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U.S. Nuclear Regulatory Commission
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Submission of X Energy, LLC (X-energy) Xe-100 Topical Report: Control Room Staffing Analysis Methodology

The purpose of this letter is to submit the subject topical report on behalf of X Energy, LLC ("X-energy"). This submission provides X-energy's approach to conduct Control Room Staffing analysis based on the guidance of NUREG-1791 and the Xe-100 Human Factors Engineering (HFE) Program based on the guidance provided in NUREG-0711. X-energy intends this Topical Report to facilitate on-going discussion with the NRC staff on the proposed approach. The specific review schedule will continue to be developed with X-energy's NRC project manager and we request a nominal review duration of 12 months be considered.

This report was reviewed for proprietary and export-controlled information and found to be fully releasable.

If you have any questions or require additional information, please contact Ingrid Nordby at inordby@x-energy.com.

Sincerely,

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Enclosures:
1) Xe-100 Topical Report: Control Room Staffing Analysis Methodology (Non-Proprietary)

Xe-100 Licensing Topical Report

Control Room Staffing Analysis Methodology

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10 CFR 810 Export-Controlled Information Disclaimer

This document was reviewed by X-energy and determined to not contain information designated as export-controlled per Title 10 of the Code of Federal Regulations (CFR) Part 810 or 10 CFR 110.

Department of Energy Acknowledgement and Disclaimer

This material is based upon work supported by the Department of Energy under Award Number DE-NE0009040.

EXECUTIVE SUMMARY

The Xe-100 pebble-bed high-temperature gas-cooled reactor is an advanced reactor design offered in plant configurations from a single unit to multiple units in operation. Each plant has some shared facilities, in operation from the commissioning of the initial unit, that contribute to safe and efficient operations. The Xe-100 was designed for simplicity of operations and relies primarily on inherent safety characteristics as part of its safety design approach, leading to a design that requires fewer operator tasks and no credited operator actions to perform required safety functions.

This licensing topical report provides detail on the approach that X Energy, LLC (X-energy) is taking to establish a Human Factors Engineering (HFE) Program based on the guidance provided in NUREG-0711. This topical report also provides detail on the methodologies to conduct a systematic control room staffing analysis. This analysis will provide the technical basis for the number, roles, and qualifications of the control room operators at an Xe-100 plant across all modes and states, from commissioning the first unit through full power operation of multiple units.

The base case for the Xe-100 is to deploy four units at a site, managed by a 3-person control room staff in one central control room. Additional expansion capability, either by adding single units to an existing deployment or additional four-unit plants, requires consideration of options such as additional control rooms, expanding the footprint of a single control room, and changes to shift operations, as well as the associated HFE impacts. The approach described herein is intended to be flexible enough to provide credible HFE activities to validate that control room operations will be safely managed and the number of control room operators, their tasking, their span of unit control (4 units or more), and the associated control room design all support a robust defense-in-depth capability.

The approach and methodologies described in this report are intended to initiate pre-application engagement with the U.S. Nuclear Regulatory Commission (NRC). Deliverables produced from the application of this methodology, such as the development of HFE element deliverables, operator training simulator observations and staffing validation activities, and a matrix of control room operators, roles and qualifications (and applicability across the number of units and modes/states) will be provided in future revisions to this topical report or through design and licensing bases information submitted for site or design-specific licensing applications under 10 CFR 50, 10 CFR 52, or future 10 CFR 53. Other interactions with the NRC Staff such as audits and observations of simulator exercises may serve to verify and validate the results of the staffing analyses.

Ultimately, the matrix of control room operators and the supporting staffing analyses will form the technical basis for prospective Xe-100 licensees to request exemptions from the staffing requirements of Title 10 of the Code of Federal Regulations (CFR), Part 50.54(m), or for X-energy to use as part of a 10 CFR 52 Design Certification application. X-energy requests that the NRC staff review and approve the approach and the methodologies as described in this report in Section 7.

CONFIGURATION CONTROL

Document Change History

Rev.	Date	Preparer	Changes
A	6/25/2021	P Hippely	Initial document with implementation plan information added.
B	8/6/2021	P Hippely	Update with reviewer comments
1	8/12/2021	P Hippely	Final approval

Document Approval

Action	Designation	Name	Signature	Date
Preparer	Human Factors Lead Engineer	Paul Hippely		
Reviewer	Senior Licensing Engineer	Thomas Braudt		
Reviewer	Operations Training Simulator Manager	Yvotte Brits		
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ABBREVIATIONS

This list contains the abbreviations used in this document.

Abbreviation or Acronym	Definition
BNL	Brookhaven National Laboratory
CNSC	Canadian Nuclear Safety Commission
COL	Combined (Construction and Operation) License
DC	Design Certification
FA	Function Allocation
FRA	Functional Requirements Analysis
FSAR	Final Safety Analysis Report
HFE	Human Factors Engineering
HSI	Human-System Interface
KSA	Knowledge, Skills and Abilities
LWR	Light-Water Reactor
NRC	(United States) Nuclear Regulatory Commission
OER	Operating Experience Review
PRA	Probabilistic Risk Assessment
SAT	Systematic Approach to Training
SMR	Small Modular Reactor
SPV	Staffing Plan Validation
S&Q	Staffing & Qualifications
TA	Task Analysis
TIHA	Treatment of Important Human Actions
V&V	(Human Factors) Verification & Validation

DEFINITIONS

This list contains a glossary of terms used in this document.

Term	Definition
Element	From NUREG-0711 [2] the four general activities are separated into the following twelve elements: • HFE Program Management • Operating Experience Review • Functional Requirements Analysis and Function Allocation • Task Analysis • Staffing & Qualifications • Treatment of Important Human Actions • Human-System Interface Design • Procedure Development • Training Program Development • Human Factors Verification and Validation • Design Implementation • Human Performance Monitoring
Concept of Operations	The Concept of Operations describes how a Xe-100 plant intends to operate to achieve its goals and objectives. As part of the HFE Program, this document is a placeholder of conceptual information related to the operation of a Xe-100 plant useful for the development of further HFE activities.
Control personnel	Personnel are designated as control personnel, if that individual is responsible for controlling and monitoring plant or unit operations
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 definitions	The responsibilities, authorities, skills, knowledge, and abilities that are required to perform the tasks and functions.
Shift composition	Refers to the different types of jobs that must be performed on each shift and the number of personnel required for each of the jobs on a shift.
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.
Workload	The physical and cognitive demands placed on plant personnel.

1. INTRODUCTION

1.1. PURPOSE

The purpose of this report is to:

- Describe the approach for the Xe-100 reactor plant control room staffing analysis. This analysis will form the basis for establishing the optimum number and qualifications of control room operator personnel required for safe and reliable Xe-100 plant operations in a multi-unit plant configuration across various modes, states, and operating conditions,
- Describe the planned X-energy methodologies for operator task analysis (TA) and validation testing of the staffing plan, and
- Initiate NRC review of the control room staffing plan analysis approach and methodologies and obtain NRC approval of the X-energy control room staffing approach that it will successfully show a single control room with 3 operators can control 4 or more units.

1.2. SCOPE

This topical report describes the approach X-energy will employ to determine the optimum number and qualifications of control room operator personnel required for safe and reliable Xe-100 multi-unit operation. For the purposes of this report, control room operator personnel include reactor operators (ROs) and senior reactor operators (SROs) as defined by 10 CFR 55.4.

10 CFR 50.54(m) specifies minimum licensed operator staffing requirements for control rooms and responsibilities as a license condition of plant operating licenses. These requirements do not address a plant design with more than three units on a site or more than two units operated from a single control room. Further, licensee decisions regarding control room staffing, including the number, composition, and qualifications of personnel, are more appropriately based on features unique to the design rather than on the existing large, light water reactor-based staffing levels. Features unique to the Xe-100 include an safety design approach that relies on inherent safety features, increased use of automation technologies, and adopting innovative control station designs. The initial Xe-100 concept of operations establishes a shift crew of three control room operators who will oversee multi-unit operations from a single control room, optimized at the conceptual design phase for four units.

The application of HFE in the design of Xe-100 control rooms will establish the optimal staffing level for Xe-100 operators controlling multiple units and will meet the regulations promulgated in 10 CFR 50.34(f)(2)(iii) and guidance described in NUREG-0711, “Human Factors Engineering Review Model.” Specifically, the Xe-100 HFE program will incorporate the following twelve elements:

- HFE Program Management,
- Operating Experience Review,
- Functional Requirements Analysis and Function Allocation,
- Task Analysis,
- Staffing and Qualifications,
- Treatment of Important Human Actions,

- Human-System Interface Design,
- Procedure Development,
- Training Program Development,
- Human Factors Verification and Validation,
- Design Implementation, and
- Human Performance Monitoring.

This topical report presents the approach to conducting the staffing optimization analysis through the Xe-100 Human Factors Engineering (HFE) Program and will follow the guidance from NUREG-1791 [5] to develop and technically justify an alternative staffing model. Ultimately, the matrix of control room operators and the supporting staffing analyses will form the technical basis for prospective Xe-100 licensees to request exemptions from the staffing requirements of 10 CFR 50.54(m), or for X-energy to use as part of a Part 52 Design Certification application. X-energy will develop an HFE-focused Concept of Operations (ConOps) consistent with the requirements specified in 10 CFR 50.34(a)(6) and the guidance in NUREG/CR-6947 as a part of future submittals.

1.3. RELATIONSHIP TO OTHER DOCUMENTS

Reviewers are advised to reference the “Xe-100 Technology Description Technical Report” [Braudt 2021] [6] for details on the Xe-100 design and unit and plant operations. NRC staff review of that report is not requested at this time. X-energy has a series of referenced Implementation Plans for specific elements of the Xe-100 HFE Program that will be made available for audit through the review period.

1.4. DOCUMENT LAYOUT

This document presents the approach using the key tasks from the Xe-100 HFE Program. Section 2 provides relevant context to the Xe-100 plant design and safety features. Section 3 provides an overview of relevant regulatory requirements and guidance. Section 4 provides a detailed description of the Xe-100 HFE program methodology. Section 5 illustrates their compliance with the review criteria presented in NUREG-1791 [5], summarizing the overall process, the supporting data, and analysis approach to support future control room staffing exemption requests. Section 6 contains the conclusions of this topical report and Section 7 describes the request for NRC review and approval.

2. OVERVIEW OF THE XE-100 PLANT DESIGN

An overview of the Xe-100 plant design and key safety features has been provided to the NRC Staff in the Xe-100 Technology Description Technical Report [Braudt 2021] [6]. The limited description provided in that document includes a description of safety features of the Xe-100 that warrant consideration in the control room staffing optimization analysis for an Xe-100 plant in various modes, states, and operating conditions.

