Xe-100 Licensing Topical Report Atmospheric Dispersion and Dose Calculation Methodology

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Document Approval Signees

Action	Designation	Name	Signature	Date
Preparer	Licensing Project Manager	Jessica Maddocks	Maintained in Teamcenter	22-Aug-2023
Reviewer	Design Analysis Manager	Brian Froese	Maintained in Teamcenter	22-Aug-2023
Approver	Licensing Manager - Standard Design	Jon Facemire	Maintained in Teamcenter	25-Sep-2023

SYNOPSIS

One of the principal advantages of high-temperature gas-cooled reactors (HTGRs), such as the Xe-100, are their high degree of passive safety. The fuel, which does not significantly degrade during the slow accident-transients characteristic of HTGRs, is at the center of a series of barriers to radionuclide transport that constitute a robust functional containment. Therefore, the radionuclide source terms and associated radiological consequences from postulated Xe-100 events are expected to be relatively minor.

X-Energy LLC (X-energy) has developed a suite of codes, XSTERM (Reference 5), to mechanistically model the transport of radionuclides that comprise the source term, from their birth in the fuel to their potential release and transport to the environment. The code is used in combination with other thermal hydraulic software tools in the analysis of licensing basis events (LBEs). The mechanistic source term part of those methods and calculations will be documented under a separate topical report. This topical report documents the methodology associated with the calculation of atmospheric dispersion factors and doses from Xe-100 LBEs. An XSTERM code module, XDIS, can be used to calculate post-release doses at the plant Exclusion Area Boundary/Low Population Zone (EAB/LPZ) and Control Room (CR) location.

Verification of the XDIS dose calculations is documented based on hand calculations plus a comparison to the RADTRAD code (Reference 48).

To support input to the XDIS module, X-energy is developing a two-phase approach to post-accident atmospheric dispersion. Given the source terms are expected to be minor, a generic methodology is first developed assuming conservative meteorological conditions and comparisons to industry field data. These generic site atmospheric dispersion factors are documented in this report and will be either validated or replaced using site-specific atmospheric dispersion factors once Xe-100 sites are selected for specific projects and site-specific meteorology is obtained and/or collected. It is expected that site-specific EAB / LPZ atmospheric dispersion factor calculations will use the latest regulatory guidance, including Regulatory Guide (RG) 1.249 for use of the ARCON code.

CONFIGURATION CONTROL/DOCUMENT CHANGE HISTORY

Document Change History

Rev.	Date	Preparer	Page/Section Revised	Description
1	25-May-2023	J. Cajigas	N/A	Initial issue.
2	22-Sep-2023	J. Maddocks	Various	Revised to update proprietary markings. Also changed mentions of DG-4030 to RG 1.249. Added clarification of EAB / LPZ. Removed RG 1.3 and 1.4 from Section 2 for clarity. Minor editorial changes.

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Abbreviations/Acronyms

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Short Form	Phrase
AGR	Advanced Gas Reactor
ANS	American Nuclear Society
AST	Alternative Source Term
AOO	Anticipated Operational Occurence
ASME	American Society of Mechanical Engineers
AV	Arbeitsgemeinschaft Versuchsreaktor
BDBE	Beyond Design Basis Event
BUMS	Burn-Up Measurement Unit
CEB	Controls and Electrical Building
CFR	Code of Federal Regulations
Cl_2	Chlorine
CO_2	Carbon Dioxide
CR	Control Room
DBA	Design Basis Accident
DBE	Design Basis Event
DCF	Dose Conversion Factor
DG	Draft Guide
EAB	Exclusion Area Boundary
EDE	Effective Dose Equivalent
EPZ	Emergency Planning Zone
FGR	Federal Guidance Report

Short Form	Phrase
FSV	Fort St. Vrain
HBP	Helium Pressure Boundary
HTGR	High-Temperature Gas-Cooled Reactor
HVAC	Heating Ventilation and Air Conditioning
IPyC	Inner Pyrolytic Carbon
LBE	Licensing Basis Event
LOCA	Loss of Coolant Accident
LPZ	Low Population Zone
LTR	Licensing Topical Report
LWR	Light Water Reactor
MST	Mechanistic Source Term
NEI	Nuclear Energy Institute
NRC	U.S Nuclear Regulatory Commission
NIAB	Nuclear Island Auxiliary Building
OPyC	Outer Pyrolytic Carbon
PBA	Power Block Area
PDC	Principal Design Criteria
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
PyC	Pyrolytic Carbon
RCCS	Reactor Cavity Cooling System
RCS	Reactivity Control System
RG	Regulatory Guide

Short Form	Phrase
RIPB	Risk Informed Performance Based
RN	Radionuclide
RPV	Reactor Pressure Vessel
RPS	Reactore Pressure System
RSS	Reserve Shutdown System
SARRDL	Specified Acceptable Radionuclide Release Design Limit
SiC	Silicon Carbide
SSC	Structures, Systems, and Components
TRISO	TRIstructural-ISOtropic
UCO	Uranium Dicarbide
UHS	Ultimate Heat Sink
X-energy	X Energy LLC

1. Introduction

1.1 Purpose

One of the principal advantages of the high-temperature gas-cooled reactor (HTGR) is its high degree of passive safety. The reactor employs TRIstructural-ISOtropic (TRISO) fuel that does not significantly degrade during accident transients which proceed slowly due to the low power density and high heat capacity of the core (Petti 2013) Reference 1. Therefore, the *source terms*, or quantities, timing, physical and chemical forms, and thermal energy of radionuclides released to the environment during licensing basis events (LBE), (NGNP MST WP 2010), Reference 2, are expected to be minor. Modular HTGR source terms are:

- Event-specific;
- Determined mechanistically using models of fission product and radionuclide generation and transport that account for reactor inherent and passive design features and the performance of the fission product release barriers that comprise the functional containment;
- Include quantities, timing, physical and chemical forms, and thermal energy of the release; and
- Different from the light water reactor (LWR) source terms that have traditionally been based on a severe core damage event.

As emphasized above, the development of HTGR source terms is different than for LWRs. For example, the Xe-100 reactor technology as described in its Technology Description Technical Report (Braudt 2021), Reference 3, employs a radionuclide *functional containment* consisting of a series of barriers to radionuclide transport. These barriers include the layers of the TRISO fuel, the reactor core graphite and other carbonaceous materials, the helium pressure boundary (HPB), and the reactor building. Together, these barriers effectively retain radionuclides such that a traditional containment building is not necessary to meet regulatory dose requirements at the plant boundary.

1.2 Scope

The atmospheric dispersion and dose methodology discussion in this report is focused on Safety Analysis applications and preempted by a description of the Xe-100 design. The methodology associated with developing Xe-100 radionuclide source terms from postulated LBEs will be described in a separate topical report, see Reference 10. Section 3 of this report summarizes the key Xe-100 *functional containment* design features in order to preface the discussion of the dispersion of such source terms and corresponding dose to operators in the Control Room (CR) and members of the public during postulated LBEs.

The XDIS module of X-energy's code XSTERM, Reference 5, will be used to generate the associated doses from LBEs, including deterministic Design Basis Accidents (DBAs). X-energy is pursuing a two-phase approach to LBE atmospheric dispersion factors used as input to the XDIS module for the Xe-100 technology. Given that most source terms are expected to be minor and project-specific site-selection is a future activity, the first phase develops a generic methodology assuming conservative meteorological conditions and comparisons to industry field data. Development of these conservative dispersion factors is documented in this report. Once a project site is selected, X-energy will evaluate various sources of meteorological data and calculate site-specific dispersion factors using Regulatory Guide (RG) 1.249 to validate these generic factors. X-energy may also utilize these site-specific dispersion factors to calculate LBE doses as appropriate.

This effort is part of a broad licensing roadmap developed by X-energy to demonstrate the Xe-100 reactor design readiness for commercial operation consistent with applicable regulatory and nuclear industry standards. Other dispersion and dose methodologies such as use of MACCS in the Environmental Report or NRCDose for normal operation calculations are not in the scope of this licensing topical report (LTR) and will be covered in future preapplication engagements.

1.3 Interfacing Documents

This licensing topical report is one of several reports covering key regulatory issues submitted to the NRC staff as part of Xe-100 pre-application engagements. X-energy considers the proposed LBE atmospheric dispersion and dose calculation methodology as part of the safety design approach and risk-informed, performance-based licensing basis development. This safety design approach is described in Nuclear Energy Institute (NEI) 18-04, Reference 6, as endorsed and clarified by US Nuclear Regulatory Commission (NRC) RG 1.233, Reference 7. The issues most closely related to this LTR include:

- Probabilistic Risk Assessment (PRA) efforts being conducted using the standard American Society of Mechanical Engineers (ASME)/American Nuclear Society (ANS) RA-S-1.4-2021 Probabilistic Risk Assessment Standard for Advanced Non-Light Water Reactor Nuclear Power Plants (RA-S-1.4-2021) as endorsed by RG 1.247 as described in the Xe-100 PRA Technical Adequacy White Paper, Reference 11
- LBE identification and selection, Structures, Systems, and Components (SSCs) safety classification, and the evaluation of defense-in-depth adequacy methodology described in NEI 18-04 as implemented by X-energy, described in LTR XE00-R-R1ZZ-RDZZ-L-000687 "Risk-Informed Performance-Based Licensing Basis Approach for the Xe-100 Reactor" (Vaughn 2021), Reference 12;
- The integrated approach to analyzing LBEs through the development of evaluation models and implementation of various codes and analysis techniques, described in LTR XE00-R-R1ZZ-RDZZ-X-000714 Evaluation Model Development and Analysis Methodologies (Chapman 2021), Reference 13; and
- The principal design criteria (PDC) for the X-energy Xe-100 pebble-bed, high-temperature gas-cooled reactor (HTGR), Xe-100 Principal Design Criteria Licensing Topical Report, R1, Reference 8 undergoing NRC review. The PDC are developed using guidance from RG 1.232, "Guidance for Developing Principal Design Criteria for Advanced (Non-Light Water) Reactors," R1, Reference 9, and NEI 21-07, "Technology Inclusive Guidance for Non-Light Water Reactor Safety Analysis Report: Content for Applicants Using the NEI 18-04 Methodology," Revision 1, Reference 14.

1.4 Document Layout

This Section is followed by an overview of applicable regulatory requirements, Section 2.

An overview of the Xe-100 plant and the fuel functional containment design is presented in Section 3. This includes an outline of the series of transport processes that occur from the birth of radionuclides to their potential release to the environment. The functional containment approach will be further detailed in future licensing documents as part of X-energy's implementation of the risk-informed, performance-based licensing basis guidance found in NEI 18-04, Reference 6. A reader familiar with the Xe-100 technology may not need to review this section and no approval is requested associated with this content.

Sections 4 and 5 document the Xe-100 dose calculation approach and methodology respectively. Proposed generic site atmospheric dispersions calculations and results are documented in Section 6. The proposed XDIS code dose calculation approach is validated in Section 7.

1.5 Outcome Objectives

It is X-energy's objective to demonstrate and deploy the Xe-100 reactor technology in projects domestically and abroad, and to seek regulatory approvals through the various options provided in Title 10 of the Code of Federal Regulations (10 CFR) in the United States. This report has been prepared to document the proposed atmospheric dispersion and dose calculations methodology to be used in the radiological safety analysis of postulated licensing basis events.

X-energy is requesting NRC approval of the methodology described in Sections 4 through 7 of this LTR for use by prospective applicants for Construction Permits, Operating Licenses, Standard Design Approvals or Certifications, Early Site Permits, Combined Licenses, or Manufacturing Licenses for the Xe-100 technology or project as an appropriate means to calculate dose consequences of Anticipated Operational Occurrences (AOOs), Design Basis Events (DBEs), and Beyond Design Basis Events (BDBEs) for evaluation of frequency-consequence targets and quantitative health objectives (QHOs) and to evaluate DBA consequences to ensure that performance of the Xe-100 meets the dose limits in 10 CFR 50.34. Such analyses are required by 10 CFR 50.34(a)(1)(D) (Construction Permits), 10 CFR 50.34(b)(1) (Operating Licenses), 10 CFR 52.17(a)(1)(ix) (Early Site Permits), 10 CFR 52.47(a)(2)(iv) (Design Certifications), 10 CFR 52.79(a)(1)(vi) (Combined Licenses), 10 CFR 52.137(a)(2)(iv) (Design Approvals), and 10 CFR 52.157(d) (Manufacturing Licenses).

2. Overview of Regulatory Requirements

The NRC regulatory basis for the design and licensing of nuclear facilities is contained in federal regulations, and in NRC policy statements, and other regulatory guidance. The review below only addresses the development of the atmospheric dispersion methodology.

- The NRC Regulations contained in Title 10 of the Code of Federal Regulations, Parts 1 to 199 are reviewed for only those applicable to this reactor type, and are evaluated for use. When clarified, these regulations will be selected to match the Xe-100 application and circumstance type.
- NRC Regulatory Guides are guidance documents which each present a methodology, technique, and data considered acceptable to satisfy specific parts of the regulations and acknowledge that alternative methods may be deemed acceptable if they provide a basis for the findings required.

2.1 NRC Regulations

2.1.1 10 CFR 50.34

This regulation defines information requirements for Construction Permit and Operating License applications, including the need to perform evaluations and analyses of postulated fission product releases during LBEs to evaluate radiological consequences and demonstrate plant performance against dose limits. These radiation dose limits are defined by location of the receptor, event duration, and evaluation limit.

