vehicle ratio.

We supplemented the research literature with information gleaned from discussions with DoD personnel. A telephone conference call was held with researchers from the U.S. Army Research Laboratory (ARL) to discuss their unmanned-vehicle research, developmental efforts, and field experience. The team has published many articles, and two have noteworthy summaries (Barnes & Jentsch, 2010; Barnes, Jentsch, Chen, Haas & Cosenzo, 2010).

5.1.3 Review of the Pertinent Literature

We divided our findings into the following topics:

- automation and team size
- adaptive automation
- automation of vehicle-coordination tasks
- vehicular differences
- human-system interface design

5.1.3.1 Automation and Team Size

Automation is one key to changing the operator-vehicle ratio (DoD, 2009). According to ARL researchers, their approach is to identify performance bottlenecks and create automation solutions to improve the operator's performance. Their goal is for automation to become another member of the team, and have the following characteristics:

- Automation should be sufficiently autonomous to function without constant human supervision.
- Automation and its HSIs should be designed so operators understand how automation works, e.g., how it comes to decisions.
- Operators should be able to take over the automation's tasks at any time.
- The design of automation should be such that it is easy to transfer control to other operators in the same facility or different facilities.
- Over the longer term, automation should be "intuitive" (know the intentions of the human operators).

Research underway at ARL and elsewhere aims to identify what tasks should be automated in future systems, and how it can be implemented to enable crews to manage multiple unmanned aerial and ground vehicles. Many studies vary the level or type of automation and "team size," i.e. the number of vehicles operators must manage. Operators engage in tasks simulating real-world missions, such as search and rescue, or identifying hostile targets; typically, they obtain one or more measures of task performance, along with cognitive variables, such as workload and SA, to support the investigator's understanding of the overall system's performance.

Cummings et al., (2007) analyzed the requirements for controlling multiple aircraft using a supervisory control model. The model for each UAS had three high-level tasks: Aircraft control; aircraft navigation; and mission management. The first task involves local control of the aircraft, such as pitch, yaw, and airspeed, to maintain stable flight. The second task is navigating the aircraft to its target locations. The third task covers managing the mission's objectives. The tasks are hierarchal in that the first task is necessary for the success of the other two, while the second task is necessary for the success of the third, viz., to complete the mission.

Reducing crew size requires automating these tasks or aspects of them. Manual performance of the first task requires considerable attention and workload. However, it is one most amenable to automation. The second task also can be automated. However, the third task depends upon decision making, judgment, and experience; therefore, it is more difficult to automate. This finding is consistent with assessment of ARL researchers that successfully automating higher-level cognitive tasks such as decision-making is problematic.

Cummings and colleagues extended the supervisory control model to controlling multiple UAVs, indicating that for this to occur, the first two tasks have to be almost fully automated, leaving operators to manage the mission. How and to what degree the first two tasks should be automated is a major consideration. The authors acknowledge the concerns about human performance generally identified with high-levels of automation; we summarize them in Section 3.4, Item 3. Such decisions must balance technological capability to automate and its benefits on human performance and overall accomplishment of mission.

The recognition that high levels of automation affect human- and system-performance led many system designers to explore and improve the ways that personnel and automation interact, thereby, obtaining the benefits of automation, while minimizing the negative impacts to operators (O'Hara & Higgins, 2010). Accordingly, developers of the DoD's UAS system are examining different levels of automation (LOA). We briefly describe these concepts, and discuss the research on using automation in UASs.

Table 5 compares differing LOAs with respect to the functions of automation and operators; the transition from Level 1 to 5 represents increased levels of autonomy in the automatic system.

Table 5-1 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 (OBC)	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 (OBE)	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.

Using these LOA definitions, we discuss the findings from studies to automate various UAS functions and tasks. Many of them also varied team size as well, i.e., the number of vehicles the operators manage.

Calhoun et al. (2009) studied U.S. Air Force participants controlling the routes of multiple automated UAVs, supported by a route-planning aid. The participants managed team sizes of one and three UAVs. The LOA of the aid was varied across three levels: (1) The aid identified flight plan options (low LOA); (2) the aid identified flight-plan options, suggesting one that the participant could accept (OBC - medium LOA); and (3) the aid identified an optimal plan and executed it unless the operator rejected it within a prescribed time (OBE - high LOA). The primary-task performance measures included completion time for route planning, and its optimization (percentage of routes the participant inspected to verify the best one). Participants undertook a secondary task of responding to questions about the UAV's health status, but were instructed to do so only when they had free time from the primary tasks. Participant ratings of task difficulty/workload were obtained. The results indicate that both team size and LOA affected the time to compete route planning; it was significantly longer for the three UAV teams than the one. Furthermore, it was significantly longer for the low- and medium-LOAs (they did not differ significantly) compared to the high LOA. Optimum route planning was significantly better for the low LOA as compared with the other two LOAs; team size has no effect on this parameter. Secondary task performance was better for single UAV teams than three, indicating a higher workload burden in multi-UAV teams. There was no effect of LOA on secondary task response to health status questions. Finally, for subjective data, participants in the three-UAV team condition rated tasks more difficult and workload higher than under the single UAV condition. Again, there was no effect of changes in LOA. This finding is consistent with secondary task performance. In general, researchers demonstrated that increasing the LOA led to better task performance, but had little effect on workload. Decreasing team size also entailed better performance and lower workload.

Dixon et al (2005) similarly examined the effect of LOA and team size. There were three LOAs: Manual (pilots completely controlled their UAVs without any automation); auto-alert (pilots flew the UAVs, but had auditory alerts for system failures, route changes, and other updates for the mission with 100% reliability); and autopilot (pilots selected coordinates, after which the autopilot flew the UAV towards that point). There were either one or two UAVs. Each of the 36 licensed pilots flew 10 legs of a gaming area. At the end of each leg, they inspected a target and responded to questions about it (e.g., what weapons are located on the south side of the building?). During the flight legs, there was a chance that a target of opportunity (TOO) would be presented, and pilots were instructed to report what was seen (e.g., number of tanks there). Participants also had to attend to four system gauges during flight, and if they noticed a system failure, they were to press a button identifying the gauge, and then to type the current coordinates of the UAV. Performance measures included response time to target detection, TOO detection rate, and failure detection response time and accuracy. The researchers found that the first task did not vary significantly across LOAs or team size. However, TOO detection rate was significantly higher in the autopilot condition, and in the one-UAV teams. Pilots were significantly faster in detecting failure under the auto-alert and single-UAV conditions; however, there was no difference in accuracy.

In a follow-up study (Dixon & Wickens, 2006), the reliability of the auto-alert system was varied: 100% detected (15 correct alarms); 67% detected (10 correct alarms, 5 false ones); and 67% detected (10 correct alarms and 5 that the alert system missed). A manual condition (no auto-alert system) was included. They found that detection accuracy and response time were worsened with the automation's declining reliability.

In summary, the Dixon studies (Dixon et al., 2005; Dixon & Wickens, 2006) demonstrated that (1) increasing the LOA supported some but not all aspects of task performance; and (2) performance declines with increasing UAV team size and lower reliability of the automation.

The effect of automation's reliability on performance also was examined by DeVisser & Parasuraman (2007) and Ruff (2004). In the former, 12 student participants performed a simulated target recognition task with UGV teams of three or six. An automated target recognition system (ATR) with three levels of reliability was used: Low, medium, and high. They employed a variety of performance measures, including target detection, SA, workload, and trust in the automation. For comparison, they assessed the target recognition performance of the user alone and the ATR alone. Here, the performance of the joint human-ATR system was better than performance of either agent by themselves. Thus, even under the condition of low reliability, the ATR supported overall task performance. Looking at joint performance, performance was worse in the low reliability condition and the six-UGV teams. Workload was higher for the six-UGV teams than for the three-UGV teams. The reliability of the automation did not affect workload ratings, but did negatively affect trust that fell as reliability decreased. Thus, increasing the team size lowered task performance and increased workload, but had no effect on trust. Decreasing the automation's reliability lowered task performance and trust, but had no effect on workload. No significant effects on SA were apparent under any conditions.

Ruff (2004) explored the impact on task performance, workload, and trust in automation of UAV team size with two different LOAs. Sixteen participants controlled UAV teams of two or four in a planning and targeting task. Reliability of the automation also varied (low and high). The automation planned new routes and identified targets, then either waited for user input to proceed (OBC), or waited for a time and then continued unless the participant gave a stop command (OBE). Performance measures included targeting task performance, workload, and trust. Although performance between LOAs differed little, task performance was better for the smaller teams compared with larger teams. The four UAV teams also reported higher workload. Low reliability of the automation decreased task performance and trust, but had no effect on workload.

In a simulated search and rescue task Lee et al. (2010) evaluated the effect of LOA on target location; team size was not manipulated. Sixty crews, each of two operators, controlled 24 UGVs at a time. UGV maneuvering was performed manually or automated using OBE. In the manual condition, participants set waypoints for the UGVs to follow. In the OBE condition, the UGVs moved in a maze using an autopilot. If a UGV got stuck, the operator could manually control and turn it around. A second factor probed task allocation under two conditions. In the "assigned" condition, each operator in the crew was assigned 12 UGVs, but did not receive any information on the 12 UGVs assigned to the other crewmember. In the "shared" condition, both operators saw video feeds from all 24 UGVs, and each crewmember could control any of the 24. Performance measures included targets found, total search area explored, and workload. OBE led to significantly better target location than did the manual condition. With respect to search area explored, an interaction was found with task assignment. Significantly less area was explored in the manual LOA-shared control condition than the other three. Workload was higher for the assigned teams compared with the shared teams, but there was no affect of LOA. Thus, automation improved task performance yet had no significant impact on workload. Task allocation also affected performance, proving better in the assigned condition even though it entailed a higher workload. The authors postulated that the shared condition diffused responsibility, so underutilizing some UGVs (UV neglect); i.e., each crew member thought the other was responsible. This hypothesis was supported by post hoc analysis revealing that the number of robots neglected were higher for the shared team than the assigned teams.