NUREG-1791 provides examples of design features and concepts of operation for advanced reactors that could lead to acceptable bases for reduced control room operating personnel. Some of the design/technology attributes described that are applicable to the Xe-100 design include:

- safety design approach based on inherent safety features,
- high level of automation,
- extremely long grace periods during licensing basis events, and
- no risk-significant operator actions in the safety design approach.

2.1. XE-100 REACTOR DESIGN

The general HTGR concept evolved from early air-cooled and carbon dioxide (CO_2)-cooled reactors. The use of helium instead of air or CO_2 as the heat transport fluid in combination with ceramic fuel and a graphite moderator offered enhanced neutronic and thermal efficiencies and several advanced safety characteristics. The combination of helium and a ceramic core makes it possible to produce high temperature nuclear heat while maintaining a large safety margin to material limits. Two reactor core configurations, a pebble-bed core and a prismatic core, have been developed internationally for the commercial modular HTGR designs.

The Xe-100 reactor design is based on a pebble-bed core configuration. Pebble bed reactor technology dated back to the late 1960s, when the 46 MWt Arbeitsgemeinschaft Versuchsreaktor (AVR) was designed and operated in Germany. Later, advanced pebble bed reactor designs were developed in Germany, South Africa, and China. The Chinese have a modular HTGR pebble-bed reactor design, the HTR-PM, with two 250 MWt reactor units serving a single 200 MWe turbine/generator, that has started hot functional testing as of 2021. The Xe-100 reactor technology basis, design parameters, fueling scheme, pebble fuel, fuel handling and storage system, and safety characteristics are discussed in X-energy's core design reports and the Xe-100 Technology Description.

The Xe-100 reactor and steam generator systems are shown in Figure 1. The main reactor characteristics, including dimensions, thermal power, and major operating conditions are described further in the Technology Description Technical Report [6]**.** The active core volume is filled with approximately 224,000 spherical fuel elements, or pebbles[1], to form the pebble bed. Each pebble contains approximately 19,000 TRISO-coated particles. The fuel particles consist of a fissionable ceramic fuel kernel surrounded by three ceramic coating layers for retention of fission products. Fissions within the coated particles create the

[1] The Xe-100 spherical fuel elements are called pebbles in this report.

nuclear heat which is conducted to the pebble's surface. A helium circulator transports the helium heat transport fluid through the pebble bed, transporting heat from the pebbles to the steam generator.

Fuel pebbles are loaded into the core while the reactor is operating through a central tube at the top of the reactor pressure vessel (RPV). A fuel discharge system at the bottom of the core removes spent pebbles through the bottom of the RPV for assessment by the Burn-up Measurement Systems (BUMS) that evaluates each pebble for physical damage and burn-up and can return them to the top of the RPV, where they are again loaded into the core, or send them to spent fuel storage. A typical pebble goes through this process six times before it is removed from the reactor before reaching burn-up limits. The spent fuel pebbles are inventoried and placed into spent fuel casks for storage. These processes are managed via automated control systems due to the frequency of pebble circulation (hundreds of time per day) that the control room staff monitor and can intervene if necessary.

The maximum fuel temperature during normal operation is well below 1000^{o}C, which is significantly lower than many earlier HTGR designs and leaves large margins to the established TRISO performance envelope. The core excess reactivity is limited by on-line refueling since fuel can be loaded and unloaded as desired during full power operation. The Xe-100 has an overall negative temperature coefficient of reactivity due to Doppler broadening of the kernel uranium and the fuel pebble graphite and reflector graphite, ensuring stability during operations and negative reactivity insertion during core heat-up events. This inherent reactivity feedback is one of the required safety functions the fuel is credited with during transient and safety analyses and allows the Xe-100 to achieve a safe shutdown condition for certain LBEs.

Safe shutdown capability is also provided by two banks of control rods inserted into the side reflector. One control rod bank, the Reactivity Control System, is used in normal operation and can achieve hot shutdown if inserted. The second control rod bank, the Reactivity Shutdown System, credited as the diverse means of achieving the reactivity control function, is inserted by the safety-related Reactor Protection System and is used to establish long-term cold shutdown conditions. The relatively small core diameter allows safe shutdown by inserting control rods into the side reflectors only; no in-core control rods are needed. There is provision for initiating a manual trip from the control room as additional defense-in-depth, as well as provision for unloading pebbles as another means of removing excess reactivity and ensuring a subcritical state. While the control room operators monitor plant/unit responses and can provide such defense-in-depth support, these are not risk-significant actions and plant safety is assured without operator intervention.

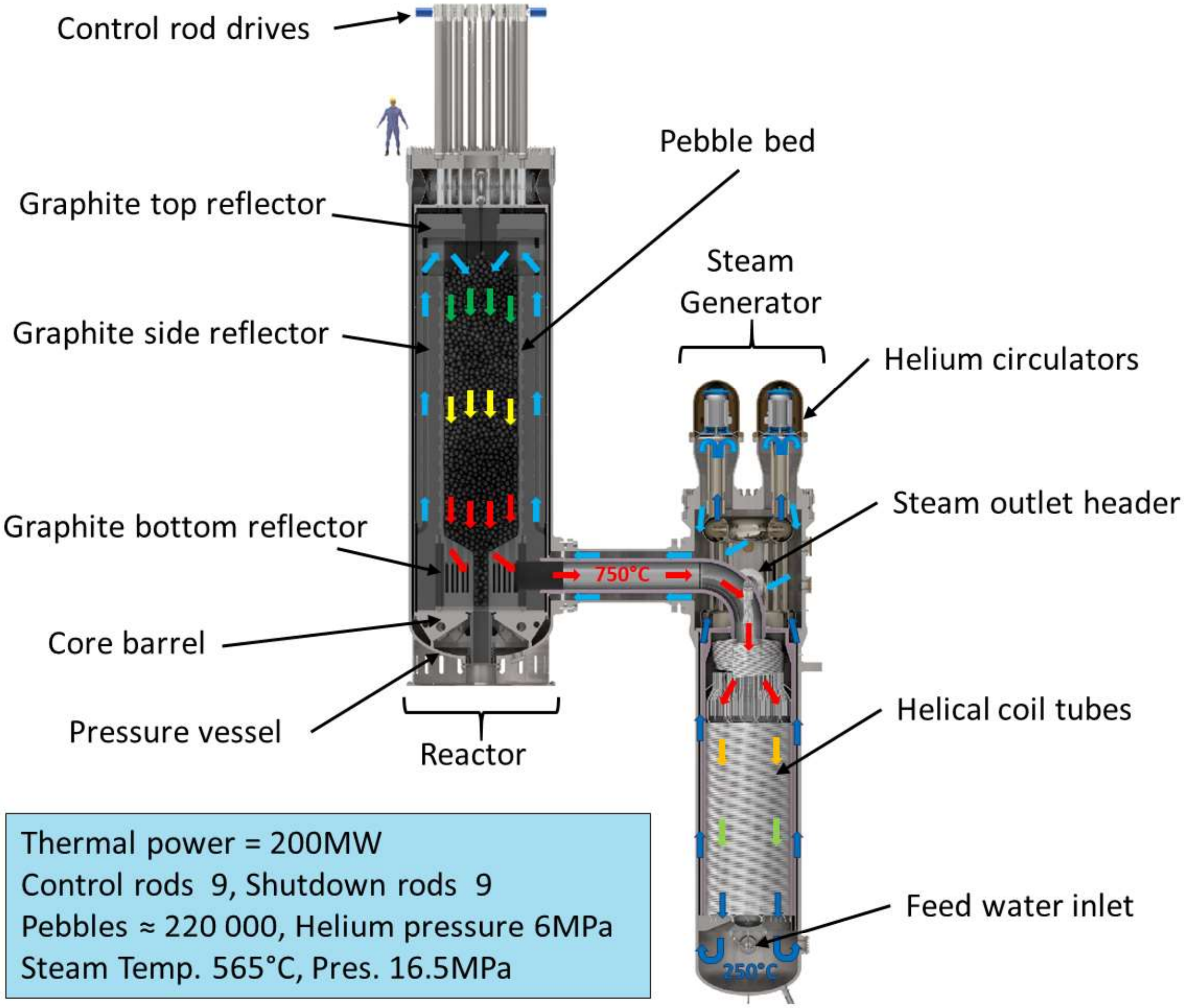

Figure 1: Xe-100 Section View

If active cooling is lost, maximum fuel temperatures are limited by design, and decay heat is passively removed from the fuel through the core structures, core barrel, and RPV via conduction, natural convection, and radiation. Heat removed from the RPV to the reactor cavity is discharged to the ultimate heat sink by one of three methods: 1) to the atmosphere by two trains of tube curtains called the Reactor Cavity Cooling System (RCCS) in an active-cooling mode, 2) to the atmosphere by the RCCS in a passive boil-off mode, or 3) directly to ground by conduction, natural convection, and radiation from the reactor cavity through the RCCS tube curtain and into (and through) the reactor building concrete structures. Design features such as the low core power density, relatively large height-to-diameter ratio of the reactor, and the non-insulated RPV ensure effective heat removal if active cooling is lost. The core power density in nearly 20 times lower than most light water reactors (LWR) [6]. The combination of a low core power density and the large structural mass and heat capacity of the graphite ensures very slow thermal transients. Thermal transients in the Xe-100 typically occur in periods of hours or days, rather than in the seconds or minutes characteristic of LWR thermal transients. Further, the functions of moderation and thermal transport are fully separated in the case of the Xe-100 versus that of typical LWRs. Therefore, losing the thermal transport medium for any reason is of no safety consequence. The moderator (pebble graphite matrix) remains in-place. These long grace periods lead to a significant difference in how operator decision-making occurs, and safe conditions in the reactor are assured even without operator intervention.

2.2. THE XE-100 SAFETY DESIGN APPROACH

2.2.1. Objectives of the Safety Design Approach

The Xe-100 safety design approach[2] supports the objectives of designing, constructing, maintaining, and operating the plant to ensure the health and safety of the public and workers and protection of the environment throughout the spectrum of Licensing Basis Events (LBEs): normal operating conditions including Anticipated Operational Occurrences (AOOs), Design Basis Events (DBEs), Design Basis Accidents (DBAs) which are analyzed assuming only the safety-related SSCs are available, and Beyond Design Basis Events (BDBEs).

The Xe-100 safety design approach is different from that of the currently licensed LWRs, which focuses on preventing and mitigating core damage and a large early release of radionuclides in the event of core damage. The safety design approach of the Xe-100 precludes fuel degradation or failure sufficient to significantly affect radiological consequences and focuses on preventing and limiting the release of relatively small amounts of radionuclides during normal operation and off-normal event sequences. X-energy uses the guidance of NEI 18-04, as clarified by Regulatory Guide 1.233, as the basis for identifying and selecting LBEs for evaluation in the design and licensing bases for the Xe-100. The implementation of

[2] X-energy takes the definition of safety design approach from NEI 18-04, as "The strategies that are implemented in the design of a nuclear power plant that are intended to support safe operation of the plant and control the risks associated with unplanned releases of radioactive material and protection of the public and plant workers. These strategies normally include the use of robust barriers, multiple layers of defense, redundancy, and diversity, and the use of inherent and passive design features to perform safety functions."