2.1.2 10 CFR 100.21(c)

This regulation ensures proposed sites for commercial power reactors evaluate site atmospheric dispersion characteristics and dispersion parameters be established.

2.2 Regulatory Guidance

2.2.1 NUREG-0800 NRC Standard Review Plan for LWRs

Chapter 2 of this NUREG discusses the site characteristics that could affect the safe design and siting of the plant. It provides information concerning conservative atmospheric dispersion factors (χ/Q value) estimates (1) at the EAB, the outer boundary of the LPZ, and at the CR for postulated design-basis accidental radioactive airborne releases and (2) at the CR from the onsite and/or offsite airborne releases of hazardous materials such as flammable vapor clouds, toxic chemicals, and smoke from fires.

2.2.2 Regulatory Guide 1.249

This RG describes an approach that is accepted by the NRC to meet the NRC requirements for determining atmospheric relative concentration (χ/Q) values in support of modeling onsite releases to offsite boundaries from a design-basis accident (DBA). This guidance includes procedures for using the ARCON code to estimate χ/Qs at the EAB and the outer boundary of the LPZ out to distances of 1,200 meters from the nearest edge of a building within the powerblock area (PBA).

The design guide also implements the methodology of RG 1.194 for offsite dose locations at boundaries out to distances of 1200 meters and provides new guidance on plausible alternate meteorological monitoring approaches.

X-energy implements this guidance in its methodology for the Xe-100 as the proposed exclusion area boundary (EAB) is expected to be significantly smaller than typical LWRs. Typical LWR analyses evaluate post-accident atmospheric dispersion factors at the EAB and LPZ using a code called PAVAN. As described in this RG, PAVAN "significantly overpredicts concentrations...in the vicinity of buildings" and this ultimately resulted in the ARCON software being created for more near-field dispersion evaluations for receptors like CRs. This RG provides direction on using the ARCON code instead of PAVAN for calculating EAB & LPZ atmospheric dispersion factors at distances <1200 meters and is the best applicable guidance for the Xe-100 technology at this time.

2.2.3 Regulatory Guide 1.194

This RG provides guidance on determining atmospheric relative concentration (χ/Q) values in support of DBA CR radiological habitability assessments at nuclear power plants. It describes methods acceptable to the NRC staff for determining χ/Q values that will be used in CR radiological habitability assessments performed in support of applications for licenses and license amendment requests.

2.2.4 Regulatory Guide 1.145

This RG provides guidance concerning criteria for atmospheric dispersion models for potential accident consequence assessments at nuclear power plants. It includes guidance on appropriate dispersion models for estimating offsite relative concentrations (χ/Q values) as a function of downwind direction and distance (i.e., at the EAB and LPZ) for various short-term periods (up to 30 days) after an accident.

2.2.5 Regulatory Guide 1.183

This RG provides guidance to licensees of operating power reactors on acceptable applications of alternative source terms; the scope, nature, and documentation of associated analyses and evaluations; consideration of impacts on analyzed risk; and content of submittals. This guide establishes an acceptable alternative source term (AST) and identifies the significant attributes of other ASTs that may be found acceptable by the NRC staff. This guide also identifies acceptable radiological analysis assumptions for use in conjunction with the accepted AST. Additionally, this RG provides a dose calculation methodology.

The AST methodology described in this regulatory guidance is for light water reactors. Therefore, it is not directly applicable to high temperature gas reactors. However, X-energy does look to the dose calculation methodology to shape the methodology for atmospheric dispersion and dose consequence for the Xe-100 technology.

2.3 Additional NRC Guidance

2.3.1 PNL-10286

This report updated the model describing atmospheric dispersion in the vicinity of buildings that was developed for the NRC in the late 1980s. That model has recently undergone additional peer review. The reviewers identified four areas of concern related to the model and its application. This report describes revisions to the model in response to the reviewers' concerns. Model revision involved incorporation of explicit treatment of enhanced dispersion at low wind speeds in addition to explicit treatment of enhanced dispersion at high speeds resulting from building wakes. Model parameters are evaluated from turbulence data. Experimental diffusion data from seven reactor sites are used for model evaluation. Compared with models recommended in current NRC guidance to licensees, the revised model is less biased and shows more predictive skill. The revised model is also compared with two non-Gaussian models developed to estimate maximum concentrations in building wakes. The revised model's concentration predictions are nearly the same as the predictions of the non-Gaussian models. On the basis of these comparisons of the revised model concentration predictions with experimental data and the predictions of other models, the revised model is found to be an appropriate model for estimating concentrations in the vicinity of buildings.

Some of the information in this report has been updated by Reference 16 in accordance with RG 1.249. See Section 5.1.1.2 for further discussion.

2.4 EPA Regulations

2.4.1 FGR No. 11

This report serves as the basis for regulations setting upper bounds on the inhalation and ingestion of, and submersion in, radioactive materials in the workplace. The report also includes tables of exposure-to-dose conversion factors, for general use in assessing average individual committed doses in any population that is adequately characterized by Reference Man (ICRP 1975). The report is used to obtain Exposure-to-Dose Conversion Factors for inhalation, Table 2.1.

X-energy is in the process of finalizing the list of Xe-100 isotopes important to dose. That information is expected to be included in a revision to the Mechanistic Source Term (MST) LTR to be submitted at a later date. The basis of the Exposure-to-Dose Conversion Factors for inhalation may require an alternate reference for isotopes not included in Federal Guidance Report (FGR) No. 11.

2.4.2 FGR No. 12

This report is a companion to FGR No. 11. It tabulates dose coefficients for external exposure to photons and electrons emitted by radionuclides distributed in air, water, and soil. The dose coefficients for exposure to external radiation presented here are intended for the use of Federal agencies in calculating the dose equivalent to organs and tissues of the body, as were those in FGR No. 11. The dose coefficients for air submersion in this report update those given in FGR No. 11. The report is used to obtain Exposure-to-Dose Conversion Factors for submersion, Table III.1

X-energy is in the process of finalizing the list of Xe-100 isotopes important to dose. That information is expected to be included in the MST LTR to be submitted at a later date. The basis of the Exposure-to-Dose Conversion Factors for submersion may require an alternate reference for isotopes not included in FGR No. 12.

3. Overview of the Xe-100 Plant Design

The purpose of this section is to introduce the reader to the Xe-100 design and describe design features relevant to the methodology used in the safety analysis of postulated post-accident doses. A reader familiar with the Xe-100 technology may not deem it necessary to read this section.

3.1 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 as well as advanced safety characteristics. This 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 internationally developed for commercial modular HTGR designs.

The Xe-100 reactor design is based on a pebble-bed core configuration. Pebble bed reactor technology dates 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. China has a modular HTGR pebble-bed reactor design, the HTR-PM, with two 250 MWt reactor units serving a single 200 MWe turbine/generator, Reference 15, that started cold commissioning in late 2020. 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, Reference 17 and 18, and the Xe-100 Technology Description, Reference 3.

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 given in Table 1. The active core volume is filled with approximately 224,000 spherical fuel elements, or pebbles, 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 nuclear heat which is conducted to the pebble's surface. A helium circulator transports the helium gas through the pebble bed transporting heat from the pebbles to the steam generator.

While the reactor is operating, fuel pebbles are loaded into the core 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 System (BUMS). The BUMS evaluates each pebble for physical damage and burn-up. The pebbles are then returned to the top of the RPV for further burnup or sent as spent pebbles to spent fuel storage. A typical pebble goes through this process six times before it is removed from the reactor prior to reaching burn-up limits. The spent fuel pebbles are inventoried and placed into spent fuel casks for storage.

During normal operations, the maximum fuel core temperature is limited to well below 1000°C, which is significantly lower than many earlier HTGR designs, Reference 35. 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 uranium kernel content and use of the fuel pebble's and reflector's graphite. This ensures stability of operations and negative reactivity insertion during core heat-up events. This inherent reactivity feedback is one of the safety functions credited from the fuel during transients and safety analysis and allows the Xe-100 to achieve a safe shutdown condition in certain LBEs, Reference 18.

Shutdown margin and reactivity control is provided by two banks of control rods inserted into the graphite side reflector. One control rod bank, the Reactivity Control System (RCS), is used in normal operation and can achieve hot shutdown if inserted. The second control rod bank, the Reserve Shutdown System (RSS), credited as a diverse reactivity control function, is inserted by the safety-related Reactor Protection System (RPS) and used to establish long-term cold shutdown conditions. The relatively small core diameter allows safe shutdown by inserting the control rods into the side reflectors without the need of in-core control rods, Reference 18.

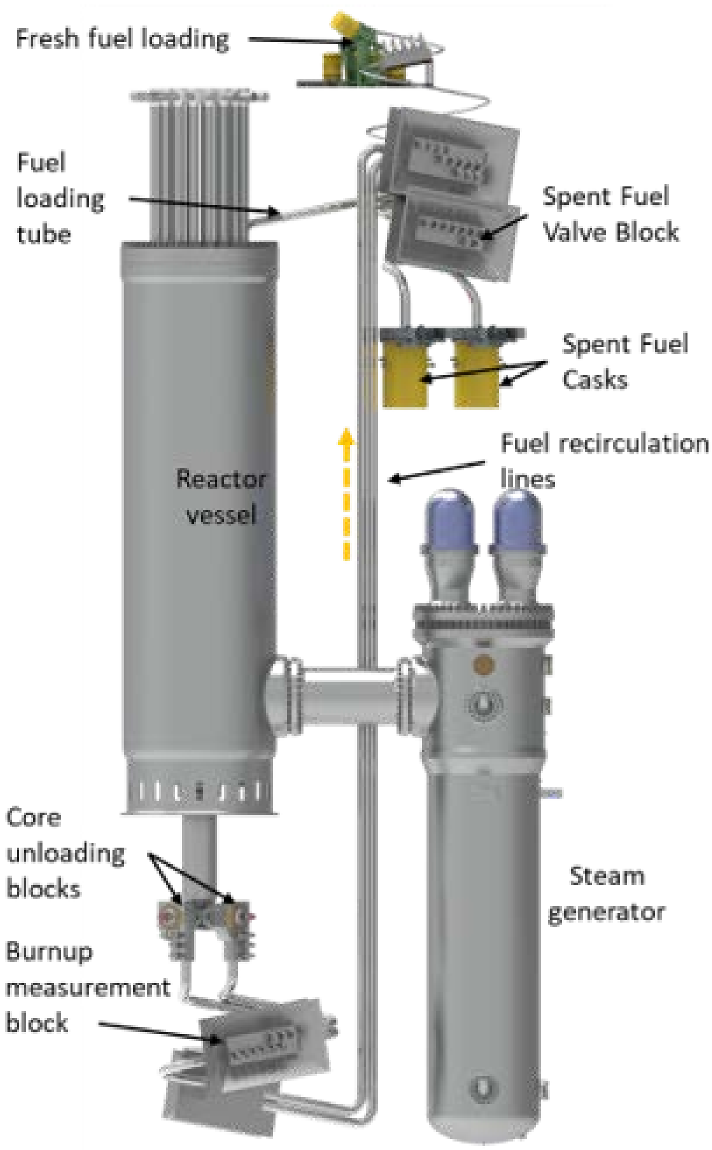

Figure 1: Xe-100 Section View

Table 1: Xe-100 Reactor Main Characteristics

Thermal Power	200 MWt	Helium flow rate (excluding bypass)	~78.6 kg/s
Core Volume	41.56 m³	Helium pressure	6 MPa
Core Average Power Density	~5 MW/m³	Pebble packing fraction	61%
Height (Flattened Pebble Bed)	~920 cm	Particle packing fraction	9.5%
Diameter of Pebble Bed	241 cm	Burnup	168 GWd/MTU
Average Pebble Passes through the Core	6	Enrichment	15.5%
Heavy Metal Loading per Pebble	7 g	Moderation ration (C/U)	551
TRISO-Coated Particles per Pebble	~19,000	U-235 per pebble	1.085 g
Gas Inlet Temperature	260°C	Daily pebble charge	~170
Gas Outlet Temperature	750°C	Average fuel residence time	~1320 days

In the event of loss of active cooling, 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 Reactor Cavity Cooling System (RCCS), which is a fully passive natural convection air-cooled ultimate heat sink (UHS). Design features such as the low core power density, relatively large reactor height-to-diameter ratio, and a non-insulated RPV ensures effective heat removal if active cooling is lost. The core power density in the Xe-100 is ~5 MW/m^3, whereas most LWRs typically operate with power densities on the order of 20 times higher. The combination of a low core power density and the large structural mass and heat capacity of the graphite ensures relatively slow thermal transients. Xe-100 thermal transients typically occur in periods of hours or days, rather than seconds or minutes characteristic of LWR thermal transients. Further, the functions of reactor moderation and thermal transport are fully separated in the case of the Xe-100 versus typical LWRs. Losing the thermal transport medium for any reason is of no reactor safety consequence in the Xe-100 as the permanent structural internals assume that function; the moderating pebble graphite matrix remains in-place, see Reference 18.

3.2 TRISO-Coated Particle Fuel

Coated particle fuel has been used in HTGRs since their inception in the early 1960s, see Reference 19. TRISO-coated particle fuel was first introduced in the Dragon reactor, Reference 20, and Fort St. Vrain (FSV) which was the first electricity producing HTGR with an all TRISO-coated particle core, Reference 21. TRISO-coated particle fuel has been the fuel of choice for all modular HTGR designs, beginning with the

German pebble bed HTR-Module, Reference 22, and the Modular High Temperature Gas-Cooled Reactor program in the U.S., Reference 23.