The finding that crews in the shared condition performed worse might suggest the operators were not effectively functioning as teams to clearly allocate their tasks and to be aware of each other's responsibilities. For example, Burke et al. (2004) found that UGV operators with higher SA working in teams were significantly better at search and rescue than their low SA counterparts. They asked more mission-oriented questions and less situational- or status-ones. By communicating with their teammates, operators created a "goal directed mental model" to assist them in identifying problems and solutions while piloting.

5.1.3.2 Adaptive Automation

In the studies we discussed above, the LOA of the task was "static," i.e., never changed. Alternatively, a task can be performed either by automatic systems or by personnel based on situational considerations, such as personnel's overall workload (Lee, 2006; Miller & Parasuraman, 2007). For example, automation may assume control over lower priority tasks when the operator's workload increases to a level where it would be difficult to complete all their current work. This approach ensures that operators focus their attention on high priority tasks by maintaining their workload within acceptable levels. This constitutes adaptive automation (AA), i.e., where the LOA is flexible and can change.

A key consideration for AA is the "triggering" condition, i.e., who/what decides when, and on what basis the responsibility for a task changes from human to machine or vice versa. In some cases, the triggering condition is the operator's decision to change the LOA. In others, the automation automatically adjusts based on some detected condition related to operator factors (Prinzel, 2003), such as:

- psycho-physiological measures
- dynamic workload assessment
- task-performance measures

Triggering conditions also can be set based on the presence of critical events or reaching a setpoint(s) of measured parameter(s) (DeVisser et al., 2008). Thus, a change in the LOA can be initiated by the operator or by some other predefined condition based on operator's or system's status.

AA is being explored for use in controlling unmanned vehicles. Parasuraman et al. (2009) examined the effect of different types of automation for supervising multiple UAVs and UGVs. University students performed tasks requiring identifying targets, planning routes, and communications. There were three different implementations of automation: Manual; static LOA; and AA. In the first, participants controlled the vehicles without the aid of automation. In the static LOA condition, an ATR system helped participants. In the AA condition, participants' performance in a change-detection task was monitored; if it fell below 50%, the ATR system was initiated, but above 50%, the ATR system was unavailable. Thus, participants' performance was the triggering condition.

Performance measures included identifying targets, detecting change, SA, and workload. The measure of change detection was intended to evaluate the difficulty operators may have detecting changes when controlling multiple UVs (such as when anomalies arise), the so-called "change blindness." To measure this, participants were asked to press a spacebar if the location of a previously identified target moved a map. SA and workload were measured using questionnaires given to participants after each trial.

The results indicated that although the type of automation did not affect target identification, it significantly affected the detection of change that was far better under both automation conditions compared with the manual one; furthermore, detection was better in the AA condition than in the static condition. The type of automation also significantly affected SA and workload. SA scores were significantly higher in both automation conditions than in the manual condition, although the two automation conditions did not differ significantly from each other. Workload was highest in the manual condition, followed by that under static automation, and lowest in the adaptive condition. Thus, the results show that the type of automation affected performance. Compared to the manual condition, both automation conditions improved task performance and SA, and lowered workload. Compared to the static LOA condition, the adaptive implementation of automation improved performance and lowered workload.

The trigger in the Parasuraman et al. (2009) study was a change in the operator's performance. Another approach used by Shaw et al. (2010) for changing the LOA in AA was a request from operators. Student participants controlled three UAVs; the task was to use unarmed UAVs to identify hostile targets, and pass the information to the armed UAV. Waypoints set by either the participants or the automation, depending on the LOA, navigated the UAVs. There were three AA conditions:

- Manual condition, wherein the operator sets waypoints, targets weapons, and launches them
- AA1 condition, in which the operator chooses between two LOA options: Manual, and partial automation that initiates "scripts", such as a targeting script, and the task is performed automatically
- AA2 condition, where the operator chooses between three LOA options: Manual, partial automation, and fully autonomous operations (in the latter, operators must approve weapons launch)

The researchers collected performance measures: One was the percent of targets successfully tracked; a second was the time participants took to handle an unexpected event that that automation could not deal with. Overall, the results showed that operators performed much better as more LOA choices were provided; AA2 offered the greatest number, yielding the best performance. Dealing with unexpected event performance did not differ significantly across conditions. Parasuraman et al. suggested that increasing the automation options available to operators helps them manage their workload. In managing unexpected happenings, operators would increase the automation of unaffected aspects of UAV control, while assuming manual control of those affected.

5.1.3.3 Automation of Vehicle-Coordination Tasks

Automation can be applied to the tasks performed to supervise multiple vehicles. Chen et al. (2010a & 2010b) developed an intelligent agent, "RoboLeader", to coordinate route planning for multiple UGVs. Its support was tested by having operators control a team of four or eight UGVs either with or without RoboLeader in a target-detection mission. There were no differences in detecting targets between operators with RoboLeader compared to those without it, but operators with RoboLeader completed the mission in significantly less time. Target detection was better and workload was lower when operators managed teams of four in comparison with eight UGVs. This study suggests that automation can be applied to higher-level supervisory functions by supporting mission planning tasks associated with multi-vehicle coordination.

5.1.3.4 Vehicular Differences

In addition to the number of UAVs, another factor affecting performance is the extent to which the UAVs differ from each other, i.e., their degree of heterogeneity, compared with their homogeneity when all vehicles in a team have the same design. ARL researchers indicated that operators find it harder to manage heterogeneous teams. The difficulty was noted by other researchers (Nehme & Cummings, 2007; Nehme et. al., 2008; Wang, Wang, & Lewis 2008). Heterogeneity causes a loss of SA, partly due to the demands of switching tasks between the different types of vehicles.

5.1.3.5 Human-system Interface Design

Several authors suggested that HSI design is important to UAV command and control (e.g., Calhoun et al., 2009; DoD, 2005; Shaw et al., 2010). The goal of HSI design is to provide the information and controls needed for operators to perform their tasks while minimizing the workload from interacting with the HSI.

Research is beginning to examine what types of displays support operators to gain UAV SA. Cook et al. (2010) evaluated the design of a situation display to support route planning tasks. They found that an augmented 2-D display that displayed goal information and used color-coding to communicate important data led to better performance than either an unaugmented one (similar to those currently used) or a 3-D display.

Cummings and Mitchell (2005) evaluated the use of a “Timeline” display that displays crucial information conveying the status of progress of a UAV’s current mission. Using a timeline approach, operators can better estimate waypoint arrival time, and can thus make any needed adjustments.

As noted earlier, ARL researchers considered that the design of the HSIs should inform operators of how the automation works, e.g., how it makes decisions. Roth et al. (2004) evaluated the extent to which UAV operators understood the plans developed by automated controllers, finding that humans and automatons cooperated as a team in planning and executing missions. These findings emphasized the need to communicate the rationale used by the automaton and offer a means for operators to modify the automaton’s operations, without which operators cannot properly assess the appropriateness of automation’s actions and whether changes are needed. Thus, HSIs should support automation-human communication so operators can determine and understand how the automation performs its tasks.

Another aspect of automation-human communication is the prompts made by the machine to operators; how they are made impacts task performance and workload (Maere et al., 2010). When prompts come too quickly, they add to workload and degrade performance. When they are not frequently enough, again, the operator’s performance is negatively impacted because they do not get necessary information. Maere et al. (2010) showed that allowing operators to control the rate of automation prompts helps to mitigate these effects.

The operator’s workload is an important consideration in HSI design because they may fail to use automation properly if too much effort is required to do so. This is especially important with AA where operators’ interaction with automation is more frequent because of the changes in LOA.

Miller and colleagues examined the issue of minimizing workload associated with operator interactions with automation, developing a "delegation interface" for interacting with automation levels (Miller & Parasuraman, 2003, 2007; Miller et al., 2005). The approach is modeled on work delegation in human teams. Delegation is the process of assigning specific roles and responsibilities for the subtasks of a parent task for which the delegating agent retains authority and responsibility. As supervisory controllers, operators select tasks for automation to perform, and set procedures for how it must accomplish them. Communication between agents is expressed in terms of goals, methods, constraints, and resource utilization. The underlying concept is that operators can delegate predefined tasks to automation, thereby giving them a flexible approach to completing tasks and an efficient means of changing the level of automation.

"Playbook" is the HSI that supports the delegation approach; its name is based on the metaphor of a sports team's use of a "playbook," i.e., a set of specific plays that all team members understand. The plays, based on a hierarchal task model, reflect the system's levels of automation. Groups of predefined tasks are organized into plays, with the relevant task parameters identified (or specified when operators call a particular play), such as times and locations, thereby establishing a common understanding for all team members of what each individual agent will do. However, although the more the operator has to specify in real time, the more effort is involved in communicating with the automation, an advantage may be that the "play" can be better tailored to a specific situation.

Playbook contains a planning function to develop a specific plan for a current situation. The planner has access to information, such as resources available (e.g., fuel), and can adjust the tasks accordingly. It alerts the operator about any constraints that would compromise success. Control algorithms for executing actions are specified in the plan. Finally, if necessary, an event-handling function makes fine adjustments during the execution of the plans.

Parasuraman, Galster, Squire, Furukawa, and Miller (2005) compared the effect of Playbook on the performance of UV tasks with a restricted interface with only one level of control. The success rate and time to completion were better with Playbook, although the benefits fell as the number of vehicles simultaneously controlled increased. The HSIs enabled operators to identify goals and instruct automation agents; also, they better adapted and responded to the automation's ineffective behavior.

The lessons learned from these studies is that providing operators with "set plays," i.e., predetermined definitions of a set of roles and responsibilities of human and machines can reduce the operator's workload in interacting with the automation.

While "plays" offer one effective means of controlling the operators' workload from interacting with automation via the HSI, another is to automate aspects of HSI interaction. Again, as above, we primarily focused on automating UAV control and supervisory tasks. Interface management is another task that can be automated. This term describes the actions taken by the operator in interacting with the HSI, rather than monitoring and controlling the system. Interface-management tasks include navigating to find and retrieve displays, and adjusting display windows. These tasks compete with the primary monitoring and control tasks for the operator's attention, and can distract and disrupt performance (O'Hara & Brown, 2002). Automating interface management tasks potentially can lower the workload associated with them.