NEI 18-04 in the Xe-100 design is further described in X-energy's licensing topical report on the Risk-Informed, Performance-Based Licensing Basis Approach for the Xe-100 Reactor.

2.2.2. Reactor Passive and Inherent Design Characteristics that Contribute to the Design Bases

Passive design features are defined as design features engineered to meet their required functional design criteria without (a) needing successful operation of active systems with mechanical components such as pumps; blowers; heating, ventilation, and air conditioning or sprays that require an external power source; (b) depending on alternating current electric power; or (c) relying on operator actions. Inherent design characteristics are those characteristics associated with the reactor concept and the properties of the materials selected for the basic reactor components. Of direct relevance here are those passive design features and inherent characteristics that serve to limit the fuel temperatures during normal operation and off-normal events such that the fuel integrity is not compromised.

In addition to the fuel, the specific characteristics of the Xe-100 design that contribute to safety include:

- A large solid graphite moderator/reflector structure with very high temperature capability. The graphite provides large heat capacity in the core that increases the time constants and reduces the magnitude of core thermal transients. Limiting transients occur over hours and days, not seconds. No fast-acting active safety systems are required to maintain the fuel within specified acceptable fuel design limits.
- A passive heat transfer path from the fuel to the ultimate heat sink, the external atmosphere or ground. This heat transfer path through graphite moderator/reflector and through the reactor vessel to the reactor cavity cooling system, and to the external atmosphere or ground has the capacity, without requiring any active systems, to limit fuel, reactor pressure vessel, and reactor cavity structural concrete temperatures. This ensures there is no degradation of the core geometry

and that degradation of the fuel pebble barriers is limited to acceptable levels.

- A large negative temperature coefficient that inherently limits reactor power levels to relatively low levels under accident conditions without reactivity control system or reactivity shutdown system rod insertion of negative reactivity.
- A low core power density and high core surface-to-volume ratio that limits the fuel temperature rise during the most limiting conditions of loss-of-forced cooling and depressurization of the primary circuit.
- A single-phase, chemically inert, neutronically transparent, and high thermal conductivity helium heat transport fluid with low stored energy, minimizing the functional requirement for containment of energy in a postulated breach of the reactor helium pressure boundary.

The Xe-100 helium pressure boundary (HPB) is shown in Figure 1. The functional layout of a single Xe-100 unit is shown in Figure 2. The Xe-100 reactor building is a vented, low-pressure reactor building. Additional reactor design parameters can be found in the Xe-100 Technology Description Technical Report.

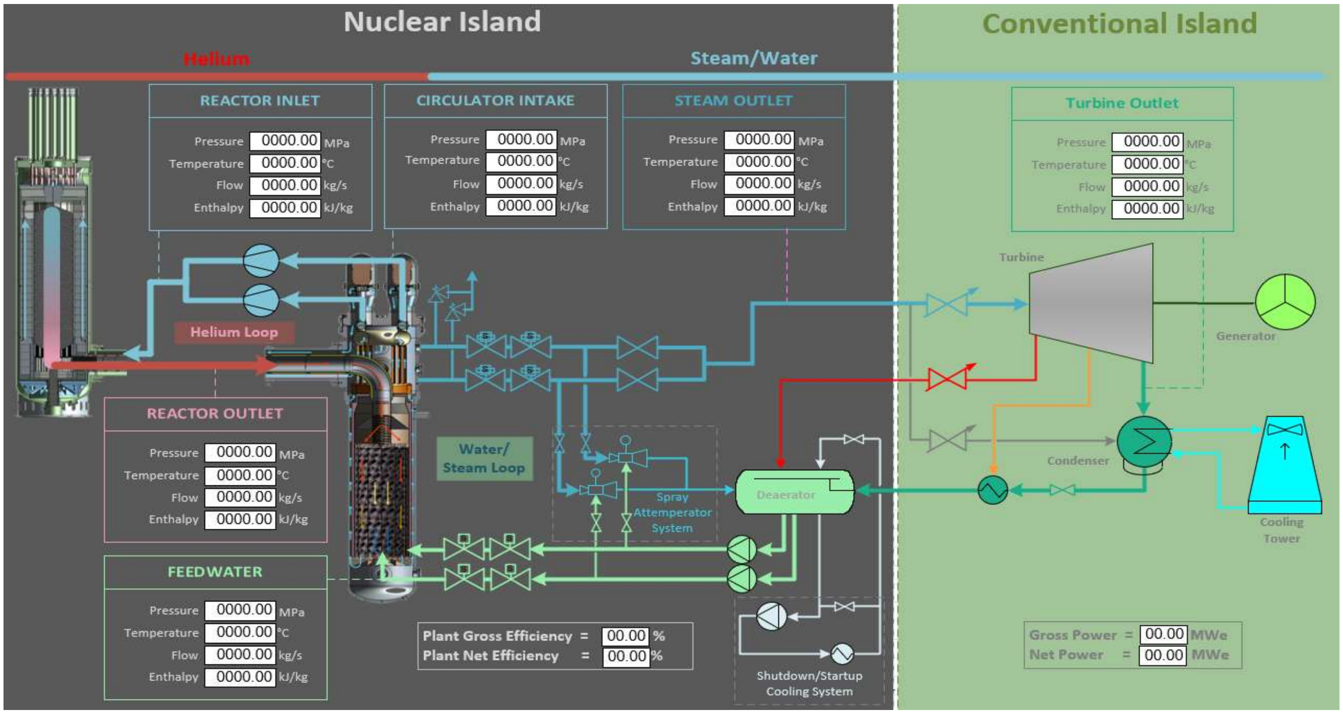

Figure 2: Functional layout of a single Xe-100 unit

3. OVERVIEW OF REGULATORY REQUIREMENTS AND GUIDANCE

10 CFR 50.54(m) specifies minimum licensed operator staffing requirements for control rooms and responsibilities as a license condition of plant operating licenses. These requirements do not address a plant design with more than three units on a site or more than two units operated from a single control room. Further, licensee decisions regarding control room staffing, including the number, composition, and qualifications of personnel, are more appropriately based on features unique to the design rather than on the existing large, light water reactor-based staffing levels. Features unique to the Xe-100 include a safety design approach that relies on inherent and passive safety features, increased use of automation technologies, and adopting innovative control station designs. The initial Xe-100 concept of operations establishes a shift crew of three control room operators who will oversee multi-unit operations from a single control room, optimized at the conceptual design phase for four units.

The hierarchy of regulatory requirements and guidance followed in the development of the approach described in this topical report and to be followed in subsequent analysis activities is illustrated below. While X-energy does not intend to use NUREG-0800 guidance across all sections of a license application, the review acceptance criteria for HFE in Chapter 18 are relevant to this topical report and the Xe-100 staffing analysis approach.

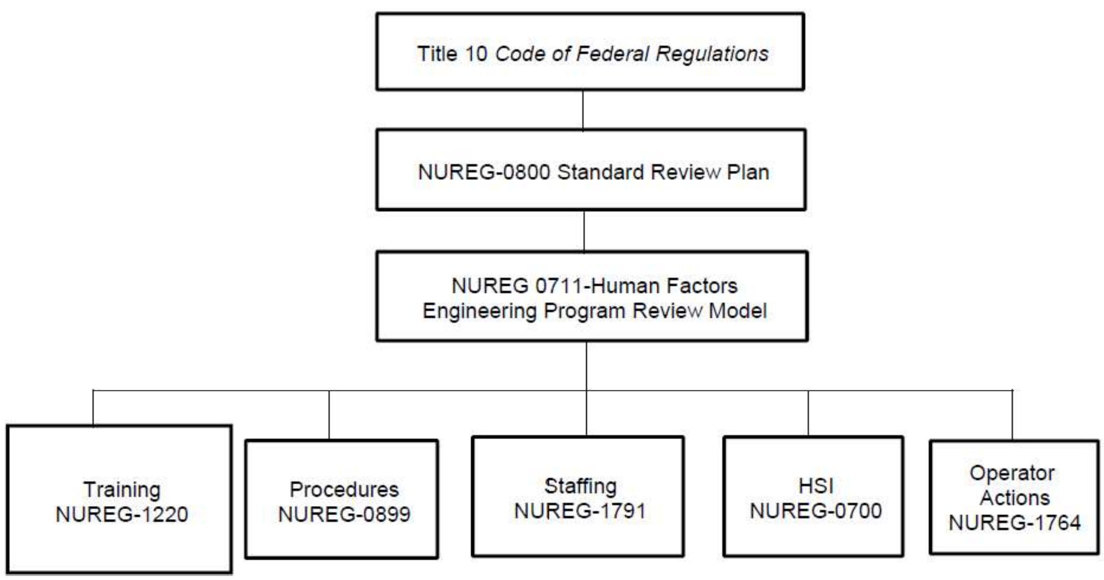

Figure 3: Relationship of NUREG-1791 and other regulation and related guidance

3.1 Code of Federal Regulations Requirements

3.1.1. 10 CFR 50.34(f)

Although consideration of this post-TMI regulation may not be specifically required for an Advanced Nuclear Reactor, X-energy will evaluate the requirements of 10CFR 50.34(f) for applicability and incorporate those requirements that should be included in the development of the Xe-100 HFE program.

3.1.2. 10 CFR 50.54(m)

The current requirements for main control room staffing are primarily found in 10 CFR 50.54(m). These requirements evolved over decades of operating experience with the large LWR fleet of designs and their concept of operations. The minimum staffing levels are often captured for convenience in Table 1 of NUREG-1791 (reproduced in Figure 4) for multi-unit sites in various modes of operation.

Number of Nuclear Power Units Operating(2)	Position	One Unit	Two Units		Three Units	
		One Control Room	One Control Room	Two Control Rooms	Two Control Rooms	Three Control Rooms
None	Senior Operator	1	1	1	1	1
	Operator	1	2	2	3	3
One	Senior Operator	2	2	2	2	2
	Operator	2	3	3	4	4
Two	Senior Operator		2	3	3(3)	3
	Operator		3	4	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.

Figure 4: Minimum Requirements Per Shift for On-Site Staffing of Nuclear Power Units by Operators and Senior Operators Licensed Under 10 CFR Part 55

- As described in NUREG-1791, there are implicit assumptions found in these requirements, and limitations on their scope, including:
  - there is a maximum of three units and three control rooms at a plant/station;
  - the number of control rooms does not exceed the number of units;
  - there are no more than two units controlled per control room;
  - there is always at least one operator at the controls for each unit (10 CFR 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 (10 CFR 50.54(m)(2)(ii));
  - there is one senior operator in the control room for each unit in operation (10 CFR 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; and

- 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 in 10 CFR Part 55.

