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U.S. Nuclear Regulatory Commission
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Submittal of X Energy, LLC (X-energy), Licensing White Paper: Xe-100 Seismic Design Methodology

The purpose of this letter is to submit the subject white paper to the U.S. Nuclear Regulatory Commission (NRC) on behalf of X Energy, LLC ("X-energy"). This submission describes the approach to develop the seismic design criteria for the Xe-100 structures, systems, and components (SSCs) in a risk-informed, performance-based manner and methodology used for the seismic qualification of the Reactor Building. It is provided for NRC review as indicated in Sections 4 and 5 of the report and is expected to be referenced in future Xe-100 licensing applications. X-energy has determined this report is available for unrestricted release. The specific review schedule will continue to be developed with X-energy's NRC project manager.

This letter contains no commitments. If you have any questions or require additional information, please contact Ingrid Nordby at inordby@x-energy.com.

Sincerely,

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Enclosure: X Energy, LLC (X-energy) Licensing White Paper: Xe-100 Seismic Design Methodology

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Enclosure

X Energy, LLC
Licensing White Paper: Xe-100 Seismic Design Methodology

Licensing White Paper
Xe-100 Seismic Design Methodology

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SYNOPSIS

This white paper presents the approach to develop the seismic design criteria for the Xe-100 structures, systems, and components (SSCs) in a risk-informed, performance-based manner. It also presents the Regulatory Guide (RG) 1.233-based methodology used for the seismic qualification of the Reactor Building (RB) which is the primary structure performing safety related functions in the plant. X Energy, LLC (X-energy) is seeking early feedback from the U.S. Nuclear Regulatory Commission (NRC) staff on this subject for advanced reactors and small modular reactors (SMRs) such as X-energy's Xe-100 design. This white paper serves the following purposes:

1. Present the seismic design bases in the form of representative design response spectra (DRS) curves and tabulate the classification for Xe-100 SSCs;
2. Present the methodology used for the development of the DRS curves;
3. Present the design features of the RB and adjacent structures; and
4. Provide a description of the methodology used for the structural qualification of the RB.

A description of the seismic design basis development is described in Section 3.1 and the RB seismic analysis methodology is described in Section 3.2. Sections 4 and 5 describe conclusions and the scope being requested for NRC review.

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ABBREVIATIONS/ACRONYMS

Short Form	Phrase
AOO	Anticipated Operational Occurrences
ARDP	Advanced Reactor Demonstration Program
ASCE	American Society of Civil Engineers
ASB	Access and Security Building
BDBE	Beyond Design Basis Event
CDC	Complimentary Design Criteria
CEB	Controls and Electrical Building
CEC	Callaway Energy Center
CEUS	Central and Eastern United States
CFR	Code of Federal Regulation
CGS	Columbia Generating Station
CI	Conventional Island
CP	Construction Permit
DBA	Design Basis Accident
DBE	Design Basis Event
DBHL	Design Basis Hazard Level
DID	Defense In-Depth
DNPP	Darlington Nuclear Power Plant
DOE	Department of Energy
DRS	Design Response Spectra

Short Form	Phrase
ER	Environmental Report
ESIM	Effective Seismic Input Method
F-C Target	Frequency-Consequence Target
FHAB	Fuel Handling Annex Building
FIRS	Foundation Input Response Spectra
FPIE	Full Power Internal Events
FRS	Floor Response Spectra
GMRS	Ground Motion Response Spectra
HBRSES	HB Robinson Steam Electric Station
HF	High Frequency
HPB	Helium Pressure Boundary
HSF	Helium Services Facility
HTGR	High Temperature Gas-Cooled Reactor
IBC	International Building Code
IDP	Integrated Decision-Making Process
ISRS	In-structure Response Spectra
IUAT	Inter-Unit Access Tunnel
LBE	Licensing Basis Event
LS	Limit States
MCE_R	Maximum Considered Earthquake
MHTGR	Modular High-Temperature Gas-Cooled Reactor

Short Form	Phrase
NAPS	North Anna Power Station
NRC	U.S. Nuclear Regulatory Commission
NEI	Nuclear Energy Institute
NI	Nuclear Island
NIAB	Nuclear Island Auxiliary Building
NSRST	Non-Safety-Related with Special Treatment
NST	Non-Safety-Related with No Special Treatment
NIW	Nuclear Island Warehouse
PAB	Protected Area Boundary
PDC	Principal Design Criteria
PRA	Probabilistic Risk Assessment
PSAR	Preliminary Safety Analysis Report
PSHA	Palo Verde Generating Station
RB	Reactor Building
RCCS	Reactivity Cavity Cooling System
RF	Reduction Factor
RFDC	Required Functional Design Criteria
RG	Regulatory Guide
RIPB	Risk Informed Performance Based
RPV	Reactor Pressure Vessel
RSF	Required Safety Function

Short Form	Phrase
RWB	Radiated Waste Treatment Building
SAR	Safety Analysis Report
SC	Steel Plate Composite
SDB	Seismic Design Bases
SDC	Seismic Design Category
SE	Seismic Event
SMR	Small Modular Reactor
SR	Safety Related
SR-SSC	Safety Related Structure, Systems, and Component
SSC	Structure, System, and Component
SSE	Safe-Shutdown Earthquake
SRP	Standard Review Plan
SSI	Soil-Structure Interaction
UHRS	Uniform Hazard Response Spectra
UHS	Ultimate Heat Sink
V/H	Vertical-to-Horizontal
X-energy	X Energy, LLC

1. Introduction

1.1 Purpose

X-energy is developing the Xe-100 modular high-temperature gas-cooled reactor (HTGR) for commercial deployment in the United States (US), Canada, and internationally. The US deployment of the Xe-100 is funded, in part, through the U.S. Department of Energy's (DOE's) Advanced Reactor Demonstration Program (ARDP). Successful ARDP awardees committed to work towards commercial demonstration of at least one advanced reactor within 7 years of award through a cooperative agreement with DOE (by 2027). X-energy is presently completing preliminary design of the Xe-100 while simultaneously developing an Environmental Report (ER) and a Preliminary Safety Analysis Report (PSAR) as part of an application under Title 10 of the Code of Federal Regulations (CFR), Part 50 for a Construction Permit (CP) for the Xe-100 technology-based project. X-energy is implementing the risk-informed, performance-based (RIPB) licensing basis development approach described in Nuclear Energy Institute (NEI) 18-04 as endorsed by RG 1.233 and clarified in X-energy's licensing topical report on the subject.

This white paper describes the RIPB physical seismic design approach taken by X-energy for the Xe-100. The approach establishes a graded, performance-based seismic design criteria to ensure that structures, systems, and components (SSCs) are designed for the appropriate seismic hazards with adequate strength and serviceability requirements to meet the required performance goals. The performance goals are defined as targeted annual frequencies of exceeding the acceptable performance levels for the SSCs. The acceptable performance levels are described by the limit states (LS) the design intends to achieve for the SSCs. The LS are consistent with the NEI 18-04-defined safety classifications of the SSCs or facility.

The documents cited in the reference section of this report are used to inform the development of the Xe-100 seismic methodologies and are currently managed under the Xe-100 configuration control program for design development and implementation. The objective of the seismic design is to ensure the suitable functioning of SSCs based on the safety classification established under the NEI 18-04 process. For the CP application, the focus is on structures that are safety-related (SR) for the same degree of seismic hazard as postulated for a Seismic Event Design Basis Hazard Level (DBHL).

The purpose of this white paper is to provide the U.S. Nuclear Regulatory Commission (NRC) staff a description of the methodologies used in the following applications for the Xe-100 design and seek feedback on their general acceptability:

- To outline the development of the seismic design basis for the plant SSCs. This includes outlining the seismic categorization and developing representative Design Response Spectra (DRS) curves for each category. (Section 3.1)
- To provide a description of the application of risk-informed, performance-based approach to the development of seismic DRS curves for generic plant design. (Section 3.1)
- To elaborate on the analytical approach for the seismic qualification of the Reactor Building (RB) structure. (Section 3.2)

1.2 Scope

This white paper describes X-energy's approach towards the development of the general seismic response spectra, soil structural interaction (SSI) methods, in-structure response spectra (ISRS) development, and focuses mainly on the Reactor Building (RB) and directly adjacent structures as defined by Principal Design Criteria (PDC) 2, "Design bases for protection against natural phenomena," of the Xe-100 PDC [23], based on Regulatory Guide (RG) 1.232 advanced reactor design criteria, and 10 CFR 50 Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants."

RG 1.233 endorsed NEI 18-04, Revision 1, "Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development," [13] which provides the option of selecting DBHLs either deterministically or probabilistically to establish design requirements. One general category of design requirements flows from the need to protect the safety related structures, systems, and components (SR-SSCs) in the performance of their required safety functions (RSF) from design basis hazards. Each hazard is characterized by a DBHL (e.g., wind speed), as discussed in NEI 18-04 Section 3.2.2, Task 6. It is important to note that the DBHLs go beyond environmental hazards originating external to the plant. The scope of the DBHLs includes external hazards such as seismic events (SEs), wind (including tornados) and wind-generated missiles, external flooding, hazards from external facilities, and internal plant hazards such as internal fires, internal floods, high energy line breaks, and internally generated missiles. These internal plant hazards are frequently described as "area events." Guidance on the scope of hazards found in Chapter 3 of NUREG-0800 (Standard Review Plan for the Review of Safety Analysis Reports (SARs) for Nuclear Power Plants: LWR Edition) is used in the Xe-100 methodology and general licensing approach. The concept is to ensure that hazards with a frequency down to 10^{-4}/plant-year are identified so that design requirements identified in the PSAR for the SR-SSCs to protect them against any DBHL can be specified. Each DBHL may impact one or more reactors as well as non-reactor radioactive sources. These levels are design requirements on the plant capabilities to enable the SR-SSCs to perform their RSFs.

Whether initially selected deterministically or probabilistically, the hazards are addressed in the site-specific probabilistic risk assessment (PRA) and can result in the identification of new licensing basis events (LBEs). When the hazards are addressed in the PRA, the response of the plant to the full frequency spectrum of the hazards will be considered and result in LBEs initiated by hazards that may appear in the anticipated operational occurrences (AOO), design basis events (DBE), and beyond design basis events (BDBE) regions. DBEs caused by a hazard would then be mapped to a corresponding design basis accident (DBA) in which only SR-SSCs would be credited with performing each RSF. DBHLs will be defined before external hazards are incorporated into the PRA with the eventual site-specific PRA ensuring that the DBHLs bound the hazard at 1E-4 for a given site or bounding site. For internal hazards, preliminary DBHLs will be developed with the associated PRA documents. In either case, to be consistent with the NEI 18-04 methodology, there must be sufficient capability in the SR-SSCs to enable the performance of their RSFs following the occurrence of a hazard at the DBHL. The DBHLs will be summarized in the PSAR along with their bases.

X-energy has identified the need for the postulation of seismic DBA based on a review of phenomena associated with pebble bed reactors that the Xe-100 is based upon. Seismic vibrations can cause pebble compaction and an associated reactivity insertion not otherwise bounded by other internal phenomena. The development of seismic DBA is beyond the scope of this white paper and will be presented in the PSAR.

1.2.1 Xe-100 Plant Layout and Overview

The Xe-100 is a 200 MWt pebble-bed, high temperature gas-cooled (HTGR) reactor with online fueling utilizing coated-particle fuel embedded in a 60mm graphite pebble as the fuel element. Figure 1 shows the proposed layout for the Xe-100 site which is placed within an overall site area of 455m by 355m. The site is broken down into two main sections: the Nuclear Island (NI) and the Conventional Island (CI). The NI structures are located within the Protected Area Boundary (PAB) fence, and the CI structures are located outside the fence but within the site boundary. The criteria presented in this document provide the general requirements and guidelines that are to be used for the design bases for the Xe-100 SSCs. The civil and structural design considers such factors as the environmental impact of construction and operation, continuous power generation, and public safety. Design criteria are established based on regulation, regulatory guidance, industry codes and standards, and other requirements as established for each project's jurisdictions. The seismic design criteria are specifically developed to assure continued structural integrity of all safety-related (SR) and Non-Safety Related with Special Treatment (NSRST) structures. The seismic analysis and design for Non-Safety-Related with No Special Treatment (NST) structures are intended to follow International Building Code (IBC) and American Society of Civil Engineers (ASCE) ASCE-7 guidelines. The plant layout in Figure 1 is preliminary and subject to change. It is provided as context for this paper's review.