Hou, Kobierski, and Brown (2007) developed an intelligent adaptive interface (IAI) that selects a display based on current situational factors involving mission changes and operator states similar to the triggering conditions discussed earlier. They investigated the efficacy of IAIs in a multi-UAV mission. The IAI was modeled as part of the UAV tactical workstations in maritime patrol aircraft. They used a performance model to compare the difference in mission activities with and without IAI agents. A prototype IAI experimental environment was implemented for a human-in-the-loop empirical investigation. Both the simulation and the experiments revealed that although multiple UAV control is a cognitively complex task with high workload, IAIs significantly reduced workload and improved SA, allowing operators to work under high time constraints.

The longer term DoD goal to use natural communication mechanisms is another way of easing the interface management load during multi-UAV interactions:

> The focus of human interface with the machine should evolve from today's current physical interfaces such as joysticks, touch screens, etc., to interaction such as hand signals, and ultimately to natural language understanding in order to be tasked for missions. (DoD, 2009, p. 27)

Thus, providing automation support for interface management, and advancing the means by which operators and systems interact, may lower the workload associated with these tasks.

5.1.4 Summary of Results

In summary, these studies we described examined the following aspects of UAS design and performance:

- UAV team characteristics
- automation design
- task allocation to crew members
- HSI design

In addition to discussing UAS design features, we also will consider the importance of performance measures and HFE methods and tools. We conclude this section by generalizing the research findings to real-world systems.

<u>UAV Team Characteristics</u>

A principal objective of much of the research was to investigate the size of the UAV team (i.e. number of UAVs), its impact on performance, and technologies for enabling operators and crews to manage large teams of UAVs. This is a major factor of interest to our work since team size is analogous to number of SMR units that an operator manages.

Nearly all studies found notable effects of team size. As the size of the UAV team increased, task performance declined and workload rose. It also impacted other factors such as UAV neglect, which rose as team size increased.

Another important characteristic of teams is their degree of homogeneity; generally, heterogeneous teams are more difficult for operators to manage.

<u>Automation Design</u>

Automation is deemed a key enabling technology for increasing team size. The aspects of automation examined encompassed

- functions automated
- LOA
- static versus flexible LOA
- transparency of automation's processes
- automation's reliability

The studies reviewed examined, and verified the successful application of automation to a variety of UAS functions:

- vehicle monitoring and control functions
- mission coordination (supervision) functions

Many studies considered the LOA; in general, increasing the LOA led to better task performance, although one study failed to find an effect of LOAs (Ruff, 2004). However, the effects were not universal for all measures (discussed further under performance measures below).

LOAs can be implemented statically or flexibly; the latter is called AA. Static LOA frequently did not significantly impact workload or SA, though most studies did not evaluate SA. AA was associated with better task performance and lower workload. Increasing the automation options available to operators may have helped them manage their workload.

Increasing the transparency of the processes of automation proved an important factor supporting the ability of operators to understand its workings. To assure its optimization, communication features should be an inherent part of the HSI allowing operators to interact with automation to better understand its behavior.

The final aspect of automation we examined was its reliability. In general, lower reliability led to declines in task performance, and a lower level of operator trust in the automation. Because the reliability of real-world systems is imperfect, their effect on operator- and system-performance is a major consideration.

Cummings et al. (2007) cautioned against over-automation; namely, it is not a good strategy to automate anything that can be due to human-performance concerns associated with high degrees of automation. Determining when and how to automate is the key consideration to success. ARL researchers echoed this same consideration, stating that their experience shows that some higher-levels of automation may be difficult to achieve. Cummings expressed the same concern about automating mission-planning functions that depend on decision making, judgment, and experience. Thus, there are both technical concerns (difficulty automating a function) and HFE concerns (negative effects on operators of high-levels of automation) that set constraints on the achievable crew-vehicle ratio.

Task Allocation to Crew Members

Performance was affected by task allocation between crew members. It was better when UAVs were assigned to specific crew members rather than shared between them. Lee et al. (2010) postulated that sharing diffused responsibility, leaving some UGVs underutilized (neglected); i.e., each crew member thought the other was responsible. However, we suggested instead that, in the sharing condition, the operators were not effectively functioning as human teams, and did not clearly allocate their tasks or maintain awareness of each other's responsibilities.

HSI Design

The design of the HSI is a key factor. As discussed under automation above, the HSI should incorporate communication features enabling operators to better understand the automation's processes. Other important considerations for HSI design include:

- providing HSI features so operators can effectively monitor multiple UVs and gain accurate SA
- managing the workload for coordinating and controlling multiple UVs, e.g., via using intelligent agents and of set plays
- managing the interface management workload because a high one can lead to the operators' disuse of automation and can distract them, thereby impairing their performance

Performance Measures

The studies reviewed illustrated the value of performance measures. Measures of primary task performance must be selected carefully. Many studies recorded effects on one performance measure but not another. Thus, important aspects of the primary task should be measured to avoid the possibility of committing a Type 2 error, i.e., failing to identify significant effects when they exist.

Researchers should carefully choose measures that are sensitive to the expected variations in performance. That is, the measures selected should avoid floor and ceiling effects. For example, in a search and rescue task, primary task measures might include number of targets retrieved, and response time. If under the task constraints, most operators retrieve all the targets, then that measure will not be sensitive to changes in automation. Thus the measure will exhibit a ceiling effect, in which case, response time may be a more sensitive one.

The studies also illustrate the need for comprehensive performance measures that encompass primary task measures, and measures of SA, workload, and trust. These cognitive measures were found to be viable constructs essential to understanding and predicting human-system performance in complex systems, especially those employing extensive automation (Parasuraman, Sheridan, & Wickens, 2008). For example, Wickens et al. (2010) noted that SA was a critical factor in dealing with automaton failure, and tended to mitigate the poor handling of disturbances often associated with high LOAs. They indicated that designers need to focus on increasing the operators' SA for automation by finding its right level for tasks, improving the HSI for automation and training. Furthermore, the benefits of automation can be offset when operators do not trust it. Then, they may not use it, or it may increase their workload significantly by overly verifying the automation's behavior. Similarly, failures of automation can remain undetected if operators trust it too much and hence, become complacent. Thus, constructs such as these are important to assess as part of developing and evaluating a system.

These studies reviewed above also illustrated some additional measures that are important considerations for multi-unit operations: Neglect time (Crandall & Cummings (2007), and change detection/blindness (Parasuraman et al., 2009). The latter refers to the phenomenon of failing to see large, salient changes in the environment (Simons & Ambinder, 2005).

HFE Methods and Tools

In addition to using traditional HFE methods and tools in developing future UASs, human performance modeling and simulation methods are playing an increasing role, consistent with the DoD's overall goal of increasing the use of these methods (DoD, 2003).

Generalizing of the Research Findings to Real-world Systems

The research undertaken constitutes an important technical basis for developing future UASs. Like any research findings, a major consideration lies in generalizing the results to the applicable operational systems. In this development, the DoD's research is focused on a target operational context, characterized along the dimensions illustrated in Table 5-2. Research findings are generalized most easily to this operational context when they closely match the target's operational context. Table 5-2 illustrates that the main difference between the studies we reviewed and the systems to which they will be generalized is complexity of the operational environment, as we discuss next.

Typically, the systems and HSIs used in these studies were simplified representations of actual UASs, as were the tasks participants performed. Further, participants in most studies were relatively inexperienced with limited training. Domain experts and naïve participants differ in their cognitive approaches to task performance and decision making; ultimately, research findings must be confirmed with domain experts and in real-world settings (de Greef, Arciszewski, & Neerincx, 2010; Zsambok & Klein, 1999). Thus, the results must be interpreted with these differences in mind.

Table 5-2 Comparison of the Operational Contexts of the Actual Systems and the Studies Reviewed

Generalization Dimension	Target Operational Context	Typical Study Reviewed
Application Domain	UAS systems designed for various military missions	While the domains varied, the simulated systems usually were very simple and did not involve the complexity of real-world operations
Functions and Tasks	Mission planning, UAV coordination, and vehicle control loops identified by Cummings et al. (2007)	Simplified versions of the types of UASs
System Representation	A variety of UAVs designed for various purposes	Simulated vehicles with limited control capabilities
HSIs	Alarm, displays, and controls presented in control stations for one or more operators	Very simple, lacking the complexity and number of displays as are found in a typical UAS control station
Personnel	Highly-trained, professional operators	While some professional operators (pilots) participated in these studies, most research used students with very limited experience and training

We emphasize that this is not a criticism of the research we reviewed. Future UAS systems are in the early design phase where research can be directed to identifying issues and developing approaches and concepts for addressing them. Studies like those we reviewed provide important contributions at this stage. Once identified, promising technologies and strategies to achieving DoD's long-term goals can advance to the systems development and evaluation phase, where real-world mission constraints can be addressed.

The difficulties of addressing UAS issues in a real-world context was illustrated by ARL researchers who summarized the current status of DoD's efforts to achieve the one-to-many ratio of operators to UVs by indicating how difficult it is to attain a 1:1 ratio. The principal reasons include (1) the degree of automation needed is difficult to achieve, (2) high workload is a problem, and (3) switching tasks between vehicles is very disruptive.

5.1.5 Pertinent Challenges for Modular Reactor Operations

In this section, we summarize the challenges identified for future UAS development that are relevant to SMR operations.

1. The characteristics of the UAV team proved important, especially its size (number of vehicles monitored and controlled by an operator or crew), and the homogeneity of the vehicles assigned to an operator (vehicular differences compound the difficulty operators have managing the team). Both these issues are significant to developing SMR ConOps, and were identified earlier in this report. SMR designers will have to identify the manageable number of units; wherein unit differences may play a role in determining the specific number. We expect the SMR units at a site generally to be the same, but some differences likely will develop over time.

2. Increasing the number of UAVs assigned to an operator (or crew) depends on the automation's design. Automation is being applied to supervisory- and interface-management, as well as monitoring and control functions. SMR designers recognized the need to increase automation; similar to UAS designers, they are likely to apply automation to more than monitoring and control. As its usage extends to diagnostics, situation assessment, prognostics, and other support aids, the systems' reliability will be a key issue. UAS researchers found that as automation's reliability declines, operator's performance and trust is degraded. As we noted earlier, the reliability of real-world systems is imperfect. Therefore, it is vital to quantify the reliability of automation in general, and of decision support systems in particular. A further consideration is assessing the effects of differences in automation's reliability on SMR operators.