In the Xe-100 design, the TRISO fuel particles consist of a uranium dicarbide (UCO) fuel microsphere ("kernel") coated with multiple layers of pyrocarbon and silicon carbide (SiC) as shown in Figure 2. Using UCO for the Xe-100 design allows the use of the ongoing Advanced Gas Reactor (AGR) Fuel Development and Qualification Program at Idaho National Laboratory and Oak Ridge National Laboratory, AGR TDP 2016, Reference 24. The different coating layers, consisting of the buffer, inner pyrolytic carbon (IPyC), SiC, and outer pyrolytic carbon (OPyC) layers are collectively referred to as a TRISO coating. The coating system constitutes a miniature multi-shell pressure vessel that provides retention of the fission products generated by fissioning of the nuclear material in the kernel. A substantial fraction of the fission products is retained inside the kernel itself. The performance of these coatings directly supports the functional containment approach for evaluating the Xe-100 design and safety analyses.

As shown in Figure 2, the four coating layers of a TRISO-coated particle have specialized purposes but in composite constitute a high-integrity pressure vessel which retains fission products. The functions of the low-density buffer layer are 1) to provide a reservoir for fission gases (Noble gases and Halogens classes) released from the fuel kernel, 2) to attenuate fission recoils, and 3) to accommodate kernel swelling under irradiation. The main functions of the high-density IPyC coating are to provide a smooth regular substrate for the deposition of a high integrity SiC coating and to prevent chlorine (Cl_2) and hydrogen chloride (HCl) from reacting with the fuel kernel during the SiC deposition process; hence, a major benefit of the IPyC coating is realized during fuel fabrication. The IPyC coating, which is intimately bonded to the SiC coating, also helps to maintain the SiC coating in compression, as the former shrinks under irradiation, while the latter is dimensionally stable.

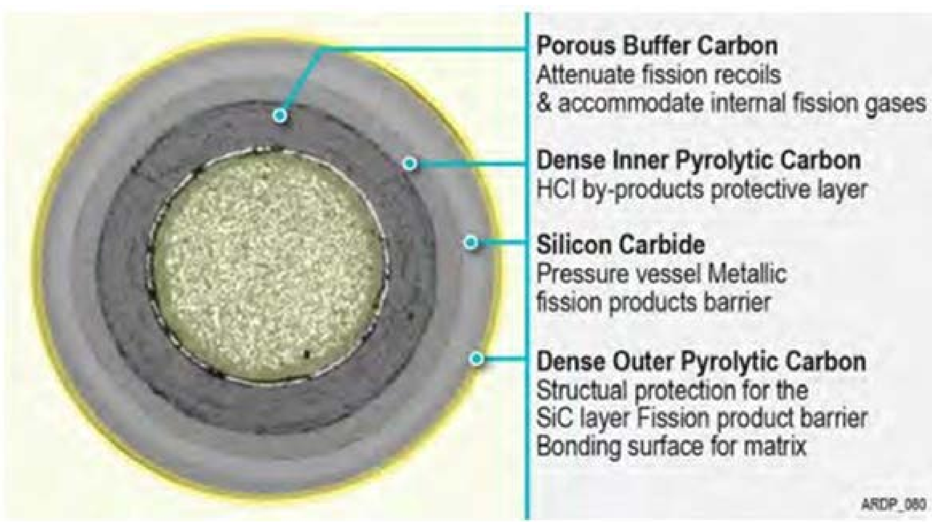

Figure 2: TRISO Fuel Particle Configuration and Coating Functions

The SiC coating is the most important in the TRISO coating system in terms of radionuclide (RN) retention. It serves as the primary barrier to the release of fission products from the coated particle, particularly some of the volatile metallic fission products such as cesium (Alkali Metals class). The high-density OPyC coating, which shrinks under irradiation, also generates a compressive stress in the dimensionally stable

SiC, partially compensating for the tensile stress component induced by the internal gas pressure. The pyrolytic carbon (PyC) coatings effectively retain fission gases (Noble gases and Halogens classes), including radiologically dominant iodine isotopes (Halogens class), at temperatures up to approximately 1800°C for tens to hundreds of hours in fuel particles with defective (as-manufactured) or failed (in-service) SiC layers, Reference 19.

The physical properties and performance capabilities of the TRISO-coated particles are among the most important factors impacting the radiological safety of the HTGR. Fission product retention in the fuel, as well as the high fuel burnups and temperatures that can be tolerated in the reactor core, are primarily determined by the fuel particle properties, see NGNP FQ WP 2010, Reference 19.

3.3 Pebble Fuel Design for the Xe-100

The defining characteristic of the pebble-bed reactor and the key to the safety and operational simplicity of the Xe-100 is the use of TRISO-coated fuel particles embedded in fuel spheres, or pebbles. The design of the coated particles and fuel sphere, including their nominal dimensions, is depicted in Figure 3.

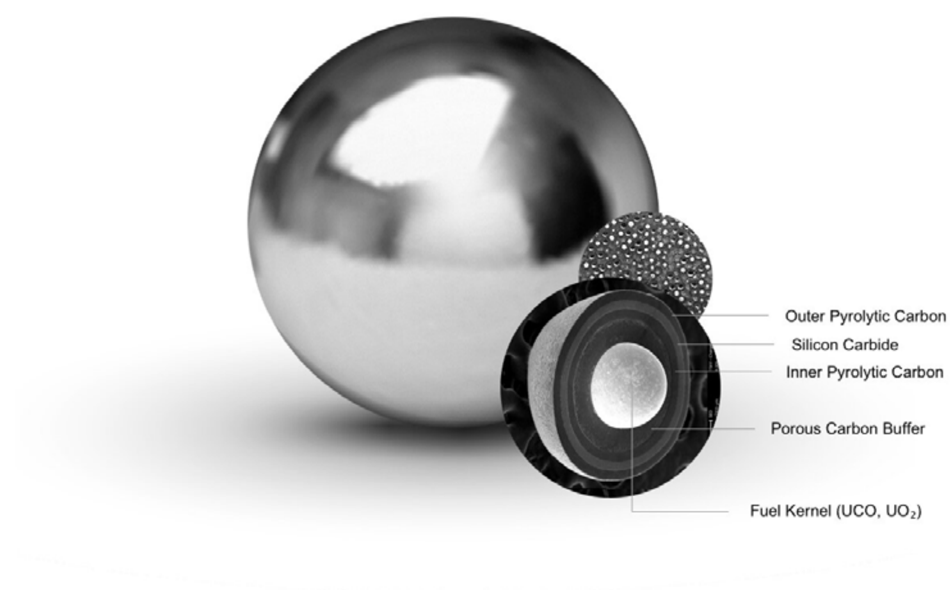

Figure 3: Xe-100 Reference Fuel Element (Pebble) Design

In Figure 3, the 60 mm-diameter spherical fuel element consists of two zones: the inner spherical region known as the fuel zone, and the outer shell surrounding the fuel region known as the fuel free zone. The 50-mm diameter fuel zone of each fuel sphere contains thousands of TRISO-coated fuel particles evenly distributed in a carbonaceous matrix material. The fuel-free zone is a 5 mm thick shell of the same matrix material formed by a high-pressure isostatic pressing process and machined to final dimensions. The relatively low particle packing fraction in the fuel zone (about 10% in the Xe-100) and the pebbles being fully wetted by the helium coolant, leads to lower temperature gradients across the fuel particle, as compared to prismatic fuel designs, and lower maximum fuel temperatures during normal operation.

3.4 The Xe-100 Safety Design Approach

3.4.1 Objectives of the Safety Design Approach

The Xe-100 safety design approach 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 LBEs: normal operating conditions including AOOs, DBEs, DBAs analyzed assuming only safety-related SSCs are available, and BDBEs.

The Xe-100 safety design approach is different from that of currently licensed LWRs which focus 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 instead focuses on preventing and limiting the release of relatively small amounts of radionuclides during normal operation and off-normal event sequences.

3.4.2 Functional Containment Approach for the Xe-100

A distinctive difference between a LWR and the Xe-100 safety design approach is how principal barriers to the release of radionuclides to the environment or defense-in-depth are demonstrated. In the current LWR designs, the principal barrier to RN release credited during severe accidents is the pressure-retaining, low-leakage containment building. The limiting LBE for the LWR is the LOCA scenario resulting from a breach of the primary coolant system. This postulated accident sequence is a rapid transient of seconds to minutes in duration characterized by a high energy release of high temperature, pressurized-water primary coolant into the containment building. The LWR LOCA is assumed to result in significant damage to the oxide fuel pellets and zirconium cladding, followed by hydrogen generation from fuel clad/steam interaction and potential hydrogen detonation. Since the initiating event is a breech in the primary coolant circuit, it is assumed that all but one of the principal barriers to RN release are compromised: the fuel cladding and reactor coolant pressure boundary. These characteristics require the containment building to absorb the stored energy of the coolant system, absorb the energy of potential detonation of hydrogen, and contain RNs released from the fuel, all reliant on the integrity of its design basis functions of pressure-retention and low-leak rates.

In contrast to LWRs, modular HTGRs use a *functional containment* approach as part of the safety case that is fundamental to the Xe-100 licensing strategy, Wang 2018, Reference 25. The functional containment is the collection of multiple independent radionuclide release barriers that, taken as a group, ensure that radionuclides are retained in the fuel and that regulatory requirements and facility design goals for release of radionuclides are met at the EAB across a broad spectrum of LBEs As shown in Figure 4, these five release barriers are (See Hanson 2018, Reference 26 and NGNP DID WP 2009, Reference 27) the:

- Fuel particle kernel (a heterogeneous mixture of UO_2 and UC_x);
- SiC and PyC coatings applied to the fuel kernel;
- Fuel matrix and fuel free zone of the fuel pebble;
- Reactor HPB; and

- Reactor building.

The most important consideration in predicting the radionuclide release rates from a HTGR core is to predict the in-service performance of the TRISO-coated fuel particles. TRISO fuel is an integrated system of multiple barriers to radionuclide release. The kernel, two PyC layers, SiC layer, and fuel pebble matrix all act together to retain fission products through different physical processes. For example, the dense TRISO coating layers (PyC and SiC) are gas-tight and act as diffusion barriers. The kernel retains many metallic (Alkali metals, Tellurium group, Alkaline earths, and Lanthanide classes) fission products and some fraction of the fission gases (Noble gases and Halogens classes). The pebble fuel matrix provides some retention of metallic fission products (e.g., retention of cesium (Alkali Metals class) by a factor of 10 and strontium (Alkaline Earths class) by a factor of more than 100) but is essentially non-retentive for the gaseous fission products (e.g., iodine and noble gases).

In some cases, the fuel itself may be the only set of barriers required to meet the top-level radionuclide control requirements. Other parts of the reactor system act as additional barriers to radionuclide release, and their effectiveness is quantified.

Each of these barriers contributes to limit the release of RNs to the environment and meet the top-level design criteria. The contribution of each of the barriers in limiting RN release to the environment is calculated for each licensing basis event as a function of the reactor response to the event. The contribution of each barrier is design, event, and radionuclide species' dependent. The phenomena that determine RN transport and release from licensing basis events are shown schematically in Figure 4.

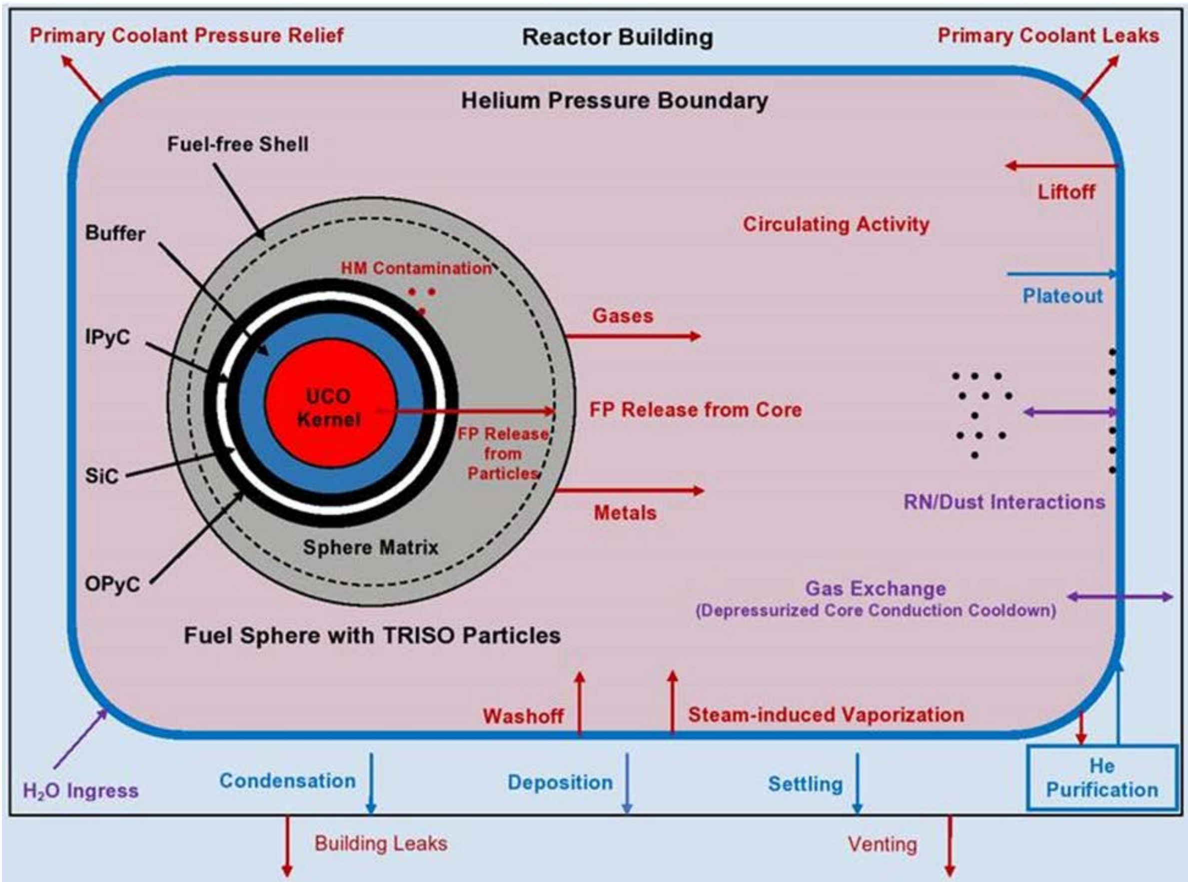

Figure 4: Pebble Bed HTGR Radionuclide Retention System

Collectively, the fuel pebble comprises the first three release barriers. Typically, the fuel particles retain the bulk of the fission products even during BDBEs. Therefore, the fuel is a "containment" barrier. In a Xe-100 reactor, failure of one of the fuel "containment" barriers, for example a broken pebble, or failure of TRISO-coated particles do not have an impact on any of the neighboring radionuclide barriers.

