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Methodology to Assess the Workload of Challenging Operational Conditions In Support of Minimum Staffing Level Reviews

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Acronyms and Abbreviations

ANS	American Nuclear Society
ANSI	American National Standards Institute
BTP	Branch Technical Position
AO	auxiliary operator
CFR	U.S. Code of Federal Regulations
COL	combined licenses
ConOps	concepts of operations
CP	Construction Permit
CTA	cognitive task analysis
DoD	U.S. Department of Defense
EOF	emergency operations facility
FRA&FA	functional requirements analysis and function allocation
HARDMAN	Hardware vs. Manpower (human performance model)
HED	human engineering discrepancy
HFE	human factors engineering
HPM	human performance monitoring
HSI	human-system interface
I&C	instrumentation and control
IMPRINT	Improved Performance Research Integration Tool (human performance model)
ISV	integrated system validation
KSAs	knowledge, skills, and abilities/aptitudes
LOCA	loss of coolant accident
MCR	main control room
MUX	multiplexer
NASA	National Aeronautics and Space Administration
NEI	Nuclear Energy Institute
NRC	U.S. Nuclear Regulatory Commission
NPP	nuclear power plant
O&M	operations and maintenance
OL	operating license
OSC	operational support center
PBMR	Pebble Bed Modular Reactor
PRA	probabilistic risk assessment
RCS	reactor cooling system
RG	regulatory guide
SA	situation awareness
SG	steam generator
SGTR	steam generator tube rupture
SME	subject matter expert
SMR	small modular reactor
SOC	sampling of operational conditions
SRP	Standard Review Plan
STA	shift technical advisor
TA	task analysis
TLX	Task Load Index
TMI	Three-Mile Island (nuclear power plant)
TSC	technical support center
S&Q	staffing and qualifications
SWAT	Subjective Workload Assessment Technique

SWORD	subjective workload dominance (technique)
V&V	verification and validation
VACP	visual, auditory, cognitive, and psychomotor (component of workload)

1 Introduction

The nuclear industry is currently developing new, advanced nuclear power plants (NPPs), while at the same time modernizing existing plants, to support future power generation. These trends are based on new technology, new systems, and new tools to support the work of plant personnel. These changes have led to the emergence of concepts of operations (ConOps) that may be significantly different from those used in operating plants over the past half century (see O'Hara, Higgins & Pena (2012) for a more detailed discussion of new ConOps).

One aspect of new ConOps is the operation of the plant with fewer staff. A special committee of the American Nuclear Society (ANS) evaluated the staffing of small modular reactors (SMRs) and concluded lower levels are possible (ANS, 2010). Grenci and Haemer (2010) assessed the staffing needs for SMRs and concluded that staffing levels can be reduced below current regulatory requirements and the collateral duties performed by operators can be increased. The technical basis for their conclusion is that differences from current designs lead to fewer needed human actions and increased time availability. Should additional staff be needed due to transients or accidents, the longer times to core damage and radioactive releases should provide sufficient time, in most cases, to get them on-site. The authors refer to the operating experience in other industries to justify their conclusions that increases in automation can lead to reductions in staffing, e.g., the reduction in flight-deck crew from three to two in modern airliners. Grenci and Haemer (2010) cautioned that their general conclusions need to be confirmed for individual designs.

Advances in NPP technologies may change several aspects of current staffing practices, e.g.:

- *Reduced staffing levels* - reducing operator workload may enable safe operation of a NPP with fewer staff than currently required.

- *Changes in responsibilities/configurations* – changes may be made to the types of operations staff (e.g. licensed verses non-licensed) per unit per control room, the scope of work for operators, and the types of functions and tasks an operator can complete given various task demands, timing constraints, and prioritization.

- *Sharing of* crews - other forms of staffing reductions are possible, such as combining the role of the operator with the role of the maintenance person, and greater automation that expands the operator's role to one of a supervisor

Such new staffing practices have potentially significant safety impacts. The U.S. Nuclear Regulatory Commission (NRC) recognized that proposed staffing levels might deviate from the regulations and identified Issue 4.1, Appropriate Requirements for Operator Staffing for Small or Multi-Module Facilities, in SECY-10-0034 (NRC, 2010). The SECY states that changes in staffing is "…a potential policy issue that may require changes to existing regulations." Concerns over staffing have been identified in other NRC and industry studies as well (Mallett, 2010; Mays & Williams, 2010; Smith, 2009 & 2012; O'Hara et al., 2012; Tran et al., 2007).

In part, the safe NPP operation is based on ensuring that the demands of the work do not exceed the available staff resources. Staffing considerations in NPP control rooms include the numbers, qualifications, responsibilities, and authorities of operational crews. Currently, staffing requirements for licensed operators are defined in Title 10, Section 50.54(m), of the Code of Federal Regulations [10 CFR 50.54(m)] (see Table 1-1) and all operating NPPs meet these requirements. These regulations were established in the 1980's based on judgment and experience with operating light-water reactors at the time.

Table 1-1 Minimum Requirements[1] Per Shift for On-Site Staffing of Nuclear Power Units by Operators and Senior Operators Licensed Under 10 CFR Part 55

Number of nuclear power units operating[2]	Position	One Unit	Two units		Three units	
		One control room	One control room	Two control rooms	Two control rooms	Three control rooms
None	Senior Operator	1	1	1	1	1
	Operator	1	2	2	3	3
One	Senior Operator	2	2	2	2	2
	Operator	2	3	3	4	4
Two	Senior Operator		2	3	[3]3	3
	Operator		3	4	[3]5	5
Three	Senior Operator				3	4
	Operator				5	6

[1]Temporary deviations from the numbers required by this table shall be in accordance with criteria established in the unit's technical specifications.

[2]For the purpose of this table, a nuclear power unit is considered to be operating when it is in a mode other than cold shutdown or refueling as defined by the unit's technical specifications.

[3]The number of required licensed personnel when the operating nuclear power units are controlled from a common control room are two senior operators and four operators.

Note: This table is from 10 CFR 50.54(m).

The detailed guidance for performing staffing reviews is provided in several NUREGs. Chapters 13 and 18 in the NRC's, "Standard Review Plan" (SRP) (NUREG-0800) and the "Human Factors Engineering Program Review Model," (NUREG 0711), provide guidance for reviewing applicants' staffing plans. In addition, the "Guidance for Assessing Exemption Requests from the NPP Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)" (NUREG-1791) specifically focuses on the review minimum staffing in the main control room. The use of these NUREGs in staffing reviews is discussed in more detail in Section 3 of this report.

One concern the NRC has with the currently available guidance is that it may not address the full set of demands on operating crews that go beyond performing a primary task. That is the guidance does not adequately consider the full range of operator activities and duties that (1) contribute to the physical and cognitive workload of operators or that (2) limit their availability as a functioning member of the operating crew. For example, while traditional task analysis methods may analyze procedure driven tasks, such as starting up the reactor, they may fail to consider real world multitasking demands on operators such as manning a fire brigade or interacting with other personnel on unrelated matters. Thus a methodology is needed to identify plant operational conditions posing very-high workload that reflect the full set of demands on operators and to analyze their impacts on crew workload.

With such a methodology, the NRC can review an applicant's analysis to determine whether the workload during these scenarios is at acceptable levels. Acceptable levels of workload will, in part, justify an applicant’s proposed staffing level. If the workload for some of the selected scenarios is too high, it may indicate that the staffing levels for these scenarios is not adequate and, therefore, unacceptable.

2 Objectives

Our objective was to develop a methodology to identify high-workload operational conditions and analyze the workload associated with them. We used the NRC's draft methodology (Pieringer, 2014) as a starting point.

Two principles guided the methodology development:

- First, as noted in the introduction, the NRC has existing guidance to address an applicant request for exemptions for minimum staffing requirements. The new methodology should have a well-defined role within the broader context of the staff's safety review of such requests.

- Second, the methodology should be consistent with the overall human factors engineering (HFE) program review process described in NUREG-0800 and NUREG-0711 and have clear interfaces with the existing HFE review elements.

A detailed examination of the NRC's guidance for staffing exemption requests and the role of existing guidance is provided in Section 3 of this report. Section 3 also discusses the need for additional guidance. Section 4 provides the technical approach to the important considerations needed for developing the new methodology. Section 5 provides detailed methodology to addresses that need. Finally, Section 6 offers some conclusion about the methodology and a path forward to assisting reviewers faced with integrating the guidance from multiple source documents that address the review of staffing levels.

3 Overall Regulatory Context for the Evaluation of Minimum Staffing

3.1 General Considerations for the Review of Minimum Staffing Exemption Requests

Plant personnel play a diverse role in plant operations and safety. They monitor plant systems and performance and various barriers that prevent release of radioactive material. They take actions to initiate, adjust, and terminate operations as needed. They also respond to transients, accidents, and other failures. They also are responsible for managing operations-related administrative duties. Personnel are supported in these tasks by human-system interfaces (HSIs), procedures, and training. To accomplish their responsibilities, personnel work in teams.

The minimum number of operators needed to fulfill all personnel roles and responsibilities is a complex question that depends on assumptions related to what the credible high-workload scenarios will be and the timeline along which additional staff are needed and available. Licensees establish a minimum staffing level to address immediate and "short-term" actions[1] that need to be taken and the time required to augment the staff with additional personnel as needed over time.

Our main focus in this project is the minimum staffing level needed to address immediate and short-term actions. Scenarios that evolve slowly and within time envelopes required to bring in additional staff are easier to address from a staffing perspective.

As noted above, the NRC has established minimum acceptable staffing levels in 10 CFR 50.54(m). However, technological advances and changes in ConOps have led to an interest in staffing levels below those specified in the regulations (as discussed in Section 1). To evaluate applicant requests for staffing exemptions that allow for reduced staffing levels, the NRC review needs criteria by which these requests can be evaluated.

A top priority criterion is task performance. An acceptable minimum staffing level is one that can successfully accomplish the most demanding tasks, under conditions that reflect real-world challenges including the demands of multi-tasking. Tasks have to be performed accurately and on time, so that overall plant operational and safety goals can be achieved. Successful task performance is the main criterion for evaluating a proposed staffing level. That is, if the crew at the minimal staffing level, cannot perform their tasks, the staffing level is not acceptable. However, while task performance is an important acceptance criterion, it's not the only one.

Crew task performance can be negatively impacted by many factors and some of these factors need to be considered as well. One of the factors that can negatively impact a crew's ability to accomplish their tasks is workload. High workload can delay a task's performance until it is too late or cause a task to be missed altogether. Even when tasks are performed accurately and on time, high workload causes performance to be "fragile," in that there may be little or no margin for dealing with added complications. If additional complications are encountered, the workload

[1] The definition of "short-term" is determined by the assumptions made by licensees about when additional staff will be available to support the on-shift crew. The most demanding staffing requirements that a shift faces is the first hour of a severe casualty, before the emergency response facilities can be staffed. Staffing and activating the operational support center (OSC), technical support center (TSC) and the emergency operations facility (EOF) reduce the burden on the shift. The OSC, TSC, and the EOF are typically required to be operational within thirty minutes to one hour of an emergency declaration. The emergency facility staffing would generally include extra senior reactor operators. This is addressed in the methodology, Section 5.1.

level may rise to the point where task performance is negatively impacted. Thus it's important to know that not only is task performance acceptable, but workload levels are not excessive.

In addition to workload, there are other factors that impact task performance. For example, failure to properly monitor the plant, or inattention, can also cause tasks to be delayed or overlooked. This condition is sometimes caused by "underload," i.e., insufficient workload. Insufficient workload is a concern in highly automated plants where the operator's primary role is monitoring and supervisory control (O'Hara & Higgins, 2010). Operators perform best when workload is neither too high nor too low. Staffing levels that are too high in relation to what tasks operators have to perform, may lead to underload even if those levels are below those specified in the regulations.

Another factor impacting task performance is situation awareness (SA). A crew may not perform a task accurately and on time because they have a misunderstanding of the current plant state. In this case they may not perform the necessary tasks because they do know they need to be done. Poor SA can result from high workload because the workload does not provide staff with the time necessary to maintain accurate SA.

High workload, inattention, and poor SA are examples of the factors that can lead to poor task performance and hence should be considered in staffing evaluations.