3. UAS designers found that increasing the LOA generally improves performance and providing flexibility over the level, such as AA, supports workload management. They are evaluating the use of different LOAs and LOA flexibility to achieve the benefits of automation, while minimizing the negative effects of very high levels on human performance. These considerations must be examined for in designing SMR automation, finding the proper mix of automation and human involvement to ensure the safety of SMR operations.

4. Applying automation to SMR operations needs to be carefully tested. UAS researchers encountered difficulties achieving the levels of automation needed to improve the operator-to-vehicle ratio. Careful evaluations considering the performance of the entire system will assure the success of automated systems in achieving their functions and their acceptable integration into the human-automation team. Herein, the UAS community employs operator-in-the-loop simulations as a primary tool.

5. UAS researchers reported that the allocation of tasks between crew members affected performance, which will be an important consideration in developing SMR ConOps. For

example, at a site with four SMR units and two operators, each might monitor two reactors along with their BOP systems. Alternatively, one operator might manage all four reactors, while the other operator manages the four BOP systems. The advantages and disadvantages of different task allocations must be assessed, while also considering the impacts on teamwork and supervision.

6. UAS researchers highlighted the importance of HSI design when managing multiple vehicles; this also is applicable for SMR operators managing multiple units. Designing the HSI for multi-unit monitoring and control is a new challenge to designers and regulators for which there is little precedent.

7. The UAS research emphasizes the importance of measuring performance. A comprehensive set of measures is needed to address, at a minimum, important aspects of primary task performance, teamwork, SA, trust (in automation), and workload; the same considerations are needed in developing and evaluating SMRs. The UAS studies suggest some additional measures, such as unit neglect time and change blindness, may be useful in evaluating them. As well as selecting the right aspects of performance to measure, the measures should be sensitive to the expected reasonable variation in performance. Measures with restricted ranges, such as ceiling and floor effects, should be avoided because they produce misleading results.

5.2 Oil Refineries

5.2.1 Introduction

An oil refinery (Figure 5-2) comprises a series of processes that convert crude oil into different petroleum products; many refineries are made up of multiple units. In new and modernized facilities, these units are monitored and controlled from a single central control room. We made a site visit to one such facility.

Figure 5-2 Oil refinery
(Source:http://www.google.com/images?hl=en&biw=1276&bih=859&gbv=2&tbs=isch%3A1&sa=1&q=oil+refinery&aq=f&aqi=&aql=&oq=)

This plant was built in 1955 and was expanded and upgraded over the years. Its overall mission is to process crude oil into products such as gasoline, diesel, propane, and butane. It also manufactures asphalt, heating fuels, and sulfur for fertilizers. Of particular note is the centralization of operations from multiple distributed control rooms into a modern, digital, centralized control room (CCR) from where operators monitor and control multiple process units with operational demands similar to those anticipated for SMRs.

In this section, we summarize the information obtained from the site visit and identify those issues potentially pertinent to SMR operations.

5.2.2 Methodology

Two BNL project staff visited the refinery to observe the operations of the control room operations while operators were performing their tasks, and to interview them to obtain specific information about their approach to operations. The questions asked were a variant of the ConOps questionnaire in the Appendix.

5.2.3 Results

The overall mission of the facility is to process crude oil into a variety of products, such as jet fuel, gasoline, diesel, propane, and heating fuels. Environmental protection and safety are a priority in the facility.

The facility accomplishes these functions through nine processes: Sulfur, Crude, Naphtha I and Naphtha II, Distillate, Coker, Gas Oil (GO), Alky, and Fluid Catalytic Cracker (FCC). Some of them have three units (e. g., crude, distillate, hydrogen units, and GO). All units are not identical.

The processes are highly automated, so that the operating staff's main role is to oversee them and make any needed adjustments. There also are local operators out in the plant whose main responsibility is ensuring the equipment's reliability. Two key areas not automated are the startup and shutdown of the various units; these evolutions are performed manually, requiring additional staff to accomplish all the needed tasks.

Control room operations have evolved. Before the late 1990s, each process was managed from its own control room. The control rooms were distributed throughout the plant. Thereafter, facility management integrated all the local control rooms into a CCR.

In the CCR, one operator, the project lead (PL), is assigned to each of the nine processes. There also is a control room supervisor and a day shift "bench lead" for each process who fills in where needed. For each process, there also are three to five local personnel consisting of at least one local lead and two auxiliary operators. The total operating shift comprises about 50 people. It takes six months to train a new operator, using structured training and on-the-job training. Operators are tested using a skills demonstration and an oral exam.

Figure 5-3 shows the layout of the CCR, consisting of three "pods" and nine "consoles."

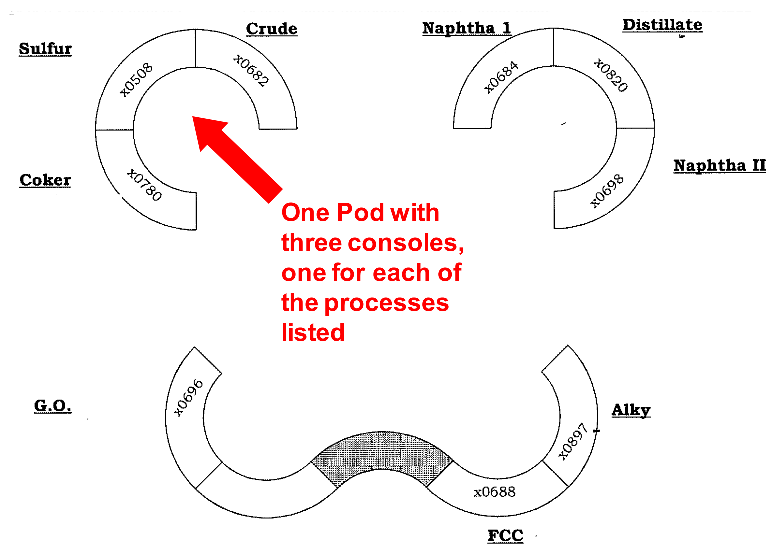

Figure 5-3 Layout of the refinery control room
(Figure provided by refinery staff and annotated by the authors)

A console is a workstation, one for each process, and a pod is a group of connected consoles. The figure identifies which process is controlled from which console. The consoles are sit-down workstations manned by one PL; they have sufficient room for additional staff when needed.

Some processes involve up to three units that are monitored and controlled from a single console by a single PL; about 250 controls and 2000 indicators are available at the console. Workload is a key consideration in evaluating the assignment of units to PLs. For each PL, engineering analyses ensure that the workload is acceptable, and the required tasks can be successfully performed. Evaluations of task loads determined the number of controls and indicators that the PL can manage.[15] Engineers can reassign parts of a process or secondary functions to another PL, should the workload prove too high. Facility management also brings in additional staff when they anticipate high workload, such as during startup, shutdown, or major transients.

Screens display almost all of the information and controls. Each console has approximately three monitors for the distributed control system (DCS), and five to seven monitors for other purposes.

The DCS is the most important I&C system; it is used to monitor and control key process parameters and identify critical alarms. Facility personnel stated that the design of the alarms is

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[15] Following our visit, we contacted Beville Engineering to obtain more information on the types of studies done. They performed a variation on time-and-motion studies to determine operator workload and the workload associated with the position of each console, This entailed repeated four-hour observations of operator activity that were encoded into different types of tasks. Since working with the refinery, Beville has used this methodology to evaluate over 300 console positions, encompassing over 2400 hours of observation. From that data, they developed a correlation between alarms/control changes and total workload. Underlying the approach is the premise that the console's position should be staffed for steady-state workload, while the operator-process system (automation, interface, and training) should be designed to enable that staffing to handle foreseeable upsets. Unfortunately, Beville has not published the method, but did provide additional information and more concrete examples (personal communication August 13, 2010).

critical to operations. Each alarm must be identified carefully. The criterion determining whether a parameter should be an alarm is that it must be unique information requiring an achievable action. An alarm is considered critical when immediate action by operations is needed. The facility receives an estimated two critical alarms per shift across all nine processes. The secondary alarms, also called Console Action Plan alarms, are non-critical alarms (Figure 5-5).

Some PLs monitor three similar units. The alarms for all three are integrated; that is, they are presented together so that PLs only have to look at one screen to see them all. However, the displays for each unit are separate. The two primary types of displays are process (mimic) displays and trend displays, fairly standard display formats used in modern digital systems. The crude process, for example, contains three crude units, numbered 1, 2 and 3. Unit 1 has a small capacity, while Units 2 and 3 are large capacity. Both the inputs to and the outputs of the process for each of the units differ, as do, the number and sizes of their components. The PLs indicated that these differences made it easier for them to distinguish between the units, i.e., they look different on the displays so they are easily distinguished. These differences between multiple units within one process are addressed in training.

Soft controls (on-screen controls), also called faceplates, control the equipment. Like the mimic displays, the soft controls were typical of modern computer-based systems.

Procedures guide personnel action. PLs must follow them and sign off upon completing a step. However, there is a formal deviation sheet if needed. The refinery undertakes an annual review of the accuracy of procedures, noting any improvements.

Each console has two redundant DCS pathways, and two failures are needed to fail the DCS. Power is supplied through an uninterruptable power supply (UPS). PLs have separate alarms for problems with the DCS system for each console. However, there have been no DCS failures since the system was installed in 1997/8. The computer workstations (non-DCS) could fail since they are single path I&C. However, should that happen, operators can then use the DCS or operate equipment locally. PLs have a procedure for loss of DCS and are trained in what to do when failures occur.

5.2.4 Pertinent Challenges for Modular Reactor Operations

In this section, we summarize challenges identified at the refinery that are relevant to SMR operations.

