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Human Factors Engineering Technical Support Services Guidance Development: Process and Guidance Development for Technical Review of Non-Large Light-Water Reactors

Technical Letter Report for Subtask E

Development of HFE Review Guidance for Advanced Reactors

Prepared For:

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ABSTRACT

The objective of this U.S. Nuclear Regulatory Commission (NRC) research project was to develop a human factors engineering (HFE) review process tailored to small, advanced reactors and their unique characteristics. To achieve this objective, we first developed a characterization of small, advanced reactors. Such a characterization is necessary to understand the range of design and operational characteristics the new review process must accommodate. We examined the information available for eight reactors representing four reactor technologies: Heat pipe reactors, helium-cooled fast reactors, high-temperature gas cooled reactors, and molten salt reactors. We used a concept-of-operations model to collect information about each design. Based on this review we identified 13 general characteristics of small, advanced reactors. In addition, we identified five HFE technical issues that need to be addressed: Identification of important human actions, autonomous operations, approaches to staffing, HSIs for monitoring and controlling the reactor and interfacing systems, and remote operations.

We next examined the way the HFE aspects of nuclear facilities are addressed as presented in existing NRC review processes described in standard review plans (SRPs). We also evaluated their suitability for reviewing small, advanced reactors. The SRPs depict a wide range of approaches to reviewing the HFE aspects of nuclear facilities. In our assessment of HFE issues associated with small, advanced reactors, we determined that the issues are partly addressed in current review processes but there remain aspects of each that require further consideration.

Next, we reviewed NRC documents that discuss a new vision for reviewing advanced reactors including the requirements set forth in Public Law 115–439, the Nuclear Energy Innovation and Modernization Act (NEIMA) passed by Congress in 2019. Based on this information we identified the characteristics that a review process has to meet to be suitable for the review of small, advanced reactors.

We used this information to develop a new process that can accommodate the characterization of these new reactors, as well as the more general expectations set forth in the NRC's vision of a new review process. The new review process is summarized below.

The overall objective of the staff's HFE review is to verify that the design supports safe operation by reflecting state-of-the art HFE design principles. The HFE review consists of a series of steps culminating in the development of a facility specific review plan and an HFE review using the plan. The steps are:

- Review Applicant Submittals
- Conduct Targeting Process
- Conduct Screening Process
- Conduct Grading Process
- Assemble Review Plan and Conduct Review

Applicant submittals initiate the review process, so their content is important. The submittal must have the information needed by the NRC staff to conduct the review. The expected content of applicant submittals is described in the review process.

Targeting is the process by which the HFE reviewer identifies aspects of the applicant's design and operations that warrant an HFE review. Unlike large light-water reactor (LLWR) reviews, in

this new approach to HFE review not all aspects of the facility design and operations need to be reviewed. Thus, the reviewer must target those that will be.

Screening is the process by which HFE activities, such as function and task analysis, are selected for review. Appendix A of this report provides descriptions of typical HFE activities and includes information about how the activity contributes to an applicant's design and the NRC staff's objectives when evaluating an applicant's performance of the activity. The screening process enables the review process to flexibly adapt to the applicant's HFE activities.

The next step is the grading process. Grading is the process by which the HFE reviewer identifies the appropriate acceptance criteria to use for the review. Reviewers have a great deal of flexibility in review criteria selection. They can use the review criteria available in NRC guidance documents, such as NUREG-0711, and can adapt them as needed. They may not need all the review criteria for a specific HFE activity and can eliminate those not needed. Reviewers can also use guidance from non-NRC documents, if they determine that it better meets the needs of the review. Non-NRC documents may be preferred, for example, if the guidance is based on a more recently developed technical basis than the corresponding NRC guidance or if it addresses facility characteristics for which the NRC has no review criteria.

In the last step the reviewer assembles the review plan for the facility. The review plan identifies the aspects of the facility's design and operational characteristics and HFE analyses that are to be reviewed and the review criteria to be used. The applicant's treatment of HFE technical issues is also addressed in the review. The plan is uniquely tailored to the facility under review.

Unlike LLWR reviews, the new HFE review strategy is process-based and not dependent on a deterministic application of a review methodology and criteria. Using this process, the NRC staff defines a review plan that is uniquely tailored to the facility being reviewed. The most significant difference between this new strategy and that used for LLWRs is the role of existing review guidance, such as NUREGs-0800, -0711, and -0700. For LLWR reviews, the guidance in the SRP is used to structure the review activities. NRC reviewers follow the guidance to request information from applicants and to review their submittals. Applicants are expected to provide information demonstrating how their design process and products conform to the NRC's guidance or to provide justification as to why their alternative approach is acceptable.

In the new approach, existing NRC review processes and criteria do not structure the review process. Instead, they serve as resource material the reviewer can use, if appropriate. However, the guidance can be omitted if the reviewer determines it is not applicable to the design being reviewed.

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ACRONYMS

AA	adaptive automation
AC	alternating current
ADAMS	Agencywide Documents Access and Management System (NRC)
AEC	Atomic Energy Commission
ARDC	advanced reactor design criteria
ASME	American Society of Mechanical Engineers
BOP	balance of plant
CBP	computer-based procedure
CD	core damage
CDF	core damage frequency
CFR	Code of Federal Regulations
COL	combined license
ConOps	concepts of operations
COPS	Computerized Operating Procedure Systems
D3	diversity and defense in depth
DC	design certifications and direct current
DCD	design control document
DID	defense-in-depth
DoD	Department of Defense (U.S.)
EBR	experimental breeder reactor
EM2	Energy Multiplier Module
EOP	emergency operating procedure
EP	emergency planning
ESF	engineered safety feature
FAA	Federal Aviation Administration (U.S.)
FHR	Fluoride Salt-Cooled High Temperature Reactor
FMEA	failure mode and effects analysis
FRA	functional requirements analysis
FSAR	final safety analysis report
FV	Fussell-Vesely
GA	General Atomics
GDC	General Design Criterion
HA	human action
HED	human engineering discrepancy
HFE	human factors engineering
HRA	human reliability analysis
HSI	human-system interfaces
HTGR	high-temperature, gas-cooled reactors
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
ICCDP	integrated conditional core damage probability
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
IMSR	Integral Molten Salt Reactor
IN	information notice
iPWR	Integral PWR
IROF	item relied on for safety
ISA	integrated safety analysis
ISFSI	independent spent fuel storage installations

ISG	interim staff guidance
ISO	International Organization for Standardization
KP-FHR	Kairos Fluoride Salt-Cooled High Temperature Reactor
kWe	kilowatts electric
LANL	Los Alamos National Laboratory
LBE	licensing basis event
LERF	large early release frequency
LLWPB	Low-Level Waste and Projects Branch
LLWR	large light-water reactor
LMP	Licensing Modernization Project
LMR	liquid-metal reactors
LSMR	light-water SMR
MCFR	molten chloride fast reactor
MHA	maximum hypothetical accident
MOX	mixed oxide (fuel)
MSR	molten salt reactor
MWe	megawatts electric
NASA	National Aeronautics and Space Administration (U.S.)
NEI	Nuclear Energy Institute
NEIMA	Nuclear Energy Innovation and Modernization Act
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission (U.S.)
NSRST	nonsafety-related with special treatment
OER	operating experience review
PBMR	Pebble Bed Modular Reactor
PDC	principal design criteria
PIRT	Phenomena Identification and Ranking Table
PRA	probabilistic risk assessment
PWR	pressurized water reactor
RAW	Risk Achievement Worth
RCS	reactor control system
RES	NRC’s Office of Nuclear Regulatory Research
RG	regulatory guide
RIHA	risk-important human action
RO	reactor operators
RPS	reactor protection system
RTR	research and test reactor
S&Gs	standards and guidelines
SA	situation awareness
SAR	safety analysis reports
SECY	Commission Paper
SER	safety evaluation report
SME	subject matter expert
SMR	small modular reactor
SPDS	safety-parameter display system
SR	safety related
SRO	senior reactor operator
SRP	standard review plan
SSC	structure, system, and component
STA	shift technical advisor
TEDE	total effective dose equivalent

TRISO	TRi-structural ISOtropic (fuel)
TWRS-P	tank waste remediation system privatization
UAV	unmanned aerial vehicle
V&V	verification and validation

1 BACKGROUND

1.1 HFE Safety Reviews of Small Advanced Reactors

This report describes the development of a human factors engineering (HFE) review process for small, advanced reactors including small light-water reactors, non-light-water reactors, small modular reactors, microreactors, and fusion reactors. Unlike most commercial reactors in use today, many of these reactors do not use light water as a coolant. Instead, they may use high-temperature gas, liquid metal, or molten salt as a coolant. These reactors are much smaller than the large light-water reactors (LLWRs) in use today. LLWRs generally produce 1000 or more megawatts electric (MWe) while these small reactors generally produce less than a few hundred MWe's and often much less than that. According to the classification adopted by the International Atomic Energy Agency (IAEA), a "small reactor" is one with a total power of 300 MWe or less. Reactors delivering between 300-700 MWe are called "medium sized reactors" (IAEA, 2005, 2006).[1]

Small, advanced reactors are often transportable, largely self-contained, and require less human control and intervention. Their small and simple design leads to a lower potential for significant accident consequences than LLWRs; thus, the exposure to the public from postulated accidents may be small (Samanata, Diamond & O'Hara, 2020). Section 2 of this report describes the characteristics of small, advanced reactors in detail.

Small, advanced reactors can meet needs not easily met by LLWRs. Their characteristics make them attractive to users in locations where the nuclear infrastructure is very limited or does not exist at all, such as:

- locations not on a power grid, such as remote communities in largely underdeveloped locations
- areas where power is needed to deal with an emergency
- military applications where needs for a reactor may not be limited to one place
- space applications where only limited maintenance can be performed

One type of small, advanced reactor is the micro-reactor, which is generally very small, e.g., 10 MWe. Micro-reactors can also enhance the Department of Defense's (DoD's) use of new technologies, such as "advanced computing, big data analytics, artificial intelligence, autonomy, robotics, directed energy, and biotechnology" (NEI, 2018).

Many small, advanced reactors designs allow individual units to be grouped together to scale up the energy output needed to meet local demands. These are called small modular reactors (SMRs). SMRs are "modular." They can be fabricated in a factory and transported to the plant site for assembly. If an SMR produces 100 MWe, a utility needing 200 MWe can install two units, while a second one needing 400 MWe can install four, and so on. As future electrical demands change, additional units can be added (or removed) as needed, thereby scaling their number to meet the changing demands. SMRs can also serve purposes other than power generation, e.g., hydrogen production.

Thus, small, advanced reactors represent a much more diverse range of technologies than LLWRs that characterize the current fleet of commercial nuclear reactors.

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[1] The IAEA uses the abbreviation "SMR" to mean small and medium reactors.

In addition to the advances in reactor technologies, there have been significant increases in the capabilities of digital instrumentation and control (I&C) systems, and the design of human-system interfaces (HSIs) used by operators to monitor and control nuclear power plants (NPPs). These advances have enabled the development of novel concepts of operations (ConOps) that are very different from those used in the previous half century of NPP operations. Just as technology has continued to evolve, so have the methods and tools used by HFE practitioners to integrate personnel into plant operations, analyse personnel tasks, design control rooms, and evaluate/validate designs.

There is considerable industry interest in small, advanced reactors. According to one report, there are about 50 such designs currently under development internationally (Mignacca, Locatelli, & Sainati, 2019). Thus the U.S. Nuclear Regulatory Commission (NRC) is examining the regulatory needs for licensing them. Both the NRC and industry have recognized that the regulatory review processes used by the NRC for LLWRs may not be appropriate for small, advanced reactors.

The NRC's current review guidance was developed for LLWRs and over 100 have been licensed. A strong regulatory basis was developed for LLWR reviews consisting of regulatory requirements in the Code of Federal Regulations (CFR) and detailed safety review guidance in NUREG-0800 and supporting regulatory documents. NUREG-0800, Chapter 18, Human Factors Engineering (NRC, 2016b) and NUREG-0711 (O'Hara, Higgins, Fleger & Pieringer, 2012) are the principal guidance used by the NRC staff to conduct HFE reviews of reactors. The applications for licenses of these new reactors may or may not be risk-informed and they are expected to vary in level of detail of the applicant's HFE program and may not be aligned with or address all program elements in NUREG-0711. Therefore, a new review process is needed to (1) assess the potential contribution of human performance to risk, and (2) assess, commensurate with that risk, whether the facility design is adequate to identify and address the contribution of human performance to facility risk.

During this time, the NRC and its predecessor organization, the Atomic Energy Commission (AEC), were gaining experience with non-LWR designs. They reviewed 20 non-LWR designs between 1951 and 2010. Four designs were licensed for operation and three were built: Fermi 1, a 200 megawatts thermal (MWt) sodium-cooled reactor; Peach Bottom 1, a 115 MWt high temperature gas-cooled reactor (HTGR); and Fort St. Vrain, a 330 MWe HTGR. A good review of this experience can be found in an NRC report (2016a).

To prepare for applicant submittals for small, advanced reactor licensing, the NRC has developed a vision and strategy document and supporting action plans (NRC, 2016c) that outline the tasks that must be undertaken to advance technical and regulatory readiness for these reviews. A significant consideration is identifying an appropriate review approach for small, advanced reactors. For example, if they are power reactors, should they be reviewed like LLWRs, while considering their unique features? If such an approach were applied, the degree to which LLWR guidance can be applied would likely differ for different chapters of NUREG-0800. However, if they have low source terms[2] on par with non-power reactors, perhaps they can be reviewed using an approach like that taken for research and test reactors.

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[2] 10 CFR § 50.2 defines source term as: "…the magnitude and mix of the radionuclides released from the fuel, expressed as fractions of the fission product inventory in the fuel, as well as their physical and chemical form, and the timing of their release."

The NRC envisions a review process that effectively and efficiently addresses safety, without imposing unnecessary regulatory burden. The process should create a “flexible regulatory framework, allowing potential applicants to select a best-fit path towards regulatory reviews and decisions.”

1.2 Research Objective

The objective of this NRC research project was to develop an HFE review process tailored to small, advanced reactors and their unique characteristics.

To achieve this objective, we first developed a characterization of small, advanced reactors. Such a characterization is necessary to understand the range of design and operational characteristics the new review process must accommodate.

We next examined the existing NRC review processes and evaluated their suitability for reviewing small, advanced reactors. As part of this review, we examined a wide range of standard review plans (SRPs) for both reactor and non-reactor facilities.

Lastly, we used this information to develop a new process that can accommodate the characteristics of these new reactors as well as the more general expectations set forth in the NRC’s vision for a new review process.

The specific objectives for these individual research activities are described in the appropriate sections of this report.

1.3 Organization of This Report

In Section 2, we describe the characterization of small, advanced reactors. In Section 3 we discuss the existing NRC regulations and guidance available to support advanced reactor reviews.

Section 4 describes the approach taken to develop a new HFE review process and the process itself. Section 5 presents a summary of the research and our main conclusions. All cited references are listed in Section 6.

Four appendices are provided at the end of the document. Appendix A contains a list of HFE activities commonly used in design projects and are used in HFE reviews. Appendix B describes the ConOps model used in our evaluation of small, advanced reactor design and operations. The model is also used in the review process.

Appendices C and D contain descriptions of the technical issues associated with advanced reactor designs and operations.

2 CHARACTERISTICS OF ADVANCED REACTORS

2.1 Objective

The purpose of this task was to develop a characterization of small, advanced reactor designs based on ConOps dimensions that focus on all aspects of facility design and operations, as well as the design processes used to develop, evaluate and validate the reactor design, especially as they pertain to HFE aspects of the design and to the methods used to evaluate risk.

In addition, we sought to identify potential technical issues. Issues may include:
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- an aspect of the development or design for which information suggests it may negatively impact human performance

- an aspect of reactor 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 potentially impacting human performance that may be used for a plant's design or implementation for which there is little or no review guidance

2.2 Methodology

The methodology consisted of the following activities.

Define the Scope of Small Advanced Reactors to be Addressed

We reviewed both general descriptions of advanced reactors as well as descriptions of selected designs to the extent that information was available. The sample of reactors is presented in Section 2.4.1 below.

Technical descriptions of the selected designs were obtained from vendor web pages summaries from NRC Periodic Stakeholder Meetings available at NRC Advanced Reactor webpage, and articles published in the technical literature. In addition, we sought design information in licensing/certification documents available through the NRC's Agencywide Documents Access and Management System (ADAMS). All the information reviewed was non-proprietary and in the public domain.

Adapt a Model of Concept of Operations to Small Advanced Reactors

According to the Institute of Electrical and Electronics Engineers (IEEE), a 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)

A ConOps is specified at a high level very early in the design process. It then becomes more detailed as the design matures.

We developed a ConOps model and delineated its key dimension (O'Hara Higgins, & Pena, 2012) (see Figure 2.1):

- Plant Mission
- Agents' Roles and Responsibilities[3]
- Staffing, Qualifications, and Training
- Management of Normal Operations
- Management of Off-Normal Conditions and Emergencies
- Management of Maintenance and Modifications

A full description of each dimension is in Appendix B. To facilitate the model's use, we developed a set of questions pertaining to each dimension of the model. We made some modifications to the model's original form. The *Agents' Roles and Responsibilities* and *Management of Off-Normal Conditions and Emergencies* dimensions were modified to explicitly incorporate important human actions.

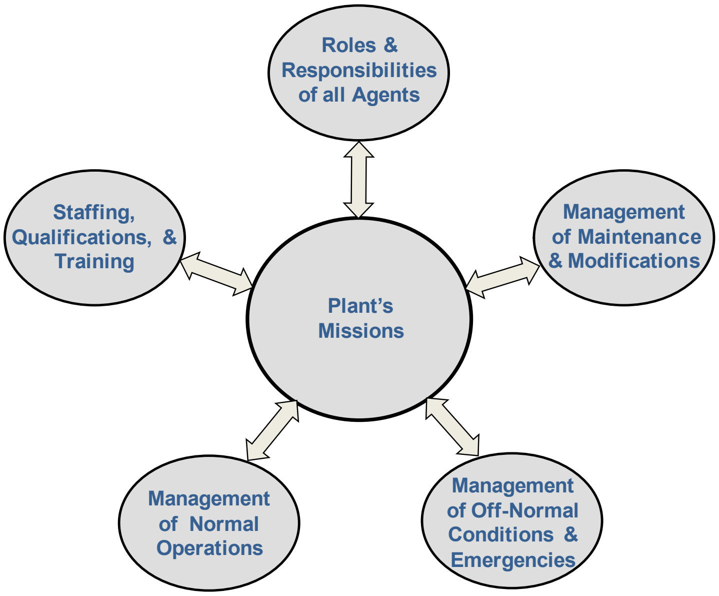

Figure 2.1 Concept of Operations Model

We employed the ConOps model to obtain information about each reactor's design and operational characteristics. From an HFE perspective, a ConOps identifies the design's high-level goals and the functions and operational practices needed to address both normal and off-normal situations. It is used to identify expectations related to human performance (Pew & Mavor, 2007). A ConOps covers all facets of the interactions of personnel with a complex

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[3] As used in this document, "agents" refers to personnel or automation (or any combination thereof) that are responsible for completing a plant function.

system and guides the formation of requirements, the details of design and operation, and the evaluation of the system (AIAA, 1992; DoD, 1995, 2000; Fairley & Thayer, 1977; IEEE, 2007). Increasingly, many industries are employing ConOps documents to provide a vision of how personnel are integrated into a new design or major modification (Thronesbery et al., 2009).

In prior research we used this ConOps model to structure information about SMRs. The types of SMRs addressed included some of those of interest in the current study: high-temperature, gas-cooled reactors (HTGRs), and liquid-metal reactors (LMRs) (see Table 2.1). These reactors were between 10 (the 4S design) and 335 MWe (the international reactor innovative and secure design). Insights from that study are relevant to the current research.

Table 2.1 SMR Reactor Class and Designs Examined in Prior Research

Reactor Class and Design		Vendor
Integral PWRs (iPWRs)		
NuScale		NuScale Power, Inc.
International Reactor Innovative and Secure		Westinghouse Electric Corp.
mPower		Babcock & Wilcox
High-temperature, Gas-Cooled Reactors		
Turbine-Modular Helium Reactor		General Atomics
Pebble Bed Modular Reactor		PBMR (Pty.), Ltd.
Liquid-Metal Reactors		
4S (super-safe, small and simple) Reactor		Toshiba Corp.
Hyperion Power Module		Hyperion Power Generation, Inc.
Power Reactor Innovative Small Module		GE Hitachi Nuclear Energy

Note: Source is O'Hara, Higgins & Pena (2012).

Identify Significant Design and Operational Characteristics of Small, Advanced Reactors and Potential Technical Issues Related to Them

We used the same approach here, i.e., we used the ConOps model to collect information about the new reactors. The specific reactors evaluated are listed in the next section. In addition, we identified potential technical issues.

A limitation of the prior study, which is also applicable to this work, is that detailed information about the individual designs was often lacking. In addition, there is a lack of operating experience for small, advanced reactors. However, a value of a ConOps is that it provides a structured framework to identify all the aspects of plant design and operations that support safety. Thus, it helps to identify where additional information is needed for a design review.

2.3 Results

2.3.1 Sample of Selected Small Advanced Reactors

As noted above, there are about 50 such small, advanced reactor designs currently under development (Mignacca, Locatelli, & Sainati, 2019). Thus, we identified a sample of them to include in the evaluation. Of primary interest are the small, advanced reactor designers that have had regulatory interactions with the NRC. A complete list of those reactors can be found on the NRC's website (https://www.nrc.gov/reactors/new-reactors/advanced.html[4]). Our sample included:

- General Atomics Helium-Cooled Fast Reactor
- X-Energy LLC XE-100 Modular High Temperature Gas-Cooled Reactor
- Kairos Power Fluoride Salt-Cooled, High Temperature Reactor (KP-FHR)
- Terrestrial Energy Integral Molten Salt Reactor (IMSR)
- TerraPower, LLC Molten Chloride Fast Reactor (MCFR)
- Westinghouse Electric Company eVinci Micro Reactor

In addition, we consulted NRC SMEs for additional reactor designs of interest. As a result, the following designs were added to the sample:

- Los Alamos National Laboratory MegaPower Reactor
- OKLO Power Aurora Reactor

Our sample of reactors is listed in Table 2.2, organized by reactor type.

Table 2.2 Sample of Small Advanced Reactor Designs

Reactor Technology	Design
Heat Pipe Reactors	Los Alamos National Laboratory MegaPower
	Westinghouse eVinci Mobile Nuclear Power Plant
	Oklo Power Aurora
Helium-Cooled Fast Reactors	General Atomics Energy Multiplier Module (EM2)
High-Temperature Gas Cooled Reactors	XE-100
Molten Salt Reactors	Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)
	Terrestrial Energy Integral Molten Salt Reactor
	TerraPower Molten Chloride Fast Reactor

2.3.1.1 Heat Pipe Reactors

Heat pipe reactors use heat pipes to cool the reactor core. A heat pipe transfers heat from one end to the other as it moves from boiling at one end to condensation at the other end. This makes it possible to extract heat from the reactor. Heat pipes operate in a passive mode at relatively low pressures, less than an atmosphere. Each individual heat pipe contains only a small amount of working fluid, which is in a sealed metallic pipe. These reactors have few moving parts.

Los Alamos National Laboratory MegaPower

Los Alamos National Laboratory's (LANL) MegaPower reactor is a 5 MW thermal, fast reactor design concept to generate electricity. The heat pipes provide passive heat transfer, which eliminates severe accident scenarios involving loss-of-forced-cooling. Los Alamos has partnered with Westinghouse to refine the design under the name eVinci (Tyler, 2019). eVinci is discussed next below.

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[4] As of June 16, 2020

Information on MegaPower mainly came from technical reports.

Plant Mission

The plant mission can be described in terms of the following: Goals and objectives, evolutionary context, high-level functions, boundary conditions, and constraints.

The primary purpose of the MegaPower Reactor system is to generate electricity. No detailed information on the above aspects of plant mission was available.

Agents' Roles and Responsibilities

This dimension clarifies the relative roles and responsibilities of system's agents, namely, personnel and automation, and their relationship. This information is not addressed.

Staffing, Qualifications, and Training

This dimension addresses the number and capabilities of staff needed to accomplish the human roles and responsibilities. However, no information is available on how MegaPower will be staffed or the qualifications of staff positions. No information on training is currently available.

Management of Normal Operations

No information on the key aspects of normal operations is available, i.e., Identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

Management of Off-Normal Conditions and Emergencies

Some information on the key aspects of off-normal operations is available, i.e., Identification of key scenarios. However, information on the tasks needed to perform them and the HSIs and procedures essential to supporting the tasks is not available.

An evaluation of failure modes of the MegaPower reactor has been performed. McClure, Poston, Rao and Reid (2015) and Sterbentz et al. (2017) conducted a Phenomena Identification and Ranking Table (PIRT) analyses and identified several concerns that may challenge its licensing. One significant concern is an inadequate approach to defense-in-depth through barriers to prevent and mitigate radioactive releases during failure events and thermal stress levels exceeding American Society of Mechanical Engineers (ASME) pressure vessel code limits. MegaPower's double containment satisfies the single failure criterion but is not sufficient for defense-in-depth (Sterbentz et al., 2017).

The analysis also identified several phenomena whose impact to the reactor system is "unknown" due to a lack of detailed analysis and experimental data. Some of these phenomena may be major concerns, such as seismic event impacts, heat pipe performance under long-term irradiation exposure, understanding of heat pipe failure modes, and design and implementation of the shell and tube primary heat exchanger. The accident of greatest concern is when multiple heat pipes fail. The failure of one can lead to the failure of surrounding heat pipes. If enough heat pipes fail, the reactor core may not be adequately cooled.

While these PIRT analyses provided important insights into MegaPower's safety concerns, more formal analyses, such as PRA, have not been conducted. Thus, the detailed analysis of failure modes and the human role, if any, in managing accident conditions is not discussed.

Management of Maintenance and Modifications

Information on maintaining and modifying the MegaPower reactor is not available.

Westinghouse eVinci Mobile Nuclear Power Plant

Westinghouse's eVinci Micro Reactor is a high- temperature heat pipe reactor. The primary purpose of the eVinci microreactor system is to generate electricity and heat. The reactor produces between 200 kWe to 5 MWe depending on its configuration as a single unit or SMR. eVince can operate in load-following mode. The reactor is being designed to operate autonomously. eVince is built in a factory and transported using a standard transportation infrastructure. It has a 40-year design life and must be refueled approximately every three years.

For military application, eVinci can be transported to different locations to provide a power supply where needed.

Information on eVinci came from the vendor website (https://www.westinghousenuclear.com/new-plants/evinci-micro-reactor), Westinghouse fact sheet (Westinghouse, 2019), and technical reports.

Plant Mission

The plant mission can be described in terms of the following: Goals and objectives, evolutionary context, high-level functions, boundary conditions, and constraints.

eVinci is designed for electricity and process heat production. When producing electricity, it can be operated in base-load or load-following modes.

No detailed information on the above aspects of plant mission was available.

Agents' Roles and Responsibilities

This dimension clarifies the relative roles and responsibilities of system's agents, namely, personnel and automation, and their relationship. Information on the design features supporting overall safety is provided (see Management of Off-Normal Conditions and Emergencies below), including one required human action.

The overall scope of human actions is not addressed.

Staffing, Qualifications, and Training

This dimension addresses the number and capabilities of staff needed to accomplish the human roles and responsibilities. However, no information is available on how eVinci will be staffed or the qualifications of staff positions. No information on training is currently available.

Management of Normal Operations

No information on the key aspects of normal operations is available, i.e., identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

Management of Off-Normal Conditions and Emergencies

Some information on the key aspects of off-normal operations is available, i.e., identification of key scenarios. However, no details about the tasks needed to perform them is provided; nor are the HSIs and procedures essential to supporting the tasks discussed.

eVinci is an inherently safe reactor design that does not rely on a safety-related instrumentation and control system, AC power, or operator actions to achieve safe shutdown. It will address some of the most challenging NPP scenarios, including primary coolant loss, positive reactivity injection due to water entering the core, high-pressure eruptions and ejections, positive reactivity injection due to control rod ejection, and station blackout (Arafat & Van Wyk, 2019).

Maioli et al. (2019) described PRAs performed early in the design's development, thus they were limited by the level of detail about the design. The PRA examined at-power internal events for a single reactor module. ASME/ANS RA-S-1.4-2013 (ASME, 2013) was used as guidance for the development of the PRA methodology.

Only one operator action was included in the PRA model - to trip the Control Drum Subsystem. A conservative screening value was used for the human error probability and the action did not affect the risk estimate.

While the design features supporting safety are provided, the analysis of failure modes and the human role, if any, in managing accident conditions is not discussed.

Management of Maintenance and Modifications

When the eVinci micro reactor core has reached the end of its operable lifetime, Westinghouse plans to change out the entire *reactor* module with new one. The reactor module can be transported back to the factory where it can be refueled and its components can be refurbished.

No other aspects of maintaining or modifying the reactor are discussed.

OKLO Power Aurora

The OKLO Aurora reactor is a fast reactor, using metal uranium zirconium fuel to generate heat. Heat pipes are used to transport the heat from the reactor core.

Information on the Aurora reactor came from the Safety Analysis Report (OKLO Power, 2020), specifically:

- Part II: The Safety Case
- Part V: Non-Applicabilities and Requested Exemptions

Plant Mission

The plant mission can be described in terms of the following: Goals and objectives, evolutionary context, high-level functions, boundary conditions, and constraints.

The Aurora reactor is designed for electricity and process heat production. When producing electricity, it can be operated in base-load or load-following modes.

No additional information on plant mission was available.

Agents' Roles and Responsibilities

This dimension clarifies the relative roles and responsibilities of system's agents, namely, personnel and automation, and their relationship.

Information on the design features supporting overall safety is provided (see Management of Off-Normal Conditions and Emergencies below).

Staffing, Qualifications, and Training

This dimension addresses the number and capabilities of staff needed to accomplish the human roles and responsibilities.

The Aurora reactor submittals have the most detailed description of plant staffing of any of the small, advanced reactors. Aurora is expected to operate automatically, many of the operational roles associated with traditional reactors are unnecessary. OKLO Power states that onsite personnel do not perform any credited operator actions; therefore, no licensed operators are necessary.

The staffing organization is headed by the Plant Manager. During normal operation, two onsite monitors are at the site: a Primary Site Monitor and a Secondary Site Monitor.

According to OKLO's submittals to the NRC, during normal operation, the Onsite Monitors:

- Monitor key parameters during normal operations
- Ensure the reactor is operating within the technical specifications
- Perform rounds to ensure proper operation of equipment
- Perform necessary duties as per the radiation protection program
- Occupy the Monitoring Room and perform duties as per the physical security plan

During normal operations, Oncall Monitor(s) are available. Oncall Monitors are Onsite Monitors that are not on shift but are expected to be fit for duty and able to respond to an emergency.

There is also a Startup Operators who performs startup tests, initiates reactor startup, performs reactivity changes, and monitors and control key unit parameters.

During emergencies, the Primary Site Monitor's role includes "Onsite Emergency Coordinator" and the Secondary Site Monitor's role includes the "Onsite Emergency Supporter." These monitors carry out actions specified in the Emergency Plan. To be an Onsite Monitor, personnel must have a high-school diploma or a general equivalency development degree. While the

Onsite Monitors do not have any credited operator actions, they can manually initiate a reactor trip.

No information on training is currently available.

Management of Normal Operations

The key aspects of normal operations include: identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

Manual user actions are minimal during normal operation. The two Onsite Monitors monitor the reactor status and the operation of plant equipment. They address issues with the secondary system when needed. Onsite Monitors are trained prior to assuming their duties.

Startup Operators handle reactor startup tasks, including the initial criticality and ascent to power. Startup Operators do not monitor the reactor during normal operation. Startup Operators have the ability to control the rotation of control drums and the insertion and removal of shutdown rods.

Personnel can monitor Aurora from the onsite monitoring room or remotely. Aurora's information display system presents the plant parameters needed to monitor the current state of the plant. The information display system presents key parameters on fixed displays while other parameters are presented on user-configurable displays.

Management of Off-Normal Conditions and Emergencies

No information on the key aspects of off-normal operations is available, i.e., identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

We did not identify any HFE aspects considered with respect to:

- emergencies that may impact safety, such as a loss of heat sink
- loss of plant systems for which compensation is needed
- failed equipment, such as pumps and valves
- degraded I&C and HSI conditions (such as a faulty sensor, loss of an aspect of automation, or degradation of a workstation)

Reactor trip is fully automatic and Aurora personnel do not have any credited safety actions. The only action available to Onsite Monitors is to initiate a reactor trip which can only put the reactor into a shutdown state. The manual trip is initiated by buttons that are hard-wired. They can be accessed in several locations. After the reactor trip conditions have been addressed, personnel must "unlatch" the reactor trip by pressing a button.

While the design features supporting safety are provided, the analysis of failure modes and the human role, if any, in managing accident conditions is not discussed.