In this section we will discuss the guidance available to the NRC for making a safety determination for applicant requests for exemptions from minimum staffing requirements. The guidance is contained in several documents: NUREG-0800, NUREG-0711 and NUREG-1791. After examining the available guidance, we will assess the need for additional guidance.

3.2 NUREG-0800

NUREG-0800[2], the NRC's Standard Review Plan (SRP), has two sections that directly address staffing, namely Section 18.0, Human Factors Engineering and Section 13.1.2-13.1.3, Operating Organization.

SRP Section 18.0, Rev. 2 dated March 2007 has a section titled "Review Interfaces" which refers to SRP Section 13.1.2-13.1.3 and which notes:

> Section 13.1.2-13.1.3 addresses the review for specific staffing requirements. In addition, Chapter 18 specifies a systematic analysis of staffing requirements that includes a thorough understanding of task requirements and applicable regulatory requirements. The Chapter 18 analysis addresses the requirements from Section 13.1.2-13.1.3 as an input. Reviewers should verify that staffing requirements addressed under Section 13.1.2-13.1.3 are properly considered in the Chapter 18 analysis.

The pertinent portion of Section 18.0 for this current effort is Section II.A, Review of the HFE Aspects of a New Plant. It is organized into the same 12 elements as NUREG-0711 and refers to NRC regulations, Regulatory Guides (RGs) and to the review guidance provided in NUREG-0711 and NUREG-1791. The guidance of these other two NUREGs is discussed in Sections 3.1 and 3.2 above, and is not repeated here.

[2] NUREG-0800 sections are periodically updated. The latest versions of all sections can be found at: http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0800/

SRP Section 13.1.2-13.1.3, Rev. 6, March 2007, in “Areas of Review” states, “This section of the SAR should also describe any requests for exemptions from the requirements regarding the number of licensed personnel, as specified in Title 10, Section 50.54(m), of the Code of Federal Regulations [10 CFR 50.54(m)].” This SRP section also addresses conformance with NRC regulations, RGs and review guidance. This SRP section is specifically written to be the focal point of the NRC staff review of NPP staffing including the evaluation of any exemptions from the 10 CFR 50.54(m), licensed operator staffing. Some examples from the SRP are provided here. It also identifies a review interface with SRP Section 18.0.

- Subsection I.1 for Construction Permits (CPs) and Combined Licenses (COLs) states the information from applicants should include commitments to: RG 1.33, which endorses American National Standards Institute (ANSI) N18.7-1976/ANS 3.2, Administrative Controls and Quality Assurance for the Operating Phase of Nuclear Power Plants. It should also include commitments to the Commission’s Policy Statement on Engineering Expertise on Shift, and the TMI (Three Mile Island) Action Plan Items I.A.1.1 and I.A.1.3 of NUREG-0737 for the Shift Technical Advisor (STA) and for shift manning.

- Subsection I.2 for an Operating License (OL) or COL holder, provides for the review of functions, responsibilities, and authorities of a wide variety of plant positions, including licensed operators. In I.2.G it states “… the total number of personnel that will man each shift should be described for all combinations of units planned for the station in both operating and cold shutdown modes.”

- Subsection II, Acceptance Criteria, includes the following as item 4, “Any requests for exemptions from the requirements of 10 CFR 50.54(m) concerning the number of licensed personnel should be justified and reviewed using the NRC’s ‘Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)’ (NUREG-1791).”

Hence, it is clear that this SRP section is the focal point for the staffing review and any related exemption.

Subsection II, Acceptance Criteria, also includes review to 10 CFR 50.54(j), (k), (l), and (m), RG 1.33, ANSI N18.7/ANS-3.2, and TMI action plan Items I.A.1.1 and I.A.1.3. The SRP includes the licensed operator staffing table from 50.54(m), supplemented to also include auxiliary operators (AOs). The SRP in this section also addresses, shift supervisor requirements, engineering expertise, and health physics and rad/chem expertise on shift. Use of overtime versus staffing levels is also reviewed.

Given the manner in which the NRC has structured its review of any request for exemption from operator staffing requirements, it appears that use of this new guidance should most likely be linked to or referenced in SRP Section 13.1.2-13.1.3 (or both 13.1.2-13.1.3 and 18.0).

3.3 NUREG-0711

NUREG-0711 (O’Hara, Higgins, Fleger & Pieringer, 2012) provides a comprehensive approach to reviewing staffing levels by examining staffing adequacy throughout the applicant’s HFE program. The HFE program review is divided into 12 elements (see Figure 3-1). Key NUREG-0711 elements addressing staffing levels and workload are briefly discussed below.

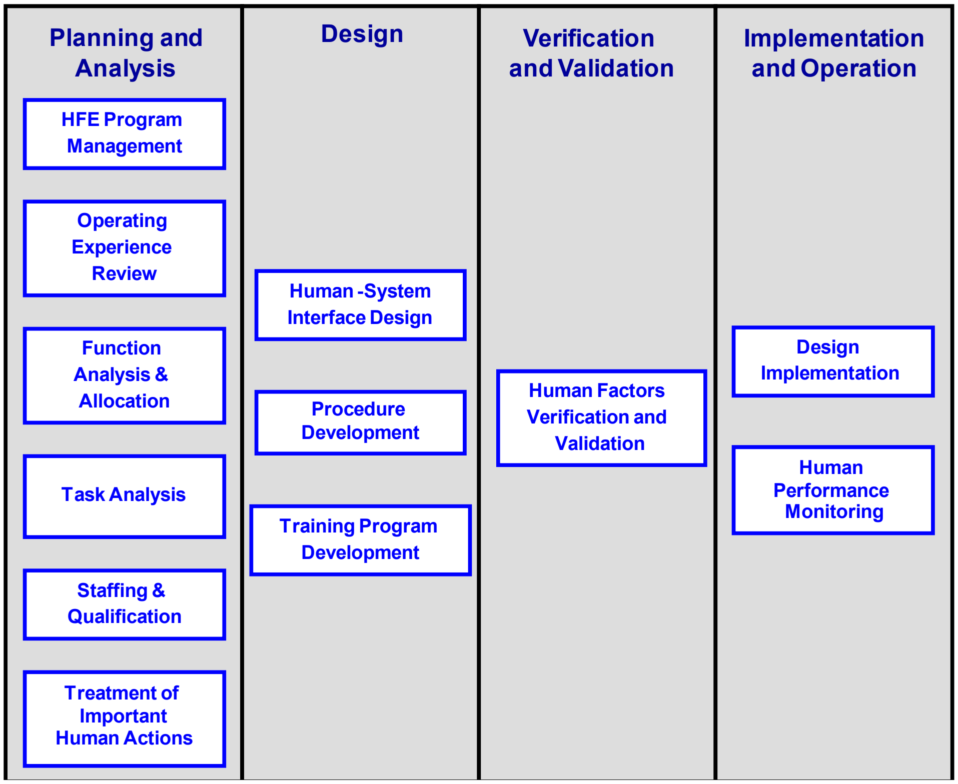

Figure 3-1 NUREG-0711's HFE review elements.

Functional Requirements Analysis and Function Allocation (FRA&FA)

FRA&FA examines the applicant's use of personnel and automation in support of overall plant performance. Plant functions are accomplished by a combination of automatic systems and personnel tasks. All other things being equal, if fewer staff are expected to operate a plant, more of the tasks are performed by automation. One consideration in the allocation of functions among automatic systems and personnel is workload. FRA&FA Criterion 6 recognizes the impact on crew performance of factors that complicate task performance:

(6) The applicant's FA should consider not only the primary allocations to personnel (those functions for which personnel have the primary responsibility), but also their responsibilities to monitor automatic functions, detect degradations and failures, and to assume manual control when necessary.

Task Analysis (TA)

TA examines the detailed means by which personnel tasks should be performed and the requirements of successful task performance. There are several TA review criteria related to the current effort. Criterion 1 identifies the scope of the applicant's TA, including important HAs and the "full range of plant operating modes, including startup, normal operations, low-power and shutdown conditions, transient conditions, abnormal conditions, emergency conditions, and severe accident conditions." One of the sub-bullets of this criterion includes the types of tasks that should be included:

- tasks anticipated to impose high demands on personnel, e.g., little time or high workload (such as administrative tasks that contribute to work load and challenge ability to monitor the plant)

Thus Criterion 1 addresses the impact of collateral tasks on the primary tasks being performed, but does not elaborate on them, particularly in the context of challenging scenarios. For example, an operator called for drug testing superimposed on a fire scenario can result in an operator credited for the fire response team being unavailable. (Note that the issue of the impacts of collateral tasks on primary task performance is also addressed within the context of TA in the Staffing and Qualifications element, see below.)

Workload is identified as one of many factors applicants consider when analyzing task requirements (see NUREG-0711, Table 5-1). Using the expected workload along with other task considerations, the applicant identifies the number of people required to perform tasks (See NUREG-0711, TA Criterion 6). NUREG-0711 does not provide examples of acceptable approaches applicants can use to conduct workload analysis in the context of TA.

Staffing and Qualifications (S&Q)

While staffing is an important consideration in FRA-FA and TA, it becomes the main focus in the S&Q element. The objective of this element is "… to verify that the applicant has systematically analyzed the required number and necessary qualifications of personnel, in concert with task requirements, and regulatory requirements." The review criteria address the basis for the applicant's staffing level. One consideration is estimated workload (See NUREG-0711, S&Q Criterion 3).

Criterion 2 addresses 10 CFR 50.54m requirements. The additional information of this criterion states "For plant staffing levels that require an exemption from 10 CFR 50.54, the NRC's reviewers should use the guidance in NUREG-1791 (Persensky et al., 2005) and NUREG/CR 6838 (Plott et al., 2004)[3]." We will review the contribution of NUREG-1791 in Section 3.3 below.

Criterion 6 identifies the role of the other HFE elements in determining staffing levels and using workload as an input. With respect to TA, the criterion identifies factors that complicate task performance; specifically the "availability of personnel considering other work that may be ongoing, and for which operators may be responsible outside the control room (e.g., fire brigade)."

Human-System Interface (HSI) Design

The HSI design element provides criteria for the review of the design of the control room(s). Criterion 1 identifies the accommodation of staffing levels as a design input. Section 8.4.6 discusses the use of tests and evaluations as part of the design process to assess design options and acceptability. While this section does not identify specific topics, a "minimal staffing level below regulatory requirements" would qualify as a design option that should be assessed for acceptability and that such an evaluation would be expected by the staff. The applicant's test program would provide an early opportunity (before the design is completed) to *empirically*[4]

[3] Note that NUREG-1791 has the actual review process and criteria; NUREG/CR-6838 contains the technical basis for NUREG-1791.

[4] We emphasize the term *empirically* to distinguish it from workload assessments based on *analyses* of the type that would be performed during task analysis (see Section 4.3 for a detailed discussion of this distinction).

examine the acceptability of the staffing level in performance-based tests that assesses task performance in an integrated fashion that can incorporate the complicating factors identified above, such as workload associated with collateral tasks. It is the first opportunity to actually measure workload is a setting that approximates actual real-world, integrated task performance using the entire crew. Integrated system validation provides another opportunity, but occurs later in the design process.

<u>Verification and Validation (V&V)</u>

Two aspects of V&V are relevant to the purpose of the proposed workload methodology: the sampling of operational conditions (SOC) and integrated system validation (ISV). SOC is the process of identifying the scenarios that will be the focus of V&V, especially ISV. The staff's objective in reviewing an applicant's SOC is to ensure:

> The applicant identified a sample of operational conditions that (1) includes conditions representative of the range of events that could be encountered during the plant's operation, (2) reflects the characteristics expected to contribute to variations in the system's performance, and (3) considers the safety significance of HSIs.