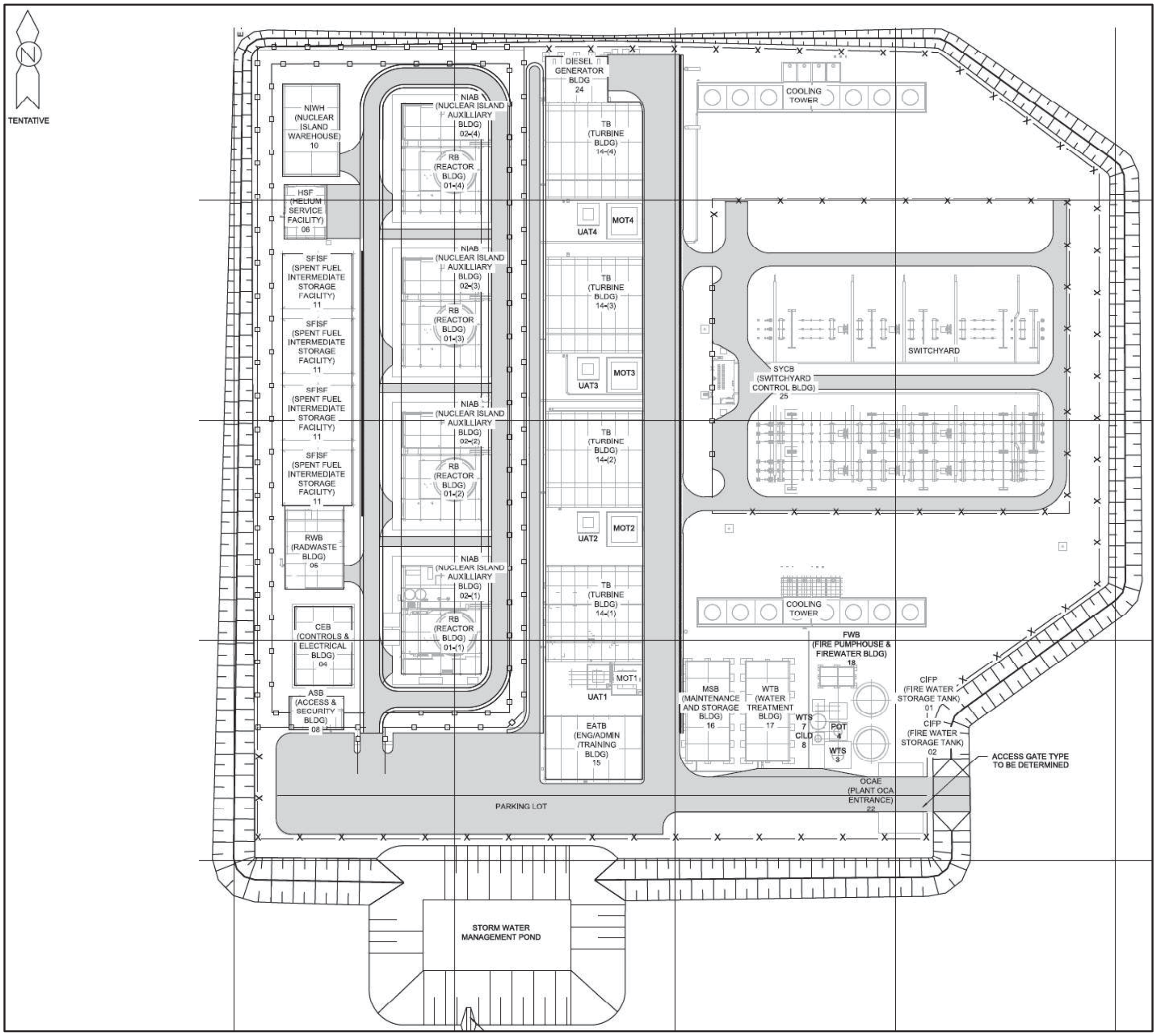

Figure *1*: Xe-100 Site Layout (4-Unit Layout)

1.2.2 Background

The Xe-100 PDC-RFDC 2 establishes the design requirement, “Structures, systems, and components that are required to perform RSFs shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect: (1) Appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena, (3) the importance of the safety functions to be performed." This white paper addresses how the standard plant seismic design criteria have been selected to ensure high confidence that SR-SSCs will perform their required safety functions in accordance with Xe-100 PDC-RFDC 2.

The overall safety design approach taken by X-energy for the Xe-100 is described in Reference [24]. This white paper provides clarification on how that approach is adopted for seismic design considerations.

1.2.3 External Hazards and Component Classification

The SSC safety classification process for the Xe-100 is also described in Reference [24]. This process is iterative with initial classifications informed by the selection of LBEs as informed by the full power internal events (FPIE) PRA. This process includes identification of RSFs (including the function to maintain geometry) and aligns with Xe-100 PDCs 2, 70, and 71, that are aligned with a selected set of SR-SSCs and establish required functional design criteria (RFDC) for them. Design requirements are then established to protect all SR-SSCs from any adverse impacts as a result of DBHLs, in accordance with NEI 18-04 and NEI 21-07. Section 3.1 establishes the methodology of establishing a standard plant seismic DRS which should bound the DBHL for a given site as part of design requirement establishment. Site-specific analysis will be conducted for any Xe-100 project to confirm the site-specific DBHL is bounded by the DRS or provide site-specific detailed analyses as necessary.

The maturing PRA will update the seismic analysis as the design progresses to ensure that seismic challenges are properly addressed and accounted for. In line with NEI 18-04, the risk for seismic hazards will be accounted for in the Frequency-Consequence Curve and appropriately addressed by the integrated decision-making process (IDP).

1.2.4 Relationship to Other Documents

In this document are tags and cross-references that link to Section 6, "Cross Reference and References". This section includes a listing of all associated documentation that is referenced throughout this report. This includes both X-energy documentation and industry standards, codes, requirements, and guides.

2. Definitions

Definitions

Phrase	Definition
Beyond Design Basis Event (BDBE)	Rare event sequences that are not expected to occur in the life of a nuclear power plant, which may include one or more reactor modules, but are less likely than a DBE. Event sequences with mean frequencies of 5×10^{-7}/plant-year to 1×10^{-4}/plant-year are classified as BDBEs. BDBEs take into account the expected response of all SSCs within the plant regardless of safety classification.
Design Response Spectra (DRS)	Site-independent seismic design response spectra used for generic design of the Xe-100 plant SSCs.
Ground Motion Response Spectra (GMRS)	Site-specific ground motion response spectra characterized by horizontal and vertical response spectra determined as free-field motions on the ground surface or as free-field outcrop motions on the uppermost in-situ competent material using performance-based procedures in accordance with RG 1.208.
Frequency-Consequence Target (F-C Target)	A target line on a frequency-consequence chart that is used to evaluate the risk significance of LBEs and to evaluate risk margins that contribute to evidence of adequate Defense-in-Depth (DID).
Foundation Input Response Spectra (FIRS)	When the site-specific GMRS and the site independent DRS are determined at different elevations, the site-specific GMRS need to be transferred to the base elevations of each Seismic Category I foundation. These site-specific GMRS at the foundation levels in the free field are referred to as FIRS and are derived as free-field outcrop spectra.
Licensing Basis Event (LBE)	The entire collection of event sequences considered in the design and licensing basis of the plant, which may include one or more reactors. LBEs include AOOs, DBEs, BDBEs and DBAs.
PRA Safety Function (PSF)	Reactor design-specific SSC functions modeled in a PRA that serve to prevent and/or mitigate a release of radioactive material or to protect one or more barriers to release. In ASME/ANS-Ra-S-1.42013 these are referred to as “safety functions.” The modifier PRA is used in NEI 18-04 to avoid confusion with safety functions performed by SR-SSCs.
Required Functional Design Criteria (RFDC)	Reactor design-specific functional criteria that are necessary and sufficient to meet the Required Safety Functions.
Required Safety Function	A PRA Safety Function that is required to be fulfilled to maintain the consequence of one or more DBEs or the frequency of one or more high-consequence BDBEs inside the F-C Target.
Risk-Significant SSCs	SSCs that perform risk-significant functions which: · Prevent or mitigate any LBE from exceeding the F-C Target o DBEs and BDBEs are already covered under bullets 1 & 2 from Safety-related above o That leaves “SSCs needed to keep the consequences below the AOO limits in the F-C Target, and DBEs where the reliability of the SSCs should be controlled to prevent an increase of frequency into the AOO region with consequences greater than the F-C Target.”
Safety-Related SSCs	SSCs that perform required safety functions which means they are required to do one of the 3 things below: 1. Mitigate the consequences of DBEs to within the LBE F-C Target

Phrase	Definition
	2. Perform RSFs to prevent the frequency of BDBE with consequences greater than the 10 CFR 50.34 dose limits from increasing into the DBE region and beyond the F-C Target 3. Mitigate DBAs that only rely on the SR SSCs to meet the dose limits of 10 CFR 50.34 using conservative assumptions
Safety-Significant SSC	An SSC that performs a function whose performance is necessary to achieve adequate DID or is classified as risk significant.
Uncertainty	Epistemic – lack-of-knowledge Aleatory – “Random” May occur in collected data, input parameters, or within the model. Collected data may be considered either epistemic or aleatory. Parameter within the model or the model itself (Parametric vs. modeling) is explicitly treated as either Epistemic or Aleatory.

3. Discussion

3.1 Xe-100 Seismic Design Bases

The seismic design bases (SDB) for the Xe-100 plant are developed with the objective of being able to site the generic plant at multiple locations within the United States (and the rest of the world) without having to undergo significant design changes. A graded approach is used in developing the seismic design criteria using methods outlined in ASCE standard 43-05 [5] for a performance-based approach to the physical design of SSCs for a nuclear facility. To implement the graded approach for seismic design, ASCE 43-05 [5] tabulates twenty (20) SDBs entities developed as a matrix (see Table 2) of five (5) seismic design categories (SDCs) with a qualitative limit state (LS) goal to demonstrate acceptable structural behavior. Numerical target performance goals are associated with each SDC expressed as the mean annual probability of exceedance at the specified LS for SSCs. The Xe-100 SSCs are assigned to SDCs based on their NEI 18-04-developed safety-significance [13] and relative hazards.

The Xe-100 structures are categorized based on their safety and seismic classifications. The safety classifications are determined based on the risk-informed performance-based guidance provided in NEI 18-04 [13]. The seismic categorization for structures is applied taking into account their safety classification and safety-significant functions. The seismic design basis for Xe-100 structures consists of the following three (3) categories:

1. Seismic Category I: This category is applicable to SR structures, which per requirements in NEI 18-04 [13], are defined as structures that are available to perform their RSF to mitigate the consequences of DBEs to within the LBE frequency-consequence target (F-C Target), and to mitigate the DBAs that only rely on the safety-related structures to meet the dose limits of 10 CFR 50.34 [11]using conservative assumptions.
2. Seismic Category II: This category is applicable to NSRST structures, which are defined as non-safety-related structures relied on to perform risk-significant or other functions requiring special treatment for defense-in-depth adequacy (DID).
3. Seismic Category III: This category is applicable to NST structures, which are defined as non-safety significant.

Safety classifications for NI and CI structures are listed in Table 1 to provide an illustration of the correlation between safety classification and seismic categorization for Xe-100 building structures. For non-structure SSCs, the seismic category guidance above will be considered but is not mandated.

The IDP will determine the necessary seismic category to apply as special treatment based on safety-significance and the LBEs in which the SSC is modeled or credited in.

For the Xe-100 plant design, SR structures and systems designated as Seismic Category I per the IDP are assigned a designation of SDB 5D to indicate the highest pedigree of seismic design and an essentially elastic limit state. NSRST structures and systems designated as Seismic Category II per the IDP are assigned a designation of SDB 3D to indicate a graded reduction in seismic risk hazard level and an essentially elastic limit state. NST SSCs are assigned SDBs 1A through 2B based on the design parameters (i.e., site classification, importance factor, response modification factors, etc.) to be applied per ASCE 7-16 for the type of SSC designed.

Soil profile inputs were developed for the generic plant design to incorporate bounding values for soil properties with the understanding that detailed static and dynamic analyses will be performed for the soil and/or rock properties and profiles for the selected plant site. The generic soil properties used for design are for softer soil and hard rock and are representative of lower and upper bounds of soil stiffness properties.

The development approach for seismic design curves for each category is summarized as follows:

- Develop enveloped broadband bounding curves for Seismic Category I using the ground motion response spectra (GMRS) information available in current literature for existing nuclear plants (e.g., ML14136A126 [2] and NUREG/KM-0017 [3]). These curves represent the horizontal and vertical plant DRS for 5% damping.
- The Seismic Category II curves are developed by evaluating a reduction factor (RF) between the target performance goals for SDC 5 and SDC 3 SSCs. The DRS for performance goal of SDC 3 are calculated per the method outlined in ASCE 43-05 [5] for the sites governing the Seismic Category I envelope. A RF is determined by taking a ratio of the SDC 5 curves with SDC 3 curves for the enveloping site. This RF is then conservatively applied to the enveloped Category I DRS curve to determine the 5% damped Category II curves in both horizontal and vertical directions.
- The Seismic Category III curves are developed using the risk-targeted Maximum Considered Earthquake (MCE_R) maps and procedures outlined in ASCE 7-16.

Table 1: Preliminary Classification of Xe-100 Buildings

Building Name	Safety Classification			Seismic Classification		
	SR	NSRST	NST	Cat. I	Cat. II	Cat. III
Reactor Building (RB)	X			X		
Fuel Handling Annex Building (FHAB)		X			X	
Nuclear Island Auxiliary Building (NIAB)		X			X	
Inter Unit Access Tunnel (IUAT)		X			X	
Radioactive Waste Treatment Building (RWT)			X[1]			X
Helium Storage Facility (HSF)		X			X	
Controls and Electrical Building (CEB)		X			X	
Access and Security Building (ASB)		X			X	

[1] The RWT building is being designed to conform with classification guidance in RG 1.143, and its preliminary classification will be revised once additional hazard analyses confirm the relevant dose consequence estimates for subject events.

Building Name	Safety Classification			Seismic Classification		
	SR	NSRST	NST	Cat. I	Cat. II	Cat. III
Nuclear Island Warehouse (NIW)			X			X
Spent Fuel Intermediate Storage Facility (SFISF)		X			X	
Conventional Island (CI) Buildings			X			X

Table 2: Seismic Design Bases for SSCs in Different SDCs and Limit States (ASCE 43-05)

	Limit State			
	A	**B**	**C**	**D**
	Large Permanent	**Moderate**	**Limited**	
	Distortion	**Permanent**	**Permanent**	**Essentially**
SDC	**(Short of Collapse)**	**Distortion**	**Distortion**	**Elastic**
1	SDB-1A	SDB-1B	SDB-1C	SDB-1D
	ASCE 7	ASCE 7	ASCE 7	NA
2	SDB-2A	SDB-2B	SDB-2C	SDB-2D
	ASCE 7	ASCE 7	NA	NA
3	SDB-3A	SDB-3B	SDB-3C	SDB-3D
	ASCE 43-05	ASCE 43-05	ASCE 43-05	ASCE 43-05
4	SDB-4A	SDB-4B	SDB-4C	SDB-4D
	ASCE 43-05	ASCE 43-05	ASCE 43-05	ASCE 43-05
5	SDB-5A	SDB-5B	SDB-5C	SDB-5D
	ASCE 43-05	ASCE 43-05	ASCE 43-05	ASCE 43-05

Notes:
-NA = Not addressed by ASCE 7.
-Shaded boxes, SDC 1 and 2, not addressed in ASCE 43-05 [5].