Additionally, 10 CFR 50.54(m)(2)(iv) requires a person holding a senior operator license (or senior operator license limited to fuel handling) to directly supervise alterations of the core of a nuclear power unit during fuel handling without any other assigned duties. Due to the continuous refueling regime of a pebble-bed reactor, this requirement is not logical or practical for the Xe-100 operational staff. The basis for this consideration is moving bundles of fuel discretely to manage core load requirements. In comparison, the Xe-100 concept of refueling operation (i.e., automated, continuous recirculation and replenishment of pebbles representing extremely small fractions of the total excess reactivity, with the ability for operator intervention when necessary) does not warrant continuous SRO supervision. The Xe-100 approach to continuous fuel movement and resultant impact on operator workload will be addressed in the control room staffing analysis.

3.2. SUPPORTING REGULATIONS

3.2.1. Exemption Requests in Regulations and Regulatory Guidance

10 CFR 50.12 provides the authority for the Commission to grant specific exemptions from the regulations. The technical basis for assessing exemption requests from licensed operator staffing requirements specified in Part 50.54(m) are provided in NUREG/CR-6638. NUREG-1791 provides additional guidance for assessing control room staff exemption requests, and which special circumstances exist that provide justification for §50.12 exemptions.

3.3. NUREG-0711 HUMAN FACTORS ENGINEERING PROGRAM REVIEW MODEL

The Xe-100 Control Room Staffing methodology will use accepted HFE standards and guidelines, including the applicable guidance provided in Human Factors Engineering Program Review, NUREG-0711, Rev. 3. The planning and analysis portion of the HFE Program will include a staffing and qualifications analysis to establish the number and qualification of licensed operators required for safe and reliable operations

3.3.1. NUREG-1791 Guidance for Assessing Exemption Requests for the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)

NUREG-1791 provides the primary guidance for the NRC staff to evaluate exemption requests for the minimum staffing requirements of 10 CFR 50.54(m) and provides a systematic approach to determining the acceptability of such requests. It provides a review process that addresses the major elements, mostly related to a comprehensive HFE program, that will provide the technical bases for an exemption from regulatory requirements, which includes:

- Discussion of each review process step and the basis for inclusion,
- Data and information requirements to support NRC review of each step,
- Review criteria for evaluating an applicant's submittals, and
- Recommended additional information that may be useful in performing the review.

It also provides checklists for each review step, some of which are described later in this topical report.

3.3.2. NUREG/CR-6838 Technical Basis for Regulatory Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)

This contractor-developed NUREG provides the technical bases for NUREG-1791 and the systematic approach to reviewing exemption requests for 10 CFR 50.54(m). The control room staffing analysis methodology described herein applies to the HFE elements that provide a technical basis for determining the number and qualification of licensed operator personnel as defined in 10 CFR 55 "Operators' Licenses". This topical report does not provide a methodology for analysis of non-licensed operators, maintenance or craft personnel, or other plant support staff (i.e., health physics, engineering, security, emergency operations, etc.) numbers or qualifications. As part of the HFE elements described herein, the task analysis and job description activities (among others) may identify impacts on licensed operator workload for further analysis in the area of non-licensed operator personnel, which will be provided in future licensing submittals when necessary.

3.3.3. NUREG-0700 Human-System Interface Design Review Guidelines, Revision 3

This guidance, co-authored with Brookhaven National Laboratory, provides guidelines to evaluate the interfaces between plant personnel and plant systems as part of the overall HFE program review. Since task analysis and functional requirement analysis and function allocation play a significant role in establishing the bases for licensed operator personnel numbers and qualifications, and these activities are dependent on some amount of human-system interface development, X-energy uses NUREG-0700 as a key reference to develop the human-system interfaces for the control room.

3.4. COMMISSION POLICIES

X-energy reviewed the following Commission policies considered relevant to the analysis methodology described in this topical report.

3.4.1. Policy Statement on the Regulation of Advanced Reactors, 73 FR 60612 (NRC-2008-0237)

This policy statement, an affirmation of the Commission's earlier Advanced Reactor Policy of 1984 with further clarifications, the Commission provides its expectation that advanced reactors "will provide enhanced margins to safety and/or use simplified, inherent, passive or other innovative means to accomplish their safety and security functions". Two specific attributes related to this topical report are:

> *Simplified safety systems that, where possible, <u>reduce required operator actions</u>, equipment subjected to severe environmental conditions, and components needed for maintaining safe shutdown conditions. Such simplified systems should facilitate operator comprehension, reliable system function, and more straightforward engineering analysis.*
>
> and

> *Designs that include considerations for safety and security requirements together in the design process such that security issues (e.g., newly identified threats of terrorist attacks) can be effectively resolved through facility design and engineered security features, and formulation of mitigation measures, <u>with reduced reliance on human actions</u>.*

The Xe-100 safety design approach included consideration of safety and security requirements early in development to produce a multi-unit plant that, by design, requires fewer human actions during normal operation and across the spectrum of LBEs. The use of inherent system characteristics to manage heat generation and removal, protect the multiple barriers providing radionuclide retention, and maintain the overall system geometry to assure the required safety functions are provided for meets the expectation of simplified safety systems. This safety design approach supports a control room staffing analysis approach with expected results that will differ from the large LWR designs.

3.4.2. Policy Statement on Engineering Expertise on Shift, 50 FR 43621

This policy statement provides the Commission's expectations regarding educational experience and combining certain roles within the licensed operator personnel on shift during nuclear power plant operations. It provides the Commission's expectation that engineering and accident assessment expertise be provided on shift to provide for immediate actions that may become necessary during off-normal conditions. In evaluating the roles and responsibilities of the Xe-100 control room operator personnel, including necessary qualifications, the HFE Program will address the adequacy of such technical expertise available for normal operations and the spectrum of LBEs. This will include consideration of the most recent industry guidance, operating experience, and related Commission Policies (i.e., Education for Senior Reactor Operators and Shift Supervisors at Nuclear Power Plants 54 FR 33639).

3.4.3. Policy Statement on the Conduct of Nuclear Power Plant Operations, 54 FR 3424

This policy statement provides the Commission's expectations with respect to a professional, controlled environment in a nuclear power plant's main control room, emphasis on licensed operators' conduct and attentiveness, and other direction to enhance the safety of plant operations. The systematic methodology described in this report will enable X-energy to provide a sound basis for future licensees to conduct operations in a professional and safe manner and meet the Commission's previously established expectations. Areas analyzed in the HFE process include:

- the control room design and layout,
- operator tasks and job descriptions,
- operator knowledge, skills, abilities, and
- the identification of the number of licensed operators.

3.5. SECY PAPER PRECEDENTS

The NRC has released Commission SECY papers relevant to development and use of a control room staffing analysis and HFE Program. X-energy reviewed these documents as part of the developing the control room staffing analysis methodology described in this topical report.

3.5.1. SECY-93-092 Issues Pertaining to the Advanced Reactor (PRISM, MHTGR, and PIUS) and Candu 3 Designs and Their relationship to Current Regulatory Requirements

Section F "OPERATOR STAFFING AND FUNCTION" of this SECY paper provided considerations for advanced reactor designs (of the time period) regarding Operator Staffing and Function. These considerations are similar to issues identified for LW-SMRs developed in later years. In SECY-93-092, the NRC staff provided the following specific recommendations:

Staff Recommendation

The staff believes that operator staffing may be design dependent and intends to review the justification for a smaller crew size for the advanced reactor designs by evaluating the function and task analyses for normal operation and accident management. The function and task analyses must demonstrate and confirm the following through test and evaluation:

- *Smaller operating crews can respond effectively to a worst-case array of power maneuvers, refueling and maintenance activities, and accident conditions.*
- *An accident at a single unit can be mitigated with the proposed number of licensed operators, less one, while all other units could be taken to a cold-shutdown condition from a variety of potential operating conditions, including a fire in one unit.*
- *The units can be safely shut down with eventual progression to a safe shutdown condition under each of the following conditions: (1) a complete loss of computer control capability, (2) a complete station blackout, or (3) a design-basis seismic event.*
- *The adequacy of these analyses shall be tested and demonstrated. The staff is currently recommending that an "actual control room prototype" be used for test and demonstration purposes.*

These considerations will be addressed in the Xe-100 design through implementation of the Control Room Staff Analysis methodology.

3.5.2. SECY-11-0098 Operator Staffing for Small or Multi-Module Nuclear Power Plant Facilities

This Commission paper provided the NRC staff's assessment of approaches to resolve the issue of control room staff compliment determinations for multi-unit facilities and exemptions to the minimum staff requirements of 10 CFR 50.54(m). The proposed approach was to process a limited number of applications using exemption requests before considering rulemaking to codify any changes to the regulation. The NRC staff reference earlier work on the subject (e.g. SECY-10-0034) and on-going efforts to understand various stakeholder positions on the subject. The staff provide a path to develop exemptions via the guidance provided in NUREG-1791, described in this report in a later section.

Of particular interest from this SECY, the NRC staff observes the following significant differences between existing large LWR designs and the SMRs under consideration:

- *The SMRs may require different operator tasks. The task requirements will include operating multiple units in different modes of operation. A major challenge will be to identify tasks that may be omitted and those that could substantially affect operator workload.*

- *Very limited operational experience will be available to use as a resource, as these designs are first of a kind. The use and observation of simulator activities will be important to the verification of the task analyses and staffing plans. Parallels in other industries may be useful, if they exist.*
- *Integration challenges exist in defining not only tasks required for operating the unit but also for interacting with other on-site maintenance and support organizations for multiple units.*
- *The skill set for control room operators may require a different distribution of qualifications (e.g., more senior reactor operators, fewer reactor operators).*
- *For some SMR designs, operators will face the challenge of managing the operation of additional units as they are placed online. As the number of modules increases, the demands on the operators will change, and potentially the number of operators required for safe operation (i.e., multiple staffing plans may be needed to address the addition of up to 11 more units during the construction period or subsequent operating period).*

These considerations will be addressed in the Xe-100 design through implementation of the Control Room Staff Analysis methodology.

4. CONTROL ROOM STAFFING ANALYSIS METHODOLOGY

The X-energy Control Room Staffing Analysis Methodology will be based on the guidance provided in NUREG-0711 on developing an HFE program and will include the 12 elements required to analyze and describe the results of an acceptable HFE program as delineated in that guidance.

4.1. CONCEPT OF OPERATIONS

The Xe-100 Concept of Operations [14] provides an understanding of how the initial staffing fits into the overall plant design and operation. The document introduces the staffing, qualifications and operation assumptions that will be subsequently consolidated, modified, or dismissed during the development of the HFE Program. The document introduces the staffing, qualifications, and operation assumptions that will be subsequently consolidated, modified, or dismissed during the development of the HFE Program.

