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Technical Basis for Regulatory Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)

Micro Analysis and Design

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U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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ABSTRACT

This document provides the technical basis for methods that can be used for reviewing requests for exemptions from any of the requirements of Title 10, Part 50, of the *Code of Federal Regulations* (CFR) related to the number of licensed personnel needed to safely operate a nuclear power plant. The introduction of advanced reactor designs and the increased use of advanced automation in existing nuclear power plants may change the roles, responsibilities, composition, and size of the crews required to control plant operations. Current regulations regarding control room staffing, based upon the concept of operation for existing light-water reactors, may no longer apply. Therefore, applicants for an operating license for an advanced reactor, and current licensees who have implemented significant changes to existing control rooms, may wish to submit applications for exemptions from current staffing regulations. The US Nuclear Regulatory Commission (NRC) staff is responsible for reviewing the exemption requests and determining whether the staffing proposals provide adequate assurance that public health and safety are maintained to a level that is comparable to compliance with the current regulations.

This contractor report provides a discussion of the issues related to assessing requests for exemption from staffing requirements included in 10 CFR 50.54 for advanced reactor designs and control room upgrades. The report includes discussions of the potential impacts of these technological changes on staffing, relevant regulations and regulatory guidance, and available methods for conducting staffing assessments. The report concludes with a recommended approach for evaluating staffing-related exemption requests.

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EXECUTIVE SUMMARY

U.S. Nuclear Regulatory Commission (NRC) regulations currently prescribe the qualifications and staffing levels for licensed operating personnel for nuclear power plants. The design features and concepts of operations for new generations of advanced reactors, as well as the introduction of new automated systems into existing plants, may lead applicants to request variations in the prescribed number, composition, or qualifications of licensed personnel. This will require the applicants to submit exemption requests from applicable regulations included primarily in Title 10, Section 50.54 (m), of the *Code of Federal Regulations* (10 CFR 50.54(m)).

The purpose of this document is to describe the technical basis for a set of technically sound methods that the NRC staff may use for evaluating requests for exemption from current control room staffing regulations. These methods focus on the development and validation of staffing plans for personnel who are responsible for the safe operation of a nuclear power facility. The staffing plan may address personnel outside of those licensed to operate the facility, depending on the nature of the exemption requested.

We begin with a brief review of the potential impacts of new technologies on the roles and responsibilities of licensed personnel. These new technologies will likely change the overall concept of operations for nuclear power plants by introducing things such as passive safety features, automated systems, operator aiding technologies, the possibility of operating multiple modular reactors from the same control unit, and enabling remote operations. These new concepts of operations may require changes not only in the roles and responsibilities of personnel, but their numbers, job functions, or qualifications.

The current regulations and regulatory guidance addressing licensed personnel are then addressed. This includes guidance from other portions of the *Code of Federal Regulations*, the *Standard Review Plan*, and applicable Regulatory Guides, NUREGs, and other guidance documents. In addition, the process of submitting an exemption request is reviewed.

We then provide technical discussions of and the bases for methods and approaches for developing, validating, and evaluating staffing plans in support of the exemption requests. This discussion of staffing plan development includes the application of methods such as function analysis, task analysis, and job definition. Staffing plan validation addresses methods such as table top analysis, simulator studies, and human performance modeling, along with their supporting technical bases. Finally, we provide our conclusions and a recommended approach for evaluating a staffing-related exemption request.

The appendices provide a sample of human performance measures that may be used for staffing plan evaluation as well as a more in depth discussion of state-of-the-art methods for assessing situation awareness and cognitive workload.

FOREWORD

"Technical Basis for Regulatory Guidance for Assessing Exemptions from the Nuclear Power Plan Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)" provides the technical justification and describes approaches for regulatory review of requests for exemptions from any of the requirements of Title 10, Part 50, of the *Code of Federal Regulations* (CFR), as they relate to the number of licensed personnel needed to safely operate a nuclear power plant. The introduction of advanced reactor designs and the increased use of advanced automation technologies in existing nuclear power plants will likely change the roles, responsibilities, composition, and size of the crews required to control plant operations. Current prescriptive regulations regarding control room staffing, which are based on the concept of operation for existing light-water reactors, may no longer apply. Therefore, applicants for an operating license for an advanced reactor, and current licensees who have implemented significant changes to existing control rooms, may wish to submit applications for exemptions from current staffing regulations. An earlier study, NUREG/IA-0137, A Study of Control Room Staffing Levels for Advanced Reactors, found that:

> Therefore, decisions about control room staffing should be based upon design features including function allocation, automation, integration, and plant-specific characteristics (e.g., passive system performance). Validation and verification using measures of operator and crew performance are necessary to determine the staffing complement needed to operate the plant.

The purpose of this document is to describe the technical basis for a set of technically sound methods that the NRC staff may use for evaluating requests for exemption from current control room staffing regulations. These methods focus on the development and validation of staffing plans for personnel who are responsible for the safe operation of a nuclear power facility. The approach is consistent with Chapter 18, Standard Review Plan (NUREG-0800) and NUREG-0711, Rev. 1, Human Factors Engineering Program Review Model. The staffing plan may address personnel outside of those licensed to operate the facility, depending on the nature of the exemption requested. This document is intended to identify any gaps in the regulations with respect to control room staffing and address any limitations.

Technical discussions of and the bases for methods and approaches for developing, validating, and evaluating staffing plans in support of the exemption requests are provided. This discussion of staffing plan development includes the application of accepted human performance methods such as function analysis, task analysis, and job definition. Staffing plan validation addresses methods such as table top analysis, simulator studies, and human performance modeling, along with their supporting technical bases.

The US Nuclear Regulatory Commission (NRC) staff is responsible for reviewing the exemption requests and must determine whether the staffing proposals provide adequate assurance that public health and safety will be maintained at a level that is comparable to compliance with the current regulations. The process recommended in this document provides a comprehensive overview and suggests the use of the performance-based approach as opposed to the deterministic approach currently used in the current regulations. The guidance described for this technical basis will inform the decision-making process and allow staff to make better technical judgements upon receipt of an exemption request to modify staffing levels.

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ACRONYMS

CFR	Code of Federal Regulations
CR	Contractor Report
CW	Cognitive Workload
HFE	Human Factors Engineering
HSI	Human System Interface
HRA	Human Reliability Analysis
IMPRINT	Improved Performance Research Integration Tool
KSA	Knowledge, Skills and Abilities/Aptitudes
MRQ	Multiple Resources Questionnaire
NASA/TLX	National Aeronautics and Space Administration Task Load Index
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation
NUREG-nnnn	NRC Staff reports on Regulatory Technical and Administrative Issues
OER	Operating Experience Review
PRA	Probabilistic Risk Assessment
RO	Reactor Operator
SA	Situation Awareness
SACRI	Situation Awareness Control Room Inventory
SAGAT	Situation Awareness Global Assessment Technique
SART	Situation Awareness Rating Technique
SME	Subject Matter Expert
SRO	Senior Reactor Operator
SRP	Standard Review Plan
SWAT	Subjective Workload Assessment Technique
TA	Task Analysis
TNM	Task Network Model
V & V	Verification and Validation
WL	Workload

1.0 Introduction

Micro Analysis & Design (MA&D) was tasked to assist the US. Nuclear Regulatory Commission (NRC) with the development of guidance for the review of exemptions from the staffing requirements of 10 CFR 50.54. In order to accomplish this task MA&D:

- Performed a literature review on the effects of staffing on human performance and to identify human performance measures, methods, and other factors to consider when assessing staffing.
- Reviewed current regulations and regulatory guidance related to control room staffing.
- Reviewed available information and interviewed NRC staff and reactor vendors to gain an understanding of the design of advanced reactors and the anticipated staffing approaches and issues for these designs.
- Held a peer review workshop in March of 2003 to obtain input from subject matter experts on initial draft of guidance for assessing exemptions from 10 CFR 50.54(m).

As part of the tasking, and as verified by the reviews and peer reviewers, we determined that the introduction of advanced reactor designs and the increased use of advanced automation in existing nuclear power plants will likely change the roles, responsibilities, composition, and size of the crews required to control plant operations. The design features and concepts of operations[1] for new generations of advanced reactors, as well as the introduction of new automated or digital systems into existing plants, may lead to reductions in staff size and a changing role for the operator. Some of the possible changes in current approaches to control room staffing may include:

- Smaller control room crews,
- Smaller, or similarly sized, crews that are responsible for a greater number of reactors,
- The use of “control suites” that allow operational control of multiple reactors with a single set of controls and displays,

[1]For the purpose of this document, the term, “concept of operations,” refers to a description of how a licensee’s or applicant’s organizational structure, staffing, and management framework relate to the systems, design, and operational characteristics of the plant.

- Off-site operations of one or more reactors, or
- Entirely new staff positions requiring different qualifications.

Current regulations regarding control room staffing are prescriptive and are based upon the design and concept of operations of existing light water reactors. The regulations incorporate several assumptions that may not apply to advanced reactors or to new control room configurations. Some of these assumptions include:

- The controls and displays needed to support operations are located on site in permanent control rooms,
- There is a maximum of three units and three control rooms,
- There are no more than two units per control room, and
- There is at least one senior operator on site at all times and at least one in the control room for each unit in operation.