The Xe-100 source term is mechanistically evaluated as follows. The release fraction from the particles is calculated accounting for the as-manufactured fuel quality (e.g., the allowable heavy-metal contamination and coating defects), fuel failure during irradiation, incremental fuel failure under accident conditions, and diffusion of fission products through the intact particle coatings under normal operating and accident conditions. These factors are calculated by the X-energy code suite XSTERM on an event specific basis, as a function of fuel burnup, maximum operating temperature, maximum post-accident temperature and, where applicable, air and/or moisture contamination in the reactor helium coolant, (e.g., as a result of a steam generator tube rupture). See Reference 28 for regulatory requirements on Non-LWRs. Since the Xe-100 TRISO fuel demonstrates exceptional capability to perform the RN retention function, there is less reliance on downstream components to achieve the RN retention function and thus the functional containment approach is a primary component in the Xe-100 design. A schematic of the ex-core RN release barriers (the reactor helium pressure boundary and the reactor building) and phenomena of interest is also depicted in Figure 4.

3.4.3 Xe-100 Reactor Passive and Inherent Design Characteristics that Contribute to the Design Bases

Since their inception, e.g., Reutler 1984, Reference 22, modular HTGRs have been characterized by a strong emphasis on passive safety based on the inherent characteristics of the ceramic reactor core embedded in a steel RPV and the TRISO-coated particle fuel. The hallmark feature of modular HTGRs is a reactor and fuel design where radionuclides are largely retained in the fuel during both normal operations and a broad spectrum of off-normal events.

Passive design features are defined as design features engineered to meet their required functional design criteria without (a) the need of active systems with components such as pumps, blowers, heating ventilation and air conditioning (HVAC) or sprays requiring external power sources; (b) dependence on diesel generators, batteries or offsite power; or (c) 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, NGNP DID WP 2009, Reference 27. Xe-100 passive design features and inherent design characteristics 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 Xe-100 specific design characteristics that contribute to safety include:

- A large solid graphite moderator/reflector structure with very high temperature limits. The graphite provides a 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 UHS and the atmosphere. Heat transfers through the graphite moderator/reflector, through the reactor vessel to the reactor cavity cooling system and finally to the atmosphere. The heat sink has the capacity, without requiring any active systems, to limit fuel, RPV, and reactor cavity structural concrete temperatures so that degradation of the fuel pebble barriers is limited to acceptable levels and without degradation of the core geometry;
- A large negative temperature coefficient that inherently limits reactor power to relatively low levels under accident conditions without RCS or RSS 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; and
- 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 in a postulated breach of the reactor helium pressure boundary.

The Xe-100 exemplifies a modular 200 MWth, multi-pass, pebble-bed HTGR coupled to modern steam cycle power conversion technology. The layout of a single Xe-100 unit and the HPB is shown in Figure 5 and Figure 6 respectively.

The Xe-100 Reactor Building (Figure 7) is a vented, low-pressure building wholly contained within the NIAB as depicted in Section 5. Reactor design parameters can be found in the "Xe-100 Technology Description Technical Report," Braudt 2021, Reference 3.

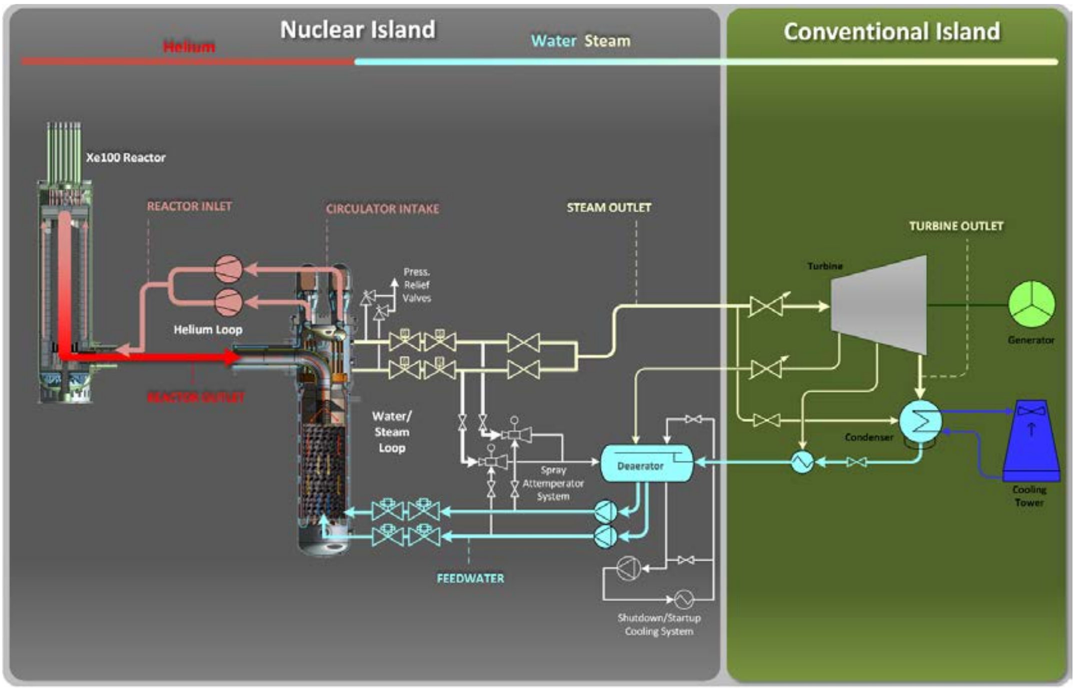

Figure 5: Schematic Layout of a Single Xe-100 Unit

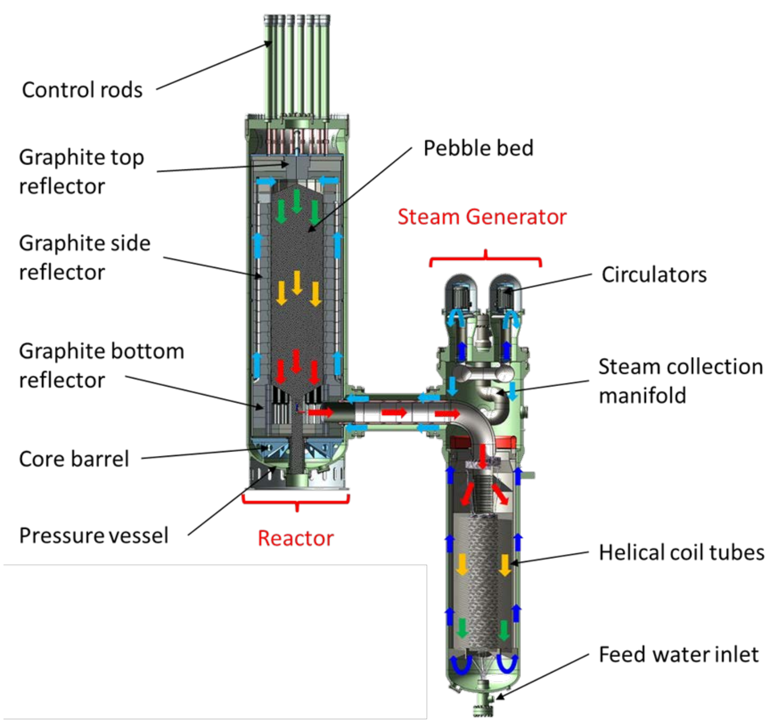

Figure 6: Schematic of Xe-100 Helium Pressure Boundary

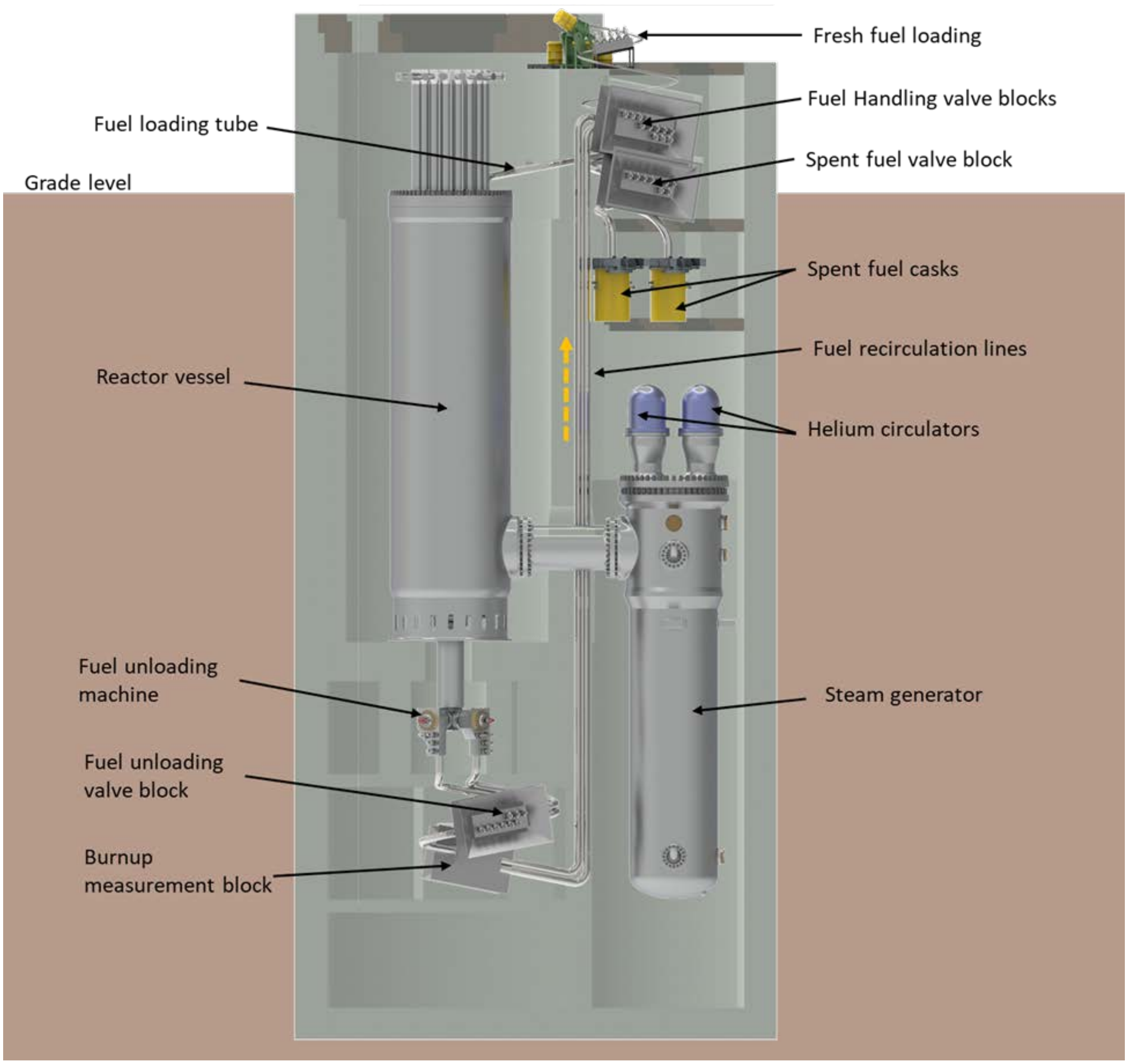

Figure 7: Schematic of the Xe-100 Reactor Building

4. Dose Calculation Approach

4.1 General Approach

Due to its robust TRISO fuel design, the Xe-100 design generates a relatively small post-accident source term compared to LWRs. X-energy has developed the XSTERM code, currently XSTERM v1.8.2 in May 2023, Reference 5, to mechanistically simulate the source term's radionuclides release from their birth in the fuel to their potential release to the environment. The code is used in combination with other thermal hydraulic software tools in the analysis of LBEs. The smaller source term enables a reduced plant footprint as reduced postulated post-accident doses to the public provide a technical bases for performance-based emergency planning zone (EPZ) sizing.