1. Operators can monitor and control multiple units, and the refinery's operating experience supported this conclusion. Keys to making this possible include:

    - careful analyses of workload to ensure operators are not overloaded
    - automation, so operators can focus on monitoring and managing processes

2. Careful attention to designing the alarm systems design is essential so the number of alarms is manageable, each alarm is unique, and each is associated with an achievable action. In the refinery, alarms for different units are integrated into a single display rather than being presented separately for each unit.

3. Unit differences, as depicted in the HSIs, supported operators in maintaining awareness of the status of individual units.

4. Organizational changes are needed during emergencies to manage events occurring at one unit. The availability of additional staff during periods of high workload (such as startup/shutdown and to manage major off-normal conditions) is necessary for the refinery's multi-unit operations.

5. Important contributors to safe, reliable operation we noted during our visit were:

   - a highly trained, experienced staff
   - a professional attitude amongst operators and engineers
   - a well-designed CCR
   - careful analysis of operator workload and its implications for staffing

5.3 Tele-intensive Care Units

5.3.1 Introduction

Tele-intensive care units (tele-ICUs) are emerging as an alternative to and backup for traditional hospital ICUs.[16] Tele-ICUs are facilities that remotely monitor intensive-care patients and notify on-site hospital staff when conditions warrant medical intervention. They share many characteristics with other high-risk, high-reliability organizations; that is, a critical mission, wherein the consequences of error can be unacceptable, is accomplished by a formalized organization of highly trained experts, using pre-established procedures, supported by state-of-the-art computer technology.

The need for such facilities arose from the dearth of physicians specializing in critical-care medicine (so-called intensivists). The shortage is especially acute during overnight hours when hospitals may not have intensivists on shift, and at rural hospitals where such specialists may not be available.

Tele-ICUs have a control room from where the tele-ICU staff can monitor many more patients in hospitals remote from the facility than can the on-site hospital staff. For example, an ICU nurse in the hospital may monitor two patients, while a tele-ICU nurse may monitor as many as 30 patients. One hospital's intensivist may administer to 10 ICU patients in a hospital, while a tele-ICU intensivist is available to well over 100 patients located at many different hospitals.

Studies of patients monitored by tele-ICUs found reductions in patient mortality, length of stay, and cost compared with traditional ICU methods (Kohl et al., 2007; Lilly & Thomas, 2009; Heightman, 2009). Further, the availability of tele-ICUs has improved critical care services in small rural hospitals and reduced patient transfers to larger ones (Zawada et al., 2009).

[16] Lilly and Thomas (2009) comprehensively reviewed Tele-ICUs.

Remote monitoring of and intervention for multiple patients places demands on human performance analogous to those that SMR operators may face; they may need to do the following:

- monitor multiple independent “units” (patients or reactors)
- monitor the same multiple parameters of those independent units
- maintain SA of multiple independent units
- deal with differences in information available across “sites” (it may vary from one hospital to another)
- deal with differences in the presentation of information across “sites” (it may vary from one hospital to another)
- manage events that may arise and cope with the workload of emergency management
- manage multiple events occurring among independent units when such situations arise
- coordinate shifts in staff responsibilities to manage emergencies
- manage increased communication demands during emergencies
- deal with bringing new independent units on-line

Thus, tele-ICUs may provide insights to the issues that SMR operators may face.

Below, we summarize the information obtained from a site visit to one tele-ICU, highlighting the issues potentially pertinent to SMR operations.

5.3.2 Methodology

On March 24, 2010, two BNL project staff visited a tele-ICU located in the United States from approximately 4PM to 8PM, a span that included a shift turnover.

We had two objectives: Observe control-room operations while facility personnel were performing their tasks; and interview staff to obtain specific information about their concept of operations.

5.3.3 Results

The tele-ICU, operated for over 5 years, provides a remote ICU monitoring control room for four hospitals (one major hospital and four rural ones).

The high-level functions that the tele-ICU staff performs involve monitoring patients, assessing conditions, and responding to events.

- *Patient monitoring* – Tele-ICU staff monitor the vital signs and medications of each patient, classified into one of three categories: Red (most serious), yellow, and green (least serious). This classification guides the extent of monitoring of individual patients.
- *Assessment of conditions* – When an abnormal vital sign is identified, assessment of conditions requires access to the patient’s data, charts, test results, X-rays, and visual observation of the patient. For example, the tele-ICU nurse may communicate with on-site

staff to check a lead on measuring equipment to determine if an abnormal heartbeat is due to a loose connection.

- *Responding to events* – If the facility's staff determines that intervention is required, they need communication equipment to contact on-site staff to take necessary actions. Common information displays for the tele-ICU staff and the local hospital's staff support their communication.

The facility is staffed as follows:

- one intensivist[17] (night shift only)
- three ICU nurses (providing round-the-clock coverage)
- two clerks providing round-the-clock coverage

As noted above, the on-shift staff emphasized the importance of communication with in-hospital staff on patient interventions.

The tele-ICU we visited has one experienced nurse (at least 5 years of work experience) for every 30 patients. The ideal patient-to-physician ratio still is being determined, but probably will be between 120 to 150 patients per physician.

The ICU monitoring system is supplied by VISICU.[18] The control room layout includes a workstation for each of the nurses and the doctor (Figure 5-4). Each workstation has five monitors, keyboard, mouse, camera controls, and telephone. The data displayed for each patient includesS

- demographic data (including names of patient and their physician)
- vital signs (heart rate, heart rhythm, blood pressure, respiratory rate, oxygen saturation)
- laboratory tests
- X-rays

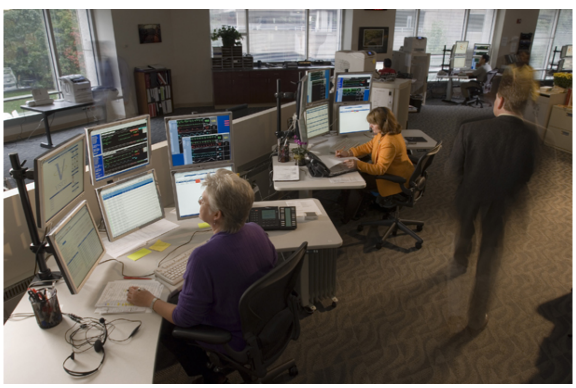

Figure 5-4 Tele-ICU control room
(not the site visited)
(Source: http://visicu.mediaroom.com/index.php?s=13&cat=8&mode=gallery)

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[17] Daytime shifts for weekends and holidays supplement ICU coverage when rural hospitals have decreased staffing.
[18] Information in Visicu is available at: http://www.visicu.com/index_flash.asp

Monitoring is supported by alarms and signal processing of the patient's vital signs. Cameras enable the tele-ICU staff to observe patients, and with the communication equipment, interact with on-site staff.

5.3.4 Pertinent Challenges for Modular Reactor Operations

We next summarize the challenges we identified at the tele-ICU that are relevant to SMR operations.

1. Monitoring individual patients can be viewed as analogous to monitoring individual reactor units. The tele-ICU staff indicated that monitoring and intervention can be complicated by the differences between hospitals. For example, different hospitals' chart formats create higher workload and slow the physician's response. If the modular reactors monitored by the control room staff are at different sites, site differences may impose additional complications, as do different hospitals. Also, there may be variations in the design between reactors and/or their HSIs. At one site Modular reactors are planned to be standard, but changes in design likely will evolve.

2. Another issue concerns possible differences in the I&C system when new units are brought on-site. Also, when hospitals are brought on-line, new ones may have more recent versions of VISICU, entailing differences in data and data presentation between new and old hospitals. This problem may arise as new reactors are brought on-line. Indeed, the development of I&C systems is so rapid that reactors brought on-line a decade apart may have different I&C systems, different levels of data processing, and might measure different parameters.

3. Organizational changes are needed during emergencies to manage events occurring at one unit. For example, when a nurse is intervening with a critical patient, a particular specialist may have to be called in, and the monitoring of less critical patients delegated to other nurses. A similar flexible adaptability to emergency events might be used in operating modular reactors.

4. Some aspects of the HSI are not well suited to monitoring multiple "units," e.g., the tele-ICU lacks a flexible means simultaneously to display the vital information for many patients. The approach to HSI design for monitoring multiple reactor units will be a key aspect of safe operations, and may involve novel approaches to HSI design.

5. HSI support is needed for monitoring multiple "units." The tele-ICU gives patient criticality codes to guide where to focus monitoring attention ("red" patients). Alarms and signal-processing aid personnel to monitor individual parameters. Reviewing HSI designs of modular reactors must consider HSI support for the workload associated with monitoring.

6. The staff of the tele-ICU deemed their familiarity and trust with staff at the local ICU as an important feature. Without these, smooth operations are impossible. This aspect could be pertinent to modular reactors, for example, the familiarity of control room operators with all the local operators on site, who may alternate between units.

5.4 Insights for SMR ConOps from Surrogate Facilities

We examined the ConOps of the surrogate facilities, and from the information obtained, we offer the following as considerations for SMRs.

1. Monitoring and controlling multiple units can be accomplished by a single operator or crew in a single control room, and is part of the ConOps for normal operations in refineries and tele-ICUs. The DoD is developing this capability for UASs by DoD, and it's proving a challenge to designers.

2. Enabling technologies that support operators to monitor multiple units include:

    - extensive use of automation
    - advanced designs of HSIs and alarm systems
    - design of control room that fosters teamwork and communication
    - procedures and HSIs that support the transition from normal operation to off-normal/emergency management
    - extensive information technology support for troubleshooting the problems users encounter

3. The effect of unit differences (heterogeneity) is unresolved. At the refinery, such differences helped somewhat in monitoring and distinguishing between units, while for tele-ICUs and UAS operators, differences complicated operations. We noted at the tele-ICUs the negative effects of differences at higher levels of organization on monitoring individual units. By analogy, these might be effects due to different locations, e.g., if several SMRs are located at one place, while others are elsewhere.

4. Automation is a key enabling technology. Concerns about over-automation and its potentially negative effects on human performance have entailed more interactive and flexible approaches to automation. Adaptive automation, for example, may be valuable in assisting operators to manage the workload in supervising multiple plants. Training improves operators' understanding and use of automation.

5. Clear staffing responsibilities are defined for personnel at the refinery and tele-ICU, and is underway for UAS staff. Allocating tasks to crew members is vital in terms of the performance of the overall team and integrated system.