Because these assumptions may no longer hold true for advanced designs, applicants for an operating license for an advanced reactor, and licensees who have implemented significant changes to existing control rooms, may submit applications for exemptions from current staffing regulations.

Further, research conducted by the NRC at the Halden Reactor Project (NUREG/IA-0137) indicated that decisions about staffing for advanced reactor designs are more appropriately based on plant design features such as levels of automation, function allocation, and plant specific operating characteristics rather than on prescribed staffing levels.

Therefore, the NRC staff determined that the best approach for accommodating these anticipated changes would be through the exemption request process detailed in 10 CFR 50.12. The NRC staff will review the exemption requests and determine whether the staffing proposals will provide adequate assurance that public health and safety are maintained to a level that is comparable to compliance with the current regulations. A systematic process for analyzing and evaluating exemption requests to current staffing requirements will be needed. Therefore, the NRC Office of Nuclear Regulatory Research sponsored this project to develop guidance for the NRC staff to use in reviewing requests for exemptions from current staffing regulations for advanced reactor designs or for other proposed changes to the manner in which reactors are operated due to automation. The project resulted in publication of a NUREG, titled "Regulatory Guidance for Assessing Exemptions from Nuclear Power Plant Licensed Operator Staffing Requirements 10CFR50.54(m)." This NUREG/CR presents the technical bases for the guidance document.

1.1 Purpose, Scope and Objective

The purpose of this document is to describe a set of technically sound methods that the NRC staff may use for evaluating requests for exemption from any of the requirements of Part 50 of Title 10 of the *Code of Federal Regulations* (CFR) related to the number and qualifications of licensed personnel needed to safely operate a nuclear power plant. A request for exemption would be based on the implementation of advanced technologies that change the roles and responsibilities of personnel licensed under 10 CFR Part 55. Because the nature of potential exemption requests based upon advanced technologies is currently unknown, a major objective of the project was to develop a flexible review process that could be used to evaluate a wide range of staffing-related exemption requests.

1.2 Intended Use

The review methods described in the guidance document are applicable when a request is submitted for an exemption from the requirements of 10 CFR 50.54(m). Within the overall regulatory framework, the guidance document presents a more detailed process for implementing the guidance contained in Sections 13.1.2-13.1.3, "Operating Organization," and 18, "Human Factors Engineering," of NUREG-0800, "Standard Review Plan" (SRP) (NRC, 1998). The guidance also expands on Section 6, "Staffing and Qualifications," of NUREG-0711 "Human Factors Engineering Program Review Model" (NRC, 2002). This document provides additional detail and discussion of the many issues that may arise in the evaluation of an exemption request and may be useful as a companion document to staffing review guidance. The relationship of staffing review guidance to current regulations and other, related guidance is illustrated in Figure 1.

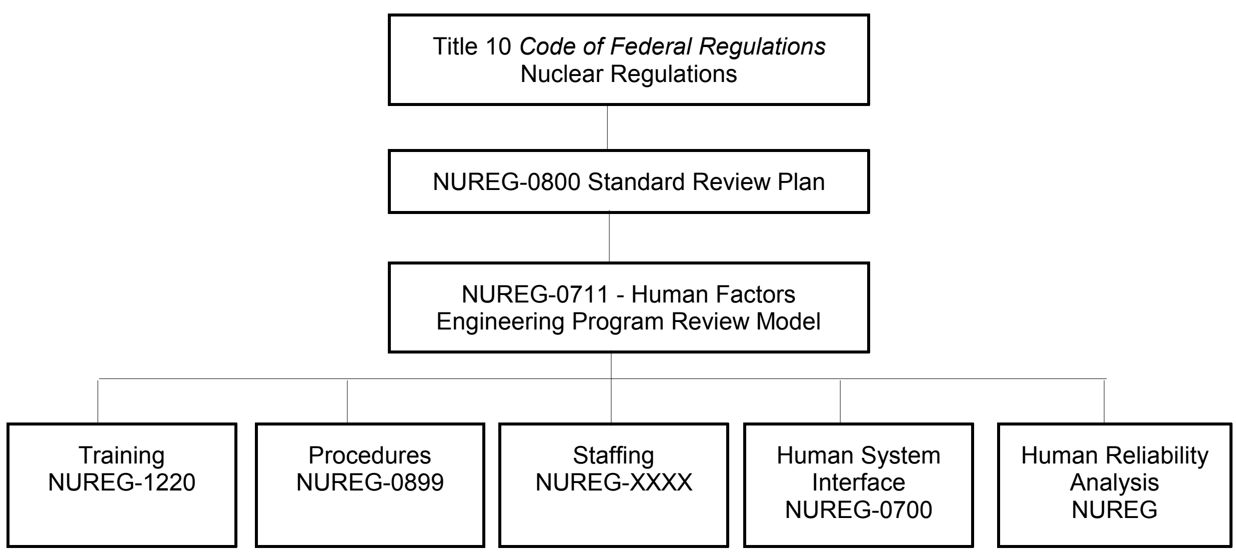

Figure 1 Relationship of this Document to Current Regulations and Other Guidance

1.3 Organization of the Document

To set the context for discussion of the proposed staffing evaluation methods, a brief review is provided of the potential impacts of new technologies on the roles and responsibilities of licensed personnel in section 2. In section 3, the current regulations and regulatory guidance addressing licensed personnel are reviewed. The likely form and content of exemption requests are then addressed in section 4, as they relate to the requirements of 10 CFR 50.54(m).

The remaining sections discuss potential staffing evaluation methods. Section 5 includes discussion of the methods and approaches for developing, validating, and evaluating staffing plans in support of the exemption requests and the information that reviewers will need to evaluate an exemption request. Appendix A supplements section 5 by providing samples of human performance measures. Appendix B further supplements the technical basis by providing a discussion of methods for measuring situation awareness and cognitive workload. Conclusions and a summary of the recommended process for reviewing exemption requests are presented in Section 6.

2.0 Impact of New Technologies on the Roles and Responsibilities of Licensed Personnel

Based on our review of the literature on advanced reactor designs, interviews with vendors developing advanced reactors, and comments received from peer reviewers at a the peer review workshop, we determined that there is a relatively wide range of potential changes to reactor designs, and to the technologies that will be available for maintaining operational control of new and existing nuclear power plants. Simplified designs and operations, increased use of advanced automation, the possibility of operating multiple modular reactors from the same control unit, and new technologies for human-system interfaces (HSIs) will change the role of the human in plant operations. Automation technologies are rapidly changing, however, and it is difficult to predict how the new technologies will be implemented in future nuclear power plants and how the roles of licensed personnel will change as a result. In this section, a few of the possible changes and their implications for control room staffing are discussed.

Many advanced reactor designs incorporate passive safety features that require minimal operator intervention to mitigate accidents in the event of malfunction. These *passive safety features* are based on natural forces, such as convection and gravity, making safety functions less dependent on active systems and components, such as pumps and valves. The passive features allow operators more time to perform safety actions. The increased time available to respond to events could reduce the number of personnel required on each shift, because there would be time to augment the staff to respond to the event.

For both advanced plant control room designs and some potential upgrades to existing control rooms, the increased use of automated control, monitoring, and protection systems will bring the plant back to normal conditions or to a safe shutdown state, without the need for operator action. This reduction in the need for human intervention could also reduce the number of people required for control operations.

Automated systems that support and supplement human cognitive functions associated with controlling the plant may also affect staffing configurations in both advanced and existing plant control rooms. Technological advances, such as intelligent agents, computer-supported cooperative work, knowledge engineering, and knowledge-based systems, are leading to designs of automated systems that enhance control room personnel capabilities for monitoring, disturbance detection, situation assessment, response planning, and response execution.

Along with these advances in automation technology, new human system interface (HSI) technologies are also emerging. Rather than having control rooms with panels full of controls and displays, there will be "control suites," consisting of a set of computer displays and input devices. Information can be displayed dynamically across the monitors in the display and enhanced auditory signals, such as speech, will be possible. An array of input capabilities including touch, gesture, and speech are also possibilities. Intelligent support systems can enhance the timing and forms of information provided to operations personnel and enhance the management of both automated and manual actions. These advances may reduce the number of plant personnel required to maintain operational control of a single reactor or may allow plant personnel to maintain control of multiple units from one control suite.

In addition, advances in the bandwidth and reliability of telecommunications technologies (including wireless) create the possibility of remote operations from both remote control suites and from portable devices, such as laptop computers or personal digital assistants. Telecommunications technologies may allow personnel to monitor and control multiple reactors from remote locations, though security constraints may limit the use of these technologies.

Implementation of advanced technologies may change some or all of the HSI elements upon which current staffing approaches are based. The advanced technologies will likely result in changes to the allocation of functions and tasks among personnel and systems. The character of the functions and tasks may also change, resulting in changes to the number and qualifications of personnel needed. For example, because monitoring of plant parameters and most control tasks may be fully automated, on-site operations personnel may be able to perform the majority of site maintenance tasks or tasks currently assigned to other plant personnel. As a result, the knowledge, skills and abilities that operations personnel are required to master may change.

Some of these potential changes to plant designs and to systems used to control plant operations may make obsolete the concept of a traditional control room staffed by a crew of licensed operators as well as change what it means to be a licensed operator of a plant. For this reason, in the remainder of this document, we use the term “control personnel” to identify those individuals who will be responsible for the safe operation of the plant, regardless of the location at which they will perform their tasks or their qualifications relative to current standards.