Management of Maintenance and Modifications

Personnel perform maintenance on the control enclosures. Prior to performing maintenance, personnel must bypass the enclosures using a manual switch.

Another maintenance activity is to update the upper limits for the control drum angular positions to allow additional reactivity to be added. This is a manual task. Changing the limit setpoints requires personnel to manually change the appropriate limit monitor after it has been bypassed.

No other aspects of maintaining or modifying the Aurora are discussed.

2.3.1.2 Helium-Cooled Fast Reactors

General Atomics (GA) Energy Multiplier Module (EM2)

The Energy Multiplier Module (EM2) is a helium-cooled nuclear reactor. GA states that the EM2 was designed to achieve four objectives in comparison to LLWRs: "significantly enhanced safety, reduced waste, strong proliferation resistance, and production of low-cost, and clean electricity." EM2 reactors can be operated as SMRs if desired, so the energy output can be scaled to meet energy demands as high as 265 MWe.

EM2 is designed to be factory fabricated and has modular construction. All components are transportable using the existing transportation infrastructure. The reactor is designed so the core can last for 30+ years.

The reactor is designed to be placed below-grade in a sealed containment and relies on passive safety methods for heat removal and reactivity control. Its design is simpler than LLWRs; it does not have steam generators, the main steam system, and the feedwater-condensate system.

Information about EM2 was mainly obtained from GA's website (http://www.ga.com/nuclear-fission/). A document entitled *Energy Multiplier Module Powering Innovation* was downloaded from the website.

Plant Mission

The plant mission can be described in terms of the following: Goals and objectives, evolutionary context, high-level functions, boundary conditions, and constraints.

The primary mission of the EM2 is electricity production either as a single unit or in an SMR configuration. No detailed information on the other characteristics of plant mission was available.

Agents' Roles and Responsibilities

This dimension clarifies the relative roles and responsibilities of system's agents, namely, personnel and automation, and their relationship. Information on the design features supporting overall safety is provided (see Management of Off-Normal Conditions and Emergencies below).

Staffing, Qualifications, and Training

This dimension addresses the number and capabilities of staff needed to accomplish human roles and responsibilities. No information is available on how EM2 will be staffed or the qualifications of staff positions. No information on training is currently available.

Management of Normal Operations

No information on the key characteristics of normal operations is available, i.e., identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

Management of Off-Normal Conditions and Emergencies

No information on the key aspects of off-normal operations is available, i.e., Identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

We did not identify any HFE aspects considered with respect to:

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

There is general information about design features that support safety. Safety is addressed through passive design features, such as fuel that can tolerate temperatures more than twice that of LLWRs. GA states that the core cannot meltdown; thus Fukushima-type accidents cannot happen. GA indicates that operator action is not needed to support EM2's safety features.

EM2 can be located below grade and away from population centers.

While the design features supporting safety are provided, the analysis of failure modes and the human role, if any, in managing accident conditions is not discussed.

Management of Maintenance and Modifications

No aspects of maintaining or modifying the EM2 are discussed.

2.3.1.3 High-Temperature, Gas-Cooled Reactors

X-Energy XE-100

The Xe-100 reactor is a pebble-bed, high temperature, gas-cooled reactors (HTGC). Each reactor will produce approximately 75 MWe. The Xe-100 is used in an SMR configuration of four units, generating approximately 300 MWe. Additional units can be added to increase electricity production. The XE-100 components are modularized and can be transported by existing transportation means.

Information about the Xe-100 reactor came mainly from the vendor website (https://www.x-energy.com/),

Plant Mission

The plant mission can be described in terms of the following: Goals and objectives, evolutionary context, high-level functions, boundary conditions, and constraints.

The XE-100 is designed for electricity and process heat production. When producing electricity, it can be operated in base-load or load-following modes.

No detailed information on the above characteristics of plant mission was available.

Agents' Roles and Responsibilities

This dimension clarifies the relative roles and responsibilities of the system's agents, namely, personnel and automation, and their relationship.

Information on the design features supporting overall safety is provided (see Management of Off-Normal Conditions and Emergencies below); however, human actions, if any, are not addressed.

Staffing, Qualifications, and Training

This dimension addresses the number and capabilities of staff needed to accomplish the human roles and responsibilities. However, no information is available on how EM2 will be staffed or the qualifications of staff positions. No information on training is currently available.

Management of Normal Operations

No information on the key aspects of normal operations is available, i.e., identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

Management of Off-Normal Conditions and Emergencies

No information on the key aspects of off-normal operations is available, i.e., identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

We did not identify any HFE aspects considered with respect to:

- emergencies that may impact safety, such as a loss of coolant accident

- loss of plant systems for which compensation is needed, such as the failure of a cooling-water system

- failed equipment, such as pumps and valves

- degraded I&C and HSI conditions (such as a faulty sensor, loss of an aspect of automation, or degradation of a workstation)

The XE-100 requires a 400-yard safety perimeter; much smaller than large LWRs.

X-Energy stated that the XE-100 has a simple design that is “meltdown-proof” and supports “walk-away” safety implying no human actions are required.

The analysis of failure modes and the human role, if any, in managing accident conditions is not discussed.

Management of Maintenance and Modifications

The XE-100 supports online refueling and is designed for a 60-year operational life.

No other aspects of maintaining or modifying the XE-100 are discussed.

2.3.1.4 Molten Salt Reactors

Before considering individual molten salt reactors (MSR) designs, we note that general challenges to MSR safety have been addressed by Holcomb and Flanagan (2019) and McFarlane, Taylor, Holcomb and Poore (2019). These studies identified numerous potential challenges to MSR safety at the individual component level such as the presence of bubbles (fission product gasses) passing through the core. The authors indicate that little information or operating experience is available to evaluate these issues. Holcomb and Flanagan (2019) note that:

- major phenomena have not been identified or ranked
- accident sequences and initiating events have not been identified
- qualified safety analysis tools are not yet available
- nonprototypic (scaled) separate and integral effects tests need to be used
- quality data and benchmarks need to be developed
- test and prototype reactors are needed

We will review three MSRs: the Kairos Fluoride Salt-Cooled High Temperature Reactor (FHR), the Terrestrial Energy Integral Molten Salt Reactor (IMSR), and the TerraPower Molten Chloride Fast Reactor (MCFR).

Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)

The Kairos Power fluoride salt-cooled high temperature reactor (KP-FHR) uses TRi-structural ISOtropic (TRISO) fuel particles in a pebble bed design. The fuel design plays a significant role in the safety of the reactor. The particles are made up of uranium, carbon, and oxygen. These fuel elements are encased in ceramic-based materials. This design helps prevent the release of radioactive fission products (https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth) under normal operations and accident conditions without requiring active design features or operator actions (Kairos Power, 2018, 2019).

Information on the KP-FHR was mainly available from the vendor website (https://kairospower.com/). In addition, several technical reports on the KP-FHR design were reviewed. These reports were available through ADAMS.

Plant Mission

The plant mission can be described in terms of the following: Goals and objectives, evolutionary context, high-level functions, boundary conditions, and constraints.

The KP-FHR is designed for electricity production.

No additional information on the above aspects of plant mission was available.

Agents' Roles and Responsibilities

This dimension clarifies the relative roles and responsibilities of system's agents, namely, personnel and automation, and their relationship.

Information on the design features supporting overall safety is provided (see Management of Off-Normal Conditions and Emergencies below). However, little discussion of the overall human role in KP-FHR operation is presented. Human actions are identified in the PRA analysis; however, operator actions are not required to achieve safety goals (Kairos Power, 2018).

Staffing, Qualifications, and Training

This dimension addresses the number and capabilities of staff needed to accomplish the human roles and responsibilities. No information is available on how the KPFHR will be staffed or the qualifications of staff positions. No information on training is currently available.

Management of Normal Operations

No information on the key aspects of normal operations is available, i.e., identification of key scenarios describing normal operations; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

Management of Off-Normal Conditions and Emergencies

Some information on the key dimensions of off-normal operations is available, i.e., identification of key scenarios and the tasks generally needed to perform them (Kairos Power, 2020). However, the reported analysis is mainly presented as an illustration of the methodology Kairos intends to perform. Further, no information about the HSIs and procedures essential to supporting the tasks is provided.

Kairos states that the KP-FHR's fuel design and low-pressure coolant result in an inherently safe design. Since it is inherently safe, no operator intervention is required. No active components are needed to keep the plant in a safe state.

Kairos Power (2020) describes their risk informed, performance-based methodology. The methodology identifies the licensing basis events (LBE), the classification of structures, systems, and components (SSCs), and the defense-in-depth (DID) adequacy. The methodology was developed in conjunction with the industry's Licensing Modernization Project (LMP) (Maioli et al., 2019) and (NEI, 2012). The LMP sought to develop technology inclusive, risk-informed, and performance-based regulatory guidance for licensing non-LWRs. NEI 10-04 (NEI, 2012) was endorsed by regulatory guide, DG 1353 "Guidance for a technology inclusive, risk informed, and performance-based approach to inform the content of applications for licenses, certifications, and approvals for non-light water reactors" (NRC, 2019a).

While human actions are identified in the probabilistic risk assessment (PRA); Kairos indicates that no operator actions are required for safety (Kairos Power, 2018). It should be noted that the report provides a sample of the methodology, not the full methodology or final results.

In a decay heat removal scenario, a failure of a normal reactor trip occurs. This can result in additional core heat being added to the system before the safety scram actuates. This can create a bounding challenge to structural temperatures. This sequence involves operator actions to enhance heat removal capability or to realign normal decay heat removal. However, this human action is not required to maintain safe conditions.

Another sequence defines the beyond design basis conditions for a reactivity control scenario featuring a failure of the normal reactor shutdown system and the automatic safety control elements. This sequence relies on a combination of inherent reactivity feedback mechanisms of the core to reduce power on increasing temperature and manual operator actions to recover the control elements. However, this human action is not required to maintain safe conditions.

Kairos Power identifies some of the support for these operator actions, including a control room or reactor building with equipment used by operators to manually recover from a failure to scram automatically.

Operator actions are integrated into the reactors defense-in-depth design. However, they are in the fourth layer which comes into play in the rare case of concurrent failures of layer 1 (normal resilience to upset conditions using non-safety equipment), layer 2 (plant's response to a failure), and layer 3 (safety related equipment) (Denman, Hagaman, Tinsley, 2019).

Management of Maintenance and Modifications

No information on maintaining or modifying the KP-FHR is discussed.

Terrestrial Energy Integral Molten Salt Reactor

Terrestrial Energy's Integral Molten Salt Reactor (IMSR) uses molten salt as coolant and fuel. Terrestrial Energy states molten salts are thermally very stable and superior to water as a coolant enabling the reactor to operate at both high temperature and lower pressure. The reactor generates 195 MWe. It can be used in an SMR configuration and can be operated in load-following mode. The reactor is manufactured in modules and transported by truck or rail for assembly.

Information on the IMSR came from the vendor's website (http://terrestrialusa.com/).

Plant Mission

The plant mission can be described in terms of the following: Goals and objectives, evolutionary context, high-level functions, boundary conditions, and constraints.

The reactor is designed for electricity, hydrogen, and process heat production.

No additional detailed information on the above aspects of plant mission was available.

Agents' Roles and Responsibilities

This dimension clarifies the relative roles and responsibilities of system's agents, namely, personnel and automation, and their relationship. Information on the design features supporting overall safety is provided (see Management of Off-Normal Conditions and Emergencies below), but human actions are not addressed.

Staffing, Qualifications, and Training

This dimension addresses the number and capabilities of staff needed to accomplish the human roles and responsibilities. However, no information is available on how the IMSR will be staffed or the qualifications of staff positions. No information on training is currently available.

Management of Normal Operations

No information on the key aspects of normal operations is available, i.e., identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

Management of Off-Normal Conditions and Emergencies

No information on the key aspects of off-normal operations is available, i.e., identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

We did not identify any HFE aspects considered with respect to:

- emergencies that may impact safety, such as a loss of coolant accident
- loss of plant systems for which compensation is needed, such as the failure of a cooling-water system

- failed equipment, such as pumps and valves
- degraded I&C and HSI conditions (such as a faulty sensor, loss of an aspect of automation, or degradation of a workstation)

The vendor states that when a molten salt coolant and molten salt fuel are used in combination, the reactor has passive, inherent safety.

Management of Maintenance and Modifications

The only maintenance issue discussed is the replacement of the reactor's graphite. The ISMR has an integrated primary reactor that includes the graphite. It's a replaceable modular unit that is replaced every seven years.

TerraPower Molten Chloride Fast Reactor (MCFR)

TerraPower's molten chloride fast reactor (MCFR) is a molten salt reactor that operates at high temperatures and generates electricity as well as process heat.

The information on TerraPower reactor came from the vendor's website: (https://terrapower.com/technologies/mcfr).

Plant Mission

The plant mission can be described in terms of the following: Goals and objectives, evolutionary context, high-level functions, boundary conditions, and constraints.

The MCFR is designed for electricity and process heat production.

No detailed information on the above aspects of plant mission was available.

Agents' Roles and Responsibilities

This dimension clarifies the relative roles and responsibilities of system's agents, namely, personnel and automation, and their relationship.

The MCFR description indicates that the design's inherently safe operation requires no operator actions.

Staffing, Qualifications, and Training

This dimension addresses the number and capabilities of staff needed to accomplish the human roles and responsibilities. However, no information is available on how the MCFR will be staffed or the qualifications of staff positions. No information on training is currently available.

Management of Normal Operations

No information on the key aspects of normal operations is available, i.e., identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

Management of Off-Normal Conditions and Emergencies

No information on the key aspects of off-normal operations is available, i.e., identification of key scenarios; the tasks needed to perform them; and the HSIs and procedures essential to supporting the tasks.

We did not identify any HFE aspects considered with respect to:

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

No operator actions are required for ensuing plant safety.

Management of Maintenance and Modifications

No information on maintaining or modifying the MCFR are discussed.

2.3.2 General Characterization of Small Advanced Reactors

A characterization of the technical aspects of these reactors was developed based on an evaluation of the reactor designs and the ConOps of eight advanced reactors. The characterization is general and may not apply to all designs. The following 13 characteristics were identified:

- Some reactors are constructed in a factory and transported to the needed site using the existing transportation infrastructure (e.g., road, rail, or waterway).
- Some reactors rely on simpler designs, involving fewer systems and moving parts.
- Some reactors are constructed using a modular approach to simplify maintenance; so, when maintenance is needed, modules are instead replaced.
- Some reactors are self-contained and designed to operate for many years without shutting down, being refueled, or maintained.

- Some reactors rely on design features that make them inherently safe, such as natural physical processes that do not require automatic or human intervention.

- Some reactors produce public exposure to postulated accidents that is much lower than current reactors.

- Some reactors may operate at higher temperatures than LLWRs and thus can support new missions, e.g., the production of multiple products in addition to electricity, such as industrial process heat (new missions create new systems, personnel tasks, and workload).

- Some reactors can be operated in load-following mode.

- Some reactors can be operated in an SMR configuration and therefore scalable to meet energy demands – in an SMR configuration there may be shared systems.

- Some reactors are highly automated, including some that may operate in a fully autonomous mode, and may not require human monitoring, control, and intervention.

- Some reactors may not have a control room in the traditional sense; reactor monitoring and control may be accomplished from simple panels either locally or remotely.

- Some reactors may be staffed by few or no onsite personnel.

- Some reactors may rely on staffing organizational structures that are quite different than that described in current regulations and may include different staff positions possibly involving no licensed operators or credited human actions.

These characteristics, which in many instances are the result of or enabled by safety improvements, reflect significant differences between advanced reactors and the current fleet.

2.3.3 Potential HFE Technical Issues

The design and ConOps of small, advanced reactors have given rise to the recognition by industry, the NRC, and research organizations of HFE-related technical issues that need to be addressed. These issues are:

- Identification of important human actions
- Autonomous operations
- Approaches to staffing
- HSIs for monitoring and controlling the reactor and interfacing systems
- Remote operations

Detailed descriptions of each are provided in Appendix C. Appendix D contains the SMR issues identified in the previous study. These issues are largely applicable here.

2.4 Summary

We reviewed information available on a sample of small, advanced reactors to develop a characterization of their key design and operational features that are pertinent to HFE safety reviews. The reactors represented the following types of technology: Heat pipe reactors, helium-cooled fast reactors, high-temperature gas cooled reactors, and molten salt reactors.

The information was organized by a ConOps model along the following 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

The review was limited by the fact that information on many of these dimensions was not available for some designs.

We identified 13 characteristics of small, advanced reactors although not all characteristics apply to every design.

We also identified potential technical issues that should be consider in the review of small, advanced reactors. They include identification of important human actions, autonomous operations, approaches to staffing, HSIs for monitoring and controlling the reactor and interfacing systems, and remote operations.

Taken together, these differences signify the need for a new approach to the HFE review of license applications for small advanced reactors (NEIMA, 2019).

3 REVIEW OF EXISTING NRC HFE GUIDANCE AND ITS SUITABILITY FOR THE REVIEW OF SMALL ADVANCED REACTORS

3.1 Objectives

The purpose of this task was to:

1. Identify, compile, and review the NRC's HFE guidance documents for all reactor types to determine how the HFE aspects of the designs are identified and addressed.
2. Using the information obtained about small, advanced reactor design and operations and the technical issues identified in Section 2.3.3 above, determine the suitability of the existing guidance for reviewing them, i.e.:
    - Do the existing regulations and guidance suitably address HFE issues for small, advanced reactors?
    - What modifications of the regulations and guidance might be needed?
    - Will new guidance be needed to support small, advanced reactor licensing reviews?
3. Identify the NRC's general expectations for advanced reactor reviews.

3.2 Method

New HFE guidance needs to be consistent with the NRC's overall infrastructure guiding the assurance of public safety (see Figure 3.1). This infrastructure consists of:

- Requirements defined in the Code of Federal Regulations (CFR).
- The guidance contained in the NRC's standard review plans (SRPs) which define the methods the staff has found acceptable for meeting the regulatory requirements. The SRP guidance may provide valuable insights for small, advanced reactor reviews.
- The NRC's general vision for advanced reactor licensing. The HFE guidance developed needs to be consistent with the NRC's overall approach.

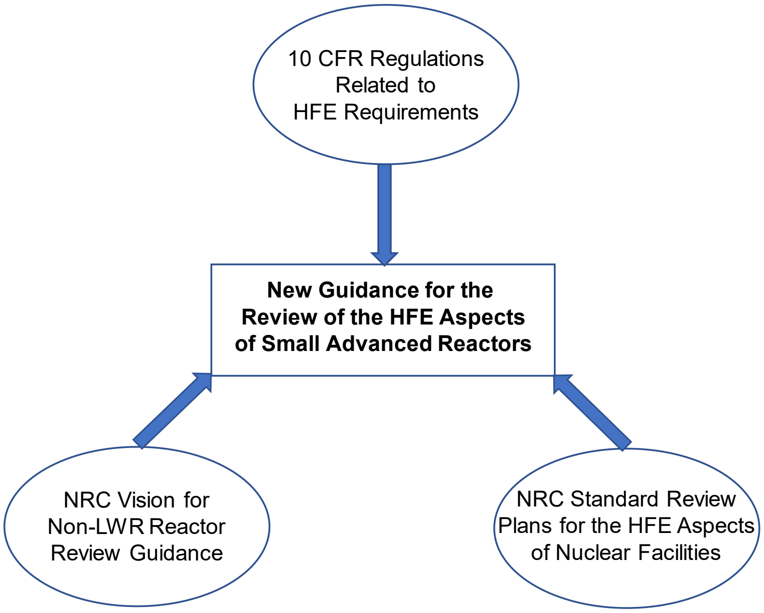

Figure 3.1 Regulatory Infrastructure Supporting New Review Guidance Development

Our task was to identify relevant information within NRC's existing regulatory infrastructure as depicted in Figure 3.1. The scope of the evaluation includes those topics addressed in NUREG-0800, Chapter 18, Human Factors Engineering (NRC, 2016a). As stated in NUREG-0800, Section II, Review Interfaces, the HFE review involves many overlapping review responsibilities. For instance, NUREG-0711 addresses several aspects of operational programs, such as procedures and training, for which other NRC reviewers have primary responsibility. In this evaluation, we have not included all aspects of these topics. We have included staffing in the evaluation because staffing is integral to the design of control rooms and human-system interfaces (HSIs).

3.3 Results

The goal of an NRC safety review is to achieve a conclusion with reasonable assurance of adequate protection of public health and safety. This is accomplished by ensuring that applicants have met the CFR requirements (or have acceptable justification for receiving exceptions from the requirements). The NRC staff makes this assessment by performing safety reviews with the support of SRPs and other guidance documents. As the NRC considers safety reviews for new small, advanced reactors, they recognize that changes to the existing regulatory infrastructure may be necessary.

In this section we will review the HFE requirements in the CFR and the existing SRPs used to guide safety reviews for nuclear facilities. We will then review the NRC's strategic vision for how the guidance should be modified for small, advanced reactors.

In the review of the NRC documents, we tried to use the exact wording from the documents where possible.

3.3.1 HFE Requirements in the Code of Federal Regulation

3.3.1.1 HFE Regulations

HFE regulations are contained in the U.S. Code of Federal Regulations (CFR). Title 10 of the CFR addresses Energy and contains the regulations pertaining to the NRC. Several of the regulations address the HFE aspects of nuclear facilities. For commercial nuclear power plants, one of the more important HFE regulations is 10 CFR 50.34(f)(2)(iii) and 10 CFR 52.47(a)(1)(ii) which requires an applicant to:

> Provide, for Commission review, a control room design that reflects state-of-the-art human factor principles prior to committing to fabrication or revision of fabricated control room panels and layouts.

This requirement is important in that it provides the regulatory basis for the NRC's general approach to HFE review described in Chapter 18, Human Factors Engineering, of the *Standard Review Plan* (SRP), NUREG-0800, (NRC, 2016a). The SRP defines what applicants need to address to satisfy the CFR requirements. The SRP provides an acceptable method to meet the requirement that the control room reflects "state of the art human factors principles."

In addition to the general control room requirement, there are other CFR requirements that involve HFE. SRP Chapter 18, Subsection III, Acceptance Criteria, contains a list of HFE-related requirements (see Table 3.1).

Table 3.1 HFE Requirements in the Code of Federal Regulations

Regulations Addressing General Requirements Related to the Main Control Room
10 CFR 50.34(f)(2)(ii) – continuing improvement of HFE and procedures
10 CFR 50.34(f)(2)(iv) – safety parameter display system
10 CFR 50.34(f)(3)(i) – use of operating experience
10 CFR 50.54 (i) to (m) - staffing
10 CFR 52.47 – level of detail required in design certifications (DCs)
10 CFR 52.47(a)(8) – inclusion of 10 CFR 50.34(f) for Part 52 applications
10 CFR 52.79 – content of combined operating license (COL) applications
Specific Requirements Related to the Main Control Room
10 CFR 50.34(f)(2)(v) – automatic indication of the bypassed and operable status of safety systems
10 CFR 50.34(f)(2)(xi) – relief and safety valve indication
10 CFR 50.34(f)(2)(xii) – auxiliary feedwater system flow indication
10 CFR 50.34(f)(2)(xvii) – containment related indications
10 CFR 50.34(f)(2)(xviii) – core cooling indications
10 CFR 50.34(f)(2)(xix) – instrumentation for monitoring post-accident conditions that includes core damage
10 CFR 50.34(f)(2)(xxi) – auxiliary heat removal (Boiling Water Reactor)
10 CFR 50.34(f)(2)(xxiv) – reactor vessel level monitoring (Boiling Water Reactor)

This table contains a list from SRP Chapter 18 of the of HFE related requirements in the CFR. It does not contain the general control room requirement in 10 CFR 50.34(f).

In addition to the parts of 10 CFR listed above, there are numerous parts that address specific types of facilities that vary in their treatment of HFE requirements. We have identified these in the discussion of the SRPs in Section 3.3.2 below.

3.3.1.2 General Design Criterion 19

An important HFE-related requirement is contained in 10 CFR Part 50, Appendix A, General Design Criteria (GDC) for nuclear power plants (NPPs). The GDC serve as the fundamental criteria used by the NRC when reviewing the structures, systems, and components (SSCs) that make up a NPP design. The GDC requirements establish the necessary design, fabrication, construction, testing, and performance requirements for SSCs that are important to safety. Taken together, they provide reasonable assurance that an NPP can be operated without undue risk to the health and safety of the public.

GDC Criterion 19 addresses the need for and characteristics of a control room. It states:

> *Criterion 19—Control room.* A control room shall be provided from which actions can be taken to operate the nuclear power unit safely under normal conditions and to maintain it in a safe condition under accident conditions, including loss-of-coolant accidents. Adequate radiation protection shall be provided to permit access and occupancy of the control room under accident conditions without personnel receiving radiation exposures in excess of 5 rem whole body, or its equivalent to any part of the body, for the duration of the accident. Equipment at appropriate locations outside the control room shall be provided (1) with a design capability for prompt hot shutdown of the reactor, including necessary instrumentation and controls to maintain the unit in a safe condition during hot shutdown, and (2) with a potential capability for subsequent cold shutdown of the reactor through the use of suitable procedures.
>
> Applicants for and holders of construction permits and operating licenses under this part who apply on or after January 10, 1997, applicants for design approvals or certifications under part 52 of this chapter who apply on or after January 10, 1997, applicants for and holders of combined licenses or manufacturing licenses under part 52 of this chapter who do not reference a standard design approval or certification, or holders of operating licenses using an alternative source term under § 50.67, shall meet the requirements of this criterion, except that with regard to control room access and occupancy, adequate radiation protection shall be provided to ensure that radiation exposures shall not exceed 0.05 Sv (5 rem) total effective dose equivalent as defined in § 50.2 for the duration of the accident.

In recognition of the differences between LLWRs and the new advanced reactors, the NRC has proposed modifications to GDC 19. These modifications are contained in Regulatory Guide (RG) 1.232 (NRC, 2018a) and are discussed below.

3.3.1.3 Summary

Per the GDC and CFR (i.e., 10 CFR 50.34(f) and 10 CFR 52.47(a)(1)(ii))), a control room is required that must reflect “state-of-the-art human factors principles.” Also, there are additional HFE-related requirements addressing detailed aspects of HSIs, procedures, and training. Unless modified by changes to the regulations or new review approaches and guidelines, these requirements are applicable to small, advanced reactors. It should be noted that the NRC’s review process allows applicants to request exemptions from requirements with appropriate justification.

3.3.2 Standard Review Plans for Nuclear Facilities

In this section we review several SRPs to determine how the HFE aspects of the facilities are identified and addressed. There are over 20 SRPs that address reviews of diverse facilities.[5] Our review included SRPs for facilities where processes are being monitored and controlled. Some of the SRPs we did not review addressed topics outside the scope of our evaluation, such as license examiner standards, environmental qualifications, decommissioning, and transportation.

We examined the following SRPs:

NUREG-0800, Light Water Reactor Edition: *Standard Review Plan, Chapter 18, Human Factors Engineering* (NRC, 2016a)

NUREG-0800: *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: Light-Water Small Modular Reactor Edition* (NRC, 2014a)

NUREG-1537: *Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors: Standard Review Plan and Acceptance Criteria* (NRC, 1996)

NUREG-1702: *Standard Review Plan for the Review of a License Application for the Tank Waste Remediation System Privatization (TWRS-P) Project* (NRC, 2000a)

NUREG-1718: *Standard Review Plan for the Review of an Application for a Mixed Oxide (MOX) Fuel Fabrication Facility* (NRC, 2016d)

NUREG-1520, Rev 2: *Standard Review Plan for Fuel Cycle Facilities License Applications* (NRC, 2015)

NUREG-1567: *Standard Review Plan for Spent Fuel Dry Storage Facilities* (NRC, 2000c)

NUREG-1536, Rev 1: *Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility* (NRC, 2010a)

NUREG-2215: *Standard Review Plan for Spent Fuel Dry Storage Systems and Facilities* (NRC, 2020c)

NUREG-2126: *Standard Review Plan for Conventional Uranium Mill and Heap Leach Facilities* (NRC, 2014b)

NUREG-1200, Rev 3: *Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility* (NRC, 1994a)

We begin our review with the current process for LLWRs (NUREG-0800). This reflects the most detailed review of HFE.

3.3.2.1 NUREG-0800, NUREG-0711, NUREG-0700, NUREG-1764 and Current LLWR HFE Reviews

The NRC's review guidance takes a broad perspective on plant safety. NUREG-1649 (NRC, 2016e) describes the NRC's Reactor Inspection and Oversight Program (ROP) for operating reactors. This program monitors plant performance in several strategic performance areas:

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[5] See https://www.nrc.gov/reading-rm/basic-ref/srp-review-standards.html#2

reactor safety, radiation safety, safeguards, occupational radiation safety, public radiation safety, and security. They are further defined using the cornerstones of initiating events, mitigation systems, barrier integrity, and emergency preparedness. The program has three cross-cutting areas one of which is Human Performance. Human Performance is defined as follows: “This area monitors the licensee’s decision-making process, availability and adequacy of resources to ensure nuclear safety, coordination of work activities, and personnel work practices.” Well-designed HSIs, procedures and training are important to optimizing each of these ROP cornerstones and in helping to assure the radiation-safety goals of minimizing the radiation exposure of plant workers and the general public during routine operations. One of the principal purposes of this program is assisting the NRC staff’s verification that HSIs, procedures, and training support human performance.

NUREG-0800, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition[6]

To support the NRC staff’s responsibility to evaluate applicant submittals to ensure the CFR requirements are met, the NRC developed a series of standard review plans (SRPs). The plans describe methods the staff have found acceptable for meeting NRC requirements. However, they are guidance and not required. NUREG-0800, Chapter 1, states that:

> The SRP is not a substitute for the NRC's regulations, and compliance with it is not required. However, an applicant is required to identify differences between the design features, analytical techniques, and procedural measures proposed for its facility and the SRP acceptance criteria and evaluate how the proposed alternatives to the SRP acceptance criteria provide acceptable methods of compliance with the NRC regulations.

SRPs are often supported by companion documents, such as NUREGs and Interim Staff Guidance (ISG) documents that provide more detailed review guidance for selected topics. Using the guidance, the reviewer makes a safety determination about the design’s acceptability.

The main SRP used for commercial power reactors is NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition”. NUREG-0800 is used to review the LLWR HFE programs of applicants for NPP construction permits, operating licenses, standard design certifications, and combined operating licenses. It contains the NRC’s guidance for the review of all aspects of reactor design and operation. In addition to LLWRs, the NRC reviews other types of nuclear facilities, such as research reactors, test reactors, and spent fuel facilities. These facilities are reviewed using different SRPs tailored to their unique characteristics (described in the sections to follow).

For a LLWR safety review the staff will use NUREG-0800, Chapter 18, *Human Factors Engineering* (NRC, 2016b) for guidance on conducting the HFE part of the review. Chapter 18 provides high-level guidance for HFE reviews. As noted above, it describes methods or approaches applicants can use which the staff have found acceptable for meeting NRC’s CFR requirements. HFE is an important aspect of the safety review and helps to ensure that personnel performance and reliability are appropriately supported.

The HFE reviews of large commercial reactors encompass both (1) the design process, such as the use of task analysis, (2) and its products, such as the design of the main control room and

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[6] The SRP is available at https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0800/index.html.

its HSIs. Using the HFE guidance, the reviewer makes a safety determination of the design's acceptability.

Applications of SRP Chapter 18 include the review of:

- Operating License Applications
- Combined License Applications
- Design Certification Applications
- Plant and Control Room Modifications
- Important Human Actions
- Local Control Stations
- Decommissioning Activities

The SRP has two attachments. Attachment A provides guidance for evaluating credited manual operator actions. Attachment B provides a methodology to assess the workload associated with challenging operational conditions in support of minimum staffing level reviews. Additional information on the workload assessment methodology is available in a technical report (O'Hara & Higgins, 2015).

While the SRP contains high-level guidance, it directs reviewers to detailed review criteria contained in supporting documents, such as:

- the *HFE Program Review Model*, NUREG-0711 (O'Hara, Higgins, Fleger & Pieringer, 2012)

- the *Human-System Interface Design Review Guidelines*, NUREG-0700 (O'Hara & Fleger, 2020)

- the *Guidance for the Review of Changes to Human Actions*, NUREG-1764, Rev 1, (Higgins, O'Hara, Lewis, Persensky, Bongarra, Cooper & Parry, 2007)

We will describe these three supporting documents next. The SRP references other HFE review guidance documents as well to address specific topical areas.

