July 25, 2025

TP-LIC-LET-0433
Docket Number 50-613

U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
ATTN: Document Control Desk

Subject: Submittal of Approved TerraPower, LLC Design Basis Accident Methodology for In-Vessel Events without Radiological Release Topical Report

References:

1. U.S. Nuclear Regulatory Commission, TerraPower, LLC – Final Safety Evaluation of Topical Report NAT-9390, Design Basis Accident Methodology for In-Vessel Events without Radiological Release, Revision 2 (ML25106A040)

The U.S. Nuclear Regulatory Commission (NRC) provided the final safety evaluation for the TerraPower, LLC (TerraPower) Design Basis Accident Methodology for In-Vessel Events without Radiological Release Topical Report in Reference 1. The topical report provides an overview and description of the model developed to evaluate in-vessel Design Basis Accident events for the Natrium®[1] Plant.

Enclosures 2 and 3 of this letter provide the accepted version of the topical report with additional content incorporated per NRC staff request, designated NAT-9390-A.

The report contains proprietary information and as such, it is requested that Enclosure 3 be withheld from public disclosure in accordance with 10 CFR 2.390, "Public inspections, exemptions, requests for withholding." An affidavit certifying the basis for the request to withhold Enclosure 3 from public disclosure is included as Enclosure 1. Enclosure 3 also contains ECI which can be disclosed to Foreign Nationals only in accordance with the requirements of 15 CFR 730 and 10 CFR 810, as applicable. Proprietary and ECI materials have been redacted from

[1] Natrium is a TerraPower and GE-Hitachi Technology.

the report provided in Enclosure 2; redacted information is identified using [[ ]]$^{(a)(4)}$, [[ ]]^{ECI}, or [[ ]]$^{(a)(4), ECI}$.

This letter and the associated enclosures make no new or revised regulatory commitments.

If you have any questions regarding this submittal, please contact Ian Gifford at igifford@terrapower.com.

Sincerely,

George Wilson

George Wilson
Senior Vice President, Regulatory Affairs
TerraPower, LLC

Enclosures:
1. TerraPower, LLC Affidavit and Request for Withholding from Public Disclosure (10 CFR 2.390(a)(4))
2. TerraPower, LLC Topical Report NAT-9390-A, Revision 2, Design Basis Accident Methodology for In-Vessel Events without Radiological Release – Non-Proprietary (Public)
3. TerraPower, LLC Topical Report NAT-9390-A, Revision 2, Design Basis Accident Methodology for In-Vessel Events without Radiological Release – Proprietary (Non-Public)

cc: Mallecia Sutton, NRC
Josh Borromeo, NRC
Nathan Howard, DOE

ENCLOSURE 1

TerraPower, LLC Affidavit and Request for Withholding from Public Disclosure (10 CFR 2.390(a)(4))

Enclosure 1
TerraPower, LLC Affidavit and Request for Withholding from Public Disclosure
(10 CFR 2.390(a)(4))

I, George Wilson, hereby state:

1. I am the Senior Vice President, Regulatory Affairs and I have been authorized by TerraPower, LLC (TerraPower) to review information sought to be withheld from public disclosure in connection with the development, testing, licensing, and deployment of the Natrium® reactor and its associated fuel, structures, systems, and components, and to apply for its withholding from public disclosure on behalf of TerraPower.
2. The information sought to be withheld, in its entirety, is contained in Enclosure 3, which accompanies this Affidavit.
3. I am making this request for withholding, and executing this Affidavit as required by 10 CFR 2.390(b)(1).
4. I have personal knowledge of the criteria and procedures utilized by TerraPower in designating information as a trade secret, privileged, or as confidential commercial or financial information that would be protected from public disclosure under 10 CFR 2.390(a)(4).
5. The information contained in Enclosure 3 accompanying this Affidavit contains non-public details of the TerraPower regulatory and developmental strategies intended to support NRC staff review.
6. Pursuant to 10 CFR 2.390(b)(4), the following is furnished for consideration by the Commission in determining whether the information in Enclosure 3 should be withheld:
    a. The information has been held in confidence by TerraPower.
    b. The information is of a type customarily held in confidence by TerraPower and not customarily disclosed to the public. TerraPower has a rational basis for determining the types of information that it customarily holds in confidence and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application and substance of that system constitute TerraPower policy and provide the rational basis required.
    c. The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR 2.390, it is received in confidence by the Commission.
    d. This information is not available in public sources.
    e. TerraPower asserts that public disclosure of this non-public information is likely to cause substantial harm to the competitive position of TerraPower, because it would enhance the ability of competitors to provide similar products and services by reducing their expenditure of resources using similar project methods, equipment, testing approach, contractors, or licensing approaches.

I declare under penalty of perjury that the foregoing is true and correct.

Executed on: July 25, 2025

George Wilson

George Wilson
Senior Vice President, Regulatory Affairs

TerraPower, LLC

ENCLOSURE 2

TerraPower, LLC Topical Report
“Design Basis Accident Methodology for In-Vessel Events without Radiological Release,”
NAT-9390-A, Revision 2

Non-Proprietary (Public)

TerraPower, LLC
15800 Northup Way
Bellevue, WA 98008

A TerraPower & GE-Hitachi Technology

Design Basis Accident Methodology for In-Vessel Events without Radiological Release

NAT-9390-A

Revision 0

July 2, 2025

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

April 17, 2025

George Wilson
Vice President, Regulatory Affairs
TerraPower, LLC
15800 Northup Way
Bellevue, WA 98008

SUBJECT: TERRAPOWER, LLC – FINAL SAFETY EVALUATION OF NAT-9390, "DESIGN BASIS ACCIDENT METHODOLOGY FOR IN-VESSEL EVENTS WITHOUT RADIOLOGICAL RELEASE," REVISION 2 (EPID NO. L-2023-TOP-0050)

Dear George Wilson:

By letter dated September 29, 2023, TerraPower, LLC, (TerraPower) submitted Topical Report (TR) TP-LIC-RPT-0004, "Design Basis Accident Methodology for In-Vessel Events without Radiological Release," Revision 0 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML23272A260), which summarizes the approach taken to satisfy the guidance outlined in Regulatory Guide (RG) 1.203, "Evaluation Model Development and Assessment Process (EMDAP)," for in-vessel design basis accident (DBA) events without radiological release in the Natrium reactor. On October 31, 2023, the U.S. Nuclear Regulatory Commission (NRC) staff determined that the TR provided sufficient information for the NRC staff to begin its detailed technical review (ML23303A168).

On March 5, 2024, the NRC staff transmitted an audit plan to TerraPower (ML24064A195) and subsequently conducted an audit of materials related to the TR from March 25, 2024, to June 27, 2024. The NRC staff issued the audit summary dated November 27, 2024 (ML24255A017). On October 11, 2024, TerraPower submitted a revision of the TR (ML24295A202), which was renumbered from TP-LIC-RPT-0004 to NAT-9390, to clarify portions of the TR as discussed in the audit summary.

The enclosed final Safety Evaluation (SE) is being provided to TerraPower, because the NRC staff has found NAT-9390, Revision 2, acceptable for referencing in licensing actions to the extent specified and under the limitations and conditions delineated in the TR and the SE. The final SE defines the basis for the NRC staff's acceptance of the TR.

The NRC staff requests that TerraPower submit to NRC staff an approved version of this TR within 3 months of receipt of this letter. The approved version should incorporate this letter and the enclosed SE after the title page. The approved version should include a "-A" (designating approved) following the TR identification symbol.