The concept of operations, degree of automation, and the Xe-100 plant design is different than existing LWR operations during normal, abnormal, and emergency situations.

The Concept of Operations includes the starting premises for:

- primary design and operating characteristics of the plant,
- specific staffing goals and assumptions necessary to implement the concept of operations,
- number of personnel who will have plant monitoring and operational control responsibilities on each shift,
- roles and responsibilities of everyone designated as control room personnel, if that individual is responsible for controlling and monitoring plant or unit operations,
- overall operating environment and primary HSIs to be used by control personnel,
- interactions of control personnel with each other and with people not directly responsible for the control and safe operation of the plant,
- interaction of control personnel with automated support systems and the role of these systems in the overall management and control of the plant,
- changes in the responsibilities or qualifications of the control personnel, such as combining the responsibilities for operations and fuel handling,
- aspects related to multi-unit operations during construction of additional units (as applicable),
- interaction of control personnel with automated systems, including responsibilities for monitoring, operating, and overriding automated systems, and
- other mechanisms that enable or support control personnel responsibilities for monitoring, disturbance detection, situation assessment, response planning, response execution, and the management of transitions between automatic and manual control.

The Concept of Operations provides a staffing baseline for the beginning of the HFE Program. The staffing configuration and the above listed aspects might evolve during the execution of HFE activities, especially during the S&Q element. During execution the following items will be assessed:

- staffing levels for personnel across shifts, and
- training and qualifications required for control personnel.

4.2. OPERATIONAL CONDITIONS CONSIDERED IN THE HFE PROGRAM

For the purposes of the HFE Program, it is necessary to select the operational conditions based on the results from various sources of event sequences, which will provide a robust sample to be further analyzed and tested. The selection will compile those conditions that present the greatest challenges to human performance and those critical for plant safety.

Subsequent analysis activities of the HFE Program focus on the operational conditions chosen. The scope of the analysis will include:

- a description of the operational conditions selected for analysis, and
- the rationale for selecting the operational conditions analyzed and for excluding others that could have been analyzed.

The following activities may provide sources to identify the operational conditions:

- PRA, Probabilistic Risk Assessment,
- HRA, Human Reliability Analysis,
- OER, Operating Experience Review,
- TIHA, Treatment of Important Human Actions, and
- TA, Task Analysis.

The selected operational conditions will be turned into a sample of prioritized interfaces and operational scenarios to be verified and tested (validated). This task is carried out in the HFE Program in the HF V&V element prior to performing the following activities:

- HSI Task Support Verification,
- HSI Design Verification, and
- Integrated System Validation.

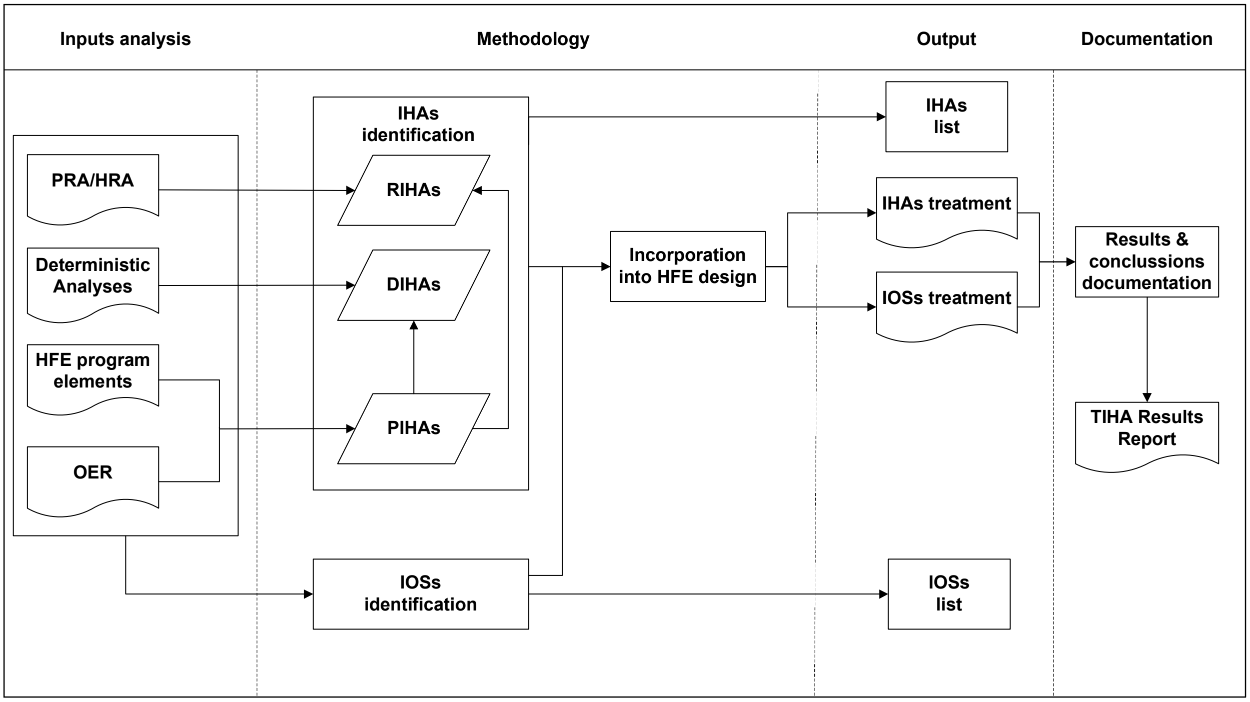

Figure 5: TIHA activities flowchart

Within the Xe-100 HFE Program, the TIHA analysis, as described in its implementation plan [16], envelops the above concept of operational conditions. As shown in Figure 5, the TIHA identifies: the actions (or IHAs) and the operating sequences, or IOS. Each IHA has a detailed description, including the context in which the IHA was identified. It may refer to specific plant conditions and/or events. The IOS is defined in the same manner. The IHAs and IOS are later incorporated, with a specific resolution (called treatment in the flowchart above), into the rest of the HFE program elements.

4.3. OPERATING EXPERIENCE

The Xe-100 shares similarities with several existing reactor types and precedents. While the majority of operating HTGRs were developed and operated outside of the U.S., several mature designs have progressed through the U.S. licensing framework to varying degrees, and these designs share operating characteristics with the Xe-100 design. The international experience with pebble-bed HTGRs was principally established in Germany and is now growing with the Chinese demonstration plants.

X-energy has conducted an initial search for operating experience (OPEX) from domestic and international HTGR plants to inform the plant design. Multi-unit operational considerations were not applicable to those plants, so alternative sources of OPEX will be explored for these considerations. Specific insights from the number and qualifications of control room operators and their contributions to safe plant operation will be developed as part of the NUREG-0711 HFE program.

The operating experience review of the HFE Program should identify staffing issues to be avoided. Also, it should identify staffing practices that have proven to be effective and therefore be incorporated into the operation environment.

Since the operating experience from new reactor designs is limited, research will be oriented to past high-temperature gas-cooled reactor designs, prototype reactors and recent modular designs. Multi-unit operation experiences can be found in other industries giving valuable insights for the Xe-100 plant operation.

Research sources for potential Operating Experiences are:

- NRC Database;
- IAEA Database;
- INPO Database;
- NEA Scientific and technical publications;
- CANDU Database; and
- Sources from non-nuclear industries:
    - Non-nuclear Electric Generating Stations,
    - Chemical industry,
    - National Transportation Safety Board,
    - Aviation Safety Network, and
    - Natural Gas Generating Stations.

Finally, the operating experience review provides useful input to the rest of the HFE Program elements and activities, especially Task Analysis, in which the issues found related to the impact of staffing shortfalls may be useful. The operating experience review can also be a source for identifying operational conditions relevant to the control room staffing analysis.

The methodology for conducting the Operating Experience Review for the Xe-100 consists of three steps, illustrated in Figure 6, and it is fully described in the OER Implementation Plan [15].

Figure 6: OER methodology process

4.4. FUNCTIONAL REQUIREMENTS ANALYSIS AND FUNCTION ALLOCATION

As explained in the HFE PMP [13], the Functional Requirements Analysis aims to identify the functions that must be performed to achieve Xe-100 plant goals. The analysis will define and assess the aspects of the control room staffing analysis on the functions, especially those allocated to the operator.

Performance of the function allocation analysis assigns the functions to personnel, system elements or combination of both. The results from this analysis provide a concept of the level of plant automation necessary to achieve the functions not being performed by the personnel.

This analysis is linked to the staffing requirements, as the workload of the operators is closely related to the level of plant automation. A reduction of workload and staff necessary to monitor and control the reactor units is linked to the levels of automation and their reliability and should support a reduction in the number of operators in charge of plant operations due to the increased level of reliable automation.

The HFE Program will ensure that the allocation of functions enables the plant's goals to be accomplished, specifically for functions under the operational conditions relevant for the staffing exemption. This fact can only be satisfied if Task Analysis, Staffing and Qualifications, and Design Verification and Validation tests further validate the outputs from the Function Allocation.

If, during the validation tests of the operational conditions, the shift crew compliment is not proven to be sufficient to achieve a safe operation of the plant, then a review of the functional analysis will be conducted and a reallocation of the functions may be required.

The HFE Program activities, such as Function Allocation, will be iterated until the final staffing meets the operational needs.

Functional Requirements Analysis will be conducted to ensure that the functions necessary to accomplish plant goals are identified and sufficiently defined. The analysis will consist of a functional breakdown, where plant goals are in the top level and plant component statuses are in the lowest level. A plant goal is met if the related plant components are operating in their specified status. Hence, the functional requirements to accomplish the plant goals are the plant components properly operating.

Function Allocation will be performed to assign the functions to personnel and/or automation, considering their relative capabilities, strengths, and weaknesses. Therefore, the allocation methodology is based on HFE criteria. The objective is to avoid operation mistakes and maximize efficiency and reliability of the plant by maintaining the operator's awareness of plant status.

The results of the FA will provide the aggregate of human actions needed to perform the functions. These human actions will be further analyzed in the Task Analysis (Section 4.5). The overall process is shown in Figure 7.

The methodology to conduct Functional Requirements Analysis and Function Allocation is described fully in the Xe-100 FRA & FA Implementation Plan [17].