An XSTERM code module, XDIS, is used to calculate post-accident doses to the plant EAB / LPZ as well as to the CR location to evaluate doses to receptors of interest. XDIS generates dose dispersion factors based on user inputs or utilizes dispersion factors calculated elsewhere and input by the user. The code calculates offsite doses based on a Gaussian plume model.

X-energy is in the process of finalizing a list and classification of Xe-100 isotopes significant to dose calculations. That information is expected to be included in the MST LTR to be submitted at a later date.

A generic set of dispersion factors has been developed to provide generally conservative values as part of the standard Xe-100 technology development process. This allows X-energy to evaluate the Xe-100 LBEs in a manner similar to other reactor technologies that consider a range of prospective project sites defined by a parameter envelope. These conservative dispersion factors are calculated for a generic site using applicable regulatory guidance and the theory and site field data presented in Reference 16. This methodology is described in Section 5.1 and ensures that conservative post-accident doses are calculated for most locations within the continental United States. Once a site is selected for a project, site-specific evaluations will be conducted to either 1) affirm the Xe-100 analysis results using these generic dispersion factors are conservatively bounding, or 2) provide site-specific analysis results using dispersion factors developed during site characterization.

4.2 Dispersion Factor Calculations

Following project site selection, X-energy plans to use the ARCON code, Reference 42, to calculate the Xe-100 plant dispersion factors based on site-specific meteorology data sources in accordance with RG 1.249, Reference 40 and incorporate those results into the project's license application material. Note that in accordance to Section B of RG 1.249, "ARCON refers to both the ARCON96 and ARCON 2.0 versions of the code. For consistency across versions of the code, and because the updated ARCON 2.0 version only updated the user interface and not the underlying dispersion algorithms, this RG will refer to the code simply as ARCON when the discussion is applicable to either version." X-energy follows this convention in this LTR.

4.3 Dose Calculations

Using the conservative dispersion factors described in Sections 4.1and 5.1, the user input dispersion factor option of the XDIS module will be used to calculate post-accident doses for LBEs. This option of XDIS allows the user to input dispersion factors calculated outside the code to generate doses based on specific user requirements such as ground level releases and conservative meteorological conditions. The theoretical methodology for these calculations is described in Section 5.2.

4.4 Execution and Evaluations of AOOs, DBEs, and BDBEs Analyses

Per the X-energy Risk Informed Performance Based (RIPB) LTR (Reference 30), the NEI 18-04 (Reference 6) methodology and NEI 21-07 (Reference 16) informed processes are used to develop the Xe-100 design and licensing bases. These methods do not require deterministic analyses to be performed for AOOs, DBEs, and BDBEs. For the analyses identified as AOOs, DBEs and BDBEs using NEI 18-04, the evaluation model and methods described in Sections 5 and 6 of this report will be used to calculate atmospheric dispersion factors and doses at the EAB / LPZ and the CR.

4.5 Execution and Evaluation of DBAs and External Hazards

These methods also require that specifically defined deterministic analyses be performed for DBAs to evaluate the effectiveness of safety-related SSCs in performing their required safety functions. For analyses identified as DBAs using NEI 18-04, the evaluation model and methods described in Sections 5 and 6 of this report will be used to calculate atmospheric dispersion factors and public doses at the EAB / LPZ. In accordance with the Xe-100 Principal Design Criteria LTR, Reference 11, the CR is not credited in the performance of any required safety functions in these DBAs and therefore no CR dose is evaluated for these deterministic events.

External hazards are still in the process of being identified and evaluated for the standard Xe-100 design. It is expected that evaluations of the plant's performance in external hazard event sequences will use the same dispersion and dose methodology as other internal events.

5. Methodology Overview

5.1 Atmospheric Dispersion Factors Calculation Methodology

As described in Reference 40, RG 1.249, Section B:

"In the mid-1980s, the NRC staff determined that its design-basis accident atmospheric dispersion modeling guidance, which included RG 1.145 and PAVAN, significantly overpredicted concentrations during light winds in the vicinity of buildings, and the NRC embarked on a series of studies that ultimately resulted in the ARCON96 model. The ARCON model is based on field measurements taken at seven reactor sites. The downwind distances of the field measurements ranged from locations on and adjacent to buildings out to distances of 1,200 m (3937 ft). The results were a set of revised diffusion coefficients that had low wind speed and building wake corrections. The resulting dispersion algorithms improved model performance by reducing overpredictions without significantly increasing underpredictions. The staff subsequently endorsed, in large part, ARCON96 in RG 1.194 as a method for determining atmospheric relative concentrations in support of design-basis radiological habitability assessments for the control room.

"The NRC has determined that the ARCON computer code, which was developed to model shorter distances in the vicinity of buildings typical of control room habitability dose evaluations, is acceptable for modeling EAB and LPZ χ/Q values at relatively short distances. The ARCON dispersion algorithms are based on field measurements taken out to distances of 1,200 m (3,937 ft) (Ramsdell et. al,1998). Therefore, this guidance is applicable to EAB and LPZ distances from source locations within the nuclear island to a distance of 1,200 m (3,937 ft)."

As indicated in Sections 4.1 and 4.2, following site selection, X-energy plans to use the ARCON code, ARCON96, References 42 and 43, to calculate the Xe-100 plant dispersion factors based on site-specific meteorology in accordance with RG 1.249, Reference 40. Prior to site selection and in the absence of site-specific data, conservative dispersion factors are calculated for a generic site using the theory and site field data presented in PNL-10286, Reference 41 and updated in Reference 12 of 1.249, Reference 16. The following sections describe the development of the generic site dispersion factors.

5.1.1 Inputs, Methodology, and Assumptions

5.1.1.1 Inputs

5.1.1.1.1 Distance from Nuclear Island Auxiliary Building to the Control Room

Modeling of release events for the Xe-100 is based on the assumed performance of the NIAB as the release point to the nearest receptor of interest location. The distance from the edge of the nearest NIAB to the CR is determined as 16.6 m. This distance is based on information from Reference 33 and shown in Figure 8 where the release is from the closest side of the NIAB to the nearest edge of the Controls and Electrical Building (CEB) where the CR is located. This distance is used as a conservative bounding value since it does not include the distance to the air intake from the edge of the CEB. This may be updated to reflect the actual CR HVAC intake location once the CEB HVAC design is finalized. The orientation of this drawing may not represent the actual site orientation (i.e., rotation) and is not to scale.

5.1.1.1.2 Distance to Exclusion Area Boundary

Based on a four unit Xe-100 plant site, the distance to the EAB and LPZ is determined as 400 meters in accordance with Reference 34; see Figure 9 for additional detail.

Note as previously mentioned the EAB and LPZ are taken as the same distance of 400 m from the edge of the NIAB in this case, as it is a design objective of the Xe-100 that they are the same if possible.

5.1.1.1.3 Nuclear Island Auxiliary Building Cross Section

A NIAB area of 746 m^2 (21.25 m by 35.1 m) is determined as the minimum vertical cross-section of the NIAB in accordance with Reference 33. The height conservatively does not include the building parapet.

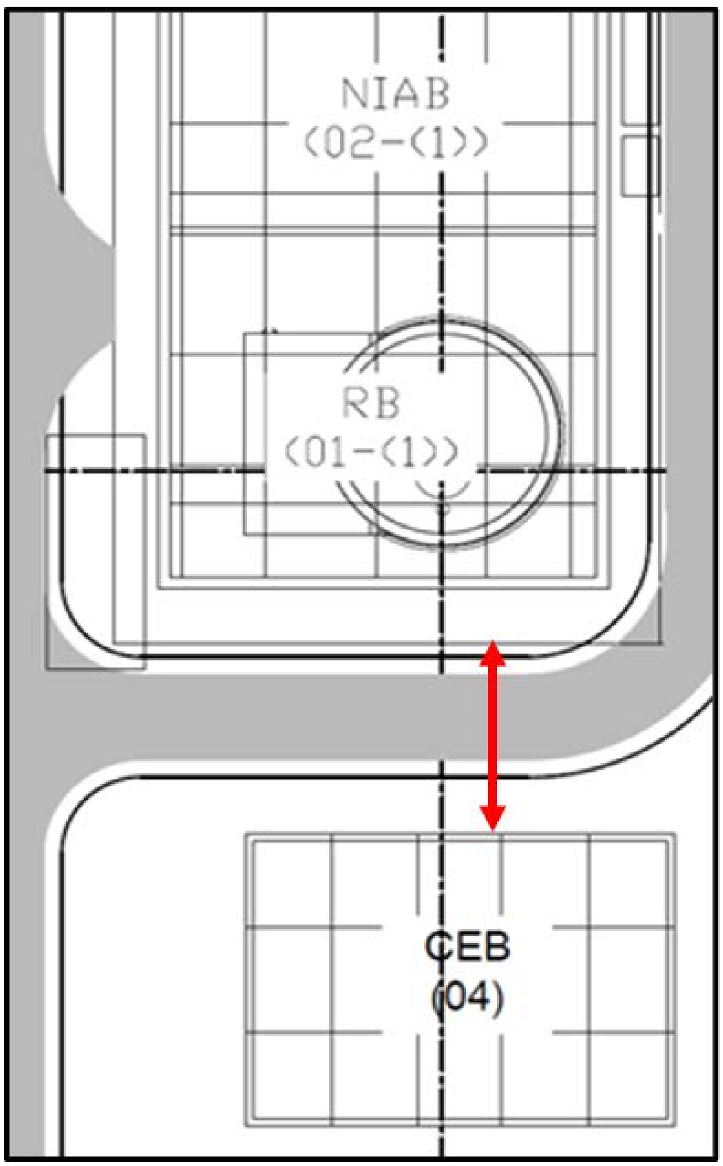

Figure 8: Representative Control Room Distance to the NIAB

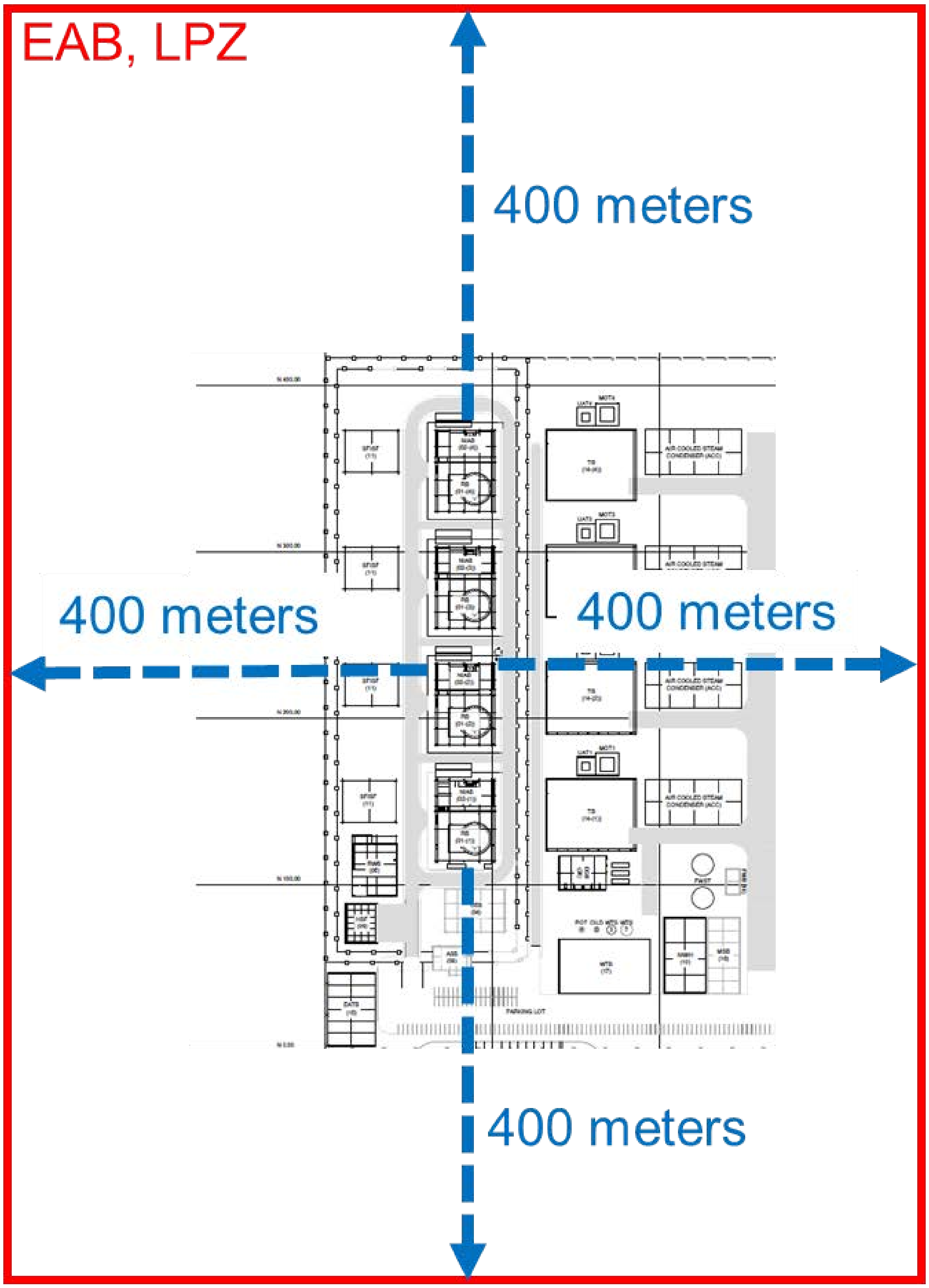

Figure 9: Xe-100 Four Reactor Plant Layout Site Schematic

5.1.1.2 Methodology

5.1.1.2.1 EAB / LPZ Dispersion Factors Methodology

In accordance with RG 1.249, Reference 40, Figure 10 depicts how an applicant may use the building locations within the PBA to determine the most limiting distance from the edge of the building to the EAB / LPZ. The preferred, and most conservative method is to use the limiting distance from the nearest building edge and apply that distance over all 16 sectors, thus creating a uniform circle around the PBA. As such, the edge of the NIAB is the appropriate LBE release location as this minimizes distance to the receptor. While the Xe-100 design features a short stack, it is anticipated that this stack and the balance of the nuclear island HVAC system will be not be safety-related and therefore should not be credited for performance in DBAs.