If you have any questions, please contact Roel Brusselmans at (301) 415-0829 or via email at Roel.Brusselmans@nrc.gov.

Sincerely,

/RA/

Joshua Borromeo, Chief
Advanced Reactor Licensing Branch 1
Division of Advanced Reactors and Non-Power
Production and Utilization Facilities
Office of Nuclear Reactor Regulation

Project No.: 99902100

Enclosure:
As stated

cc: TerraPower Natrium via GovDelivery

SUBJECT: TERRAPOWER, LLC – FINAL SAFETY EVALUATION FOR NATRIUM TOPICAL REPORT NAT-9390, “DESIGN BASIS ACCIDENT METHODOLOGY FOR IN-VESSEL EVENTS WITHOUT RADIOLOGICAL RELEASE,” REVISION 2 (EPID L-2023-TOP-0050) DATED: APRIL 17, 2025

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ADAMS Accession Nos.:
Pkg: ML25106A038
Letter: ML25106A040
Public Enclosure: ML25106A043
Non-Public Enclosure (Proprietary - ECI): ML25106A042

OFFICE	NRR/DANU/UTB2:TR	NRR/DANU/UTB2:BC	NRR/DANU/UAL1:PM
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TERRAPOWER, LLC – FINAL SAFETY EVALUATION FOR TOPICAL REPORT NAT-9390, "DESIGN BASIS ACCIDENT METHODOLOGY FOR IN-VESSEL EVENTS WITHOUT RADIOLOGICAL RELEASE," REVISION 2 (EPID L-2023-TOP-0050)

SPONSOR AND SUBMITTAL INFORMATION

Sponsor:	TerraPower, LLC
Sponsor Address:	15800 Northup Way, Bellevue, WA 98008
Project No.:	99902100
Submittal Date:	September 29, 2023; October 11, 2024

Submittal Agencywide Documents Access and Management System (ADAMS) Accession Nos.: ML23272A260; ML24295A202

Brief Description of the Topical Report: By letter dated September 29, 2023, TerraPower, LLC, (TerraPower) submitted Topical Report (TR) TP-LIC-RPT-0004, "Design Basis Accident Methodology for In-Vessel Events without Radiological Release," Revision 0 [1], for the U.S. Nuclear Regulatory Commission (NRC) staff's review. On October 31, 2023, the NRC staff determined that the TR provided sufficient information for the NRC staff to begin its detailed technical review [2]. On March 5, 2024, the NRC staff transmitted an audit plan to TerraPower [3] and subsequently conducted an audit of materials related to the TR from March 25, 2024, to June 27, 2024. The NRC staff issued the audit summary dated November 27, 2024 [4]. TerraPower submitted a revision of the TR [5], which was renumbered from TP-LIC-RPT-0004 to NAT-9390, to clarify portions of the TR as discussed in the audit summary.

NAT-9390, Revision 2, describes the methodology used to evaluate in-vessel design basis accidents (DBAs) that do not result in radiological releases for the Natrium reactor.[1] The TR also summarizes the approach used to satisfy the guidance in Regulatory Guide (RG) 1.203, "Transient and Accident Analysis Methods" [6], regarding the evaluation model development and assessment process (EMDAP) for the methodology, though it notes that the strategy to follow the EMDAP is still ongoing and not yet complete.

REGULATORY EVALUATION

The regulations that are applicable to the review of this TR are:

- Title 10 of the *Code of Federal Regulations* (10 CFR) section 50.34(a)(4) and 10 CFR 50.34(b)(4), which requires certain information to be submitted by applicants for

[1] To address DBAs that have the potential to result in radiological releases, TerraPower submitted a separate TR, TP-LIC-RPT-0007, "Design Basis Accident Methodology for Events with Radiological Release," by letter dated March 22, 2024 (ML24082A261).

construction permits and operating licenses, respectively. These sections require, in part, 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 the operation of the facility and including the determination of the margins of safety during normal operations and transient conditions anticipated during the life of the facility, and the adequacy of the SSCs provided for the prevention of accidents and the mitigation of the consequences of accidents.

- Regulation 10 CFR 50.43(e), which requires that reactor designs that differ significantly from light-water reactor designs licensed before 1997, or that use simplified, inherent, passive or other innovative means to accomplish their safety functions have an appropriate demonstration of their safety features. Sections 50.43(e)(1)(i) and (ii) require a demonstration of safety feature performance and interdependent effects through analysis, appropriate test programs, experience, or a combination thereof. Section 50.43(e)(1)(iii) requires that sufficient data exist regarding the safety features of the design to assess the analytical tools for safety analyses over a sufficient range of plant conditions, including certain accident sequences.

- Regulations 10 CFR 50.46(a) and Appendix K, "ECCS Evaluation Models," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," discuss the acceptance criteria for emergency core cooling systems (ECCSs) for light-water reactors. While not applicable to TerraPower's Natrium reactor as described in the TR because it is not a light-water reactor, the TR cites 10 CFR 50.46, "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors," and Appendix K in relation to conservatism and uncertainty analysis for the evaluation model (EM). When discussing EM analysis, 10 CFR 50.46 states that either "[c]omparisons to applicable experimental data must be made and uncertainties in the analysis method and inputs must be identified and assessed so that the uncertainty in the calculated results can be estimated" or "an ECCS evaluation model may be developed in conformance with the required and acceptable features of appendix K ECCS Evaluation Models." Regulation 10 CFR Part 50, appendix K, "ECCS Evaluation Models," provides a conservative methodology which if followed does not require an uncertainty analysis.

The NRC guidance documents that are applicable to the review of this TR are described below.

RG 1.203 provides the EMDAP as an acceptable framework for the developing and assessing of EMs for reactor transient and accident analyses. RG 1.203 outlines the four elements of an EMDAP, which is broken into 20 component steps. In the subject TR, TerraPower describes the EM for in-vessel DBAs without radiological release for the Natrium reactor and the assessments that have been or will be performed in the context of the EMDAP steps. TerraPower's TR only fully addresses 8 of the 20 steps of an EMDAP and provides an approach for addressing the remaining steps.

Step 4 in the EMDAP is to identify and rank the key phenomena and processes, resulting in a phenomena identification and ranking table (PIRT) that provides critical information to inform the EM development and assessment. Additional information for the creation of a PIRT is provided in NUREG/CR-6944, "Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)," Volume 1 [7]. NUREG/CR-6944 documents the performance of a PIRT for the

Next Generation Nuclear Plant, a conceptual high temperature gas-cooled reactor design. The development of a PIRT is relevant to all reactor designs, regardless of technology.

Step 10 of the EMDAP relates to the plan to develop the EM, of which quality assurance (QA) is an important component. RG 1.203 Appendix B, "Example Showing the Graded Application of the EMDAP," provides an example execution of the EMDAP, in which Step 10 references NUREG-1737, "Software Quality Assurance Procedures for NRC Thermal Hydraulic Codes," [8] for procedures for the development and maintenance of NRC thermal-hydraulic codes used in reactor plant system transient analysis, including quality assurance. NUREG-1737 provides guidance for documentation, review, testing, and assessment of thermal-hydraulic codes used by the NRC staff. The TR references NUREG-1737 in its discussion on Step 10 and describes how the concepts in this NUREG are applied through TerraPower's commercial grade dedication process.