NUREG-0711 - Human Factors Engineering Program Review Model

NUREG-0711, Rev. 3, (O'Hara, Higgins, Fleger & Pieringer, 2012) contains the detailed review criteria for evaluating an applicant's HFE program. The review methodology is based on a systems engineering model (e.g., IEEE, 2005b) and is focused on a "top-down" design process methodology that incorporates "life cycle" considerations.[7] "Top-down" refers to an approach to HFE that starts at the "top," i.e., with the plant's high-level mission and goals. These are divided into the functions necessary to achieve the goals which are then allocated to human and system resources. Functions are broken down into tasks and analyzed to identify the HSIs (e.g., alarms, displays, and controls) that will be needed to support operator performance. Tasks are arranged into work activities to be performed by individual crewmembers and teams. The detailed design of the HSI, procedures, and training represents the "bottom" of the top-down process. Thus, the effective integration of HFE considerations into the design is accomplished

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[7] See O'Hara, Higgins, Brown, Fink, Persensky, Lewis, Kramer, Szabo & Boggi, (2008) for a more detailed discussion on the NRC's HFE guidance development method.

by providing a structured top-down approach to system development that is iterative, integrative, and interdisciplinary. It controls the total system development effort for the purpose of achieving an optimum balance of all system elements, including human roles and responsibilities. The approach is consistent with the recognition in the nuclear industry that HF issues and problems emerge throughout the NPP design and evaluation process and, therefore, HFE issues are best addressed with a comprehensive top-down approach.

HFE should be addressed over the plant life cycle. Life cycle stages include initial planning, HFE analyses, design, verification and validation, design implementation, and operations.

NUREG-0711 states that the overall purpose of the HFE review is to verify that:

- The applicant integrates HFE into the development, design, and evaluation of the plant.
- The applicant provides HFE products (e.g., HSIs) that facilitate the safe, efficient, and reliable performance of operations, maintenance, tests, inspections, and surveillance tasks.
- The HFE program and its products reflect state-of-the-art human factors engineering principles and satisfies the applicable regulatory requirements.

An applicant's HFE program provides reasonable assurance of plant safety when it conforms to the following high-level principles:

- The HFE program is developed and carried out by a qualified HFE design team, using an acceptable HFE program plan
- The design is derived from suitable HFE studies and analyses that afford accurate and complete inputs to the assessment criteria for the design process, and the verification and validation (V&V) process
- The design is based on proven technology incorporating accepted HFE standards and guidelines and evaluated with a thorough V&V test program
- The design is implemented such that it effectively supports operations
- The human-machine system is monitored during operations to detect changes in human performance

NUREG-0711 provides the detailed review criteria to assess whether these principles are achieved. NUREG-0711 is not a design guideline. It is a *design process assessment guideline* in the same family as other process assessment guidelines and standards, e.g., ISO/TS 18152:2010 (ISO, 2010) and ISO/TR 18529:2000 (ISO, 2000). A process assessment guide consists of a process model which is divided into key elements. Each key element has indicators that represent the best practices for the element and are used as criteria to review the applicant's process. Figure 3.2 depicts a generic process model architecture.

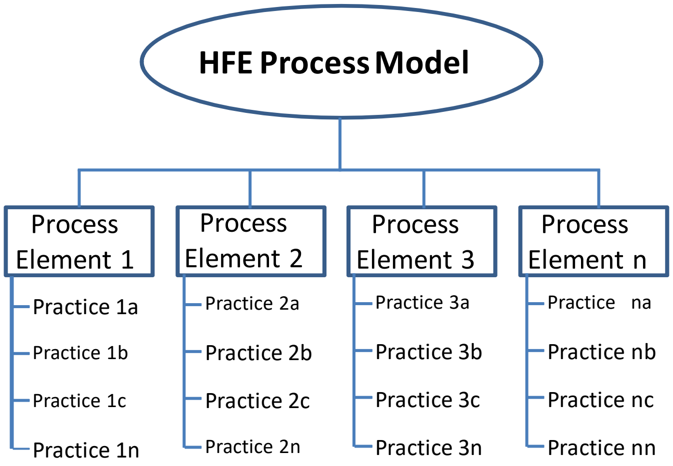

Figure 3.2 Process Model Architecture

As noted above, NUREG-0711's HFE process model is rooted in systems engineering. Systems engineering provides a broad approach to design that is based on a series of clearly defined developmental steps, each with defined goals and specific management processes to attain them. The development of the HFE model and elements for NUREG-0711[8] is based on this approach.

The NUREG's development began with a technical review of HFE guidance and practices to identify important HFE program elements relevant to the technical basis of a design process review. Several types of documents were assessed:

- Systems theory and engineering literature representing the theoretical basis for systems engineering, generally applicable to the design and evaluation of complex systems.
- NPP regulations, NPP HFE standards, guidance, and recommended practices developed in the NPP industry, including the NRC.

From this review, an HFE development, design, and evaluation model was defined. Once specified, the key HFE elements were identified and general criteria by which each could be assessed were developed.

Since its original development, NUREG-0711 has been updated three times[9] to improve the comprehensiveness and completeness of the guidance.

NUREG-0711, Rev 3, (O'Hara, Higgins, Fleger & Pieringer, 2012) contains 12 HFE elements as shown in Figure 3.3. For each key element, best practices are identified and serve as review criteria for evaluating the applicant's HFE activities. A brief description of each element is given in Appendix A, HFE Activities.[10] Each of the 12 elements is divided into five sections: Background, Objective, Applicant Submittals, Review Criteria, and Bibliography. A topic

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[8] See NRC,1994b for a more complete description of the model's development and for the references for the discussion to follow.

[9] Rev 0, 1994; Rev 1, 2002 ; Rev 2, 2004; and Rev 3, 2012

[10] See NUREG-0711 for detailed information about each of these elements and their review criteria.

characterization is provided in the Background section and is used to organize the review guidelines. For example, the characterization of the HSI design element includes:

- Design Inputs
- Concept of Operations
- Functional Requirements Specification
- Concept Design
- Detailed Design and Integration
- HSI Tests and Evaluations

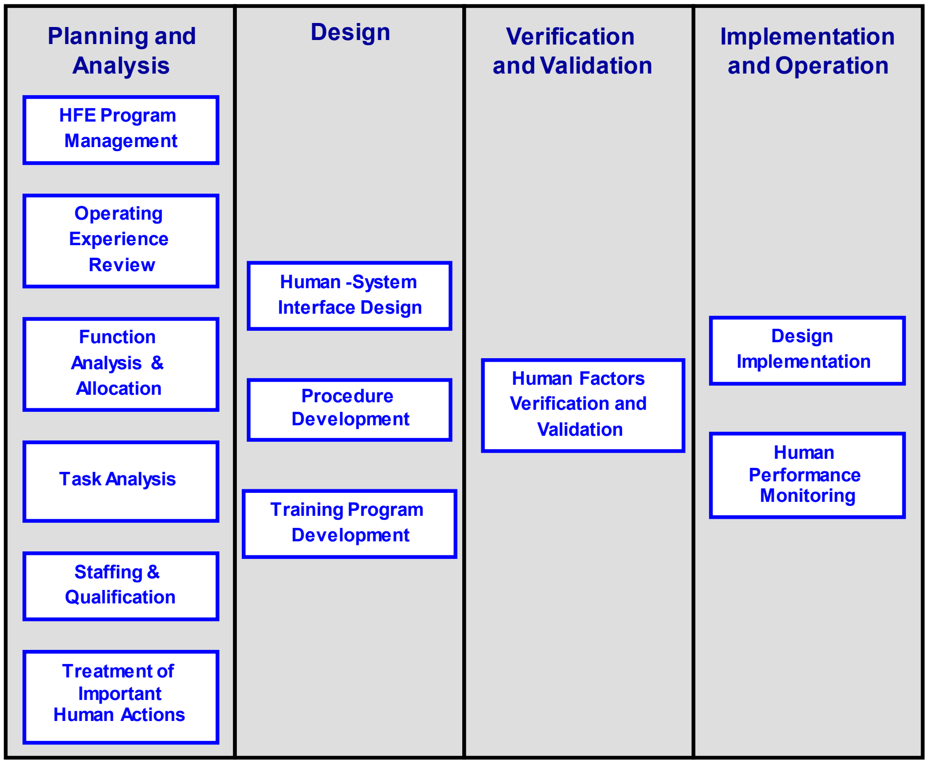

Figure 3.3 Key NUREG-0711 Elements/Activities

NUREG-0711 is also consistent with other HFE process models in the literature. Applicants use a *design process model* that is typically based on national and international HFE standards and guidance (S&Gs) documents. HFE S&Gs play an important role in the design and evaluation of complex systems (Karwowski, 2006). Many HFE S&Gs are developed by professional organizations using a consensus process. These organizations include the Institute of Electrical and Electronics Engineers (IEEE), the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), and government organizations such as the Department of Defense (DoD) and the Federal Aviation Administration (FAA). Typically, S&Gs are periodically updated to keep them current with lessons learned, new research, and technological developments.

The IEEE is a significant contributor to HFE standards and guidelines. An overview of their recent development efforts is provided in Desaulniers and Fleger (2019). IEEE 1023-2004 (IEEE, 2004) provides a model of the HFE design process. It states that the implementation of HFE in the life cycle activities of nuclear facilities should employ an integrated, systematic approach that considers the human as an integral part of the overall system. The standard also provides a "generic engineering process model" with the following stages:

- Planning
- Analysis
- Specification
- Testing and evaluation
- Operations and maintenance

As a generic model, any of the specific stages require more detailed guidance for implementation, e.g., designers need more detailed guidance to conduct analyses such as function analysis and task analysis. The standard notes that the HFE activities documented should be "tailored to the needs and constraints of the specific facility."

Another example of an HFE design model is the *Ergonomic Design of Control Centres,* ISO 11064 (ISO, 2006). ISO 11064 is a family of standards that establish HFE requirements for control centres, including those for NPPs. The standard describes a comprehensive approach to HFE that is divided into five stages or phases (see Figure 3.4):

- Phase A – Clarification of goals and requirements
- Phase B – Analysis (e.g., function, task, and job analysis)
- Phase C – Conceptual design
- Phase D – Detailed design
- Phase E – Real-world validation (e.g., operating experience of the plant)

Each of these phases contains HFE activities like NUREG-0711 elements.

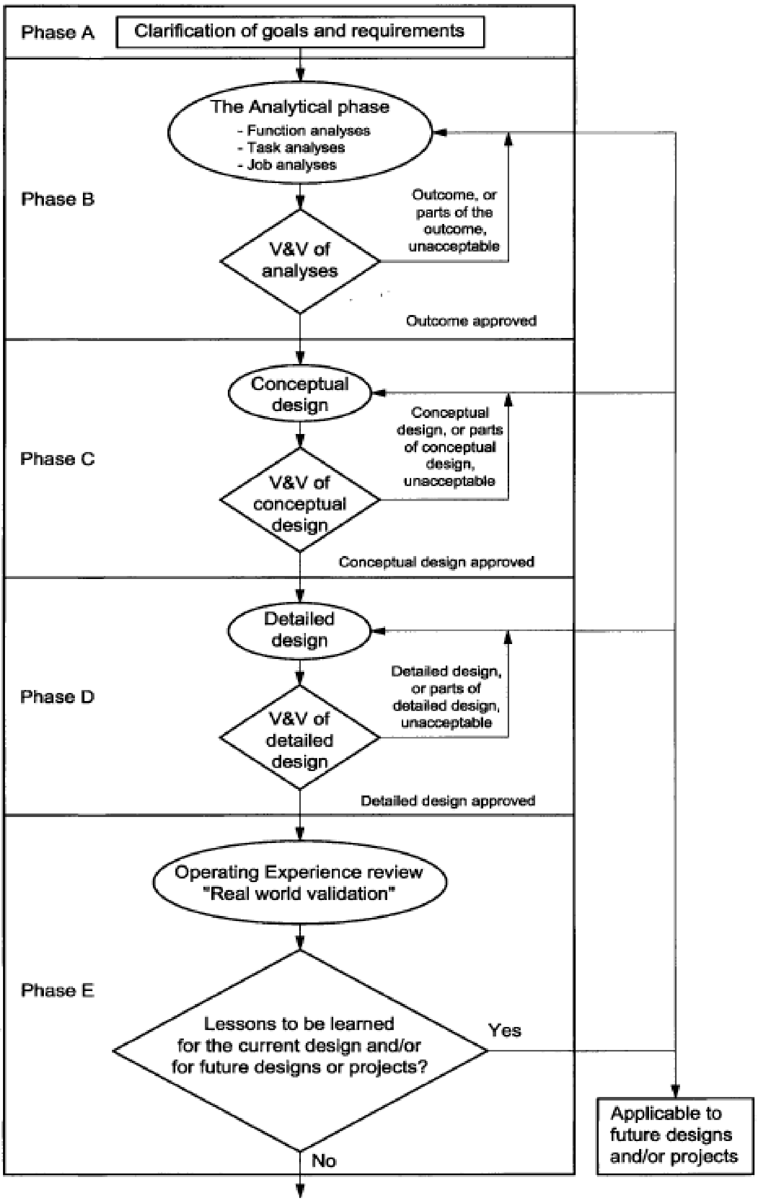

Figure 3.4 ISO 11064-7 Depiction of HFE in the Design Process
(Source: Figure 2 from ISO 11064-7: 2006©)

Like ISO 11064, IEC 60694, *Nuclear Power Plants - Control Rooms – Design,* (IEC, 2009), is a family of standards addressing the HFE aspects of NPP control room design. IEC 60694 distinguishes between functional and detailed design (see Figure 3.5). Functional design includes function allocation (the allocation of functions to personnel or machines), the relationships of personnel and automation, and task responsibilities. Detailed design includes HSIs, e.g., alarms, displays, controls, control room layout, and control room environment. HSIs are validated to ensure they support the operators' functions and tasks.

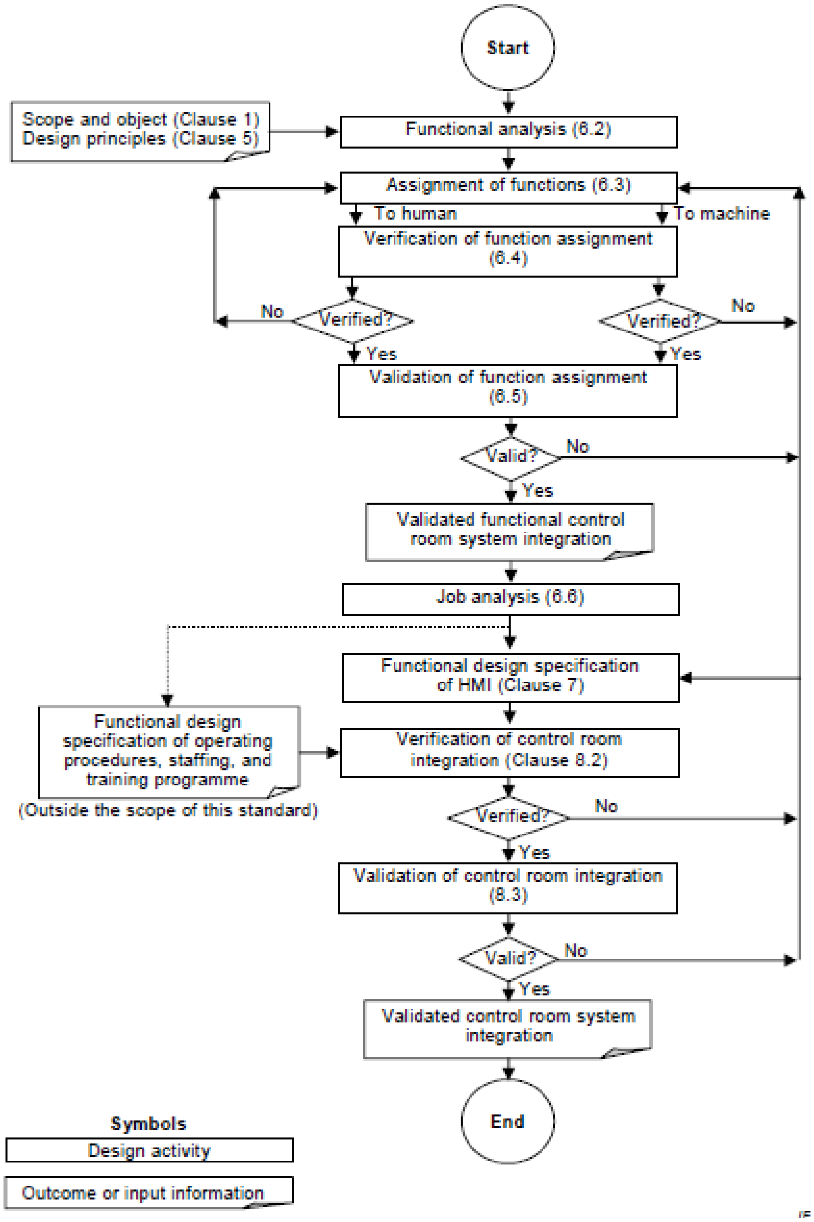

Figure 3.5 IEC 60694 Depiction of HFE in the Design Process
(Source: Figure 2 from IEC 60694: 2009©)

These design standards identify HFE activities that are comparable to NUREG-0711's process assessment model. Different models that are based on a common set of HFE activates strengthens our use of these activities in a new review process.

As stated above, applicants use the HFE S&G documents as general guidance to develop models applicable to their needs. The standards typically lack sufficient detail to provide the "how to" guidance needed by designers. In our experience, applicants develop their own vendor-specific design processes (often proprietary) which detail the methodologies for conducting HFE activities.

For the review of LLWRs, the staff uses the full NUREG-0711 model and evaluates each HFE element using the criteria provided. Applicants can propose alternatives to the criteria but must provide justification for the alternative approach. An assessment is made as to the applicant's compliance with the review criteria for each element.

While the staff's review of LLWRs utilizes a full HFE model, not all SRPs do. Some use a tailored approach by identifying a subset of elements and HSIs to review. Still others identify HSIs to review without referencing the appropriate HFE review criteria to use in the assessment.

The HF process described in NUREG-0711 can impose substantial costs to applicants when implemented in full. Given that some small, advanced reactor designs may pose only low accident consequences, these costs may not be justified.

NUREG-0700 – Human-System Interface Design Review Guideline

NUREG-0700, Rev 3 (O'Hara & Fleger, 2020) is used to review the detailed design of the main control room and other HSIs in the plant. The HSI design review is specified in both NUREG-0800 and NUREG-0711.

The importance of HSIs stems from the fact that personnel use them to perform their functions and tasks. Major HSIs resources include alarms, information displays, controls, and procedures. Use of HSIs can be influenced directly by the following factors and NUREG-0700 has review guidance for them as well:

- the organization of HSIs into workstations (e.g., consoles and panels)
- the arrangement of workstations and supporting equipment into facilities, such as a main control rooms, remote shutdown stations, local control stations, technical support centers, and emergency operations facilities
- the environmental conditions in which the HSIs are used, including temperature, humidity, ventilation, illumination, and noise

The NUREG-0700 evaluation is performed to verify that the HSIs are designed to accommodate human capabilities and limitations as reflected in HFE guidelines. The review criteria address the physical and functional characteristics of the HSIs. The topics addressed in NUREG-0700 are shown in Figure 3.6.

Part I Basic HSI Elements
- 1 Information Display
- 2 User-Interface Interaction and Management
- 3 Analog Display and Control Devices

Part II HSI Systems
- 4 Alarm System
- 5 Safety Parameter Display System
- 6 Group-View Display System
- 7 Soft Control System
- 8 Computer-Based Procedure System
- 9 Automation System
- 10 Communication System

Part III Workstations and Workplaces
- 11 Workstation Design
- 12 Workplace Design

Part IV HSI Support
- 13 Maintainability of Digital Systems
- 14 Degraded HSI and I&C Conditions

Figure 3.6 Organizational Structure of NUREG-0700, Rev 3

Each section has a topic characterization and review guidance. The characterization describes the key functions and characteristics of the HSI being reviewed, e.g., an alarm system. Characterizations are developed by examining existing and emerging systems, as well as the research on the effects of system design characteristics on human performance. As an example, the characterization of an alarm system includes:

- High-Level Alarm Functions
- Information Display, User-System Interaction and Controls
- Reliability, Test, Maintenance, and Failure Indication
- Alarm Response Procedures
- Control-Display Integration and Layout
- Integration with Other HSI Elements

NUREG-1764 - Guidance for the Review of Changes to Human Actions

NUREG-0800 states that “NUREG-1764 (Higgins, O'Hara, et al., 2007) is particularly useful when evaluating changes to manual actions resulting from plant modifications, procedure changes, equipment failures, justifications for continued operations, and identified discrepancies in equipment performance or safety analyses.” Relevant considerations for review are described in NRC information notices and generic issues. Generic Letter 91-18 (NRC, 1991) discusses the conditions under which manual actions may be used in lieu of automatic actions for safety-system operations. Information Notice 97-78 (NRC, 1997) alerts licensees to the importance of considering the effects on human performance of such changes made to plant safety systems.

The review guidance in NUREG-1764 is a risk-informed approach that is consistent with RG 1.174 (NRC, 2002). It uses tailored versions of NUREG-0711 based on risk analysis to determine the extent of HFE review needed. Thus, it provides guidance for use in determining the appropriate level of HFE review of changes to HAs based upon their risk-importance. This guidance is consistent with RG 1.174, Rev.1 (NRC, 2002). The approach addresses licensee submittals that are risk-informed or not. HAs that are considered more risk-significant receive a detailed review, while those deemed less significant receive a less detailed review.

The guidance uses a two-phased approach to reviewing HAs. Phase 1 is a risk screening and analysis of the affected HAs identified by the licensee to determine their risk-importance. Phase 2 is an HFE review of the HAs that are found to be risk important. The next two subsections describe these phases in greater detail.

Phase 1 - Risk Screening Process

RG 1.174, Section 2.3 discusses the risk screening for risk-informed licensee submittals, and Section 2.4 discusses the risk screening for those that are not risk informed. For risk-informed submittals, the staff uses a four-step screening process to locate the plant modification and its associated HAs in risk space. The first two steps are quantitative, the third is qualitative, and the fourth involves an integrated assessment that considers the results of the first three steps and determines the appropriate level of review. Essentially, plant modifications and their associated HAs can be categorized into regions of high, medium, and low risk. Risk screening is described in a bit more detail below.

Before submitting a change request to the NRC, the licensee evaluates a proposed plant change to identify HAs that constitute new or modified actions, or involve modified task demands. The licensee also conducts an evaluation, in accordance with Title 10, Section 50.59, of the *Code of Federal Regulations* (10 CFR 50.59), to identify any changes that affect the plant's final safety analysis report (FSAR). This evaluation may identify activities that require the NRC's review and approval before they are implemented.

For a risk-informed review, the licensee performs an initial risk screening calculation, which is then submitted to the NRC with the licensee's request for approval of the change. The first step in the risk screening evaluates the full modification, including both equipment and HAs and is conducted using RG 1.174. Risk calculations include the change in core damage frequency (CDF) attributable to the full modification (Δ CDF_{mod}). This assessment may determine that the full modification, including the HA, is low risk. If so, the only NRC review may be an evaluation of whether there is a valid technical basis for the determination of low risk.

The risk screening calculations also consider whether the proposed change is permanent or temporary. If temporary, the screening considers the length of time the change will be in place. Then, the method assesses the integrated risk attributable to the change, over the time that it will be in place (i.e., the integrated conditional core damage probability, or ICCDP). Similar calculations are performed for large early release frequency (LERF), where appropriate.
The second step of the risk screening process uses both the Risk Achievement Worth (RAW) and the Fussell-Vesely (FV) risk-importance measures to determine the risk-significance of the HA. This step identifies the effect on risk of failing to perform the HA (using the RAW), as well as the action's relative contribution to risk (using the FV importance).

Uncertainty about HAs is treated by setting their failure probability to 1.0. This second step of the risk screening process tentatively places the HA in one of three risk levels (high, medium, or low) to determine the level of HFE review to be performed by the NRC. The importance of the HA with respect to both CDF and LERF is then assessed.

The third step of the risk screening is qualitative, and allows the NRC to adjust the quantitative evaluation from Step 2, if necessary, considering factors for which the probabilistic risk assessment (PRA) model cannot quantitatively account. This step considers several factors, such as personnel functions and tasks, design support for task performance, and performance shaping factors.

The fourth step is an integrated assessment that considers the results of the first three steps and determines the appropriate level of HFE review.

Phase 2 - Human Factors Engineering Review

In this phase, the NRC reviews the proposed changes to HAs to ensure the appropriate conditions are in place to help ensure that the change in HA does not significantly increase the potential for risk. Again, the details of the review are commensurate with the risk and divided into three levels. The review criteria are based on a tailoring of NRC review guidance, as found in NUREG-0800, NUREG-0711, NUREG-0700, and IN 97-78 (NRC, 1997).

A Level I review is used for HAs in the high-risk category, and requires the most stringent review. A Level I review includes most of the key elements of NUREG-0711.

A Level II review is for HAs in the medium risk category. While the guidance addresses key NUREG-0711 elements, the extent of the staff's review is notably less. The Level II evaluation process addresses general deterministic review criteria, analysis, HSI design, procedures, training, and HA verification. The evaluation processes for this level are less prescriptive and afford greater latitude to both the licensee and the NRC reviewers for collecting and analyzing information.

HAs in the low risk category receive a Level III review, which is generally limited to verifying that the HA is properly classified in Level III. Typically, no detailed HFE review is necessary. However, the NRC review may include a few review elements based on the results of Step 3 of the risk screening process. Licensees may choose to use the Level II guidance to address HFE considerations for HAs that fall into Level III.

Final Decision on Acceptance of Human Actions

The NRC's review of licensee submittals involving changes to HAs is an iterative process. That is, the final results of the HFE review provide input to integrated decision-making (see RG 1.174, Section 2.2.6). The results of the various analyses are considered in an integrated manner, i.e., the decision is not solely driven by the numerical results of the risk assessment. This approach complements the NRC's deterministic approach; supports its traditional defense-in-depth philosophy; considers traditional engineering, HFE, and risk information; and uses both qualitative and quantitative analyses and information. The decision-making process considers the following major factors:

- Change in CDF: The increase in CDF attributable to the modification (Δ CDF_{mod}).
- Change in LERF: The increase in LERF attributable to the modification (Δ $LERF_{mod}$).
- Risk-Importance Measures for the HA: The values of the RAW and FV risk-importance measures.

- Time and Integrated Risk: Risk integrated over the length of time that a temporary change will be in place.

- Human Factors: The basis for concluding that operators can perform the actions required for the modification, as determined by the HFE review criteria that the NRC used for the review.

- Deterministic Criteria: Satisfaction of the deterministic review guidance provided in the Level I or Level II review guidance.

NUREG-0800, Chapter 18 and its supporting guidance documents, such as those described above, form a comprehensive and detailed review model that addresses the key elements of an HFE program and the detailed acceptance criteria for each.

In the discussion of the NRC vision for a new review approach for advanced reactors (see Section 3.3.4), limitations of existing approaches used for LLWRs are discussed.

3.3.2.2 NUREG-0800, Part 2 - Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: Light-Water Small Modular Reactor Edition

NUREG-0800, Part 2 (NRC, 2014a) describes the review process for new light-water SMRs (LSMRs). Non light-water designs are specifically excluded from consideration. Also excluded from consideration is HFE. The SRP notes that programmatic, procedural, organization, or other non-SSC (systems, structures, and components) topics are outside its risk-informed and integrated review framework and are not subject to the safety/risk categorization process. This includes quality assurance, training, HFE, health physics programs, and operating procedures. It is expected that these topics will be evaluated using NUREG-0800, Standard Review Plan, *Light Water Edition* to reach a finding of reasonable assurance. Thus, the HFE review of LSMRs will be based on Chapter 18 of the Light Water Edition described above.

3.3.2.3 NUREG-1537 - Standard Review Plan: Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors

The Office of Nuclear Reactor Regulation developed this SRP (NRC, 1996) and its companion ISGs (NRC 2012a & 2012b) to provide guidance for the conduct of licensing reviews of non-power reactors (NPRs) such as research and test reactors (RTRs), medical isotope production reactors, and reactors to be used for medical therapy. The SRP (NUREG-1537) consists of two parts. Part 1 provides format and content guidance, and Part 2 provides the acceptance criteria.

The SRP does not have a chapter dedicated to HFE. However, Section 7, Instrumentation and Control Systems, contains HFE considerations and addresses traditional control room HSIs such as the design of alarms, displays, and controls. The review of the HSIs is performed by instrumentation and control (I&C) subject matter experts (SMEs).

Section 7.6 specifically addresses the control console HSIs. The SRP states that “The non-power reactor control room, containing the control console and other status display instruments is the hub for reactor facility operation. It is the location to which all information necessary and sufficient for safe and effective operation of the facility is transmitted, and the primary location from which control and safety devices are actuated either manually or automatically."

The introduction to Section 7 states that the I&C system gives the operator information with which to control both the mode of operation and neutron flux (power) level of the reactor. It gives input to the reactor control system (RCS), allowing for changes in reactivity and automatic control of reactor level by insertion or withdrawal of control rods. The SRP assumes a control console and other display instruments will present current and historical parameter and system status information with which the operator can decide on what further action to take, such as whether to take manual control of the reactor.

The objective of the HFE review is to evaluate whether displays and operator control systems are designed and located to promote efficiency in the performance of operations necessary for the safe control of the reactor. The information provided by the applicant should include the following:

- design criteria, bases, and guidelines used to design the control console and information display system

- descriptive information such as logic, functional control and schematic diagrams, and equipment location drawings showing interrelationships in the control console

- analysis of the adequacy of the design to perform the necessary, control and protection actuation, and information management, storage, and display functions coordination with review of other safety analysis reports (SARs) chapters to inputs and displayed parameters apply for the systems involved

- coordination with technical specifications review to verify that appropriate surveillance tests and intervals are specified to ensure that the instruments and equipment will perform their functions as designed

The SRP guides the reviewer to evaluate the control console and HSIs to determine that the following are included:

- signals from instrument systems monitoring the reactor and other system
- process variables
- analytically or digitally processed outputs based on monitored variables
- indication of RCS or reactor protection system (RPS) status
- recording of selected variables and operating data
- annunciators and alarms
- personnel and equipment protection interlock status
- inputs to the RCS or RPS
- analog or computer hardware and software that manages the combination and presentation of reactor and process variable information for the operators

The SRP guides the reviewer to evaluate the arrangement of HSIs and the planned operator station to determine whether the operator can quickly understand information and take proper action. The acceptance criteria should include the following considerations:

- A control console instrument system failure should not prevent the RPS from performing its safety function and should not prevent safe reactor shutdown.

- The designed range of operation of each device should be sufficient for the expected range of variation of monitored variables under conditions of operation.

- When required by the safety analysis, the control console instruments and equipment should be designed to assume a safe state on loss of electrical power or should have a reliable source of emergency power sufficient to sustain operation of specific devices.

- The outputs and display devices showing reactor nuclear status should be readily observable by the operator while positioned at the reactor control and manual protection systems.

- Control, safety, and transient rod position indication and limit lights should be displayed on the console and should be readily accessible and understandable to the reactor operator.

- Other controls and displays of important parameters that the operator should monitor to keep parameters within a limiting value, and those which can affect the reactivity of the core should be readily accessible and understandable to the reactor operator.

- Annunciators or alarms on the control console should clearly show the status of systems such as operating systems, interlocks, experiment installations, pneumatic rabbit insertions, ESF (engineered safety feature) initiation, radiation fields and concentration, and confinement or containment status.

- Reactor operation should be prevented and not authorized without use of a key or combination input at the control console.

The evaluation findings section of the SAR should contain sufficient information to support the following types of conclusions, which will be included in the staff’s safety evaluation report:

- The applicant has shown that all nuclear and process parameters important to safe and effective operation of the (facility being reviewed) non-power reactor will be displayed at the control console.

- The display devices for these parameters are easily understood and readily observable by an operator positioned at the reactor controls.

- The control console design and operator interface are sufficient to promote safe reactor operation.

- The output instruments and the controls in the control console have been designed to provide for checking operability, inserting test signals, performing calibrations, and verifying trip settings. The availability and use of these features will ensure that the console devices and subsystens will operate as designed.

- The annunciator and alarm panels on the control console give assurance of the operability of systems important to adequate and safe reactor operation, even if the console does not include a parameter display

- The locking system on the control console reasonably ensures that the reactor facility will not be operated by unauthorized personnel.

Risk is analyzed by postulating the maximum hypothetical accident (MHA). The MHA should bound all credible potential accidents at the facility. In addition to the MHA, other accident scenarios should be considered, such as loss of coolant or loss of power. No specific method for conducting the accident analysis is identified. Rather the SRP states that “The mathematical models and analytical methods employed, including assumptions, approximations, validation, and uncertainties, were clearly stated.” While operator error is considered in the analysis, it does not drive the HFE review.