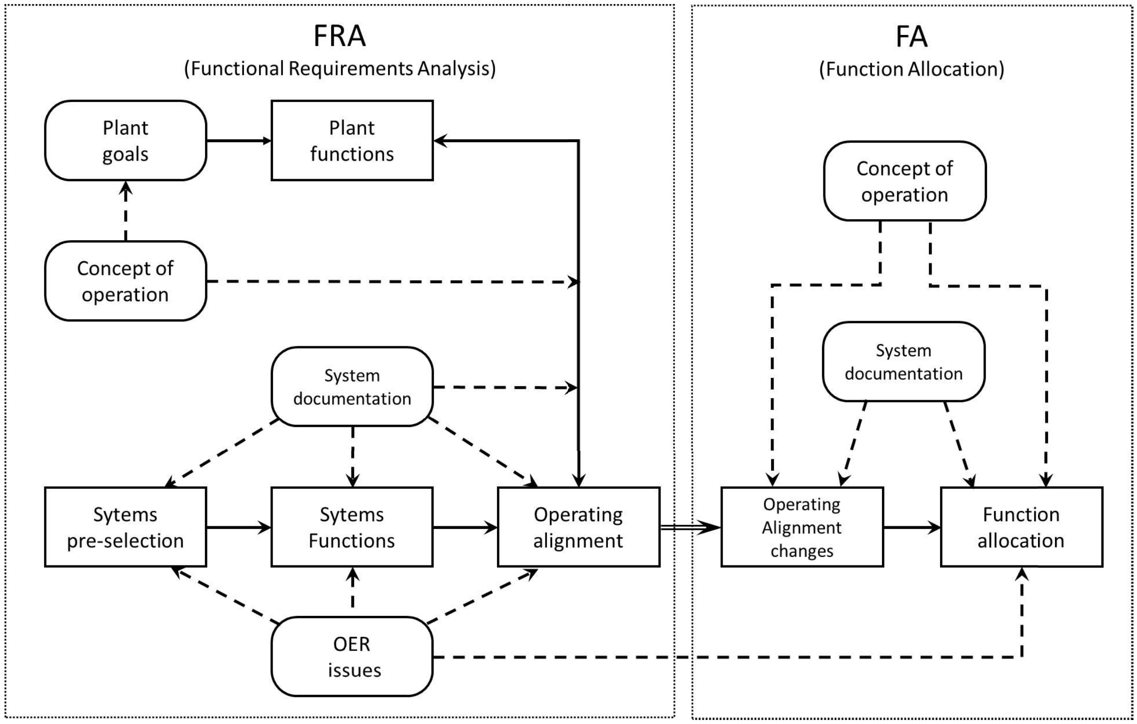

Figure 7: FRA & FA overall process

4.5. TASK ANALYSIS

Similar to the Functional Requirements Analysis and the Function Allocation, the Xe-100 Task Analysis addresses the operational conditions relevant to demonstrate changes in the shift crew make up. Human actions are needed to accomplish functions, and human actions can be further divided into smaller elements called *activities*. An individual activity is defined as a single action performed by the operator contributing to the completion of a task. For each activity, the information, control, and support requirements will be addressed as applicable.

Performance of the TA is rarely a "one-step" process, usually requiring one or more iterations as more detailed information about the plant or its systems becomes established, and the roles of various personnel become clearer. As the design matures, the TA becomes more detailed. TA and system design (including interface design) initially consider the types of information personnel need to understand the current system status, and requirements for information processing and display. In parallel, the types of controls necessary for response to presented information are also identified. After information and response requirements (e.g., displays, controls, procedures, etc.) are identified, ways the requirements are to be satisfied are specified. The importance of this formal and systematic approach becomes evident when considering the complexity of some human operations within system operations, and the coordination required to integrate various design decisions affecting human tasks at different stages during the design process.

The objective of an initial TA is collection and organization of information (data), facilitating subsequent use of the information for a variety of purposes (e.g., development of training requirements and training content, input to HFE design and design review, etc.). Specifically, the purpose of TA is appropriate HFE design, so the information is managed and structured toward definition of the optimum human-system interface based on the requirements made evident by the inherent predictive nature of TA.

The information compiled and analysis conducted are predictive, attempting to determine requirements for definition of an optimum human-system interface based on the information derived from the system design bases and experience of the industry. Information is also sought concerning the training requirements of operations and maintenance personnel and requirements for plant procedures.

The task analysis provides information to identify task timing and workload issues, giving potential information to determine conflicts that would affect the staffing configuration. Detailed task descriptions are developed for operating sequences which affect plant safety, applying a graded approach to the TA. Therefore, tasks required to fulfill *important operating sequences* identified in the Treatment of Important Human Action process (those performed under the chosen Operation Conditions, see Section 4.2) will be more thoroughly described.

Detailed task descriptions provide:

- Information required (parameters, units, precision, accuracy),
- Information source (alarms, displays, verbal communication, etc.),
- Actions to be taken,
- Overlap of task requirements (serial vs. parallel tasks),
- Frequency,
- Time available for operator response based on the plant response characteristics,
- Temporal constraints (task ordering),
- Tolerance and accuracy,
- Operational limits of personnel performance, and of machine and software,
- Feedback required to indicate adequacy of the actions taken,
- Cognitive and physical workload,
- Tools and equipment required,
- Computer processing support aids,
- Workspace location,
- Number of personnel, their technical specialty, and their specific skills,
- Communication required, including type,
- Personnel interaction when more than one person is involved, and
- Job aids or reference materials required.

The steps for compiling and organizing information in TA methodology are structured as follows:

1) Converting functions to operating sequences,

2) Developing narrative task descriptions, and
3) Developing detailed task descriptions.

The full methodology to conduct the Task Analysis is described in the Xe-100 TA Implementation Plan [18].

4.6. JOB DEFINITIONS

A job is a group of tasks and functions that are assigned to a specific operational position.

As the Xe-100 job definition may vary from traditional jobs in the control room, it is necessary to precisely define the qualifications (knowledge, skills, and abilities) with the tasks that an individual must perform. The job definition in the design certification will be addressed after the HFE Task Analysis by the Systematic Approach to Training (SAT) process.

By following the SAT process for the training material development, matching between the KSAs (Knowledge, Skills, and Abilities) list, job definition, and Staffing & Qualification is ensured, as all the activities are connected and take the same Task Analysis as input. The Staffing & Qualifications (S&Q) activities describe and define the scope and impacts on the roles, responsibilities, and qualifications of control room personnel.

4.7. STAFFING PLAN

The next step is to analyze the number of personnel necessary to perform each job. The staffing plan is supported by the results of the preceding analyses and it provides information about the operational staff shift composition and shift scheduling. In the case of operations that take place outside the main control room, the location and personnel will be specified. This includes specified maintenance jobs that operational staff may need to perform when they are not in the control room supporting plant operation.

The S&Q element of the HFE Program involves a theoretical assessment of the staffing plan under the operational conditions selected in terms of response time. It is characterized by a systematic approach, namely the different stages of the methodology that are intended to be followed in the order in which they are presented.

Figure 8 presents a high-level representation of the S&Q process to be followed during the S&Q analysis development.

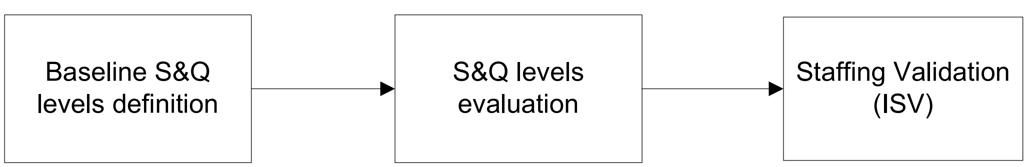

Figure 8: S&Q overall process

The analysis is iterative; that is, the initial staffing goals are defined for the personnel in the control room and then will be re-evaluated as information from other HFE elements becomes available, until the ISV is completed and the staffing level is validated.

The methodology to conduct the S&Q analysis is described in the Xe-100 S&Q Implementation Plan [19].

4.8. ADDITIONAL DATA AND ANALYSES

Other data and analysis may be provided:

- Human reliability analysis, used to demonstrate how risk-important human actions affect staffing levels.
- Data from the HSI development and verification, to demonstrate that the design supports the previous HFE analysis, which is ensured because the HFE Program follows NUREG-0711 [2].
  - The Xe-100 will be a predominately software-controlled installation; all the operation tasks are accomplished through interaction using a human-software interfaces.
  - The goal of the HFE program elements is to provide an analysis that supports the software based HSI and provide alternative HSI options if the use of software HSI is not a viable option for specific applications.

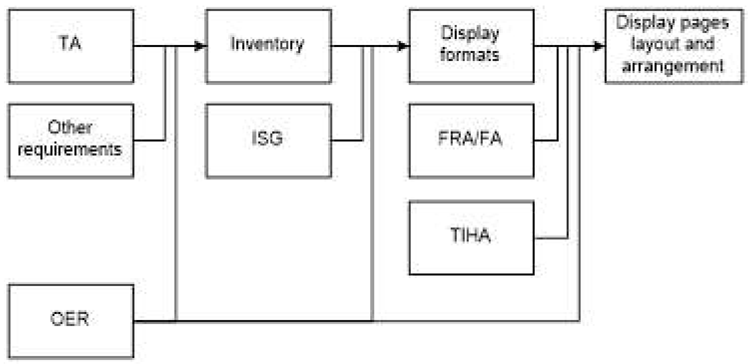

Figure 9: HSI design path

  - The HSI will also address the diversity and defense-in-depth of the allocation of displays and controls for manual system-level actuation of critical safety functions, and for monitoring those parameters that support them.
  - The HSI design methodology is described in the HSI Design Implementation Plan [20]. A representation of the HSI design path is provided in Figure 9.
- KSA analysis and list to support task analysis and job definitions.
- Procedures and Training Program documentation demonstrating the implementation of concepts from the HFE Program that support the staffing exemption.

4.9. STAFFING PLAN VALIDATION

Staffing baseline resulting from the S&Q analysis is tested in the HFE Program during the Verification and Validation activities.

The staffing plan validation (SPV) refers to an assessment using performance-based tests to determine whether the staffing plan meets performance requirements and acceptably supports safe operation of the plant.

The validation tests of the HFE Program will be performed during different phases of the design. In the beginning, this is done by early partial validations with portions of the HSI design. Finally, when the complete simulation environment is ready, the Integrated System Validation (ISV) is performed. In this way, the HFE Program ensures operator's gradual adaptation to the HSI and control room environment from the beginning of the design.

The assessment should demonstrate that the proposed Xe-100 plant shift crew, three operators in one control room operating multiple reactor units, can satisfy the plant and human performance requirements identified in the functional requirements analysis, function allocation, and task analyses. This assessment should include the range of operational conditions identified as relevant.

Therefore, the demonstration is done through simulations that involve the operators and operating experience contribution. The following detailed test objectives and considerations will be addressed to provide evidence that the integrated system adequately supports plant personnel in safely operating the plant:

- Validate the acceptability of the shift staffing level(s), the assignment of tasks to crew members, and crew coordination within the control room, between the control room and local control stations and support centers, and with individuals performing tasks locally.
- Validate that the design has adequate capability for alerting, informing, controlling, and providing feedback such that personnel tasks selected are successfully completed during normal plant evolutions, transients, design-basis accidents, and a range of licensing basis events, including risk-significant events beyond-design basis events, as defined by sampling operational conditions.
- Validate that specific personnel tasks can be accomplished within the time and performance criteria, with effective situational awareness and acceptable workload levels that balance vigilance and personnel burden.
- Validate that the HSIs minimize personnel error and assure error detection and recovery capability when errors occur.
- Validate the assumptions about performance on identified important human actions.