6. Crew flexibility is key to managing off-normal situations. At refineries and tele-ICUs, significant organizational changes are made to manage them. The availability of additional staff for the off-normal unit was necessary. They also were used for some transitions, such as unit start-up or shut-down at the refinery. Having a way to transfer responsibilities for reactors in off-normal states to a person or team specialized in dealing with them may be beneficial to SMR operations. Communication between personnel then is crucial. Maintaining SA during off-normal situations is easier when operators have a simple means to communicate with other personnel.

7. Staff at the refinery and tele-ICU emphasized the importance of familiarity of control room staff with local operators; it fosters trust and smooth operations.

8. Designing the HSI for multi-unit monitoring and control is challenging. HSIs must enable monitoring of the overall status of multi-units, and the easy retrieval of detailed information on an individual unit. The design of alarms particularly must ensure operators are aware of important disturbances, so minimizing that the effects of change blindness and neglect. The organization of information is another critical HSI consideration, e.g., deciding to what information crew members need access, individually and as a crew, to support teamwork. HSIs also must support the transfer of operations between crew members.

9. The design for multi-unit management also is aided by detailed HFE analyses of staffing and operator tasks, via task analysis, human-performance modeling, and operator-in-the-loop simulations.

6 POTENTIAL HUMAN-PERFORMANCE ISSUES

We evaluated several sources of information about SMRs and related systems in Sections 3, 4, and 5, identifying potential challenges to human performance that touch upon several technological disciplines, such as HFE, I&C, plant operations, maintenance, and PRA. In this section, we integrate this information to identify a set of potential human-performance issues to consider in research on, and in regulatory reviews of SMRs. There is some redundancy therein because different sources of information often identified the same or similar challenges. This redundancy is good because it is a measure of the converging validation of the issues. In describing the issues, we often integrated individual challenges we separately identified in previous sections into a single one, particularly when the issues highlighted different aspects of the same topic.

There are some dependencies between the final set of issues, often reflecting their hierarchal relationships. For example, new missions lead to new staffing approaches that necessitate new designs for the control room and HSI. We point out these relationships when they are significant.

In Section 3, we found that SMRs differ from currently operating plants in many important ways, as summarized in Table 3-2. Many issues discussed in this section stem from them. Individual SMR designs also differ from each other. Thus, not all issues described below pertain to all designs.

We also identified several issues that are not solely related to SMRs, such as passive systems, and non-LWR technology. We included them here because they will have to be addressed in SMR licensing reviews, even though they are not strictly limited to SMRs.

Table 6-1 lists the issues identified for each ConOps dimension, all of which are discussed below. We first describe each one, and then detail its implications for research and for design reviews. Several pathways may be involved in resolving the issues:

- *Policy implications/regulation update* – Resolution may necessitate updating the NRC's policy and/or regulations.
- *Guidance update* – Resolution may require updating HFE design review guidance, such as NUREG-0711 and NUREG-0700.
- *NRC research needed to support guidance development* – Resolution may require research to (1) determine whether an issue is a potential safety concern, and (2) if so, to establish a technical basis upon which to formulate review guidance. We note that not all issues requiring an update of HFE review guidance necessarily require new research to support the development of guidance.
- *Industry actions* – Resolution may be addressed in industry research or vendor/utility HFE programs, such that additional action by the NRC probably is not needed.

Where possible, we pointed out the resolution pathways applicable for each issue. A given issue can have more than one implication category; we give examples of the usage of the categories.

Table 6-1 Potential Human-Performance Issues

ConOps Dimension	Human Performance Issue
Plant Mission (Section 6.1)	New Missions
	Novel Designs and Limited Operating Experience from Predecessor Systems
Agents' Roles and Responsibilities (Section 6.2)	Multi-unit Operations and Teamwork
	High Levels of Automation for All Operations and Its Implementation
	Function Allocation Methodology to Support Automation Decisions
Staffing, Qualifications, and Training (Section 6.3)	New Staffing Positions
	Staffing Models
	Staffing Levels
Management of Normal Operations (Section 6.4)	Different Unit States of Operation
	Unit Design Differences
	Operational Impact of Control Systems for Shared Aspects of SMRs
	Impact of Adding New Units While Other Units are Operating
	Managing Non-LWR Processes and Reactivity Effects
	Load-following Operations
	Novel Refueling Methods
	Control Room Configuration and Workstation Design for Multi-Unit Teams
	HSI Design for Multi-unit Monitoring and Control
	HSIs for New Missions (e.g., steam production, hydrogen)
Management of Off-normal Conditions and Emergencies (Section 6.5)	Safety Function Monitoring
	Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units
	Handling Off-Normal Conditions at Multiple Units
	Design of Emergency Operating Procedures (EOPs) for Multi-Unit Disturbances
	New Hazards
	Passive Safety Systems
	Loss of HSIs and Control Room
	PRA Evaluation of Site-wide Risk (i.e., across all units)
	Identification of Risk-Important Human Actions (RIHAs) when One Operator/Crew is Managing Multiple SMRs
Management of Maintenance and Modifications (Section 6.6)	Modular Construction and Component Replacement
	New Maintenance Operations
	Managing Novel Maintenance Hazards

6.1 Plant Mission

We identified two issues for this aspect of SMR ConOps:

- New Missions
- Novel Designs and Limited Operating Experience from Predecessor Systems

6.1.1 New Missions

Issue Description

The primary mission of current U.S. NPPs is to safely generate 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 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 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. Questions important in multi-mission operations include:

- If process-heat applications are envisioned for multi-unit sites, will different ones be 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?
- How will plant staff manage these new missions?
  - Will new process applications use the same or different operators as the NPP?
  - Will new staffing positions be created?
  - 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?

Implications

The determination of the importance of this issue will depend upon additional information from vendors. How they answer the questions we raised above will help assess the extent to which the safety of reactor operations may be impacted. Current licensing reviews do examine the hazards of nearby facilities, such as natural gas; now, 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.

In the near-term, HFE reviewers of applications for SMRs that include new missions should ensure that applicants address these questions.

Additional details related to new missions are encompassed in many issues below.

6.1.2 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. Those that are somewhat similar to SMRs (in terms of size and output) are research -and demonstration-plants operated as a single unit and use 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.

Implications

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. For addressing SMRs, NUREG-0711, Section 3, Operating Experience Review, must be revised.

The second implication is that operating experience may be lacking for predecessor designs in comparison with those new reactors that underwent design-certification reviews. The extent to which OpE is lacking should be evaluated to determine the potential impact on 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.

6.2 Agents' Roles and Responsibilities

We identified three issues for this aspect of SMR ConOps:

- Multi-unit Monitoring and Teamwork
- High Levels of Automation for All Operations and its Implementation
- Function Allocation Methodology to Support Automation Decisions

6.2.1 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, 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, 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 6.4.1)
- unit design differences often exist (see Section 6.4.2)

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

Implications

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 facilities. 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.

Until such research in complete, HFE reviewers should request applicants to justify their proposed multi-unit operational strategy, e.g., by simulations. However, this is not a substitute for the research needs identified above. The NRC still needs an enhanced technical basis to ensure they ask the proper questions, and that the review guidance addresses those aspects of multi-unit operations impacting human performance and plant safety.

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, 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 6.3.2.and 6.5.3.

6.2.2 High Levels of Automation for All Operations and its Implementation

Issue Description

The findings from our surrogate facilities 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 (O’Hara & Higgins, 2010), as summarized in Section 3.4, Insights for SMR ConOps from SMR Design and Operations.

Concerns about these negative effects of over-automation increased the usage of more interactive automation implemented at different levels (summarized in Table 5-1). 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.

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 identified in Item 3 in Section 3.4, Insights for SMR ConOps from SMR Design and Operations. 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.

Implications

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 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 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 issue in Section 6.4.3, Operational Impact of Control Systems for Shared Aspects of SMRs.

6.2.3 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." More comprehensive and objective methodologies are needed to support function allocation analyses by designers.

Implications

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) that 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.

6.3 Staffing, Qualifications, and Training

We identified three closely related issues for this aspect of SMR ConOps:

- New Staffing Positions
- Staffing Models
- Staffing Levels

6.3.1 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.

Implications

This issue has potential impact on 10 CFR 50.54, Staffing, and 50.120, Training, the implications of which are detailed in Section 6.3.3, Staffing Levels.

6.3.2 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).[19] 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. (Section 4.3, Staffing, Qualifications, and Training, has more details)

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.

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.

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[19] 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.

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 6.2.1, Multi-unit Operations and Teamwork, that the crews in some of our surrogate facilities 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-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.

Implications

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 6.3.3, Staffing Levels.

6.3.3 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 SRO, two 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 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.

Implications

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 levels. As we noted in Section 4.3, 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.

Other impacted regulations were noted in the implications discussed in Section 6.3.1 above.

6.4 Management of Normal Operations

We identified 10 issues for this aspect of SMR ConOps:

- Different Unit States of Operation
- Unit Design Differences
- Operational Impact of Control Systems for Shared Aspects of SMRs
- Impact of Adding New Units While Other Units are Operating
- Managing Non-LWR Processes and Reactivity Effects
- Load-following Operations
- Novel Refueling Methods
- Control Room Configuration and Workstation Design for Multi-Unit Teams
- HSI Design for Multi-unit Monitoring and Control
- HSIs for New Missions (e.g., steam production, hydrogen)

6.4.1 Different Unit States of Operation

<u>Issue Description</u>

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.

<u>Implications</u>

This issue has two implications. First, the applicants need to determine how the crew will 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. Second, the NRC and industry need research data assessing the ability of operators and crews to maintain SA of units in different states and to act appropriately as they arise for each unit based on their state. In addition, the ability of operators to respond to off-normal conditions based on unit state must be investigated.

The findings will offer guidance for addressing unit states as part of the HFE program reviewed via NUREG-0711, and for depicting unit status and status changes in the control room's HSIs, reviewed using NUREG-0700.

6.4.2 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.

Implications

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 these unlikenesses in the units lead to the need for different responses, then they may compromise the operator's response and open in a way that is 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.

6.4.3 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.

Implications

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. Another question, 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.