It has been suggested that NUREG-1537 may provide an approach that is more in appropriate for the review of small, advanced reactors than the current LLWR regulatory guidance (Belles, Flanagan & Voth, 2018; Kairos, 2019; Owusu, Holbrook, Sabharwall & Bragg-Sitton, 2018; NRC, 2020b). SECY-20-0093 (NRC, 2020e) states that a licensing strategy might be to abandon the LLWR licensing model and approach and treat microreactors like research and test reactors because of their low consequences. The SECY states:

> To classify micro-reactors based on demonstrated consequences with other similar low-consequence facilities as part of a future rulemaking. Whatever the process used to define and demonstrate potential radiological consequences, the NRC would establish dose thresholds and applicants would be required to demonstrate that it is unlikely to exceed the established threshold during the life of the facility, similar to the accident dose criterion of 1 rem total effective dose equivalent (TEDE) proposed for research reactors in the Non-Power Production or Utilization Facility License Renewal proposed rule (82 FR 15643). The NRC would then align the requirements and guidance for micro-reactors, where appropriate, with those used in assessing nonpower reactors or other NRC-licensed uses of special nuclear and byproduct materials with comparable risk profiles.

However, we note several limitations of this NUREG-1537 from an HFE perspective. There is no HFE model guiding the review and only limited, high-level acceptance criteria are provided. The focus is on design products with little focus on design process, although the SRP does state that some such information should be provided (see applicant supplied information above). Yet judging the acceptability of many aspects of the review criteria would require input from HFE process analyses. In addition, the SRP makes no reference to using HFE reviewers to support the evaluation of HFE aspects of the design. It also does not reference available NRC guidance, such as NUREG-0700, to support reviewers in the evaluation of control consoles or HSIs. This SRP, like many others, replaces more detailed HFE review guidance with SME judgement, even when no HFE SME input is identified.

3.3.2.4 NUREG-1702 - Standard Review Plan for Tank Waste Remediation System Privatization

The next three SRPs were all prepared by the Office of Nuclear Materials Safety and Safeguards and are very similar in their approach to HFE safety reviews. They are

- NUREG-1702, addressing Tank Waste Remediation
- NUREG-1718, addressing the Mixed Oxide (MOX) Fuel Fabrication Facility
- NUREG-1520, addressing fuel cycle facilities

Due to their similarities, we will describe NUREG-1702 in more detail than the others.

NUREG-1702 was developed for the review of a license application for the Tank Waste Remediation System Privatization (TWRS-P) Project (NRC, 2000a). SRP Section 11.6, Human Factors Engineering/Personnel Activities provides guidance to establish, with reasonable assurance, that the applicant has applied HFE to HAs identified as *items relied on for safety* (IROFs) in the facilities integrated safety analysis (ISA).

In contrast to PRA, an ISA is a different type of hazard analysis. It is defined in 10 CFR 70.4 as:

> Integrated safety analysis means a systematic analysis to identify facility and external hazards and their potential for initiating accident sequences, the potential accident sequences, their likelihood and consequences, and the items relied on for safety. As used here, integrated means joint consideration of, and protection from, all relevant hazards, including radiological, nuclear criticality, fire, and chemical. However, with respect to compliance with the regulations of this part, the NRC requirement is limited to consideration of the effects of all relevant hazards on radiological safety, prevention of nuclear criticality accidents, or chemical hazards directly associated with NRC licensed radioactive material. An ISA can be performed process by process, but all processes must be integrated, and process interactions considered.

In the context of ISA, IROFS are defined in 10 CFR 70.4 as:

> Items relied on for safety mean structures, systems, equipment, components, and activities of personnel that are relied on to prevent potential accidents at a facility that could exceed the performance requirements in § 70.61 or to mitigate their potential consequences. This does not limit the licensee from identifying additional structures, systems, equipment, components, or activities of personnel (i.e., beyond those in the minimum set necessary for compliance with the performance requirements) as items relied on for safety.

10 CFR 70.61(e) requires a safety program to ensure that each IROFS will be available and will reliably perform its intended function when needed. An HFE review is performed to demonstrate compliance with 10 CFR 70.61(e) and that personnel activities will enhance safety by reducing the challenges to IROFS.

The SRP states that the evaluation should be conducted by an HFE specialist as the primary reviewer. The review of the HFE design should be broad-based and include aspects of normal and emergency operations, testing, maintenance, etc., consistent with findings in the ISA. The SRP states that the applicant's treatment of personnel activities identified as IROFS should be acceptable if the applicant applies HFE practices, guidelines, and criteria to the personnel activities and supporting HSIs. The application of HFE will provide reasonable assurance that the personnel activities will be performed correctly and satisfy their safety functions when needed as required by 10 CFR 70.61(e). This also provides assurance that the possibility of human error in the facility operations is addressed during the design of the facility and that a means for correcting, or compensating for error, is available.

The review process focuses on the applicant's HFE practices and guidelines and can be divided into the following nine areas of review:

- HSI Design Review Planning
- Identification of Personnel Activities
- Operating Experience Review

- Function and Task Analysis
- HSI Design, Inventory and Characterization
- Staffing
- Procedure Development
- Training Program Development
- Human Factors Verification and Validation

The HFE areas are briefly discussed below.

HSI Design Review Planning

The reviewer evaluates whether the applicant has adequately considered the role of HFE and how it is applied during design, construction, and operation of the facility to improve the reliability of personnel activities identified in the ISA. It is expected that the applicant will address the following topics:

- General HFE Functional Goals and Scope
- HFE Team and Organization/Individual and Responsibilities
- HFE Process and Procedures
- HFE Issues Tracking
- HFE Functional Description

Identification of Personnel Activities

The reviewer evaluates whether the applicant has identified personnel activities and their task requirements, which HSIs are involved, and the importance of the action. The personnel activities should include:

- Accident sequences in which human errors are causes

- Operator actions that are credited as safeguards

- HSIs intended to support those personnel activities required to prevent, detect, and correct that could be root-causes or contributing factors to accidents

- HSIs intended to support those personnel activities required to mitigate the consequences of accidents

Operating Experience Review

The reviewer evaluates whether the applicant has identified and analyzed relevant HFE-related problems and issues encountered in previous designs that are like the proposed design under review.

Functional Allocation Analysis and Task Analysis

The reviewer evaluates whether (1) the allocation of functions between personnel and plant system elements takes advantage of human strengths and avoids demands that are not compatible with human capabilities, and (2) the task requirements on plant personnel have reasonable performance demands for accomplishing the allocated functions.

HSI Design

The reviewer evaluates whether the applicant has appropriately translated function and task requirements to the detailed designs of HSI components (such as alarms, displays, controls, and operator aids) through the systematic application of HFE principles and criteria. In addition, the reviewer evaluates whether the applicant has appropriately considered environmental conditions that could influence personnel involved in the activity and factored those considerations into the HSI design.

Staffing

The reviewer evaluates whether the applicant has reviewed the requirements for the number and qualifications of personnel in a systematic manner that includes a thorough understanding of task requirements and applicable regulatory requirements for the range of applicable plant conditions and personnel activities.

Procedure Development

The reviewer evaluates whether procedures for personnel activities identified as IROFS satisfy the acceptance criteria in SRP Section 11.5. The procedures should integrate the personnel activities and the associated HSIs needed to accomplish those activities.

Training Program Development

The reviewer evaluates whether the description of the process for the development of personnel training satisfies the acceptance criteria in SRP Section 11.4. Training requirements should be based on the task analyses and should focus on the relationship between the personnel activities and the associated HSIs needed to accomplish those activities.

Verification and Validation

The reviewer evaluates whether the design conforms to HFE design principles that enable plant personnel to successfully perform personnel activities to achieve plant safety. The scope of V&V should address those personnel activities discussed in *Identification of Personnel Activities* above and HSI design requirements. An acceptable V&V process should consist of a combination of the five activities listed below:

> *HSI task support verification* - an evaluation to ensure that HSI components are provided to address personnel activities identified in the ISA. The HSI task support verification verifies that the aspects of the HSI (e.g., alarms, controls, displays, procedures, and data processing) that are required to accomplish personnel activities are available through the HSI. It should also be verified that the HSI minimizes the inclusion of information, displays, controls, and decorative features that inhibit personnel activities.

HFE design verification - an evaluation to determine whether the design of each HSI component reflects HFE principles, standards, and guidelines. The method and the results of the HFE design verification are acceptable if the HSI has been designed to be appropriate for personnel activities and operational considerations as defined by the HSI design process consistent with accepted HFE guidelines, standards, and principles. Mockup(s), model(s), or other tools can be used by the applicant to perform the HFE design verification.

Integrated system validation - a performance-based evaluation of the integrated design to ensure that the HFE/HSI supports safe operation of the plant. Integrated system validation should be performed after the HFE problems identified in earlier review activities have been resolved or corrected because these may negatively affect performance and, therefore, validation results. All important personnel activities as defined in the task analysis and the ISA should be tested and found to be adequately supported by the design, including the performance of such actions outside the control room.

Human factors issue resolution verification - an evaluation to ensure that the HFE issues identified during the design process have been acceptably addressed and resolved. Issue resolution verification is acceptable if all issues documented in the HFE issue tracking system are satisfactorily addressed. Issues that cannot be resolved until the HSI design is constructed, installed, and tested should be specifically identified and incorporated into the final plant HFE/HSI design verification.

Final plant HFE/HSI design verification - assurance that the implementation of the final design of the HSI and supporting systems (for example, procedures and training programs) conform to the design that resulted from the HFE design process and was verified and validated. Final plant HFE/HSI design verification should be performed if the V&V activities, described above, did not fully evaluate the actual installation of the final HSI design in the plant. Final verification should be acceptable if in-plant implementation of the HFE design conforms to the design description that resulted from the HFE design process and V&V activities. V&V activities should be performed in the order listed above, as necessary. However, iteration of some steps may be necessary to address design corrections and modifications that occur during V&V.

The reviewer screens each area of review to select the areas to include in the review. It is based on (1) provisions made to address personnel activities identified in the ISA, (2) the similarity of the associated HFE issues to those for similar type plants, and (3) the determination of whether items of special or unique safety significance are involved.

NUREG-1702's HFE review model is based on NUREG-0711. In fact, this SRP is a tailored version of NUREG-0711. The tailoring involves two levels. The first aspect of tailoring is that the HFE review model does not include all NUREG-0711 review elements. For example, Design Implementation and Human Performance Monitoring are not included. The second level is that the review criteria for each element are not as comprehensive as is found in NUREG-0711.

Another difference between this SRP and NUREG-0711 is what triggers the HFE review. In this SRP, an HFE review is triggered by the identification of a human action as an IROF. For NUREG-0711, an HFE review is applied to the entire design; while increased emphasis is given to important human actions, the review is not limited to them.

3.3.2.5 NUREG-1718 - Standard Review Plan for a MOX Fuel Fabrication Facility

The Office of Nuclear Materials Safety and Safeguards NRC (2016d) developed this SRP to support the staff's review of an Application for a Mixed Oxide (MOX) Fuel Fabrication Facility (NUREG-1718). HFE is addressed in SRP Section 12, Human Factors Engineering for Personnel Activities.

The primary reviewer responsible for the HFE review is a human factors specialist. The SRP states that the purpose of this review is to establish that HFE is applied to personnel activities identified as safety-significant, consistent with the findings of the ISA, and the determination of whether an IROF has special or unique safety significance.

The application of HFE to personnel activities ensures that the potential for human error in the facility operations is addressed during the design of the facility by facilitating correct decisions and inhibiting wrong decisions by personnel and by providing the means for detecting and correcting or compensating for error. The personnel activities addressed by the HFE program are those identified as IROFS and personnel activities that support safety, such as maintenance. The applicant should provide a description of the safety-significant personnel actions, the associated HSIs, and the consequences of incorrectly performing or omitting actions for each personnel activity.

The areas of review are the same as those described above for NUREG-1702. Again, not all the areas may be necessary for a specific application. Areas of review should be based on a screening process that considers the same factors as those in NUREG-1702.

Similar to NUREG-1702, the evaluation of the HFE aspects of the design is broad-based and includes normal and emergency operations, testing, maintenance, etc., consistent with findings in the safety assessment of the design basis (application for construction approval) or in the ISA Summary (license application for operations).

The same comments made about the tank waste remediation SRP can be applied to the MOX SRP.

3.3.2.6 NUREG-1520, Rev 2 - Standard Review Plan for Fuel Cycle Facilities License Applications

The Office of Nuclear Materials Safety and Safeguards developed NUREG-1520, Rev 2 (NRC, 2015) to provide guidance for the review of applications to construct or modify and operate nuclear fuel cycle facilities. Chapter 3, Appendix E, addresses *Human Factors Engineering for Personnel Activities*. As noted above, NUREG-1520 is basically the same as NUREG-1702 and NUREG-1718 as far as the HFE review guidance is concerned.

The purpose of the HFE review is to establish that HFE is applied to personnel activities identified as safety significant in an ISA and the determination of whether an IROF has special or unique safety significance. The applicant identifies those personnel activities that are considered IROFS and personnel activities that support safety (e.g., maintenance). The HFE review is conducted by human factors and ISA specialists. The SRP states that the application of HFE to personnel activities helps to ensure that the potential for human error is addressed during the design of the facility. The application of HFE will facilitate correct performance, inhibit errors, and provide a means for detecting and correcting error.

The areas of review are the same as in NUREG-1702 and NUREG-1718 and the same comments apply. Screening is also used if not all areas are necessary for a specific application.

3.3.2.7 NUREG-1567 - Standard Review Plan for Spent Fuel Dry Storage Facilities

The NRC's Office of Nuclear Material Safety and Safeguards developed NUREG-1567 (NRC, 2000c) to provide guidance for the review of Spent Fuel Dry Storage Facilities. This includes commercial independent spent fuel storage installations (ISFSIs) that may be co-located with a reactor or may be away from a reactor site. Chapter 3, Operation Systems, includes the HFE aspects of the facilities.

In Section 3.4.5, Control Room and Control Area, the SRP states that 10 CFR 72.122 requires that the applicant's SAR include a discussion of how a control room and control room areas permit the facility to operate safely under normal, off-normal, and accident conditions. The reviewer evaluates the control room and control area functions, equipment, instrumentation and controls, and staffing for consistency and appropriateness for the intended functional control and safety roles. The SRP states that a control room, as well as redundancy for control of functions important to safety in a separate control area, are acceptable for ISFSIs with pool facilities.

Omission of a control room is acceptable for ISFSI operations that do not involve control of operations within a pool or use a powered cooling system for material in storage. The SRP indicates that when an application does not include a control room as part of facility design, the SAR should include an explanation for its omission. The explanation can include:

- a description of functions and procedures that provide for performance without the need for a centralized control room
- the acceptability of accident and off-normal event/condition analyses that show acceptable levels of maximum response and safety without use of a control room
- the use of passive measures to avoid damage and provide mitigation

The SAR does not specify the technical expertise of the reviewer. There is no HFE model or review criteria to support the reviewer in assessing the acceptability of the control room, or control area, to support the role of personnel. It also does not provide guidance for determining if the methods of assessing whether the HFE aspects of the design are appropriate.

3.3.2.8 NUREG-2215 - Standard Review Plan for Spent Fuel Dry Storage Facilities

The Office of Nuclear Materials Safety and Safeguards developed this SRP for the review of Spent Fuel Dry Storage Systems and Facilities (NUREG-2215). NUREG-2215 (NRC, 2020c) states that applicant submittals should include clear descriptions of the control room and control area and should include a discussion of how they achieve safe operations under normal, off-normal, and accident conditions. The control room should be designed to permit occupancy and actions to be taken to monitor the safety of the facility under these conditions. The SRP states that the applicant should make provisions for isolation of the control room upon smoke detection at the air intakes.

In addition, reviewers should verify that the accident analysis and design criteria confirm that:

- The control room or control area ventilation system piping and instrumentation drawings show monitors located in the system intakes that can detect radiation, smoke, and toxic chemicals.
- The monitors actuate alarms in the control room or other suitable locations.

Like NUREG-1567, the SRP indicates that the facility design may not include a control room for ISFSI operations that do not involve use of a powered cooling system for materials in storage. The SRP indicates that the applicant should provide an explanation for omission of a control (and/or monitoring) room/area. The SRP lists the same justifications as NUREG-1567 described above.

The SAR does not specify that HFE aspects of the design should be reviewed by reviewers with HFE expertise. There is no HFE model or detailed review criteria guiding the review. The SRP identifies high-level considerations, such as whether there is a control room or not, and the availability of specific HSIs. Little consideration for what constitutes an acceptable application of HFE is provided nor are supporting HFE review guidance documents, such as NUREG-0700, referenced,

3.3.2.9 NUREG-2126 - Standard Review Plan for Conventional Uranium Mill and Heap Leach Facilities

The Office of Nuclear Materials Safety and Safeguards developed NUREG-2126 (NRC, 2014b) to provide guidance to the staff performing safety reviews of applications to develop and operate conventional uranium mills or heap leach facilities.

The only HFE consideration identified in the SRP is that the reviewer should evaluate how the applicant prevents off-normal conditions due to human error. However, no guidance is provided to make such a determination.

There is no HFE model or review criteria to support the reviewer assessing if human error was considered or where and when in the analysis it should be. It also doesn’t provide guidance for determining if the methods of assessing human error in off-normal conditions are appropriate.

3.3.2.10 NUREG-1536, Rev 1 - Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility

The Office of Nuclear Materials Safety and Safeguards developed NUREG-1536, Rev 1 (NRC, 2010a) to provide guidance for reviewing applications for Certificates of Compliance for dry storage systems used at general license facilities.

Regarding HFE considerations, the SRP indicates that an applicant’s SAR should address off-normal conditions. These conditions should include variations in temperatures beyond normal, failure of 10 percent of the fuel rods combined with off-normal temperatures, failure of one of the confinement boundaries, partial blockage of air vents, *human error*, and out-of-tolerance equipment. However, no guidance is provided to assess human error.

The approach to HFE in this SRP is the same as NUREG-2126. There is no HFE model or review criteria to support the reviewer in assessing if and how human error was considered. It also doesn't provide guidance for determining if the methods of assessing human error in off-normal conditions are appropriate.

3.3.2.11 NUREG-1200, Revision 3 - Standard Review Plan for a Low-Level Radioactive Waste Disposal Facility

The Office of Nuclear Materials Safety and Safeguards developed this SRP for the review of license applications for Low-Level Radioactive Waste Disposal Facilities (NUREG-1200, Revision 3) (NRC, 1994a). The primary responsibility for the review is the Low-Level Waste and Projects Branch (LLWPB) staff with no secondary or supporting responsibilities.

Subsection 4.3.4, Area Radiation and Airborne Radioactivity Monitoring Systems, states that the acceptability of the airborne radioactivity-monitoring system is based on the following criteria (there are additional non-HFE criteria):

- Each monitor has an audible alarm and variable alarm set points.
- Monitors in high-noise areas should also have visual alarms.
- The applicant provides displays and annunciators in a centrally staffed location.

Subsection 4.2, Regulatory Guidance, identifies industry standards and contains a reference to *Criticality Accident Alarm Systems* (ANSI NI6.2-1969). The American National Standards Institute (ANSI) standard addresses the prevention of criticality accidents while handling, storing, processing, and transporting fissionable materials for consideration in facility design features. The standard has been updated as ANSI/ANS-8.3-1997 (ANS,1997), reaffirmed in 2017, and endorsed with some exemptions in RG 3.71, Rev 3, *Nuclear Criticality Safety Standards for Nuclear Materials Outside Reactor Cores* (NRC, 2018b). However, this standard has limited HFE guidance.

In Section 8.3, Training Program, one additional HFE topic is specified - task analysis. Subsection 2, Areas of Review, Criterion (3) states that the applicant's plans should include conducting a position task analysis for all operating personnel, in which the tasks performed by the person in each position are defined and the training, in conjunction with education and experience, is identified to provide assurance that the tasks can be effectively performed. The primary responsibility for this aspect of the review is a health physicist, with no secondary expertise identified. One supporting responsibility identified is an Operations Specialist.

This SRP addresses a very limited consideration of HFE. HFE review expertise is not identified as a review responsibility. The only HFE process addressed is task analysis; however, no guidance is provided to judge the completeness and technical acceptability of the task analysis is provided.

The only HFE product consideration is radiation monitoring HSIs. However, the criteria have limitations:

- No criteria are provided for determining if the displays and annunciators are the correct ones

- The SRP only identifies that the HSI be present, but no criteria are identified for evaluating the acceptability of the design of these HSI resources.

- The SRP does reference a supporting standard for criticality alarm design; however, it contains limited HFE guidance.

3.4.2.12 Summary

We reviewed 11 SRPs used to conduct safety reviews of a wide range of nuclear facilities. The degree to which the HFE aspects are identified and addressed differ widely across the SRPs. There are several factors that differentiate them. These factors are described below:

- What triggers the HFE review?
- What is the scope of the review?
- What is the technical basis of the review?
- Who conducts the HFE review?

What Triggers the HFE Review

This factor addresses the aspect of the facility design or operation that initiates the need for an HFE review. An HFE review has been an integral part of the safety evaluations of LLWRs because (1) NRC regulations require a control room reflecting state-of-the-art HFE principles, and (2) there are a large number of human functions that govern normal operations, and which ensure off-normal operations happen as planned. This is not the case for other types of facilities. Many SRPs use the results of risk analyses to trigger HFE reviews. Analyses such as PRA and ISA identify important HAs and the HFE review is conducted to ensure the actions will be appropriately performed. Some of these approaches are limited in that an integrated view of human actions does not emerge. Instead, each human action is assessed in isolation of the other human actions.

In other SRPs, the review is triggered by the presence of control rooms and specific HSIs.

What is the Scope of the Review

This factor describes the scope of the review, i.e., HFE process, products, or both. Some of the SRPs identified both the applicant’s HFE processes, such as the use of task analysis, and the products of the process, such as the HSIs used by operators to perform their tasks. Other SRPs bypass process considerations and focus only on the products themselves, such as the availability of a control room and the design of alarms and displays.

In some SRPs, a screening process is used to determine which aspects of the HFE program to include in the review. Such screening processes may be useful in the consideration of advanced small reactors.

An additional consideration is whether the facility design includes a control room. Two of the SRPs acknowledge that a control room may not be necessary in some facilities. In such cases, applicants are expected provide a justification for omitting a control room.

What is the Technical Basis of the Review

In the discussion of NUREG-0800 and NUREG-0711, we noted that HFE process review standards and guides consist of a model of the process that is divided into key elements and indicators of the best practices for each element that are used as review criteria to assess an applicant's process. Reference to supporting acceptance criteria is important. While NUREG-0800 utilizes a full HFE model/acceptance criteria approach, not all SRPs do. Some use a tailored approach by identifying a subset of elements and HSIs to review. Still others identify HSIs to review without referencing the HFE review criteria to use in the assessment. Without reference to an HFE review model, elements, and review criteria, the technical basis for the HFE review is lacking.

Who Conducts the HFE Review

The SRPs identify a range of SMEs for reviewing the HFE aspects of the safety reviews. Some identify HFE SME while many others do not.

For more complex reviews, an HFE SME is preferred for assessing the acceptance criteria and for evaluating safety concerns that are not well addressed by existing detailed guidelines. When faced with such a situation, knowing the questions to ask, how to evaluate their importance, and arriving at a safety determination requires an HFE expert. The fewer HFE review criteria that are available, the more HFE expertise is needed. However, these SRPs, such as NUREG-1537, contain many HFE aspects to include in the review, but detailed review criteria are not provided and an HFE reviewer is not identified. The SRP replaces more detailed HFE review guidance with engineering judgement, even when no HFE SME input is identified.

HFE reviews typically require more than one area of expertise. For instance, for identifying the important HAs, HFE reviewers are supported by risk analysis SMEs to evaluate the PRA, ISA, or other type of analysis. I&C expertise is also needed for many aspects of HFE reviews.

Table 3.2 provides a summary of these factors for the SRPs described.

Table 3.2 Summary of the HFE Review in SRPs

SRP	Facility Type	Trigger	Scope	Tech Basis	Reviewer
0800	LLWR	NRC requirements - extensive crew involvement in operations	process and product	NUREG-0711 12 element model and acceptance criteria	HFE
0800P2	LSMR	NRC requirements - extensive crew involvement in operations	process and product	12 element model and acceptance criteria	HFE
1537	non-power reactors	NRC requirements - presence of HSIs associated with RCS and RPS systems	products and limited process without explicit criteria	no specific model and limited explicit acceptance criteria	I&C

1702	tank waste remediation systems	Risk criteria - HAs classified as IROS in an ISA and supporting HA, such as maintenance	processes and products	tailored version of NUREG-0711 12 element model and acceptance criteria	HFE
1718	MOX fuel fabrication facility	Risk criteria - HAs classified as IROS in an ISA and supporting HA, such as maintenance	processes and products	tailored version of NUREG-0711's 12 element model and acceptance criteria	HFE
1520	nuclear fuel cycle facilities	Risk criteria - HAs classified as IROS in an ISA and supporting HA, such as maintenance	processes and products	tailored version of NUREG-0711 12 element model and acceptance criteria	HFE
1567	spent fuel dry storage facilities	presence of HSIs	products	very high-level criteria for some aspects of the design, such as presence or absence of a control room	NRC Staff Reviewer
1536	spent fuel dry storage systems	no HFE review; only check that human error does not cause off-normal conditions	none	none	None
2215	spent fuel dry storage facilities	presence of HSIs	products	very high-level criteria for some aspects of the design, but not all such as alarms	NRC Staff Reviewer
2126	conventional uranium mills and heap leach facilities	no HFE review; only check that human error does not cause off-normal conditions	none	none	None
1200	low-level radioactive waste disposal facilities	presence of HSIs	limited process and products	no specific model and limited explicit acceptance criteria	LLWPB staff, a health Physicist, an Operations Specialist

Two additional considerations were addressed in some SRPs that are relevant to the review of small, advanced reactors: use of a screening process and omission of a control room from facility design.

Use of a Screening Process

Three SRPs acknowledged that not all HFE considerations presented in the SRP may be necessary for a facility review. The reviewer screens each area to select those to include. The decision is based on (1) provisions made to address personnel activities identified in the ISA, (2) the similarity of the associated HFE issues to those for similar type plants, and (3) the determination of whether items of special or unique safety significance are involved.

Omission of a Control Room from Facility Design

When a facility is proposed without a control room the applicant is expected to provide a justification. Appropriate justifications identified in the SRPs include:

- a description of functions and procedures that provide for performance without the need for a centralized control room

- the acceptability of accident and off-normal event/condition analyses that show acceptable levels of maximum response and safety without use of a control room

- the use of passive measures to avoid damage and provide mitigation

3.3.3 Suitability of the NRC Guidance for Addressing Advanced Reactor HFE Technical Issues

An objective of the current research was to determine the suitability of the existing guidance for reviewing the HFE technical issues identified in Section 2.3.3 above. Where the guidance does not adequately address the issues, we sought to identify the needed guidance modifications or new guidance. Our evaluation of the suitability of existing guidance is presented in Appendix C. Appendix C provides a detailed description of each issue along with the guidance suitability assessment.

3.3.4 NRC General Expectations for Advanced Reactor Reviews

NEIMA provides expectations for how the NRC should review advanced nuclear reactors. The law seeks to improve the licensing process for advanced reactors. Section 103, Advanced Nuclear Reactor Program, states:

> For commercial advanced nuclear reactors, the NRC must (1) establish stages within the licensing process; (2) increase the use of risk-informed, performance-based licensing evaluation techniques and guidance; and (3) establish by the end of 2027 a technology-inclusive regulatory framework that encourages greater technological innovation.

The NRC has used this general guidance to develop a more detailed vision of an advanced reactor review process (NRC, 2016b) and the plans (NRC, 2016c) to realize that vision.
The current application and licensing requirements, developed for LLWRs and non-power reactors as outlined in 10 CFR Part 50 and 10 CFR Part 52, do not fully consider the diversity of designs and safety characteristics of advanced reactors (NRC, 2020b). In addition, the NRC has identified policy and technical issues that need to be resolved to support review process development.

The NRC envisions a review process that effectively and efficiently addresses safety, without imposing unnecessary regulatory burden. The process should create a “flexible regulatory framework, allowing potential applicants to select a best-fit path towards regulatory reviews and decisions.” Further definition of the review process is provided by SECY-20-0032 (NRC, 2020b):

- continue to provide reasonable assurance of adequate protection of public health and safety and the common defense and security

- promote regulatory stability, predictability, and clarity

- reduce requests for exemptions from the current requirements in 10 CFR Part 50 and 10 CFR Part 52

- establish new requirements to address non-light-water reactor technologies

- recognize technological advancements in reactor design

- credit the response of advanced nuclear reactors to postulated accidents, including slower transient response times and relatively small and slow release of fission products

The NRC recognizes that while current guidance can be used, it may not be efficient when applied to advanced reactors (NRC, 2016b):

> The NRC is fully capable of reviewing and reaching a safety, security, or environmental finding on a non-LWR design if an application were to be submitted today. However, the agency has also acknowledged the potential inefficiencies for non-LWR applications submitted under 10 CFR Part 50 or Part 52 that are reviewed against existing LWR criteria, using LWR-based processes, and licensed through the use of regulatory exemptions and imposition of new requirements where design-specific review, analysis, and additional engineering judgement may be required.

Consistent with the NEIMA requirements, the NRC is developing Part 53 of the Code of Federal Regulations (NRC, 2020d). This rulemaking would create 10 CFR Part 53, “Licensing and Regulation of Advanced Nuclear Reactors,” in keeping with the NRC vision and strategy report and the statutory provisions in NEIMA Section 103(a)(4).

As discussed above, several characteristics of a review process for advanced nuclear reactors were identified in NEIMA. The characteristics included the identification of stages in the review process; increase in the use of risk-informed, performance-based licensing evaluation techniques and guidance; and a technology-inclusive regulatory framework that encourages greater technological innovation. Additional characteristics are identified in NRC guidance documents.

We have summarized the new review strategy in terms of the following characteristics:

- technology inclusive
- risk informed
- performance based
- staged
- based on process and methods rather than prescriptive guidance
- within the bounds of existing regulations

- flexible
- scalable
- supportive of preapplication interactions that occur early and often

Technology Inclusive

The NEIMA defined technology inclusive as ‘‘a regulatory framework developed using methods of evaluation that are flexible and practicable for application to a variety of reactor technologies, including, where appropriate, the use of risk-informed and performance-based techniques and other tools and methods.” Thus, the review process should be applicable to all designs and not focused on specific technological approaches.

Risk Informed

NEIMA characterized a review process that is risk informed. A risk informed process enables both the applicant and NRC staff to focus their attention on those aspects of the design that greatly impact facility risk. It also provides a basis to scale a regulatory review process that is more streamlined than the broad process used for LLWRs.

For HFE considerations, a risk-informed process is needed to (1) assess the potential contribution of human performance to risk, and (2) assess, commensurate with that risk, whether the facility design or design process adequately addresses the risk.

Recognizing that the scope, depth, and quality of applicant PRAs may vary, alternative means of gaining and applying risk-related design insights are needed as well.

Performance Based

The NEIMA characterized a review process that is performance based. HFE reviews have typically relied on two types of performance-based activities: analytical evaluations and data-based evaluations. Analytical evaluations include analyses that provide estimates of human performance using tools such as human reliability analysis (HRA), task analysis, and workload analysis. An example is, SRP Chapter 18, Attachment B – provides a “Methodology to Assess the Workload of Challenging Operational Conditions in Support of Minimum Staffing Level Reviews” NRC (2016f)*)*. It is an analytical approach to human performance evaluation before more data-based methods can be used.

Data-based methods are used to measure actual human performance. These methods can be used early in the design process to support design decisions, e.g., which of two alarm system designs leads to more rapid event detection. Data-based evaluations can later be performed to support validation tests and other types of evaluations. Data-based methods may use walk-throughs, prototype evaluation, and simulators to provide an environment that approximates what operators and other personnel may encounter.

Staged

The NEIMA stated that the NRC must establish stages within the licensing process. In *A Regulatory Review Roadmap for Non-Light Water Reactors* (NRC, 2017), the NRC described a flexible non-LWR regulatory review process, including interactions during stages such as the construction permit, operating license, standard design approval, design certification, and combined license. Stages may also be defined to correspond to the applicant's design process, such as conceptual design phase, preliminary design reviews, and verification and validation. Stages designed with respect to an applicant's design process enable reviews at various levels of completion or maturity.

Based on Process and Methods Rather Than Prescriptive Guidance

The review process that has been used for LLWRs is largely prescriptive since its application is based on designs that had many design features in common across facilities. This will not be the case for advanced reactors. Advanced reactors will be highly diverse and based on varying nuclear system designs, widely varying support system designs, and diverse applications. Hence, a prescriptive approach is not practical. Instead, the review guidance should be based on a process approach and not a defined set of prescriptive guidelines. In SECY 20-0010, the NRC stated that it intends to develop 10 CFR Part 53 with as few connections as possible to prescriptive or programmatic criteria specified in 10 CFR Part 50 and 10 CFR Part 52 (NRC, 2020b).

Within the Bounds of Existing Regulations

Achieving a new review process, while maintaining the capability to review applications in the near term, will require the development of guidance for a "flexible non-LWR regulatory review process *within the bounds of existing regulations"* (NRC, 2016b). Until a new process is available, and changes are made to the existing regulations, the NRC will handle the discrepancies between regulatory requirements and plant design and operations with exemption requests. As SECY 20-0093 (NRC, 2020) states:

> In the near term, the staff plans to license micro-reactors under the existing regulations for power reactor licenses in 10 CFR Part 50 and 10 CFR Part 52. Because of the significant differences between large LWRs and micro-reactors, the staff is receptive to requests for exemptions from the existing regulations in the areas above and would evaluate such exemptions on a case-by-case basis using existing agency processes.