For background, the Kemmerer Power Station Unit 1 construction permit application TerraPower submitted on behalf of US SFR Owner, LLC, for a Natrium Reactor is following the process outlined in Nuclear Energy Institute (NEI) 18-04, "Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development" [9], as endorsed by the NRC in RG 1.233, "Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors" [10]. This guidance defines risk-informed, performance-based, and technology-inclusive processes for the selection of licensing basis events (LBEs); safety classification of SSCs; and the determination of defense-in-depth adequacy for non-light-water reactors. NEI 18-04 provides a frequency-consequence target curve that is used to assess events, SSCs, and programmatic controls. LBEs are categorized by the frequency of occurrence, separated into anticipated operational occurrences, design-basis events (DBEs), and beyond-design-basis events. DBAs are derived from DBEs by prescriptively assuming that only safety-related (SR) SSCs are available to mitigate postulated event sequence consequences to within the 10 CFR 50.34, "Contents of applications; technical information" dose limits, using conservative assumptions. The purpose of the subject TR is to provide a methodology for analyzing certain DBAs as defined in NEI 18-04.

TECHNICAL EVALUATION

1.0 INTRODUCTION

TerraPower requested that the NRC staff review the proposed methodology as an appropriate and adequate means for future applicants using the Natrium design (as described in the TR) to evaluate in-vessel DBA events that do not lead to radiological release. The TR summarizes TerraPower's approach to develop and assess the DBA without radiological release EM following the EMDAP described in RG 1.203. The EMDAP consists of four main elements, including determining the requirements of the EM, developing an assessment base, developing the EM, and assessing EM adequacy. Each element is also broken into component steps.

All elements and steps of the EMDAP are explicitly discussed in the TR, though TerraPower notes certain steps are ongoing. For the purposes of developing this safety evaluation (SE), the NRC staff reviewed each of TerraPower's EMDAP elements and steps against the applicable step of RG 1.203. The technical evaluation section is generally organized by the EMDAP step, with each section discussing the guidance of RG 1.203, the relevant information from the TR, and the NRC staff's evaluation.

However, as noted in the executive summary of the TR, "…the strategy to follow the EMDAP defined in RG 1.203 is still under development for the DBA methodology for in-vessel events without radiological release," and, as documented in the TR, many EMDAP steps remain incomplete at this time. For EMDAP steps that are complete in NAT-9390, Revision 2, this SE provides NRC staff determinations on the acceptability of those steps. For EMDAP steps that are not complete in NAT-9390, Revision 2, the NRC staff focuses its review on whether an adequate approach is in place to address the relevant EMDAP step in a future TR revision or licensing submittal. The NRC staff imposed limitations and conditions, provided at the end of the SE, to address those portions of the EMDAP not completed in NAT-9390, Revision 2.

2.0 BACKGROUND

TR section 1.2, "Sample Plant Description," provides an overview of the Natrium reactor design.[2] The Natrium reactor is a pool-type sodium-cooled fast reactor (SFR) with metal fuel. In the primary heat transport system (PHT), liquid sodium is transferred from the cold pool using mechanical primary sodium pumps (PSPs) to the lower plenum and through the reactor core, where it is heated. The hot sodium then enters the hot pool and transfers its heat via intermediate heat exchangers (IHXs) to the intermediate heat transport system (IHT) sodium loops before returning to the cold pool. Liquid sodium is circulated around the intermediate loops using mechanical intermediate sodium pumps (ISPs), which enables heat to be transferred from the core to a molten salt loop via a sodium-salt heat exchanger (SHX). This molten salt is pumped between the SHX and the energy island, where it can be stored and converted to electricity.

The Natrium plant's safety-related means of residual heat removal is the reactor air cooling system (RAC). The RAC cools the reactor by supplying natural draft outside ambient air down into the reactor cavity and past the outside of the reactor. The RAC is an open, passive system that is always in operation. The Natrium plant can also be cooled via the intermediate air cooling system (IAC). The IAC is non-safety-related and serves as the normal shutdown cooling system. Each intermediate loop contains a sodium-to-air heat exchanger (AHX). Active forced circulation through both the IHT (via ISPs) and IAC (via air blowers) supports normal controlled cooling operations. If power is not available to support forced flow, the natural draft of air through the IAC can provide passive cooling.

The Type 1 fuel proposed for the Natrium core consists of metallic uranium-zirconium alloy slugs contained in right cylindrical fuel pins, arranged in a triangular pitch to form hexagonal fuel assemblies. Additional details regarding Natrium Type 1 fuel and its qualification are provided in TerraPower's TR NATD-FQL-PLAN-0004, "Fuel and Control Assembly Qualification," Revision 0 [11], which was submitted to the NRC staff for review in January 2023. By letter dated October 15, 2024, the NRC issued the final safety evaluation for topical report

[2] TerraPower, on behalf of US SFR Owner, LLC, a wholly owned subsidiary of TerraPower, submitted the construction permit application for Kemmerer Power Station Unit 1 on March 28, 2024 (ML24088A059). The NRC staff's review of that construction permit application is ongoing. The staff is not making any determinations on the acceptability of the Natrium reactor design in this SE. The description of the Natrium reactor in this SE is based on the description in Revision 2 of the TR.

NATD-FQL-PLAN-0004, "Fuel and Control Assembly Qualification," Revision 0 [12]. The NRC staff notes that while the fuel is not discussed in detail in Section 1.2 of the TR, the EM developed in the TR is predicated on the use of Type 1 fuel, as discussed further in Section 3.1.1 of this SE. This limitation is captured in Limitation and Condition 1, below.

3.0 METHODOLOGY

3.1 Element 1: Establish Requirements for Evaluation Model Capability

The first element of the EMDAP is to establish requirements for the EM capability, which frames and focuses the process. During Element 1, mathematical modeling methods, components, phenomena, physical processes, and parameters needed to evaluate event behavior relative to the chosen figures of merit (FOMs), are identified. Element 1 ensures that the EM can appropriately analyze selected events and that the validation process addresses the key phenomena for those events. TR chapter 2, "Evaluation Model Capability Requirements: EMDAP Element 1," outlines TerraPower's approach to the four steps of the EMDAP Element 1.

3.1.1 Step 1: Specify Analysis Purpose, Transient Class, and Power Plant Class

The first step of establishing EM requirements and capabilities is specifying the analysis purpose and identifying the transient and power plant class to be analyzed. This is important to ensure that the EM is applicable to the scenario(s) being analyzed, as dominant processes, safety parameters, and acceptance criteria can change in different scenarios.

TR section 2.1, "Analysis Purpose: EMDAP Step 1," states that the purpose of the analysis is "…to demonstrate that the plant operates such that all relevant acceptance criteria are satisfied under normal operational conditions, and continue to be satisfied during in-vessel DBAs without radiological release." TerraPower selected three scenarios as representative of the types of events included in the in-vessel DBA envelope: (1) Loss of Offsite Power (LOOP), (2) Rod Withdrawal at Power (RWAP), and (3) Loss of Heat Sink (LOHS). These are explored in later steps of the EMDAP, including during the PIRT process. TerraPower also noted in this section, that the EM is intended to be conservative, not best-estimate, and as such does not provide an explicit quantification of uncertainties.

The NRC staff notes that the EM scope identified in Step 1 informs the rest of the EMDAP, as illustrated by numerous references to items such as the plant design and analysis assumptions throughout the rest of this TR. As such, the NRC staff determined that it is necessary to limit the applicability of this EM to the Natrium design as described in section 2.0 of this SE and TR section 1.2, including the use of Natrium Type 1 fuel,[3] or otherwise provide justification that departures from these design features do not affect the conclusions of the TR and this SE. This limitation is captured in Limitation and Condition 1, below.