The fundamental characteristics for the SPV are introduced below:

1. V&V sampling. Using the operational conditions as input, a sample of interfaces and scenarios are selected. The sampling dimensions to identify the conditions to be addressed are:
    - Plant Conditions:
        - Normal operations,
        - I&C and HSI failures,
        - Off-normal conditions and emergencies,
        - Transients (abnormal operational events) and accidents (emergency operational events),
        - Maintenance;
    - Personnel Tasks;
    - Error forcing contexts;
2. Testbed conditions. A description of the validation environment, providing:

- the scenarios to be tested,
- a representative number of crews and scenario repetition,
- the state of the simulator,
- the simulation conditions, and
- the number and duties of the HFE observers.

3. Human Performance Measurements. Data will be collected during the tests, through observation, questionnaires, and other techniques. The measurements can be typically classified according to a human cognitive model in the following fields:
   - Monitoring and detection,
   - Situation assessment,
   - Response planning,
   - Response implementation,
   - Situation awareness
   - Workload, and
   - Communication and teamwork

The data are analyzed and processed by considering a set of performance measurements that are established prior to the validation, for example:

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

The methods for data analysis and assessment will be described in a Validation Procedure and documented in the Validation Result Summary Report.

4. Validation criteria. Applicable criteria are identified in advance to determine the acceptability of the results. Examples of acceptability criteria are:
   - Main plant parameters were kept inside normal operational range,
   - The scenario finished with the plant stable,
   - Plant mode X was reached,
   - Nominal task performance times have not been exceeded by more than 10 percent,
   - No more than 60 seconds have been required to begin Task X after Event Y, and
   - No actions have been omitted.

The process and methodology for the human-in-the-loop simulations are described further in the Xe-100 Verification & Validation Implementation Plan [21]. The specific details for each validation test will be provided for in a Validation Procedure and documented in a Validation Result Summary Report. A summary of the V&V process activities is shown in Figure 10.

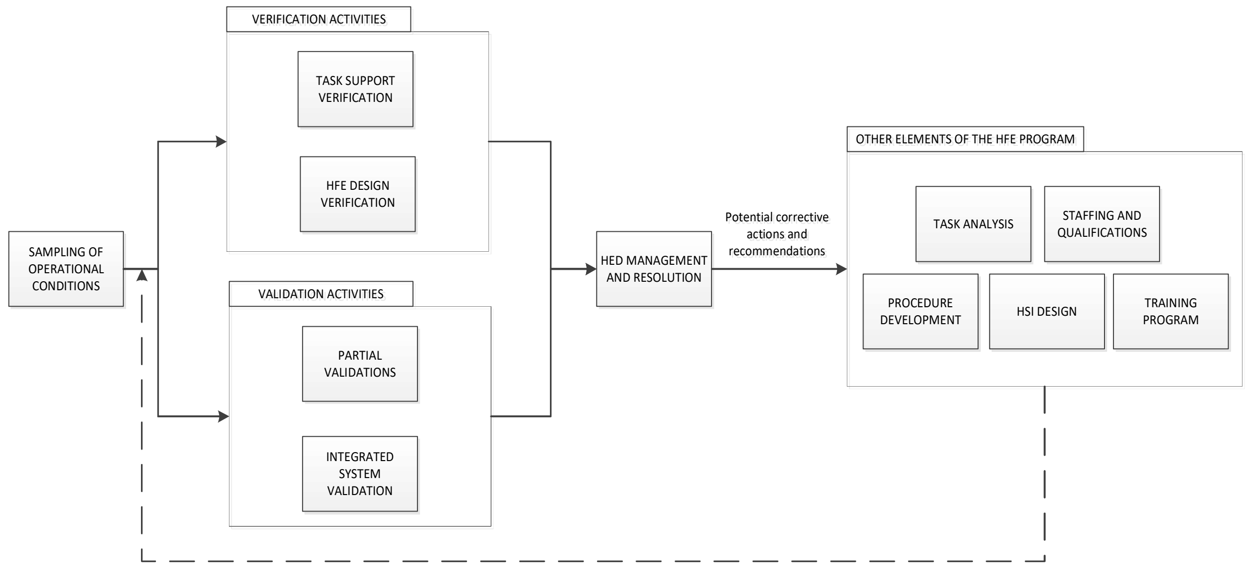

Figure 10: V&V overall process

4.10. EXEMPTION REQUEST PROCESS

NUREG-1791 provides the NRC's review guidance for exemption requests and, by extension, an approach to develop the technical basis for an exemption request for license applicants to the regulatory requirements of 10 CFR 50.54(m). This approach has also been recently applied to develop similar technical bases for a Part 52 Design Certification application. The specific approach to licensing will be made on a project-specific basis, but the control room staffing analysis methodology described herein will support a variety of options. During the development of the Xe-100 Implementation Plans of the NUREG-0711 [2] elements, additional requirements from NUREG-1791 [5] were added to ensure completeness of the methodology. For a license application. the exemption review is guided by the path shown on Figure 11, which is excerpted from NUREG-1791 [5]. NUREG/CR-6838 [7] comprises the basis for these eleven steps, which are further explained in NUREG-1791 [5].

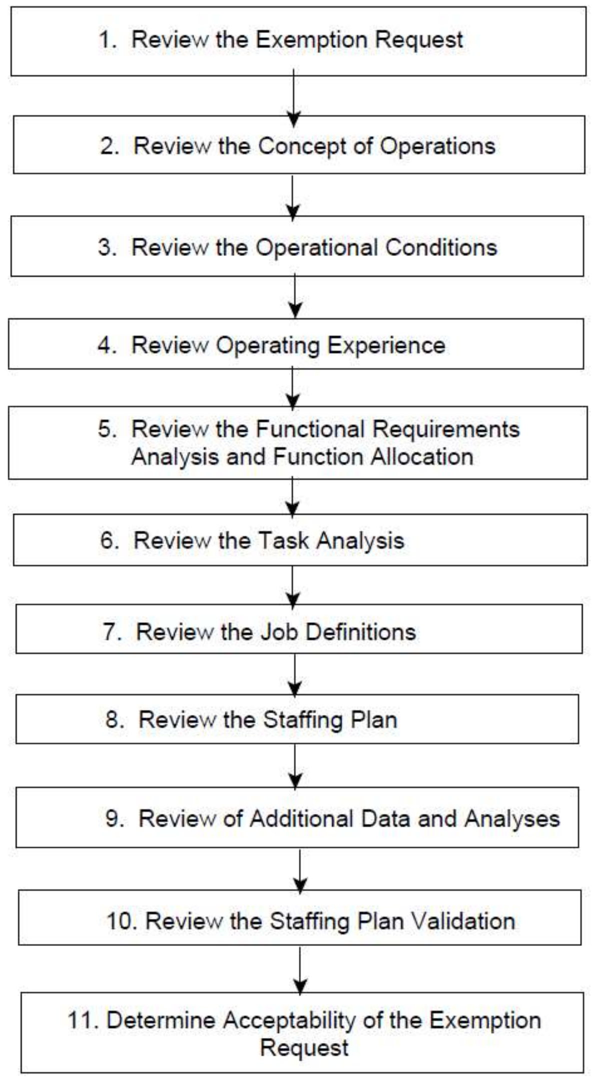

Figure 11: Exemption Request Review Process

The following tasks provide support to the exemption request and will be reviewed together:

- Operating experience review (OER),
- Functional requirements analysis and function allocation (FRA & FA),
- Task analysis (TA),
- Human Factors Verification & Validation (HF V&V).

Specifically, the HF V&V element contains performance-based tests to determine whether the Staffing & Qualifications support a safe operation of the plant.

Additional analyses and studies may also support the exemption request and review process. Figure 12 shows the importance of each NUREG-0711 [2] element in the strategy, from darkest blue, most important, to lightest blue, least importance.

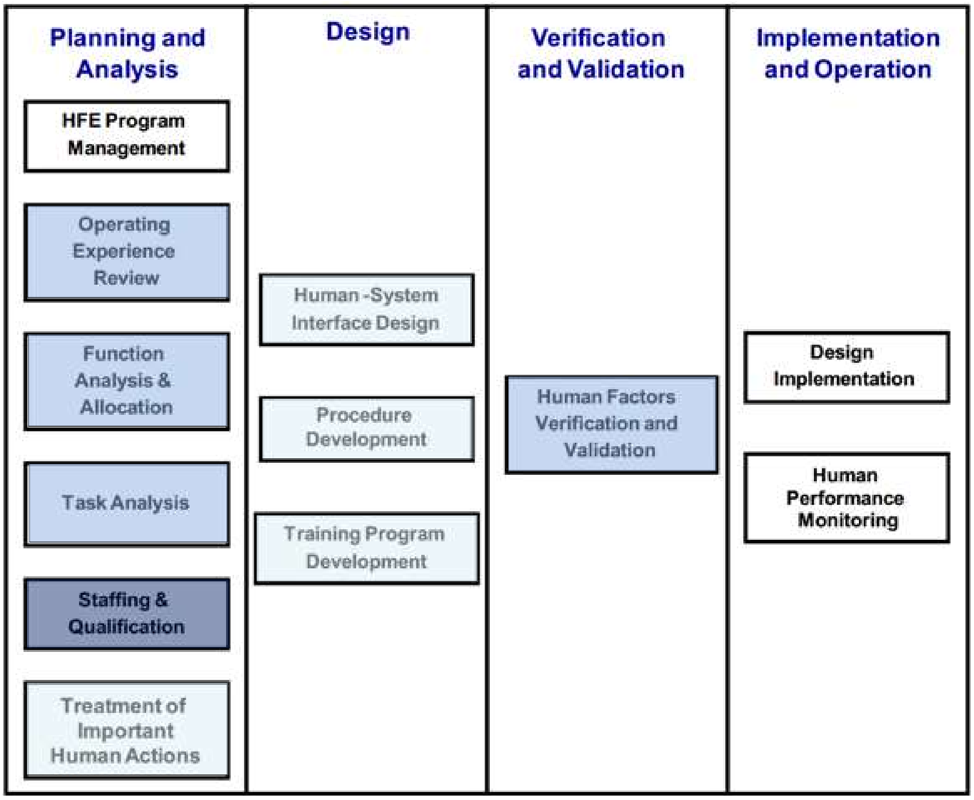

Figure 12: NUREG-0711 elements relevance in the NUREG-1791 approach

5. DEVELOPING THE CONTROL ROOM STAFFING ANALYSIS

Figure 13 shows the process to be followed by the Xe-100 HFE Program to develop the control room staffing analysis based on NUREG-1791 [5].