Section 11.4.1.1, Sampling Dimensions, identifies dimensions intended to identify "Plant conditions, personnel tasks, and situational factors known to challenge personnel performance." The criteria include:

- plant conditions such as transients and accidents, including "reasonable, risk-significant, beyond-design-basis events that should be determined from the plant-specific PRA (probabilistic risk assessment)"
- personnel tasks such as a "range of knowledge-based tasks"
- "situational factors … known to challenge human performance"

With respect to the third bullet, Criterion 3 states:

> (3) The applicant should include the following situational factors or error-forcing contexts known to challenge human performance. It also should include situations specifically designed to create human errors to assess the system's error tolerance, and the ability of personnel to recover from any errors, should these occur, for example:
>
> - *High-Workload Situations* – The sample should include situations where variations in human performance due to high workload and multitasking situations can be assessed.
> - *Varying-Workload Situations* – The sample should include situations wherein variations in human performance due to workload transitions can be determined. These include conditions where there is (1) a sudden increase in the number of signals that must be detected and processed after a period in which signals were infrequent, and (2) a rapid reduction in the need for detecting signals and processing demands following a time of high sustained task-demand.
> - *Fatigue Situations* – To the extent possible, the sample should include situations that may be associated with fatigue, such as work on backshifts and tasks performed frequently with repetitive actions, such as repeated inputs to a touch screen during plant operations or pulling rods.

Thus, factors potentially impacting crew performance, such as workload and multitasking, are addressed in the effort to identify challenging scenarios for V&V.

The scenarios identified in SOC are used in ISV. ISV is an evaluation using performance-based tests to determine whether an integrated system design (i.e., hardware, software, and personnel elements) meets performance requirements and supports the plant's safe operation. Using trained crews and a near-final design, crews perform the scenarios and their performance is measured. A wide range of comprehensive measures is used including overall plant performance, task performance, situation awareness, and workload. Measured performance is then compared with predefined criteria to determine if the scenarios were acceptably performed.

Staffing level is an explicitly-defined aspect of a design that needs to be validated. In the review criteria for test objectives, Criterion 1 states, in part:

> The applicant should develop detailed test objectives to provide evidence that the integrated system adequately supports plant personnel in safely operating the plant, to include the following considerations:
>
> - Validate the acceptability of the shift staffing level(s), the assignment of tasks to crew members, and crew coordination within the control room, between the control room and local control stations and support centers, and with individuals performing tasks locally. This should encompass validating minimum shift staffing levels, nominal levels, maximum levels, and shift turnover

<u>Human Performance Monitoring (HPM)</u>

An applicant's HPM program should ensure that the conclusions drawn from the ISV remain valid with time. The NRC staff reviews the program to verify that it adequately accomplishes this function. Reduced staffing levels should be one of the considerations within the scope of the applicant's HPM program. However, the likelihood of experiencing one of the very demanding scenarios is very small.

3.4 NUREG-1791

In 2005, the NRC conducted a project to develop criteria specifically for reviewing requests for exemptions from the minimal staffing levels identified in 10 CFR 50.54. The resulting guidance was published in NUREG-1791 (Persensky et al., 2005) and the technical basis for the guidance development was published in NUREG/CR 6838 (Plott et al., 2004). The NUREG-1791 guidance is based on NUREG-0711 and essentially constitutes a tailored version of review criteria to focus on staffing levels. It does have some unique aspects as well.

NUREG-1791 provides an eleven-step process for systematically reviewing and assessing exemption request submittals and details the information, data, and review criteria necessary to review them (see Figure 3-2). The NUREG provides a checklist for each step containing a list of items the reviewer should consider (see Appendix A of NUREG-1791).

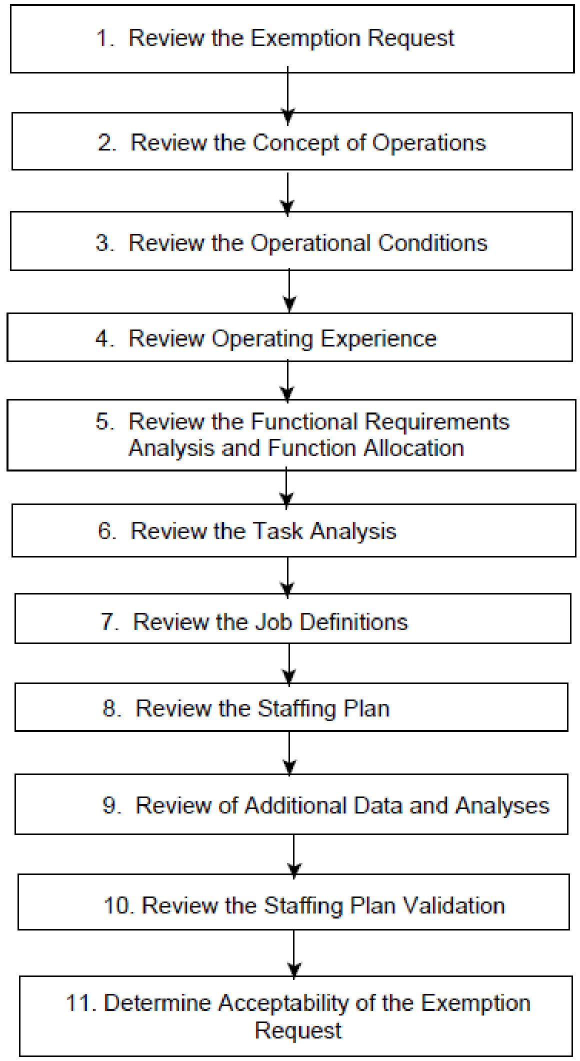

Figure 3-2 NUREG-1791's eleven step review process

One unique aspect of the guidance is the ConOps. An applicant's request would include a specification of a detailed ConOps, which is "a description of how the design, systems, and operational characteristics of a plant, such as an advanced reactor, relate to a licensee's or applicant's organizational structure, staffing, and management framework." NUREG-1791 indicates that the ConOps description should include an explanation of how the staffing concept addresses "the number of personnel who will have plant monitoring and operational control responsibilities on each shift (i.e., "control personnel") and staffing levels for these personnel across shifts." NUREG-0711 does not specifically address the availability and use of a well-defined ConOps, especially one developed early in the design process. Most of the piece parts are addressed across the entire HFE program, but we do think it is important to identify a ConOps early on, especially for more advanced plants making use of new technology and new operational concepts (see O'Hara, Higgins, & Pena, 2010, for a detailed discussion and model of a ConOps).

In NUREG-1791, Step 3, Review the Operating Conditions, the review seeks to verify that those conditions with the *greatest challenge to the effective and safe performance* are identified (emphasis ours). The step references the NUREG-0711 guidance on SOC to provide the basis for sampling. NUREG-1791 notes that the sample should be selected to reflect the context of the exemption request as should be reflected in the ConOps.

Steps 4, 5 and 6 are basically the same as NUREG-0711 with the emphasis ensuring the analyses are relevant to the staffing exemption request.

Step 7 addresses job definitions. This step expands the guidance in NUREG-0711 into the areas of SA and teamwork. Criterion 3 of the S&Q states:

> The applicant should use the results of the task analysis as an input to the staffing and qualification analyses. Personnel tasks, addressed in task analysis, should be assigned to staffing positions to ensure that jobs are defined considering:
>
> - the task characteristics, such as the knowledge and abilities required, relationships among tasks, time required to perform the task, and estimated workload
> - the person's ability to maintain situation awareness within the area of assigned responsibility
> - teamwork and team processes, such as peer checking

NUREG-1791 also expands this guidance to include the specific knowledge, skills, and abilities/aptitudes (KSAs). This is addressed in Criterion 7 of NUREG-0711's TA element, but not specifically tied to job descriptions.

Step 8 provides guidance for reviewing the applicant's staffing plan. The plan should identify "how many individuals must be qualified and available to fill each job." The staffing levels should be justified based on the results of the prior step. This is similar to NUREG-0711 where the basis for the proposed staffing profile is derived from prior HFE analyses (See S&Q, Criterion 6).

Step 10 is essentially validation of the staffing plan using ISV. NUREG-1791 states:

> The purpose of reviewing the validation of the staffing plan is to ensure that the applicant fully considered the dynamic interactions between the plant design, its systems, and control personnel for the operational conditions identified for the exemption request. Staffing plan validation refers to an evaluation using performance-based tests to determine whether the staffing plan meets performance requirements and acceptably supports safe operation of the plant.

The NUREG identifies sources of data that can be used for validation, including operating experience, human-in-the-loop simulations, and human performance models. Data from human-in-the-loop simulations is consistent with the validation guidance in NUREG-0711. However, our current belief is that the other sources of data do not provide sufficient information to meet the purpose of validation as described in NUREG-1791 (identified above).

Operating experience is an important input to determining staffing levels, but there is very limited direct operating experience for a proposed staffing level for a unique plant design under review. Operating experience will not typically provide data in the human performance categories described in NUREG-1791. Further any data that is available from operating experience was not collected under controlled circumstances needed for validation tests.

Human performance models (HPMs) are simulations of various aspects of human performance used to support HFE programs. An HPM is (1) mathematical, programmable, and executable rather than purely explanatory; and (2) applied in the engineering design and evaluation of complex systems. HPMs can provide an analysis capability that contributes important input to determining staffing levels, e.g., they may be particularity useful in testing different staffing profiles under widely varying scenarios by linking the HPM with a plant specific simulation model. However, the fidelity of the models may not be sufficiently robust to serve as or be used in place of operator-in-the-loop validation. In our opinion, the results of HPM testing still should be validated with trials with human crews until such time that the models themselves have been validated for this purpose (O'Hara, 2009). The use of HPMs in staffing and workload analysis is discussed further in Section 4.3 and the Appendix of this report.

Step 11, Determine the Acceptability of the Exemption Request, is where the staff's decision is made. NUREG-1791 provides little guidance for making this determination beyond indicating it should be based in the information provided in the previous steps.

In summary, NUREG-1791 provides a review methodology that is based on NUREG-0711, but tailored to highlight its use for staffing exemption requests. In addition, it provides some useful augmentations to NUREG-0711, such as the identification of a concept of operations.

3.5 Need for Additional Review Guidance

Based on the review of the guidance provided in NUREGs-0800, -0711, and -1791, we identified three aspects of the current review criteria in need of additional detail:

- Identification of high-workload scenarios that include realistic factors that contribute to operator workload and/or distract operators from their primary tasks

- Identification of high-workload scenarios *early* in the HFE program so they can be used to support TA and other HFE activities during the design process and to provide a basis to perform analyses of staffing acceptability before the design is very mature and it becomes difficult to make changes

- The analysis of the workload impacts within the context of operations during minimal staffing configurations

With respect to identifying high-workload scenarios, as shown in the discussion of both NUREG-0711 and 1791, both documents address the need to identify plant conditions that challenge operator performance and both include criteria for including collateral tasks in the analysis. What they don't do is clearly establish the need for such a detailed identification and development of scenarios prior to the TA itself. In NUREG-0711, the main treatment of scenario identification does not appear until the V&V element. Addressing more detailed scenario guidance much earlier in the HFE program would be a significant improvement over current guidance. If such guidance were developed, it could also be used to improve the V&V SOC guidance for addressing similar concerns.

Further, there is a need to focus on tasks that are performed in parallel with the primary task being analyzed and that can contribute to workload and detract from primary task performance. While this is mentioned in both NUREG-0711 and NUREG-1791, little detail is provided. Thus both applicants and reviewers may not be clear about what sorts of tasks should be considered for analysis and whether the tasks that are evaluated represent the types of very high-workload conditions that the operators are expected to experience. Additional guidance on this topic would be an improvement over current guidance. (This issue is specifically addressed in Sections 4.2, 5.3, 5.5, and 5.5 of this document.)

With respect to the emphasis on workload, both NUREG-0711 and NUREG-1791 already identify workload as a task factor to be addressed in TA and in S&Q. However, little guidance is provided as to how such an analysis can be acceptably performed. Not having such guidance makes it difficult for reviewers to evaluate the acceptability of an applicant's workload analysis. Additional guidance on this topic would be an improvement over current guidance.

The supplemental guidance for evaluating applicant requests to reduce staffing levels should:

- clearly establish the need for applicants to identify high-workload scenarios early in the design process and a process for doing so (the guidance addressing this aspect of the methodology can also be used to improve the V&V SOC guidance for addressing a similar concern).

- provide a focus on tasks that are performed in parallel with the plant control tasks being analyzed and may contribute to workload and detract from plant control task performance.

- provide guidance on the different approaches to workload analysis and how they can be acceptably performed

The focus of the supplemental guidance will be on the early phases of design, e.g., when function allocation and task analysis are mainly performed. For mature designs, measuring workload within empirical performance evaluations (as part of HSI design and ISV) is more important and more conclusive than task analysis.