Table 3: Summary of Earthquake Design Provisions (ASCE 43-05 [5])

	SDC		
	3	4	5
Target Performance Goal (P_F)	1 x 10^{-4}	4 x 10^{-5}	1 x 10^{-5}
Probability Ratio (R_P)	4	10	10
Hazard exceedance probability (H_D) *($H_D = R_P \times P_F$)*	4 x 10^{-4}	4 x 10^{-4}	1 x 10^{-4}

3.1.1 Regulatory Basis

The following regulations were assessed as applicable to the Xe-100 seismic design and analysis approach:

As part of the Preliminary Safety Analysis Report (PSAR) for an application, 10 CFR 50.34(a)(12) requires that applicants:

> *"who apply for a CP, as partial conformance to General Design Criterion 2 of Appendix A to this part, shall comply with the earthquake engineering criteria in Appendix S to this part."*

10 CFR 50 Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants", requires that SSCs that shall be designed to withstand the effects of the safe-shutdown earthquake (SSE) ground motion or surface deformation are those necessary to assure: (1) the integrity of the reactor coolant pressure boundary, (2) the capability to shut down the reactor and maintain it in a safe-shutdown condition, and (3) the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposures comparable to the guideline exposures of 10 CFR 50.34(a)(1) or 10 CFR 100.11.

For the Xe-100, "the integrity of the reactor coolant pressure boundary" is not directly applicable since helium in the helium pressure boundary can be lost without failing the RSF of controlling heat removal. The Xe-100 PDC-RFDC for residual heat removal (PDC-RFDC 34) states "A passive system to remove residual heat shall be provided. During postulated accidents, the passive system RSF shall provide effective cooling." For the Xe-100 design this RFDC requires a heat removal path from the fuel, through the reactor internals to the Reactor Pressure Vessel (RPV) to the reactor cavity and the Reactivity Cavity Cooling System (RCCS) and atmosphere as the Ultimate Heat Sink (UHS). This criterion shall be met regardless of the primary heat transport system pressure and fluid composition. Therefore item 1 of 10 CFR 50 Appendix S quoted above should only be applicable to the Helium Pressure Boundary (HPB) in-so-far as it pertains to maintaining core geometry.

The Xe-100 PDC-RFDC 16 for functional containment only credits the fuel particles and pebbles (as described in the Xe-100 TRISO-X Pebble Fuel Qualification Methodology topical report [25]) as the barriers credited to perform the RSF of retaining radionuclides. Current analysis suggests the HPB does not need to be credited to meet criteria 3 of 10 CFR 50 Appendix S described above, which will be confirmed in the analyses supporting the CP or other applications. X-energy is providing this information to provide context to the discussion in 3.1 for which SSCs will receive seismic special treatments.

10 CFR 100.23(d)(1) specifies the requirements for defining the safe shutdown earthquake (SSE) ground motion for the site and the need to address resulting uncertainties in the site investigation performed. The purpose of these investigations is to determine the site-specific GMRS and the SSE at the site. The

GMRS is defined as the free-field horizontal and vertical GMRS at the site and must satisfy the requirements of 10 CFR 100.23. The SSE represents the design earthquake ground motion at the site and is the vibratory ground motion for which certain SSCs are designed to remain functional. Seismic Special Treatments for SR-SSCs will ensure these criteria will be met.

The following regulatory guidance documents were evaluated for applicability to the Xe-100 seismic design basis development:

> Regulatory Guide (RG) 1.232, "Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors" describes the NRC's approach to adapt and supplement the 10 CFR 50 Appendix A general design criteria to develop PDC that address two types of non-LWR technologies: sodium cooled fast reactors and Modular High Temperature Gas Cooled Reactors (MHTGRs).
>
> Regulatory Guide (RG) 1.233, "Guidance for a Technology-Inclusive Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors" endorses NEI 18-04 as an acceptable method for identification of LBEs informed by PRA, SSC Classification, special treatment development and as a means to assess DID adequacy. However RG 1.233 does note: "Designers may likewise use the design criteria from RG 1.232 and confirm or refine them throughout the design process to develop the final PDC provided in an application."

X-energy submitted a topical report on the development approach and resulting Xe-100 PDC [23] to demonstrate aligning the guidance in RG 1.232 and RG 1.233. The Xe-100 PDC approach also describes the establishment of preliminary RFDC (for SR-SSCs) and complementary design criteria (CDC) for NSRST-SSCs) following both NEI 18-04 and NEI 21-07.

The MHTGR-DC-2 from RG 1.232 "Design bases for protection against natural phenomena" requires that nuclear power plant SSCs important to safety be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The bases for design of important to safety SSCs is determined by the SSCs' safety functional requirements.

This is refined in the Xe-100 PDC development into a RFDC for SR-SSCs: "Structures, systems, and components that are required to perform RSFs shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect: (1) Appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena, (3) the importance of the safety functions to be performed."

A complimentary design criteria for NSRST-SSCs was also developed: "Structures, systems, and components that are required to perform non-safety-related with special treatment PRA safety functions shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect: (1) Appropriate consideration of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena, (3) the importance of the safety functions to be performed."

As discussed in [24]: “The Xe-100 SSCs that are required to perform RSFs are designed to withstand the effects of Design Basis Hazard Levels (DBHLs) without loss of capability to perform their safety functions or are designed such that their response or failure will be in a safe condition. The SR-SSC design bases reflect appropriate consideration of the most severe of the historical natural phenomena, and include sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated. These will be defined in the [PSAR] as DBHLs. The CDC clarifies that the NSRST-SSCs may not have to withstand DBHLs and their design against hazards will ensure their capability targets identified under the NEI 18-04 IDP shall be met."

The above aligns with the discussion in Section 3.1 of this white paper. The phrase “important to safety” is changed to “safety-significant” to align with NEI 18-04 terminology which applies to both SR and NSRST-SSCs.

NUREG-0800 SRP 3.7.1, Rev. 4 [10] provides regulatory guidance for the development of site design ground motion acceleration response spectra and time histories, as well as the appropriate sections of RGs referenced within that Standard Review Plan (SRP) section.

RG 1.208, “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion,” Revision 0,[1] specifies the performance-based approach in Chapters 1 and 2 of ASCE/SEI 43-05 [5] standard as an acceptable approach for defining the SSE ground motion response spectra (GMRS) that satisfies the requirements of 10 CFR 100.23. The performance-based site-specific SSE spectra is defined based on the results of a site probabilistic seismic hazard analysis (PSHA) following the provisions of Chapter 2 of ASCE/SEI 43-05 [5] standard. Development of the ground motions for a license or permit application’s (SAR) begins with implementation of the provisions of RG 1.208 [18], “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion”. This RG describes acceptable methods to conduct geological, seismological, and geophysical investigations of a proposed site and region around the site, identify and characterize seismic sources, perform a probabilistic seismic hazards analysis (PSHA), perform site response analysis, and determine the GMRS using a performance-based approach.

3.1.2 Development of DRS for Seismic Category I SSCs

The Seismic Category I designation is applicable to an appropriate set of SSCs that are primarily categorized as safety-related as determined by the IDP. The seismic design basis for Xe-100 is developed with the intent of bounding multiple locations within the continental United States and Canada. The DRS curves are developed by enveloping the GMRS for the 64 Central/Eastern United States (CEUS) Nuclear Plants, as well as Palo Verde Generating Station (PVGS), Columbia Generating Station (CGS) which was formerly known as WNP-2, and Darlington Nuclear Power Plant (DNPP) in Ontario, Canada.

The continental United States is approximately 3.13 million Sq. Miles (2,002,990,080 acres) in area. The CEUS western boundary is typically placed along a longitude of 104 to 105 degrees, just along the front of the Rocky Mountain range. This accounts for approximately 1.87 million square miles (1,196,192,000 acres) encompassed by the GMRS curves for the 64 CEUS sites. Treating PVGS as representative of the state of Arizona and CGS as representative of the state of Washington, an additional 185,362 square miles (118,631,680 acres) is encompassed. Therefore, the GMRS curves bounding the 64 CEUS plants, along with PVGS and CGS, encompass approximately 66% of the continental US. Only the GMRS curves for the

Diablo Canyon plant in California are excluded from the enveloped seismic design basis. Thus, the seismic design basis for the Xe-100 plant is inclusive of the seismic response design bases of 97 out of the 99 nuclear plants operational in the continental United States as of May 2017. Figure 4 provides a pictorial view of the overall coverage of Xe-100 seismic design basis. The coverage map may be relaxed in future revisions to possibly remove certain high seismic CEUS sites that would require site-specific analysis should such a location become a candidate site for an Xe-100 project. However, the overall procedure for development of DRS curves and subsequent applications shall remain the same.

The GMRS curves were initially obtained from *"2014-05-21 NRC memo GMRS Curves for Seismic Hazard Reevaluations ML14136A126"* [2], as well as the PVNGS response to the NRC memo. The GMRS curves for CGS were obtained from the Seismic Hazard evaluation performed in Columbia Generating Station Docket No. 50-397 [7]. Recently NRC published NUREG/KM-0017 *"Seismic Hazard Evaluations for U.S. Nuclear Power Plants"* [3] which represents the current best knowledge and practices for characterizing the site-specific seismic hazards for each nuclear power plant in the United States. The GMRS curves from this document were compared against the 2014 NRC memo and checked for exceedances. The variations between the new database of GMRS curves, especially for the bounding sites, to the developed seismic design basis enveloped DRS curve were found to be minimal and were ignored for the purposes of creation of DRS curves.

3.1.3 Procedure for Development of Enveloped GMRS Curves

The Xe-100 design basis DRS curves are site-independent seismic design response spectra curves developed for the standard plant design. The DRS for the Xe-100 plant design envelopes the GMRS curves for the (i) 64 CEUS operating nuclear plant fleet, (ii) Palo Verde Generating Station, (iii) Columbia Generating Station, and (iv) Darlington Nuclear Power Plant (DNPP) UHRS (For hazard exceedance return period of 10^{-4}).

The 5% damped horizontal enveloped DRS curve is generated using the GMRS curves outlined in References 2 and 3 which are then enveloped as shown in Figure 2. Only the 5% damped plots are presented here for ease of review and comparison. Additionally, these curves are also compared to the response spectra from RG 1.60, Rev. 2, [19] anchored to a ZPA of 0.3g's to demonstrate compliance. The NRC staff has used the RG 1.60, Rev. 0 version of the response spectra for numerous siting and licensing activities since its initial publication and it has also been used effectively by both domestic and international stakeholders. It forms part of the licensing basis for nuclear power plants constructed during the 1970s and 1980s. Although RG 1.60 is no longer used to characterize the hazard for the seismic design of nuclear power plants, the DRS for several new reactor designs are derived from RG 1.60 spectra with modified control points to broaden the spectra in the higher frequency range. Specifically, the RG 1.60 spectral values are based on deterministic values for Western United States earthquakes and provides higher acceleration values in the lower frequency ranges (i.e., <10 Hz).

The proposed DRS provides robust coverage, especially in the high frequency zone, up to 100 Hz with a ZPA of 0.6 g's. An evaluation of the GMRS curves has determined that the enveloping curves were controlled by seven sites. The controlling sites included: H.B. Robinson, North Anna, Catawba Units 1 & 2, VC Summer, Columbia Generating Station, Pilgrim, and Indian Point. Figure 2 provides the enveloped horizontal 5% damped DRS curve for the design of Seismic Category I SSCs.

Vertical DRS are typically developed using site specific Vertical-to-Horizontal (V/H) spectral ratios. For the purpose development of generic DRS that envelopes multiple sites, a representative set of V/H ratios are used, which are consistently applied to all plants that form the envelop. This approach is followed for all plants with the exception of those for which vertical GMRS was available from plant licensing documents. See Table 4 for V/H spectral ratios used for vertical DRS generation. Figure 3 provides the enveloped vertical 5% damped DRS curve for the design of Seismic Category I SSCs.