3.0 Current Regulations and Regulatory Guidance Related to Licensed Personnel

As indicated below, the NRC has published regulations and regulatory guidance related to staffing levels (i.e., staff size) and staffing design (i.e., composition, qualifications) for the current generation of nuclear power plants. The NRC staff may review requests for exemptions from one or more of the requirements described in this section.

The current requirements for control room staffing are primarily contained in 10 CFR 50.54(m). For convenience, Table 1 presents the requirements of 10 CFR 50.54(m)(2)(I), which prescribe licensed operator staffing levels.

Table 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	One control room	Two 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	5[(3)]	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 is two senior operators and four operators.

Several limitations in the scope of these requirements, as well as the requirements of 10 CFR 50.54(m)(2)(ii), (iii), and (iv), exist. Some key assumptions are also implicit in the requirements. As briefly discussed in Section 1, these limitations and assumptions include:

- There is a maximum of three units and three control rooms.
- The number of control rooms does not exceed the number of units.
- There are no more than two units per control room.
- There is always at least one operator at the controls for each unit (50.54(m)(2)(iii)).
- There is always at least one, and sometimes two additional operator(s) on site, for each unit in operation.
- There is at least one senior operator on site at all times (50.54(m)(2)(ii)).
- There is one senior operator in the control room for each unit in operation (50.54(m)(2)(iii)).
- There is one more senior operator than the number of units operating when multiple units are in operation in more than one control room, except when three units are in operation in two control rooms.
- Operator and senior operator are the only two job functions addressed by the *Code of Federal Regulations*, and their roles, responsibilities, and qualifications are as defined 10CFR55.

Finally, 10 CFR 50.54(m)(2)(iv) requires the following:

> Each licensee shall have present, during alteration of the core of a nuclear power unit (including fuel loading or transfer), a person holding a senior operator license or a senior operator license limited to fuel handling to directly supervise the activity and, during this time, the licensee shall not assign other duties to this person.

These assumptions and limitations reflect a concept of operations that is consistent with the design and operation of conventional light-water reactors. Also reflected is a "margin of safety" policy that suggests that there should be a sufficient number of operators and senior operators to safely operate the plant, plus one more, in case something happens to one of them.

NUREG-0800 "Standard Review Plan" (NRC, 1998) Section 13.1.2-13.1.3 "Operating Organization" further addresses additional operating personnel, as follows:

- Acceptance Criterion C.1 states that a shift supervisor with a senior operator's license, who is also a member of the station supervisory staff, be onsite at all times when at least one unit is loaded with fuel.

- Acceptance Criterion C.2 states that an auxiliary operator (non-licensed) be assigned to the control room when a reactor is operating.

- Acceptance Criterion C.6 states that "Assignment, stationing, and relief of operators and senior operators within the control room shall be as described in Regulatory Guide 1.114."

- Acceptance Criterion D states that staffing plans include total complements of licensed personnel of no less than that needed for five shift rotations.

Finally, the "Policy Statement on Engineering Expertise on Shift," published in the Federal Register (50 FR 43621), October 28, 1985 provides licensees with the option of combining the senior operator and shift technical advisor functions into a "dual role" position. The qualifications for the shift technical advisor are given in NUREG-0578 (NRC 1979) and NUREG-0737, Item I.A.1.1 (NRC 1980).

10 CFR 50.54(m) and the related guidance described above primarily address crew composition and crew size as they relate to the numbers of units and control rooms. Other parts of 10 CFR 50.54 and 10 CFR Part 55 address licensed personnel qualifications and authorities, and specifically their authorization for being "at the controls," as follows:

- 10 CFR 50.54(I), which states that: "Except as provided in 55.13 of this chapter, the licensee may not permit the manipulation of the controls of any facility by anyone who is not a licensed operator or senior operator as provided in part 55 of this chapter."

- 10 CFR 50.54(j), which states that: "Apparatus and mechanisms other than controls, the operation of which may affect the reactivity or power level of a reactor shall be manipulated only with the knowledge and consent of an operator or senior operator licensed pursuant to part 55 of this chapter present at the controls."

- 10 CFR 50.54(k), which states that: "An operator or senior operator licensed pursuant to Part 55 of this chapter shall be present at the controls at all times during the operation of the facility."

- 10 CFR 50.54(I), which states that: "The licensee shall designate individuals to be responsible for directing the licensed activities of licensed operators. These individuals shall be licensed as senior operators pursuant to part 55 of this chapter."

- 10 CFR 55.4, which states that the definitions for controls, facility, licensee, operator, and senior operator must be included in a request for licensing.

- 10 CFR 55.41 and 55.43, respectively, which state that the roles, responsibilities, and capabilities implied by the operator and senior operator examination requirements be included in a request for licensing.

This set of regulations requires that anyone who will manipulate a control that may affect the reactivity or power level of a reactor, or who directs others who can, must be licensed as either a reactor operator or senior operator, respectively. The licensing requirements for these positions are based on the technologies and concept of operations for light water reactors. Given the concepts of operations that advanced nuclear power reactor designs and technologies make possible, applicants may also submit requests for exemptions from this set of regulations as well.

Additional regulations and guidance associated with personnel qualifications and authorities include:

- Regulatory Guide 1.114: *Guidance to Operators at the Controls and to Senior Operators in the Control Room of a Nuclear Power Unit*, (NRC 1989).
- *U.S. Code of Federal Regulations*, Part 50.120, "Training and qualification of nuclear power plant personnel," Title 10, "Energy."
- Regulatory Guide 1.8: *Qualification and training of personnel for nuclear power plants* (NRC 2000).
- NUREG-1122: *Knowledge and abilities catalog for nuclear power plant operators: Pressurized water reactors* (NRC 1998).
- NUREG-1123: *Knowledge and abilities catalog for nuclear power plant operators: Boiling water reactors* (NRC 1998).
- Regulatory Guide 1.149: *Nuclear power plant simulation facilities for use in operator license examinations* (NRC 1996).
- NUREG-1220: *Training review criteria and procedures* (NRC 1993).

These documents should also be reviewed by the staff to assess their applicability to advanced reactors and may need to be modified or supplemented.

4.0 Exemption Requests

When an exemption is requested in accordance with 10 CFR 50.12, the applicant must submit evidence that the staffing proposal is adequate for the safe operation of the plant under all relevant operational conditions. The applicant's request for exemption should be clear and specific about the portion(s) of 10 CFR 50.54(m) and related requirements from which an exemption is requested. The exemption request could include straightforward variations on the requirements of 10 CFR 50.54(m), such as:

- a greater number of units controlled per control room.
- a greater number of units for which an operator or senior operator is responsible.
- changes in the responsibilities or qualifications of the control personnel, such as combining the responsibilities for operations and fuel handling.

More complex requests may also be submitted, such as:

- the definition of new jobs that include functions not currently assigned to licensed operators.
- control of operations at multiple sites from one control room .
- an expanded definition of "at the controls" to include portable monitoring devices that would allow responsible personnel to monitor plant parameters and maintain operational control from either outside the control room or off-site during normal operations.

These latter, non-traditional concepts of operations may result in the need to redefine terms such as "control room," "operator," and "at the controls." They may also result in the need for new operational terms and definitions. When this is the case, the applicant must indicate the need for, and provide definitions for, these new ideas and terms as part of the exemption request. When this type of information is not provided or when the reviewer feels uncertain about what is being requested, clarification from the applicant should be requested.

The applicant may also indicate that further exemptions from the regulations that may be required. Given the number of possible types of exemptions that might be requested and the interrelationship of part 50.54(m) to other NRC regulations, it is possible that exemptions from other regulations also may be necessary.

5.0 Technical Basis for Staffing Plan Evaluation

In our review of methods and techniques used in various industries and the military for developing and validating staffing plans we found that there are several elements that are common to such development. Methods such as those described by Becht (2002) in "Strategic Staffing" for use in general industry, by Medsker and Campion (1997) for job and team design, or sociotechnical approaches such as those described by Hendrick (1997), provide valuable information for the development of the proposed guidelines for NRC use. NUREG-0711, Section 6 "Staffing and Qualifications." also includes high level review guidance for staffing plans.

In order for NRC personnel to evaluate staffing exemption requests submitted in accordance with 10CFR50.12, they will need data from the applicant substantiating the request. These data would come from the analyses the applicant has performed to develop the staffing proposal. Reviewers will also need data from validation activities demonstrating that licensees can implement the proposed plan and provide adequate assurance that public health and safety are maintained to a level that is comparable to compliance with the current regulations. In this section, we discuss some of the methods that reviewers would find acceptable for development and validation of staffing proposals.

5.1 Developing Staffing Plans

The guidance in NUREG-0800 "Standard Review Plan" (NRC, 1998) and the guidance provided by NUREG-0711 "Human Factors Engineering Program Review Model" (NRC, 2002) address a systematic analysis and design process for assuring the safe operation of the facility. Staffing is specifically addressed in the Standard Review Plan in Section 13.1.2-13.1.3 "Operating Organization," and in NUREG-0711 in Section 6 "Staffing and Qualifications." Methods for reviewing staffing analysis and validation are not provided in these sources, however.