4 Technical Approach

In this section we address the approach to addressing the three considerations discussed in the previous sections:

- identify challenging operating conditions early in the design process
- identify tasks that are performed in parallel with the primary tasks
- identify approaches to workload analysis

4.1 Identifying Challenging Operating Conditions

To assess ability of a crew to manage challenging conditions, the first thing applicants need to do is identify those conditions. A comprehensive set of guidelines for selection of operational conditions for verification and validation is provided in NUREG-0711, Section 11.4.1, Sampling of Operational Conditions. While the sampling process in NUREG-0711 was intended for selection of scenarios for validation using actual crews and simulators, this guidance provides an excellent starting point for the identification of challenging scenarios in support of the workload analysis. However, the guidance needs to be modified and expanded in order to accomplish this purpose in the context of workload analysis performed before the final design is available.

The NUREG states:

> "… the objective of the Sampling of Operational Conditions review is to verify that the applicant identified a sample of operational conditions that (1) includes conditions representative of the range of events that could be encountered during the plant's operation, (2) reflects the characteristics expected to contribute to variations in the system's performance, and (3) considers the safety significance of HSIs. These sample characteristics are best identified by using a multidimensional sampling strategy …"

We reviewed this guidance and found it to be very suitable for use in identifying challenging operating condition with several modifications.

First, some sampling considerations were deleted because they were not relevant to challenging conditions and one additional consideration was added to ensure that all important scenarios that may create high staff workload are captured. The deleted considerations are:

- Criterion (2), bullet 5, Range of Procedure-Guided Tasks
- Criterion (3), bullet 2, Varying-Workload Situations
- Criterion (3), bullet 4, Environmental Factors

The added consideration is:

- Criterion (1): Add external events (fires, floods, seismic, and loss of large area).

Second, the following “additional information” was included in Criterion (1):

> Additional Information: NRC-approved industry FLEX strategies, written to meet the Japan Lessons Learned mitigation strategies order for beyond design basis external events, are based on minimum shift staffing for the first two phases. Staffing analyses are to evaluate minimum staffing, so typically these analyses should include Phase 1 and 2 events and actions in the selected scenarios. For the second or transition phase, some plants may involve off-site or recalled personnel (NEI 12-06). If, a plant’s mitigation strategy specifies recalled/offsite personnel for selected events, then those events do not need to be included in the staffing analyses for minimum staffing.

Third, new Criteria (4) and (5) are included related to issues identified in NUREG/CR-6947 and -7126:

(4) The applicant should include the following considerations with respect to emerging technology in NPPs, as described in more detail in Section 3 of NUREG/CR-6947.

- Automation (see Section 3.1.1 of NUREG/CR-6947)
- Specific changes to operations (see Section 3.1.3 of NUREG/CR-6947)
- Advances in HSI technology (see Section 3.1.3 of NUREG/CR-6947)
- Complexity (see Section 3.1.3 of NUREG/CR-6947)
- Disturbance and emergency management (see Section 3.1.4 of NUREG/CR-6947)
- Design and evaluation of digital systems and software (see Section 3.1.5 of NUREG/CR-6947)

(5) The applicant should include the following considerations for Human-Performance Issues Related to Design and Operation of SMRs, if pertinent. These topics are described in more detail in Section 6 of NUREG/CR-7126.

- Plant mission (see Section 6.1 of NUREG/CR-7126)
- Roles and responsibilities. This includes multi-unit monitoring and teamwork, and high levels of automation (see Section 6.2 of NUREG/CR-7126)
- Management of normal operations. This includes 10 issues of which the first 7 relate to staffing and workload, while the last 3 relate more to HSI design. (see Section 6.4 of NUREG/CR-7126)
- Management of off-normal conditions and emergencies. This includes nine issues of which the first seven relate to staffing and workload, while the last two relate more to design and analysis. (see Section 6. of NUREG/CR-7126)

Fourth, the following revisions were made:

- Criterion (1) was revised to consider transients and accidents during the conditions of the first bullet.
- Criterion (2), bullet 1, was revised to include only important Human Actions, dropping important systems and dominant accident sequences.
- Criterion (2), bullet 4, was revised to include only high workload personnel tasks.

The updated version of NUREG-0711, Section 11.4.1, to be used by applicants to identify challenging conditions is in Section 5.1 of this report.

4.2 Identifying Tasks that are Performed in Parallel with the Primary Tasks

Once the set of challenging operating conditions is identified, the applicant will next need to identify the tasks that the operating staff will need to perform to respond to the specified event or conditions. These tasks are typically detailed in the various operating procedures. In this guidance we refer to these as "primary tasks." Primary tasks then will need to be broken down into more detailed steps (using task analysis) in order to be able to perform the workload analysis.

However, in order to reflect realistic workload levels during actual plant operations, we have to recognize that operators are required to perform other tasks at the same time as the primary tasks. These additional tasks add to the operator's workload and may delay or disrupt primary task performance.

Some of these tasks are related to primary tasks. These are "dependent tasks" and while they may not be specifically linked to a single procedure-driven primary task, operators must still perform them. An example is communicating with offsite emergency organization. Dependent tasks can be categorized as administrative tasks, communications, or system/equipment-related actions.

Finally, there are tasks that must be performed by operators during primary tasks, but which are unrelated to them. These are "independent tasks." An example is manning a fire brigade. Like dependent tasks, they can be categorized as administrative tasks, communications, or system/equipment-related actions.

Thus both dependent and independent tasks should be identified and addressed in the workload analyses. In order to assist in the identification of these tasks, the guidance in Sections 5.3 and 5.4 of this document provides tables of generic tasks, both dependent and independent, that may be pertinent to many different plants. There may also be plant-specific dependent or independent tasks that should be identified and addressed.

4.3 Identifying Approaches to Workload Analysis

Applicants will analyze crew workload associated with the tasks performed during challenging scenarios to determine its acceptability. There is a distinction between workload *measurement* and workload *analysis.* Workload *measurement* is an evaluation approach based on collecting data from operators while performing the tasks of interest. NUREG-0711's guidance for ISV identifies workload to be measured as part of the data collected during ISV trials. Numerous techniques are available to measure operator workload both during actual plant operations or during simulator trials (see O'Hara et al., 1997, for a review of these methods). An example of a workload measurement technique used in many NPP studies (including ISVs) is the NASA Task Load Index (TLX). The TLX contains rating scales that are filled out by operators following a scenario. The scales reflect different dimensions of workload. However, to *measure* workload, actual operators have to be available and the design must be sufficiently mature so the factors that impact workload are adequately and accurately represented during scenario performance.

Prior to the availability of a mature design and, therefore, the capability of measuring operator workload directly during or after task performance, workload *analysis* is conducted to predict workload. The importance of conducting workload analyses in early design phases is reflected in the human engineering requirements in the Department of Defense's (DoD's) MIL-STD-46855A (DoD, 2011):

> Human engineering principles and criteria shall be applied to analyses of tasks and workload, including cognitive task analysis if required. These analyses shall also be available for developing preliminary manning levels; equipment procedures; and skill, training, and communication requirements; and as integrated logistic support inputs, as applicable….
>
> Operator and maintainer (individual and team) workload analyses shall be performed and compared with performance criteria. To avoid overloading or underloading, the degree to which demands of any task or group of tasks tax the attention, capacities, and capabilities of system personnel (individually and as a team) and thus affect performance shall be evaluated. Sensory, cognitive, and physiological limitations shall be considered, as applicable. The workload analyses shall define operational sequences and task times. Preliminary workload estimates shall correlate required actions with team tasks for each task component (visual, auditory, motor, and cognitive) specified in terms of time, workload, mental effort, and psychological stress. A workload estimate for each individual shall be defined in a fashion permitting individual and team workload to be related to operational procedures. (p. 10-11).

Workload analysis is an analytical approach to evaluating workload, typically using timeline analysis and predictions of workload based on subject matter expert judgment. Human performance models can also be used to support workload analysis. These approaches are briefly described below.

<u>Timeline Analysis</u>

Timeline analysis is one common method of analyzing workload (Charlton, 2002; Kirwan & Ainsworth, 1992; Wickens et al., 2004). Time stress is an important component of workload and an assessment of it is included in many workload assessment scales, e.g., the NASA TLX has a "temporal demand" dimension and the Subjective Workload Assessment Technique (SWAT) has a "time load" dimension.

A timeline analysis assesses time stress by determining the ratio of time required to do a task(s) to the time available to do them. As the ratio approaches 1.0 performance begins to suffer. Ratios above one indicate that the operator's tasks will not be accomplished. The data for each crew member can be assessed to determine if the allocation of tasks across crewmembers is acceptable.

To improve the accuracy of the evaluation, the timeline analyst should include (1) system timing constraints, such as the time the system takes to respond to an action before another action can be taken; and (2) the timing required for operators to perform covert cognitive tasks, such situation assessment and response planning (Proctor & van Zandt, 1994).

There are limitations to timeline analysis. For example, workload is multidimensional and affected by more than just time available. Also, operators may postpone or delay tasks as part of a workload management strategy. In addition, some well-practiced tasks become "automatic" and can be performed with little mental effort even though they take time. Thus, timeline analysis can be augmented with estimates of other workload dimensions.

See DoD (1999, Section 8.3.10, Timeline) and Kirwan & Ainsworth (1992, pp 135-145) for a detailed description of procedures for timeline analysis.

Workload Estimation

Workload estimation techniques (also called workload prediction or projection) rely on the judgment of subject matter experts (SMEs). Research has shown the SMEs can make fairly accurate predictions of a new systems workload when the predictions are compared with actual workload on the system (Eggleston & Quinn, 1984; Masline & Biers, 1987; Vidullch, Ward, & Schueren, 1991).

Typically SME are given system and operations descriptions of a proposed system and they use their experience and expertise to predict what the workload of the new system will be. The SMEs often have familiarity with similar or predecessor systems.

The SME predictions are more reliable when formal techniques to collect workload estimates are used, such as subjective workload scales developed to collect actual workload measurements from operators. For example, Vidullch, Ward, and Schueren (1991) used the Subjective Workload Dominance (SWORD) technique to obtain workload predictions. SWORD workload ratings are based on relative judgment. Rather than rating a single system, operator judge a system relative to another one with respect to the workload experienced.
In one study, SWORD was administered protectively and retrospectively to groups of F-16 pilots evaluating aircraft cockpit displays. The correlation between the projective and retrospective groups of pilots was highly positive, and both groups′ ratings correlated positively with the simulator study performance.

Similarly, Reid et al. (1984) adapted the Subjective Workload Assessment Technique (SWAT) for use in obtaining workload predictions. They called the technique “Projective SWAT.” It has three dimensions: Time, mental effort, and stress load. Its use as a workload estimation technique is also supported in the literature (Masline & Biers, 1987).

Thus SME provided with detailed information about a new system’s design can make predictions about the workload those systems are likely to impose on operators. The use of established rating scales enables the workload assessments to be more robust than time stress alone can provide by including other workload dimensions in the evaluation.

Human Performance Models

The technology available to HFE practitioners for conducting staffing and workload analysis has been expanding to include human performance models (HPMs). HPMs are mathematical, programmable, and executable representations of individual and crew performance, typically in in the context of tasks performed in system operations. They are applied in the engineering design and evaluation of complex systems.

HPMs such as MicroSaint and the *Improved Performance Research Integration Tool* (IMPRINT) have been used in multiple industries, including the nuclear industry. A brief summary of these applications is provided in the Appendix to this report. Additional detail can be found in O’Hara (2009).

In Section 3.4 above, we expressed reservations about using HPMs as an alternative means for conducting validation. However, in the context of supporting predictions of workload and performance, HPMs have been found to be useful. In the present context, the results of the workload analysis will later be subject to validation with operating crews.

Acceptance Criteria

Regardless of the approach to workload evaluation, a criterion for success is needed. The type of criteria used will depend on the specific method of workload analysis used.

As noted in the discussion of timeline analysis above, as the ratio of time required to time available approaches 1.0 performance begins to suffer. While, ratios above one indicate that the operator's tasks will not be accomplished, Kirwan & Ainsworth (1992) suggest the ratio should not go above 0.8.

The Department of Defense (DoD, 1999) gives the following criteria for workload analysis based on time utilization.