Per RG 1.145, Reference 31, Regulatory Position 1.3, dispersion factors at 10-meter level wind speed less than 6 mph and [[ ]]P can be calculated through the selective use of the following set of equations for ground level concentrations at the plume centerline.

$$\frac{\chi}{Q} = \frac{1}{U\left(\pi\sigma_y\sigma_z + \frac{A}{2}\right)} \quad \textbf{(1)}$$

$$\frac{\chi}{Q} = \frac{1}{U(3\pi\sigma_y\sigma_z)} \quad \textbf{(2)}$$

$$\frac{\chi}{Q} = \frac{1}{U(\pi\Sigma y\sigma_z)} \quad \textbf{(3)}$$

Where:

χ/Q = Atmospheric dispersion factor [s/m^3]

U = Wind speed at 10-meter elevation [m/s]

σ_y, σ_z = Lateral and vertical plume spread dispersion standard deviations [m]

A = Smallest vertical-plane cross-sectional area of the release building [m^2]

Σ_y = Lateral plume spread with meander and building wake effects as a function of stability class and wind speed [m], $\Sigma_y = M\sigma_y$ for distances <800 meters, where M is the meander correction factor taken from Figure 3 of RG 1.145, Reference 31.

Results from Equations 1 and 2 are compared and the higher selected. This value is then be compared with the result from Equation 3 and the lower of these two is selected for use.

Values for the σ_y and σ_z dispersion standard deviations are calculated based on the following equations provided in Reference 36, based on standard deviation of azimuthal wind direction (σ_θ) and [[ ]]P see Section 5.1.1.2.1, Assumption 1.

$$\sigma_y = 0.0722x^{0.9031} \quad (4)$$

$$\sigma_z\ (x < 100m) = 0.053x^{0.814} \quad (5)$$

$$\sigma_z\ (100m < x < 1000m) = 0.086x^{0.74} - 0.35 \quad (6)$$

Where x = distance in meters.

5.1.1.2.1.1 EAB / LPZ Dispersion Factors Methodology Assumptions

The methodology and calculations described in Section 5.1.1.2.1 require some further assumptions and justification as listed below:

1. A wind speed of **1 m/s** and [[ ]]P are assumed. These are conservative assumptions as previously suggested in, now withdrawn, RG 1.3 (Reference 37) and RG 1.4 (Reference 38), Regulatory Positions 2.h and 2.g respectively, and RG 1.194 (Reference 39), Section 4.2, for *generic sites* at the 0 – 8-hour ground level release atmospheric conditions. Based on 1 m/s wind speed and [[ ]]P the meander correction factor **M=4** is determined from Figure 3 of RG 1.145, Reference 31.
2. [[

 ]]P
3. [[

]]P

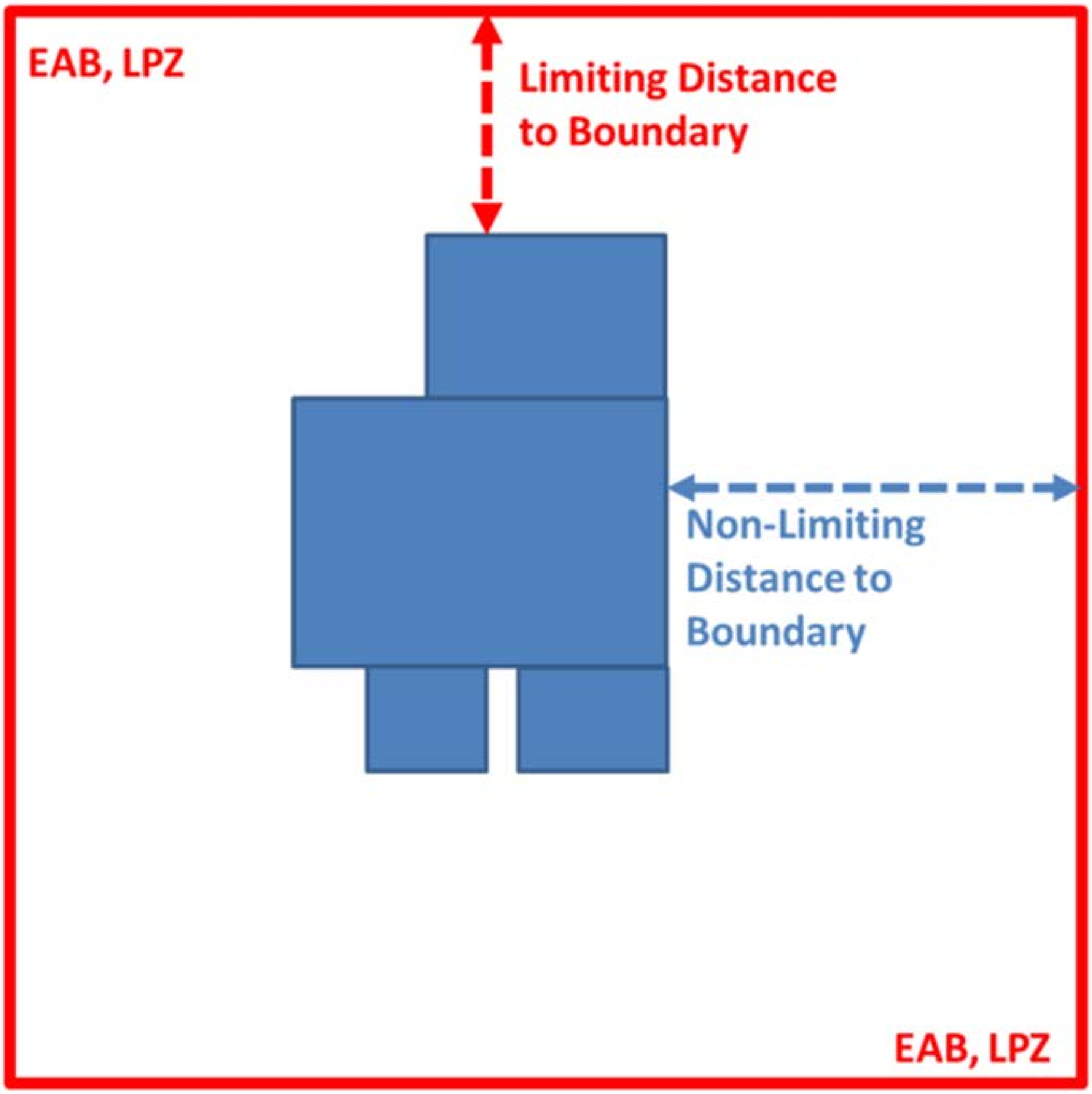

Figure 10: RG 1.249 Example of Limiting and Non-Limiting Distances to the EAB / LPZ

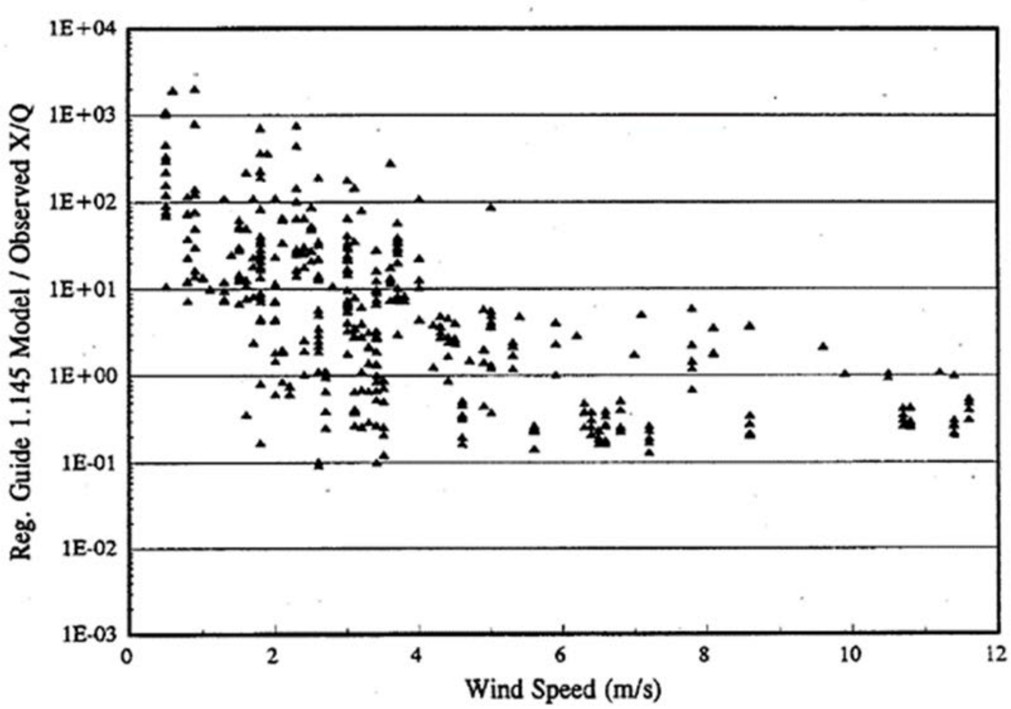

Figure 11: Bias in RG 1.145 Model Concentration Predictions vs Site Data

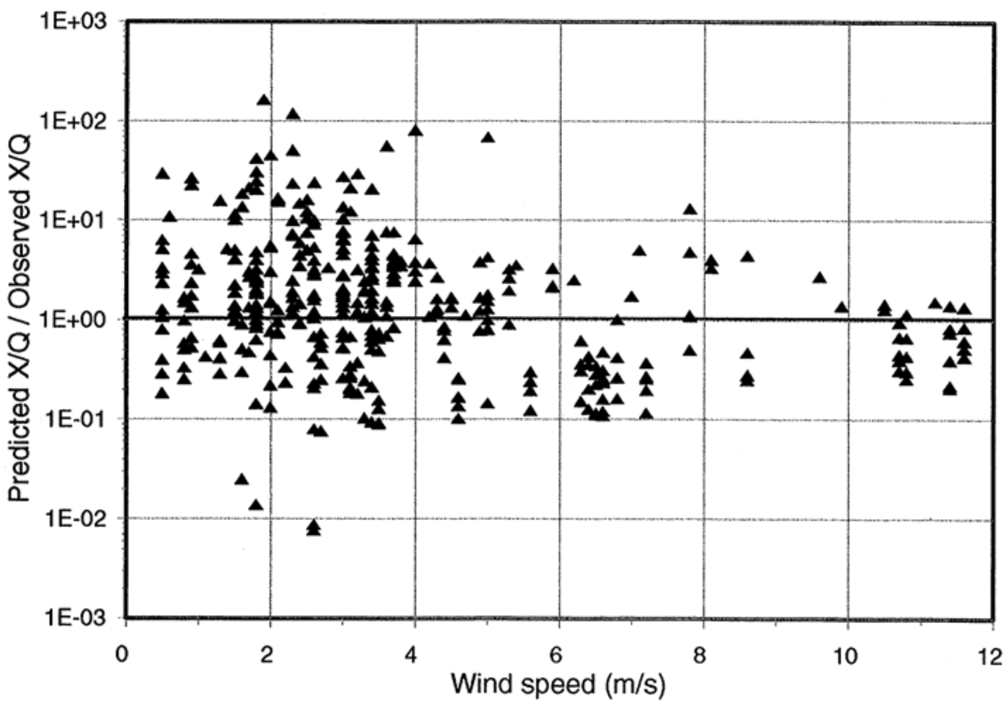

Figure 12: Bias in ARCON Model Concentration Predictions vs Site Data

5.1.1.2.2 Control Room Dispersion Factors Methodology

The CR dose calculation methodology is described in RG 1.194, Reference 39 based on a diffuse source-point receptor methodology. Per RG 1.194, Section 4.2, Equation 8 is appropriate when the assumed activity is released from many points on the surface of the building. The methodology is also appropriate for point source-point receptors where the difference in elevation between the source and the receptor is greater than 30 percent of the height of the upwind building, typically the containment of an LWR, which creates the most significant building wake impact. Per Section need 5.1.1.1.3, the NIAB is 21.25 m high and the CEB containing the CR is 10 m high, Reference 33, thus the entire potential CR receptor point's locations are higher than the 30% NIAB height limit of 6.4 m. Equation 8 of RG 1.194 is reproduced below:

$$\frac{X}{Q} = \left[U\left(\pi\sigma_y\sigma_z + \frac{A}{K+2}\right)\right]^{-1} \quad (7)$$

Where:

χ/Q = Relative concentration at plume centerline for time interval 0-8 hours, s/m^3

U = Wind speed at a height of 10 meters, m/s

σ_y,σ_y = Standard deviation of the gas concentration in the horizontal and vertical cross wind directions evaluated at distance x and by stability class, m

K = $3/(s/d)^{1.4}$

s = Shortest distance between the NIAB surface and CR receptor location, m

d = Diameter or width of NIAB, m

A = Cross-section area of NIAB, m^2

5.1.1.2.3 CR Dispersion Factors Methodology Assumptions

The CR dispersion factor calculations are based on a Diffuse Source to Point Receptor model introduced by Murphy in Reference 42. Therefore, no additional reduction factor is appropriate as in Section 5.1.1.2.1, items 2 and 3 bias between the RG 1.145 and RG 1.194 ARCON Model used in EAB / LPZ dispersion factors.

