



UNITED STATES  
NUCLEAR REGULATORY COMMISSION  
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OFFICE OF NUCLEAR REACTOR REGULATION

REGULATORY AUDIT REPORT

XE-100 TOPICAL REPORTS:

REACTOR CORE DESIGN METHODS AND ANALYSIS TOPICAL REPORT

TRANSIENT AND SAFETY ANALYSIS METHODOLOGY TOPICAL REPORT

MECHANISTIC SOURCE TERM APPROACH TOPICAL REPORT

GOTHIC AND FLOWNEX ANALYSIS CODES QUALIFICATION TOPICAL REPORT

X ENERGY, LLC.

DOCKET NO.: 99902071

## 1.0 BACKGROUND

By letter dated April 8, 2024, X-energy submitted TR 2024-XE-NRC-009, "Xe-100 Licensing Topical Reactor Core Design Methods and Analysis," Revision 2 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML24099A183) for NRC staff review. This TR provides the methods and computer codes used to support the Xe-100 reactor core design and analysis.

By letter dated April 30, 2024, X-energy submitted TR 2024-XE-NRC-010, "Xe-100 Licensing Topical Report, Licensing Topical Report Transient and Safety Analysis Methodology," Revision 1 (hereafter referred to as TSAM) (ML24121A285) for NRC staff review. TSAM provides the approach used to develop an evaluation model (EM) and analysis methods used for transient and safety analyses for the Xe-100 reactor.

By letter dated May 10, 2024, X-energy submitted TR 2024-XE-NRC-011, "Xe-100 Licensing Topical Report Mechanistic Source Term Approach," (ML24131A146) for NRC staff review. This TR describes the functional containment and mechanistic source term methodology used in Xe-100 design and safety analysis and the plans to verify and validate the computer code that model these physical phenomena.

By letter dated May 22, 2024, X-energy submitted TR 2024-XE-NRC-012, "Xe-100 Licensing Topical Report GOthic and Flownex Analysis Codes Qualification, Revision 2" (hereafter referred to as GFQ) (ML24143A192) for NRC staff review. This TR describes the GOthic and Flownex models and computer codes that represent the thermal-hydraulic phenomena associated with the transient and safety analysis EM for the Xe-100 reactor.

The NRC staff conducted a regulatory audit as part of its review of the TRs and development of the safety evaluations (SE).

The NRC staff provided its audit plan to X-energy on August 29, 2024 (ML24236A768). The regulatory audit was conducted from September 3, 2024 through April 11, 2025, using X-energy's Certrec electronic reading room (eRR). On April 11, 2025, the NRC staff held an audit exit meeting with X-energy and summarized the audit purpose, activities, and high-level results. The NRC staff did not acquire any documents during the audit.

As a result of the audit, X-energy submitted revisions to the TRs as listed below:

- TR 2024-XE-NRC-009, "Xe-100 Licensing Topical Reactor Core Design Methods and Analysis," Revision 2 (ML25071A399), March 12, 2025.
- TR 2024-XE-NRC-010, "Xe-100 Licensing Topical Report, Licensing Topical Report Transient and Safety Analysis Methodology," Revision 2 (ML25077A288), March 14, 2025.
- TR 2024-XE-NRC-011, "Xe-100 Licensing Topical Report Mechanistic Source Term Approach," Revision 3 (ML25073A093), March 14, 2025.
- TR 2024-XE-NRC-012, "Xe-100 Licensing Topical Report GOTHIC and Flownex Analysis Codes Qualification," Revision 3 (ML25076A053), March 13, 2025.

## 2.0 AUDIT REGULATORY BASES

The regulatory basis for this audit includes the following regulatory requirements: Title 10 of the *Code of Federal Regulations* (10 CFR) 50.34(a)(4) and 10 CFR 50.34(b)(4) apply to applicants for construction permits and operating licenses, respectively. In part, these sections require an analysis and evaluation of the design and performance of structures, systems, and components (SSCs) of the facility with the objective of assessing the risk to public health and safety resulting from operation of the facility and including determination of the margins of safety during normal operations and transient conditions anticipated during the life of the facility, and the adequacy of SSCs provided for the prevention of accidents and the mitigation of the consequences of accidents. Similar regulatory requirements exist for design certification applications, combined license applications, standard design approvals, and manufacturing licenses (10 CFR 52.47(a)(4), 10 CFR 52.79(a)(5), 10 CFR 52.137(a)(4), and 10 CFR 52.157(f)(1), respectively.