The NRC staff determined that the analysis purpose, transient class, and power plant class described in the TR meets the guidance provided in Step 1 of RG 1.203 and is therefore acceptable. The NRC staff determined that the methodology discussed in the TR is

[3] Type 1 fuel proposed for use in the Natrium core consists of metallic uranium-zirconium alloy slugs contained in right cylindrical fuel pins, arranged in a triangular pitch to form hexagonal fuel assemblies.

appropriately scoped to a specific subset of DBAs. For this EM, the LOOP DBA encompasses loss of flow DBAs, the RWAP encompasses reactivity addition DBAs, and the LOHS encompasses loss of normal cooling DBAs. The NRC staff compared prior pool-type SFR licensing efforts, such as that performed for the Power Reactor Innovative Small Module (PRISM) reactor [13], to the primary core-wide in-vessel DBAs that would not result in fuel failure described in the TR. TerraPower submitted other TRs to address DBAs outside this scope (e.g., transients that result in fuel failure and release, local faults, ex-vessel accidents) [14, 15]. Because EMDAP Step 1 frames the work done in the rest of the EMDAP, application of this TR outside the intended scope discussed in TR section 2.1 and this SE would require further justification, as described in Limitation and Condition 1, below.

3.1.2 Step 2: Specify Figures of Merit

The second step of the EMDAP involves selecting FOMs, which are defined in RG 1.203 as "quantitative standards of acceptance that are used to define acceptable answers for a safety analysis."

TR section 2.2, "Figures-of-Merit: EMDAP Step 2," discusses how TerraPower selected its FOMs for this EM. Because the EM covered in the TR only addresses DBAs without the potential for radiological release, TerraPower focused on FOMs that can be used to ensure that fuel cladding remains intact, and that there are no significant disruptions to the core or primary coolant pressure boundary.

Metallic fuel failure phenomena are discussed in more detail in TerraPower's fuel qualification TR, NATD-FQL-PLAN-0004. For the purpose of the DBA without radiological release methodology, TerraPower chose to focus on fuel and cladding temperatures, which would reflect whether cladding is at risk of failure by melting of the fuel, overheating of the cladding, or eutectic penetration of the cladding, as well as cladding strain. TerraPower also considered coolant temperature for its possible effect regarding the reactor vessel integrity. Based on these considerations, TerraPower chose three FOMs for this EM:

(1) Fuel centerline temperature;
(2) Coolant temperature; and
(3) Time-at-temperature for peak cladding temperature (PCT).

Because the fuel centerline temperature must remain below the fuel solidus temperature to avoid fuel damage, TerraPower chose a temperature limit based on potential formation of high temperature uranium-iron eutectic at 1080 degrees Celsius (°C) (1976 degrees Fahrenheit (°F)), which the NRC staff expects will envelope possible time-in-life effects and provide conservativism for the analysis. TerraPower's fuel centerline temperature calculations include hot channel factors (HCFs) that account for manufacturing and analytical variability and uncertainty, as discussed further in section 3.4.8 of this SE.

For the second FOM, coolant temperature, TerraPower analyzes the coolant temperature to ensure that there is no sodium boiling in the core, which can cause positive reactivity feedback. This FOM is also used to examine the integrity of the primary coolant boundary, which can fail if high temperatures are experienced for significant lengths of time. TerraPower indicated that though coolant temperature is tracked as a FOM, it is expected that the third FOM, the time-at-temperature criterion, also relates to coolant boiling. The NRC staff notes that the no sodium boiling criterion imposed on this EM has a significant effect on the types of transients considered and the models needed to evaluate them, as will be discussed throughout this SE.

To ensure that cladding does not fail, TerraPower developed a third FOM based on the acceptance criteria for PCT based on a time-at-temperature approach. The acceptance criteria for time-at-temperature no-failure (TATNF) for PCT accounts for strain, cladding wastage, and thermal creep. TerraPower applies the **[[**

]].

The NRC staff reviewed TerraPower's FOMs and determined that they are adequate for DBA without radiological release analyses because they can be used to ascertain whether fuel has failed and whether phenomena would challenge the primary coolant boundary. As such, the NRC staff concludes that the approach to Step 2 is acceptable. The NRC staff determined that the **[[**

]] are discussed in additional detail in TerraPower's TR covering DBAs that result in radiological releases [14].

3.1.3 Step 3: Identify Systems, Components, Phases, Geometries, Fields, and Processes that Must Be Modeled

The third step of the EMDAP process is to identify EM characteristics. This is done via hierarchical system decomposition, in which a system is broken down into subsystems, subsystems into modules, etc. Ingredients at each hierarchical level are decomposed into the ingredients of the next level down. By defining the number and type of ingredient at each level, the basic characteristics of the EM can be established.

TR section 2.3, "Systems, Components, Phases, Geometries, Fields, and Processes Modeled: EMDAP Step 3," provides the hierarchical system decomposition for the Natrium design. At each level of the hierarchy discussed in RG 1.203, TerraPower identifies the ingredients that must be modeled. As discussed previously, TerraPower designed the methodology to analyze in-vessel DBAs that do not result in fuel failure or sodium boiling. TerraPower stated that the EM is scoped to cover the primary and intermediate systems, out to the SHX, RAC, and IAC. The NRC staff reviewed Step 3 and determined that TerraPower's identification of physical components, phases, geometric configurations, fields, and transport processes that must be modeled, is acceptable because its list of ingredients is consistent with those discussed in Step 3 of RG 1.203.

3.1.4 Step 4: Identify and Rank Key Phenomena and Processes

In the fourth step of the EMDAP, key phenomena and processes are identified and ranked with respect to their influence on FOMs. This is accomplished by developing a PIRT. A given scenario is divided-up into characteristic time periods where dominant phenomena and processes remain relatively constant. For each time period, phenomena and processes are identified for each component. The phenomena and processes that the EM should simulate are determined by examining experimental data, expert opinion, and code simulations related to the specific scenario. After identification, the phenomena and processes are ranked by importance determined with respect to their effect on the relevant FOMs. In NUREG/CR-6944, phenomena are evaluated by importance and knowledge level. Importance rankings are categorized by high (H), medium (M), or low (L) depending on their effect on the FOMs. Knowledge levels are also categorized by the state of knowledge breaking down into known (H), partially known (M), or unknown (L).

TR section 2.4, “Identification and Ranking of Phenomena and Processes: EMDAP Step 4,” discusses how TerraPower proposes to accomplish Step 4 for this EM. It appropriately references TerraPower internal documentation detailing the PIRT process and results for this EM, which were audited by the NRC staff [4]. TerraPower initially developed two internal PIRTs covering LOOP and RWAP scenarios. As the Natrium design evolved, TerraPower had an external panel develop three additional PIRTs covering each scenario identified in Step 1 (LOOP, RWAP, and LOHS). TerraPower informed the PIRT evaluations with the results of representative SAS4A/SASSYS-1 (SAS)[4] code calculations. TerraPower stated that each PIRT identified important phenomena and processes and evaluated their importance over three characteristic time periods that are applicable to all three transients – initiation, from the onset of the transient to the time control rods start to drop; transition, from the time control rods start to drop to the time natural circulation is established; and post-scram cooling, from the time of natural circulation to the termination of the transient.