5.2 XSTERM Code Suite Overview

As part of X-energy's radiological code development process, a comprehensive software code, XSTERM, has been developed for the quantification of the Xe-100 source terms and dose calculations.

The code includes modules for:

- Thermal hydraulic modeling and transient analysis (e.g., reactor physics and thermal hydraulic simulations);
- Radionuclide production, decay, transmutation and transport in the fuel sphere;
- Radionuclide retention, transport and release from fuel pebbles into the helium;

- Transport and distribution of radionuclides, including dust effects, within the HPB;
- Transport of radionuclides into the reactor building and the environment; and
- Point-source point-receptor dose calculations.

XSTERM (Reference 5) includes several code modules that operate in a chain fashion to evaluate the source term and subsequent dose consequences of Xe-100 post-accident evaluation models. Each code module has specific modeling requirements. Figure 13 shows the interaction between the individual XSTERM code modules. Applications of XSTERM include evaluating radionuclide design criteria, performing dose consequence calculations for LBEs identified by probabilistic risk assessments to develop the frequency-consequence curves specified in NEI 18-04, Reference 6, and calculating the source term and dose consequences of deterministically evaluated DBAs.

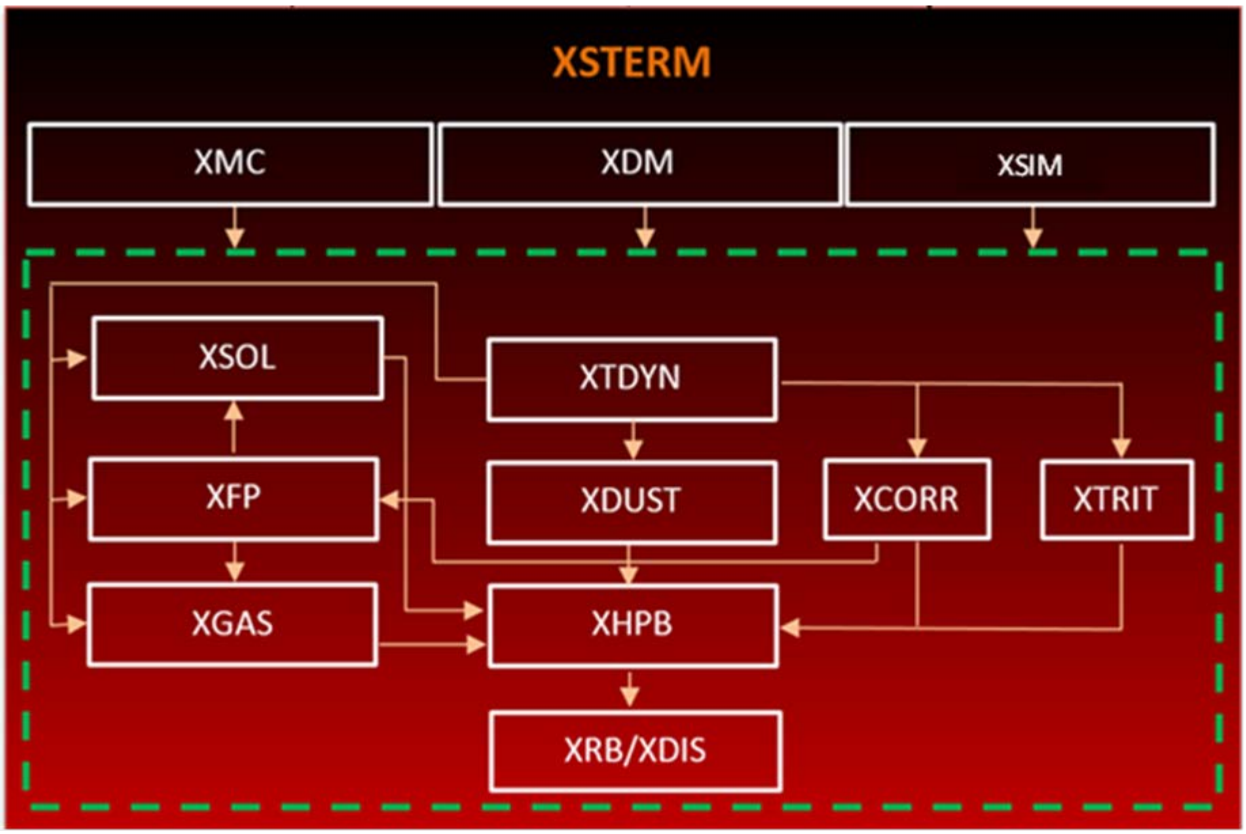

Figure 13: Xe-100 MST Analysis Codes

5.2.1 XDIS Code

Once released to the environment in a postulated event, radionuclides are transported to receptors via atmospheric dispersion phenomena, resulting in potential doses to plant workers and members of the public. These phenomena are modeled, and doses are calculated in the XDIS module of XSTERM.

5.2.1.1 Overview of the XDIS Code

The XDIS module is described in Reference 5. XDIS receives release data for dose-significant radionuclides either from XSTERM's XRB module during an "integrated run" or as a separate user-generated source term *release* file (see Section 5.2.1.2). Running XDIS with a user-input source term is referred to as a "standalone" mode. The code uses a Gaussian plume model described in Section 5.3 to calculate CR and EAB / LPZ doses caused by the affected Xe-100 unit for the event sequence.

5.2.1.2 Phenomena Modeled by XDIS

The XDIS module performs the following main functions:

- Data initialization. These data include plume dose factors for beta air, beta skin, beta body, gamma air, breathing rates, stack height, distance from release point, inhalation dose factors (i.e., liver, bone, total body, thyroid, kidney, lung, gastro), etc.;
- Dispersion factors for the selected atmospheric conditions and wind speed. Currently there are six atmospheric condition options (A-F) available in XDIS. A user input dispersion factor is also an option;
- Calculation of dose based on user input source term or from upstream XSTERM modules from the reactor building as a function of time; and
- The Gaussian plume exposure model calculates:
    - Gamma air dose
    - Beta air dose
    - Gamma whole body
    - Thyroid CEDE (Committed Effective Dose Equivalent)
    - TEDE (Total Effective Dose Equivalent)
    - Data logging of transient dose

5.3 Dose Calculation Methodology

There are two primary calculations performed in XDIS; atmospheric dispersion factors and doses. A user input dispersion factor option is available to calculate the dose and bypass the XDIS dispersion factors calculations. As documented in Section 5.1, the dispersion factors in the Xe-100 safety analyses will be calculated independently and used via the XDIS user dispersion factors input option.

The XSTERM source terms used by XDIS are added either directly from an input file if XDIS is run in "standalone" mode or released activity from the XRB module (the Reactor Building module) during an "integrated run."

The Gaussian Plume Dose Model in XDIS is based on the HotSpot code, Section 7 of Reference 45 as follows in Equation 8:

$$C(x,y,z,H) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} \exp[-\frac{\lambda x}{u}]DF(x) \qquad \textbf{(8)}$$

Where:

C = Time-integrated atmospheric concentration (Ci-s)/(m^3).

Q = Source term (Ci).

H = Effective release height (m).

λ= Radioactive decay constant (s^{-1}).

x = Downwind distance (m).

y = Crosswind distance (m).

z = Vertical axis distance (m).

σ_y = Standard deviation of the integrated concentration distribution in the crosswind direction (m).

σ_z = Standard deviation of the integrated concentration distribution in the vertical direction (m).

u = Average wind speed at the effective release height (m/s).

DF(x) = Plume Depletion factor. The Plume Depletion (DF) factor accounts for ground deposition during the release. Consistent with Regulatory Position 4.1.7, of RG 1.183, Reference 29, no correction is made for the effluent plume deposition on the ground, thus the DF factor is not credited in XDIS dose calculations.

Radioactive decay of the plume, the $\exp[-\frac{\lambda x}{u}]$ term in Equation 8, is conservatively not credited.

When doses are calculated using "user input" dispersion factors, the right-hand side of Equation 8 can be re-arranged to:

$$Q(Ci)*\chi/Q\ (s/m^3)*\exp[-\frac{\lambda x}{u}]DF(x) = Q(Ci)*\chi/Q\ (s/m^3) \qquad \textbf{(8a)}$$

Since both $\exp[-\frac{\lambda x}{u}]$ and DF(x) are conservatively not credited and assumed as 1.0 as indicated above, the χ/Q term can be demonstrated by the balance of the terms in this equation.

The dose is then calculated using Equation 8a, or the dose in Ci (or Bq) times the χ/Q (s/m^3) times the appropriate activity to Dose Conversion Factor (DCF) for submersion or inhalation. This methodology is verified in Section 7 of this LTR.

5.3.1 EAB / LPZ Doses

Based on the above, XDIS is used to calculate isotopic EAB / LPZ Immersion doses as follows:

Isotopic EAB / LPZ Whole Body Dose = An (Bq) * χ/Q (s/m^3) * DCF (Sv-m^3/Bq-s) * Decay Factor **(9)**

Where:

A_n = isotopic activity released in Bq

χ/Q = user input as calculated per Table 3 of Section 6.2

DCF = isotopic Immersion Dose Conversion Factor in accordance with Table I.I.I.1 of US EPA FGR No. 12, Reference 46, Sv-m^3/Bq-s.

Decay Factor = $\exp\left[-\frac{\lambda x}{u}\right]$, unitless, radioactive decay of the plume is conservatively not credited, assume 1.0.

Similarly, the isotopic EAB / LPZ Whole Body **Inhaled Dose** is calculated using an inhalation DCF per Table 2.1 of US EPA FGR No. 11, Reference 47, Sv-/Bq, combined with breathing rates (BR) in accordance with Regulatory Position 4.1.3 of RG 1.183, Reference 29, in m^3/s.

5.3.2 Control Room (CR) Doses

CR Effective Dose Equivalent (EDE) immersion and inhalation doses to operators are calculated similarly to the EAB / LPZ doses using the appropriate distance to the CR nearest wall and the CR Dispersion Factor Methodology, see Table 3 in Section 6.2.

CR dose to operators' guidance is provided in Regulatory Position 4.2 of RG 1.183. The Xe-100 CR dose is calculated assuming **no credit** for:

- CR building shielding
- CR isolation
- HVAC filters
- personal protective equipment or prophylactic drugs

CR doses associated with radiation shine from the reactor building, direct or sky-shine, is deemed negligible but will be confirmed by analysis and described in future license applications.

CR operator occupancy factors and breathing rates will be used in accordance to RG 1.183, Regulatory Position 4.2.6. The RG 1.183 occupancy factors may be revised as applicable to Xe-100 post-accident operations and documented in a revision to this report if required.

6. Generic Site Atmospheric Dispersion Factors Calculations

6.1 Generic Site Dispersion, Standard Deviation Calculations

Using Equations (4)-(6), dispersion standard deviations (σy & σz) are determined at 400 meters and 16.6 meters (See Sections 5.1.1.1.1, and 5.1.1.1.2) respectively for inputs and assumptions):

Table 2: Generic Site Dispersion Standard Deviations

Dispersion Coefficient [m]	16.6 meters	400 meters
	(Control Room)	(EAB / LPZ)
σ_y (σ_θ=0)	[[	]]^P
σ_z [[		]]^P

6.2 Generic Site Dispersion Calculations

Using Equations (1), (2),(3), and (7), the assumptions in Section 5.1.1.2 and standard deviations from Table 2, generic atmospheric dispersion factors for 16.6 meters (Control Room) and 400 meters (EAB / LPZ) distance are calculated and summarized in Table 3. At the 400m EAB / LPZ, an example is shown below using Equation (2).

$$\frac{X}{Q}_{400,[[\quad]]^P} = [[\quad]]^p$$

Using Equation (7), the Control Room generic site atmospheric dispersion factor is calculated as follows:

$$\frac{X}{Q}_{CR,\ [[\quad]]^P} = [[\quad]]^p = 1.39 \times 10^{-2}\ s/m^2$$

In Table 3, the appropriate dispersion factor for each equation is italicized based on the logic from RG 1.145, Reference 31, addressed in Section 5.1.1.2. [[

]]^P

Table 3: Calculated Generic Site Dispersion Factors

RG 1.145 Eqn. No.	**EAB / LPZ (400 m) DBA Dispersion Factor [s/m^3]**	**EAB / LPZ (400 m) non DBA Dispersion Factor [s/m^3]**	**Control Room (16.6 m) Dispersion Factor [s/m^3]**
[[			
			]]^p
Reduction Factor	[[		]]^p
Final	**3.57E-04**	**1.89E-04**	**1.39E-02**

6.3 Generic Site Dispersion Factors Summary

Generic site atmospheric dispersion factors appropriate for DBA analysis are calculated in this report. These dispersion factors are based on existing regulatory precedent in accordance with RG 1.145, RG 1.194, and RG 1.249 (References 31, 39 and 40). The dispersion factors reflect ground-level (EAB / LPZ only) non-location-specific, non-directional releases and are intended to be bounding for potential Xe-100 sites. A summary of the results is presented in Table 4.