## 3.0 AUDIT PURPOSE AND OBJECTIVES

The purpose of the regulatory audit was to support the efficiency of the NRC staff review by: (1) gaining timely access to the detailed information supporting the TRs, (2) verifying information, and/or (3) identifying information that will require docketing to support the development of the safety evaluation.

#### 4.0 SCOPE OF THE AUDIT AND AUDIT ACTIVITIES

During the review of the TRs, the NRC staff developed preliminary questions and discussed them with X-energy during a public meeting held on August 20, 2024 (ML24334A037). Subsequently, the NRC staff and X-energy agreed to have a regulatory audit of X-energy's documents supporting the information in the TRs.

During the regulatory audit, X-energy made the proprietary documents listed in Enclosure 1 available to the NRC staff in the eRR. The scope of the regulatory audit focused on this information. The NRC audit team followed the guidance in the Office of Nuclear Reactor Regulation Office Instruction LIC-111, "Regulatory Audits" (ML19226A274). Members of the audit team included the NRC staff listed below.

Ian Jung	Senior Reliability and Risk Analyst
Timothy Drzewiecki	Senior Reactor Systems Engineer
Pravin Sawant	Senior Nuclear Engineer
Jason Schaperow	Senior Reactor Systems Engineer
Dan Beacon	Nuclear Engineer
Inseok Baek	Nuclear Engineer
Tracy Radel	Nuclear Engineer
Michael Salay	Senior Reactor Systems Engineer
Santosh Bhatt	Senior Nuclear Engineer
Ondra Dukes	Project Manager
Adrian Muñiz	Senior Project Manager
Denise McGovern	Senior Project Manager

#### 5.0 SUMMARY OF OBSERVATIONS

During the regulatory audit, the NRC staff reviewed the documents in the eRR and sent questions to X-energy via eRR. X-energy entered the NRC staff's questions and the associated written responses into the Certrec Information Management System to support the interactions between the NRC staff and X-energy. The NRC staff and X-energy held several meetings to discuss the questions and responses as well as other topics. The summary of the NRC staff's observations during the regulatory audit is described below.

##### **Audit Activity Specific to Reactor Core Design Methods and Analysis**

NRC staff raised several technical inquiries that led to clarifications and subsequent updates to the Licensing Topical Report (LTR).

The NRC staff inquired about the 3-D Monte Carlo N-particle (MCNP) model, how the model is used in the calculations, and what assumptions are made. X-energy clarified the control rod worth analysis and subsequently updated the LTR.

The NRC staff asked if the ASTRA experiment will be used to compare kinetics parameters. X-energy confirmed that it plans to utilize the ASTRA experiment to validate kinetics parameters and subsequently updated the LTR.

The NRC staff noted that in TR section 3.2.8, "Thermal Hydraulics," multiple terms in the conservation equations used are neglected but does not provide specific justifications. X-energy explained which terms are neglected and why and subsequently updated the LTR.

The NRC staff asked questions regarding helium bypass flow in the TH modeling. X-energy confirmed that the helium bypass flow distribution (paths and mass flows) are included in Very Superior Old Program (VSOP) modelling as an input from FLOWNEX analysis. The LTR was updated to clarify this information.

### **Audit Activity Specific to Transient and Safety Analysis Methodology**

NRC staff reviewed X-energy's mapping of TSAM content to the Evaluation Model Development and Assessment Process (EMDAP) and identified several areas requiring clarification, which X-energy addressed during the audit.