Table 4: V/H Ratios for Vertical DRS

Frequency (Hz)	V/H Spectral Ratio
$0 \le f \le 7.3$	0.83
$7.3 \le f \le 7.5$	0.85
$7.5 \le f \le 10.0$	1.00
$10.0 \le f \le 100$	1.10

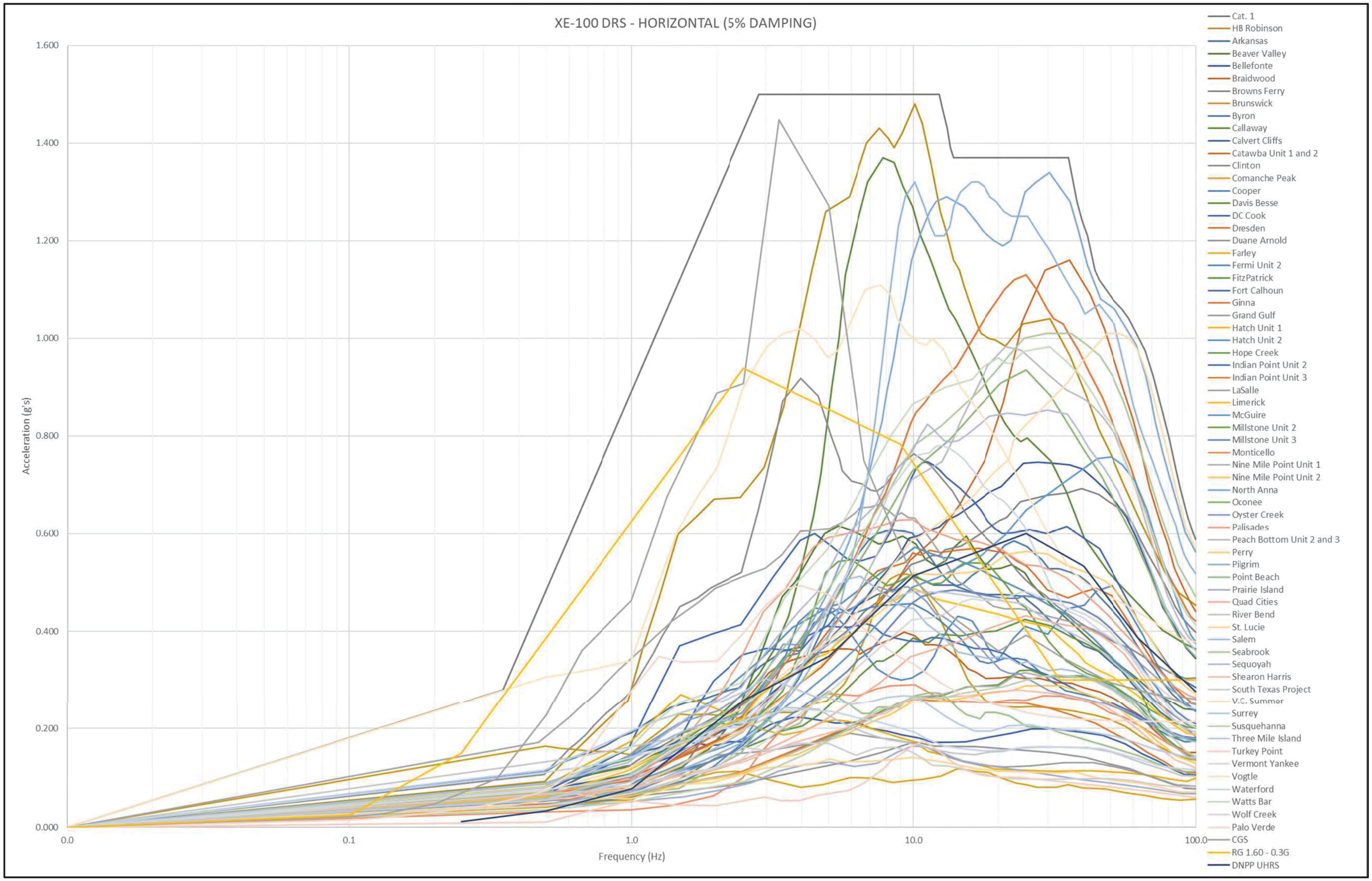

Figure *2*: Xe-100 Horizontal DRS Curve Envelope – 5% Damping

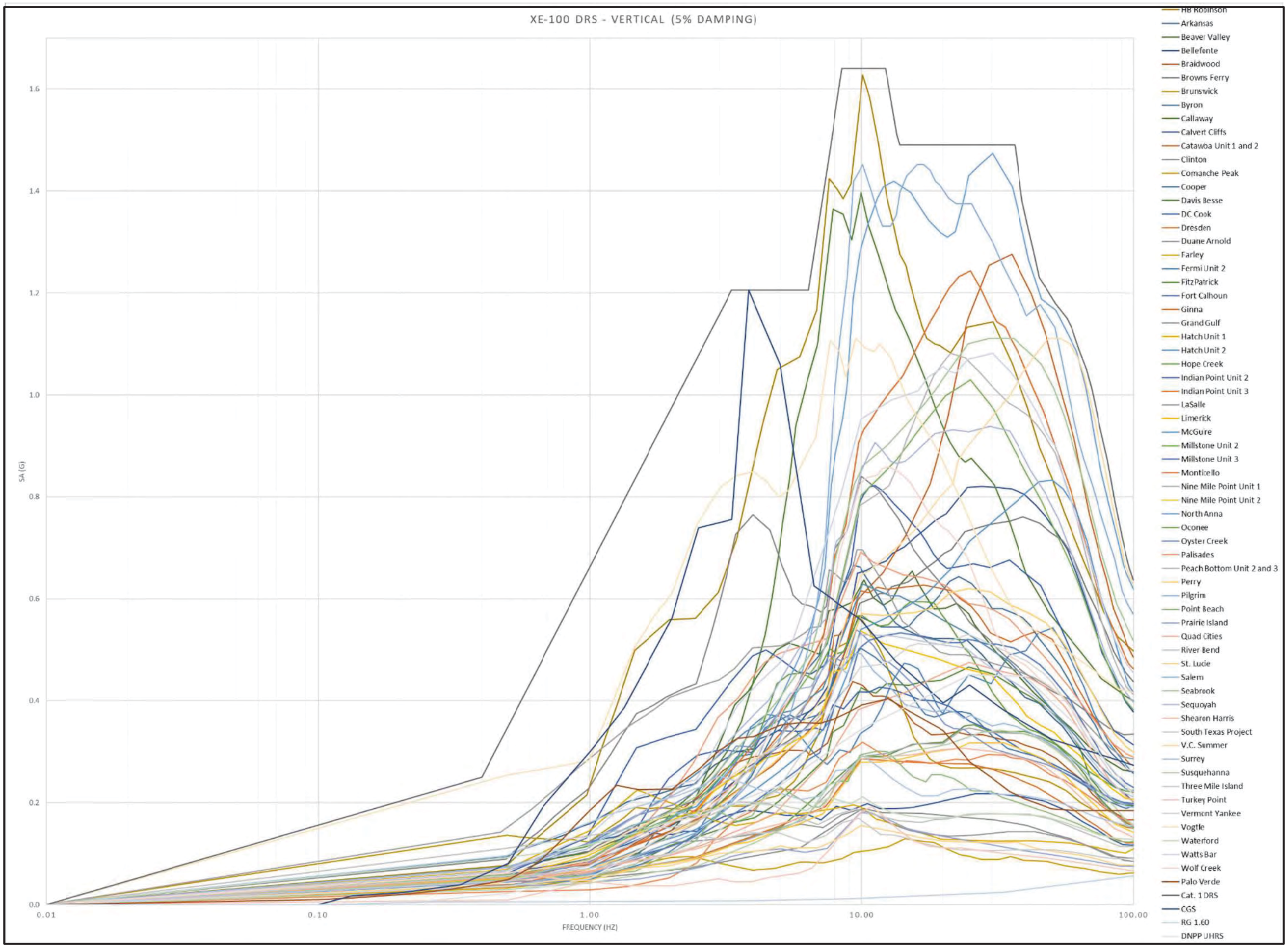

Figure 3: Xe-100 Vertical DRS Curve Envelope – 5% Damping

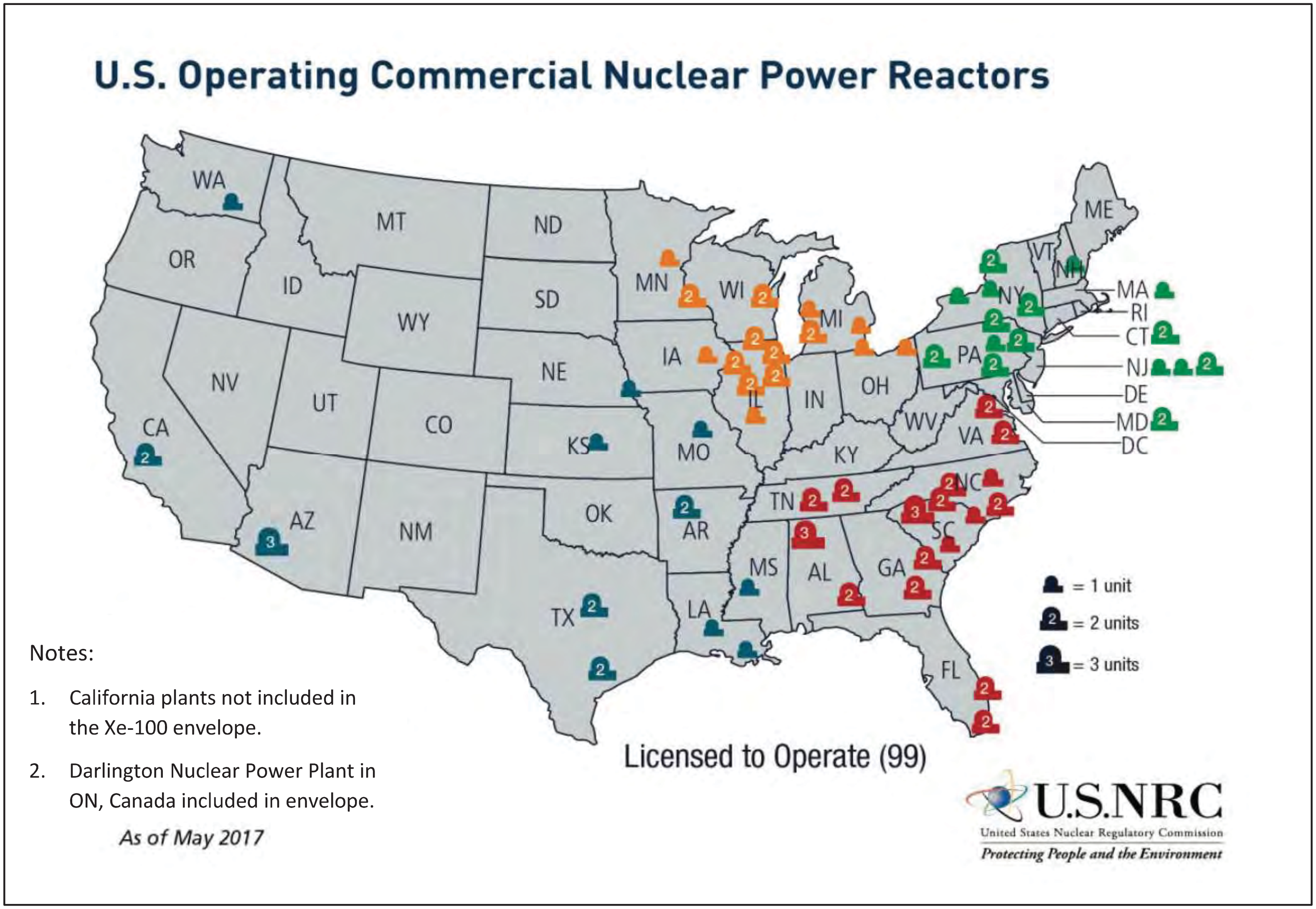

Figure 4: Sites Included in Xe-100 Envelope

3.1.4 Soil Profiles

Bounding soil profiles for the development of soil properties and subsequently to be used for SSI analyses are outlined in this section. It is not technically feasible to generically envelope all possible sites for the placement of the Xe-100. Hence profiles corresponding to a relatively soft soil and hard rock are chosen to generically bound the seismic design basis for the Xe-100 plant. The conceptual design for the plant was performed using the two site-specific soil profiles for CGS and DNPP as these are deemed to be representative of soft soil and hard rock cases thus providing adequate coverage for the broadband design curve. These soil profiles may be modified as deemed necessary to account for site excavation and construction methods.

The CGS soil shear wave velocity profile is shown in Figure 5. It represents the lower bound of soil stiffness and demonstrates a gradually increasing stiffness profile with increased depth. The shear wave velocities vary between 500 ft/s at the surface to approximately 2000 ft/s at 100 ft depth and increases to 5000 ft/s at 115 ft depth (RB basemat elevation). The DNPP soil shear wave velocity profile is shown in Figure 6. It represents the upper bound of soil stiffness and shows a steady soil/rock stiffness of approximately 7000 ft/s from 5-10 ft below grade to well below the RB basemat elevation.

The approach for Xe-100 generic plant design varies from that of most recent new plant designs in that only two bounding sites are chosen along with broadband DRS. Design certification applications in the recent past have used multiple soil profiles with design motions that approximately match the frequency content of the chosen soil profile. This results in several analyses cases pairing matching soil profiles with input motions. However, since the Xe-100 DRS curve provides broadband coverage with high seismic content ranging from 1 Hz – 100 Hz, coupled with a ZPA of 0.6 g's, the application of two soil profiles, representing upper and lower bound frequency content, is deemed to be sufficiently robust for the generic design and performance evaluation of plant SSCs.

3.1.5 DRS Development for Seismic Category II SSCs

The seismic category II designation is applicable to an appropriate set of SSCs that are primarily categorized as NSRST as determined by the IDP. The enveloped response spectra for this category of SSCs are developed for a seismic hazard exceedance probability of $4x10^{-4}$ or SDC-3 (Seismic Design Category 3) per Table 1-2 of ASCE 43-05 [5] which is derived using a Target Performance Goal (P_F) of 1×10^{-4} and a Probability Ratio of 4. Limit State D is chosen for these structures to allow them to remain essentially elastic post-accident since SSCs in this category are not required to perform RSFs during a SE.

The DRS for Seismic Category II SSCs are developed by applying a RF to the Seismic Category I DRS. The Seismic Category I DRS is primarily driven by responses for a handful of governing sites: namely Callaway Energy Center (CEC), Columbia Generating Station (CGS), North Anna Power Station (NAPS), and HB Robinson Steam Electric Station (HBRSES). The seismic hazards and screening reports developed for these sites provide the mean and fractile seismic hazard curves for frequencies of interest. The uniform hazard response spectral (UHRS) accelerations are interpolated for a mean hazard frequency of $4x10^{-4}$ and $4x10^{-5}$ from the tables available in these reports to compile the UHRS for each of the governing plants for 5% damping. The procedure outlined in Section 2.2 of ASCE 43-05 [5] is then used to determine the design factor and the DRS for Seismic Category II SSCs. The DRS thus developed is for a hazard exceedance probability (H_D) of $4x10^{-4}$ for SDC-3 and is defined at the same control location in the free field as that at which the hazard curve and UHRS are defined. The RF is then determined by taking a ratio of the site specific GMRS to the SDC-3 hazard curve. Based on the evaluations performed for CGS, CEC, NAPS, and

HBRSES site locations, the least RF value obtained from the ratio of the plant specific GMRS to the $4x10^{-4}$ mean hazard is 1.94. This factor is conservatively reduced to 1.5 and applied to the enveloping Seismic Category I DRS curves to derive the DRS curves for Seismic Category II SSCs. The horizontal and vertical 5% damped curves for the Cat. II DRS are shown in Figure 7 & Figure 8 respectively. As indicated in previous discussions, the Seismic Category II DRS acceleration magnitudes are 1.5 times lower than those of Seismic Category I DRS.