> 8.3.13.2.2 Operator loading. In general, workloads over 100 percent are not acceptable, between 75 percent and 100 percent are undesirable, and under 75 percent are acceptable provided that the operator is given sufficient work to remain reasonably busy. (p. 158)

A staffing workload analysis methodology will have to address acceptance criteria that will be linked to the method(s) of analysis.

5 Methodology to Assess the Workload of Challenging Operational Conditions

The methodology to assess workload of challenging operational conditions is divided into seven steps, see Figure 5-1. Each of these steps is described below.

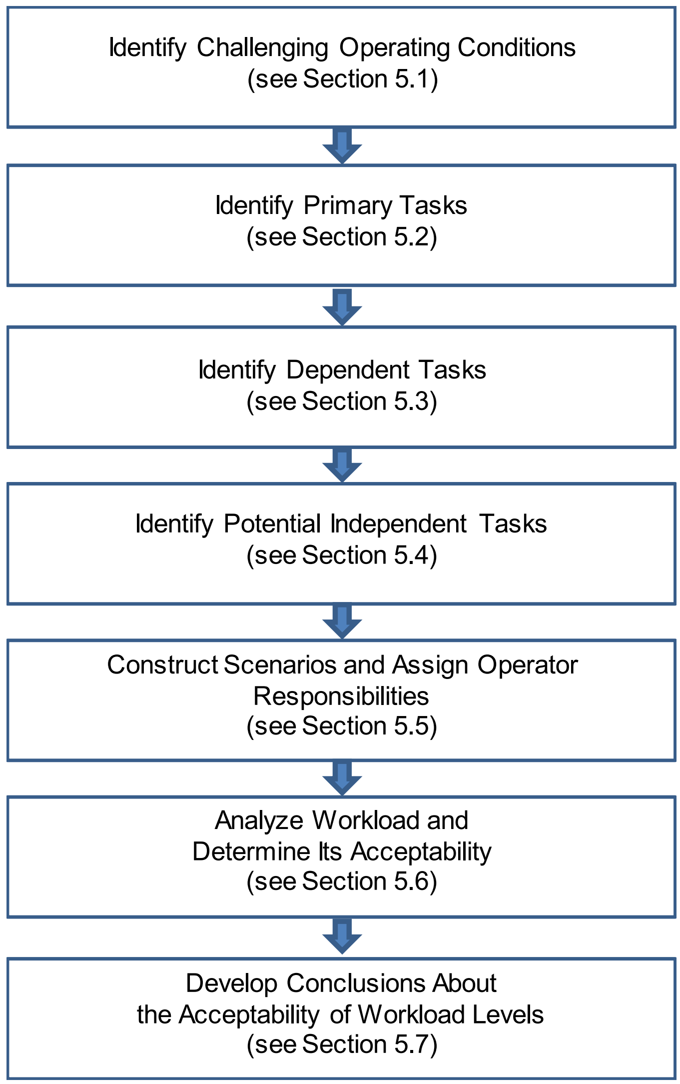

Figure 5-1 Methodology to assess the workload of challenging operational conditions

5.1 Identify Challenging Operating Conditions

The applicant should identify the plant specific operating conditions that are challenging and create high workload using the considerations presented below. The objective of identifying these conditions is the evaluation of the minimum staffing level needed to address immediate and short-term actions. Scenarios that evolve slowly and within time envelopes required to bring in additional staff are easier to address from a staffing perspective.

The applicant should consider the following plant conditions, personnel tasks, and situational factors in their sample of challenging conditions for workload analysis.

(1) Plant Conditions

- Consider transients and accidents starting during normal operations, plant startup, shutdown, and refueling
- Consider instrumentation and control (I&C) and HSI failures and degraded conditions that encompass:
  - The I&C system, including the sensor, monitoring, automation and control, and communications subsystems; [e.g., safety-related system logic and control unit, fault tolerant controller, local "field unit" for multiplexer (MUX) system, MUX controller, and a break in MUX line]
  - common cause failure of the I&C system during a design basis accident (as defined by Branch Technical Position (BTP) 7-19)
  - HSIs including, loss of processing or display capabilities for alarms, displays, controls, and computer-based procedures
- Consider transients and accidents, such as:
  - transients (e.g., turbine trip, loss of off-site power, station blackout, loss of all feedwater, loss of service water, loss of power to selected buses or main control room (MCR) power supplies, and safety and relief valve transients)
  - accidents (e.g., main-steam-line break, positive reactivity addition, control rod insertion at power, anticipated transient without scram, and various-sized loss-of-coolant accidents)
  - reactor shutdown and cooldown using the remote shutdown system
  - reasonable, risk-significant, beyond-design-basis events that should be determined from the plant-specific PRA
  - External events (fires, floods, seismic events, and loss of large area of the plant)

Additional Information:
The most demanding staffing requirements that a shift faces is the first hour of a severe casualty, before the emergency response facilities can be staffed. Staffing and activating the operational support center (OSC), technical support center (TSC) and the emergency operations facility (EOF) reduce the burden on the shift. The OSC, TSC, and the EOF are typically required to be operational within thirty minutes to one hour of an emergency declaration. The emergency facility staffing would generally include extra senior reactor operators. Operating conditions selected need only be carried out far enough to address the period up to when added staffing is in place.

NRC-approved industry FLEX strategies, written to meet the Japan Lessons Learned mitigation strategies order for beyond design basis external events, are based on minimum shift staffing for the first two phases. Staffing analyses are to evaluate minimum staffing, so typically these analyses should include Phase 1 and 2 events and actions in the selected scenarios. For the second or transition phase, some plants may involve off-site or recalled personnel (NEI 12-06). If a plant's mitigation strategy specifies recalled/offsite personnel for selected events, then those events do not need to be included in the staffing analyses for minimum staffing.

(2) The applicant should consider the following types of personnel tasks:

- *Important Human Actions* – The sample should include all important HAs, as determined in NUREG-0711, Section 7.
- *Manual Initiation of Protective Actions* – The sample should include manual system-level actuation of critical safety functions.
- *Automatic System Monitoring* – The sample should include situations in which humans must monitor a risk-important automatic system.

- *OER-Identified Problematic Tasks* – The sample should include high-workload personnel tasks identified as problematic during the applicant's review of operating experience.
- *Range of Knowledge-Based Tasks* – The sample should include tasks that are not well defined by detailed procedures (see NUREG-0711 for additional information).
- *Range of Human Cognitive Activities* – The sample should include the range of cognitive activities that personnel perform, including:
  - detecting and monitoring (e.g., of critical safety-function threats)
  - situation assessment (e.g., interpreting alarms and displays to diagnose faults in plant processes and in automated control and safety systems)
  - planning responses (e.g., evaluating alternatives to recover from plant failures)
  - response implementation (e.g., in-the-loop control of plant systems, assuming manual control from automatic control systems, and carrying out complicated control actions)
  - obtaining feedback (e.g., feedback of the success of actions taken)
- *Range of Human Interactions* – The sample should include the range of interactions among plant personnel, including tasks performed independently by individual crew members, and those undertaken by a team of crew members. These interactions among plant personnel should include interactions between:
  - main control room operators (e.g., operations, shift turnover walkdowns)
  - main control room operators with auxiliary operators and other plant personnel performing tasks locally (e.g., maintenance or instrumentation and control (I&C) technicians, chemistry technicians)
  - main control room operators and the TSC and the EOF
  - main control room operators with plant management, the NRC, and other outside organizations

(3) The applicant should include the following situational factors or error-forcing contexts known to challenge human performance. It also should include situations specifically designed to create human errors to assess the system's error tolerance, and the ability of personnel to recover from any errors, should these occur, for example:

- *Fatigue Situations* – To the extent possible, the sample should include situations that may be associated with fatigue, such as work on backshifts and tasks performed frequently with repetitive actions, such as repeated inputs to a touch screen during plant operations or pulling rods.

(4) The applicant should include the following considerations with respect to emerging technology in NPPs, as described in more detail in Section 3 of NUREG/CR-6947.
- Automation (Section 3.1.1)
- Specific changes to operations (Section 3.1.3)
- Advances in HSI technology (Section 3.1.3)
- Complexity (Section 3.1.3)
- Disturbance and emergency management (Section 3.1.4)
- Design and evaluation of digital systems and software (Section 3.1.5)

(5) The applicant should include the following considerations for Human-Performance Issues Related to Design and Operation of SMRs, if pertinent. These topics are described in more detail in Section 6 of NUREG/CR-7126.
- Plant mission (Section 6.1)

- Roles and responsibilities. This includes Multi-unit Monitoring and Teamwork, and High Levels of Automation (Section 6.2)
- Management of normal operations. This includes 10 issues of which the first seven relate to staffing and workload, while the last three relate more to HSI design. (Section 6.4)
- Management of off-normal conditions and emergencies. This includes nine issues which the first seven relate to staffing and workload, while the last two relate more to design and analysis. (Section 6.5).

5.2 Identify Primary Tasks

(1) For each of the challenging operating conditions, the applicant should identify the primary plant control tasks which operators need to perform to a level of detail to support workload analyses.

Additional Information: If available, plant-specific procedures can be used to identify the tasks and task sequences for addressing each operational condition. If the actual detailed operating, off-normal, and emergency procedures are not available there may be vendor procedure guidelines or predecessor plant procedures that can be used.

Depending on their level of detail, procedures may only define the tasks that operators perform at a high level. In that case, applicants should conduct task analyses to develop the detail needed to support workload analyses. For example, one cannot determine the workload of a primary task like ‘Start Pump A,’ without breaking it down to more-detailed subtasks not typically described in procedures. The subtasks may include detailed actions such as: navigate to the feedwater display, locate the pump to be controlled, verify that the correct pump has been selected, assess that the preconditions for starting the pump are acceptable, click on the pump icon to access the pump controls, select “on” and click “Enter,” and finally verify that the pump has been turned on and is operating properly. These subtasks are the detailed means by which the higher-level plant control task is accomplished.

(2) The applicants should include an analysis of the operator tasks associated with new design features, even when the tasks are mainly cognitive activities such as monitoring.

Additional Information: For example, in a highly automated plant, operators will spend considerable time and effort monitoring the automation and assessing its performance. Cognitive task analysis techniques may to useful for analyzing such cognitive tasks.

In summary, the analysis of the operators’ primary tasks may require a combination of procedures, procedure guidelines, and task analyses to identify all of the detailed tasks and activities that operators will need to perform during the challenging operating conditions.

5.3 Identify Dependent Tasks

(1) For each of the challenging operating conditions, the applicant should identify the dependent tasks, which operators need to perform in support of the primary tasks.

Additional Information: Dependent tasks are those not specifically part of the procedure-driven primary tasks, but which operators still have to perform in the same time frame. When such tasks are performed in the same time period as the primary tasks, they contribute to crew’s workload, may introduce distractions or interruptions, and reduce the time available to perform primary tasks.

Dependent tasks are divided into two categories: Generic dependent tasks and plant-specific dependent tasks. Generic tasks are those that apply to all or most plants and can be further categorized as administrative tasks, communications, and system/equipment-related actions. Generic dependent tasks are shown in Table 5-1.

Plant-specific dependent tasks are unique to the applicant's design. Applicants should systematically analyze the plant design, the use of new technologies and new ConOps to identify plant-specific dependent tasks that should be included in the scenarios to be analyzed (as determined in Section 5.5).

Applicants should consider the following in their analysis of plant-specific dependent tasks:

- Special work needed to access underground equipment
- Work related to passive systems
- Work related to operate backup systems to the passive systems
- Fuel loading
- Load-following operations
- Novel refueling methods
- Any special situation related to the primary task that results in reduced time for operators to respond
- Monitoring requirements for multiple reactor configurations

Table 5-1 Generic Dependent Tasks

Type of Dependent Task	Example Activities
Administrative	Initiate Tech Spec actions
	Apply error-prevention tools, such as independent verification of valve repositioning, related to primary tasks
	Log keeping
Communications	Communicate with Auxiliary Operators
	Task briefings
	Manage command & control challenges
	Interface with in-plant emergency or support organizations
	Communicate with offsite emergency organization
	Communicate with the NRC
System/equipment-related actions	Alarm monitoring and response for primary task equipment
	Initiate emergency response actions

5.4 Identify Potential Independent Tasks

(1) For each of the challenging operating conditions, the applicant should identify any independent tasks which operators may need to perform.