While the guidance needs to support near-term reviews, it also needs to support the transition to a new process that meets the NRC's long-term vision. Two of the main considerations for the near-term reviews are whether the current guidance can support (1) reviews of the new characteristics of advanced reactors (see a list of characteristics in Section 1.1 above), (2) exemption requests, and (3) HFE-related technical issues associated with advanced reactors.

Based on our evaluation of available guidance, we concluded that the guidance is only partly sufficient to review advanced reactors (O'Hara, 2021). While guidance is available to support NRC staff reviews of many characteristics of these reactors, there remain issues defining important characteristics that need to be addressed by research. In addition, new issues and needs will also be identified based on applicant submittals. It should be noted that where guidance is somewhat lacking, the staff can perform reviews using engineering judgement, but the process would not have the predictability desired.

As these research needs are met, additional review processes and guidance can be developed and integrated into the overall review process. In this way, near-term review approaches can evolve into the type of advanced reactor review process envisioned by the NRC for long-term review needs.

Flexible

The NRC's vision is to create a "flexible regulatory framework, allowing potential applicants to select a best-fit path towards regulatory reviews and decisions" (NRC, 2020b). A new review process needs to be flexible to address the wide range of technologies and operational practices that characterize advanced reactors.

Scalable

The HFE review strategy needs to be *scalable*. A scalable process is one that can be designed to be a full HFE review, like HFE reviews of LLWRs; or minimal when there are few human actions, or anything in between.

Supportive of Preapplication Interactions That Occur Early and Often

Given the diverse characteristics of advanced reactors, the NRC will encourage applicants to begin interacting with the staff early in the application process (NRC, 2017). This is consistent with a staged approach and will support a timelier understanding of the applicant's design and ConOps.

A new HFE review process should conform to these characteristics. In addition, new review guidance needs to be consistent with the NRC's overall infrastructure guiding the assurance of public safety. This infrastructure consists of:

- HFE requirements defined in the Code of Federal Regulations (CFR)

- The guidance contained in the NRC's standard review plans (SRPs) which define the methods the staff has found acceptable for meeting the regulatory requirements

- The NRC's general vision for advanced reactor licensing

To achieve a new review process, while maintaining the capability to review applications in the near term, will require the development of guidance for a "flexible non-LWR regulatory review process *within the bounds of existing regulations"* (NRC, 2016b).

Until a new process is available, and changes are made to the existing regulations, the NRC will handle the mismatches between regulatory requirements and plant design and operations with exemption requests. From an HFE perspective, the infrastructure of HFE review guidance needs to support near-term review needs and the transition to a new process that meets the NRC's long-term vision.

The current HFE review infrastructure includes HFE regulatory requirements and an extensive set of documents including SRPs, ISGs, and supporting guidance documents. Most of these documents are based on LLWRs and a need to consider alternative approaches exists. For example, SECY-20-0093 (NRC, 2020e) states that a licensing strategy might be to abandon the

LLWR licensing model and treat microreactors like research and test reactors because of their low consequences. The SECY does state that such an approach would need to be evaluated due to the different operational characteristics of small, advanced reactors.

Following the NRC's vision for near-term application reviews, the staff "plans to license micro-reactors under the existing regulations for power reactor licenses." Thus, the existing review guidance will be used to guide the overall review. One of the main considerations for the near-term reviews is whether the current guidance can support exemption request reviews.

Many of the HFE research needs pertaining to small, advanced reactors have been identified in multiple documents, including the NRC's User Needs (Brown, 2019), five-year plan (NRR, 2019d) and technical reports on numerous topics that identify detailed HFE issues and research needs. Most of the needs identified pertain to near-term HFE reviews. The development of guidance to resolve these issues may require the development of additional technical basis using the NRC's HFE guidance development methodology.

In addition to research needs identified above, new needs will also be identified based on applicant submittals, i.e., applications that provide information on the applicant's "HFE program," if any, supporting the design, and the exemption requests being sought.

As each of these research needs are met, additional review processes and guidance can be developed and integrated into the overall review process. In this way, near-term review approaches can evolve into the type of small, advanced reactor review process envisioned by the NRC.

Given the anticipated diversity of small, advanced reactor design and ConOps, two additional considerations need to be addressed as guidance is developed: screening and grading the HFE review guidance.

Both in the near- and far-terms, a screening process will be needed to select the aspects of HFE to be included in a specific review. By screening, we mean a process to select the appropriate HFE review elements to include in the review and to identify those that may be disregarded. Three SRPs included a screening process. The reviewer screens each HFE element, or topical area, based on (1) provisions made to address personnel activities identified in the ISA, (2) the similarity of the associated HFE issues to those for similar type plants, and (3) the determination of whether items of special or unique safety significance are involved. The screening process is likely to be design-specific in that the selection of review elements will be based on the design and operational characteristics of the reactor to be reviewed. We expect the screening process will consist of criteria that support inclusion vs. exclusion decisions.

Once the screening process is applied and appropriate HFE review elements are identified, a grading or tailoring process is needed to evaluate each element to identify which aspects and review criteria are appropriate to the reactor being reviewed and which are not.

3.4 Summary

Identify Current HFE Guidance Documents

One of our objectives was to identify, compile, and review the NRCs current HFE guidance documents to determine how the HFE aspects of the designs are identified and addressed.

We reviewed 11 SRPs used to conduct safety reviews of a wide range of nuclear facilities. The degree to which the HFE aspects are identified and addressed differ widely across the SRPs. There are several factors that differentiate them:

- What triggers the HFE review?
- What is the scope of the review?
- What is the technical basis of the review?
- Who conducts the HFE review?

Table 4.2, Summary of the HFE Review in SRPs, summarizes these factors for the SRPs reviewed. Not surprisingly, the treatment of HFE varies greatly across SRPs, somewhat driven by the extent of HAs involved in operations. The factor of "What triggers the HFE review" provides insight into the extent of HFE review. Some SRPs use risk insights to drive the HFE review, while others simply rely on the presence of HSIs to review. The former typically involves more extensive HFE reviews involving process and product, while the latter is limited to an HSI review.

Two additional considerations that are relevant to the review of small, advanced reactors were addressed: use of a screening/tailoring processes and omission of a control room from facility design:

- Use of a Screening/Tailoring Processes – The NRC has recognized that not all HFE elements addressed in an SRP may be needed for a particular facility review. The SRPs included a screening/tailoring processes that a reviewer could use to determine those areas of HFE to include in the review.

- Omission of a Control Room from Facility Design – Applicants have submitted facility designs that do not include a control room. The NRC has found such an approach acceptable so long a justification is provided. The NRC provided examples of justifications that might be used. We noted some limitations to these considerations to be addressed as additional guidance is developed.

Collectively, these documents provide guidance for reviewing small, advanced reactors, including their current design and operations, as well as exemption requests. However, there will likely be gaps in the guidance, i.e., important topics for which no guidance is available. Until new guidance is developed that resolves the HFE technical issues identified, reviewers will need to adapt existing guidance to the needs of the reactor design under review. In part, those can be addressed by applying general HFE principles (O'Hara & Higgins, 2004).

Determine the Suitability of the Existing Guidance for Reviewing Small Advanced Reactors

Another objective of this phase of the project was to determine the suitability of the existing guidance for reviewing small, advanced reactors, specifically:

- Do the existing regulations and guidance suitably address HFE technical issues for small, advanced reactors?

- What modifications of the regulations and guidance might be needed?

- Will new guidance be needed to support small, advanced reactor licensing reviews?

The assessment of HFE technical issues associated with small, advanced reactors in Appendix C suggests that the issues are partly addressed but there remain aspects of each that require further consideration. The same conclusion can be made for the HFE issues identified for small modular reactors and discussed in Appendix D. For each of these issues our assessment identified the research that needs to be performed to develop a technical basis to support HFE guidance development.

As noted above, many of these issues are already identified as NRC's HFE research needs and pertain to small, advanced reactors (Brown, 2019; NRR, 2019). Some of this needed research is already underway. Projects that the staff proposes to authorize and initiate during the current five-year planning horizon include:
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Projects that Maintain NUREG-0711

- Project 17: Update and Consolidate Guidance for the Assessment of Facility Minimum Staffing Levels
- Project 18: Validation of Control Room Designs and Modifications
- Project 14: NUREG-0711, Rev. 4
- Project 19: Integration of Instrumentation and Control (I&C) Systems to Enhance Operator Performance

Projects that Maintain NUREG-0700

- Project 4: Managing Alarm Overload
- Project 6: Group-View Display Functionality
- Project 7: Computer-Based Procedures
- Project 1: Develop NUREG-0700 Rev. 4

Projects that are currently projected for possible implementation beyond the current 5-year planning horizon include:

- Project 9: Function Allocation
- Project 8: HSI Design for Multi-unit Monitoring and Control
- Project 11: Effect of Differing Unit Operational States on Crew Performance
- Project 12: Effect of Unit Differences on Crew Performance
- Project 13: Design of Emergency Operating Procedures (EOPs) for Multi-unit Disturbances

The results from these research projects will provide the needed technical basis upon which review guidance for small, advanced reactors can be developed.

NRC Vision for an Advanced Reactor Review Strategy

We reviewed NRC documents that discuss a new vision for reviewing advanced reactors. In addition, we examined the requirements set forth by NEIMA. We summarized the new review strategy in terms of the following characteristics:

- technology inclusive
- risk informed

- performance based
- staged
- based on process and methods rather than prescriptive guidance
- within the bounds of existing regulations
- flexible
- scalable
- supportive of preapplication interactions that occur early and often

A challenge in developing a review strategy for small, advanced reactors is determining the role of an HFE program in the development of the HFE aspects of a plant. In some of the SRPs we reviewed HFE products such as HSIs are reviewed without considering the HFE analyses they are based on. It is tempting to view HFE analyses as unnecessary for very simple HSIs or when a facility has no control room; however, an HFE review is typically based on a process review model that is divided into key elements and acceptance criteria. The implications of eliminating a process model needs to be considered.

Determining the role of HFE expertise is another challenge. LLWR reviews are conducted by HFE SMEs, with support from other NRC SMEs such as risk and I&C experts. However, some of the SRPs examined did not include HFE as a needed expertise for reviewing the HFE aspects of the facility. We noted above the limitations of such an approach. In fact, we think such expertise is especially needed when the review guidance in an SRP is limited.

Resolving challenges such as these, and those posed by HFE technical issues, will support the development of a new approach to reviewing small, advanced reactors.

4 DEVELOPMENT OF AN HFE REVIEW STRATEGY

4.1 Objective

The purpose of this task was to develop a technical strategy for the review of the HFE aspects of small, advanced reactors. The strategy has to accommodate a broad diversity of reactor designs and operational characteristics, as well as the HFE activities applicants will employ.

4.2 Method

The new review strategy is based on the inputs that are shown in Figure 4.1.

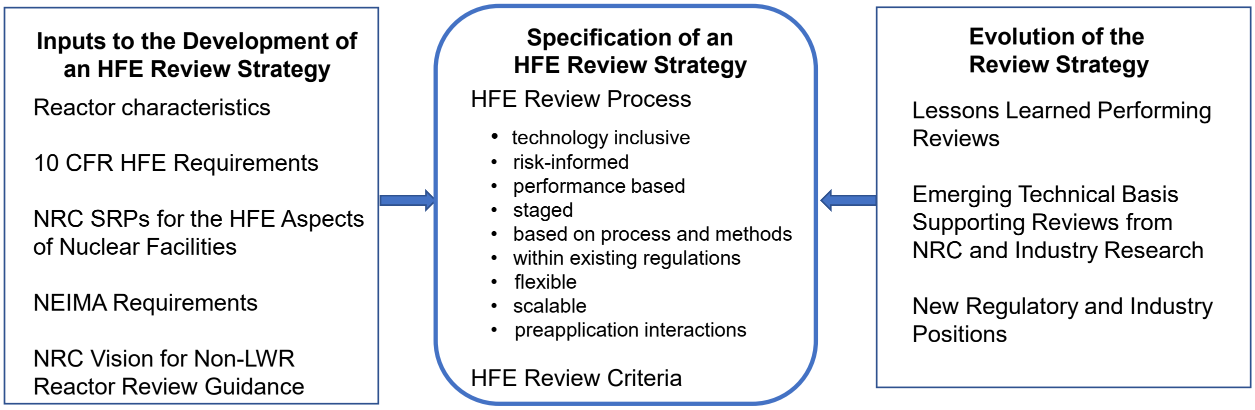

Figure 4.1 HFE Review Strategy Development

The HFE review strategy is informed by the following:

- Reactor characteristics
- HFE requirements defined in the *Code of Federal Regulations* (CFR)
- The guidance contained in SRPs
- The requirements set forth by NEMIA
- The NRC's general vision for advanced reactor licensing

A review strategy consists of a process and review criteria (acceptance criteria). To develop a new HFE review strategy for advanced reactors, the review process and the acceptance criteria were decoupled to allow the strategy to be adapted to the diversity of design and operational characteristics. The review process can be applied to any reactor (and non-reactor facilities) and used to identify review criteria which can vary based on the needs of the specific design under review.

The strategy must comply with the overall characteristics of the new review strategy listed in Section 3.3.4. The strategy can also evolve as experience and new information becomes available. The process is fixed, but the review criteria are not and can evolve as new information becomes available.

4.3 Results

This section describes the new HFE review strategy. It begins with an overview of the entire process, then presents each aspect of the process in detail. The section is intended to provide a basis for the development of interim staff guidance for advanced reactor HFE reviews. Some of the material in the previous sections of this report is repeated here where needed as part of the review process.

4.3.1 General Approach

The HFE review is initiated when an applicant makes a submittal. The expected contents of the submittal are discussed in Section 4.3.5.

The HFE review consists of a series of steps culminating in the development of a facility specific review plan and HFE review using the plan (see Figure 4.2). The steps are:

- Review Applicant Submittals
- Conduct Targeting Process
- Conduct Screening Process
- Conduct Grading Process
- Assemble Review Plan and Conduct Review

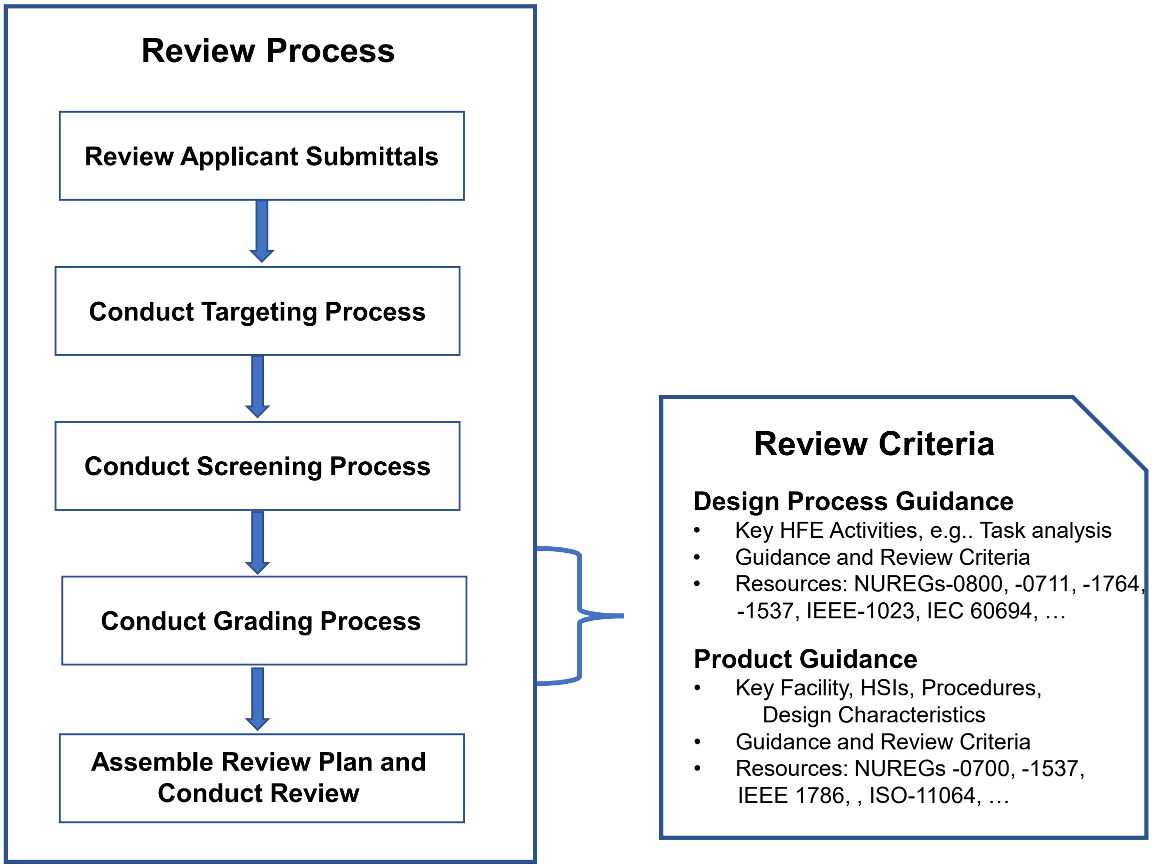

Figure 4.2 HFE Review Strategy

Unlike LLWR reviews, the new HFE review strategy is process based and not dependent on deterministic application of a review methodology and criteria. Using this process, the NRC staff defines a review plan that is uniquely tailored to the facility being reviewed. The most significant difference between this new strategy and that used for LLWRs is the role of existing review guidance, such as NUREGs-0800, -0711, and -0700. For LLWR reviews, the guidance in these NUREGs is used to structure the review activities. As discussed above, NRC reviewers follow the guidance in them to request information from applicants and to review their submittals. In this sense, the review is largely deterministic. Applicants are expected to provide information demonstrating how their design process and products conform to the NRC's guidance or to provide justification as to why their alternative approach is acceptable.

In the new approach, the existing review elements and criteria do not structure the review process. Instead, they serve as resource material the reviewer can use, if appropriate. However, the guidance can be omitted if the reviewer determines it is not applicable to the design being reviewed.

The approach to defining an HFE review strategy is to make the review process itself streamlined, while pointing reviewers (and applicants) to more detailed information that can be consulted to help ensure key design and operational characteristics and HFE activities are addressed. There is detailed technical information provided in four appendices (see Figure 4.3). The information contained in the appendices can be consulted by the staff to support the review. It is informative, not mandatory. Some examples follow to illustrate the relationship of the review process to the supporting information.

- Reviewers can identify key HFE activities by consulting Appendix A. Appendix A provides a list of HFE activities and the purposes of each. A reviewer can consult the list to aid in identifying which are appropriate to the applicant's design efforts. Reviewers are not constrained to the list of activities in Appendix A, rather the list is intended to provide an overview of possible activities the applicants may have included in their HFE design efforts. Other HFE activities may be used as well.

- An important characteristic of advanced reactors is the human role in safety function management. Reviewing this facility characteristic is supported by Appendix C.1, Identification of Important Human Actions, and Appendix D.5.6, Passive Safety Systems.

- Automation is a key design feature of advanced reactors. Reviewing this characteristic is supported by Appendix C.2, Autonomous Operations and Appendix D.2, Agents' Roles and Responsibilities.

An advantage of separating the more detailed information about HFE activities and technical issues into appendices rather than embedding the information into the review process is that it can be revised and updated, as needed, rather than modifying the review process itself. The process can remain stable despite changes in the technical information it references.

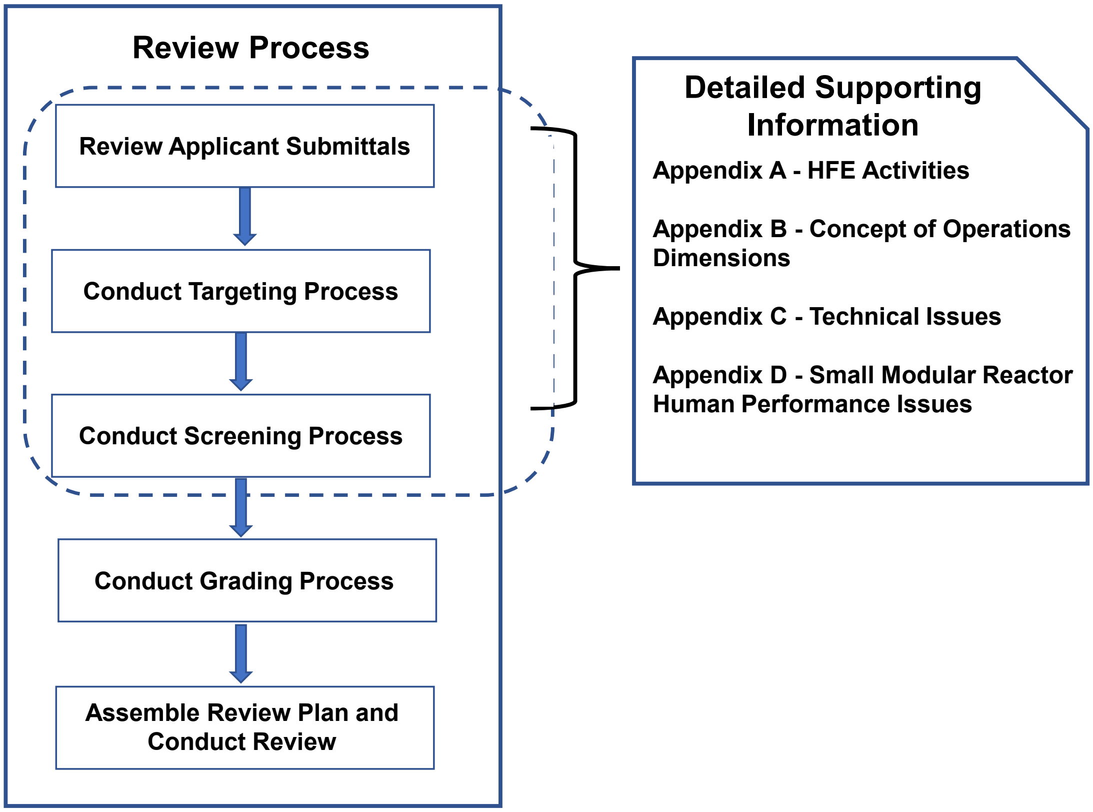

Figure 4.3 Use of Detailed Supporting Information

4.3.2 Objectives

The overall purpose of the staff's HFE review is to verify that the applicant integrates appropriate HFE activities into the development, design, and evaluation of the facility.

- The applicant provides HFE products (e.g., HSIs) that facilitate the safe and reliable performance of operations, and support tasks such as aligning system components, performing inspections, tests, maintenance, and surveillance tasks.

- The applicant's HFE activities and their products reflect state-of-the-art human factors principles [cf. 10 CFR 50.34(f)(2)(iii) and 10 CFR 52.47(a)(8)] and satisfy all regulatory requirements.

The state-of-the-art human factors principles are those currently accepted by human factors practitioners; here, "current" refers to the time when a plan or product is prepared. "Accepted" is regarded as a practice, method, or guide that is (1) documented in the human factors literature within a standard or guidance document that underwent a peer-review process, or (2) is justified through scientific research and/or industrial practices.

For applicant's whose designs have multiple important human actions, the HFE activities provide reasonable assurance of facility safety when they conform to the following high-level principles:

- The applicant’s HFE activities are developed and carried out by qualified HFE personnel, using an acceptable HFE plan.

- The HFE aspects of the design are derived from HFE studies and analyses that afford accurate and complete inputs to the assessment criteria for the design process and verification and validation (V&V) of the design.

- The design is based on proven technology incorporating accepted HFE standards and guidelines and evaluated with a thorough V&V test program.

- The design is implemented such that it effectively supports facility operations.

- The facility is monitored during operation to detect changes in human performance.

For designs that have few, if any, important human actions, the applicant’s HFE activities may be very limited. For such applications, the above list has to be modified as well. The review process is scalable to reflect the degree to which human actions are vital to the performance of safety functions.

4.3.3 Review Responsibility

The HFE staff has the primary review responsibility. They are supported by other NRC technical specialists, such as I&C, accident analysis, and PRA, as necessary.

4.3.4 Definitions

This section contains definitions of the terms used in the review strategy description. Some of these terms may be used in other documents with slightly different meanings. We recognize these definitions are somewhat arbitrary, so defining them as they are used here is important to achieve clarity.

Strategy – The high-level approach to conducting a safety review. A strategy consists of a review process, review criteria, and a means of evolving the strategy as new information becomes available.

Design process – The steps used by the applicant to design the facility.

Review process – The steps followed by an NRC staff to conduct a safety review. The process itself is independent from the review criteria used to evaluate an applicant’s submittal.

Review criteria – The explicit criteria used by an NRC staff to evaluate an applicant’s submittal.

Targeting – Targeting is the process by which the HFE staff identifies aspects of the applicant’s design and operations that warrant an HFE review.

Screening – Screening is the process by which the HFE staff identifies HFE activities, such as function analysis and task analysis, for review.

Grading – Grading is the process by which the HFE staff identifies the appropriate acceptance criteria to use for the review.

4.3.5 Applicant Submittals

Applicant submittals initiate the review process. The submittal must have the information needed by the NRC staff to conduct the review. Characterization should be initiated during pre-application engagement and completed as part of the application acceptance review. Review of the characterization should confirm that sufficient information is available to understand the facility design for purposes of a licensing review. Where the application lacks sufficient detail, interactions with the applicant are necessary to obtain what is needed.

This section describes the expected content of applicant submittals. The topics include:

- ConOps
- Approach to Plant Safety
- Identification of Important Human Actions
- Facility Characteristics
- Facility Operations
- Compliance with HFE Requirements in the Code of Federal Regulation
- Design Process
- Technical Issues

Given the diversity of small, advanced reactors, flexibility is required with respect to the contents of the submittal for a specific facility design. The expected contents as described here are applicable to a facility with numerous important actions and HFE activities. The applicant's description should be scaled to the extent the design relies on human action to ensure safety. Thus, for facilities with little human involvement, the submittal's contents may vary from what is described in this section. Applicants should address each topic, even to indicate that a particular topic is not applicable. The applicant should address in greater detail, those topics discussed below that are applicable to their design.

HFE-related information may be in other (non HFE) submittals as well. The applicant can provide cross reference to them as appropriate. There also may be information obtained from pre-application activities that can be identified in the applicant's submittal. Early engagements between the staff and applicants are encouraged. For the NRC staff, these pre-application activities, such as audits, public meetings, and results of preliminary reviews, help to establish an understanding of the design and the applicant's planned interactions with the staff. For the applicant, the pre-application activities provide an opportunity to clarify the staff's questions, and to better understand the review process so needed information to support the reviews will be provided.

When applicants plan multiple submittals, they should describe the expected content and timing of each. They may submit information about the design of their facility in stages. The stages can reflect regulatory stages, such as construction permit, operating license, standard design approval, design certification, and combined license. Alternatively, they may use design process stages such as requirements definition, subsystem design, and integrated system design (see Figure 4.4). Such an approach to design staging is consistent with international standards such ISO 11064-7 (ISO, 2006). In our experience, applicants are likely to have their own vendor-specific process, informed by industry standards and practices. Applicants should describe the relationship between their stages and submittals to the staff.

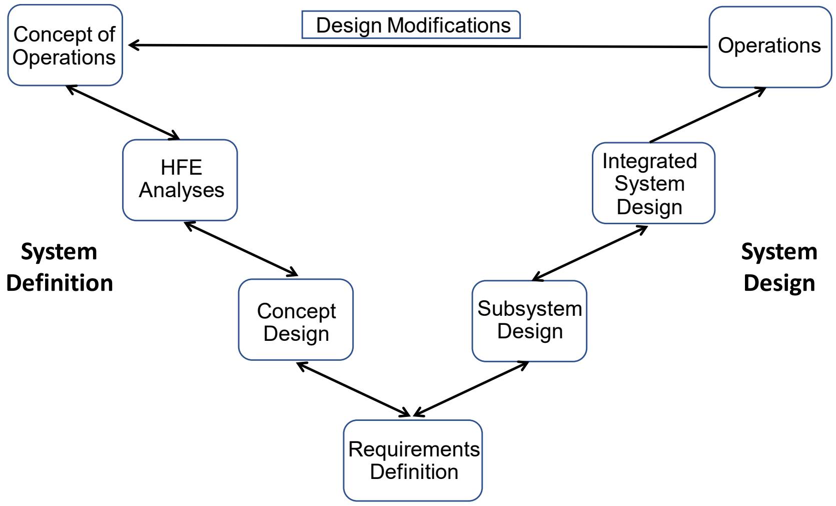

Figure 4.4 Generic Design Process Stages

4.3.5.1 Concept of Operations

Applicants should describe their ConOps for the facility. A ConOps identifies the high-level facility missions and goals and the functions and operational practices needed to manage both normal and off-normal situations. It identifies expectations related to human performance. A ConOps identifies the interactions of personnel with a facility that helps ensure that safety systems will function correctly when needed. The ConOps guides the formation of requirements, the detailed design, and the evaluation of the system. Thus, the facility ConOps provides a broad view of facility purpose, design, and operations. A more detailed discussion of key HFE areas of interest is addressed in subsequent sections.

The following six ConOps dimensions are applicable to most designs:

- Facility Missions
- 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 of the dimensions is briefly described below. More detailed descriptions are provided in Appendix B.

Applicants may have their own ConOps model that differs from the one described here. Alternate ConOps may be acceptable so long as the content of their document addresses the considerations reflected in the dimensions described below.

Facility Mission

A ConOps reflects top-down design considerations. At the top is the facility's mission and the high-level goals which drive all aspects of the design, including the technological infrastructure needed to support them.

Agents' Roles and Responsibilities

This dimension clarifies the relative roles and responsibilities of all agents, namely, personnel and automation, and their relationship. Defining human roles and responsibilities, especially those that are important human actions, is the first step toward integrating humans and systems, and the step from which other aspects of the ConOps should flow.

Automation is a key feature of advanced reactors that can result in significant changes from the traditional role of personnel in plant operations. This is a complex issue with many human performance considerations:

- allocation of functions
- identification of human actions (HAs) needed to support autonomy
- management of degraded conditions and automation failures
- staffing decisions related to autonomous operations
- HSI designs to support automation-related HAs

These issues are fully described in Appendix C.2. The applicant should identify how their facility's automation is implemented regarding these issues.

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 jobs and the qualifications necessary for each should be defined.

Staffing is currently prescribed by 10 CFR 50.54(m) requirements which and based on LLWRs operations. The design and operational differences between small, advanced reactors and LLWRs have led designers to propose alternative approaches to staffing. Some new approaches may raise issues with current regulations. For example, current regulations require that the operation of reactivity controls be performed only by licensed operators and that the manipulation of HSIs that can affect power level can only happen if authorized by a licensed operator [per 10 CFR 50.54(i), (j), (k), and (m)]. Some advanced reactor designs may use non-licensed personnel to perform these tasks. Others may eliminate human operators as a diverse means of defense-in-depth for the assurance of reactor safety. However, if operator action is not a means of DID, some other means of DID is still needed.

Issues related to staffing and qualifications for small, advanced reactors has been widely recognized as has the need for updated regulatory review guidance. Until such guidance is developed, staffing issues have to be addressed in each review. The considerations characterizing this issue include:

- alternative staffing approaches
- training and qualification
- beyond control room staffing

These issues are fully described in Appendix C.3.

Management of Normal Operations

This dimension encompassed three main considerations: Identifying key scenarios; identifying the tasks needed to perform them; and identifying the HSIs and procedures necessary to support personnel tasks.

Management of Off-Normal Conditions and Emergencies

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

- emergencies that may impact safety
- loss of facility systems for which compensation is needed
- failed equipment, such as pumps and valves
- degraded I&C and HSI conditions such as a faulty sensor, loss of an aspect of automation, or degradation of a workstation
- human actions needed to address these conditions

Management of Maintenance and Modifications

This dimension encompasses the installation of facility upgrades, maintenance, and configuration management. Like the previous two dimensions, personnel tasks and how the HSIs and procedures support those tasks is considered.

4.3.5.2 Approach to Plant Safety

The applicant should describe the plant safety functions and the reactor and protection systems that support them. The description should include the identification of the most important transients, how rapidly they evolve, and how they are managed.

The role of automation, passive systems, and inherent safety characteristics should be identified. The applicant should also describe the role of personnel in the achievement of safety goals, whether that role includes direct or backup actions.

4.3.5.3 Important Human Actions

A key input to scaling the review is the presence of *important human actions* in facility operations. The applicant should identify all important human actions, the methodologies used to identify them, and how they were addressed by designers to ensure they will be reliably performed when needed.