The most appropriate approach to performing a staffing analysis in support of an exemption request is within the context of the analyses that are conducted in support of the facility design. This provides the most straightforward evaluation of the proposed plan by maintaining the context, data sources, and interrelationships among the analyses that the NRC reviewers are using to assess the overall design of the facility.

Analyses and data that would be needed to perform a review include:

- a description of the concept of operations for the control personnel.
- a description of the operating conditions applicable to the exemption request.
- a description of new or modified positions for control personnel, preferably in the form of job definitions.
- operational experience.
- functional requirements analysis and function allocation.

- task analysis.

- staffing plans.

- other analyses described in NUREG-0711.

In the remainder of this section we describe the information that reviewers would need for each of these analysis areas in support of an exemption request.

5.1.1 Concept of Operations

The purpose of reviewing the concept of operations is to provide the reviewer with a more comprehensive understanding of how the proposed staffing and associated exemption request(s) fit into the overall design and operation of the plant. At the most general level, the term, "concept of operations," refers to 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.

The term, “concept of operations,” may also be used when discussing a system. For example, an applicant may intend to add an intelligent monitoring system that will monitor plant parameters and take control actions in response to certain conditions that were previously performed by an operator. The concept of operations in this case would describe the purpose of the new system, its relationship to other systems, the system's characteristics and operations, user interactions with the system as well as training and procedures requirements.

5.1.2 Operating Conditions

The reviewer should verify that the applicant has identified and analyzed the set of operating conditions that are relevant to the exemption request. The set of operating conditions that present the greatest potential challenges to the effective and safe performance of control personnel, under the conditions of the requested exemption, should be included in this set. During the normal course of the licensing process, an applicant must analyze the full range of operational conditions that personnel need to manage. For the purpose of justifying a given exemption or set of exemptions to 10 CFR 50.54(m), however, analysis of the full range of potential conditions may be unnecessary.

NUREG-0711, Section 11.4.1, "Operational Conditions Sampling," provides a robust set of guidelines for identifying operational conditions for use in verification and validation of control room designs. This same basic guidance can be used for the purpose of reviewing requests for exemptions from 10 CFR 50.54(m). The focus of the sampling should be adjusted to the conditions relevant to the exemption request and the emphasis should be on those operational conditions known to present the greatest challenges to human performance.

The exemption request should provide a discussion of the rationale for selecting specific conditions and for not analyzing others. The reviewer should assess whether this set of operations is reasonable, based on the design of the plant, the concept of operations, and the range of operational conditions that could be considered.

5.1.3 Job Definitions

The purpose of reviewing any new job definitions is to confirm that clear and rational definitions for jobs have been established for the personnel who will be responsible for controlling the plant, in the case of a new plant design. For an existing plant in which new systems will be implemented, the purpose of the review is to verify that clear and rational definitions for jobs have been retained for control room personnel. A *job* is defined as the group of tasks and functions that are assigned to a personnel position. A *job definition* specifies the responsibilities, authorities, skills, knowledge, and abilities that are needed to perform the tasks and functions assigned to a job.

An applicant's job definitions should describe the impact of the exemption request on each job affected. For example, an exemption request could entail re-defining and re-assigning the functions and tasks of the current senior operator position. Current senior operator responsibilities for coordinating and overseeing the activities of reactor operators in a control room located on-site could be eliminated, partially re-allocated to intelligent monitoring systems, and/or assigned to off-site personnel who monitor on-site activities remotely.

Alternatively, a new job could be created that has no analogue in the existing plant or under the current regulations. As a hypothetical example, a specialist job could be created in which an individual is uniquely trained and qualified to troubleshoot the software that supports new systems or new HSIs and to assume control if systems fail and backups must be used.

A job that consists of interrelated responsibilities and authorities that do not conflict would be coherent. A classic example of conflicting responsibilities would be a senior operator in a traditional control room who is charged with maintaining an overview of operational conditions as well as performing a variety of administrative tasks. These administrative responsibilities may compromise his or her ability to maintain "the big picture." The reviewer should verify that the applicant's job definitions appropriately prioritize the responsibilities of each position and do not incorporate role conflicts.

An important aspect of the job definition review is to verify that the qualifications needed for each position are delineated. The qualifications needed for a plant staff position consist of the knowledge, skills and abilities (KSAs) an individual must possess to meet the performance criteria established for the tasks assigned to the position. The information derived from the function and task analyses should provide a basis for identifying the needed KSAs for each position.

The scope of the job definition review should be limited to the jobs of control personnel who are impacted by the exemption request. Within a job, the scope of the review may also be limited by the extent (e.g., only a few job functions or tasks impacted) and character (e.g., only responsibilities affected, not qualifications) of the exemption request.

5.1.4 Operating Experience

The purpose of the operating experience review is to verify that the applicant has reviewed the relevant operational experience to identify and address staffing-related lessons learned that may be important to the exemption request. Previous staffing-related problems need to be reviewed in order to avoid repeating them, should the exemption request be approved. Operating experience may also be reviewed to identify similar staffing practices that have proven to be effective and lessons learned from successful implementation of similar technologies and concepts of operations.

The amount of relevant operating experience available will vary, depending upon whether the exemption request involves new reactor designs or the introduction of new systems into an existing plant. The greatest amount of information will be available for systems and staffing practices that have been implemented in other nuclear power plants. Information regarding new system designs and staffing practices should also be sought from other industries in which similar systems or practices have been implemented (e.g., chemical manufacturing plants, other types of power generating plants, some military systems).

The results of the operating experience review may be used as input to several of the exemption request analyses. For example, review of the applicant's operating experience may identify problematic operations and tasks that should be considered in the selection of operational conditions and tasks to be analyzed. Experience regarding the impacts of staffing shortfalls may also be useful in the task analysis, for defining jobs and in developing the staffing plan. Operating experience from implementing the same or similar technologies in other settings may be used as the basis for allocating functions between the technologies and control personnel. Operating experience may also provide data to support the staffing plan verification and validation process.

5.1.5 Functional Requirements Analysis and Functional Allocation

The reviewer should confirm that the results of functional requirements analysis and function allocation support the staffing plan, job definitions, and exemption request. The impact of the exemption request on the plant/system functions that must be performed to satisfy plant safety objectives should be defined and evaluated. The applicant's allocation of functions to humans and systems should result in a role for personnel that uses human strengths, avoids human limitations, and can be performed under the operational conditions evaluated in the exemption request.

A *function* is a process or activity that is needed to achieve a desired goal. *Functional requirements analysis* is the identification of functions that must be performed to prevent or mitigate the consequences of postulated accidents that could damage the plant or cause undue risk to the health and safety of the public. The functional requirements analysis is also conducted to identify and define functions for all other normal operating conditions with the goal of achieving effective, efficient, and safe operations. A functional requirements analysis is conducted to:

- determine the objectives, performance requirements, and constraints of the design.

- define the high-level functions that have to be accomplished to meet the objectives and desired performance.

- define the relationships between high-level functions and plant systems responsible for performing the function, and.

- provide a framework for understanding the role of controllers (whether personnel or system) for controlling the plant.

Function allocation is the analysis of the requirements for plant control and the assignment of control functions to:

- personnel (e.g., manual control).

- system elements (e.g., automatic and passive control, self-controlling phenomena).

- combinations of personnel and system elements (e.g., shared control and automatic systems with manual backup).

Functional requirements and function allocation analyses are also needed when implementing new systems in existing plants. Plant modifications may change the level of automation of the original design and change the functions that are allocated to systems and personnel, leading to an exemption request.

5.1.6 Task Analysis

The purpose of the task analysis review is to verify that the applicant's analysis identifies the specific tasks that are needed to accomplish functions and their staffing implications. The functions allocated to plant personnel define their jobs. Human actions are performed to accomplish these functions. Human actions can be further divided into tasks. A *task* is a group of related activities that have a common objective or goal. *Task analysis* is the identification of requirements for accomplishing these tasks, i.e., for specifying the requirements for the displays, data process, controls, and job aids needed to accomplish tasks.

The scope of task analyses performed by an applicant will vary, depending upon the nature of the design or system(s) for which the exemption request has been initiated. In the case of a modification to an existing plant, the task analysis should address the tasks that have changed. In the case of a new plant or control room design, the task analysis should address the set of tasks that control personnel will perform in the defined operational conditions.

For each task, the information, control, and task-support requirements should be addressed by the applicant's task analysis, as applicable. The information should be used to identify issues of task timing, workload, and situation awareness and to determine resource conflicts that would affect staffing assignments. (Workload and situation awareness are discussed in greater detail in Appendix B).

There are a number of acceptable methods for conducting task analyses. The reviewer should verify that the applicant has used a generally recognized approach.

5.1.7 Staffing Plans

The purpose of reviewing the staffing plan is to verify that the applicant has followed a systematic process to determine the number of qualified personnel necessary to operate the plant safely under the operational conditions analyzed. That is, how many individuals must be qualified and available to fill each job?

The applicant's staffing plan should be supported by the results of the functional requirements analyses and function allocation, task analyses, and the job definitions for each position identified under the operational conditions considered. In addition, the applicant's submittal should define the proposed shift composition and shift scheduling. *Shift composition* refers to the different types of jobs that must be filled on each shift and the number of personnel required for each of the jobs on a shift. In the case of remote operations or operations that will take place outside of a traditional control room, the locations of the personnel comprising a shift should also be defined.