The different ways that a plant may select to implement procedures for each unit (Section 6.4.2 implications) may, in turn, impact the HSI's design, particularly if the choice is separate procedures for each unit.

Research on this issue will afford a basis for writing NUREG-0700 guidance to help ensure the SMR control room and HSIs provide the necessary information to enable detection of degradation on the control system and SA.

6.4.4 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.

Implications

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. Research will clarify these issues, from which to develop guidance to assess proposed vendor approaches to introducing new units; it is likely to impact both NUREG-0711 and NUREG-0700.

6.4.5 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.

Implications

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 support 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. Thus, the new guidance will impact both NUREG-0711 and NUREG-0700.

6.4.6 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.

Implications

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. Guidance will be needed for both NUREG-0700 and 0711 to review the applicants' analyses of load-following operations and the HSI that manages them.

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

6.4.7 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. For example, we repeat the information we obtained about the current NuScale refueling concept discussed in Section 3.1.

> 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.

Implications

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 support the review of the associated HSIs, procedures, and training. See also, the discussion in Section 6.4.1, Different Unit States of Operation.

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

Issue Description

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, 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.

Implications

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 an 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 implication discussed in 6.2.1, Multi-unit Operations and Teamwork, and Section 6.4.9, HSI Design for Multi-unit Monitoring and Control.

6.4.9 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 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. Alarm design is especially important in ensuring that operators are aware of important disturbances, thereby 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.

<u>Implications</u>

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.

The NRC reviews the detailed design of control room HSIs, in part using the guidance in NUREG-0700. Thus, the research on this issue should provide a technical basis for developing new guidance.

See also the implication discussed in 6.2.1, Multi-unit Operations and Teamwork, and 6.4.8, Control Room Configuration and Workstation Design for Multi-unit Teams.

6.4.10 HSIs for New Missions

<u>Issue Description</u>

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 must be answered.

<u>Implications</u>

The design of the new HSIs themselves probably can follow 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.

6.5 Management of Off-normal Conditions and Emergencies

One important aspect of managing off-normal conditions and emergencies already raised issue 6.3.2, Staffing Models, that discusses, among other aspects, the operational team's transitions that may be required to manage off-normal units, such as transferring the unit to another operator(s).

We identified nine other issues for this aspect of SMR ConOps:

- Safety Function Monitoring
- Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units
- Handling Off-Normal Conditions at Multiple Units
- Design of Emergency Operating Procedures (EOPs) for Multi-Unit Disturbances
- New Hazards
- Passive Safety Systems
- Loss of HSIs and Control Room
- PRA Evaluation of Site-wide Risk
- Identification of Risk-Important Human Actions (RIHAs) when One Operator/Crew is Managing Multiple SMRs

6.5.1 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 (O'Hara et al., 2002). 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.

Implications

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 be needed to support the formulation of new guidance.

6.5.2 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 MCR and the HSI must support the effective transfer of a unit to other operators.

Implications

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 approaches to handle unplanned shutdowns and degraded conditions; it will impact NUREG-0711 and NUREG-0700.

6.5.3 Handling Off-normal Conditions at Multiple Units

Issue Description

Evaluations are needed of the crew's ability to handle off-normal conditions and emergencies in a control room with multiple units, as we commented on earlier in Sections 6.2.1 and 6.3.2. 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.[20]

- With the large number of operating units on a site, e.g., 12, a transient frequency of once per reactor-year becomes once per calendar-month for the site. How such events will be addressed poses several issues:
  - 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?
- For an "accident" in contrast to a transient, there will likely be augmented crew per emergency planning (EP) requirements. But questions remain about the EP staff needed on shift to immediately respond to an accident while awaiting augmented staff:
  - 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?

These questions should be addressed considering the potential for common-cause initiating events that could affect multiple onsite units, or even all of them. Examples are LOOP and "external events" such as fire, flood, and earthquakes.

A related question, discussed in Section 6.5.2, pertains to the control location(s) where the affected units are managed. Is it acceptable to have the affected unit controlled from the same workstation as unaffected units, or is it preferable to switch operations of the affected unit to separate workstation?

[20] 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.

Implications

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 discussion in Section 6.5.2, Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units.

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

Issue Description

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. Some questions that arise are:

- Will each unit have independent procedures or will they be integrated?
- As noted in Section 6.4.2, how will procedures address differences in units?
- Will a set of common procedures apply to all units?
- How will the execution of common procedures be managed?

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 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.

Implications

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.

6.5.5 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/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, the HSIs that personnel employ to monitor the plant, the procedures they use to address hazards, and operator training.

Implications

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 the training in the overall management of hazards; this probably will affect the guidance in NUREG-0711 and NUREG-0700.

6.5.6 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.

We reiterate the IAEA's (2009) 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.

Implications

Active safety systems must be tested periodically, thereby giving operators 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. The new guidance likely will impact the review guidance in both NUREG-0711 and NUREG-0700.

6.5.7 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 6.5.8 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

Implications

Using a single MCR for multiple units has implications for various aspects of CR requirements, guidance, and analyses, including design, PRA and failure analysis, HRA, GDC 19 compliance, MCR evacuation, Appendix R and remote shutdown. The HFE guidance in NUREG-0711 most likely will be affected because it addresses analyses and evaluations of degraded conditions.

6.5.8 PRA 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 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.

<u>Implications</u>

The overall issue of site-wide PRAs is a policy issue for the NRC. From an HFE perspective, calculating 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 6.5.9, Identification of RIHAs when One Operator/Crew is Managing Multiple SMRs.

6.5.9 Identification of Risk-important Human Actions when One Operator/Crew is Managing Multiple SMRs

<u>Issue Description</u>

An area where new techniques may be needed is the identification of RIHAs. Plant designers typically identify and address them 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 upon. If the PRA is more troublesome to quantify, it will be harder accurately to identify RIHAs.

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 PRA and HRA methods to account for these effects.

<u>Implications</u>

This issue has implications for PRA and HRA techniques and for calculating risk-important human actions. The HFE guidance most likely to be affected is NUREG-0711, which addresses how applicant's HFE program addresses RIHAs.

See also the discussion in Section 6.5.7, PRA Evaluation of Site-wide Risk.

6.6 Management of Maintenance and Modifications

We identified three issues for this aspect of SMR ConOps:

- Modular Construction and Component Replacement
- New Maintenance Operations
- Managing Novel Maintenance Hazards

6.6.1 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.

Implications

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.

6.6.2 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 are 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.

Implications

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.

6.6.3 Managing Maintenance Hazards

Issue Description

We identified several potential challenges in human factors associated with maintaining each specific design we examined; we list them in Section 3.4, Insights for SMR ConOps from SMR Design and Operations, item 19. These new maintenance practices should be analyzed carefully to ensure personnel and plant safety.

Implications

This issue can most likely be addressed by industry research, and vendors' HFE programs addressing maintenance design and planning, rather than by the NRC.

6.7 Conclusions

In this section, we identified potential human-performance issues associated with the ConOps of SMRs. Table 6-1 lists these issues.

Some of them can be addressed relatively simply by modifying the wording of existing guidance to make is less reflective of LWR technology and more technologically neutral. An example is the guidance on monitoring safety functions. HFE-related regulations are similarly modifiable, but the process is not as simple because a change is needed in 10 CFR.

Other issues necessitate additional research to determine whether additional guidance is warranted; if so, it will establish a technical basis upon which to develop HFE review guidance. The NRC has an HFE guidance-development process that can be followed to guide the work.

Until such detailed guidance is available, HFE reviews can make use of our findings. First, the issues we discussed give reviewers information about what questions to ask SMR design applications, knowing what questions to ask is a vital aspect of conducting a design review. This is typically guided by the SRP and supporting review guidance. Lacking such guidance, knowledge of those design aspects that might impact performance provides a basis for seeking information about it. Our detailing of issues identifies these information needs.

In lieu of detailed review guidance, reviewers can evaluate, design information 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

Flexibility is essential in a safety-review process to accommodate any of 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.

7 DISCUSSION

The main objective of our research was to identify potential human-performance issues associated with SMR design and operations. For our purposes, the term “issue” refers to:

- an aspect of SMR development or design for which information suggests that human performance may be negatively impacted
- an aspect of SMR development or design that may degrade human performance, but additional research and/or analysis is needed to better understand and quantify the effect
- a technology or technique that will be used for a new plant design or implementation for which there is little or no review guidance

To accomplish this objective, we developed a six-dimensional ConOps model. We used it to evaluate information about SMRs obtained from (1) design and operational information for eight SMR designs, and (2) general literature about SMRs and related studies pertaining to specific aspects of their operations, such as multi-unit monitoring and control. Since there is limited detailed information about operational and HFE aspects of SMRs, we examined several “surrogate facilities” where operators manage multiple units in a manner similar to what might be expected at SMRs. The surrogate facilities were unmanned vehicles, petroleum refineries, and remote intensive-care medical centers.

From these sources of information, we identified numerous challenges to human performance. We then integrated the information, identifying a set of potential human-performance issues to be considered in research and regulatory reviews of SMRs.

Here, we offer our general conclusions and observations from our research.

1. Potential human-performance issues exist pertaining to the design and operational characteristics of SMRs. Our review of SMR designs highlighted the differences between them and currently operating plants, as summarized in Table 3-2. From these differences and other considerations we identified the human performance issues and their implications, as summarized in Table 6-1 and discussed in Section 6.

2. Additional information is needed on the ConOps of SMRs. Much of the information on the operational- and HFE-aspects of SMRs that we reviewed was in the preliminary stages of design; it continues to evolve as the plant designs are refined and the vendors prepare for licensing activities. As more such details are developed, new issues may arise, whereas some of those we discussed in Section 6 may have to be reevaluated. Therefore, we recommend updating the findings of this study as new information emerges.

3. The monitoring and control of multi-unit facilities by a single operator or crew in a single control room is possible and is part of the ConOps for normal operations in several industries. However, the successful accomplishment by a single crew of multi-unit operations in the commercial nuclear industry is yet to be demonstrated. First, the unique operational demands of different types of complex systems must be addressed before we can formulate conclusions about multi-unit NPP operations. The special demands of one industrial application may limit our making generalizations to another. For example, while multi-unit operations are routine in the petrochemical industry, it is proving a difficult challenge for unmanned vehicle operations. We recommend conducting more research on surrogate facilities to answer questions, such as the impact of unit differences on monitoring,

and to verify our findings, thereby expanding the technical basis of information pertaining to multi-unit control.