TR table 2-4, “PIRT Phenomena and Processes,” provides descriptions of each of the phenomena or processes that TerraPower identified through the PIRT. TerraPower than ranked each phenomenon or process by importance and knowledge level for each time period using the same categories employed in NUREG/CR-6944. TerraPower summarized the results for each PIRT in TR table 2-5, “Combined PIRT for LOOP, RWAP, and LOHS Licensing Basis Events without Fuel Failure.” For the composite PIRT, TerraPower stated that the most conservative values for each phenomenon were kept (highest importance level, lowest adequacy of knowledge). TerraPower stated that in the initiation phase, transients are generally driven by **[[ ]]**.

[4] SAS is a physics simulation software developed by Argonne National Laboratory (ANL) to perform deterministic analysis of anticipated events and DBAs for SFRs [16]. SAS is one-dimensional and composed of two computer codes, SAS4A and SASSYS-1. SAS4A contains detailed, mechanistic models of transient thermal, hydraulic, neutronic, and mechanical phenomena to describe the response of the reactor core, its coolant, fuel elements, and structural members to accident conditions. SASSYS-1 provides the capability to perform a detailed thermal-hydraulic simulation of the primary and intermediate sodium coolant circuits and the balance-of-plant steam-water circuit.

TerraPower stated that in the transition phase, transient response is driven by **[[ ]]**. In the post-scram cooling phase, TerraPower stated that the **[[ ]]**.

The NRC staff reviewed TerraPower's PIRT development process and determined that it is acceptable because it follows the guidance in Step 4 of RG 1.203. TR section 2.2 identifies that the TATNF criteria was developed after the initial PIRT, noting that "[e]valuation of the time dependent criteria's potential impact on the PIRT must still be performed." However, TerraPower also states in section 2.2 of the TR that the TATNF criteria are consistent with the FOM used within the PIRT. The NRC staff verified this statement through audit of the PIRT documentation and therefore determined that the use of the TATNF criteria will not affect the final result of the PIRT.

The NRC staff determined that the PIRT phenomena are appropriate for the scenarios considered in the EM because they are consistent with the Natrium design and past SFR operating experience. The NRC staff notes that the identified states of knowledge for the phenomena are also appropriate; high-importance phenomena are typically identified to have a **[[ ]]** state of knowledge, with two important exceptions: **[[ ]]**, which are explicitly addressed by experiments as discussed in section 3.2, "Element 2: Develop Assessment Base," of this SE.

Because TerraPower used an acceptable process to develop the PIRT and arrived at a reasonable set of PIRT phenomena and rankings, the NRC staff determined that the PIRT is acceptable for the methodology scope defined by EMDAP Steps 1 through 3. TerraPower additionally indicated in TR section 2.4 that the PIRT may be updated "if other events are identified to be representative, or as significant design changes occur." Any changes to the PIRT must be documented in a revision to the TR, or must be justified to not affect the NRC staff's conclusions in this SE.

Beyond what is normally performed under EMDAP Step 4, TerraPower also provided a preliminary evaluation of the data required for the PIRT phenomena in TR section 2.5, "Preliminary Evaluation of Highly-Ranked Phenomena." TerraPower identified several phenomena as not needing additional experimental data, including: **[[ ]]**.The NRC staff reviewed these phenomena and determined that they either represent parameters that will be controlled by the reactor or core design (e.g., **[[ ]]**) and would be inputs to the analysis that could be conservatively biased, or are appropriately addressed by other qualification methodologies (e.g., **[[ ]]**, which are discussed by TerraPower's fuel qualification methodology [11]).

For the phenomena discussed in TR section 2.5 that TerraPower considered to have adequate data, TerraPower plans to use sensitivity studies to quantify their effects. The remaining highly-ranked phenomena will be examined using available data from legacy experimental data sets and through integral effects tests (IETs) and separate effects tests (SETs) designed by TerraPower, accomplished in Element 2. TR appendix A, "Supporting Information Regarding Assumptions and Modeling Practices," provides additional information regarding how these sensitivity studies will be used. For each phenomenon, relevant SAS input parameters were identified and sensitivities performed to assess the importance of each parameter's impact on PCT. Appendix A states that future studies are planned to complete preliminary assessments, noting that the final method for these sensitivity analyses are still under development. Appendix A also discusses input data sources and SAS implementation for this set of highly-ranked phenomena. The NRC staff reviewed the phenomena selected for sensitivity analysis and compared them with inputs discussed in the SAS4A/SASSYS-1 Code Manual, Version 5.7.1 (SAS Code Manual) [16]. The NRC staff determined that the inputs available in SAS are relevant to the phenomena TerraPower selected for sensitivity studies. As such, the NRC staff determined that TerraPower's approach to quantify the effects of the highly-ranked phenomena discussed in TR section 2.5 is appropriate to help frame EMDAP Elements 2 and 3. However, the NRC staff has not made a determination with respect to TerraPower's execution of the sensitivity studies discussed in the TR as they have not been performed. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to discuss the state of these sensitivity studies and justify that the state is adequate for the intended licensing application.

3.2 Element 2: Develop Assessment Base

The second element of EMDAP as discussed in RG 1.203 is to develop an assessment base consistent with requirements determined from Element 1. This assessment base is used to validate calculational devices or codes used by the EM and may consist of a combination of legacy experiments and new experiments. The validation is done under EMDAP Element 4. The database, particularly SETs, may also be used to develop closure relations to be included in the EM during Step 12 (Element 3).

TR section 3.1, "Developmental Assessment: Input to Element 3, Step 12," discusses the database that TerraPower used to support EM development efforts, which TerraPower refers to as the "EM development assessment matrix." TerraPower stated that this database focuses on closure relationships implemented in the EM and represents a "collection of existing data and calculational assessment problems" which is "not specific to the Natrium reactor" and constitutes a wider range of experiments than that needed for scope considered in this methodology. The TR states that this matrix must be expanded to account for the experiments supporting the new closure relationships implemented in the TR, which are discussed by the NRC staff in more detail below in section 3.3.3.3, "New Closure Models Added to SAS," of this SE. The EM development assessment matrix is not discussed further in the TR. The rest of TR chapter 3, "Assessment Base Development: EMDAP Element 2," focuses on the data that will be used to address code adequacy under Element 4, which is introduced as the code adequacy assessment matrix in section 3.2, "Code Adequacy Assessment Matrix: Input to Element 4."

While RG 1.203 notes that closure models may be selected from the existing database literature, it does not explicitly separate EM development and assessment data. However, the NRC staff determined that TerraPower's approach is acceptable because the closure models' performance as part of the EM will be validated against the code adequacy assessment database in addition to the experiments that were used to develop them.

3.2.1 Step 5: Specify Objectives for Assessment Base

In RG 1.203, Step 5 of the EMDAP involves identifying the objectives for the database that will be used to assess the EM and if necessary, develop correlations. This database should include results from IETs and SETs. It can optionally include benchmarks with other codes or plant transient data, if available. Additionally, it should include simple test problems to illustrate the fundamental calculational device capacity.

TR section 3.3, "Assessment Base Objectives: EMDAP Step 5," states that the objective of Step 5 is to identify sufficient experimental data to form a complete assessment base for assessing the adequacy of the EM; this is consistent with the definition in RG 1.203. The TR presents an approach that categorizes the scalability of data into three distinct areas: geometry and phenomena (Category 1), physical properties (Category 2), and phenomena character, event timing, and order (Category 3). An IET or SET must be scaled to match geometrically with an acceptably small distortion to meet the requirements of Category 1. TerraPower stated that the complete assessment matrix includes experimental data from a least one Category 1 IET and all supporting Category 1 SETs deemed necessary for all highly-ranked phenomena identified in Element 1. Additionally, experimental data from other IETs and SETs (including Category 2 and 3 data) is included to provide credibility for the EM at a variety of scaling factors and conditions.