Additional Information: Independent tasks are not specifically linked to the primary tasks, but may need to be performed within the same time frame as primary tasks, thus may increase operator or overall staff workload. Even when independent tasks do not significantly add to workload, they can still create distractions that may impede primary task performance. An activity that shifts attention away from the primary tasks, even momentarily, can interfere with performance even if little workload is added.

An example of such an independent task is provided in NRC Information Notice (IN) 91-77 (NRC, 1991). The IN documented two instances of plants' difficulty in staffing the fire brigade during a plant fire. In another more recent example, LER 50-259/22013-005-01, (TVA, 2014), describes a situation where the plants minimum staffing analysis did not fully consider the impact on staffing of the fire brigade, an Appendix R safe shutdown, and the emergency response organization. In another recent example an SRO who was the fire brigade leader in case of fire was called for drug testing. After he left a fire occurred. The fire brigade responded with no leader for about 30 minutes. The SRO did not leave drug testing because previous communications had reinforced that anyone who did not complete drug testing within prescribed time frame was considered "unfit for duty."

Another example of a common independent task is communicating with plant staff on matters unrelated to the primary task.

Generally it is assumed that independent actions will be stopped when any plant transient occurs. However, operating experience shows there have been cases where confusion arises. Such conflicts should be addressed in plant administrative procedures to guide operators in how to manage independent tasks when they may impact operational primary tasks. Without such specific guidance, operators will make decisions on an ad hoc basis.

Like dependent tasks, we can divide independent tasks into generic and plant-specific tasks. Further, the independent generic tasks can be categorized as: administrative tasks, communications, and system/equipment-related. Table 5-2 provides independent tasks in each of these categories. Note that some of these activities that can be either a primary, dependent, or independent task (e. g., Tech Spec related activities).

Table 5-2 Generic Independent Tasks

Type of Independent Task	Example Activities
Administrative	Technical Specifications activities
	Apply error-prevention tools, such as independent verification of valve repositioning, unrelated to primary tasks
	Log keeping
	Drill participation
	Corrective action generation and processing
	Drug testing
	Outage schedule reviews
	Scheduling of operations, maintenance, and testing
	Training
Communications	Manage standard communications
	Communicate with Auxiliary Operators or fire brigade
	Shift turnover
	Staff meetings
System/equipment-related actions	Alarm monitoring and response for equipment unrelated to primary task
	Trouble shooting and investigations
	Manage in progress activities (operations and maintenance)
	Manage plant configuration, e.g., equipment tag-outs, operational lineups, and operability evaluations
	Monitor plant risk using the safety or risk monitor
	Perform surveillance testing and post maintenance testing
	Plant walkdowns
	Work related to unplanned shutdowns
	Participate in fire brigade

Applicants should also systematically analyze the plant design and the use of new technologies and new ConOps to identify if there are any plant-specific independent tasks that should be included. The following are examples of the types of activities to consider for identifying plant-specific independent tasks:

- Work-related handling of conditions of one unit that impact other units
- Data entries needed for using automation and computer-based human-system-interfaces.
- Managing novel maintenance hazards (e. g., reactor cooling system (RCS) partial drain for steam generator (SG) tube inspections)
- Modular construction and component replacement
- Control actions and operations and maintenance (O&M) planning related to multiple modules

A representative set of independent tasks should be included in the scenarios to be analyzed (see Section 5.6). The applicant need not include independent tasks are characterized by the following conditions:

- An independent task that can be delayed or stopped to permit operators to accomplish the scenario-required primary tasks, and

- An applicant has established guidance for prioritizing and/or postponing independent tasks that may arise during plant events.

The concept of giving operational activities priority attention over administrative or other independent tasks is well-recognized and generally supported by guidance from NRC, INPO, and

ANSI/ANS standards. Some examples of such guidance are given here even though they don't explicitly address the situation we are concerned with here. Hence, applicants would need to establish (or commit to establish) appropriate administrative controls.

An example of addressing task postponement in the face of more important tasks is provided in ANSI/ANS-3.2-2012. Section 3.5.1, Procedure Adherence, states in part:

> *In the event of an emergency not covered by an approved procedure or an emergency not following the path upon which the approved procedure is based, operations personnel shall be instructed to take action so as to protect public health and safety and to minimize personnel injury and damage to the facility*.

This can be interpreted as allowing the postponing of less important tasks, that impacts the staffing needed to respond to events, but it doesn't require NPPs to have such specific words in their administrative controls. NRC Regulatory Guide 1.33 endorses ANSI/ANS-3.2-2012.

Two key INPO documents related to plant operations are as follows (identified here for information only):

- INPO 10-004 Principles for a Strong Plant Operational Focus, June 2013, Rev. 1
- INPO 01-002 Guidelines for the Conduct of Operations at Nuclear Power Stations, May 2001

INPO 10-004 provides the general practices needed to attain high-levels of operational safety and reliability at NPPs. It emphasizes the importance of plant operations. INPO 01-002 provides guidelines for achieving excellence in the various aspects of plant operations. One aspect noted is ensuring that administrative duties assigned to operators do not detract from their ability to safely operate the plant.

(2) Applicants should identify their assumptions regarding the status of these excluded independent actions, e.g., "we have not included drug testing actions in our analysis because we assume such actions will not interfere with the primary control tasks based on administrative procedures."

5.5 Construct Scenarios and Assign Operator Responsibilities

Applicants should construct scenarios based on combining the primary, dependent, and independent tasks. These scenarios will be used to conduct the workload analysis described in Section 5.6. Scenario construction should follow the guidance contained in NUREG-0711, Sections 11.4.1.2, Identification of Scenarios, and 11.4.1.3, Scenario Definition) as adapted below.

(1) Selection and construction of scenarios: The applicant should use the results of Sections 5.1 through 5.4 to identify a reasonable set of scenarios for subsequent staffing analysis. A given scenario may combine many of the characteristics identified in the "identification of challenging operating conditions" and other analyses. Five to ten scenarios should be sufficient provided they define what the applicant/licensee believes to be a set of the highest-workload conditions the operator might face. The applicant should use risk and cases of anticipated high workload to screen the scenarios and items contained in the scenarios.

Additional Information:

Workload can be anticipated to be high for scenarios with the characteristics listed in Table 5-3. This table is not meant to be comprehensive, and the characteristics identified are not mutually exclusive, but they may be useful for screening scenarios for potential high workload.

Table 5-3 Scenario Characteristics Associated with High Crew Workload

Characteristic	Considerations
Scenarios with Complex Relationships Among Primary Tasks	NUREG-0711 Task Analysis Criterion 4 addresses the relationships among tasks, e.g., some tasks can be carried out in any order or in parallel, some tasks have to be performed in a linear sequence, while for others the relationship is conditional (if such a condition exists, perform task A). Some tasks may involve coordinated actions among crew members or control room crew members and local personnel. These relationships can introduce task delays and multitasking requirements that contribute to the complexity and workload of performing primary tasks.
Scenarios that are unfamiliar or unusual	The scenario is not one that operators encounter frequently or on which they train. Thus, even with procedures the scenario has high uncertainties and operators have to analyze many parameters, select among many possible mental models for the situation, and evaluate multiple outcomes.
Scenarios that require knowledge based behavior	Knowledge-based task demands occur during scenarios for which there are no detailed procedures or for which procedures are not having their intended effects. Operators must assess the situation and develop response plans as they manage the situation.
Scenarios with distracting and interrupting demands	Some scenarios may produce a high level of distractions and interruptions, which raises workload and disrupts performance. An example would be a second failure occurring while operators are addressing the first failure.
Scenarios that are highly dynamic	In dynamic scenarios, the frequent onset of new or changing information makes it difficult to assess plant conditions, plan appropriate responses, or execute complex tasks. In such scenarios, operators have to frequently update and revise their understanding of the situation and how they manage the event.
Scenarios with time pressure	Complex tasks that need to be completed within a limited period of time may require operators to make a trade-off between the thoroughness of performing tasks (e.g., continuing data monitoring to assure the assessment, evaluating alternatives, confirming the actions before moving to the next step) and completing tasks in time.
Scenarios causing prolonged stress	Scenarios that require operators to work long working hours on non-routine, stressful tasks.
Rapid workload transitions	Periods of rapid workload transition are difficult to operators. For example, if an automatic system fails and operators have to suddenly perform the tasks manually, the workload experienced is typically high.
Scenarios with significant consequences	The potential consequences of the operator's performance impact workload. If the consequences are significant, then more workload is experienced than if the consequences are less severe.
Scenarios with actions having little margin for error	When operator tasks require very precise responses with little performance margin, the demands on attention are great and workload high.

(2) Scenario Definition: For each scenario, the following information should be defined to reasonably assure that important dimensions of performance are addressed:

- a description of the scenario and any pertinent prior history necessary for analysts to understand the state of the plant at the start-up of the scenario

- specific initial conditions
- events (e.g., failures) that will occur during the scenario and their initiating conditions, e.g., based on time, or a value of a specific parameter
- dependent tasks related to each primary task
- independent tasks that may occur during each scenario
- definition of workplace factors, (e.g., environmental conditions)
- needs for task support (e.g., procedures and technical specifications)
- staffing level (should be the minimum levels are identified in the exemption request)
- responsibilities of each operator
- communication requirements between control room personnel and remote personnel (e.g., load dispatcher via telephone)

(3) The applicant's scenarios should realistically represent operator tasks in the plant; so that the findings from the analysis can be generalized to the plant's actual operations. One important aspect of this is the timing for plant dynamics and postulated accidents. This would be provided by a full-scope plant simulator later in the design stage, but at the time of initial staffing evaluations, it may need to come from analytic work by the design team.

(4) When appropriate, the scenarios should include work associated with operations remote from the main control room.

5.6 Analyze Workload and Determine Its Acceptability

(1) The applicant should identify the method or methods to be used to analyze staff workload and the workload acceptance criteria for each.

(2) The applicant should have a detailed task analysis of the scenarios to be analyzed.

Additional Information: To provide reasonable estimates, SME's should have a detailed analysis of crew tasks so they know not only what tasks need to be performed, but how they are performed. The task analysis should meet the review criteria provided in Section 5 of NUREG-0711, Applicants may use a combination of traditional task analysis methods, along with cognitive task analysis (CTA) methods.[5] The latter may be especially useful for cognitive and supervisory control activities and when the task situation is not well-defined from an operator's perspective. Applicants may also use human performance modelling techniques, provided they can show that those techniques can provide reasonable results. In addition, SMEs should have system descriptions to fully understand the tasks and how they are performed.

(3) The applicant should conduct a timeline analysis of the time required to complete tasks with respect to the time available. The analysis should consider:

- system timing, such as the time the system takes to respond to an action before another action can be taken
- the time required to perform covert cognitive tasks, such situation assessment and response planning
- the effects of multitasking and the potential for primary task disruption created by overlapping primary tasks, dependent tasks, and independent tasks

(4) The applicant should analyze the physical and cognitive workload associated with task performance. The analysis should consider the effects of multitasking and the potential for primary task disruption created by overlapping primary tasks, dependent tasks, and independent tasks.

Additional Information: Applicants can use or adapt a subjective workload measure to obtain SME workload estimates along workload dimensions.

(5) The applicant should evaluate the acceptability of workload by comparing time and workload results to the established criteria.

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[5] The CTA addresses limitations in current task analysis methods, such as:

- Traditional task analysis methods mainly focus on physical activity (observable behaviors). However, as modern plants become much more highly automated, the role of personnel becomes less-and-less activity oriented, and more-and-more cognition oriented. Traditional methods are limited in their ability to analyze cognitive, supervisory control tasks.

- Traditional methods tend to focus on the ways tasks should be performed from the perspective of designers, procedure developers, and trainers. These perspectives do not always capture how work is actually performed in the plant under the demands of the real work environment. (This is one of the primary concerns addressed in this new guidance.)

- Traditional methods do not address well what makes situations demanding and difficult. However, in real world settings, task difficulty is an important determinant of performance and safety.

- Traditional methods are well-suited to clearly-defined situations, but are less well suited to analyzing unplanned and unanticipated situations, such as situations that have not been assessed by designers and not been experienced by operations experts. Yet it's just these types of situations that can pose the greatest risk to safety.