As noted earlier, one of the goals of the NRC's safety program has been to use risk analyses to prioritize activities. This helps to ensure that regulators and licensees focus efforts and resources on those activities that best support reasonable assurance of adequate protection of the public's health and safety. Risk-informing the review process is also emphasized in the NEIMA requirements. From an HFE perspective, a risk-informed process is needed to (1) assess the potential contribution of human performance to risk, and (2) commensurate with that risk, assess whether the facility design adequately addresses the risk.

A risk-informed process also provides a basis to identify a regulatory review process that is more streamlined than the broadly scoped process used by in LLWR reviews. HFE contributes to this goal by applying a tailored design review focusing greater attention on HAs most important to safety.

According to NUREG-0711, important HAs consist of those actions that meet either risk or deterministic criteria:

- *Risk-important human actions* - Actions defined by risk criteria that plant personnel use to assure the plant's safety. There are absolute and relative criteria for defining risk important actions. For absolute ones, a risk-important action is any action whose successful performance is needed to reasonably assure that predefined risk criteria are met. For relative criteria, the risk-important actions are defined as those with the greatest risk compared to all human actions. The identifications can be made quantitatively from risk analyses, and qualitatively from various criteria, such as concerns about task performance based on considering performance-shaping factors.

- *Deterministically-identified human actions* - Deterministic engineering analyses typically are completed as part of the suite of analyses in the FSAR/DCD in Chapters 7, Instrumentation & Controls, and 15, Transient and Accident Analyses. These deterministic analyses can credit human actions.

Risk Analyses

Identifying important human actions using risk models such as PRA, is based on modeling, quantification, and criterion selection. Models represent plant components and their interconnections. Human actions are included in the models where appropriate. The modeling is not an HFE activity; however, HFE can provide inputs to modelers. HFE reviewers should work with NRC risk analysis SMEs to determine the correctness and completeness of the applicant's modeling of human action.

The second aspect of PRA that is important to the identification of risk-important human actions is quantification. Error probabilities are assigned to all components and human actions. Human error probabilities are determined through methods such as human reliability analysis (HRA). The analyst evaluates the human action by examining the time available, task demands, performance shaping factors, and factors such as teamwork. The human error probabilities are included in the models.

The third consideration is the determination of the selection criterion. This is the criterion for identifying a human action as important. There is no universally agreed upon criterion for determining importance, it is established on a case-by-case basis.

If the model is poor and does not adequately include human actions, if the quantification of human error probability is poor, or if the selection criterion is unreasonable, then the ability to identify risk-significant HAs is severely compromised.

In addition to standard PRAs, applicants may perform modified PRAs (see discussion in C.1, Identification of Important Human Actions) and other types of risk analyses, such as ISAs. ISAs focus on identifying items relied on for safety (IROFS). IROFS can include HAs. Both the CFR and several SRPs identify ISAs as acceptable analysis methods. An issue arises in the use of ISAs for assessing HAs. ISAs can mask HAs by identifying them as component failure, e.g., modeling a pump failure in the ISA where it is really a failure of personnel to start the pump. While specific HFE guidance is not presently available to review this type of analysis, reviewers can apply the approaches used by previous NRC reviews, such as the review of the MOX facility, to determine an appropriate review strategy for the facility currently being reviewed.

Deterministic Analyses

Deterministic engineering analyses are also used. These are completed as part of the applicant's transient and accident analyses. These analyses identify HAs that are credited in the analyses to prevent or mitigate the accidents and transients. These HAs may, or may not, be identified in the risk analyses. Nonetheless, all credited HAs should be considered important HAs.

Important HAs may also be identified when applicants perform diversity and defense-in-depth (D3) analyses. D3 analyses are performed to demonstrate that a design adequately addresses vulnerabilities to common cause failures in digital I&C systems (NRC, 2009). The applicant may identify backup systems involving HAs necessary for accomplishing required safety functions. In general, the applicant's analysis should identify back-up HAs for safety functions that are part of the facility's defense-in-depth (DID). These HAs should be treated as important human actions.

Applicants should also identify technical support actions that were not picked up in other analyses. These can include actions such as performing and verifying system line-ups necessary for the performance of safety functions. They may also include maintenance actions. post-maintenance tests, and surveillances required for verifying and maintaining the capabilities of systems supporting facility safety. Such HAs are applicable to fully autonomous systems and passive systems in performing their safety functions (even those with no credited human actions). HFE contributes to processes designed to ensure the reliability of these human actions.

Thus, important HAs can be identified through numerous types of risk and deterministic analyses. The HFE reviewer should verify that the approach used by the applicant is appropriate and complete so there is reasonable assurance that important human actions have been identified.

Complicating the identification of important HAs is the fact that the means of managing off-normal events is different for advanced reactors when compared to LLWRs. In current plants, managing off-normal events typically involves a combination of automation and HAs. Many advanced reactors depart from this approach. Instead, they rely on inherently safe design features and passive safety systems which do not rely on human actions.

There are several technical issues to be addressed when important human actions are identified. These issues are characterized by concern that important human actions may not be identified. The identification of important human actions may be complicated by several factors:

- Use of non-traditional risk analysis methods
- Lack of supporting analyses used to identify human tasks
- Identifying the human role in managing safety functions in new systems

These issues are fully described in Appendix C.1. The applicant should address these considerations in their application.

4.3.5.4 Facility Characteristics

The applicant should describe the design of the HSIs, workstations, and workplaces (including local control stations and technical support centers). The HSIs are used by personnel in performing their functions and tasks. Major HSIs include alarms, information displays, and controls. Each type of HSI is characterized in terms of its important physical and functional characteristics. Use of HSIs is influenced by (1) the organization of HSIs into workstations, including consoles and panels; (2) the arrangement of workstations and supporting equipment into workplaces such as a main control room, remote shutdown station, local control station, technical support center, and emergency operations facility; and (3) the environmental conditions in which the HSIs are used, including temperature, humidity, ventilation, illumination, and noise. Also important is the siting of monitoring and control functions.

There are two aspects of facility characteristics that should be given special attention. The first are those characteristics that directly influence the performance of important human action. For example, specific alarms, displays, and controls may be necessary to perform an important HA.

The second aspect of facilities that require special attention is novel designs, such as a new alarm system that is based on novel processing techniques. Another example is a facility design with no control room or where the facility is unmanned. Novel characteristics may not be modeled well in risk analyses or evaluated deterministically. Applying HFE activities to such characteristics can help provide reasonable assurance that the novel characteristics are acceptably implemented and operationally acceptable. The applicant should identify novel characteristics and the basis for each should be described. They should also identify if any are used in the performance of important human actions.

Facility characteristics that directly influence the performance of important human action and are based on novel designs features should be given special attention.

Some small, advanced reactor designers may have few safety-related HAs and there may be an overall reduction in the HAs needed for monitoring and controlling the facility when compared with current facilities. This will have profound implications for the design of the control room and HSIs. In fact, a traditional control room may not be necessary. What also needs to be considered are the HAs need for monitoring and control of the interfacing systems, such as balance of plant (BOP) systems and those of other missions like generation of industrial heat.

Applicants should describe how their facility design addresses these issues which are fully described in Appendix C.4.

4.3.5.4 Facility Operations

The way the facility will be operated should be described. The description should include all phases of operation, including the human role in normal, off-normal, and emergency conditions. In addition to operational phases, the description should include support tasks such aligning system components, as well, as inspections, tests, maintenance, and surveillance.

Aspects that require special attention are those involving important HAs and novel operations, such as a unique way of responding to an emergency based on new systems to mitigate the emergency. Like novel facility characteristics, novel operations may not be modeled well in risk analyses or deterministic analyses. Applying HFE activities to such characteristics can help provide reasonable assurance that the novel operations are acceptably implemented and operationally acceptable. The applicant should identify facility operations involving important HAs and novel operations and the basis for each should be described.

Applicants should identify any remote operations. A decision to locate HSIs at a remote location may be informed by the analysis of how HSIs are used for monitoring and controlling the facility. Such a ConOps is not addressed in current regulations or review guidance. At present, the HFE requirements for remote operations are not known and give rise to questions such as:

- Will HSIs have to be modified from what they would be if located on-site?
- If remote operations means that there are no operations personnel onsite, then how will the lack of local operations staff be compensated for?

If planning on remote operations, the applicant should interact with the staff early in the preapplication stage. Issues related to remote operations are fully described in Appendix C.5.

4.3.5.5 HFE Requirements in the Code of Federal Regulation

The applicant should describe how their design complies with the HFE requirements in the Code of Federal Regulation. The requirements are summarized below. In cases of non-compliance, the applicant should include an exemption request in their application.

Federal regulations are contained in the CFR. Title 10 addresses Energy and contains the regulations pertaining to the NRC. Several of the regulations address the HFE aspects of nuclear facilities. 10 CFR Part 50, Appendix A, General Design Criteria (GDC) 19 specifies the need for and characteristics of a control room (discussed further below).

For commercial NPPs, one of the more important HFE regulations is 10 CFR 50.34(f)(2) and 10 CFR 52.47(a)(1)(ii)) (refer to Table 4.1 for a description). An applicant is required to:

> (iii) Provide, for Commission review, a control room design that reflects state-of-the-art human factor principles prior to committing to fabrication or revision of fabricated control room panels and layouts.

Note that 50.34(f)(2)(iii) does not apply to new Part 50 applicants, whereas it does apply to Part 52 applicants. An update to this requirement is being addressed in the Part 50/52 and Part 53 rulemaking.

In addition to the general control room requirement in 10 CFR 50.34(f), there are other CFR requirements that involve HFE (see Table 4.1).

Table 4.1 HFE Requirements in the Code of Federal Regulations

Regulations Addressing General Requirements Related to the Main Control Room
10 CFR 50.34(a)(6) - a preliminary plan for the applicant's organization, training of personnel, and conduct of operations
10 CFR 50.34(f)(2)(ii) – continuing improvement of HFE and procedures
10 CFR 50.34(f)(2)(iv) – safety parameter display system
10 CFR 50.34(f)(3)(i) – use of operating experience
10 CFR 50.54 (i) to (m) - staffing
10 CFR 52.47 – level of detail required in DCs
10 CFR 52.47(a)(8) – inclusion of 10 CFR 50.34(f) for Part 52 applications
10 CFR 52.79 – content of COL applications
Specific Requirements Related to the Main Control Room
10 CFR 50.34(f)(2)(v) – automatic indication of the bypassed and operable status of safety systems
10 CFR 50.34(f)(2)(xi) – relief and safety valve indication
10 CFR 50.34(f)(2)(xii) – auxiliary feedwater system flow indication
10 CFR 50.34(f)(2)(xvii) – containment related indications
10 CFR 50.34(f)(2)(xviii) – core cooling indications
10 CFR 50.34(f)(2)(xix) – instrumentation for monitoring post-accident conditions that includes core damage
10 CFR 50.34(f)(2)(xxi) – auxiliary heat removal (Boiling Water Reactor only)
10 CFR 50.34(f)(2)(xxiv) – reactor vessel level monitoring (Boiling Water Reactor

This table contains a list of HFE related requirements in the CFR and listed in the SRP Chapter 18.

10 CFR Part 50, Appendix A, General Design Criteria for NPPs serves as the fundamental criteria used by the NRC when reviewing the structures, systems, and components (SSCs) that make up a NPP design. The GDC requirements establish the necessary design, fabrication, construction, testing, and performance requirements for SSCs that are important to safety. Taken together, when met they provide reasonable assurance that an NPP can be operated without undue risk to the health and safety of the public.

GDC 19 addresses the need for and characteristics of a control room. It states:

> *Criterion 19—Control room.* A control room shall be provided from which actions can be taken to operate the nuclear power unit safely under normal conditions and to maintain it in a safe condition under accident conditions, including loss-of-coolant accidents. Adequate radiation protection shall be provided to permit access and occupancy of the control room under accident conditions without personnel receiving radiation exposures in excess of 5 rem whole body, or its equivalent to any part of the body, for the duration of the accident. Equipment at appropriate locations outside the control room shall be provided (1) with a design capability for prompt hot shutdown of the reactor, including necessary instrumentation and controls to maintain the unit in a safe condition during hot shutdown, and (2) with a potential capability for subsequent cold shutdown of the reactor through the use of suitable procedures.

> Applicants for and holders of construction permits and operating licenses under this part who apply on or after January 10, 1997, applicants for design approvals or certifications under part 52 of this chapter who apply on or after January 10, 1997, applicants for and holders of combined licenses or manufacturing licenses under part 52 of this chapter who do not reference a standard design approval or certification, or holders of operating licenses using an alternative source term under § 50.67, shall meet the requirements of this criterion, except that with regard to control room access and occupancy, adequate radiation protection shall be provided to ensure that radiation exposures shall not exceed 0.05 Sv (5 rem) total effective dose equivalent as defined in § 50.2 for the duration of the accident.

In recognition of the differences between LLWRs and the small, advanced reactors, the NRC has proposed modifications to GDC 19 in Regulatory Guide 1.232. RG 1.232 (NRC, 2018a) discusses how the GDC can be adapted to non-LWRs resulting in advanced reactor design criteria (ARDC). The revised criterion 19 still defines a control room and does not consider a situation where a control room may not be needed. It states (changes are shown in italics):

> ARDC 19 - A control room shall be provided from which actions can be taken to operate the nuclear power unit safely under normal conditions and to maintain it in a safe condition under accident conditions. Adequate radiation protection shall be provided to permit access and occupancy of the control room under accident conditions without personnel receiving radiation exposures in excess of 5 rem *total effective dose equivalent as defined in § 50.2* for the duration of the accident. Adequate habitability measures shall be provided to permit access and occupancy of the control room during normal operations and under accident conditions. Equipment at appropriate locations outside the control room shall be provided (1) with a design capability for prompt hot shutdown of the reactor, including necessary instrumentation and controls to maintain the unit in a safe condition during hot shutdown, and (2) with a potential capability for subsequent cold shutdown of the reactor through the use of suitable procedures.

However, the ARDC is not a formal requirement. Applicants can modify and propose changes to the ARDC as appropriate for their facility. For instance, an applicant with a design without a control room could potentially revise ARDC 19 in a way that does not include a control room and propose a corresponding PDC to the NRC for review. Supporting evidence may be necessary that clarifies how the intent of ARDC 19 is met without a main control room. Also, there are additional HFE-related requirements addressing detailed aspects of HSIs, procedures, and training.

General human performance issues associated with the facility's compliance with HFE regulations and facility design without a control room are discussed in Appendix C.4, HSIs for Monitoring and Controlling the Reactor and Interfacing Systems.

4.3.5.6 Design Process

The applicant should identify the HFE activities that are used as part of the design process. Appendix A contains descriptions of HFE activities that are commonly used in the design of HFE products, including:

- HFE Program Management
- Operating Experience Review
- Functional Requirements Analysis and Function Allocation
- Task Analysis
- Staffing and Qualifications

- Treatment of Important Human Actions
- Human-System Interface Design
- Procedure Development
- Training Program Development
- Human Factors Verification and Validation
- Design Implementation

The activity descriptions in Appendix A include information about how each contributes to the facility design.

This list of activities is not all encompassing. The applicant should describe their HFE activities, including those not listed in Appendix A. HFE also makes use of analyses performed by other disciplines, such as PRA. Such supporting analyses should be identified.

4.3.5.7 Technical Issues

The applicant may have some unique issues applicable to their design. In general, an issue is:

- an aspect of facility development or design for which information suggests there may be a negative impact on human performance

- an aspect of reactor design that may degrade human performance; however, additional analysis is needed to better understand and quantify the effect

- a technology or technique that will be used in the facility design or implementation for which there is little or no guidance

The applicant should identify all human performance issues that are applicable to their design and discuss how they were addressed.

4.3.6 Conduct Targeting Process

Targeting is the process by which the HFE reviewer identifies aspects of the applicant's design and operations that warrant an HFE review.[11] Unlike LLWR reviews, in this new approach to HFE review, not all aspects of the facility design and operations are reviewed. Thus, the reviewer must select those that will be.

There are precedents for targeting/screening in NRC guidance documents and several approaches have been described. NUREG-0800, Chapter 18 and NUREG-0711, Section IV, Review Procedures, include guidance for alternative approaches to a full HFE review. NUREG-0800, Chapter 18 states that:

> The degree to which the NRC staff applies the review methodology in this SRP will reflect the specific circumstances of individual applications. For example, the review of the HFE aspects of a new plant will entail a comprehensive, detailed evaluation, while the review of individual modifications to existing designs may be less extensive. The following elements are considered when deciding the depth of review.

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[11] Previous NRC guidance documents did not distinguish between targeting (selecting facility deign and operational characteristics) and screening (selecting HFE activities, such as task analysis). The guidance provided was applicable to both.

- risk importance
- the similarity of the associated HFE issues to those recently reviewed for other plants or similarity with previous approved designs
- the determination of whether items of special or unique safety significance are involved (such as items deemed important to safety based on a qualitative or deterministic basis)

Similarly, NUREG-0711, Section 1.3, Use of This Document, includes guidance for risk-informed applications:

> The NRC, the nuclear industry, and the public have adopted a broader consideration of risk in many activities associated with NPPs. Therefore, the concept of risk importance is integral to the guidance in this document. Applying the precepts of risk importance will help reviewers decide which particular items to review and the depth of those reviews. The level of NRC staff's review of an applicant's HFE design should also reflect the unique circumstances of the review. For example, a review of a new nuclear power plant will likely use all the elements, while a review of changes to the HSIs of an existing plant will likely use only a subset of the elements.

A more detailed approach to screening is described in NUREG-1764 (Higgins et al., 2007). It uses a two-phased approach to reviewing changes caused by plant modifications to HAs that are credited in safety analyses. An example of such a modification is the substitution of manual actions for automatic actions to perform design functions described in the SAR.

Phase 1 uses a risk screening process to determine the risk-importance of the affected HAs. The risk screening process is based on RG 1.174 (NRC, 2002). Phase 2 is an HFE review of the HAs that are found to be risk important. The reviews ensure that the appropriate conditions are in place so the change in HA does not significantly increase the potential risk. The details of the review are commensurate with the risk and divided into three levels. A Level I review is used for HAs in the high-risk category and requires the most stringent review, including most of the elements of NUREG-0711.

A Level II review is for HAs in the medium risk category. While the guidance addresses key NUREG-0711 elements, the extent of the staff's review is notably less. The Level II evaluation process addresses general deterministic review criteria, HFE analysis, HSI design, procedures, training, and HA verification. The evaluation processes for this level are less prescriptive and afford greater latitude to both the licensee and the NRC reviewers for collecting and analysing information.

HAs in the low-risk category receive a Level III review, which is generally limited to verifying that the HA is properly classified in Level III. Typically, no detailed HFE review is necessary.

Three SRPs for non-electricity producing facilities include a common targeting/screening process: They are NUREG-1702 (NRC, 2000a), NUREG-1718 (NRC, 2016d), and NUREG-1520 (NRC, 2015). In these SRPs, the reviewer screens each HFE activity based on (1) provisions made to address personnel activities identified in an ISA, (2) the similarity of the associated HFE issues to those for similar type plants, and (3) the determination of whether items of special or unique safety significance are involved. The screening process is design-specific in that the selection of HFE activities is based on the design and operational characteristics of the facility to be reviewed.

In summary, targeting/screening has been addressed in numerous NRC documents. The guidance ranges from high-level qualitative considerations to detailed quantitative analyses of risk importance. The NRC reviewer can conduct screening using this guidance as appropriate.

In this new review process, the identification of a human action's importance (both from risk and deterministic criteria) plays a prominent role. The targeting process is one of the main ways the review is scaled. When a lot of the facility's design and operational characteristics are targeted, the review is likely to be larger than when only a few are targeted.

The applicant's submittals should be reviewed along with additional information that may be available from preapplication activities. The submittals provide the information used in the targeting process. The reviewer should examine the submittal and supporting information to determine if the facility's design and operations are sufficiently described to support the review. If not, the staff should request additional information from the applicant.

If the information in the applicant's submittal is sufficient, then it can be evaluated to identify areas to target. One topic that will always be targeted is the treatment of important HAs. One of the main justifications applicants can provide for minimizing HFE activities is that there are few, if any, important HAs. Before such a position can be accepted, the reviewer should determine whether the applicant's methods for identifying important HAs are acceptable. Important HAs are determined through both risk and deterministic analyses. For these evaluations, the HFE reviewer should consult with other NRC SMEs as needed.

For the risk analyses, the reviewer should:

- Verify that the applicant's risk model correctly represents human actions, where applicable.

- Verify that the quantification of human error probabilities was based on analyses that include factors such as task demands, performance shaping factors, and teamwork.

- Verify that the applicant's selection criteria for identifying risk-important HAs are reasonable.

- Verify that the applicant assessed risk for all types of safety function management scenarios and that the scenarios were analysed to identify important HAs.

For deterministic analyses, the reviewer should:

- Verify that applicant's deterministic analyses were sufficiently comprehensive to identify important HAs.

- Verify that the analysis included HAs necessary to address common cause failures and technical support actions.

If the analyses are determined to be inadequate, the staff should interact with the applicant to improve their assessments to identify important HAs.

If the analyses are found to be adequate, the reviewer should identify the procedures, HSIs, training, etc., that support important HAs. They support personnel so that the important human actions can be safely and reliably performed when needed. These should be targeted for review.

An assessment should be made of applications claiming that their facility has no important HAs. The reviewer should determine whether the applicant's analyses were sufficiently comprehensive to support that claim, e.g., ensuring that the risk and deterministic analyses are correct and that no potentially important HAs, such as backup actions (such as defense-in-depth actions, manual actuations for diversity, and safe shutdown), were overlooked.

The next area to consider is the applicant's ConOps. The ConOps is very broad and touches on many aspects of facility design and operation. The reviewer should consult Appendix B for the types of information that can be provided in a ConOps document. Aspects of the applicant's ConOps involving important HAs should be targeted for review. In additions, any aspect of the ConOps that is new or novel in comparison to current plants should be targeted for review. Examples include:

- facilities with mixed missions
- facilities with new staffing approaches, such as the use of non-licensed personnel to perform tasks undertaken by operators in current plants
- potential new hazards

The reviewer should next consider the facility design, facility operations, requirements compliance, and human performance issues. Some aspects of these topics may have already arisen in the ConOps review, so they do not have to be considered again.
Aspects of the facility design that support important human actions should be targeted for review. Also. novel aspects of the design should be targeted, e.g., a facility design with no control room.

With respect to facility operations, the reviewer should target for review operations involving important human actions, as well as, all novel operations, such as a unique way of responding to an emergency based on new systems to mitigate the emergency.

The reviewer should examine the applicant's compliance with CFR HFE requirements. Any deviations from the requirements or requests for exemptions from them should be targeted for review.

Next, the reviewer should examine the applicant's treatment of technical issues applicable to their facility. The reviewer should determine whether the applicant correctly identified any technical issues and whether they were acceptably addressed.

4.3.7 Conduct Screening Process

Screening is the process with which HFE activities, such as function and task analysis, are selected for review. Appendix A of this report provides descriptions of common HFE activities and includes information about how the activity contributes to an applicant's design and the NRC reviewer's objectives when evaluating the applicant's performance of the activity. The screening process enables the staff's review process to flexibly adapt to the applicant's HFE activities.

The selection is largely based on the reviewer's assessment of which HFE activities are needed to fully support important HAs and the design of novel features. These activities should be reviewed.

The applicant's use of novel HFE methods, such as a new method to model human performance, for which little is known should also be selected.

Importantly, the reviewer should identify HFE activities that the applicant should have performed but did not. For example, the applicant may have identified an important HA, but failed to analyze the task demands of the action or its HSI requirements.

4.3.8 Conduct Grading Process

Grading is the process with which the HFE reviewer identifies the appropriate acceptance criteria to use for the review. Reviewers have a great deal of flexibility in review criteria selection. The staff will select appropriate review criteria based on the considerations described in Sections 4.3.5, 4.3.6, and 4.3.7 of this document. These criteria may be selected from the NRC guidance documents and consensus standards such as the following:

- NUREG-0711
- NUREG-0700
- NUREG-1537
- IEEE-1023
- IEEE-1786
- ISO-11064

Applicants may propose alternative guidance and standards documents and the staff will consider them.

Thus, the staff can use criteria from non-NRC documents, if it is determined that the criteria better meet the needs of the review. Non-NRC documents may be preferred, for example, if the guidance is based on a more recently developed technical basis than the corresponding NRC guidance or if it addresses facility characteristics for which the NRC has no review criteria. For example, if criteria are needed to review a computer-based procedure system, the reviewer may determine the guidance in IEEE's Guide for *Human Factors Applications of Computerized Operating Procedure Systems (COPS) at Nuclear Power Generating Stations and Other Nuclear Facilities* (IEEE-2011) is better suited to the procedure system under review than the guidance in NUREG-0700. It is a more recent document and addresses aspects of procedure automation not addressed in the NRC review guidance.

The staff can adapt the criteria in selected documents as needed. For example, all the review criteria for a specific HFE activity may not be needed and can be eliminated from the review.

As discussed earlier, HFE S&G's documents play an important role in the design and evaluation of complex systems like NPPs. S&Gs provide HFE SMEs with principles to help ensure that the physiological, cognitive, and social characteristics of personnel are accommodated in system design. They also support standardization and consistency of facility characteristics and functionality.

The reviewer should assess the value of diverse guidance documents, including those provided by the NRC, such as NUREG-0800, non-LLWR SRPs, such as NUREG-1537, and non-NRC guidance, such as IEEE-1023. More than one source of guidance may be selected as review criteria if warranted to meet the needs of the reviewer.

When using non-NRC guidance, there are two considerations that should be addressed: guidance validity and independence. The NRC's HFE guidance is developed and updated using a standard methodology (O'Hara, Higgins, Brown, Fink, Persensky, Lewis, Kramer, Szabo & Boggi, 2008). A high priority is placed on establishing the validity of the guidelines; defined along two dimensions: internal and external. *Internal validity* is the degree to which the guidelines are linked to a clear, well founded, and traceable technical basis. *External validity* is the degree to which the guidance is supported by independent peer review. Peer review is a good method of screening guidelines for conformance to generally accepted HFE practices and to industry-specific considerations, i.e., for ensuring that the guidelines are appropriate based on practical operational experience in actual systems. When a reviewer selects criteria from guidance documents other than those developed using the NRC guidance development process, the validity of the guidance should be assessed.

The second consideration is the independence of the criteria. When using industry guidance, there is the possibility that the guidance is based on a specific vendor's approach. Review criteria developed by the NRC has a technical basis that is largely independent from industry priorities and concerns.

The use of industry documents is supported by the NRC's endorsement (usually in Regulatory Guides). NRC endorsement provides joint concurrence on the value of the guidance between the staff and industry developers. It also identifies aspects of the guidance that the NRC finds exceptions to. Unfortunately, at the present time, there are not many industry HFE documents that have NRC endorsement.

4.3.9 Assemble Review Plan and Conduct Review

In this step. the reviewer assembles the review plan for the facility. The review plan identifies the aspects of the facility's design, operational characteristics, and HFE analyses that are to be reviewed and the review criteria to be used. The plan is uniquely tailored to the facility under review.

With respect to the facility's design and operational characteristics, the reviewer seeks to verify that the characteristics conform to the HFE guidance selected for review. Any technical issues identified should be addressed. The reviewer can apply existing guidance that is generally applicable to the subject matter of the issue and high-level HFE principles, such as those in Appendix A of NUREG-0700.

For nonconformances, a human engineering discrepancy (HED) is identified. The applicant should either provide justification for the HEDs or analyze them to identify corrective actions. A general approach to HED analysis can be found in NUREG-0711, Section 11.4.4.

For the applicant's HFE activities, the reviewer should first verify that the applicant has used the appropriate HFE activities. Where it is determined that necessary HFE activities were not performed, the applicant should either provide justification for not performing the activity or commit to performing it. Next, the reviewer should verify that the analyses were conducted correctly, e.g., determine that the applicant's task analyses were performed correctly. If not, the reviewer should interact with applicant to either justify their approach or change their methodology.

Any technical issues identified should be addressed, although the guidance for reviewing them may be limited. The reviewer can apply existing guidance that is generally applicable to the subject matter of the issue and high-level HFE principles, such as those in Appendix A of NUREG-0700.

The results of the review should be documented in a Safety Evaluation Report.

4.3.10 Review Process Evolution

An important aspect of a new HFE review strategy is identifying how it can evolve (1) to better conform to the NRC strategic vision for advanced reactor reviews, and (2) to address existing and emerging needs for review guidance. The capability to update the review process and review guidance will be based on the ongoing NRC activities to develop new review guidance where needed. The technical basis information needed to develop guidance can come from a variety of sources, including:

- lessons learned performing reviews
- results of NRC and industry research
- new regulatory and industry positions

Figure 4.5 illustrates this evolution in the context of the overall review strategy.

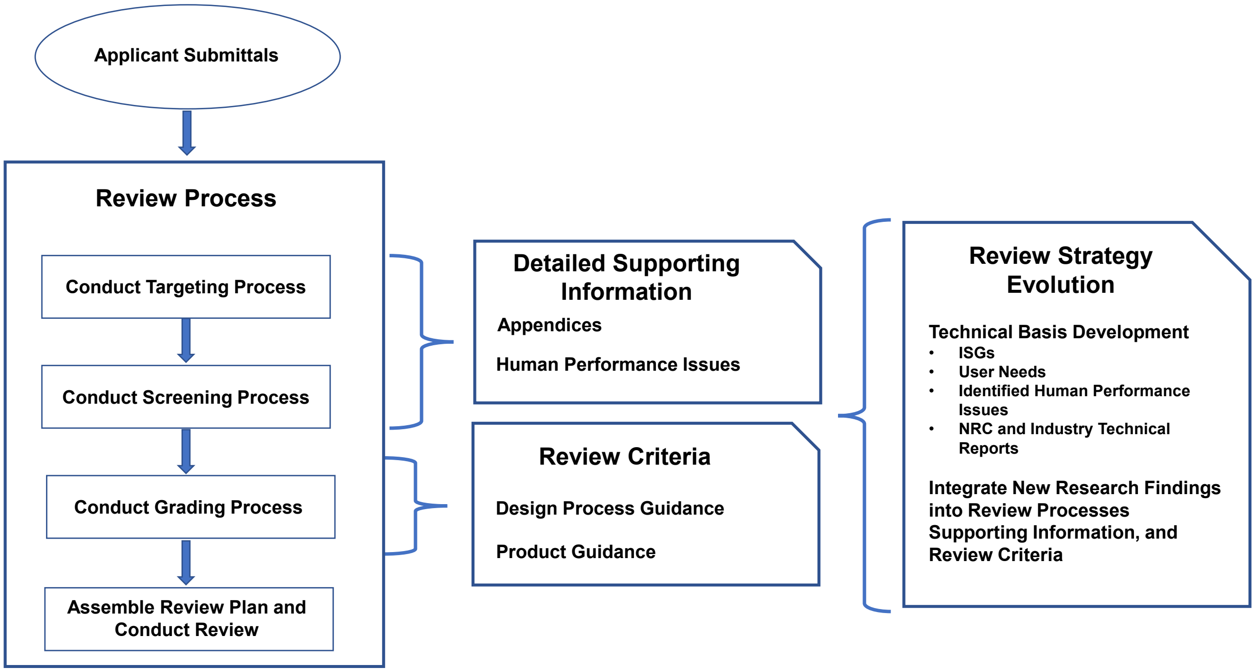

Figure 4.5 Review Strategy Evolution

5 DISCUSSION

The objective of this research project was to develop an HFE review process tailored to small, advanced reactors and their unique characteristics. We developed a process consisting of a series of steps culminating in the development of a facility specific review plan and HFE review using the plan. The steps are:

- Review Applicant Submittals
- Conduct Targeting Process
- Conduct Screening Process
- Conduct Grading Process
- Assemble Review Plan and Conduct Review

The most significant difference between this new strategy and that used for LLWRs is the role of existing review guidance, such as that provided by NUREGs-0800. For LLWR reviews, the guidance in these NUREGs is used to structure the review activities. NRC reviewers follow the guidance in them to request information from applicants and to review their submittals. In this sense, the review is largely deterministic. With the new process, the existing review elements and criteria only serve as resource material which the staff can use, if appropriate. They can also use criteria from non-NRC documents when they better meet the needs of the review.

The new HFE review process is consistent with NEIMA requirements and the NRC vision for advanced reactor reviews, as reflected in the review process characteristics defined in Section 3.3.4 above:

- technology inclusive
- risk informed
- performance based
- staged
- based on process and methods rather than prescriptive guidance
- within the bounds of existing regulations
- flexible
- scalable
- supportive of preapplication interactions that occur early and often

The review process needs to be technology inclusive because of the wide variety of reactor technologies the review process must accommodate. The LLWR reviews were focused on only two types of LLWR technology: boiling water reactors and pressurized water reactors. The new process needs to address these technologies, but it also must be suitable for technologies such as heat pipe reactors, helium-cooled fast reactors, high-temperature gas cooled reactors, and molten salt reactors. The HFE review process is technology neutral, thus can be used no matter what technology is used.