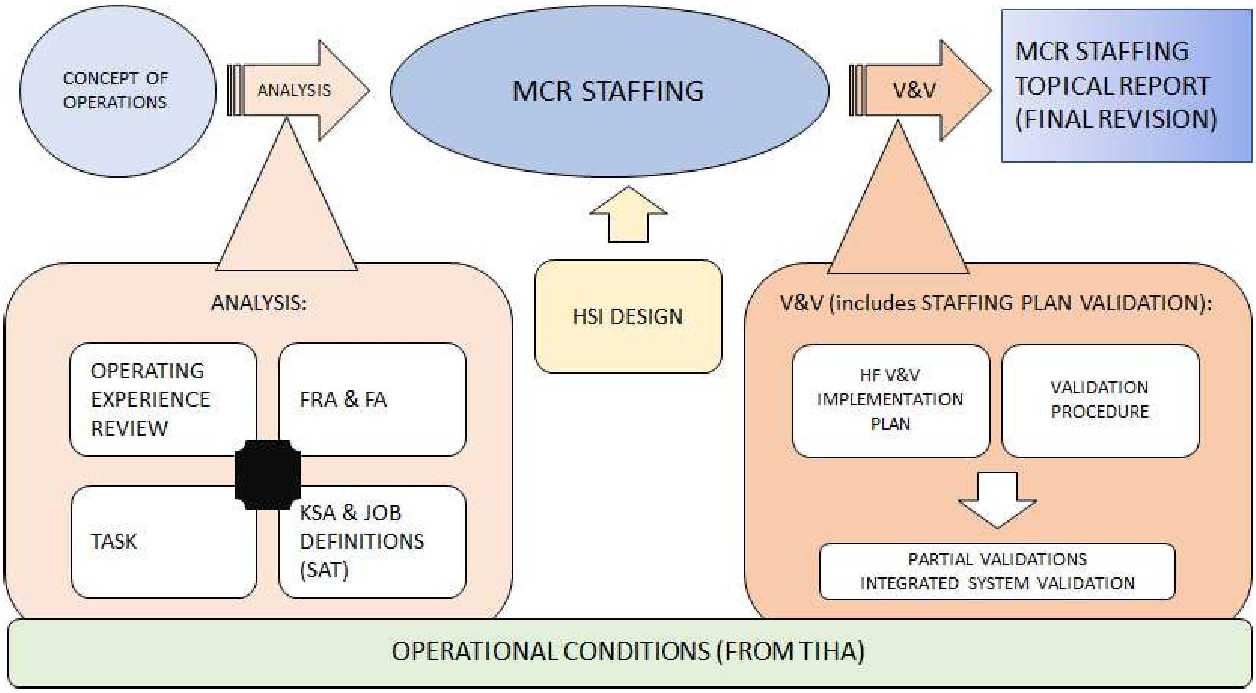

Figure 13: Xe-100 HFE Program Staffing Exemption Request Process

The concept of operations provides the staffing plan premises for the plant. The Staffing Plan is developed during the Xe-100 HFE Program. After several analysis steps (i.e. OER, FRA & FA, TA, and KSA and Job Definitions from Systematic Approach to Training), the S&Q will be established and assessed. Following the validation plan and tests, this topical report will be updated to include the results and conclusions of each element to provide the comprehensive technical basis and control room staff plan.

The HFE elements will be supplemented with the criteria listed in NUREG-1791 [5] during their development. The elements which should be provided to support the technical basis include:

- Operating Experience Review,
- Treatment of Important Human Actions,
- Functional Requirements Analysis and Function Allocation,
- Task Analysis,
- Staffing & Qualifications, and
- Human Factors V&V.

An HFE software database tool that contains the information and data resulting from the development of each element activities will be utilized to generate the following outputs:

1. OER Results Summary Report;

2. TIHA Results Summary Report;
3. FRA & FA Results Summary Report;
4. TA Results Summary Report;
5. S&Q Results Summary Report;
6. V&V:
   i. Task Support Verification Report(s),
   ii. HFE Design Verification Report(s),
   iii. Partial Validation Report(s),
   iv. ISV Procedure (if applicable, as it could be part of the ISV report), and
   v. ISV Report;

Additional (non-mandatory):

- Treatment of Important Human Actions,
- Human System Interface Design,
- KSA analysis (Non-HFE Program),
- Training material & Procedures (Non-HFE Program), and
- PRA (Non-HFE Program).

The HFE Program's support to the control room staffing approach is summarized in the following actions:

- Follow the process shown in Section 5 and provide the submittals from Section 6;
- Develop the Implementation Plans including the methodology of the NUREG-0711 [2] elements, but also considering NUREG-1791 [5] guidance;
- Develop NUREG-0711 [2] elements incorporating the guidance from NUREG-1791 [5]; particularly, ensure that the submittals fulfill the review criteria from NUREG-1791 [5] Appendix A, "Review Checklists;"
- Address as context for each NUREG-0711 [2] element the most challenging operational conditions for human performance and plant safety;
- Perform a complete Task Analysis, which is of key importance to supporting the staffing reduction, describing each task in terms of operation performance requirements (see Section 4.5);
- Ensure proper correspondence between the Training Program development and the HFE Program, by following the SAT process and using the Task Analysis as input for KSA list and Job Definition;
- Incorporate in the HFE Program the methodological details of the Staffing Plan Validation, first in the V&V Implementation Plan [21], and later in the Validation Procedures or in the Result Summary Reports. These details, among others, refer to:
  - data collection method,

- performance measures, and
- validation criteria;

- Perform a staggered SPV through human-in-the-loop simulations from the initial partial validations until the final integrated system validation to ensure end-user and human-oriented HSI design.
- Include simultaneous abnormal and emergency events on multiple units in the control room simulator in the SPV. Those scenarios produce likely challenging and high workload conditions which are needed to assess the proposed staffing reduction to ensure plant operational and safety goals are achieved.

6. CONCLUSION

X-energy will continue to pursue development of the Xe-100 HFE Program described herein. Implementation Plans for each of the subject elements provide guidance for developing the information necessary to demonstrate execution of a successful NUREG-0711-based program and control room staffing analysis, and developing the technical bases described here to support a single control room with 3 operators controlling 4 or more units.

7. NRC TOPICAL REPORT REVIEW OBJECTIVES

X-energy's objective is to license the Xe-100 modular high temperature gas reactor design for construction and operation. This requires the development of a control room staffing approach that meets regulatory requirements and provides an optimal staffing model for control room operations of multiple units from a single control room. This report has been prepared to provide the proposed methodology for the Xe-100 HFE Program, which will be used as the basis for developing the technical basis for control room staffing in accordance with the guidance in NUREG-1791, or in support of a future 10 CFR 52 Design Certification application. X-energy is requesting NRC review and approval of this approach as a means to conduct the HFE program methodologies to ensure regulatory acceptance of the Xe-100 control room staffing in one control room for 4 or more units and develop a valid basis for licensees requesting exemptions from 10 CFR 50.54(m) or X-energy to use in support of a future Design Certification application.

8. REFERENCES

The following documents are referenced within this topical report.

Document Title	Preparer/ Author	Document Number	Revision or Date of Issue	Classification	Applicable[3] (Yes/No)
[1] NUREG-0800, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition, Chapter 18, "Human Factors Engineering"	NRC	N/A	2016	N/A	Yes
[2] NUREG-0711, Human Factors Engineering Program Review Model	NRC	N/A	Rev 3	N/A	Yes
[3] REGDOC-2.5.1, General Design Considerations Human Factors	CNSC	N/A	2019	N/A	Yes
[4] REGDOC-2.2.5, Minimum Staff Complement	CNSC	N/A	2019	N/A	Yes
[5] NUREG-1791, Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10CFR50.54(m)	NRC	N/A	2005	N/A	Yes
[6] Xe-100 Technology Description Technical Report	X-Energy	001118	1	XE00-P-G1ZZ-RDZZ-D	
[7] NUREG/CR-6838, Technical Basis for Regulatory Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)	NRC	N/A	2004	N/A	Yes
[8] NUREG/CR-7202, NRC Reviewer Aid for Evaluating the Human Factors Engineering Aspects of Small Modular Reactors	NRC	N/A	2012	N/A	Yes

3 Applicable documents are applicable to the extent specified within this document and thus deemed to form part of this document.

Document Title	Preparer/ Author	Document Number	Revision or Date of Issue	Classification	Applicable[3] (Yes/No)
[9] BNL-20918-1-2015, Methodology to Assess the Workload of Challenging Operational Conditions in Support of Minimum Staffing Level Reviews	BNL	N/A	2015	N/A	Yes
[10] SECY-14-0095, Status of the Office of New Reactors Readiness to Review Small Modular Reactor Applications	NRC	N/A	2014	N/A	Yes
[11] SECY-11-0098, Operator Staffing for Small or Multi-Module Nuclear Power Plant Facilities	NRC	N/A	2011	N/A	Yes
[12] ML18130A949 (ADAMS accession number), Updated Policy Table for Non-LWR	NRC	N/A	2018	N/A	Yes
[13] TEC-XE100-HFE-PMP, HFE Services for the Xe-100 Plant Design – Human Factors Engineering Program Management Plan	Tecnatom	N/A	Rev 0	N/A	Yes
[14] TEC-XE100-HFE-COO, Concept of Operations	Tecnatom	N/A	Rev 0	N/A	Yes
[15] Operating Experience Review Implementation Plan	Tecnatom	000982	Rev 1	XE00-R-R1ZZ-RDZZ-X	Yes
[16] Treatment of Important Human Actions Implementation Plan	Tecnatom	000984	Rev 1	XE00-R-R1ZZ-RDZZ-X	Yes
[17] Functional Requirements Analysis and Function Allocation Implementation Plan	Tecnatom	000985	Rev 1	XE00-R-R1ZZ-RDZZ-X	Yes
[18] Task Analysis Implementation Plan	Tecnatom	000986	Rev 1	XE00-R-R1ZZ-RDZZ-X	Yes
[19] Staffing & Qualifications Implementation Plan	Tecnatom	000987	Rev 1	XE00-R-R1ZZ-RDZZ-X	Yes
[20] Human-System Interface Design Implementation Plan	Tecnatom	000988	Rev 1	XE00-R-R1ZZ-RDZZ-X	Yes
[21] Human Factors Verification and Validation Implementation Plan	Tecnatom	000989	Rev 1	XE00-R-R1ZZ-RDZZ-X	Yes

Document Title	Preparer/ Author	Document Number	Revision or Date of Issue	Classification	Applicable[3] (Yes/No)
[22] Plant Staffing Report	X-Energy	000077	Rev 3	XE01-P-X-Z-D	Yes