3.1.6 DRS Development for Seismic Category III SSCs

The seismic category III designation is primarily applicable to SSCs that are categorized as NST. The enveloped response spectra for this categorization of SSCs are developed based on procedures outlined in ASCE 7-16, Section 11.4. The mapped parameters selected for the development of the DRS curves envelope all regions within the continental U.S. with the exception of coastal California and areas in close vicinity to the New Madrid fault line. The DRS acceleration values are obtained from the USGS Risk-Targeted MCE_R maps in Section 22 of ASCE 7-16. The MCE_R response spectrum derived per Section 11.4.7 of ASCE 7-16 is used for both horizontal and vertical directions. Per Section 11.9 of ASCE 7-16 vertical ground motions can be reduced but for the purposes of development of Seismic Category III DRS it is kept the same as the horizontal direction.

The seismic evaluations for Seismic Category III SSCs may be performed using the Equivalent Lateral Force or Linear Dynamic Analysis approach outlined in Chapter 12 of ASCE 7-16. For SSCs designed using Linear Dynamic Analysis approach, seismic excitations are applied simultaneously in three directions. The parameters used for the development of Seismic Category III DRS to be used in conjunction with the Modal Response Spectrum Analysis method are listed below. The DRS is generated using a response modification factor “R” of 4.0 paired with an importance factor of 1.5. Per Table 12.2-1 of ASCE 7-16 an “R” value of 4 is deemed sufficiently conservative for the type of seismic force resisting systems typically used for NST structures designed using the Linear Dynamic Analyses methods. The DRS curves for design of Seismic Category III curves for horizontal and vertical 5% damping are displayed in Figure 7 and Figure 8 respectively.

Seismic Site Parameters for Development of Category III DRS

- Site Classification = D (Stiff soil)
- S_S = 1.50g (Mapped short period acceleration for generic site and 5% damping)
- S_1 = 0.75g (Mapped acceleration for period of 1s for generic site and 5% damping)
- F_a = 1.60 (short period site coefficient at 0.2s conservatively used for Site Class D)
- F_v = 2.40 (long period site coefficient at 1.0s conservatively used for Site Class D)
- R = 4.00 (response modification factor used for Seismic Cat. III structures)
- I_e = 1.50 (Importance factor used for Risk Category IV structures)
- $S_{MS} = F_a * S_S = 2.4g$
- $S_{M1} = F_v * S_1 = 1.8g$
- $S_{DS} = (2/3) * S_{MS} = 1.6g$
- $S_{D1} = (2/3) * S_{M1} = 1.2g$

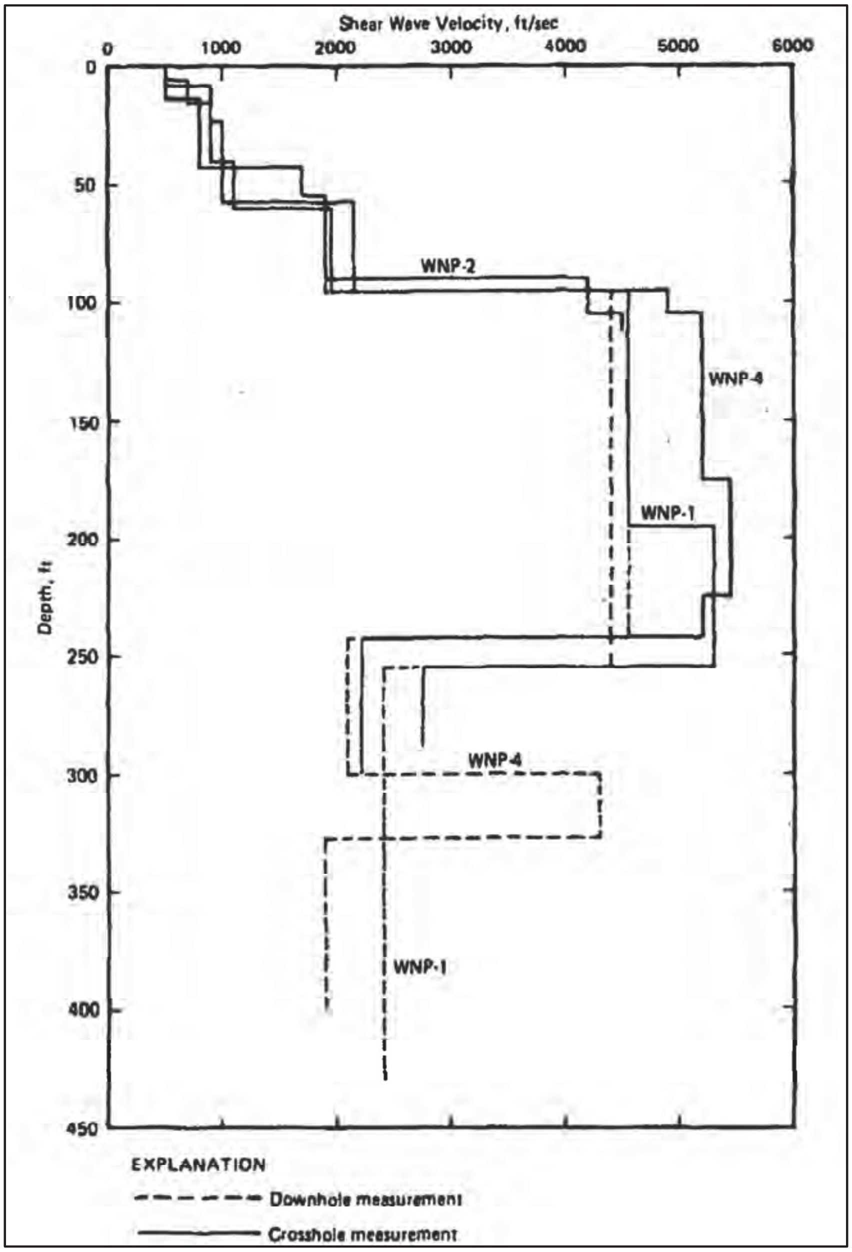

Figure *5*: CGS Soil Profile - Shear Wave Velocities (Soft Soil Case)

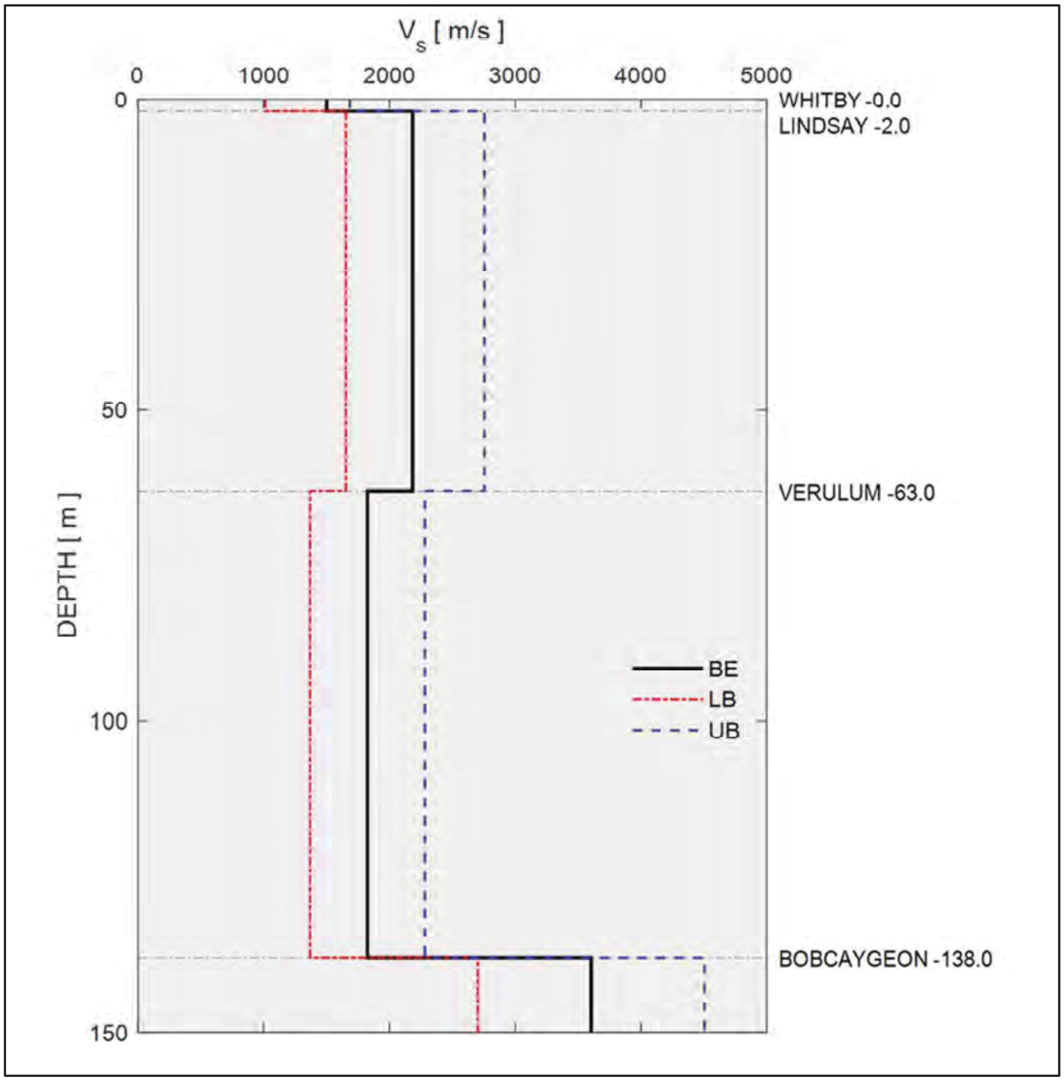

Figure *6*: DNPP Soil Profile – Shear Wave Velocities (Hard Rock Case)