5.1.8 Other Analyses

Applicants may provide additional supporting data and analyses as part of the exemption request submittals. These additional submittals should be reviewed based on their applicability to the requested exemption and the need for the supporting data and analyses. Additional review areas may include:

- human reliability analysis used to demonstrate the impacts of risk-important human actions.

- human-system integration data used to demonstrate that the design of the HSIs supports the concept of operations, function analysis and allocation, the task analysis, staffing plan, and operating experience .

- the KSA analysis used in support of new or changing job definitions.

- the KSA analysis used to support modified tasks or human-system interfaces.

- procedures and training documentation that demonstrate the implementation of components of the concept of operations, function analysis and allocation, or the task analysis.

The reviewer should also consider additional submittals that would be expected, based on the character of the exemption request. For example, if remote support operations are proposed, data supporting the new communications skills needed for control personnel may be appropriate. NUREG-0711 includes review criteria for these areas and should be the starting point for further review.

5.2 Validating Staffing Plans

The purpose of validating the staffing plan is to verify that applicants have 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 supports safe operation of the plant.

The reviewer should consider data or demonstrations that the control personnel specified in the staffing plan can satisfy the plant and human performance requirements identified in the functional requirements analysis, function allocation, and task analyses. These data or demonstrations may come from tabletop analyses, operating experience, in-simulator studies, human performance models, or a mix of these methods. The data or demonstrations should include the full range of operational conditions identified for the exemption request as well as a reasonable representation of the human performance variability expected in the context of the operational conditions.

Staffing plan validation methods include:

- Table Top Analysis
- Data from Operational Experience
- Simulator Studies
- Human Performance Models

It is likely, and recommended, that the applicant will use more than one of these approaches in validation efforts. Each approach has its strengths and limitations, and although there is some cross over between them, the approaches largely compliment each other.

Before discussing these methods however, we provide a discussion of human performance measures. The human performance measure used for validation should be identified and defined by the applicant, regardless of the methods used. This discussion reflects the range of measures that applicants should consider.

5.2.1 Human Performance Measures

In order to evaluate performance of personnel in any system, there must be measures of performance and other variables thought to influence performance. The inclusion of variables other than outcome variables is important when identifying the causes of any human performance shortcomings. Some of these other variables are cognitive workload and situation awareness.

Although it is important to understand what contributes to success or failure, overall system performance is the outcome measure of principal interest for evaluating the adequacy of the staffing proposal. Measures of human performance used to evaluate individual and crew performance of the control personnel in the scenarios need to be identified. Outcome-oriented human performance measures include measures such as:

- time to complete actions.
- timeliness of actions.
- accuracy and completeness of actions.
- omitted actions.

Outcome measures can usually be observed, measured directly, and be linked to overall plant and system performance measures. The measures may be aggregated to the crew level in evaluating crew performance, and ultimately, the adequacy of the staffing plan.

Measures of conditions that can affect the response of control personnel should also be addressed. To the extent that environmental conditions such as heat, cold, or lighting need to be considered, their impacts on control personnel performance should be addressed. If shift durations or scheduling have the potential to cause sleep loss and fatigue among control personnel, these impacts will need to be assessed as well. The impacts of these types of conditions are most often seen as degradations in control personnel performance, which may not always result in degraded system performance or failure. Degraded personnel performance increases the risk of failure, however, so the frequency and extent to which control personnel are exposed to the adverse conditions should be assessed.

Time and information processing demands placed on the control personnel may also degrade performance. The impacts of these types of demands can be assessed using measures of cognitive workload and situation awareness.

Cognitive workload refers to the degree to which an individual's cognitive and perceptual capabilities are taxed during the performance of the tasks that comprise his or her job. Most cognitive workload measures are structured self-reports from the users of a system regarding the time pressure they experience, the mental effort involved in performing their tasks and the amount of stress they experience. Excessive cognitive workload will lead to performance decrements, such as delays, inaccurate responses, errors in diagnoses, and omissions

Situation or situational awareness (SA) is defined as an individual's mental model of what has happened, the current status of the system, and what will happen in the next brief time period (Endsley & Garland, 2000). Because the quality of a person's decision selection and performance is determined by the "goodness" (accuracy, completeness, relevance) of the internal, or mental, model of the system, it is critical for control personnel to form and maintain complete and accurate SA. To determine if new plant designs and/or new staffing arrangements adequately support SA, it is important to evaluate the degree to which control personnel demonstrate adequate SA.

In addition to defining the measures of human performance used in validating the staffing plan, criteria need to be established to determine the acceptability of the results obtained. Example criteria include:

- Nominal task performance times will not be exceeded by more than 10%.
- No more than 60 seconds will be required to begin Task X after Event Y.
- Temperatures will be maintained within +/-5 degrees.
- No actions will be omitted.

For reference, Appendix A provides a listing of human performance measures at the task level adapted from NUREG-0711. Appendix B provides a discussion of state-of-the-art methods for assessing situation awareness and cognitive workload. The remainder of this section describes analytic methods that have been used in various situations for validating proposed staffing plans and may be used in a nuclear setting.

5.2.2 Table Top Analysis

Table top methods are the most straightforward and accessible methods for assessing staffing levels. They can use approaches based on management theory (e.g., Badawy, 1992), sociotechnical systems design (e.g., Hendrick, 1997), or function and task analytic methods (e.g, Kirwan & Ainsworth, 1992).

Table top analysis is typically performed by a group of plant operations experts who systematically work through the relevant operating conditions to confirm that the data from the staffing analysis supports the proposed staffing plan. At a minimum, the group should consist of people with the following expertise:

- control room design and operations.
- out of control room operations.
- reactor system design and operations.
- turbine system design and operations.

A group leader develops a discussion framework based upon the scenarios of interest and focuses the discussion of the group on specific issues that are of concern at the time. The group walks through each of the scenarios and determines if the proposed staffing complement is adequate to meet the safety needs for the plant.

The group reviews the proposals for the numbers of and types of control personnel and the job definitions for each of the positions. The leader steps the group through the scenarios soliciting more detailed information about personnel tasks and performance. Task analysis data will typically be used as the framework for the discussion. The group may use additional tools such as Gantt charts to help track timing, personnel usage and workload, during the scenario.

After reviewing the scenarios in detail, the group comes to a consensus about whether the scenario can be safely performed with the proposed control personnel. Because the table top analysis cannot be re-run, the outcomes, supporting data, and rationale are typically documented such that an independent analysis of the conclusions can be performed.

Table top analysis is typically used for early design evaluations when simulators are not available. The analysis can aid in evaluating task flows and multitasking demands, task assignments, workload demands and situation awareness requirements of individual tasks, and the skill and ability requirements for the control personnel.

Table top analysis does have weaknesses in predicting personnel performance (Laughery, Plott & Persensky, 1996) because it is typically ineffective at:

- fully assessing the impacts of variability in task durations and timing on the demands for the same skill sets or personnel.
- accounting for the cumulative effects of workload when multitasking.
- representing actual situation awareness, rather than situation awareness requirements.

The relative strengths and weaknesses of the table top analysis method are summarized below.

<u>Strengths</u>

- can be performed at any phase of design and can identify potential problems early (Kirwan & Ainsworth, 1992).
- requires no special equipment.
- can be completed in a relatively short time.

<u>Weaknesses</u>

- very subjective in nature and the group may be dominated by certain members (Kirwan & Ainsworth, 1992).
- error prone (Laughery, Plott and Persensky, 1996).
- convening panel of experts may prove problematic, especially if a large number of scenarios need to be reviewed.
- not easily documented.
- not easy to reproduce or change after initial evaluation.

5.2.3 Operating Experience

Operating experience reviews are a common practice within the nuclear industry for assessing all aspects of nuclear operations, including staffing. The current staffing regulations are based, in large part, on operating experience. The need for the Shift Technical Advisor was identified based on operating experience (FR 43621, 1985). In addition, operating experience review is a pragmatic and widely accepted approach used within almost all industries.

Data from operating experience tends to carry high face validity. It is most useful when it is drawn from similar plants, technologies, or organizations that are implementing similar concepts of operations. The longer the duration of successful operations or success in mitigating unwanted events, the more support operating experience can provide to the staffing plan and exemption request. Data from training or licensing of control personnel that demonstrates effective performance may also be considered, particularly for operational conditions that have never actually occurred or that have occurred at low frequencies.

To use data from operations, the applicant would need to review and compile existing data that might be relevant to evaluating proposed staffing levels and configurations. These data can be drawn from predecessor or related plants, similar systems or technologies, or organizations that have implemented similar concepts of operations. Regardless of the source, the scope of the review should include:

- identification of similarities and differences.
- recognized historical staffing issues.
- issues identified by operations personnel.
- identification of risk-important human actions.