The NRC staff determined that TerraPower's objectives for the assessment base are acceptable because these objectives are consistent with Step 5 of RG 1.203 that states SETs and IETs are required for EM assessment and may not be substituted with benchmarks or test problems.

3.2.2 Step 6: Perform Scaling Analysis and Identify Similarity Criteria

In RG 1.203, Step 6 of the EMDAP ensures that the experimental data and models based on that data will be applicable to the full-scale analysis of plant transients. This requires scaling analyses to demonstrate the relevancy and sufficiency of the collective experimental database for representing behavior expected during postulated transients, and to investigate the scalability of the EM and its component codes (in this case, SAS) for representing important phenomena. This process involves both top-down and bottom-up approaches. A top-down scaling methodology derives non-dimensional groups that govern similitude between facilities, shows that these groups scale the results among experimental facilities, and determines whether the ranges of group values provided by the experiment set encompass the corresponding plant and transient-specific values. The bottom-up scaling analyses address issues related to localized behavior and are used to explain differences among tests in different experimental facilities. These bottom-up approaches help infer expected plant behavior and determine whether experiments provide adequate plant-specific representation.

3.2.2.1 Hierarchical Scaling

TR section 3.4.1, "Hierarchical Two-Tiered (H2TS) Scaling," describes TerraPower's scaling methodology used to accomplish Step 6 of the EMDAP. TerraPower stated its purpose is to "(a) specify and design the IET and SET experimental facilities with acceptable distortion levels for the specified highly-ranked phenomena and (b) determine the distortion levels, if necessary, for data recorded in legacy experimental facilities."

TerraPower stated that the H2TS methodology has four key elements: system decomposition to create a hierarchical structure, identification of scales within each level of the hierarchy, top-down or system-scaling analysis, and bottom-up or process scaling. For the top-down or system-scaling analysis, TerraPower provided averaged balance equations (i.e., conservation of mass, momentum, and energy) for a given representative region (hierarchical level) and then TerraPower derived time-ratio groups to determine the scaling hierarchy down to the process-level description. TerraPower stated that bottom-up or process scaling focuses on the processes that have large contributions to the FOMs such that the pedigree, fidelity, and scalability of the models and correlations for the processes are addressed.

TerraPower stated that the system decomposition is done based on the structural or functional description of the system, subsystem, module, and components down to a representative volume and the top-down analysis is performed on this volume and based on the processes contributing to the rate of change in the different field variables described by balance equations. This breakdown is shown in TR figure 3-3, "Hierarchical Decomposition."

3.2.2.2 Example of Top-down Approach Applied to PHT Loop Flow Dynamics

TerraPower applies the implementation of the top-down H2TS methodology as an example to PHT loop flow dynamics in TR section 3.4.2, "Top-down Description of PHT Loop Flow Dynamics." TR figure 3.4, "The Hierarchical Decomposition of the PHT System," shows that the PHT system is decomposed. TR figure 3-5, "Schematic View of a Closed Forced/Natural Circulation Flow Loop," provides a schematic of the PHT flow loop.

To characterize the single-phase flow around the loop depicted in TR figure 3-5, the TR assumes one-dimensional mass, momentum, and thermal energy equations are applicable. The TR then summarizes the equations used to represent conservation of mass, momentum, and thermal energy. **[[**

]]. The NRC staff noted that the conservation equations posed in the TR were appropriate for the scenarios modeled in the methodology (i.e., single-phase flow of sodium).

TerraPower appropriately recognizes, in the TR, that the assumption of one-dimensional flow does not capture all phenomena or processes in the PHT, particularly in large open sections of the sodium pools. The NRC staff notes that in the hot pool in particular, thermal striping, thermal stratification, and flow asymmetries all present potential issues. TerraPower stated that it intends to use computational fluid dynamics (CFD) to examine distortions in these regions to determine appropriate testing to be used for assessment. The NRC staff determined that the overall approach to use CFD as an aid to develop or identify appropriate testing is acceptable, because the models will still be validated against experimental data. However, the NRC staff is not making any determinations on this work because it has not yet been performed and, as such, any effects on the scaling analyses should be discussed in a future licensing submittal. This limitation is captured in Limitation and Condition 2, below.

3.2.2.3 Similarity Criteria

In TR section 3.4.3, “Establishing Similarity Criteria based on Closed Flow Loop,” dimensionless groups are derived by normalizing the governing balance equations via selecting appropriate reference values for each quantity appearing in the equations. The TR outlines how this was accomplished for the **[[**

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3.2.2.4 Staff Evaluation

The NRC staff determined that TerraPower’s approach to EMDAP Step 6 is acceptable because the H2TS methodology presented in the TR meets the guidance in RG 1.203 – namely, that it appropriately approaches scaling from both top-down and bottom-up perspectives to establish similarity criteria. The NRC staff has not made a determination with respect to TerraPower’s execution of EMDAP Step 6 because TR section 3.4.1 identifies that scaling analyses using the H2TS methodology are ongoing. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that this step of the EMDAP has been appropriately addressed.

3.2.3 Step 7: Identify Existing Data and/or Perform IETs and SETs to Complete the Database

RG 1.203, Step 7 of the EMDAP is focused on finalizing the database necessary for assessing the EM. Experiments and data are selected to best address important phenomena identified in Step 4. The process of completing the database includes identifying existing data that fulfills the stated objective in Step 5. If available data is insufficient, additional IETs and SETs should be performed to complete the database. In selecting experiments, a range of tests should be employed to demonstrate that the code is not tuned to a single test. For integral behavior assessment, counterpart tests (similar scenarios and transient conditions) in different experimental facilities at different scales should be selected.

TR section 3.5, “Existing Data and SET/IET Needed to Complete Data Base: EM Code Assessment Matrix – EMDAP Step 7,” divides Step 7 into three tasks: (1) performing required IETs and SETs needed to complete the database; (2) identifying existing data; and (3) constructing the EM assessment matrix. TR section 3.5 documents the IETs and SETs scaled for the Natrium design which will provide experimental data regarding the highly-ranked phenomena identified from the PIRT as well as potential legacy reactor and experimental facilities that are candidates for providing assessment data for evaluating EM adequacy.

TR section 3.5.1, "Scaled IET and SET Facilities: Category 1 Data," details the IET and SETs under consideration by TerraPower which will be scaled to the Natrium design using the outputs of Step 6. TerraPower plans to develop a single IET to obtain assessment data for **[[ ]]**. Additionally, TerraPower plans to develop four SETs to obtain data for eight highly-ranked phenomena. TR sections 3.5.2 through 3.5.13 outline legacy datasets considered for inclusion in the EM assessment matrix, including data from both IETs and SETs. These are briefly described in the following SE sections and along with the NRC staff's evaluation on their applicability.

The NRC staff is not making any determinations on the scaling analyses of the test facilities and data because they are ongoing, as discussed in section 3.2.2.4 of this SE. However, TerraPower conducted a preliminary assessment of the experiments, at least to the point that they could be assigned in scaling categories 1, 2, or 3, as discussed in section 3.2.1 of this SE. This preliminary scaling assessment of the available experiments helped inform the preliminary code assessment matrix, which is discussed in the sections that follow. The NRC staff's conclusions regarding the applicability of the tests and their use in the assessment matrix are based on this preliminary scaling assessment. Because the final scaling assessment is subject to Limitation and Condition 2, the overall acceptability of the final assessment matrix is subject to Limitation and Condition 2 as well.