The process must be risk-informed to enable the safety review to focus on those aspects of the design and operation that pose the greatest challenge to plant safety. The HFE review process places great emphasis on the identification of important human actions. These actions are identified through probabilistic and deterministic methods; thus, providing a comprehensive identification process to help ensure important actions are not missed. Using both types of methods also allows the review to proceed when applicants differ in the methodological approaches used to identify important actions. For example, some applicants may use ISAs rather than PRAs to identify important actions. The HFE review process accommodates a diversity of approaches.

The HFE review process is performance based and utilizes the results of:

- analyses and simulations performed by the applicant that provide estimates of human performance

- tests using operators performed by applicants as part of their design process

- validations performed to ensure the final design supports reliable human performance

The review process accommodates staged reviews to enable applicants to provide information to the staff at times conforming to their own design process and schedule.

The HFE review process is based on process and methods rather than prescriptive guidance. This is one of the most significant changes in the HFE review process when compared with the LLWR review process. The NRC reviewer develops a review plan that is tailored to the applicant’s design and potential safety concerns. The LLWR reviews used NUREG-0711 which defined the HFE activities applicants were expected to use and the review criteria for each. In the new process, the reviewer defines the HFE activities that are applicable to the design under review and the criteria to be used in the evaluation of each. The review criteria may come from NRC documents or industry document depending on which best meet the needs of the review. This process makes the review scalable based on design and safety considerations and flexible enough to accommodate the wide diversity of designs expected.

The HFE review process is within the bounds of existing regulations and enables the staff to review applications that are like LLWRs, as well as those applications that are far different.

Finally, the process is supportive of preapplication interactions which are especially important to identify the technical information the staff needs to support the review. These interactions further help communicate to the applicant the staff’s expectations and provide an opportunity to address staff concerns in a timely manner.

In sum, the new review process is consistent with the principles outlined for the NRC’s vision for advanced reactor reviews.

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APPENDIX A: HFE ACTIVITIES

Below are the HFE activities that should be considered as part of the screening process. These descriptions are based on the element descriptions from NUREG-0711. As described above, NUREG-0711 is based on a systems engineering model that includes the HFE activities that are broadly viewed as necessary to a comprehensive HFE program. While all may not be needed in an applicant's HFE program, especially for more modest programs, each should be considered by the reviewer during the screening process and included or excluded accordingly.

The activity descriptions include information about how each contributes to an applicant's HFE program and the NRC reviewer's objectives when evaluating the applicant's performance of the activity.

HFE Program Management

In this activity, the applicant establishes an HFE design team with the responsibility, authority, placement within the organization, and composition to reasonably assure that the plant design meets the commitment to HFE. Further, a plan should be developed to guide the team to ensure that the HFE program is properly developed, executed, overseen, and documented. The program plan describes the activities needed to ensure that HFE principles are applied to the development, design and evaluation of HSI, procedures, and training.

The objective of the staff review of this activity is to verify that the applicant has established HFE program management to accomplish these elements.

Operating Experience Review

Applicants perform an operating experience review (OER) to identify HFE-related safety issues. The OER should provide information on the performance of predecessor designs. For new plants, this may be the earlier designs on which the new one is based. For plant modifications, it may be the design of the systems being changed. The issues and lessons learned from operating experience provide a basis to improve the plant's design. Thus, the negative features of predecessor designs may be avoided, while retaining positive features. The OER should consider the predecessor systems upon which the design is based, the technological approaches selected (e.g., if touch-screen interfaces are planned, their associated HFE issues should be reviewed), and the facility's HFE issues.

The objective of this activity is to verify that the applicant identified and analyzed HFE-related problems and issues in previous designs that are similar to the one under review.

Functional Requirements Analysis and Function Allocation

The personnel role in facility operations is examined in two steps: functional requirements analysis and function allocation (assignment of levels of automation). A functional requirements analysis (FRA) identifies those plant functions that must be performed to satisfy the plant's overall operating and safety objectives and goals; to ensure the health and safety of the public by preventing or mitigating the consequences of postulated accidents. This analysis determines the objectives, performance requirements, and constraints of the design, and sets a framework for understanding the role of controllers (personnel or system) in regulating plant processes.

Function allocation is the assignment of functions to (1) personnel, (2) automatic systems, and (3) combinations of both. Exploiting the strengths of personnel and system elements enhances the facility's safety and reliability, including improvements achievable through assigning control to these elements with overlapping and redundant responsibilities. Function allocations should be founded on functional requirements and HFE principles in a structured, well-documented methodology that produce clear roles and responsibilities for personnel.

The purpose of the staff's review of this activity is to verify that the applicant defined those functions that must be carried out to satisfy the facility's safety goals and that the assignment of responsibilities for those functions to personnel and automation in a way that takes advantage of human strengths and avoids human limitations.

Task Analysis

The functions allocated to plant personnel define the roles and responsibilities that they accomplish by HAs. HAs can be divided into tasks, a group of related activities with a common objective or goal. The results of the task analysis offer important inputs to many HFE activities: (1) The analysis of staffing and qualifications; (2) the design of HSIs, procedures, and training program; and (3) criteria for Task Support Verification.

The objective of this review is to verify that the applicant undertook analyses identifying the specific tasks needed to accomplish personnel functions, and the alarms, information, control, and task-support required to complete those duties. (see Roth & O'Hara, 2020 for additional information.)

Staffing and Qualifications

Plant staffing and staff qualifications are important considerations throughout the design process. Initial staffing levels may be established early in the design process based on experience with previous plants, staffing goals (such as for staffing reductions), initial analyses, and NRC regulations. However, their acceptability should be examined periodically as the design of the facility evolves.

The objective of reviewing staffing and qualification analyses is to verify that the applicant has systematically analyzed the requirements for the number of personnel and their qualifications that includes gaining a thorough understanding of the task and regulatory requirements.

Treatment of Important Human Actions

A goal of the NRC's safety program has been to use risk analyses to prioritize activities, and to ensure that regulators and licensees focus efforts and resources on those activities that best support reasonable assurance of adequate protection of the public's health and safety. HFE programs contribute to this goal by applying a graded approach to plant design, focusing greater attention on HAs most important to safety. The objective of this activity is to identify those HAs most important to safety for a plant design through a combination of probabilistic and deterministic analyses. The analyses should minimize the likelihood of personnel error and help ensure that personnel can detect and recover from any errors that occur.

The review’s objectives are to verify that the applicant has (1) identified important HAs, and (2) considered human-error mechanisms for important HAs in designing the HFE aspects of the plant.

Human-System Interface Design

In this activity, applicants translate the functional- and task-requirements to HSI design requirements, and to the detailed design of alarms, displays, controls, and other aspects of the HSI. A structured methodology should guide designers in identifying and selecting candidate HSI approaches, defining the detailed design, and performing HSI tests and evaluations.

The objective of the staff’s review of this activity is to evaluate the process used by applicants to translate requirements to HSI design. The review should also address the formulation and employment of HFE guidelines tailored to the unique aspects of the applicants’ design, e.g., a style guide to define the design-specific conventions.

Procedure Development

Procedures are essential to plant safety because they support and guide personnel interactions with plant systems and personnel responses to plant-related events. In the nuclear industry, procedure development is the responsibility of individual utilities. The objective of the NRC procedure review is to confirm that the applicant's procedure development program incorporates HFE principles and criteria, along with all other design requirements, to develop procedures that are technically accurate, comprehensive, explicit, easy to utilize, validated, and in conformance with 10 CFR 50.34(f)(2)(ii). The procedures program is reviewed by NRC staff using SRP Chapter 13.

Training Program Development

Training plant personnel is important in ensuring the safe, reliable operation of nuclear power plants. Training programs aid in offering reasonable assurance that plant personnel have the knowledge, skills, and abilities needed to perform their roles and responsibilities. The objective of the training program review is to verify that the applicant has employed a systems approach for developing personnel training. Training programs are reviewed by NRC staff using SRP Chapter 13.

Human Factors Verification and Validation

V&V evaluations comprehensively determine that the final HFE design conforms to accepted design principles and enables personnel to successfully and safely perform their tasks to achieve operational goals. This activity involves four evaluations, with the following objectives:

- *HSI Task Support Verification* - the applicant verifies that the HSI provides the alarms, information, controls, and task support that the tasks analysis defined as needed for personnel to perform their tasks.

- *HFE Design Verification* - the applicant verifies that the design of the HSIs conforms to HFE guidelines (such as the applicant’s style guide).

- *Integrated System Validation* - the applicant validates, using performance-based tests, that the integrated system design (i.e., hardware, software, procedures and personnel elements) supports safe operation of the plant.

- *Human Engineering Discrepancy Resolution Review* - The V&V evaluations above identify human engineering discrepancies (HEDs). In this activity, the applicant verifies HED resolutions and assessed the importance of HEDs, and that the corrections are acceptable.

The staff's review of HFE V&V is to ensure that the applicant's verification of their methods and results followed their specified methodologies, that any corrections were appropriately resolved, and that the results support the conclusion of safe operation.

Design Implementation

This activity addresses the implementation of the HFE aspects of the plant design for new plants and plant modifications. For a new plant, the implementation phase is well defined and carefully monitored through start-up procedures and testing. Implementing modifications is more complex.

The objectives of the design implementation review are to verify that the applicant's:

- as-built design conforms to the design that was verified and validated

- implementation of plant changes considers the effect on personnel performance, and affords necessary support to reasonably assure safe operations

Human Performance Monitoring

The objective of reviewing an applicant's human performance monitoring program is to verify that the applicant prepared a program to:

- adequately assure that the conclusions drawn from the integrated system validation remain valid with time

- ensure that no significant safety degradation occurs because of any changes made in the plant

The applicant may incorporate this monitoring program into their problem identification and resolution program and their training program.

APPENDIX B: CONCEPT OF OPERATIONS DIMENSIONS

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 dimensions. The model was used to collect information about various designs. To facilitate the model’s use, we developed a set of questions pertaining to each dimension of the model. We made some modifications. The *Management of Off-Normal Conditions and Emergencies*, to better address small, advanced reactors and to explicitly incorporate important human actions. We also modified the *Agents’ Roles and Responsibilities* dimension to explicitly incorporate important human actions

From an HFE perspective, a ConOps identifies the design’s high-level goals and the functions and operational practices needed to manage both normal and off-normal situations. It is used to identify expectations related to human performance (Pew & Mavor, 2007). A ConOps covers all facets of the interactions of personnel with a complex system and guides the formation of requirements, the details of design, and the evaluation of the system (AIAA, 1992; DoD, 1995, 2000; Fairley & Thayer, 1977; IEEE, 2007). Increasingly, many industries are employing ConOps documents to provide a vision of how personnel are integrated into a new design or major modification (Thronesbery et al., 2009).

The model has six dimensions (see Figure B-1); each of which is briefly described below:

- Facility 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

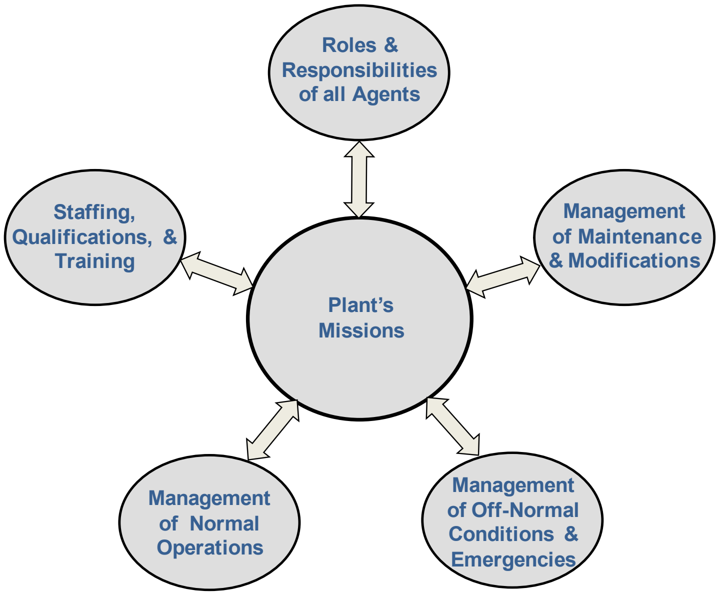

Figure B.1 Concept of Operations Model

Facility Mission

A ConOps reflects top-down design considerations. At the top is the facility's mission and the high-level goals which drive all aspects of the design, including the technological infrastructure needed to support them, and the roles/responsibilities of the crew. The mission can be described in terms of the following:

- *Goals and Objectives* - The purposes for which the facility was designed, e.g., electrical generation and safety.

- *Evolutionary Context* – The design of the predecessor facility's and the operating experience that set the foundation for the new design and 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 to achieve the 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 as 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.

Agents' Roles and Responsibilities

This dimension clarifies the relative roles and responsibilities of system's agents, namely, personnel and automation, and their relationship. Modern approaches to human-automation interaction emphasize the value of multi-agent teams for monitoring and controlling complex systems (O’Hara & Higgins, 2020; O’Hara & Higgins, 2010). The teams share and shift responsibilities to assure the facility’s overall production and safety goals are achieved. 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 automation agents can undertake any one or all these roles.

Defining human roles and responsibilities, especially important human actions, is the first step toward integrating humans and systems, from which other aspects of the ConOps and design should flow. This dimension usually is specified at a preliminary level before beginning design work, based on the operating experience from earlier designs 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 ConOps should identify how 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 identifying the HSIs and procedures necessary to support personnel tasks.

Key scenarios 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 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 discussed with respect to normal operations (key scenarios, tasks, and supporting HSI resources), except the conditions are atypical. Considerations include:

- emergencies that may impact safety, such as a loss of coolant accident
- loss of facility systems for which compensation is needed, such as the failure of a cooling-water system
- failed equipment, such as pumps and valves
- degraded I&C and HSI conditions (such as a faulty sensor, loss of an aspect of automation, or degradation of a workstation)
- human actions determined to be important needed to address these conditions

Identifying off-normal and emergency conditions and developing ways to resolve them are significant considerations affecting the planning and design of operations. There may also be differences in how safety is evaluated for small, advanced reactors and may involve methods that differ from traditional PRA/HRA methods used in applicant submittals. This ConOps dimension needs to focus on how safety significant responses, such as important human actions, to identified safety significant events are identified 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, & Anderson, 2019). .

Management of Maintenance and Modifications

This dimension encompasses the installation of facility upgrades, maintenance, and configuration management. Like the previous two dimensions, personnel tasks and how the HSIs and procedures support those tasks is considered. For example, much of the maintenance of advanced systems typically occurs at a workstation through changes in software. Such activities may be more extensive in new designs relying heavily on digital systems and automation.

APPENDIX C: ADVANCED REACTOR TECHNICAL ISSUES

The design and ConOps of advanced reactors have given rise to the recognition by industry, the NRC, and research organizations of technical issues that need to be addressed. These issues include:

- Identification of important human actions
- Autonomous operations
- Approaches to staffing
- HSIs for monitoring and controlling the reactor and interfacing systems
- Remote operations

C.1 Identification of Important Human Actions

Issue

NUREG-0711 defines *important HAs* as those actions that meet either risk or deterministic criteria:

- Risk-important human actions - Actions defined by risk criteria that plant personnel use to assure the plant's safety. There are absolute and relative criteria for defining risk important actions. For absolute ones, a risk-important action is any action whose successful performance is needed to reasonably assure that predefined risk criteria are met. For relative criteria, the risk-important actions are defined as those with the greatest risk compared to all human actions. The identifications can be made quantitatively from risk analyses, and qualitatively from various criteria, such as concerns about task performance based on considering performance-shaping factors.

- Deterministically identified important human actions - Deterministic engineering analyses typically are completed as part of the suite of analyses in the FSAR/DCD in Chapters 7, Instrumentation & Controls, and 15, Transient and Accident Analyses. These deterministic analyses also may credit human actions.

As discussed in the section on HFE triggers, the importance of identifying important HAs is that it is a basis for defining the HFE program. It is also important because it may become a basis for claims that no HAs are needed for safety-important actions.

This issue is characterized by concern that important human actions may not be easily identified. The identification of important human actions may be complicated by several factors, e.g.:

- Use of non-traditional risk analysis methods
- Lack of supporting analyses used to identify human tasks
- Human role in safety function management

Use of non-traditional risk analysis methods

The applicants may not perform traditional PRAs as are required of LLWRs. Instead, they may perform modified PRAs or other types of risk analyses, such as ISAs that focus on identifying IROFS that may not focus on quantifying human actions.

Lack of supporting analyses used to identify human tasks

The applicant may not have the supporting HFE analyses used to identify human tasks. Identifying important HAs may be more complicated for advanced reactors than LLWRs. For example, in highly automated plants, potentially important human actions include the monitoring of systems to detect failure conditions, degraded conditions, and the need to backup automatic actions if they fail. It's also important to evaluate support tasks such aligning system components as well as inspections, tests, and maintenance. At issue is whether applicants use methods that can identify these types of HAs, and the consequences of not having them on their ability to identify important HAs.

Human role in safety function management

Complicating the identification of important HAs is the fact that the means of managing off-normal events is different for advanced reactors when compared with LLWRs. In current plants, managing off-normal events typically involves a combination of the automatic control of safety systems and HAs. Many of the advanced reactors depart from this approach. Instead, they rely on different approaches to how safety functions are performed. In addition to the traditional role of humans as participants in active safety systems, advanced reactors may be designed to use passive or inherently safety systems which do not rely on human actions.

The differences in safety function management are described in Fleming et al. (2020). The following excerpt from the Fleming report captures the implications of these differences.

> They <advanced reactors> may rely on passive safety system. The safety function is achieved through reliance on laws of nature, material properties, and energy stored within the SSC. As a result, the typical causes of failure for active systems generally do not exist for a passive system; i.e., loss of power or failure of operator action. By contrast, passive systems can fail as a result of modes such as mechanical or structural failure of an SSC, or even malicious human intervention (IAEA, 2018).
>
> Other considerations are also relevant for assessing the reliability of passive safety systems. For example, passive cooling systems typically rely on natural circulation flows to transport heat to an ultimate heat sink. These natural circulation flows rely on small pressure gradients in the fluid that drive small flows. As a result, these circulation patterns can be susceptible to breakdown should these gradients be eroded. For example, a small reduction of heat transfer to the ultimate heat sink could lead to a breakdown of a natural circulation pattern. As a result, the overall reliability of a passive system can depend sensitively on how the governing physical process is influenced by boundary conditions.
>
> The characterization of these boundary conditions across a range of upset conditions can be generally difficult to assess. However, a passive safety system is designed to maintain relatively controlled boundary conditions that ensure it will function to control a plant under a broad range of internally initiated upset conditions. Passive safety systems are thus very reliable when considering the provision of their safety function to defend against internal events. An active system, by contrast, has a much higher probability of failing randomly when called upon to perform its safety function. In contrast to passive safety, inherently safe systems are those which are absolutely reliable. The classification of absolute reliability must be qualified by a detailed consideration of the range of characteristics of the SSC that support the safety function. For example, control of reactivity often involves reactivity feedback mechanisms inherent to a system preventing reactivity excursions from occurring (e.g., moderator temperature feedback). In this case, it is generally difficult to postulate an external

> perturbation that would give rise to a loss of reactivity control. However, for cooling or containment functions, it is more likely that passive systems can exhibit failures under a range of external perturbations such that they are not absolutely reliable. Under some circumstances, however, even cooling functions may be ultimately reliable should the power level of the reactor be sufficiently low that residual heat can always be rejected to the atmosphere. (pp 30-31)

Reviewers will have to assess how applicants identify risk for all types of safety function management scenarios and analyze them to support the identification of important HAs.

In addition to the above, applicants should consider SMR issues in Appendix D that are directly related to this general issue:

- D.5.6, Passive Safety Systems
- D.5.9, Identification of Risk-Important HAs

Suitability of Current Guidance

In terms of near-term application reviews, once important HAs are identified, the HFE reviewers have guidance to review them, mainly in NUREG-0800, with more specific guidance in NUREG-0711, Rev 3, Section 7, Treatment of Important Human Actions. The other SRPs currently available do not specifically address criteria for evaluating important HAs identified in facility risk analyses (O'Hara, 2021).

However, there are limitations to the near-term identification of important HAs in so far as PRA development is needed. RG 1.233 (NRC, 2020a) provides the NRC's guidance on using a risk-informed methodology, as well as technology-inclusive and performance-based methodologies to inform the licensing basis for non-LWR reactors. The RG states that the selection of LBEs; classification and special treatments of SSCs; and assessment of DID are fundamental to the safe design of non-LWRs. Nuclear Energy Institute (NEI) 18-04 (NEI, 2019c) provides a methodology for defining these aspects of advanced reactor design. RG 1.233 endorses the guidance as one acceptable method for non-LWR designers to use when carrying out these activities. Although the technology-inclusive methodology provides a common approach to selecting LBEs, classifying SSCs, and assessing DID, the applicability of specific technical requirements in NRC regulations, or the need to define additional technical requirements arising from the safety evaluations, is made on a case-by-case basis for each non-LWR design. The NRC expects that SSCs that provide essential support (including required HAs for safety related (SR) or nonsafety-related with special treatment (NSRST) SSCs will be classified in a manner consistent with the higher-level functions, even if the supporting SSC is not explicitly modeled in the PRA. The guidance in RG 1.201 and NEI 00-04 addresses the importance of a multi-discipline panel of SMEs and the role of an "integrated decision-making process" in assessing limitations of the supporting PRA, modeling SSCs and human actions, and the need to identify and address uncertainties. This guidance should support the use of common approaches to PRA and risk analysis of advanced reactors that can support the identification of important HAs. Additional guidance is also available in ASME/ANS RA-S-1.4) ASME, 2013). Guidance for the use of PRA for advanced reactors is still being developed, so its readiness to support important HAs may require development as well.

Applicants have also used integrated safety analyses (ISAs) to identify IROFS, which can include HAs. ISA has been used by applicants and both the CFR and several SRPs identify ISA as an acceptable analysis method. An issue arises in the use of ISA to assess HAs. ISAs can mask HAs by identifying them as component failure, e.g., modeling a pump failure in the ISA where it is really a failure of human action, such as failure to start the pump. Also, ISA models HAs as isolated human actions and the dependence of HAs is lost. While specific HFE review guidance is not presently available to review this type of important HA identification, reviewers can apply the approaches used by previous NRC reviews of such analyses, such as the review of the MOX facility, to determine an appropriate review strategy for the facility currently being reviewed. Limitations are discussed above to the use of ISAs are discussed in conjunction with the SRPs for facilities using such an approach.

In addition to the review of risk-important human actions, there are additional HAs that should be reviewed because they are specifically credited in design analyses. These deterministically identified *important human actions* as identified in:

- Operator actions credited in the diversity and defense in depth analysis supporting the diverse actuation system described in SRP, Chapter 7, "Instrumentation and Controls."
- Operator actions credited in the design bases analyses described in SRP, Chapter 15, "Transient and Accident Analysis."
- Risk-important human actions identified in the human reliability analysis contained in SRP, Chapter 19, "Severe Accidents."

The review guidance may also be useful in reviewing operator manual actions associated with fires especially alternate safe shutdown, flooding, beyond design basis events, and decommissioning activities. See NUREG-1764, "Guidance for the Review of Changes to Human Actions," and NUREG-1852, "Demonstrating the Feasibility and Reliability of Operator Manual Actions in Response to Fire" for specific review guidance. In addition, Chapter 18, Attachment A, "Guidance for Evaluating Credited Manual Operator Actions," provides acceptance criteria for evaluating important human actions.

Thus, in the short term, there is guidance to review important HAs that are identified in risk analyses, but the guidance has limitations that will need to be addressed by the HFE reviewer until risk analysis experts enact improvements to the methods. Risk analyses should also consider HAs for degraded conditions and failure modes that may require HA backup.

In the longer term, the identification of important HAs will be improved when the modeling of advanced reactors in PRA is improved and uncertainties reduced. It will also be important for HFE guidance to be adapted to the modeling of HAs in new PRA approaches consistent with the NEI guidance and other risk analysis methodologies. For reactor designs without reliance on HAs for safety actions, a full HFE program is probably unnecessary. But a question remains as to how much of a program is necessary to achieve reasonable assurance that the overall risk analysis program will identify important HAs and treat them appropriately.

C.2 Autonomous Operations

The issue of autonomous operations is related with the next two issues on staffing and HSI design. It is a driver for determining staffing needs, which in turn drives HSI requirements.

Issue

The NRC has identified "autonomous and remote operations" as a technical issue. SECY-11-0098 (NRC, 2011b) and SECY 20-0093 (NRC, 2020c) state that microreactor developers have expressed interest in the possibilities of autonomous and remote operation. This may raise an issue in that current regulations require operation of reactivity controls be performed only by licensed operators and that the manipulation of other HSIs that can affect power level can only happen if authorized by a licensed operator [per 10 CFR 50.54(i), (j), (k), and (m)]. Thus, autonomous and remote operations are not consistent with current regulations.

The SECY identifies policy questions raised by autonomous and remote operations:

- Eliminating human operators as a diverse means of defense-in-depth for the assurance of reactor safety.

- The facility designs may not have a control room from which individuals would be able to operate the facility.

Applicants proposing such a ConOps will need to request exemptions from these requirements. Operation of a reactor without human intervention is a significant shift from current regulations and operational practices and guidance will be needed for the staff to evaluate such requests.

This is a complex issue with many human performance considerations. We will discuss them below:

- Allocation of function decisions
- Identification of HAs needed to support autonomy
- Management of degraded conditions and automation failures
- Staffing decisions related to autonomous operations
- HSI designs to support automation-related HAs

A brief characterization of automation will be discussed to provide context for the aspects of this issue to be presented.

While a detailed ConOps of specific advanced reactors designs is not yet known, it is likely that some will include operations that are autonomous as identified in an NRC issue (see "Autonomous and Remote Operations") and in Industry studies (e.g., Fleming et al., 2020; Ramuhalli & Cetiner, 2019).

Autonomy can be conceptualized as a point on a scale extending from tasks that are performed completely by manual operations (all actions performed by human crews) to full autonomy where monitoring and control of reactor operations is performed by automation systems with no human intervention. There are many waypoints between these extremes where the level of human involvement decreases and the reliance on automation systems increases. The characterization of automation in NUREG-0700, Rev 3 includes a dimension for “Levels of Automation” along which autonomy is one endpoint.

Automation often involves cooperation and sharing of responsibilities between automatic systems and plant personnel. Intermediate levels of automation are characterized where the relative responsibilities of humans and automation in carrying out tasks varies. Table C.1, from NUREG-0700, Rev 3, illustrates one approach to classifying the levels of automation in NPP applications and identifies the general responsibilities of both automation and personnel.

Table C.1 Example of Levels of Automation for NPP Applications

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

Source is NUREG-0700, Rev 3, Table 9.1.

NPP systems are sometimes characterized at one level and, at other times, another level. Levels can be changed by predefined conditions or operator decision.

Applicants may implement designs where the levels of automation can change based on the current condition of the plant. Automation can be designed so the allocation of tasks is flexible (i.e., changeable). When automation is flexible, either the operator or automation can perform a task. The choice of whether a task is performed by personnel or automation is based on situational considerations, such as the overall workload of personnel. This is referred to as “adaptive automation” (AA).

As listed above, the decision to use a fully autonomous design has several human performance considerations:

Allocation of function decisions

One aspect of this issue is the allocation of function process used to identify autonomy as a desirable choice for level of automation of a small modular reactor. An allocation of function process examines the relative roles of humans and automation in the task performance needed to monitor and control the reactor under normal and off-normal conditions. Tasks that are better performed by humans are allocated to them, while tasks that are better performed by automation are allocated to accordingly. However, limitation to the allocation of function process have been noted (O’Hara, 2020b, c). The reviewer should evaluate the technical process used for allocation of function and how it addresses limitations of this HFE activity.

Identification of HAs needed to support autonomy

Another aspect of this issue is that there likely to be some human HAs even for fully autonomous designs. Monitoring of the performance of autonomous reactors is likely to be necessary, whether on-site or remotely. These HAs need to be identified and may serve as an aspect of the facility's DID. The reviewer should evaluate the applicant's treatment of these HAs.

Management of degraded conditions and automation failures

Another human performance aspect of this issue is the management of degraded conditions and failure modes of the autonomous systems. Applicants need to look at the need for HAs in those scenarios and the HSIs, procedures, training needed to accomplish these tasks. These analyses have Implications for staffing and control room/HSI design. Reviewers should evaluate the applicant's treatment of degraded conditions and the identification of HAs to manage them.

Staffing decisions related to autonomous operations

Autonomous operations have implications for staffing, staffing position requirements, procedures, and training. Applicants may propose that HAs related to autonomous operations will be performed by non-licensed staff, thus raising policy issues (NRC, 2020c):

> Autonomous operation necessitates evaluating the implications of reactivity operations being initiated and performed by automation rather than licensed operators, and potentially eliminating human operators as a diverse means of defense-in-depth for the assurance of reactor safety.

The biggest challenge with autonomous operation may be specifying the applicant's rationale for employing autonomous operation without a human monitor as a DID, thus leading to the conclusion that a licensed operator is not needed. The applicant should clearly define the rationale used and the analyses in support of that decision.

Reviewers should evaluate the identification of these HAs and the applicant's analyses that support their performance by non-licensed personnel.

HSI designs to support automation-related HAs

An autonomous design also has implications for the HSI design needed to support related HAs. Even where the facility design does not include a traditional control room, some monitoring and possibly control capability may be necessary. The reviewer should assess the applicant's assessment of the need for HSIs in support of HAs in autonomous systems, their HFE design, and location for personnel access.

Suitability of Current Guidance

In the near term, guidance is available in NUREG-0700, Rev 3, Section 9, Automation Systems, to review levels of automation. While no unique guidance for fully autonomous automation is provided; the review guidance in the other automation sections does apply. However, the guidance is incomplete. For example, the available guidance is sufficient to review some aspects of adaptive automation (AA), such as the monitoring of AA systems, detection of AA system failure, and the general evaluation/validation of AA systems (O'Hare 2020c). However, there are numerous areas where the guidance is insufficient to review the unique design characteristics of AA systems, such as the design of AA configurations and triggering conditions (O'Hare 2020d). Additional research is needed to provide more comprehensive guidance that can be used to evaluate these unique characteristics.

Applications submitting designs for fully autonomous operations may trigger exemption requests from a variety of regulations, such as the use of non-licensed personnel to perform activities for which the regulations require licensed personnel; NRC reviewers have guidance for reviewing some aspects of these exemption requests, but other aspects are not currently addressed.

In summary, this is a complex issue with many human performance considerations. In the near term, guidance is available to review many aspects of applicant designs and exemption requests, but not all.

In addition to the above, applicants should consider SMR issues in Appendix D that are directly related to this general issue:

- D.2.3, Function Allocation Methodology to Support Automation Decisions
- D.2.2, High Levels of Automation for All Operations and its Implementation

C.3 Approaches to Staffing

Issue

Staffing is currently prescribed by 10 CFR 50.54(m) requirements and based on LLWRs. The design and operational differences between small, advanced reactors and LLWRs have led designers to propose alternative approaches to staffing. SECY 20-0093 (NRC, 2020c) indicates that the degree of simplicity and inherent safety of small, advanced reactors may result in fewer operator actions being credited for maintaining plant safety for some designs. Other factors identified as potential justifications for fewer staff include highly automated operating systems, passive design of safety features, and large heat capacity. In fact, these design characteristics may result in few to no credited operator actions for plant safety (NRC, 2020).

The issue of staffing and qualifications for small, advanced reactors has been widely recognized. A special committee of the American Nuclear Society (ANS, 2010) evaluated the staffing of SMRs a decade ago and again in 2019 (NEI, 2019b). NEI (2019b) states that:

> The industry intends to work with the NRC to develop alternative approaches to licensed operators for micro-reactors that demonstrate they do not require continuous monitoring by an operator or any safety actions by an operator. (p. B-1)

The NRC also recognizes the need for modification of existing staffing guidance (NRC, 2011b).

The considerations characterizing this issue include:

- Alternative staffing approaches
- Training and qualification
- Beyond control room staffing

Alternative staffing approaches

By “alternative” we mean a significant departure from the staffing model required of LLWRs in 10 CFR § 50.54 and related regulations. One example of such an alternative is that proposed by OKLO Aurora. The applicant proposes to use no licensed operators and few total “operators” at the reactor during normal operations. They justify this approach on the applicant’s determination that there are no credited operator actions. This is a significant departure from current NRC guidance and industry practice.

Small, advanced reactor applicants can propose a wide range of alternative staffing approaches NEI (2019b), including:

- Changes to the roles of personnel. Performance of tasks by non-licensed personnel that are typically performed by licensed operators (e.g., emergency declarations, operability determinations, departures from license conditions or technical specifications)
- Staffing positions that are different from current LLWRs and have different qualifications and training
- No onsite personnel, personnel monitor the reactor from a remote location
- The reactor is completely autonomous, having no operations personnel at all

The staffing options in some cases would not meet current requirements, including too few operators and operator duties being performed by non-licensed personnel.