Data from existing plants, operations, or systems will be inherently limited to those scenarios, events, or operations that have actually been experienced. As a result, conditions that may place the greatest demands on control personnel may not be represented, or may be represented by only a small set of data. Differences in staffing levels, configurations, or personnel qualifications may also limit the utility of data from similar operations. A summary of the strengths and weaknesses of using data from existing operations is provided below:

<u>Strengths</u>

- very high validity.
- low data collection costs

<u>Weaknesses</u>

- the relative comparability of the plant, system, concept of operations, or staffing

- only events, scenarios, or operations that have actually occurred are represented
- many of the events, scenarios, or operations of interest may have occurred too infrequently to make reasonable comparisons or inferences

5.2.4 Simulator Studies

Advances in simulator technologies and reductions in the cost of producing relatively high fidelity, easily modifiable simulators have increased their utility for assessing staffing levels and configurations. The Navy's recent development of the Integrated Command Environment (www.manningaffordability.com) for assessing manning of future ship systems provides ample evidence of this. Within the nuclear power industry, a series of studies using advanced reactor simulators at the Halden Labs for assessing the interactions of new technologies and design concepts with staffing levels (NUREG/IA-0137, 2000) further supports their utility and value in these areas.

Simulator studies may be used as data sources when a moderate to high fidelity simulator and human system interface (HSI) are available. By running scenarios of interest with the proposed staffing complement and collecting human performance measures, the adequacy of a proposed staffing plan can be demonstrated. A pool of representative control personnel would be needed to test the scenarios of interest.

Using methods for conducting in-simulator studies for staffing, which are similar to those described in NUREG 0711 Section 11.4.3, "Integrated System Verification," leads to effective and robust data collection. The steps for conducting in-simulator studies typically include:

- define the test objectives.
- validate the test bed.
- select plant personnel.
- define scenarios.
- define performance measures.
    - define measurement characteristics.
    - Select performance measures.
    - define performance criteria.
- design test
    - couple control room personnel and scenarios.
    - create test procedures.
    - train test personnel.

- train test participants.
- perform pilot test.

- collect, analyze and interpret data.

- validate conclusions.

Using in-simulator studies for staffing plan validation will often be limited by simulator availability. Simulators can be expensive to build and run. They may also be difficult to access for validation purposes because they are often in heavy use for training or licensing examinations.

For new or modified plants or systems there may be no, or only a limited number of, control personnel who have the qualifications and capabilities to perform the roles of the "humans in the loop." There was some evidence of negative transfer in experienced conventional nuclear power plant operators when they operated the advanced design plants in the Halden simulator (Hallbert, Sebok & Morisseau, 2000). The alternative to using experienced operators would be to fully train new (inexperienced) personnel on the proposed design before testing. If new or inexperienced personnel are used, it will be important that test participants have been adequately trained and given the opportunity to become fully knowledgeable about, and comfortable with, a new design in order to achieve a valid evaluation.

Historically, in-simulator evaluations have not included the evaluation of human performance in the multi-unit scenarios that can be anticipated for new plant designs. To adequately evaluate these alternative control room configurations, the effects of these new designs on operator and team performance, situation awareness, and cognitive workload should be included in the evaluation process.

Single unit advanced nuclear power plant designs that have been evaluated to date have: 1) included more automation of functions and configurable computerized system status displays than conventional plants; 2) provided operators with greater access to the information needed to maintain situation awareness; and 3) not resulted in excessive cognitive workload. The ability of operators to maintain adequate situation awareness when monitoring several units simultaneously over extended periods has not been evaluated in a simulation.

A key benefit of data from in-simulator studies is that simulators can represent a wide range of operational conditions, often at high levels of fidelity. High fidelity simulators are often built well in advance of the actual plants they represent, so that they may be available for use in support of an exemption request. Simulators with lower levels of fidelity may also be used to provide supporting data. For example, a simulator that reflects plant or system behavior well, but does not reflect the actual HSI, may be useful for demonstrating the time and timing of events and available control personnel response times.

<u>Strengths:</u>

- high face validity, running realistic scenarios with actual personnel in a moderate to high fidelity simulation environment.

- can run a wide range of scenarios to exercise differing operating conditions.
- if budgets allow, repeated measures with the same crew, or running multiple crews through the same scenarios can provide greater statistical confidence in the results of the evaluations.

Weaknesses:

- requires relatively complete design of the plant and HSI to implement.
- often is costly due to the large amount of staff and time required for the studies.
- requires trained operators. A very limited pool of operators may be available for a new plant design.

5.2.5 Human Performance Modeling

Human performance modeling uses engineering and psychological models of human performance to estimate human performance over time. Creating models for simulation is a recognized method for identifying where a performance breakdown or bottleneck could occur (Leadbetter et al, 2001). Modeling is a way to parsimoniously represent how we think a complex entity is structured and functions.

There are a number of ways in which nuclear power plants could be modeled, but to be useful to the evaluation process, the model must reveal whether the design, including the proposed staffing, results in acceptable levels of personnel and system performance. Whatever modeling technique is employed, those doing the evaluation should be able to efficiently and effectively identify performance levels of the control personnel in the system.

One modeling approach, task network modeling (TNM), has been used for many years in a wide range of domains to make estimates about system performance. Some of the domains where TNM has been used to evaluate staffing level include:

- naval ships (Wetteland et al, 2000;Laughery et al, 2000; Archer, Lewis and Lockett, 1996; Brockett, Scott-Nash and Pharmer, 2001).
- service systems (Laughery, Plott, and Scott-Nash 1998).
- call center (Keller and Plott, 1999).
- US Army weapons systems (Walter, French and Barnes, 2000).
- hospital obstetrics wards (Archer et al, 2000).

Hardman III, a task network modeling tool developed for the Army Research Laboratory, is designed specifically to predict human performance in systems early in the design phase. The tool has gone through extensive validation and verification by the US Army (Allender et al, 1995) and has been approved for modeling human performance in Army systems. These algorithms and techniques have been implemented in newer tools such as IMPRINT as well. In a review of these and similar tools, Mitchell (Mitchell, 2000) recommends using these methods during the concept development phase to reduce the need to build costly system mock-ups.

In a comprehensive review of human performance modeling techniques, Leiden et al (2001, p. 33) concludes: "the most useful stand-alone application of task network modeling for error prediction is in the context of multi-tasking activities and high operator mental workload. In this case the modeling technique focuses on predicting error-prone operator conditions, situations or environments as well as the specific human errors that result." Embedded mental workload models (in the task-network modeling tools) predict when task shedding occurs due to high mental workload demands contributing to an error-prone situation.

Task network modeling methods have been applied to model nuclear power plant staffing. The models have been successful at predicting human performance in the system. When compared to table top analysis methods (Laughery, Plott & Persensky, 1996), TNM methods were found to:

- consistently require a more detailed level of data which led to more detailed estimates.
- better track the availability of operators to perform tasks and predict delays due to operator unavailability.
- closely track the plant status, control room operator status, and outside control room operator status.

Other attempts at modeling and simulation have shown that TNM models of nuclear power plants can indeed describe operator performance and identify bottlenecks, cognitive overload, and performance failures (Sebock, Hallbert, Plott & Scott-Nash, 1997; Scott-Nash, Carolan, Humenick, Lorenzen & Pharmer, 2000). Plott, Laughery & Haagenson (1996) developed nine task network models of advanced nuclear power plant control room operations that were validated against human performance in a simulator.

Human performance models typically require data such as tasks, task time and timing, flow logics and error probabilities. Although these data are typically available from the task analysis, some of the data frequently need to be estimated. The models also require algorithms to represent performance variations as well as measures of factors such as cognitive workload. Because the models are projections of human performance that are often based on a limited amount of concrete data, they are subject to challenge. These limitations are moderated by two considerations: (1) there are representations for which validation exists and (2) the models can be exercised across a range of values for critical parameters to assess the model's sensitivity to the data.

Another important limitation of human performance modeling is the skill and training that may be required to build the models. Many of the modeling tools and methods require considerable skill and significant training to apply them well.

Building the model consists of setting up the sequence of tasks for each scenario and then entering the task data. The task flows are drawn using the model building tools and task network. After the sequence has been entered, the individual task data can be entered. Each task will have task entry forms for data related to the following:

- task timing
- task accuracy
- error effects
- workload
- information requirements
- personnel requirements

In addition to the task entry data, there are several overall entries that will need to be made. These include:

- number of staff of each type available.
- performance shaping factors to consider (e.g., heat, noise, lack of sleep).

Once the data have been entered, the model can be executed. The model will execute a number of times to simulate potential variability among operators. If some of the parameters used in the model were in doubt, a sensitivity analysis can be performed to determine if the parameters in question have a significant impact on the model.

After the models have been run, the data can be analyzed. The model will have generated reports showing the following:

- how well function and task times met their requirements.
- effects of the errors made by the operators in the model.
- cognitive workload for each operator over time.
- quality of decision data used to make decisions.

By analyzing these data, the reviewer should be able to determine whether the staffing level used in the model was appropriate. Some of the keys to determining whether the staffing proposal was appropriate are:

- simulated operators completed the functions and tasks consistently within the constraints.

- cognitive workload of all operators was not high or low for extended time periods within each scenario.

- data used for decisions throughout the scenario were of high quality.

Data from human performance models can provide a robust representation of the performance of control personnel across the range of operational conditions. Models can easily incorporate the various conditions that may affect human performance, human performance variability, and measures of concepts, such as cognitive workload and situation awareness. Although human performance models historically have incorporated plant or system representations of limited fidelity, human performance models can now be linked to more sophisticated plant or system simulations. The human performance models also make it relatively easy to assess different staffing alternatives.