3.2.3.1 Scaled IET

TerraPower plans to construct an IET scaled to the Natrium design using the scaling analyses and similarity criteria developed in Step 6. TR section 3.5.1 details TerraPower's IET plan, listing which highly-ranked phenomena from Step 4 are covered by this experimental facility. TerraPower has additionally developed a roadmap for the IET's test campaign.

The NRC staff reviewed TerraPower's plan to conduct an IET and include it in the code assessment matrix and determined it is acceptable because phenomena selected for testing with the IET, represent the highly-ranked phenomena from the PIRT that are best evaluated with an electrically-heated IET. The NRC staff determined that other highly-ranked PIRT phenomena are best evaluated with a SET or involve reactor physics and, as such, must be evaluated against historical SFR operating data. However, though TerraPower's plan to conduct the IET is acceptable, the NRC staff has not made any determinations on final IET design. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to discuss the state of the IET, including the specific tests that were performed, to justify its inclusion in the code assessment matrix.

3.2.3.2 **[[ ]]**

TR section 3.5.1.1, **[[**

]].

The NRC staff reviewed TerraPower's plan to conduct **[[ ]]** and its inclusion in the code assessment matrix and determined it is acceptable because **[[ ]]** is an important parameter from the PIRT and it is appropriate to evaluate it with new testing that is **[[ ]]**. However, though TerraPower's plan to conduct the SET is acceptable, the NRC staff has not made any determinations on the final SET design. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to discuss the state of the SET, including a discussion of **[[ ]]**, to justify its inclusion in the code assessment matrix.

3.2.3.3 **[[ ]]**

As discussed in TR section 3.4.2, sodium mixes in the lower plenum of the hot pool after exiting the core. The hot pool contains the upper internal structure (UIS) which can impact thermal mixing. When forced flow is lost, insufficient mixing and thermal stratification may occur in the hot pool. TR section 3.5.1.2, **[[ ]]**.

The NRC staff reviewed TerraPower's plan to conduct **[[ ]]** and its inclusion in the preliminary code assessment matrix and determined it is acceptable because **[[ ]]** is an important phenomenon from the PIRT that depends heavily on the **[[ ]]**, necessitating a new SET rather than allowing for the use of historical data. However, though TerraPower's plan to conduct the SET is acceptable, the NRC staff has not made any determinations on the final SET design. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to discuss the state of the SET to justify its inclusion in the code assessment matrix.

3.2.3.4 **[[ ]]**

TR section 3.5.1.3, **[[**

]].

The NRC staff reviewed TerraPower's plan to conduct **[[ ]]** and its inclusion in the preliminary code assessment matrix, and determined it is acceptable because **[[ ]]** is an important phenomenon from the PIRT that would be expected to depend substantially on the **[[ ]]**. As such, a new SET is appropriate. However, though TerraPower's plan to conduct the SET is acceptable, the NRC staff has not made any determinations on the final SET design. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to discuss the state of the SET to justify its inclusion in the code assessment matrix.

3.2.3.5 **[[ ]]**

TR section 3.5.1.4, **[[**

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The NRC staff determined that TerraPower's plan to conduct multiple experiments to validate the **[[ ]]** is acceptable because the experiments, while not fully scaling all aspects of the **[[ ]]** in a single test, appear to cover the necessary phenomena to an adequate degree. In aggregate, the NRC staff expects these tests to provide insights into **[[ ]]** that extend beyond the legacy testing available. However, though TerraPower's plan to conduct the SET is acceptable, the NRC staff has not made any determinations on the final SET design. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to discuss the state of the SET to justify its inclusion in the code assessment matrix.

3.2.3.6 EBR-II Tests

Experimental Breeder Reactor II (EBR-II) was a pool-type SFR operated by ANL from 1964 to 1994. TR section 3.5.2, "EBR-II Tests: SHRT [Shutdown Heat Removal Test] -17, SHRT-45R, and BOP [Balance of Plant]," details tests performed to support the validation of computer codes for design, licensing, and operation of SFRs.

SHRT-17 was a protected loss of flow test, where all sodium pumps were tripped off with a simultaneous reactor scram [17]. EBR-II additionally had an auxiliary coolant pump in its primary loop, which had an emergency power supply. For SHRT-17, this auxiliary pump was also secured. Data was collected to demonstrate the effectiveness of natural circulation cooling. SHRT-45R was an unprotected loss of flow test with the plant protection system disabled to prevent a scram [17]. In this test, both the PSPs and ISPs were tripped; however, a scram did not occur. The auxiliary pump remained powered by its battery during SHRT-45R. This test demonstrated the effectiveness of EBR-II's passive reactivity feedbacks, with the reactor eventually reaching decay heat power.

TerraPower also identified BOP-301 and BOP-302R as two tests of interest. These tests were quite similar, with a differing initial reactor power of 50 percent and 100 percent, respectively [18]. Both tests were initiated by tripping the ISPs. Following this, the core inlet temperature rose, providing negative reactivity feedback. This caused the reactor power to decrease to nearly zero without the control rods scramming. The reactor did not scram, and the PSPs remained running for the entirety of the test.

In TR section 3.5.2, TerraPower identified these experiments for inclusion in the EM assessment matrix. TR table 3-3, "Pedigree of EBR-II Tests Data," discusses the quality of the data for these four experiments. **[[**

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The NRC staff reviewed the documents regarding the SHRT and BOP tests referenced in the TR and determined that TerraPower's planned use of the EBR-II test data to validate the **[[** **]]** is acceptable. The NRC staff determined that the transient performed in SHRT-17 is similar to the LOOP DBA considered by TerraPower for the Natrium reactor, which consists of a power loss causing a scram of control rods concurrently with trips of the PSPs and ISPs. The NRC staff also determined that the other experiments contain information that could be of use for code verification and validation (V&V) activities. The NRC staff notes that while EBR-II does not share all Natrium design features, the tests referenced in the TR include many phenomena that are expected in Natrium transients and should be able to be modeled by the EM. Accordingly, the NRC staff determined that TerraPower's inclusion of this EBR-II data in the code assessment matrix as an IET, is acceptable.

3.2.3.7 Fast Flux Test Facility Loss of Flow Without Scram (LOFWOS) Tests

The Fast Flux Test Facility (FFTF) was a loop-type SFR which was operated from 1982 to 1992 by the Department of Energy. In TR section 3.5.3, "FFTF Tests: LOFWOS Test #10-12," TerraPower identified the LOFWOS test series conducted at the FFTF for inclusion in the EM assessment matrix. **[[** **]]** [19]. **[[** **]]** [20].

[[**]]**.

[[

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The NRC staff reviewed the document [19] on the FFTF LOFWOS test series referenced in the TR. While the FFTF has some major design differences relative to Natrium, the LOFWOS tests referenced in the TR include many phenomena that are expected in Natrium transients that should be able to be modeled by the EM. Accordingly, the NRC staff determined that TerraPower's inclusion of the FFTF LOFWOS test data in the code assessment matrix is acceptable.