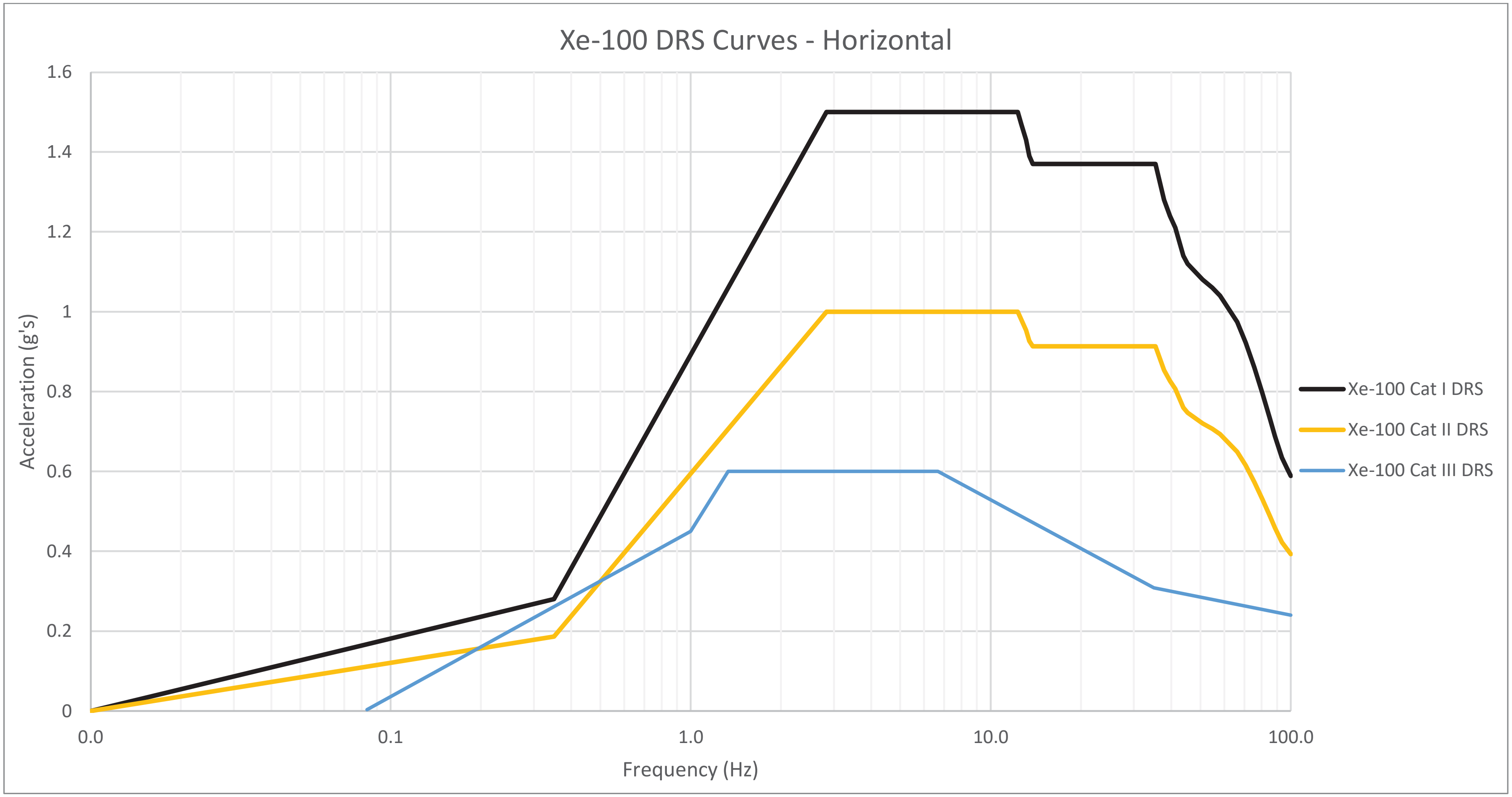

Figure 7: Xe-100 DRS Curves – Horizontal 5% Damping

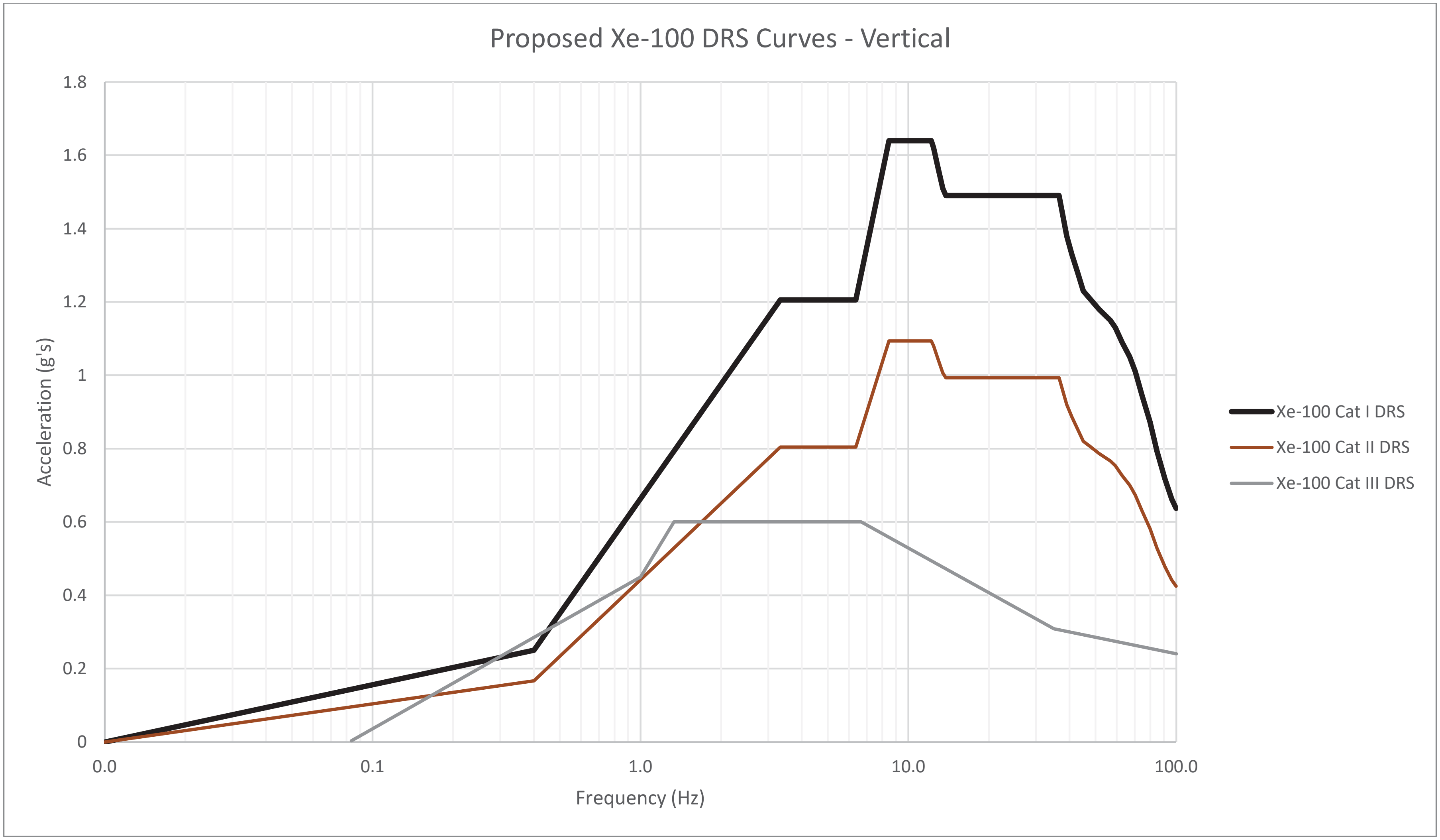

Figure *8*: Xe-100 DRS Curves – Vertical 5% Damping

3.2 Reactor Building Seismic Analysis Approach

The RB is a cylindrical shaped steel-concrete building with an outer diameter of 19.0m. The above grade building height is 10.5m and the foundation depth is -35.0m. While not expected to significantly change, these parameters may change as the design maturity progresses or site-specific considerations warrant.

The seismic analysis of the Xe-100 RB will be performed to develop design basis floor response spectra (FRS) and members forces for component and structural design. For response analysis of SR buildings, X-energy will follow the guidance in NUREG-0800 for LWRs and accepted industry analysis methods as described below.

3.2.1 Regulatory Basis for Seismic Analysis

The regulatory basis for the design of the Xe-100 RB was described in Section 3.1.1. The selection of seismic design parameters will be consistent with NUREG-0800 Section 3.7.1 [10] and seismic analysis will be performed in accordance with NUREG-0800 Section 3.7.2 [14]. A postulated Seismic Event (SE) is a DBHL that specifies design basis earthquake parameters such as safe shutdown earthquake peak ground acceleration, design response spectra, damping values, time histories, etc.

3.2.2 Regulatory Guidance for Seismic Analysis

Regulatory guidance and acceptance criteria for the Xe-100 RB seismic design will be referenced from relevant NUREG-0800 seismic sections as well as industry guidance on advanced reactors (e.g., NEI-18-04 [13]). In accordance with Reference [13], design criteria will be applied along with associated special treatments to ensure that SSC performance is acceptable during LBEs. That includes the DBA resulting from the seismic DBHL for a given site which should be bounded by the Seismic Class I hazard described in 3.1.2. Key guidance documents used in the development of the seismic analysis approach include:

a. USNRC Regulatory Guide 1.61, Rev. 1, “Damping Values for Seismic Design of Nuclear Power Plants”, 2007 [15]

b. USNRC Regulatory Guide 1.92, Rev. 3, “Combining Modal Responses and Spatial Components in Seismic Response Analysis”, 2012 [16]

c. USNRC Regulatory Guide 1.122, Rev. 1, “Development of Floor Response Spectra for Seismic Design of Floor-Supported Equipment or Components”, 1978 [17]

d. USNRC Regulatory Guide 1.208, Rev. 0, “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion”, 2007 [18]

e. NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants”

   1. Chapter 3.7.1, Rev. 4, “Seismic Design Parameters”, 2014 [10]

   2. Chapter 3.7.2, Rev. 4, “Seismic System Analysis”, 2013 [14]

f. NEI 18-04, “Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development”, 2019 [13]

g. NEI 21-07, "Technology Inclusive Guidance for Non-Light Water Reactors: Safety Analysis Report Content for Applicants Using the NEI 18-04 Methodology", 2022.[26]

3.2.3 Use of Computer Codes

The computer codes used to support the Xe-100 RB seismic design satisfy 10 CFR 50 Appendix B 'Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants' through NQA-1-based quality procedures for safety-related design software. These procedures address verification and validation in accordance with NRC requirements and guidance. In addition, the analysis codes associated with the software will be qualified for range of applicability relating to the Xe-100 application and will specifically focus on qualification of coding that is necessary for evaluation and output of results for the Xe-100 RB.

Evaluation of SSCs via Structural Modeling:

SSI and structural models are adequately refined to sufficiently capture the high frequency (HF) content of the horizontal and vertical GMRS/FIRS in the structural response. The range of HF to be transmitted covers a model refinement frequency at least equal to 50 Hz. The subsequent ISRS computed using a refined model contains spectral responses up to 100 Hz.

The criterion for structural model refinement to ensure fidelity of response at least up to 50 Hz also applies to all Seismic Category I structures included in a potential subsequent application for site specific conditions that may be found to be outside referenced generic and standardized Xe-100 RB design parameters.

The structural model captures the increased rotational and torsional components that would result from the inclusion of ground motion incoherency in the analysis. The procedure used to generate the ISRS will follow the procedure used in the generic design. Deviations from the procedure may be acceptable if adequate justifications are provided.

3.2.4 Seismic Design Parameters

3.2.4.1 Safe Shutdown Earthquake SSE

The Xe-100 DRS is defined in Section 3.1.2. Grade elevation is the control point location used to compare the DRS to a site-specific GMRS and for dynamic analysis of the RB. For seismic analysis, ground motions are deconvolved to the foundation elevation of the RB (-35.0m).

3.2.4.2 Critical Damping Values

The percentage of critical damping values in the analyses of SSCs are based on Reg. Guide 1.61 [15]. As the Xe-100 DRS is based upon a generic site PGA of 0.6g, it is expected that some portions of the RB structure will have higher critical damping values. On this basis, DRS-level damping for the RB structure will be assumed for seismic analysis. For the reinforced concrete structures (including steel plate composite (SC) members), 7-percent structural damping will be used.

3.2.4.3 Design Time Histories

The design ground motion time histories for the Xe-100 RB consist of three mutually orthogonal artificial ground motions (two horizontal and one vertical) generated from the DRS. The responses from the three components of motion are calculated simultaneously, and each component is statistically independent of the other two. They are developed meeting the guidance in NUREG-0800 3.7.1 Section II.1.B [10], and the criteria in Reg. Guide 1.208 Appendix F [18].

As the RB seismic analysis will involve nonlinear soil behavior, multiple sets of time histories will be used. The response spectra calculated for each individual time history may not envelope the DRS. However, the multiple time histories are considered acceptable if the average calculated response spectra generated from these time histories envelope the DRS. The developed time histories will meet the requirements of Option 2 of NUREG-0800 3.7.1 Section II.1.B [10].

The duration of the ground motion will be least 20 seconds and have a strong ground motion phase greater than 6 seconds.

3.2.5 Analysis Methods

The seismic analysis of the Xe-100 RB will be performed by a combination of time history and response spectrum analysis methods as described below.

3.2.5.1 Time History Method

The time history analysis method will be used to develop the ISRS for the RB. For secondary systems and subsystems that are analyzed by time history methods, time history seismic inputs will be developed at the point of attachment. The input will consider the range of site soil conditions for the postulated site locations and include a sufficient number of independent sets to account for variability in the system.

When calculating the response of the RB structures and systems (e.g., accelerations, member forces, and displacements) from non-linear analyses using multiple time histories, the average value of the responses from the multiple time histories will be used provided that the minimum number of required time history analyses are performed. Otherwise, the maximum (envelope) will be used.

3.2.5.2 Modal Response Spectrum

The modal response spectrum method will be used to develop RB member forces and moments. This evaluation will involve a fixed-base model of the RB with seismic input being the envelope of the basemat ISRS for both soil cases. For this analysis, modal responses of low frequency modes will be combined by one of the RG 1.92 [16] methods. For the seismic response spectrum analysis, the zero-period acceleration (ZPA) cut-off frequency is 50 Hz. High frequency or rigid modes will be considered using the method described in regulatory guidance.

3.2.6 Three Components of Earthquake Motion

For the RB seismic analysis, NRC RG 1.92 [16] will be utilized. RG 1.92 describes acceptable methods for combining the responses due to three components of design ground motion, for both the response spectrum method and the time history method.

3.2.6.1 Response Spectrum Method

For the RB response spectrum analysis, the representative maximum earthquake-induced response of interest in an SSC will be obtained by the square root of the sum of the squares combination of the maximum representative responses from the three earthquake components calculated separately.

As an alternative, the 100-40-40 percent combination rule may be used in lieu of the SRSS method. Combinations of seismic responses from the three earthquake components, together with variations in sign (plus or minus), will be considered.

3.2.6.2 Time History Method

For the time history analysis of the RB, when each of the three spatial components are calculated separately, the maximum response of interest of an SSC will be obtained by taking the SRSS of the maximum responses from the individual time history analysis for each of the three earthquake components.

If the three components of earthquake motion are statistically independent, the maximum response of interest of an SSC will be obtained from algebraic summation of the three individual component responses at each time step.

When the effect of all three components of earthquake motion is calculated simultaneously in a single dynamic analysis, algebraic summation is automatically achieved.

3.2.7 Soil Structure Interaction

SSI analysis for the Xe-100 RB will be performed in accordance with NUREG-0800 Sections 3.7.1 [10] and 3.7.2 [14].

The SSI analysis will account for all SSI effects for embedded structures. SSI effects shall be considered for all structures not supported by a rock (shear wave velocity at 9,200 ft/s) or rock-like soil foundation material. The RB structure, foundation, and soil will be properly modelled to ensure that the results of the analyses correctly capture spatial variation of ground motion, three dimensional effects of radiation damping, soil layering, and well as non-linear effects from site response analyses (e.g., sliding and gapping). For structures founded on materials having a shear wave velocity of 9,200 ft/s or higher under the entire surface of the foundation, a fixed-base assumption is acceptable.

The seismic input motions to the RB SSI analyses will be placed at the free ground surface. The SSI analysis will deconvolve the surface motion to the foundation soil-structure interface. The RB foundation level input motion, or Foundation Input Response Spectra (FIRS), will be compared with relevant regulatory criteria.

The RB SSI analyses of a particular site will account for the effects of the potential variability in the properties of the soil. Three soil profiles corresponding to best estimate, lower bound, and upper bound determined at the mean and ±1 standard deviation velocity/damping profiles shall be considered in the analysis.

3.2.7.1 SSI Modelling

The RB SSI model will adequately incorporate the stiffness, mass, and damping characteristics of the RB structure or secondary system. The size of the RB dynamic model will be sufficiently refined to have an adequate number of masses or degrees of freedom for computing responses of SSCs. The size of the surrounding soil domain will be adequate to ensure proper function of the LS-DYNA SSI analysis code, as discussed in Section 3.2.7.3.

Solid / shell finite element models allow modelling of systems or equipment in a more precise way. The element mesh size will be selected on the basis that further refinement has only a negligible effect on the solution results. The analysis model will be considered adequate provided that additional degrees-of-freedom do not result in more than a 10 percent increase in response or the number of degrees of freedom equals or exceeds twice the number of modes with frequencies less than 50 Hz.

Seismic subsystems can be coupled to the overall dynamic model. The criteria used for decoupling seismic subsystems are in accordance with Section II.3.B of NUREG-0800 3.7.2 [14]. If a component or subsystem is rigid compared to the supporting system, and it is also rigidly connected to the supporting system, then it will be idealized as a concentrated mass at the support point in the model.