Another key benefit of modeling, relative to simulator evaluations, is time and costs savings. In-simulator based methods can be slow and costly to perform because they require relatively expensive simulator time and the time and effort of participants and observers. Further, for the relatively slowly evolving events expected for advanced nuclear power plant designs, it may not be feasible to fully evaluate those scenarios in a simulator.

Additional benefits include:

- The process of building the model forces the modeler to make explicit any assumptions about processes, error likelihood and management, workload, and situation awareness

- The models can incorporate variability in task performance times, flows, and frequency, and thus enable testing of the overall system sensitivity based on changes in the parameters

- Human performance shaping factors such as fatigue or the effects of environmental variables such as heat, cold, or noise can be incorporated into the models to assess their impact on operator performance

- Some of the modeling tools can be linked to models of plant behavior, resulting in an integrated system model for assessing human performance

A summary of the strengths and limitations of task network modeling of human performance for staffing analysis is shown below.

<u>Strengths</u>

- useful early in the design process and can be used through implementation and plant operation.

- directly parallels task analysis data.

- tracks task interactions and resource restrictions more accurately than table top analysis.

- relatively easy to explore new scenarios.

- forces rigorous analysis.

Weaknesses

- requires more decision making than other methods.

- projection of performance, may not have as much face validity as operations data or simulator studies.

6.0 Conclusions and Summary of Recommended Review Process

6.1 Conclusions

When evaluating exemption requests, reviewers will need to assess the impact of the staffing proposals on safety issues such as:

- operators taking less active roles for ensuring the safety of the plant.
- operators having a greater range of roles and responsibilities in addition to their safety-related roles and responsibilities.
- the need for operators to maintain situation awareness across a number of units and to potentially manage simultaneous operations across these units.
- changes in the response times required from control personnel.
- plant control capabilities provided by smaller, portable, or remote human-system interfaces.
- the interaction between the control room personnel and advanced human-system interfaces including intelligent support systems.
- capabilities for managing and coordinating control room personnel functions among control room personnel who may be located remotely from each other.
- changes in the qualifications of control personnel.
- effective scheduling of reduced numbers of control personnel to optimize cognitive workload, minimizes fatigue, and support situational awareness.

Based on the methods discussed in this report, we believe that an approach that focuses on evaluation of the development and validation of an applicant's staffing plan in support of an exemption request will verify that all of the issues above can be successfully addressed. The basic analysis structure provided in NUREG-0711 helps to verify that: 1) staffing considerations are fully integrated into the overall facility design, 2) the content and form of the data will be familiar to the reviewers enabling them to be more efficient and effective, and 3) new data requirements are minimized. Further, allowing the use of a mix of validation methods will verify a comprehensive assessment of the proposed staffing plan. It also provides the opportunity for convergence of the results from multiple approaches. Convergence can increase the confidence level of the applicant and the NRC in the acceptability of proposed plans.

6.2 Recommended Review Process

An eleven-step process is recommended for conducting reviews of requests for exemptions from current staffing-related regulations: Figure 2 illustrates the overall flow of the review process.

Figure 2. The Exemption Request Review Process

The first step of the review process is to Review the Exemption Request, which is a general review of the requested exemption(s) to determine the scope of the request(s). In addition, any new or modified concepts, or changes in meanings for terms included in the regulations (e.g., operator, control room, unit) introduced as part of the application, are identified during this review.

The next step is to Review the Concept of Operations to gain an understanding of the role of plant personnel in overall plant operations. Understanding the applicant's intended concept of operations also establishes the context for subsequent steps in the review.

The third step is to Review the Operational Conditions considered by the applicant to justify the requested exemption(s). Of particular interest are those operational conditions that present the greatest challenges to the performance of licensed personnel working under the conditions included in the exemption. The operational conditions defined by the applicant are evaluated for completeness and used to assess the exemption request.

The next five steps focus on reviewing the data and analyses from the submissions to verify that they are complete and provide adequate support for the exemption request. The five areas to be reviewed include:

- operating experience
- functional requirements analysis and function allocation
- task analysis
- job definitions
- staffing plan

The reviewer may find that additional data and types of reviews may be needed to complete the review of the exemption request(s). These additional reviews could include data from areas such as human reliability analysis, human-system integration, and knowledge, skills, and abilities analysis. Data submitted for these review areas would provide further justification in support of the exemption request.

The most important step is the review of the applicant's Staffing Plan Validation. 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 last step in the review process is the Final Assessment of the Exemption Request to determine whether it is acceptable. In this step, a final decision must be made regarding the acceptability of the exemption request. The decision will be based on the aggregate findings from the previous steps of the review. The reviewer should be able to satisfactorily answer the questions below regarding the acceptability of the exemption request:

- Was sufficient justification provided to verify that the impacts of the exemption request were adequately addressed in the:
    - concept of operations
    - operational conditions
    - operating experience
    - function analyses and function allocation (or re-allocation)
    - task analyses
    - job definitions
    - staffing plan
    - additional supporting data and analyses
    - verification and validation of the staffing plan

- Were the range and combination of operational conditions considered by the applicant appropriate and adequate?

- Were the data analyses performed using appropriate parameters and methods?

- Were the assumptions and estimates used in conducting the analyses documented and appropriate?

- Will acceptance of the exemption request provide at least the same level of assurance that public health and safety are maintained, as the current regulations require?

A summary of the overall findings should be prepared along with the determination of the acceptability of the exemption request. If it is determined that there is insufficient evidence to support the exemption request, the reviewer should identify the limitations of the submittals and the further analyses, data or changes in the exemption request that are needed. As a result, the reviewer would generate a Request for Additional Information and/or develop a letter indicating the weaknesses / strengths of the exemption request.

Appendix A: Sample Human Performance Measures

Table 2 Task Performance Requirements
(Adapted from NUREG-0711, Table 5.1 Task Considerations)

Category	Data Item	Requirements
Information Requirements	Alarms and alerts	Any alarms and alerts that would trigger a task to start
	Parameters	Any parameters that would indicate the task is appropriate for performance
	Feedback needed to indicate adequacy of actions taken	Any parameter that the operator would need to monitor during the task to verify the task is correctly executed
Decision making Requirements	Decision type (relative, absolute, probabilistic)	Explanation of how and when decisions between alternative tasks are made
	Evaluations to be performed	Parameters that must be evaluated in the decision and how they are applied
	Coordination	Decisions that must be made or approved by others
Response Requirements	Type of action to be taken	A description of the operator action taken in the task
	Task frequency	A measurement of how frequently the task occurs
	Task tolerance	A measure of the allowable accuracy for the task to be considered successfully performed
	Task accuracy	The expected value of how accurately the task will be performed by the operator
	Consequences of inaccurate performance	The effect that inaccurate task performance has on other tasks in the scenario
	Time available and temporal constraints	The time allowable for the operator to complete the task

Table 2 Task Performance Requirements (Con't)

Category	Data Item	Requirements
Response Requirements (Con't)	Time required	An estimate of the amount of time required for the operator to complete the task. Statistical distributions should be provided. If distributions are unavailable, a typical minimum and maximum time should be provided.
	Physical position	The physical position and location required for the operator to perform the task
	Biomechanics	A description of the physical activity that must be performed (movements) and the forces required
Communication Requirements	Personnel communication for monitoring or control, including among control personnel and directing the activities of others	A description of the participants in the communication and information communicated
	Personnel communication for administrative, reporting, and external communications	A description of the participants in the communication and information communicated
Workload	Visual	A ranking of the visual workload
	Auditory	A ranking of the auditory workload
	Cognitive	A ranking of the cognitive workload
	Psychomotor	A ranking of the psychomotor workload
	Overlap of task requirements	An indicator if other tasks may or may not be run in parallel with this task
Task Support Requirements	Special protective clothing	Any clothing that could interfere with task performance or be required for task performance

Table 2 Task Performance Requirements (Con't)

Category	Data Item	Requirements
Task Support Requirements (Con't)	Job aids or reference materials needed	Any reference materials that could improve performance, or be required to perform the task, and any demands for multiple, concurrent use
	Tools and equipment needed	Any tools or equipment required to perform the task
Workplace Factors	Ingress and egress paths to work site	Any specific paths an operator must take to get to the work area
	Workspace envelope needed by action taken	Any space requirements needed to perform the task
	Typical and extreme environmental conditions	Measures of the typical and extreme conditions for - • lighting • heat • temperature • noise
Situational and Performance Shaping Factors	Stress	Level of stress expected based upon the severity of the scenario or conditions
	Reduced staffing	Reasonable expectations about understaffing in the scenario
	Fatigue	Typical and extreme conditions for - • time since last sleep • point in circadian cycle
Hazard Identification	Identification of hazards involved	Any hazards that may impair performance or make an operator unavailable due to injury

Appendix B: A Review of State-of-the-Art Methods for Assessing Situation Awareness and Cognitive Workload

NUREG-0711 (NRC, 2002) indicates that situation awareness and cognitive workload should be considered when validating the plant design. It provides little additional guidance. State-of-the-art techniques at the time of this writing are discussed in this appendix. Developments continue in these evaluation areas.

Situation awareness (SA)

Situation or situational awareness (SA) is defined as an operator's mental model of what has happened, the current status of the system, and what will happen in the next brief time period (Endsley & Garland, 2000). Because the quality of the operator's decision selection and performance is determined by the "goodness" (accuracy, completeness, relevance) of the internal, or mental, model of the system, it is critical for operating personnel to form and maintain complete and accurate SA.