Generic site atmospheric dispersion factors documented in this report will be validated or replaced using site-specific data once Xe-100 project sites are selected and site-specific meteorology is obtained and/or collected. Given the expected LBE's relatively small releases, X-energy intends to use the generic atmospheric dispersion factors for as many events as possible. Site-specific dispersion factors will be calculated for all sites but are expected to replace the generic factors only if the additional margin is required or the site-specific values are not bounded by the generic values.

Table 4: Generic Site Atmospheric Dispersion Factors Summary

Dose Calculation	LBE	Release Type	Reduction Factor Used	Dispersion Factor (s/m³)
DBA EAB / LPZ	DBAs Only	Ground level, point source, NIAB edge	[[ ]]P	3.57E-04
Non-DBA EAB / LPZ	AOOs, DBEs, and BDBEs	Ground level, point source, NIAB edge	[[ ]]P	1.89E-04
Control Room	AOOs, DBEs, & BDBEs (not DBAs)	Diffuse area from NIAB	[[ ]]P	1.39E-02

This data is shown on Figure 14 as a function of a potential EAB / LPZ distance up to 400 meters.

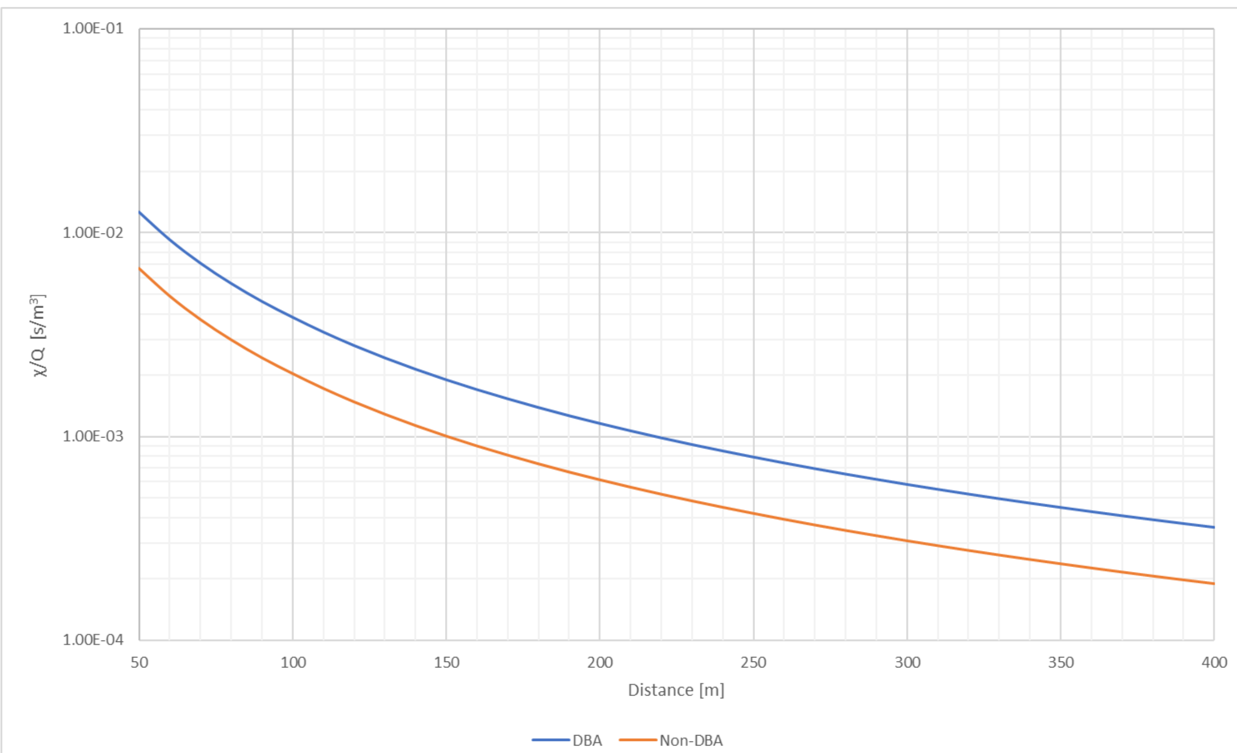

Figure 14: EAB / LPZ Generic Dispersion Factors vs. Distance

7. XDIS Dose Methodology Verification

As indicated in Section 4.3, conservative generic site dispersion factors are used via the "user input dispersion factor" option of the XDIS module to calculate post-accident doses for LBEs. The XDIS dose calculation methodology is described in Section 5.3 and verified in this Section using hand calculations and an alternate software code.

RADTRAD, Reference 48, Acceptance Test Case 1 has been selected for this purpose. RADTRAD is a well-known nuclear plant post-accident radiological dose calculation code. The test case simulates a Pressurized Water Reactor (PWR) containment release with the following characteristics. Note that the reactor type is not relevant as this calculation simply tests the capability of XDIS to calculate radionuclide doses independent of the reactor type. In accordance with Reference 48, RADTRAD Acceptance Test Case 1 involves:

- Plant Power Level = 1932 MWt
- Instantaneous TID-1484 I-131 release into a 0.1730E+7 ft^3 containment
- Containment leak into the environment @ 0.12%/day
- I-131 Core Inventory = 2.452E+04 Ci/MWt
- EAB χ/Q of 0.100E-02 sec/m^3 at 0-2 hours
- Breathing Rate, BR (0-8 hour) = 3.47E-04 m^3/sec
- I-131 Release Fraction = 0.25 @ t=0 hours (TID plateout)

7.1 Hand Calculation of Test Case EAB Dose

Calculate I-131 Total Release in Ci:

2.453E04 Ci/MWt * 1932 MWt = 47,391,960 Ci of I-131

Building Release 0.0012/24 hrs or 0.00005/hr

Total building release fraction = 0.00005/hr * 2 hrs = 0.0001

Total building release = 47,391,960 * 0.0001 = 4739.196 Ci for 2 hours

Total I-131 Released = 4739.196 Ci * 0.25 release fraction = 1184.75 Ci @ 2 hours**

1184.75 Ci * 3.7E+10 Bq/Ci = 4.3836E+13 Bq @ 2 hours**

Calculate EAB Dose:

Dose (Immersion) = A_n (Bq) * χ/Q (s/m^3) * DCF (Sv-m^3/Bq-s), Equation 34, Reference 48

Effective DCF I-131 (Immersion) = 1.82E-14 Sv-m^3/Bq-s, Table I.I.I.1, Reference 46

Dose (Immersion) = 4.3836E+13 Bq * 1.0E-03 s/m^3 * 1.82E-14 Sv-m^3/Bq-s

Dose (Immersion) = 0.0007978 Sv = 0.0007978 * 100 Rem/Sv = 0.08 Rem TEDE

Dose (Inhalation) = An (Bq) * χ/Q (s/m^3) * BR (m^3/s) * DCF (Sv/Bq) Equation 36, Reference 48

Effective DCF I-131 (Inhalation) = 8.89E-09 Sv/Bq, Table 2.1, Reference 47

Dose (Inhalation) = 4.3836E+13 Bq * 1.0E-03 s/m^3 * 3.47E-04 m^3/sec * 8.89E-09 Sv/Bq

Dose (Inhalation) = 0.1352 Sv = 0.1352 * 100 Rem/Sv = 13.52 Rem TEDE

Total EAB Dose = Dose (Immersion) + Dose (Inhalation) = 0.08 + 13.52 = 13.6 Rem TEDE**

****matches Reference 48, Supplement 2 page 15**

7.2 XDIS with X/Q Input Test Case EAB Dose

The test case was executed with XDIS and the results documented in Figure 15 and listed in Table 5. Currently, XDIS dose calculations with user input dispersion factors can only be performed at one distance per X/Q input. This model used the 0-2 hr BR of 3.47E-04 m^3/s to match the RADTRAD Test Case.

The XDIS results in this case calculate an immersion dose (7.978E-4 Sv or 0.08 Rem TEDE) almost exactly as the RADTRAD and hand calculation, but the inhalation dose is higher by about a factor of 1.008: 13.52 Rem for RADTRAD/Hand Calculation and 13.64 Rem for XDIS. The difference is the inhalation dose is due to a code default at 0-2 hr BR of 3.50E-04 m^3/s. Taking that difference into consideration, the XDIS inhalation dose scales to 13.53 Rem TEDE and the calculated total dose is 13.61 Rem TEDE.

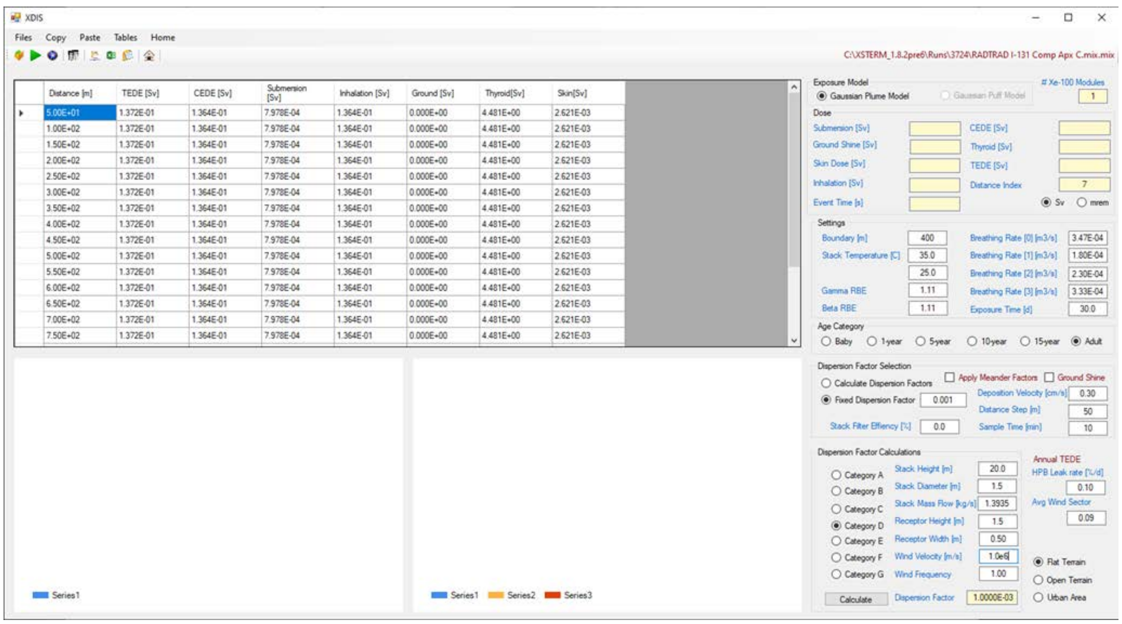

Figure 15: XDIS Test Case EAB Dose Results

7.3 XDIS Dose Methodology Verification Summary

The results of the XDIS Dose Calculation methodology verification are summarized in Table 5. The results show good agreement and demonstrate that XDIS calculates accurate and conservative doses using the dispersion factor input option.

Table 5: XDIS Dose Methodology Verification Results

Dose Calculation Methodology	2 hr EAB Dose (Rem TEDE)
RADTRAD Version 3.03	13.6 (Reference 48, Supplement 2)
Analytical	13.6 (Section 7.1)
XDIS with χ/Q Input	13.61 (Section 7.2)

8. Conclusions

This report documents the atmospheric dispersion factors and dose methodology used in the radiological safety evaluation of Xe-100 LBEs.

The conservative generic site atmospheric dispersion factors documented in this report will be evaluated for bounding results or replaced with site-specific data once Xe-100 project sites are selected and site-specific meteorology is obtained and/or collected.

A dose calculation approach using the XDIS module of the XSTERM code has been verified and validated.

X-energy is requesting NRC approval of this methodology for use by prospective applicants for Construction Permits, Operating Licenses, Standard Design Approvals or Certifications, Early Site Permits, Combined Licenses, or Manufacturing Licenses for the Xe-100 technology or project as an appropriate means to calculate dose consequences of AOOs, DBEs, and BDBEs for evaluation of frequency-consequence targets and quantitative health objectives (QHOs) and to evaluate DBA consequences to ensure that performance of the Xe-100 meets the dose limits in 10 CFR 50.34. Such analyses are required by 10 CFR 50.34(a)(1)(D) (Construction Permits), 10 CFR 50.34(b)(1) (Operating Licenses), 10 CFR 52.17(a)(1)(ix) (Early Site Permits), 10 CFR 52.47(a)(2)(iv) (Design Certifications), 10 CFR 52.79(a)(1)(vi) (Combined Licenses), 10 CFR 52.137(a)(2)(iv) (Design Approvals), and 10 CFR 52.157(d) (Manufacturing Licenses).

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