(6) The applicant should evaluate unacceptable results to determine root cause and corrective actions.

Additional Information: Note that the root cause of unacceptable workload for individual scenarios may not be due to staffing levels. For example, the high workload may be due to poor HSI design rather than insufficient staff. The human engineering discrepancy (HED) evaluation process described in NUREG-0711, Section 11.4.4, can be used for this analysis.

5.7 Develop Conclusions about the Acceptability of Workload Levels

(1) Applicants should provide overall conclusions about the acceptability of workload levels and the basis for that conclusion considering:

- Both time and workload analyses
- Consistency of results across the different challenging scenarios
- The results of HED evaluations of any findings where workload fails to meet acceptability criteria

6 Conclusions

This document describes a methodology to assess operator workload during challenging scenarios under minimum staffing configurations. 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 SMEs obtained in a manner conducive to obtaining realistic workload estimation. The document is written as NRC review guidance in a format consistent with NUREG-0711.

The methodology can be used before the design is ready for Integrated System Validation (ISV) 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.

As noted earlier in this document, 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, the methodology described here should be used within the context of the full HFE review, including, for example ISV where the proposed staffing levels can be validated.

One of the negative impacts of developing additional review guidance for staffing evaluations is that we have created yet another document for reviewers to use. Prior to the development of this new guidance, staffing level review guidance was spread across several documents: NUREG-0800 (Chapters 13 and 18), NUREG-0711, and NUREG-1791. Now there is one more to include. We have provided cross references to these other NUREGs to facilitate their integration.

We think there is 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 was the intent of NUREG-1791. However, NUREG-1791 was based on Revision 2 of NUREG-0711. There have since then been significant changes to NUREG-0711 in Revision 3, especially in the TA and ISV areas. As an aid to reviewers, this new tailored guidance has been developed. However, given the manner in which the NRC has structured its review of any request for exemption from operator staffing requirements, it appears that use of this new guidance should most likely be referenced in SRP Section 13.1.2 and 13.1.3 (or both 13.1.2/13.1.3 and 18.0).

Eventually NRC should consider providing a single source of guidance that integrates the guidance currently in the four source documents. The new document could be a significant update of NUREG-1791, or at a minimum, the new document can provide a roadmap for reviewers for determining when and how to use the various review documents. A roadmap will help reviewers understand the review process for staffing level exemption requests and the use of the various documents.

Finally, there are potential contributions of this current document to NUREG-0711 in general:

- Additional considerations for Sampling of Operational (SOC) for ISV to better reflect real world demands
- Value of identifying challenging scenarios early in the process to inform other HFE activities, such as function allocation
- The use of workload estimates in other HFE activities such as function allocation process and the allocation of tasks to crewmembers.

7 References

Allender, L., Archer, S., Kelley, T. & Lockett, J. (2005). Human performance modeling in the Army: A long and winding road. In the *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting*. San Monica, CA: Human Factors and Ergonomics Society.

ANS (2010). *Interim Report of the American Nuclear Society President's Special Committee on Small and Medium Sized Reactor (SMR) Generic Licensing Issues*. La Grange, IL: American Nuclear Society.

Archer, S., Gosakan, M., Shorter, P., & Lockett III, J. (2005). New capabilities of the Army's maintenance manpower modeling tool. *Journal of the International Test and Evaluation Association*. *26* (1), 19-26.

Baron, S., Kruser, D. & Huey, B. (Eds) (1990). *Quantitative modeling of human performance in complex, dynamic systems*. Washington, DC: The National Academies Press.

Campbell, G. & Bolton, A. (2005). HBR validation: Integrating lessons learned from multiple academic disciplines, applied communities, and the AMBR Project. In Gluck, K., & Pew, R. (Eds.). (2005). *Modeling human behavior with integrated cognitive architectures: Comparison, evaluation, and validation*. Mahwah, NJ: Lawrence Erlbaum Associates.

Charlton, S. (2002). Measurement of Cognitive States in Test and Evaluation. In T. O'Brien and S. Charlton (Eds.) *Handbook of Human Factors Testing and Evaluation (2nd Edition)*. Hillsdale, New Jersey: Lawrence Erlbaum, Associates, Inc.

DoD (2011). *Human Engineering Requirements for Military Systems, Equipment and Facilities* (MIL-STD-46855A). Washington, D.C: U.S. Department of Defense.

DoD (2003a) *Human behavior representation (HBR) literature review.* Washington, DC: Defense Modeling and Simulation Office. (Retrieved June 19, 2008 from http://vva.dmso.mil/default.htm)

DoD (1999). *Department of Defense Handbook: Human Engineering Program Process And Procedures* (MIL-HDBK-46855A). Washington, DC: Department of Defense

Eggleston, R. & Quinn, T. (1984). A preliminary Evaluation of a Projective Workload Assessment Procedure. In *Proceedings of the HFES - 28th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Gluck, K. & Pew, R. (Eds.). (2005). *Modeling human behavior with integrated cognitive architectures: Comparison, evaluation, and validation*. Mahwah, NJ: Lawrence Erlbaum Associates.

Grenci, T. & Haemer, R. (2010). Operations Staffing Issues Relating to SMRs. In ANS (Ed.) *Interim Report of the American Nuclear Society President's Special Committee on Small and Medium Sized Reactor (SMR) Generic Licensing Issues*. La Grange, IL: American Nuclear Society.

Hansberger, J. & Barnett, D. (2005). Human performance modeling for operational command, control, and communication. In *Proceedings of the HFES - 38th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Hugo, J. (2006). A model-base approach to the integration of human factors and systems engineering. *ESSA 2006 Conference*, Pretoria, South Africa: CSIR.

Kirwan, B. & Ainsworth L. (Eds) (1992). *A Guide to Task Analysis*. London: Taylor and Francis.

Laughery, R. & Persenksy, J. (1994). Network modeling of nuclear operator procedures. In *Proceedings of the HFES - 38th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Laughery, R., Plott, B., Engh, T. & S. Nash, S. (1996). Discrete event simulation as a tool to determine necessary nuclear power plant operating crew size. In *Proceedings of the 1996 Winter Simulation Conference*. San Diego, CA: The Society for Modeling and Simulation.

Lawless, K., Laughery, R. & Persensky, J. (1995). *Using Micro Saint to predict performance in a nuclear power plant control room: A test of validity and feasibility* (NUREG/CR-6159). Washington, D.C.: U.S. Nuclear Regulatory Commission.

TVA (2014). Inadequate Shift Staffing to Support Implementation of the Safe Shutdown Instructions Licensee Event Report (LER) 50-259/2013-005-01.

Mallett, B. (2010). Presentation at the *Commission Briefing on Reactor Issues - Design Certifications*. April 6, 2010 (available at: http://www.nrc.gov/reading-rm/doc-collections/commission/slides/2010/20100406/staff-20100406.pdf).

Masline, P. & Biers, D. (1987). An Examination of Projective versus Post-Task Subjective Workload Ratings for Three Psychometric Scaling Techniques. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *31* (1), 77-80.

Mays, G. & Williams, Jr. (2010). Key Technical Issues Associated with SMR Policy Issues. Paper presented at the *Regulatory Information Conference*. Washington, D.C.: U.S. Nuclear Regulatory Commission.

Mitchell, D. (2000). *Mental workload and ARL workload modeling tools* (ARL-TN-161). Aberdeen Proving Ground: Army Research Laboratory.

Mitchell, D., Samms, C., Henthorn, T. & Wojciechowski, J. (2003). *Trade study: A two- versus three-soldier crew for the mounted combat system (MCS) and other future combat system platforms* (ARL-TR-3026). Aberdeen Proving Ground, MD: Army Research Laboratory.

NEI (2012). *Diverse and Flexible Coping Strategies (FLEX) Implementation Guide,* (NEI-06), Rev. 0, August 2012. Washington, D.C.: Nuclear Energy Institute

NRC (2014). *Critical Task Sequence Identification and Evaluation Supporting Minimum Staffing in NPP Control Rooms*. Washington, D.C.: U.S. Nuclear Regulatory Commission.

NRC (2012). Interim Staff Guidance, *Compliance with Order EA-12-049, Order Modifying Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events* (JLD-ISG-2012-01), Rev. 0, Washington, D.C.: U.S. Nuclear Regulatory Commission.

NRC (2010). *Potential Policy, Licensing, and Key Technical Issues for Small Modular Nuclear Reactor Designs* (SECY-10-0034). Washington, D.C.: U.S. Nuclear Regulatory Commission.

NRC (1991), *Shift Staffing At Nuclear Power Plants* (NRC Information Notice 91-77). Washington, D.C.: U.S. Nuclear Regulatory Commission.

O'Hara, J. (2009). *Applying Human Performance Models to Designing and Evaluating Nuclear Power Plants: Review Guidance and Technical Basis* (BNL Technical Report BNL-90676-2009). Upton, NY: Brookhaven National Laboratory.

O'Hara, J. & Higgins, J. (2014). *Critical Task Sequence Identification and Evaluation Supporting Minimum Staffing in NPP Control Rooms: Review of Methodology and Recommendations for Improvement* (BNL Technical Report No. 4231/66-1-2014). Upton, NY: Brookhaven National Laboratory.

O'Hara, J, & Higgins, J. (2010). *Human-System Interfaces to Automatic Systems: Review Guidance and Technical Basis* (BNL Technical Report 91017-2010). Upton, NY: Brookhaven National Laboratory.

O'Hara, J., Higgins, J., Fleger, S., & Pieringer. P. (2012). *Human Factors Engineering Program Review Model* (NUREG-0711, Rev. 3). Washington, D.C.: U.S. Nuclear Regulatory Commission.

O'Hara, J., Higgins, J., & Pena, M. (2012). *Human-Performance Issues Related to the Design and Operation of Small Modular Reactors* (NUREG/CR-7126). Washington, D.C.: U. S. Nuclear Regulatory Commission.

Pew, R. (2008). More than 50 years of history and accomplishments in human performance model development. *Human Factors*, *50* (3), 489-496.

Pew, R. (2007). Some history of human performance models. In W. Gray (ed.). *Integrated models of cognitive systems.* New York, NY: Cambridge University Press.

Pew, R. & Mavor, A. (1998). *Modeling human behavior and command decision making: Representations for military simulations*. Washington, D.C.: The National Academies Press.

Persensky, J., Szabo, A., Plott, C., Engh, T. & Barnes, A. (2005). *Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.5m* (NUREG-1791). Washington, D.C.: U.S. Nuclear Regulatory Commission.

Pieringer, P. (2014). *Critical Task Sequence Identification and Evaluation Supporting Minimum Staffing in NPP Control Rooms*. Washington, D.C.: U.S. Nuclear Regulatory Commission.

Plott, C., Engh, T. & Barnes, V. (2004). *Technical Basis for Regulatory Guidance for Assessing Exemption Requests from Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)* (NUREG/CR-6838). Washington, D.C.: U.S. Nuclear Regulatory Commission.

Proctor, R. & van Zandt, T. (1994). *Human Factors in Simple and Complex Systems*. Needham Heights, MA: Allyn and Bacon.

Reid, G., Shingledecker, A (1984). A Projective Application of the Subjective Workload Assessment Technique. In *Proceeding of the IEEE 1984 National Aerospace and Electronics Conference*. New York: Institute of Electrical and Electronics Engineers.

Sebok, A. & Plott, B.(2008). Staffing levels: Methods for assessing requirements. In A. B. Skjerve, A. Bye, F. Øwre, K. Haugset, G. Skraaning Jr., R. Boring, & J. Neeb (Eds.) *The HAMMLAB history - 25 years of experimental research and development.* Halden, Norway: Institute of Energy Technology.

Sebok, A., Hallbert, B., Plott, B. & Nash, S. (1997). Modeling crew behavior and diagnoses in the control room. In *Proceedings of the IEEE Sixth Conference on Human Factors and Power Plants*. Orlando, FL. New York: IEEE, pp. 7.13 - 7.17.

Smith, J. (2012). Small Modular Reactor Issue Identification And Ranking Program Control Room Staffing - Final Report. In *Proceeding of the Eighth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies* (NPIC&HMIT 2012). La Grange Park, Illinois: American Nuclear Society, Inc.