To select a course of action for a nuclear power plant, operations personnel must understand the current status of the systems for which they are responsible, how they came to be in that condition, and the status of other systems that could potentially affect the systems for which they are responsible. To determine if new plant designs and/or new staffing arrangements adequately support SA, it is important to evaluate the degree to which all operating personnel demonstrate adequate SA.

Validated measures of an individual's situation awareness (Endsley & Garland, 2000) are described below. Both the Situational Awareness Global Assessment Technique (SAGAT) (see 2 below) and the verbal probe technique (see 4 below) have been adapted for assessing team situation awareness in research settings.

1) Non-intrusive human performance measures. These measures are taken while the personnel are performing their jobs, but the measurement techniques do not "intrude" on the personnel by asking questions; instead, they assess performance on observable parameters that would be affected by the degree to which the operator has adequate SA at the time the performance is assessed. These are indirect measures, which have been shown to be indicative of operator SA. Examples of non-intrusive measures include: how long it takes an operator to detect anomalous or incongruent information and how many data gathering attempts the operator makes before a course of action is selected.

The strength of these measures is that they can be assessed during task performance and they do not interrupt operations. Another strength is that the measure does not sensitize the operators to be more alert or aware because they expect questions. The weakness of this measurement technique is that there may not be good overt or observable behaviors that reflect the state of the operator's SA when the plant is functioning properly.

2) Direct experimental techniques - queries or "test" probes. These techniques assess the operators' situation awareness by asking them questions that reveal the degree to which they know what has happened, what current status is of the system is, and what they anticipate will

be the next thing to happen. To collect these data, it is common to freeze the task and ask one or more questions about the state of the task. Freezing the task can typically only be done during an experimental test of a system where the simulation can be "frozen."

SAGAT is a common query system that consists of 21 probe questions that are developed by a panel of experts. The questions are judged by the experts to be important indicators of participant SA. The questions are typically administered during a "freeze" in the simulation or when the simulation is stopped.

A direct situation awareness assessment measure developed from SAGAT for control rooms is SACRI (Situation Awareness Control Room Inventory) (Endsley & Garland, 2000). SACRI is an eighteen-item form that asks about the past, present, and future state of primary and secondary side parameters, such as temperature values and changes in other relevant parameters.

Based on the experience of the Office of Nuclear Regulatory Research and others, SACRI represents an appropriate measure for assessing situation awareness. SAGAT is the most widely used situation awareness query technique and has been validated in a number of settings (http://www.eurocontrol.fr/public/reports/eecnotes/2000/16.pdf). Using the SACRI adaptation of SAGAT verifys that the queries are relevant to nuclear power plant control rooms and allows direct measurement of situation awareness in the evaluation setting. Weights can be assigned to responses based on Subject Matter Expert (SME) ratings.

3) Subjective measures - self-assessment (Endsley & Garland, 2000). These techniques ask operators to rate the degree to which they believe they have, or had, adequate SA at specific times during the performance period. One technique that has been extensively used is SART (Situation Awareness Rating Technique). This technique does not work well for long simulations as operators forget the status of SA at earlier times when asked for retrospective ratings. Another problem is that when these measures are compared to performance measures, it is often the case that these subjective measures of SA do not correspond to performance measures of SA. Use of these measures has revealed some circumstances in which operators report that they have adequate SA, when in fact they do not.

4) Verbal probes for assessing situation awareness. This assessment technique has been successfully utilized in assessing SA in teams carrying out complex command and control tasks. While subjects are engaged in a complex team task, they are randomly selected to respond to a single spoken question to assess their current situation awareness (Cooke, Kiekel & Helm, 2001; Cooke, Salas, Kiekel & Bell, in press). The simulation is not interrupted for the probe, to which they make a brief oral response.

<u>Cognitive workload (CW)</u>

Cognitive workload is conceptualized as the degree to which the operator's cognitive and perceptual capabilities are taxed during the performance of the tasks that comprise their job. The techniques listed below are all questionnaires that are administered to assess CW while the simulation is frozen.

1) Overall Workload Scale. This is a one-item probe, but is nearly as effective as the other longer measures described below. The operator is simply asked to give an evaluation of his or her workload at pre-selected points in the performance of a task. The Overall Workload technique can be administered without interrupting task performance.

2) SWAT (The Subjective Workload Assessment Technique). This scale asks operators to rate their task workload on three scales: time load, mental effort, and psychological stress. Examples of various levels of effort are sometimes provided as anchors. The SWAT can be administered at any time during the task if the task is frozen but is typically administered as a retrospective or recall measure.

3) NASA-TLX (Task Load Index). The NASA/TLX is a recommended instrument for assessing cognitive workload. This six item questionnaire is a multi-dimensional rating procedure that provides an overall workload score based on a weighted average of ratings on six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort, and Frustration. A complete description of the NASA Task Load Index, including the validation data and instructions for computerized administration are found at http://iac.dtic.mil/hsiac/products/tlx/1.html. The NASA-TLX can be administered at the same time the SACRI is administered.

4) The Multiple Resources Questionnaire (MRQ) is a recent appearance in this category. The authors describe the questionnaire as a seventeen item easily administered measure of subjective cognitive workload with high reliability (Boles & Adair, 2001).

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GLOSSARY

10 CFR 50.54 - Conditions of licensing - The conditions that must be met in a nuclear power plant in order for a license to be issued.

10 CFR 50.54(m) - The minimum staffing requirements that must currently be met for a license to be issued for a nuclear power plant.

Advanced control room - A control room that is primarily based on digital technology. It typically provides the primary operator interaction with the plant via computer-based interfaces, such as video display units. This is in contrast to "conventional" control rooms, which provide the primary operator interaction with the plant via analog interfaces, such as gauges.

Advanced reactor - A nuclear power plant design that incorporates new technology such as advanced automation, passive safety systems, and/or new Human System Integration concepts.

Algorithm - A step-by-step procedure for solving a problem or accomplishing some task through a process especially by a computer.

Cognitive workload - The degree to which the person's mental capabilities are taxed during the performance of the tasks that comprise their job.

Concept of operations - A description of how an organization's structure, staffing, and management framework relates to the systems, design, and operational characteristics of the plant.

Control personnel - individuals licensed to manipulate controls that affect the reactivity or power level of a nuclear reactor, manipulate fuel, and/or direct the activities of individuals so licensed. The scope of an individual's license may address multiple reactors or facilities at differing geographical locations.

Exemption application - A request for licensing that asks for an exemption from any of the requirements of 10 CFR Part 50.

Finding - An observation that warrants further review within the significance determination process.

Function - A process or activity that is required to achieve a desired goal.

Function allocation - The analysis of the requirements for plant control and the assignment of control functions to personnel or system elements or a combination of personnel or system elements.

Functional requirements analysis - The identification of functions that must be performed to prevent or mitigate the consequences of postulated accidents that could damage the plant or cause undue risk to the health and safety of the public.

Human reliability analysis - The process of evaluating the potential for and mechanisms of human error that may affect plant safety.

Human-system interface (HSI) - The part of a system through which personnel interact t perform their functions and tasks. In this document, "system" refers to a nuclear power plant. Major HSIs include alarms, information displays, controls, and job performance aids.

Hybrid control room- A light-water reactor control room that has been upgraded/modified and has advanced controls and displays in some or all parts of the control room.

Integrated system validation - An evaluation using performance-based tests to determine whether an integrated system design (i.e., hardware, software, and personnel elements) meets performance requirements and acceptably supports safe operation of the plant.

Job - The group of tasks and functions allocated to an individual position.

Job definitions - The responsibilities, authorities, skills, knowledge, and abilities that are required to perform the tasks and functions.

Light-water reactor- A term used to describe reactors using water as coolant, including boiling water reactors (BWRs) and pressurized water reactors (PWRs).

Model - A representation of how a complex entity or system is structured and functions.

Operating experience review (OER) - A review of relevant history from a plant's on-going collection, analysis, and documentation of operating experiences. The OER could also include relevant experience from other plants and/or other industries.

Passive safety feature - Design characteristics that use natural forces, such as convection and gravity, which are less dependent on active systems and components like pumps and valves to maintain plant safety.

Performance shaping factors (PSFs) - Factors that influence human reliability through their effects on performance. PSFs may include environmental conditions, human-system interface design, procedures, training, and supervision.

Request for exemption - An analogous term to exemption application (above).

Shift composition - The different types of jobs that must be filled on each shift and the number of personnel required for each of the jobs on a shift.

Simulator - A facility that physically represents the human-system interface configuration and that dynamically represents the operating characteristics and responses of the plant in real time.

Situation or situational awareness - An individual's mental model of what has happened, the current status of the system, and what will happen in the next brief time period.

Task - A group of related activities that have a common objective or goal.

Task analysis - A method for describing what individuals must do to achieve the purposes or goal of their tasks. The description can be in terms of cognitive activities, physical actions, and supporting features.

Task network model - A computer model that employs task sequences to approximate system and human performance.

Validation - See Integrated System Validation (above).

Verification - The process by which the design is evaluated to determine whether it acceptably satisfies personnel task needs and HFE design guidance.

Vigilance - The degree to which an individual is alert.

Workload - The physical and cognitive demands placed on plant personnel.