3.2.7.2 Lumped-Mass Stick Model

Lumped mass and beam models will be used to discretize large Xe-100 secondary systems (e.g., RPV and Steam Generator) as well as buildings adjacent to the RB in seismic interaction analysis. For these lumped-mass and beam models, the eccentricities between the centroid (the neutral axis for axial and bending deformation), the center of rigidity (the neutral axis for shear and torsional deformation), and the center of mass of structures/components will be included in the seismic model.

Nodes will be located at mass concentrations and at additional points within the system. They will be selected in such a way as to provide an adequate representation of the mass distribution and high-stress concentration points of the system and satisfy the acceptance criteria given in Subsection II.1.A.iv of NUREG-0800 3.7. Floor response for the RB will be developed for key building and component locations. The methods for enveloping and broadening will be referenced from SRP Section 3.7.2 [14].

3.2.7.3 SSI Analysis Code

SSI of the RB will be performed using the LS-DYNA FEA code. LS-DYNA is a general purpose finite element analysis code, capable of modeling nonlinear material behavior and large deformations. LS-DYNA solves SSI analysis problems using the effective seismic input method (ESIM). The ESIM is used to incorporate forces into the SSI model using only the free-field ground motion at the soil-structure interface. The unbounded soil domain is modeled using perfectly matched layers, which absorb the outward propagating waves. The LS-DYNA code has been used for safety-related calculations and shall be verified and validated with a commercial grade dedication of the software per NQA-1 requirements in accordance with Westinghouse Quality Assurance procedures. An effort to qualify LS-DYNA for soil-structure interaction parameters in a range consistent with those considered by the Xe-100 design is ongoing and described in Section 3.2.7.4.

Current RB seismic analysis efforts are focusing on a coarse building model to allow for faster model run times and shakedown efforts. The reactor vessel and steam generator subsystems are idealized as lumped parameter models within the building model (Figure 9). The coarse building model is sufficient for capturing significant building response modes. As the modelling effort progresses, a more refined building model will be utilized. Structural materials, such as reinforced concrete and SC) walls, will be modeled as cracked members, commensurate with the level of stress. As discussed in Section 3.2.4.2 of this report, structural damping of the reinforced concrete RB will be commensurate with SSE level response, or 7 percent, from Reg. Guide 1.61 [15]. Variations in levels of concrete material cracking will be evaluated by performing seismic analysis for both uncracked and partially cracked cases. The level of partial cracking will be evaluated consistent with NUREG-0800 Section 3.7.2 [14].

The SSI model will be idealized in LS-DYNA assuming a layered site. The building model will be embedded in a soil continuum and contact elements will be used at the soil-structure interface (Figure 10). Soil material will be modelled in LS-DYNA using a nonlinear hysteretic material model.

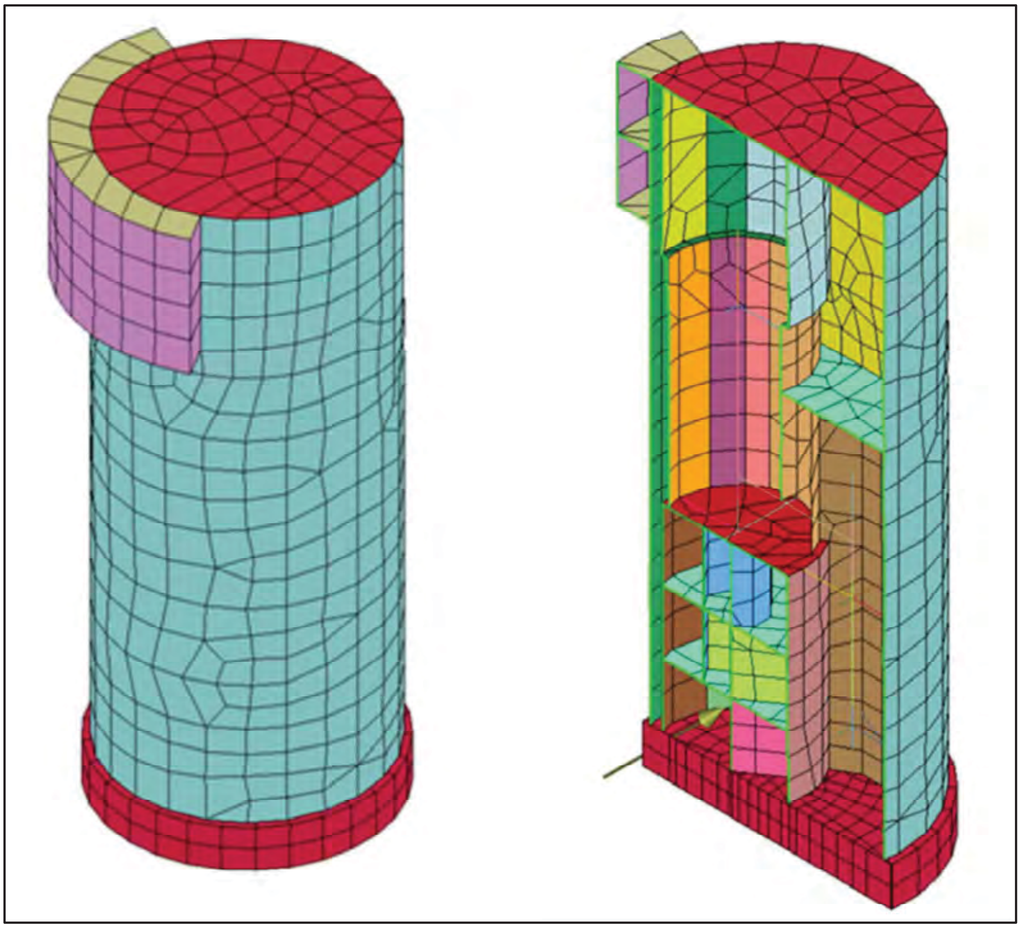

Figure *9*: Coarse FEA Model of Xe-100 Reactor Building

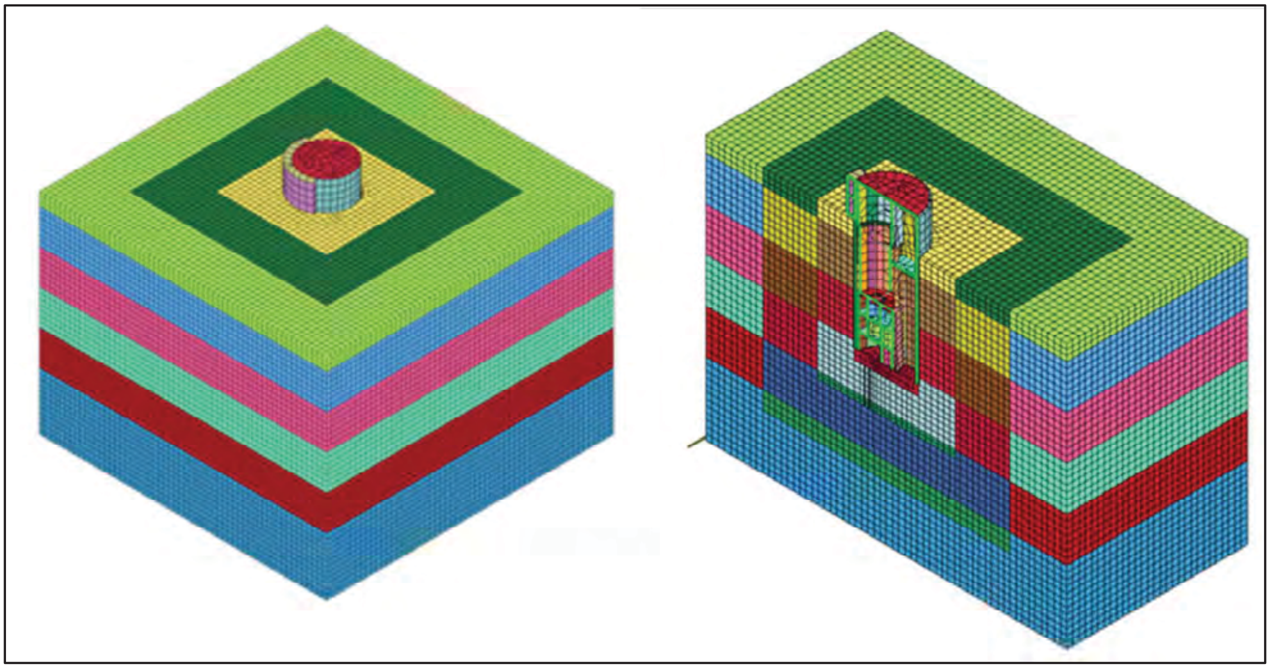

Figure *10*: LS-Dyna SSI Model (Section View on Right)

3.2.7.4 SSI Validation

The LS-DYNA code has been used to perform SSI evaluations of large civil structures (e.g., Morrow Point Dam) as well as other critical structures in published literature. To ensure the validity of the LS-DYNA code for analyzing SSI response of the Xe-100 RB, two validation problems have been evaluated. The problems involve a surface founded containment structure (Figure 11 and Figure 12) and a deeply-embedded representative RB (Figure 13). LS-DYNA and SASSI models were developed for each validation problem and results were compared. For the surface-founded model, the LS-DYNA and SASSI model results compared well. Comparisons of spectral acceleration and response spectra plots are shown in Figure 12 below. Similarly, for the deeply-embedded validation problem, the LS-DYNA overall building response for a representative RB compared well with SASSI. Comparisons of both deeply-embedded models are shown in Figure 14.

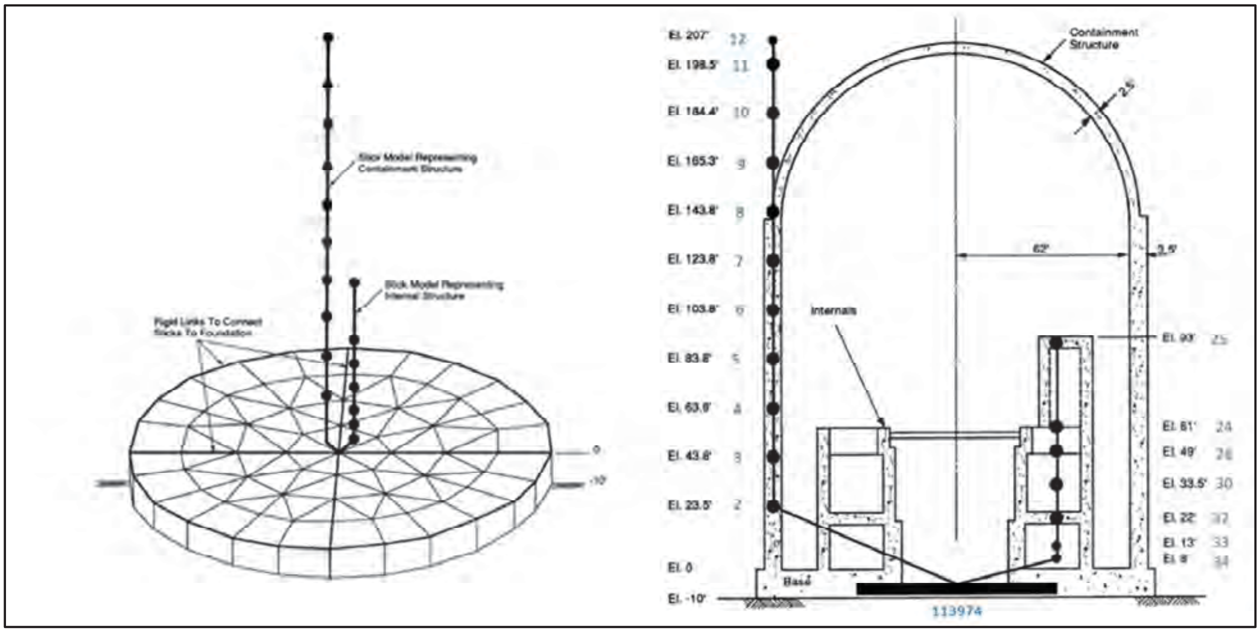

Figure *11*: Validation Problem for a Surface Founded Structure

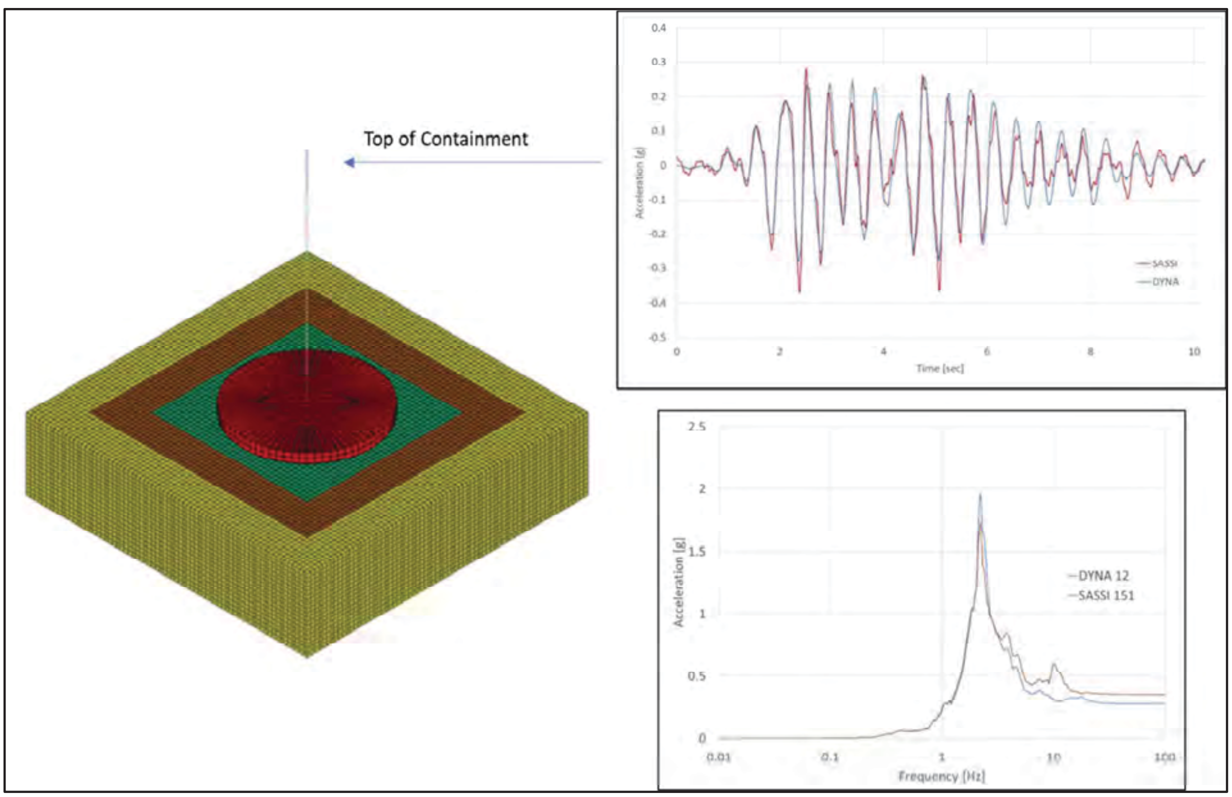

Figure *12*: LS-DYNA Results Comparison to SASSI (Top of Containment)