Training and qualification

The issue of staffing includes considerations of personnel training and qualification requirements. The determination of qualification and training requirements for personnel at advanced reactors are likely to be design specific, yet a common method for staff review of exemption requests related to them will be needed.

Beyond control room staffing

Staffing the plant involves more than the control room staffing addressed in the regulations. Considerations include staffing during refueling operations, reactor staff who interact with an interconnected manufacturing plant, supervisory staff, shift work, and training (NRC, 2010b). SECY 20-0093 (NRC, 2020c) points out that while the NRC has developed guidance (e.g., NUREG-1791) for reviewing staffing exemption requests), the guidance pertains to control room staffing. The NRC’s process for evaluating staffing exemption requests is predicated on the assumption that an applicant has an HFE program that can provide the necessary supporting analyses. As small, advanced reactor designers work toward reducing the number of plant personnel and their role, this assumption may need to be re-evaluated, and an alternative means for establishing an appropriate technical basis may be necessary.

Suitability of Current Guidance

Like other aspects of advanced reactor licensing, the NRC will use a two-phase strategy. In the near term, the NRC will address the issue of staffing through exemption requests. In the longer term, the NRC will investigate changes to the regulations that will eliminate the need for exemption requests.

In the near term, the question is whether the current guidance will support the evaluation of exemption requests. Currently, partial guidance for performing staffing exemption reviews is provided in NRC guidance documents:

- NUREG-1791, “Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)” (Persensky, Szabo, Plott, Engh & Barnes, 2005)

- NUREG/CR-6838, “Technical Basis for Regulatory Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m) (Plott, Engh & Barnes, 2004)

An issue with the guidance is that its focus is on staffing in a dedicated control room and may not be applicable to reactor designs based on novel ConOps, such as a design without a control room.

Another significant consideration is that small, advanced reactor applicants may not have conduced HFE programs consistent with the NRC’s current guidance for reviewing exemption requests (NRC, 2020c). NUREG-1791 is based on NUREG-0711 and relies on a technical basis rooted in HFE analyses. The NRC staff may not be able to review applications that are not rooted in an HFE process.

Additional guidance is available in Chapter 18, Attachment B, “Methodology to Assess the Workload of Challenging Operational Conditions in Support of Minimum Staffing Level Reviews.” This appendix provides a methodology to identify high-workload operational conditions and analyze the workload associated with them. The methodology is rooted in task analysis and relies on the identification of appropriate challenging scenarios, realistic portrayals of task performance that is complicated by separate, but often necessary, dependent and independent tasks, and the judgment of subject matter experts (SMEs) obtained in a manner conducive to obtaining realistic workload estimation. The methodology can be used before the design is ready for validation or full-mission tests using actual crews and realistic scenario simulations. Thus, it provides the NRC staff with an early means to assess the acceptability of minimum staffing requests.

However, the final acceptance of minimum staffing levels is dependent on many considerations, not all of which are addressed by the workload methodology. For example, the methodology does not address:

- actual task performance
- the effects of other important performance factors, such as situation awareness
- the effects of under-load, which is also a concern when determining staffing levels

Thus, in the short term, guidance is available to support staffing exemption request reviews. However, the guidance has limitations and may not be applicable to some design ConOps, such as the case of a design without a control room and no operational staff.

As discussed above, the available guidance to support the review of staffing exemption requests is contained in several documents, e.g., NUREG-0800 (Chapters 13 and 18), NUREG-0800, Chapter 18, Appendix B, NUREG-0711, and NUREG-1791. In the short-term, there may be value to having tailored guidance for evaluating staffing exemption requests that is based on the overall HFE program guidance but presents the detailed considerations of how the HFE program addresses levels of staffing. Granting exemptions to staffing level requirements should be based on careful consideration of the technical basis of the request. That is the intent of NUREG-1791. However, as noted above, NUREG-1791 is based on Revision 2 of NUREG-0711. There have since then been significant changes to NUREG-0711 in Revision 3, especially in the task analysis and ISV areas.

Eventually the NRC might consider establishing a single source of guidance that integrates the guidance currently available. The new guidance could be a significant update of NUREG-1791, or at a minimum, the new guidance can provide a roadmap for reviewers for determining when and how to use the various staffing documents.

SECY-93-092 (NRC, 1993) recommends an approach to staffing evaluation based on HFE analyses. The SECY states:

> The function and task analyses must demonstrate and confirm the following through test and evaluation: Smaller operating crews can respond effectively to a worst-case array of power maneuvers, refueling and maintenance activities, and accident conditions. * An accident at a single unit can be mitigated with the proposed number of licensed operators, less one, while all other units could be taken to a cold-shutdown condition from a variety of potential operating conditions, including a fire in one unit. * The units can be safely shut down with eventual progression to a safe shutdown condition under each of the following conditions: (1) a complete loss of computer control capability, (2) a complete station blackout, or (3) a design-basis seismic event. * The adequacy of these analyses shall be tested and demonstrated. The staff is currently recommending that an "actual control room prototype" be used for test and demonstration purposes.

The SECY identifies a technical basis relying on HFE analyses and simulator testing to support an applicant’s proposed staffing proposals. Applied to designs on an individual basis, the applicant’s proposed staffing plan would be evaluated as an exemption request or a new, design-specific staffing regulation.

In the long-term, changes to the regulations in 10 CFR may be necessary. Applicable regulations include:

- 50.54(i) - (m) on staffing levels
- CRF Appendix A, GDC Criterion 19 on control room design
- 50.34(f)(2)(i) on simulators

Regulatory guidance may need updating as well:

- SRP NUREG-0800 Chapters 13 and 18. guidance on operational programs and HFE
- RG 1.114 (NRC, 2008), guidance to operators at the controls
- RG 1.149 (2011) and the related ANS 3.5 (2009), guidance on simulators
- NUREG-1791 (Persensky, Szabo, Plott, Engh, & Barnes, 2005), guidance for staffing exemptions.

In addition to the above, applicants should consider SMR issues in Appendix D that are directly related to this general issue:

- D.3.1, New Staffing Positions
- D.3.2, Staffing Models
- D.3.3, Staffing Levels

C.4 HSIs for Monitoring and Controlling the Reactor and Interfacing Systems

Issue

Small, advanced reactor designers have suggested that they may have few safety-related HAs and that there may be an overall reduction in the HAs needed for monitoring and controlling the plant. As previously discussed, some designers suggest that no operator actions may be needed. The results of those assessments have profound implications for the design of the plant control room and HSIs

A control room is currently required by NRC regulations; applicants should provide, for Commission review, a control room design that reflects state-of-the-art human factor principles. NEI (2019b) has stated that due to advances in technology, a traditional control room may not be necessary. For micro-reactors that demonstrate the safety of the reactor can be assured without the need for operator action, and if an operator is unable to compromise the safety of the reactor through the manipulations of the controls, then there would be no need for requirements relating to the control room or for an operator-initiated shutdown.

The NRC review of applicant submittals without control rooms is not unprecedented. NUREG-1567 (NRC, 2000c) and NUREG-2215 (NRC, 2020c) indicate that the NRC has accepted omission of a control room for ISFSI operations that have not involved use of a powered cooling system for material in storage. The NRC has required applicants to provide a justification for control room exclusion. Justifications can include:

- a description of functions and procedures that provide for performance without the need for a centralized control room

- the acceptability of accident and off-normal event/condition analyses that show acceptable levels of maximum response and safety without use of a control room

- the use of passive measures to avoid damage and provide mitigation

While these are important considerations, we think important information may be missing. Regarding the first bullet, what description/analysis is going to show this? The decision that a control room is not necessary should consider HAs (tasks), HSIs, and training, as well as what is described. The analysis should also consider workload and timing requirements as well.

Regarding the third bullet, the applicant should describe the analyses providing information contributing to decisions regarding the acceptability of passive measures and how applicants ensure the analysis covers all safety-important scenarios.

Thus, while the lack of a control room may still be inconsistent with NRC regulations, including the revised GDC-19, the NRC has considered such a design in SRPs and provided some guidance for what information applicant's need to provide to justify such a design, presumably as part of an exemption request. We have pointed out some additional considerations that can be used in the near term to strengthen the information available to reviewers.

SECY-10-0034 (NRC, 2010b) discussed the issue of multi-modular facilities and the use of a single control room to operate more than two reactors. The current regulations do not address situations that go beyond two reactors. In addition, the SMR units may be operated by a staff that is below current staffing requirements. The SECY identifies other potential SMR issues including the possible need for requirements on control room staffing during refueling operations, reactor staff who interact with an interconnected manufacturing plant, supervisory staff, shift work, and training.

The SECY illustrates the complexities of the interrelated issues related to staffing a multi-unit plant and its control room design. It also addresses the need for a multidisciplinary approach to reviewing applicant submittals for alternative staffing approaches, including human factors and instrument and controls expertise.

If an applicant's submittal does not include a control room, what alternatives might they propose? The range of HSI options is broad and can include design solutions such as:

- No HSIs
- Simplified HSIs providing limited displays and controls, like local control stations in current plants
- Portable, and possibly wearable, HSIs that are not tied to a specific location in the plant but are taken by personnel to a location where they are needed (NEI 2019b)
- HSIs located at a location remote from the facility (this design option is discussed in the issues of "Remote Operations" in Section 5.2.5 below)

Applicants will have to provide the technical basis for the approach to HSI design proposed in their application. In addition, since some advanced reactors serve multiple missions, HSIs may be needed for monitoring and controlling them as well, such as the need to address interfacing systems serving non-electricity generation missions such as the production of process heat. This imposes control room requirements not addressed in current HSI design review guidance.

In addition to regulatory and technical concerns over the design of the HSIs themselves, another aspect of this issue is that HSIs may not be designed using an HFE program (NRC, 2020). Currently an HSI design review includes an assessment of the HSI design review process (per NUREG-0711).

Suitability of Current Guidance

In the near term, acceptance criteria for an applicant's HFE design are provided in Chapter 18 of the Standard Review Plan (NUREG-0800), NUREG-0711, and NUREG-0700. Current review guidance addresses the HFE process as well as the design of HSIs resulting from the process. A small, advanced reactor may have such a simplified design that it is difficult to review using current guidance. Very simplified HSIs for small, advanced reactors may not have been designed following such an approach.

NRC reviewers have available other SRPs that, while not developed for power reactors, may provide guidance that better matches an applicant's HSI submittals. Examples include NUREG-1537 for non-power reactors, or NUREG-1718 for the MOX facility,

The guidance and review criteria for non-power reactors is contained in NUREG-1537 (see Section 4.2.3 above). Section 7.6, Control Console and Display Instruments, states that "The non-power reactor control room, containing the control console and other status display instruments is the hub for reactor facility operation. It is the location to which all information necessary and sufficient for safe and effective operation of the facility is transmitted, and the primary location from which control and safety devices are actuated either manually or automatically." Acceptance criteria for control console review are provided. Similarly, NUREG-1537 Chapter 12 addresses facility staffing requirements and related considerations such as qualifications, selection, and training.

As discussed in Section 4,2.2, of RG 1.232(NRC, 2018a) discusses how the GDC can be adapted to non-LWRs resulting in an advanced reactor design criterion (ARDC). This guidance may be used by non-LWR reactor designers, applicants, and licensees to develop principal design criteria (PDC) for any non-LWR designs, as required by the NRC regulations.

NUREG-1718 has HFE review guidance that is a scaled down version of NUREG-0711 developed for a simplified HSI and one which identified important HAs using an ISA and not PRA.

The revised criterion still describes a control room and does not consider a situation where a control room may not be needed.

The RG discusses the NRC's rationale for modifications and clarifications of the GDC. ARDC 19 preserves the language of GDC 19 which states (with emphasis added by the NRC) "A control room shall be provided from which actions can be taken to operate the nuclear power unit …" However, clarification of this language was provided in RG 1.232: The ARDC modification recognizes the need for operator decision making support and the role of advanced HSIs in supporting this need. However, as noted above, this modification does not address the possibility of a design with no control room.

The bottom line is that guidance is available for reviewing HSIs for advanced reactors; however, none of the existing guidance is a particularly good fit.

In addition to the above, applicants should consider SMR issues in Appendix D that are directly related to this general issue:

- D.4.8, Control Room Configuration and Workstation Design for Multi-Unit Teams
- D.2.1, Multi-Unit Operations and Teamwork;
- D.4.9, HSI Design for Multi-Unit Monitoring and Control
- D.4.10, HSIs for New Missions

C.5 Remote Operations

Issue

The ConOps for some small, advanced reactors may include the use of remote operations. This issue concerns where HSIs are located. A decision for remote location may be informed by the analysis of “HSI for monitoring and controlling the reactor …” above. A reactor can be located at a desired location, while monitoring, and if necessary controlled, may be handled from a remote location. Such a ConOps is not addressed in current regulations or review guidance.

Two different types of operations are often conflated: autonomy and remote operations. However, they are separate issues. To operate a reactor remotely does not require the reactor to be autonomous. Remote operations are operation from a location removed from the plant’s site boundary. The reactor and plant may still require full-time monitoring and control yet be operated remotely. Autonomous operations, as discussed above, means the reactor does not require human intervention for most normal and safety operations. Autonomous operations are still likely to require some infrequent HAs and these may be handled from a remote site.

At present, the HFE requirements for remote operations are not known, e.g., Will HSIs have to be modified from what they would be if located on-site? What also needs to be considered are the HAs need for monitoring and control of the interfacing systems, such as balance of plant (BOP) systems and those of other missions like generation of industrial heat.

Questions such as these will need to be addressed by NRC reviewers and guidance will be needed to support them. Applicants who desire to use remote operations should discuss this with staff early during pre-application meetings so that reviewers can assess what tools are available (e.g., exemptions).

Suitability of Current Guidance

In the near-term, applicants will need to submit exemption requests related to control room requirements to support remote operations. However, there is no guidance currently available to support the “remote” aspects of the operations, e.g., the HFE requirements for remote operations. Before reviews of such an exemption request are performed, research is needed to help identify the HFE needs for remote operations. Before such research is completed, applicants can be asked to provide justification for the use of remote operations and for determining the location, such as how far from the plant site, from which operations are performed.

In the long term, the research and experience from reviews of applicant submittals can be used to suggest changes, if warranted, to the regulations and the supporting review guidance for remote operations.

To the greatest extent possible, applicants HFE programs should address issues impacting their facility design and operation to help ensure none negatively impact human performance.

APPENDIX D: SMALL MODULAR REACTOR TECHNICAL ISSUES

The issues described in this Appendix were identified in an NRC research project focusing on SMRs (O’Hara, Higgins & Pena, 2012). However, most are applicable to other advanced reactor designs as well.

While we reviewed information on SMR designs to obtain information, the designs were not completed and much of the design and operational information is not yet available. Nor was there information on multi-unit operations as envisioned for SMRs available in operating experience. Thus, to gain a better understanding of multi-unit operations we sought lessons learned from non-nuclear systems that have experience in multi-unit operations, specifically refineries, unmanned aerial vehicles and tele-intensive care units. The ConOps model described in O’Hara 2020a was used to seek and structure the information obtained. Thus, we evaluated several sources of information about SMRs and related systems to identify potential challenges to human performance.

The issues broadly addressed several technological disciplines, including HFE, I&C, plant operations, maintenance, and PRA. There is some redundancy because different sources of information often identified similar challenges. This redundancy is good because it reflects a measure of the converging validation.

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 control rooms and HSIs. Several issues such as passive systems are not solely related to SMRs and advanced reactor technology.

Table D.1 lists the issues identified for each ConOps dimension. The issues were updated to reflect information obtained after 2012. The issues are discussed in more detail below. We first describe each one, and then address its implications for design reviews and research.

Based on these issues and their implications, a reviewer aid for evaluating the HFE aspects of SMRs was developed (O’Hara, Higgins & D’Agostino, 2015). The document identifies questions that an NRC reviewer can be ask applicants whose designs have the characteristics identified in the issues. The questions for each issue were identified and organized based on the review elements and guidance contained in Chapter 18 of the *Standard Review Plan* (NUREG-0800), and the *Human Factors Engineering Program Review Model* (NUREG-0711).

Table D.1 Potential SMR Technical Issues

ConOps Dimension	Technical Issue
Plant Mission	New Missions
	Novel Designs and Limited Operating Experience from Predecessor Systems
Agents' Roles and Responsibilities	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	New Staffing Positions
	Staffing Models
	Staffing Levels
Management of Normal Operations	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	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	Modular Construction and Component Replacement
	New Maintenance Operations
	Managing Novel Maintenance Hazards

Source is O'Hara, Higgins & Pena (2012)

D.1 Plant Mission

We identified two issues for this aspect of SMR ConOps:

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

D.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 high temperature gas-cooled reactors (HTGRs) as follows:

> These applications include supplying process heat and energy in the forms of steam, electricity and high temperature gas to a wide variety of industrial processes including, for example, petro-chemical and chemical processing, fertilizer production, and crude oil refining. In addition to supplying process heat and energy the HTGR 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 the number of process applications, 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 raised above will help the assessment of the extent to which the safety of reactor operations may be impacted. 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.

D.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 of non-nuclear systems. The impact of this information gap and compensatory approaches should be evaluated.

Implications

The Advanced Reactor Policy Statement (NRC, 2008b) addressed the role of supporting technology in advanced reactor designs and NRC staff's position on development and utilization of the policy statement (Williams & King, 1988) discusses and encourages use of operating experience. NUREG-1226 (Williams & King, 1988) states that "The available sources of operating experience should be used whenever possible. It is emphasized that sources of useful operating experience are not limited to reactors." NUREG-1226 also discusses the use of information and data developed from foreign sources: "the use of foreign data to support a U.S. advanced reactor design is acceptable provided the staff has sufficient access to the design, analysis and experimental data being used."

This approach to the use of operating experience in new LWR designs is already incorporated in the staff's review of HFE described in NUREG-0711 (O'Hara, et al., 2012). Review Criterion 3.4.1 (1), *Predecessor/Related Plants and Systems,* of NUREG-0711 states that "For applicants proposing to use new technology or systems that were not used in the predecessor plants, the operating experience review should review and describe the operating experience of any other facilities that already use that technology."

For small modular reactors, data relating to heat pipes, supercritical CO_2, and other potential components are expected to be gathered from non-nuclear experience. Since the operating environment of the available data may be different than that for small modular reactors, its relevance needs to be assessed.

The extent to which operating experience is lacking should be evaluated to determine the potential impact on the HFE program and to determine whether additional tests and evaluations are needed in lieu of operational experience?

Modifications of the staff's review guidance on operating experience are needed to accommodate a greater diversity of experiences at predecessor plants 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, and small evolutionary changes from specific predecessor plants for new designs. For addressing SMRs and small, advanced reactors, NUREG-0711, Section 3, Operating Experience Review, must be revised.

D.2 Agents' Roles and Responsibilities

We identified three issues for this aspect of SMR ConOps:

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

D.2.1 Multi-Unit Operations and Teamwork

Issue Description

For some SMR designs, a single crew/operator may simultaneously monitor and control multiple units from one control room. Key issues in effectively and reliably accomplishing this task will be teamwork, situation awareness (SA), control room and HSI design, and operator workload. Maintaining enough awareness of the status of multiple SMRs may tax crews and individual operators. For example, unmanned aerial vehicle studies found that operators sometimes focus on a particular vehicle and may neglect others (this has been called "unit neglect"), or fail to notice important changes to the other vehicles (this has been called "change blindness").

When operators are focused on a problem in current plants, other operators can take over their other tasks. Such cooperation may be difficult when each operator is responsible for multiple units. In refineries, this situation was addressed by augmenting the crew with additional staff during times of high workload or special evolutions. This is a different operational practice than is used in present-day NPP 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 in 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 D.4.1)

- unit design differences often exist (see Section D.4.2)

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

In addition, 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 unit, ongoing maintenance, and trends in operation from one crew to another.

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. 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 in-depth study of multi-unit operations in other industries, like the way surrogates were used in prior NRC research (O'Hara, Higgins & Pena, 2012). Since there is limited literature available, site visits may be a good way to obtain this information. Having a more complete 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 be needed to determine whether the latter can be generalized to NPP operations.

Until such research in complete, HFE reviewers should request that applicants justify their proposed multi-unit operational strategy, e.g., by simulations. However, this is not a substitute for the research 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.

Related issues are discussed below in Sections D.3.2.and D.5.3.

D.2.2 High Levels of Automation for All Operations and its Implementation

Issue Description

The findings from surrogate facilities emphasized automation as key enabling technology for multi-unit operations. As crews are assigned more units to manage, automation must perform 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, there is a complex relationship between automation and human performance, which often fails to confirm common-sense expectations. For example, it is expected that high levels of automation will lower workload; instead, it shifts workload and creates other human-performance difficulties (O'Hara & Higgins, 2010).

Concerns about these negative effects of over-automation, has led to an increase in the usage of more interactive automation, such as adaptive automation (AA) (O'Hara, 2020c). 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 personnel needs 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. 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. 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.

O'Hara (2020d) evaluated whether the NRC's HFE guidance is sufficiently comprehensive to support AA system reviews; and when it is not, to identify what additional guidance is needed. To do the guidance in NUREG-0711 and NUREG-0700 was evaluated for reviewing the allocation of functions to AA systems, AA system design, and the evaluation and validation of AA systems. The results revealed that the available guidance is sufficient to review some aspects of AA, such as the monitoring of AA systems, detection of AA system failure, and the general evaluation/validation of AA systems. However, there are numerous areas where the guidance is insufficient to review the unique design characteristics of AA systems, such as the design of AA configurations and triggering conditions. Additional research is needed to provide more comprehensive guidance that can be used to evaluate these unique characteristics.

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. This guidance has been integrated into NUREG-0700, Rev 3 and should support HFE reviewers in addressing automation in SMR designs.

While this guidance significantly enhances the staff's reviews, additional research is needed in some areas (O'Hara and Higgins, 2010 and O'Hara, 2020c, detail the research needs listed below):

- models of teamwork
- overall impact of aa on performance
- reliability
- processes used by automation
- isolation of the effects of automation's dimensions
- triggering mechanisms for adaptive automation
- HSI design
- function allocation

In addition, a lesson learned from the Department of Defense's (DoD) 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 D.4.3, Operational Impact of Control Systems for Shared Aspects of SMRs.

D.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 considerations generally is called function 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 Pebble Bed Modular Reactor (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 (see Section 4, Functional Requirements Analysis and Function Allocation). However, modern applications of automation have much flexibility, so that operators face many different automation types of tasks and interactions. The NRC's characterization of automation (O'Hara & Higgins, 2010) 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 selecting the types of automation and levels of operator involvement to implement for specific applications; the resulting guidance should be included in NUREG-0711.

D.3 Staffing, Qualifications, and Training

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

- New Staffing Positions
- Staffing Models
- Staffing Levels

D.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, they may require new staffing positions as compared with 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 D.3.3, Staffing Levels.

D.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).[12] To meet these responsibilities, utilities employ a combination of on-site staff and off-site personnel. The staffing model chosen is a very significant design-decision as it drives many other aspects of the plant’s design, including degree of automation, the HSI design, and personnel training.

Current U.S. NPPs have many on-site personnel organized into functional groups. Operations are performed by shifts of reactor operators who the NRC licenses to manage reactor and balance of plant systems. Each shift is expected to manage all phases of plant operations including normal (e.g., startup, changing power levels, and shutdown) and off-normal conditions (e.g., equipment failures, transients, and accidents). In certain emergencies, additional staff are 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, This approach is analogous to how some unmanned vehicles and refineries are operated. 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.

The staffing models for SMRs may differ from those in currently operating plants. For example, we noted in our discussion in Section D.2.1, Multi-Unit Operations and Teamwork, that the crews in some 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, significant organizational changes are needed to manage these situations. 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 roles that best supports overall system performance and safety, and consider the impact on teamwork, e.g., on the peer-checking process.

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[12] 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.

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 D.3.3, Staffing Levels.

D.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 senior reactor operator (SRO), two reactor operators (ROs), and a shift supervisor (second SRO) are required for an operating reactor. For a two-unit site, two SROs and three ROs are needed. A three-unit site needs three SROs and five ROs. The table does not cover sites with more than three units.

Many SMRs designers propose staffing levels below these requirements and, therefore, exemptions from this staffing regulation are needed. For example, an SMR designer may assign 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 encompassing three ROs, one SRO control room supervisor, one SRO shift manager, and one shift technical advisor (STA). Thus, the staffing levels needed to safely and reliably monitor and control all SMR units must be determined and reviewed, possibly addressing new staff positions and staffing models, as described above.

Implications

As we noted above, staffing levels are identified in 10 CFR 50.54(m); hence, a change in this regulation or an exemption is needed to permit SMRs to deviate from the minimum established levels. 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, 2010b) "…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 reflects the NUREG-0711 HFE review process and addresses multi-unit operations. Additional research is warranted, aimed at verifying its approach and updating it for more recent guidance in NUREG-0711 and other NRC staffing documents. If necessary, it should better address the SMR staffing issues in light of the design developments and human-performance considerations since its publication.

D.4 Management of Normal Operations

There are 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)

D.4.1 Different Unit States of Operation

Issue Description

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

Implications

This issue has two implications. First, 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 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 using NUREG-0711, and for depicting unit status and status changes in the control room’s HSIs, reviewed using NUREG-0700.

D.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 others such as 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 are operating. While 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. The differences may impact 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 quantifying the extent to which differences impact performance and identifying which aspect of performance is 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 unit differences lead to the need for different responses, then they may compromise the operator's response. For example, an operator's response to a disturbance in Unit 2 may be 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, guidance is needed on whether and how these differences should be depicted in control room HSIs. NUREG-0700 lacks guidance on this issue. Depicting differences with no impact on operator's performance could needlessly complicate displays; failing to depict those that do impact operator performance may lead to 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 10 CFR 50.59 process, or for ways to address it, such as specific HSI design techniques. There are implications also for 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.

D.4.3 Operational Impact of Control Systems for Shared Aspects of SMRs

Issue Description

In typical plants today, 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 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 and I&C challenge. 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.

There are a couple of additional challenges. 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 challenge 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 or for errors that may occur when responsibilities are transferred.. 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 may, in turn, impact the HSI's design, particularly if the choice is separate procedures for each unit.

Research on this issue will provide a basis for developing 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.

D.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 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, and support the development of guidance to assess proposed applicant approaches to introducing new units. The new guidance is likely to impact both NUREG-0711 and NUREG-0700.

D.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 an HPM, a lead-cooled fast reactor, will involve different reactivity effects from those in LWRs. 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 performance. The acceptability of the operator's performance must be specifically tested as part of a thorough ISV program. Thus, the new guidance will impact both NUREG-0711 and NUREG-0700.

D.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 involves 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 involve 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

Applicants, 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. The RO/SRO monitor is responsible to intervene if an unsafe condition is expected/detected.

Each of the two approaches has its own issues. Method A creates 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.

Once an acceptable approach is determined, designers will need to define the operator tasks needed 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.

D.4.7 Novel Refueling Methods

Issue Description

Several SMRs 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 (O'Hara, Higgins & Pena, 2012). 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 D.4.1, Different Unit States of Operation.

D.4.8 Control Room Configuration and Workstation Design for Multi-Unit Teams

Issue Description

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 multiple 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 multiple units, considering the HSI resources needed for today's control room that monitors a single unit; expanding that to multiple units may prove more challenging.

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 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 reliable operator performance, situation awareness, and teamwork. As noted earlier, one aspect of this research is to gather experience from other industries that practice multi-unit operation.

See also the implication discussed in D.2.1, Multi-Unit Operations and Teamwork; and Section D.4.9, HSI Design for Multi-Unit Monitoring and Control.

D.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 design consideration. 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 unit neglect.

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

The organization of information in supporting teamwork is another important HSI design consideration, 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 needs to be determined.

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

Implications

Research should be undertaken to 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. Research on this issue will provide a technical basis for developing new review guidance.

See also the implications discussed in D.2.1, Multi-Unit Operations and Teamwork, and D.4.8, Control Room Configuration and Workstation Design for Multi-Unit Teams.

D.4.10 HSIs for New Missions

Issue Description

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

Implications

The review of the new HSIs themselves can likely be supported by the guidance in NUREG-0700, but the guidance may need to be expanded to address 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.

D.5 Management of Off-Normal Conditions and Emergencies

One important aspect of managing off-normal conditions and emergencies already raised issue D.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 issues for this aspect of 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

D.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), and NUREG-0737 (Supplement 1) (NRC, 1983). The HFE aspects of the NRC's SPDS guidance was integrated into NUREG-0700, Section 5 (O'Hara & Fleger, 2020).

The specific safety functions and parameters identified in the SPDS documents identified above are based on conventional LWRs. However, SMR designs, using non-LWR technology, such as HTGRs and LMRs, may require different safety functions and parameters to help operating crews to effectively monitor the plant's safety. This was partly addressed in the Revision 3 update to NUREG-0700. The treatment of SPDS functions was modified to make the review guidance technology neutral. However, new issues arise for safety function monitoring of multi-unit plants.

Implications

Research is needed on the design of SPDS in multi-unit plants to determine how individual unit status can quickly be assessed and details of units at risk can be quickly determined.

D.5.2 Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units

Issue Description

Unplanned shutdowns or degraded conditions in 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 (O'Hara, Gunther, Martinez-Guridi & Anderson, 2019). 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 control room and the HSI must support the effective transfer of a unit to other operators.

Implications

While this is clearly a broad safety issue, 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.

D.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 noted in Sections D.2.1 and D.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.[13]

- 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:

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[13] 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.

  - 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 operators?
  - 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 loss of offsite power, and “external events” such as fire, flood, and earthquakes.

A related question, discussed in Section D.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?

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 D.5.2, Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units and D.5.4, Design of Emergency Operating Procedures (EOPs) for Multi-Unit Disturbances.

D.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 A.4.2, how will procedures address differences between 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 their implementation in CBP applications using the guidance in SRP Chapter 13 and 18. 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.

D.5.5 New Hazards

Issue Description

Many SMR designs are based on non-light water technology. In contrast to LWR designs, they potentially involve new hazards, for example, 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 use to monitor the plant, the procedures they use to address hazards, and operator training.

Implications

Vendors need to address new hazards and the 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 for the overall management of hazards. This probably will affect the guidance in NUREG-0711 and NUREG-0700.

D.5.6 Passive Safety Systems

Issue Description

In response to transients and accidents, some SMRs employ passive safety systems 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 and cooling. Some passive systems use one or two valves to initiate the process.

The IAEA's (2009) raised concerns about passive systems based on the limited experience with reactor designs 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.

- Incorporating passive safety features and systems into advanced reactor designs to achieve targeted safety goals must be proven as effective.

We note that passive safety systems depend on 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 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. In addition, verification of system alignments and examinations of passive system condition may be of greater significance as periodic operational tests may not be possible. 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 specify the operator's actions for monitoring, backing-up, and securing passive systems, and NRC's guidance updated to address them. Additionally, the control room V&V program should address these aspects of operator interaction with passive systems. Another implication is that verification of system alignments and examinations of passive system condition may be of greater significance as periodic operational tests may not be possible. The new guidance likely will impact the review guidance in both NUREG-0711 and NUREG-0700.

D.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 control room, 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 D.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 control room for multiple units has implications for various aspects of control room requirements, guidance, and analyses, including design, PRA and failure analysis, human reliability analysis (HRA), GDC 19 compliance, control room 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 (O’Hara, Gunther, Martinez-Guridi & Anderson, 2019).

D.5.8 PRA Evaluation of Site-Wide Risk

Issue Description

SMR sites may have more units than current PRAs typically address. 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 high due to CD at multiple units.

Implications

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 more actions than does a single-unit PRA. These RIHAs should 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 D.5.9, Identification of RIHAs when One Operator/Crew is Managing Multiple SMRs.

D.5.9 Identification of Risk-Important Human Actions when One Operator/Crew is Managing Multiple SMRs

Issue Description

An area where new techniques may be needed is the identification of 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 to 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 operators monitor 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.

Implications

This issue has implications for PRA and HRA techniques and for calculating RIHAs. 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 D.5.7, PRA Evaluation of Site-wide Risk.

D.6 Management of Maintenance and Modifications

There are three issues for this aspect of SMR ConOps:

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

D.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 address this issue.

D.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. This operation 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 when 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 over 90%. These practices include on-line maintenance. Some of the next generation of plants similarly is likely to employ on-line maintenance practices because the same working fluids (steam and water) and equipment (pumps, motors, valves, piping, and heat exchangers) will be used. Consequently, the SMRs can be expected to be maintained online, 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 accurate situational awareness of each unit's status.

Operators are responsible for safe operation of the plant 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 should be evaluated. 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.

D.6.3 Managing Maintenance Hazards

Issue Description

We identified several potential challenges in human factors associated with maintaining each specific design we examined. They are listed in O'Hara, Higgins and Pena (2012), Section 3.4, Insights for SMR ConOps from SMR Design and Operations, item 19. These new maintenance practices should be analysed to ensure personnel and plant safety.

Implications

This issue can most likely be addressed by industry research, and vendors' HFE programs evaluating maintenance design and planning.