Smith, J. (2009). Staffing, Human Factors and Operational Issues. Paper presented at the *Workshop on Small- and Medium-Sized Nuclear Reactors (SMRs)*. Washington, D.C.: U.S. Nuclear Regulatory Commission.

Tran, T., Garcia, H., Boring, R., Joe, J. & Hallbert, B. (2007). Human Factors Issues for Multi-modular Reactor Units. In *Proceeding of the Joint 8th IEEE HFPP /13th HPRCT*. Piscataway, NJ: IEEE.

Vidullch, M., Ward, F., & Schueren, J. (1991). Using the subjective workload dominance (SWORD) technique for projective workload assessment. *Human Factors*, *33* (6), 677–691.

Walters, B. & Yow, A. (2000). An evaluation of task network modeling for use in simulating situation awareness. In *Proceedings of the IEA 200/HFES200 Congress*. Santa Monica, CA: Human Factors and Ergonomics Society.

Wickens, C., Lee, J., Liu, Y. & Becker, S. (2004). *Human Factors Engineering*. Upper Saddle River, NJ: Pearson Prentice Hall.

Yow, A., Walters, B., Plott, B., Laughery, R. & Persensky, J. (2005). Predicting nuclear power-plant operator performance using discrete event simulation. *Journal Cognition, Technology & Work*, *7* (1), 29-35.

Appendix – Human Performance Models in Staffing and Workload Analyses

This appendix is based on information contained in O'Hara (2009) and is presented here to provide a description of the use of human performance models (HPMs) in HFE programs and specifically of staffing and workload analyses.

Applications

HPMs have long have been employed in formulating and developing U.S. military systems (Allender et al., 2005). For example, MicroSaint[6] and the Improved Performance Research Integration Tool (IMPRINT)[7] are used in defense applications to support analyses of the for staffing needs in complex systems like a military vessel.

IMPRINT is based on discrete-event, task network simulation model. An analyst breaks a mission into discrete tasks, and then specifies the sequence of their performance. The analyst defines important attributes of the task, such as the persons responsible and the time required to carry out each one. Models may cover the effects of outside stressors and training on performance. Having identified and sequenced the tasks, and described their essential attributes, the IMPRINT model is run. Its outputs include the time to accomplish the mission and the likelihood of success.

HPM can represent cognitive functions. For example, IMPRINT provides two options for modeling workload (Mitchell, 2000). One represents workload as a combination of visual, auditory, cognitive, and psychomotor (VACP) components. For each task, the analyst estimates on a seven-point scale the demand level on each VACP component. When IMPRINT is run, the workload values are summed across concurrent tasks, producing a workload profile for the mission. From this profile, the analyst can identify workload peaks that may compromise performance, and, thereafter, redesign the system or reassign tasks to other personnel to mitigate potential problems with workloads.

While the VACP approach provides workload profiles, it does not estimate their effects on task performance. IMPRINT has other features analysts can use to assess this. They support analysts in modeling workload management strategies by defining rules governing how tasks may be omitted, postponed, interrupted, or reallocated in response to high workloads.

IMPRINT and its predecessor, Hardware vs. Manpower (HARDMAN), were applied to a wide variety of design projects including analyzing the maintenance staffing needs in Army systems (Archer et al., 2005), and the staffing requirements for military vehicles (Mitchell et al., 2003).[8]

[6] General information on MicroSaint is provided at http://www.microsaintsharp.com; retrieved 16 December 2014

[7] General information on IMPRINT is provided at http://www.arl.army.mil/www/default.cfm?page=445; retrieved 22 August 2014.

[8] For more information on the range of IMPRINT and HARDMAN uses, see http://www.arl.army.mil/www/default.cfm?Action=445&Page=447, retrieved 8 January 2015

HFE professionals use HPMs for many aspects of design and evaluation, such as:

- assessing the effects of organizational structures on performance
- anticipating workload at the design stage to inform decisions on the requisite size of the crew
- estimating the effects of changes in interface design on the system's performance, and
- modeling differences among displays in supporting situation awareness

These uses of HPMs are summarized briefly below. The summary is intended to illustrate the range of applications, not as a review of HPM applications in HFE. Detailed reviews of individual models and their applications are published elsewhere (DoD, 2003; Gluck & Pew, 2005; Pew, 2007; Pew, 2008; Pew & Mavor, 1998).

Hansberger and Barnett (2005) developed a task network model to represent organizational structures, individual personnel, tasks, and communication patterns. The output generated by the model includes operator workload, situation awareness, completed tasks, delayed or omitted tasks, and likelihood of correct decision. They used the model to compare the effectiveness of two different configurations of personnel in vehicles in a tactical environment. Their findings revealed the influence of organizational structure on information flow (indicated by interrupted communications and dropped tasks). The authors extended the model to the operational level by modifying its architecture to represent complex organizational structures, e.g., individuals belonging to multiple groups. Their modeling of collaborative intelligence-gathering identified individuals with high workloads as bottlenecks in the information flow. The data aided in developing and testing flexible, adaptive workload-management strategies for the modeled activity.

Mitchell et al. (2003) used a task network model to compare and predict workload for two- versus three-soldier crews. They varied the distribution of functions among crew members, and the types of scenarios crews will encounter. The model calculated that a two-soldier crew will experience excessive workload multiple times during combat scenarios. Based on these findings, Mitchell et al. recommended three-person crews.

Researchers and plant designers have used HPMs in the nuclear industry, primarily to investigate staffing issues (Laughery & Persensky, 1994; Laughery, Plott, Engh & Nash, 1996; Lawless, Laughery & Persensky, 1995).

The NRC examined the feasibility of using task network models to model the operator's performance in several highly proceduralized scenarios, including a loss of coolant accident (LOCA), steam generator tube rupture (SGTR), and load maneuver (Laughery & Persensky, 1994; Lawless, Laughery, & Persensky, 1995). The authors in both studies used the procedures to develop models, and compared their predictions to actual human performance data from simulator trials. Crews handled the events using either paper or computer-based procedures. The authors concluded the model's predictions "…were representative of actual performance," but the results "…were not good enough to declare a clear success of the modeling approach."

Sebok, Hallbert, Plott, and Nash (1997) evaluated how well the models incorporate cognitive- and decision-making activities. They developed HPMs to predict performance in the following scenarios: SGTR, LOCA, loss of off-site power, and interfacing-systems LOCA. The operators' responses to the first three scenarios are significantly determined by procedures, i.e., "rule-based." Their reactions to the interfacing systems LOCA are less-well defined and more cognitively demanding, i.e., "knowledge based." The HPM's prediction of task times and the crews' diagnoses was compared with data from simulator trials with operators. The HPM's predictions were favorable in the rule-based scenarios, but not as good for the knowledge-based scenario.

Sebok and Plott (2008) used models to predict the effects of fewer staff in the control room, and the effects of varying crew size on workload and event timing. The authors focused on two scenarios used in a previous simulation with operators, an SGTR and loss of offsite power, that compared normal versus minimal staffing. They adopted operators' descriptions of the tasks that a four-person crew must undertake in each scenario and the decision rules operators use in performing them. The operators also had estimated task times, task variability, and workload. Sebok and Plott's model predictions agreed well with the human performance data for task-time measures. Running the model 100 times allowed them to specify points in each scenario at which significant delays (sufficient to impact safety) might occur when the crew comprised three members, rather than four. Agreement between workload predictions and the operator's workload measures was not as good. The authors postulated that this discrepancy might reflect differences in how the model predicted workload and how the operators' evaluated it.

In another study, Yow et al., (2005) compared HPM predictions of the crew's response to plant disturbances to that of actual crews responding to them in a plant simulator. The performance measures were task times and workload. There was a good correlation between the results. The authors concluded that the model's performance was sufficiently good to support extrapolation of the findings to untested conditions.

In an earlier study with the same simulator data, Walters and Yow (2000) had developed a model to predict situation awareness. During pauses in the simulation, the operators were asked to recall whether selected process parameters were increasing, decreasing, or unchanging. The model's predictions did not differ significantly from the operators' recollections.

Overall, these results suggest that performance models are useful in predicting the performance of operators on procedural tasks, e.g., the models highlighted some tasks that might be delayed after a reduction in crew size. The models also could predict the general trend and magnitude of the operators' workload during the scenarios.

HPMs now are being employed by the nuclear industry in a variety of applications, and also to support plant design. Hugo (2006) used an HPM to evaluate event timing and error rate as part of the Pebble Bed Modular Reactor (PBMR) HFE program. PBMR designers also employed the HPM to evaluate the effects of performance-shaping factors and workload on task performance. As the sophistication of the HPMs improve, their application likely will be extended to more complex designs and evaluations.

Potential Benefits of Adopting HPMs for Engineering Design and Evaluation

After reviewing the application of HPMs in general as part of a National Academy of Sciences study, Baron et al., (1990, p. 86) concluded:

> Given the current state of the art in human performance modeling, is the methodology ready to be an integral part of the system design process? Although the methodology has a number of admitted weaknesses, it also has the ability to make a number of unique contributions to the process of system engineering.
>
> By beginning modeling efforts early in the design process, a formal means is provided for considering the impact of human performance capacities and limitations on the range of design issues that must be confronted while there is still time to resolve them. An early modeling effort can provide quantitative and qualitative analyses that allow design trade-off studies to include a variety of human performance factors along with other system variables. This process forces consideration of the assumptions and design decisions which underlie assertions that the system will work with available personnel.
>
> In all, there are compelling reasons to believe that systematic human performance modeling efforts should be regularly advocated and used along with expert judgment and manned part- and full-task simulation, as a regular part of the design process for large-scale human-machine systems.

Building an HPM requires the analyst to generate detailed evaluations of the tasks that people perform and to identify the links between activities inside and outside the control room, and the events in scenarios. Tasks are modeled at varying levels of detail, thus ensuring more precise modeling of the more important tasks.

HPMs can be run numerous times, while varying task characteristics and situational factors, to determine the effects on performance. Models also provide analysts with a tool for "sensitivity analyses;" i.e., to identify which factors most significantly affect human performance.

HPMs provide documentation and traceability, so that independent analysts can review the model and repeat analyses. Further, the HPM constitutes a lasting tool for testing future modifications to the plant.

The main benefits of modeling fall into the following areas:

- clear depiction of task flows, dependencies, and interrelationships
- imposition of detail and rigor on the analysis
- incorporation of the influence of many factors on performance
- ease of performing "sensitivity analyses" i.e., the sensitivity of human performance measures to changes in other factors, such as workload and staffing levels
- documentation and traceability

Potential Limitations of Using HPMs for Engineering Design and Evaluation

Although HPMs offer potential benefits in research and design applications, there are limitations that both users and reviewers of models should consider carefully.

As HPMs are abstract representation of human behavior; an exact match to human performance is unlikely (DoD, 1999a). We gave examples of this limitation in the studies described earlier. Thus, while HPMs were quite good at predicting some particular aspects of performance, they were not as good at predicting other aspects.

As the models become more complex and incorporate elements designed to address various aspects of human performance, such as visual perception, decision-making, memory, and workload, we expect they may become more predictive. However, they may become more susceptible to the effects of modeling errors, partly because errors are additive (Topcu, 2003). Thus, even though each element of a model may be accurate, the model as a whole may not be. Integrating individual elements that form the complete model may not produce meaningful results because the effects of the errors in all of them may be summed.

Misuse is another potential problem, such as when an HPM that predicts performance in one context is applied to an entirely different one. Each HPM has an intended use. As we found in reviewing the studies described earlier, an HPM may predict behavior well in a narrow range of applications, such as a particular scenario or staffing profile, but may be quite inappropriate to use for others.

When an analyst fails to consider these limitations, the model's human performance predictions may be inaccurate or incorrect, and hence, using HPM analyses alone as the basis for plant design, e.g., for task allocation, task design, staffing, and HSI design, may jeopardize the safety of plant operation. Thus we suggest their use as part of design and staffing development can provide an acceptable basis for predicting workload and performance, so long as it is followed up by testing and validation with human crews.

To be of value in engineering design and evaluation, models must be *valid* representations of human behavior, especially in safety-critical domains, such as nuclear power. As Campbell and Bolton (2005) noted, "…it is generally agreed that validation is tremendously important, and the risk of drawing erroneous conclusions from unvalidated models is unacceptable" (p. 365).