4. The issues have implications for the NRC's HFE regulations and design review guidance. As we discussed in Section 6 and in another report (Higgins & O'Hara, 2010), modifications to some HFE regulations and review guidance are likely to be needed to address SMR licensing reviews. While it is straightforward to identify many recommended changes, the substance of some of them may require additional research. For example, the integrated system validation for SMRs (NUREG-0711, Section 11) may need modification to reflect multi-unit simulation, especially for plant designs with shared systems. Hence, this may require research to determine specifically how to modify the guidance. While other specific modifications are needed, we offer two general observations:

   - First, the wording of the regulations and guidance reflects *light water reactor technology*. Since non-light water reactor technology is used in two classes of SMRs (HTGRs and LMRs) changes will be needed to address these designs. The Safety Function Monitoring issue discussed in Section 7.2 above is an example. The regulations and guidance is based on the functions and parameters of LWRs so that it may be changed to accommodate reviews of non-LWR reactors.
   - Second, the regulations and guidance reflect the current ConOps in today's plants, such as (1) the definition of crew members and their roles and responsibilities, and (2) control room staffing levels. Some SMRs are likely to employ new ConOps that may not fit the current review-criteria.

5. The concept of operations model we developed had six dimensions: Plant mission; agents' roles and responsibilities; staffing, qualifications, and training; management of normal operations; management of off-normal conditions and emergencies; and management of maintenance and modifications. The model is based on recent literature, including standards and guidance documents used in different industries. Each dimension provided information about the HFE aspects of the plant. We deem this model to be very useful, not only in discussing topics important to NPPs, but also for collecting data from surrogate facilities. While NUREG-0711addresses ConOps as part of the design review, the treatment therein is much more narrowly focused and is not addressed until HSI design. We think our model can play a more important role in design reviews and its consideration should begin much earlier in the review process, such as in HFE Program Management, to help better define the designer's goal, assumptions, and constraints. We recommend including ConOps as part of HFE Program Management in future revisions to NUREG-0800, Chapter 18 and NUREG-0711.

6. In addition to traditional HFE methods and tools, the development of future unmanned vehicle systems currently employs human performance modeling and simulation methods. This approach is consistent with the DoD's overall goal of increasing the use of modeling and simulation methods as part of systems development (DoD, 2003). SMR designers also are employing the latest HFE methods and tools as well. For example, Hugo (2006) used human performance modeling to evaluate event timing and error rate as part of the PBMR HFE program, as did PBMR designers in assessing the effects on task performance of performance-shaping factors and workload. Advances to HFE methods and tools have implications for HFE design reviews (O'Hara, 2010). The NRC currently is exploring ways to address advances in HFE methods and tools; our SMR research supports that endeavor.

7. The studies we reviewed illustrated the importance of performance measures, as discussed in Section 5.1.4. Primary task performance measures must be carefully selected. Many studies noted the effects of design or operational strategies on one primary task measure, but not another. This finding suggests that all important aspects of the operators primary tasks should be identified and assessed, using measures that are sensitive to the expected variations in performance.

   The studies also illustrate the need for comprehensive performance measures that include not only primary task measures, but also ones for situation awareness, workload, and trust in automation. NUREG-0711 already identifies situation awareness and workload as performance measures, but not trust in automation. Parasuraman, Sheridan, and Wickens, (2008) argued that these cognitive measures are essential viable constructs for understanding and predicting human-system performance in complex systems, especially those employing extensive automation. Since SMR designs will rely on extensive automation, trust may be an important construct in SMR studies and validations.

   Unmanned vehicle studies used additional measures that offer special relevance in a multi-unit system. One measure was “neglect time;” the time an operator fails to attend to one unit while attending to another unit. Another measure was “change detection/blindness, viz., failing to see large, salient changes in the environment, usually because attention is focused elsewhere. As the monitoring demand in multi-unit operations is expected to be large, both neglect and change blindness may prove significant concerns, and warrant important considerations for multi-unit operations.

   These aspects of performance measurement are important considerations in industry and regulatory SMR research along with in an applicant’s design work, such as tests, evaluations, and integrated system validations.

In conclusion, our research provided insights into the operational and HFE aspects of SMRs that will support current and future safety reviews and licensing activities. At a minimum, our work identifies the needed research and questions about SMR design and operations that HFE reviewers should address. We also believe that the HFE review process, guided by NUREG-0800, Chapter 18, NUREG-0711, and NUREG-0700, can accommodate the review of novel technology and new operational approaches using a variety of strategies until more complete, comprehensive review guidance becomes available. We discussed the robustness of the NRC’s HFE review process in Section 6.7. What is critical to an HFE reviewer in utilizing the robust review process is knowing the questions to ask about the design and operational characteristics that may impact plant safety and human performance. The results of our research provide an important step towards achieving this critical aspect of the HFE safety-review process.

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APPENDIX: CONCEPT OF OPERATIONS QUESTIONS

Section 3 describes the ConOps model we developed to support this research. This appendix includes the general questions formulated to address SMR ConOps, and the operations of other types of facilities (described in Section 4). We adapted the questions for each type of facility to better tailor them to their mission and processes.

Plant Mission

1. What is the overall mission or purpose of the facility?

2. Are there any secondary purposes of the facility other than safe electric power generation, such as hydrogen generation?

3. What is the overall approach taken to accomplish the facilities' purpose? How was the approach identified and how has it evolved?

4. For multi-unit plants, what systems, if any, do the units share?

5. If a site is expected to have multiple units, is each independent from the others or do the units share common support systems?

6. What features of the design are new or quite different from current LWRs?

7. What are the predecessor plants, if any, to the design and what is their operating experience?

8. Are there non-nuclear facilities that operate in a similar fashion to the current design, such as refineries, whose operational experience is used to inform the design?

Agents' Roles and Responsibilities

1. What high-level functions have to be performed to accomplish the mission?

2. What are the relative roles of personnel and automation in accomplishing these functions?

3. Do personnel interact with the automation or does it perform its functions independently? Can operators override automation when they think it is needed? Can operators determine whether automation or personnel should perform a function or task?

4. How were the relative roles of personnel and automation determined?

Staffing, Qualifications, and Training

1. How is the facility to be staffed?

    - What are the staff positions?
    - How many of each position are on staff at any one time?
    - What are the relative roles and responsibilities of each staff position?

2. How were staffing needs determined?

3. Are there defined qualifications for each position?

4. How were the qualifications for each position determined?

5. What type of training is provided for each staff position?

6. How are training needs determined?

7. What tools are available for training, e.g. simulators?

8. How many shifts are used and how is shift turnover managed?

Management of Normal Operations

1. What is the concept for how the plant will be operated by personnel to accomplish all of its functions for normal operations, e.g., to follow its normal evolutions, such as startup, low power, full power, shutdown, and refueling? What are the major tasks of personnel?

2. How has the current concept of operations been determined (use of engineering analyses, human factors engineering, past operating experience, etc.)? How has it been (or will be) determined how many units an operator or crew can monitor and control?

3. How is the control room designed to support the monitoring and control or multiple reactors modules, BOP systems, and secondary functions?

4. If multiple units are monitored and controlled by the same crew, do single operators monitor multiple reactors and their BOP systems or are monitoring responsibilities split between reactor and BOP?

5. How do unit differences impact multi-unit monitoring and control?

6. What human-system interfaces (HSIs) are used, e.g., alarms, displays, controls, decision/job aids, communications, etc.? How will the HSI support multi-reactors monitoring and control?

7. What procedures will be available to guide personnel actions? Do the procedures reflect multi-unit operations? Are the procedures computerized or paper-based?

8. To what degree do operators have to comply with procedures?

9. How is the need to take action identified?

10. Do control room personnel interact with personnel at other locations? If so, what are the other locations and how do they interact?

11. What aspects of normal operations may be challenging to personnel, e.g., require knowledge-based behavior or associated with high workload?

Management of Off-normal Conditions and Emergencies

1. What is the concept for how off-normal conditions and emergencies are managed? What are the main failure events and degraded conditions and how does the crew respond to them? Are there emergencies that require a change in staffing?

2. What HSIs and procedures are available to support these tasks? Are there dedicated HSIs for handling off-normal conditions and emergencies?

3. What types of equipment checks or diagnostics are available to help ensure the quality of equipment operations?

4. What type of equipment degradations and failure conditions arise?

5. How often do they impact the ability of personnel to perform their tasks?

6. When functions are degraded or lost, how do personnel recognize that such a condition exists?

7. How do personnel manage degradations and failures of the instrumentation and control system and the control room HSIs? Are their specific procedures to deal with these situations?

8. What aspects of emergency operations may be challenging to personnel, e.g., require knowledge-based behavior or associated with high workload?

Management of Maintenance and Modifications

1. What is the current concept for how the plant maintenance will be accomplished? Does plant maintenance of one unit impact other operating units?

2. How is the installation of upgrades managed? What tasks are involved?

3. What HSIs and procedures are available to support these tasks?

4. If the plant is below grade, how are maintenance activities impacted?

5. If applicable, how are additional “units” brought on line?

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11. ABSTRACT (200 words or less)
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. The design characteristics of many SMRs differ from those of current conventional plants and may require a distinct concept of operations (ConOps). In this U.S. Nuclear Regulatory Commission (NRC) research project, we examined the human factors engineering (HFE) and the operational aspects of SMRs. Our main objective was to identify potential issues in human performance related to the design and operations of SMRs. To accomplish this objective, we first developed a six-dimensional ConOps model that we then used to obtain information about SMRs. Since there is little detailed information about the operational and HFE aspects of SMRs, we also examined several "surrogate facilities," such as petroleum refineries, wherein operators manage multiple units in a manner similar to what might be expected of SMR operators. We used this information to identify a set of potential human-performance issues that might be considered in the NRC's reviews of SMR designs and future research activities.

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