The NRC staff examined, "EMDAP Concurrence Reference Table R2," which maps sections of TSAM to steps in the EMDAP described in Regulatory Guide 1.203, "Transient and Accident Analysis Methods," (ML053500170). NRC staff noted:

- EMDAP Step 1, "Specify analysis purpose, transient class, and power plant class," is addressed in TSAM section 3, "Xe-100 Plant Structures, Systems, and Component Overview";
- EMDAP Step 2, "Specify figures of merit," is addressed in TSAM section 7, "Xe-100 Figure of Merit";
- EMDAP Step 3, "Identify systems, components, phases, geometries, fields, and processes that must be modeled," is addressed in TSAM section 8, "Xe-100 Phenomena Identification and Ranking Tables";
  - X-energy attempted to address Step 3 through the phenomena identification and ranking table (PIRT) process. During the PIRT, the importance ranking associated with the highest level of the system breakdown was maintained across the system (i.e., the applicant applied PIRT ranking values were applied to all structures, systems, and components that were identified at the highest-level breakdown of the system). X-energy provided the following example:
    - If a phenomenon is associated with 'primary side metallics,' that indicated that the reactor pressure vessel, core barrel, etc. carried the same importance across the ranking.
- EMDAP Step 4, "Identify and rank key phenomena and processes," is addressed in TSAM section 8, "Xe-100 Phenomena Identification and Ranking Tables," section 9, "Transient and Safety Analysis Uncertainty Methodology," appendix C, "In-Core FOM PIRTs," and appendix D, "Xe-100 Transient and Safety Analysis PKPIRTs";
- EMDAP Step 5, "Specify objectives for assessment base," is addressed in TSAM section 6, "Code Verification and Validation Plans and Scaling";
- EMDAP Step 6, "Perform scaling analysis and identify similarity criteria," is addressed in TSAM section 6;

- EMDAP Step 7, “Identify existing data and/or perform Integral Effects Tests (IETs) and Separate Effects Test (SETs) to complete the database,” is addressed in TSAM section 6;
- EMDAP Step 8, “Evaluate the effects of IET distortions and SET scaleup capability,” is addressed in TSAM section 6;
- EMDAP Step 9, “Determine experimental uncertainties as appropriate,” is addressed in TSAM section 2.3.1.2, “Element 2: Develop Assessment Base,” and section 6 “Code Verification and Validation Plans and Scaling”;
- EMDAP Step 10, “Establish an evaluation model development plan,” is addressed in TSAM section 5, “Xe-100 Transient and Safety Analysis Code Development,” and section 12, “Quality Assurance for Transient and Safety Analysis”;
- EMDAP Step 11, “Establish evaluation model structure,” is addressed in TSAM section 10, “Xe-100 DBA Evaluation Model”;
- EMDAP Step 12, “Develop or incorporate closure models,” is addressed in TSAM section 5;
  - “EMDAP Concurrence Reference Table R2,” further states that most closure models used in the X-energy EM are standard/default option available in GOTHIC or Flownex. There are a few closure models being developed specifically for X-energy’s EM. Those specific to X-energy’s EM are still under development and/or are being validated. The current status of X-energy closure relations to be verified with separate effecting test data within the Flownex and GOTHIC models are discussed in the GOTHIC and Flownex Analysis Codes Validation documentation.
- EDMAP Element 4, “Assess evaluation model adequacy,” (Steps 13 - 20) are not addressed by TSAM.

The NRC staff inquired about the applicability of the scaling methodology discussed in section 6.5, “Xe-100 Scaling Methodology,” in TSAM. X-energy clarified that its intention is to apply the scaling methodology to legacy data for use in the EM assessment, but there are no plans at this time to build new scaled facilities.

The NRC staff inquired about the application of criteria or goals in the PKPIRT process described in section 9.3, “Xe-100 PKPIRT Methodology.” Specifically, the NRC staff inquired about the application of criteria or goals on the number of phenomena, models, and parameters that could restrict the consideration of important phenomena in the development and assessment of the EM. X-energy clarified that they did not impose any restrictions on the number of phenomena, models, or parameters in the development of their EMs.