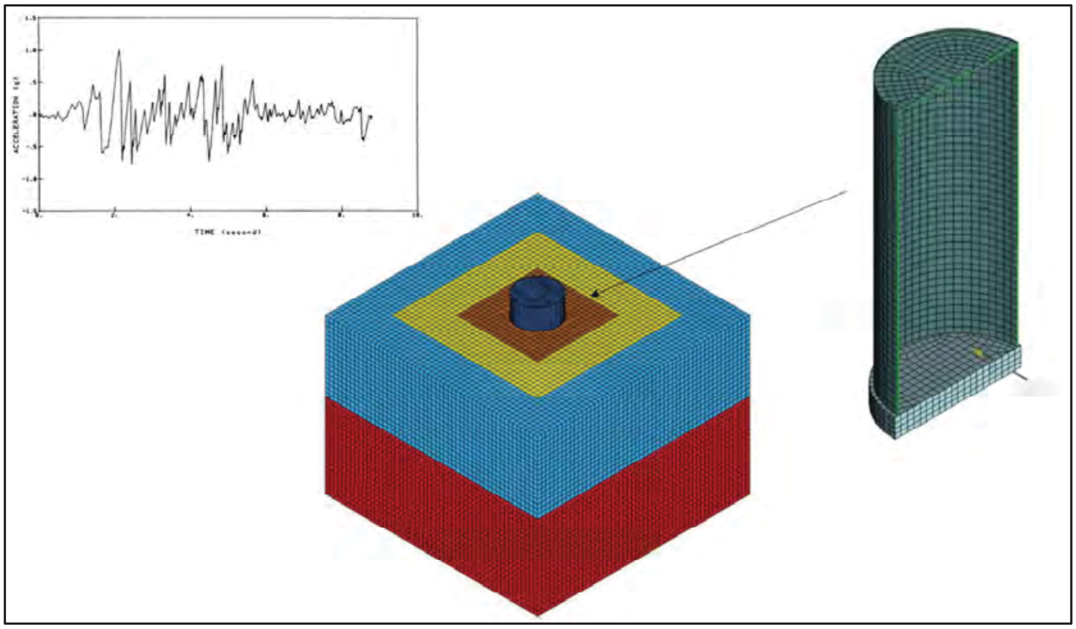

Figure *13*: LS-DYNA Embedded Foundation Validation Problem

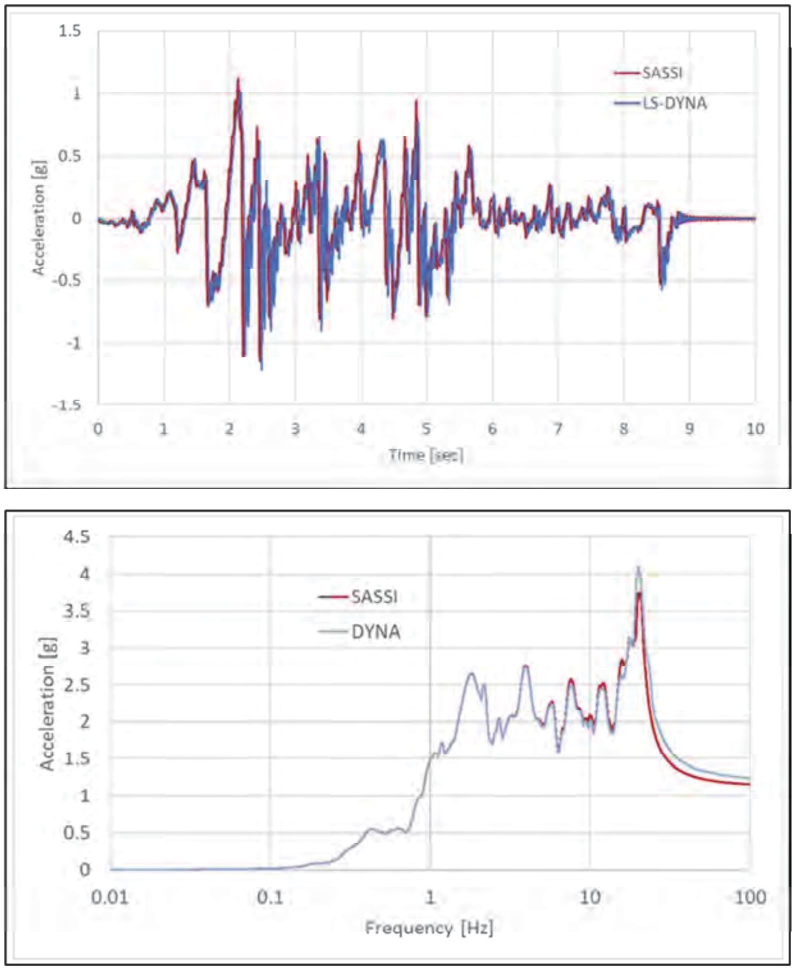

Figure *14*: LS-DYNA and SASSI Results Comparison for an Embedded Foundation (Roof Elevation)

3.2.8 Bearing Pressures and Seismic Stability

The LS-DYNA SSI model of the Xe-100 RB will have nonlinear contact capability such that sliding and uplift can be explicitly evaluated. The evaluation of dynamic bearing pressures and RB stability will be performed in accordance with NUREG-0800 Sections 3.7.2 [14] and 3.8.5 [20].

3.2.9 Lateral Soil Pressures

Lateral soil pressures acting on the RB walls will be developed in accordance with SRP Sections 3.7.2 [14] and 3.8.4. The LS-DYNA SSI model will be capable of directly outputting dynamic soil pressures due to seismic ground motions. These pressures will be combined with static and hydrodynamic soil pressures.

3.2.10 Seismic Interaction Effects

Seismic interaction effects on the RB will be evaluated for building-to-building pounding and the potential for collapsing structure. For the evaluation of pounding, buildings adjacent to the RB (e.g., FHAB, NIAB) will be idealized with lumped mass models. The effects of structure-soil-structure interaction will be modeled using LS-DYNA. A separate SSI model will evaluate the effects of closely spaced RBs (multiple units) and the potential to affect FRS.

For evaluating the collapse of structures, conservative and pragmatic assumptions will be made regarding building failure modes and collapse mechanisms. Engineering mechanics, as well as empirical methods, will be used to evaluate the effects of debris impacts (due to a failing structure) on the RB structure. For example, a group of roof purlins might be assumed to fall and impact the RB roof slab. The effect of these roof 'missiles' and their potential penetration of the RB will be evaluated using accepted methods similar to those used for tornado missile design (e.g., NUREG-0800 Section 3.5.1.4 [22]). The NIAB is an NSRST structure as indicated in Table 1 and is intended to be a Seismic Category II. However, it will be designed to prevent catastrophic failure and collapse of structural members during a Seismic Category I accident event as an added conservatism.

3.3 Quality Assurance Program and Software Verification Approach

The analyses and design of Xe-100 will be performed following a graded approach developed by X-energy and informed by the selection of special treatments described in NEI 18-04 [13]. SR-SSCs are designed and analyzed to quality assurance requirements as described in the X-energy Quality Assurance Program Description (XEQAPD) topical report that align with 10 CFR 50 Appendix B. As noted in previous sections, this includes the evaluation of the RB and applies to the software qualification requirements for analytical tools used for the design of the structure. NSRST and NST SSCs are designed and analyzed to graded quality requirements as described in the XEQAPD. Design and analyses may be performed using commercially procured software with adequate verification of performance of critical characteristics and acceptance criteria.

4. Conclusions

The intent of this white paper is to present the seismic design criteria development approach for the Xe-100 plant design and provide an outline of the methodology used for the seismic qualification of the RB, which functions as the primary safety-related structure for the plant. Together these provide confidence that the seismic DBHL selection and plant response will result in the Xe-100 achieving a safe shutdown state.

The methods outlined within this white paper summarize the overarching seismic design/analysis philosophy for the Xe-100 plant. It provides a description of the application of risk-informed performance-based approach to the development of seismic DRS curves for generic plant design. The use of non-linear modeling and analysis techniques using the LS-DYNA code for SSI evaluations are also described. Technical reports providing the detailed results of these analyses will be developed for NRC review through future licensing submittals or in connection with a license, permit, approval, or certification application.

5. Review Request

X-energy is requesting NRC feedback on the approach used to determine the generic plant DRS curves and the proposed seismic analyses methods for the RB. X-energy is also requesting NRC feedback on the seismic design basis development approach and the integration of NUREG-0800 seismic analysis guidance into the NEI 18-04 licensing basis development approach.

6. Cross References and References

	Document Title Cross References: X-energy documents that <u>may</u> impact the content of this document. References: X-energy or other documents that <u>will not</u> impact the content of this document	Document No.	Rev./ Date	Cross Reference/ Reference
[1]	NRC, "A Performance Based Approach to Define Site-Specific Earthquake Ground Motion"	RG-1.208	MAR-2007	Reference
[2]	NRC, "GMRS Curves for Seismic Hazard Reevaluations"	ML14136A126	21-May-2014	Reference
[3]	NRC, "Seismic Hazard Evaluations for U.S. Nuclear Power Plants: Near-Term Task Force Recommendations 2.1 Results"	NUREG/KM-0017	Jun-2021	Reference
[4]	NRC, "Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard-and Risk-Consistent Ground Motion Spectra Guidelines"	NUREG/CR-6728	06-Nov-2001	Reference
[5]	ASCE, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities"	ASCE/SEI 43-05	2005	Reference
[6]	ANSI, "Categorization of Nuclear Facility Structures, Systems, and Components for Seismic Design"	ANSI/ANS 2.26	12-Sep-2017	Reference
[7]	Columbia Generating Station, "Seismic Hazard and Screening Report, Response to NRC Request for Information Pursuant to CFR 50.54(F) Regarding Recommendation 2.1 of the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident"	Docket 50-397	12-Mar-2015	Reference
[8]	Palo Verde Generating Station, "SSHAC Level 3 GMRS to SSE Comparison for Palo Verde Generating Station (PVNGS)"	13Q4160-RPT-003	05-Mar-2015	Reference
[9]	NRC, "NUREG-0800 Standard Review Plan Section 2.5.2, Vibratory Ground Motion"	Section 2.5.2	Rev. 5	Reference
[10]	NRC, "NUREG-0800 Standard Review Plan Section 3.7.1, Seismic Design Parameters"	Section 3.7.1	Rev. 4	Reference
[11]	NRC, "Title 10 of the Code of Federal Regulations, Part 50"	N/A	N/A	Reference
[12]	NRC, "Title 10 of the Code of Federal Regulations, Part 52"	N/A	N/A	Reference
[13]	NEI, "Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development"	NEI 18-04	Rev. 1 - 2019	Reference
[14]	NRC, "NUREG-0800 Standard Review Plan Section 3.7.2, Seismic System Analysis"	Section 3.7.2	Rev. 4	Reference
[15]	NRC, "Damping Values for Seismic Design of Nuclear Power Plants."	RG 1.61	Rev. 1	Reference
[16]	NRC, "Combining Modal Responses and Spatial Components in Seismic Response Analysis"	RG 1.92	Rev. 3	Reference
[17]	NRC, "Development of Floor Response Spectra for Seismic Design of Floor Supported Equipment or Components"	RG 1.122	Rev. 1	Reference

	Document Title Cross References: X-energy documents that may impact the content of this document. References: X-energy or other documents that will not impact the content of this document	Document No.	Rev./ Date	Cross Reference/ Reference
[18]	NRC, "A Performance Based Approach to Define the Site Specific Earthquake Ground Motion"	RG 1.208	Rev. 0	Reference
[19]	NRC, "Design Response Spectra For Seismic Design of Nuclear Power Plants"	RG 1.60	Rev. 2	Reference
[20]	NRC, "NUREG-0800 Standard Review Plan Section 3.8.5, Foundations"	Section 3.8.5	Rev. 3	Reference
[21]	NRC, "NUREG-0800 Standard Review Plan Section 3.8.4, Other Seismic Category I Structures"	Section 3.8.4	Rev. 3	Reference
[22]	NRC. "NUREG-0800 Standard Review Plan Section 3.5.1.4, Missiles Generated by Tornadoes and Extreme Winds"	Section 3.5.1.4	Rev. 3	Reference
[23]	X-energy, "Xe-100 Principal Design Criteria Licensing Topical Report"	2022-XE-NRC-027 (004799)	Rev. 1	Reference
[24]	X-energy, "Risk-Informed Performance-Based Licensing Basis Development"	ML22074A288 (001522)	Rev. 2	Reference
[25]	X-energy, "TRISO-X Pebble Fuel Qualification Methodology"	ML21246A289 (000633)	Rev. 3	Reference
[26]	NEI, "Technology Inclusive Guidance for Non-Light Water Reactors: Safety Analysis Report Content for Applicants Using the NEI 18-04 Methodology".	NEI 21-07	Rev. 1	Reference