The NRC staff inquired regarding limitations in design margin that would necessitate the use of the error propagation approach described in section 9.3, “Xe-100 PKPIRT Methodology,” of TSAM. X-Energy clarified that short term evaluations, performed with FLOWNEX, are expected to have significant margin to design limits such that conservative biasing should be sufficient, but some long-term evaluations, performed with GOTHIC, have limited margin to fuel

temperature limits. Accordingly, X-energy is planning to use a best-estimate plus uncertainty approach for long term evaluations.

These clarifications, along with the information provided during the audit, have enabled the NRC staff to conclude the review of this portion of the TSAM with a clear understanding of the applicant's methodologies and planned EM development activities.

### **Audit Activity Specific to Gothic and Flownex Analysis Codes Qualification**

The NRC staff examined the following Flownex manuals:

- Flownex General User Manual September 2022
- Flownex Theory Manual September 2022
- Flownex Library Manual, September 2022

During this examination, the NRC staff noted that the information provided in section 4 of the GFR TR and its associated appendices appears to accurately summarize the contents of these manuals.

The NRC staff examined the X-energy Flownex Validation Plan and noted the following:

- Many of the validations for Flownex, identified in table 1, "Validation Basis," of the GFQ TR, already exist and were performed predominantly by M-Tech Industrial as part of the development and maintenance of Flownex.
- The validation results of the SANA experiment indicated that, for the step increase in power from 10 kW to 25 kW, Flownex over-predicted the initial temperature increase and slightly over-predicts the equilibrium temperature.
- The validation results of the blowdown tests indicated that Flownex slightly over-predicts pressures in depressurization cases and slightly under-predicts pressures in pressurization cases.
- The validation results of the Pebble Bed Micro Model (PBMM) experiment indicate that the Flownex simulation followed the temperature and pressure data very closely with only minor deviations in the temperature and pressure comparisons.
- The validation results of the branched piping network experiment demonstrated that Flownex has the capability to correctly predict the experimental transient trends for increasing pressures throughout the network.
- The validation results of the compressible gas in a piping network experiment, shown in figure 17, "Flownex Material Allocations," indicated that Flownex simulations followed the mass flow rate data very closely.
- The validation results of the heat exchange experiment, shown in figure 19, "SG Flow Profile View (A) Helium Side and (B) Water Side," indicated that Flownex simulations closely followed the transient temperatures at the primary inlet and secondary outlet with the temperature increase for the primary inlet being slightly more rapid in the experimental data than is shown in the Flownex calculation.

### **Audit Activity Specific to Mechanistic Source Term Approach**

The following summarizes X-energy's clarifications and revisions provided in response to the NRC staff's inquiries during the audit.

- After discussions in audit meetings, X-energy updated MST TR section 1.5, "Outcome Objectives," and section 7.1, "Conclusions," to clarify that applicability is limited to preliminary analyses.
- The NRC staff asked about GOTHIC providing input to the Solids Fission Products Transport Calculations Model. X-energy confirmed that GOTHIC is used for long-term fuel temperature calculations as input to the SOLM model.
- The NRC staff asked which flow rates are input to the Thermal-Hydraulics Model. X-energy responded that the initial flow rates can be imported from any acceptable code.
- The NRC staff asked what specific functions 2D Point Kinetics Core Simulation Model (KSIM) performs as part of the MST approach. X-energy provided written answers and discussions on the role KSIM played in the development of the PSAR and had not decided how it would be used to support the development of the FSAR.
- Responding to the NRC staff's questions, X-energy made updates to Appendix H showing MST model interfaces.

X-energy provided clarifications, updated documentation, and detailed responses to the NRC staff's inquiries regarding MST model applicability, code interfaces, and analytical inputs.

#### **6.0 REQUESTS FOR ADDITIONAL INFORMATION RESULTING FROM AUDIT**

As a result of the audit, the NRC staff did not identify any specific items as requests for additional information related to these TR.

#### **7.0 OPEN ITEMS AND PROPOSED CLOSURE PATHS**

X-energy had follow-up items as discussed above. X-energy addressed its follow-up items and submitted revisions to all four TRs for the NRC staff's review.