3.2.3.8 FFTF Cycle 8A Tests

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TR section 3.5.4 discusses the inclusion of the FFTF Cycle 8A tests in the code assessment matrix. **[[**

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These tests were described in detail in "FFTF Inherent Safety Tests: Results of Cycle 8A Steady-State Reactivity Feedback Measurements," WHC-EP-0117," provided by TerraPower during the audit, which the NRC staff determined to be consistent with the discussion in this section of the TR. The NRC staff additionally reviewed a publicly available source [21] which discusses the FFTF Cycle 8A tests described in this section. While FFTF was an oxide-fueled, loop-type SFR, the NRC staff determined that the fuel dimensions and core restraint system are very similar to the Natrium design. **[[**

]]. Therefore, the NRC staff determined that TerraPower's inclusion of the FFTF Cycle 8A tests in the code assessment matrix is acceptable.

3.2.3.9 Phenix Tests

The Phenix reactor was a pool-type SFR which operated from 1973 to 2009 in France [22]. TR section 3.5.5, "Phenix Tests: Natural Circulation Tests," identifies the Phenix Natural Circulation Test for inclusion in the EM assessment matrix. This was performed in conjunction with the International Atomic Energy Agency (IAEA) as part of the End-of-Life Tests Campaign with the goals of determining the efficacy of natural circulation and the qualification of system codes used to simulate natural circulation [22]. The Phenix Natural Circulation Test was designed to represent a protected LOHS with a delayed loss of primary flow with a resumption of secondary system heat rejection [22]. The Phenix reactor consisted of primary and intermediate sodium loops with heat rejection to steam generators (SGs).

The test began with manual dry out of the SGs. Approximately 7 minutes later, the reactor was manually scrammed, with the PSPs being tripped shortly after. The ISPs reduced speed, being powered only by backup motors. This was followed by two phases of testing. The first phase lasted three hours and examined heat losses solely along the piping and through the casing of the SGs. The second phase lasted four hours and allowed a significant heat sink in the intermediate loop by opening the casing of the SGs, allowing for efficient natural circulation of air in the SG casings [22].

[[

]]. TR appendix A states that, while the test scenario does not match any of the DBA scenarios chosen, TerraPower included this test to demonstrate the EM's capability for modeling natural circulation even under unexpected transient conditions.

The NRC staff reviewed the document [22] referenced in the TR regarding the Phenix Natural Circulation Test. While Phenix presents some design differences relative to Natrium, the NRC staff determined that TerraPower's inclusion of this test in the code assessment matrix is acceptable because the tests provide an important data set for natural circulation from a pool-type SFR which the EM should be able to model.

3.2.3.10 SADHANA Scaled Sodium-Sodium Heat Exchanger Tests

The Safety Decay Heat Analysis in Natrium Loop (SADHANA) is a test facility which was constructed to demonstrate passive decay heat removal for the Prototype Fast Breeder Reactor (PFBR) which is currently being built in India [23]. The PFBR contains an Operational Grade Decay Heat Removal system (OGDHRS) and a Safety Grade Decay Heat Removal System (SGDHRS). The OGDHRS is the typical mode of heat removal, transferring heat from the primary to an intermediate sodium loop, and then to SGs. The SGDHRS consists of a decay heat exchanger (DHX) located in the reactor vessel attached to a secondary sodium loop. The secondary sodium loop is cooled by an AHX. The SGDHRS is used in events where the OGDHRS is unavailable and is employed as a safety feature for backup means of shutdown decay heat removal up to a maximum of 8 MWt [24]. SADHANA is scaled to model the SGDHRS.

SADHANA consists of a test vessel containing a sodium pool and a sodium loop. The test vessel has immersion heaters to simulate decay heat of the PFBR. Heat is transferred from the test vessel to the sodium loop via the DHX in the sodium pool. The sodium loop is then cooled by an AHX scaled for the SGDHRS. Natural circulation drives the flow of sodium in the vessel, sodium in the loop, and air.

In TR section 3.5.7, "SADHANA Scaled Sodium-Sodium Heat Exchanger Tests," TerraPower discusses the inclusion of experimental data from scaled sodium-to-sodium heat exchanger

(HX) tests at SADHANA for inclusion in the EM assessment matrix. SADHANA's DHX and Natrium's IHX both are shell-and-tube type HXs with countercurrent flow. For both, primary sodium flows on the shell-side with secondary sodium on the tube-side [24]. **[[**

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The NRC staff reviewed documents [23,24] regarding the SADHANA facility referenced in the TR. The NRC staff determined that TerraPower's inclusion of SADHANA in the code assessment matrix is acceptable because of similarities in the **[[** **]]** between the two facilities.

3.2.3.11 STELLA-1 Scaled Sodium-Sodium Heat Exchanger Tests

The Korea Atomic Energy Research Institute (KAERI) is currently developing the Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR), a pool-type SFR. KAERI launched the Sodium Integral Effect Test Loop for Safety Simulation and Assessment (STELLA) program to collect V&V data for the PGSFR [25]. As part of this program, the STELLA-1 test loop was built to carryout SETs for the PGSFR's DHX and AHX, key portions of the PGSFR's decay heat removal system (DHRS) [26]. Unlike the Natrium design, the PGSFR DHRS system relies on DHXs attached to a secondary sodium loop which then rejects heat to air via AHXs [27]. The experiment generated V&V data for various components planned to be used in the PGSFR, including HXs, pumps, and valves.

TR section 3.5.8, "STELLA-1 Scaled Sodium-Sodium Heat Exchanger Tests," discusses the potential inclusion of experimental data from STELLA-1's scaled sodium-to-sodium HX in the code assessment matrix. STELLA-1's DHX and Natrium's IHX are shell-and-tube type HXs with countercurrent flow. For both, primary sodium flows on the shell-side with intermediate sodium on the tube-side [26].

The NRC staff reviewed available documentation [25,26] regarding STELLA-1 and the NRC staff determined that TerraPower's potential inclusion of STELLA-1 in the code assessment matrix is acceptable because of the similarities in the **[[** **]]** between the two facilities. However, the NRC staff noted that, **[[**

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3.2.3.12 STELLA-2

As part of the STELLA program, KAERI designed the STELLA-2 facility to investigate the integral effects of safety systems including interactions between the PHT, IHT, and DHRS for the PGSFR. STELLA-2's database is to be used for V&V activities for the PGSFR's safety analysis code [27]. The experiment is scaled to the PGSFR with a focus on simulating natural circulation and decay heat removal following a variety of transients.

TR section 3.5.6, "STELLA-2 Safety Systems Integral Effects Tests," discusses the inclusion of data from STELLA-2 in the EM code assessment matrix. **[[**

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The NRC staff reviewed the documents [27,28] regarding STELLA-2 referenced in the TR. The NRC staff determined that TerraPower's inclusion of STELLA-2 data in the code assessment matrix as an IET is acceptable because though the PGSFR design is not equivalent to Natrium, the tests performed with its IET include many phenomena that are expected in Natrium transients and should be able to be modeled by the EM.

3.2.3.13 Toshiba 4S Test Facility Tests

The Super-Safe, Small, and Simple Reactor (4S) was a proposed sodium-cooled fast microreactor design considered by Toshiba in the 2000s. TR section 3.5.9, "Toshiba 4S Test Facility Tests," discusses experiments conducted for the 4S design for potential inclusion in the code assessment matrix. These tests consist of:

1. **[[** **]]** [29].

2. **[[** **]]** [30].

3. **[[** **]]** [31].

4. **[[** **]]** [31].

[[

]].

The NRC staff reviewed the documents [29, 30, 31] regarding the Toshiba experiments referenced in the TR. The NRC staff determined that TerraPower's inclusion of the **[[** **]]** in the code assessment matrix is acceptable because, though there are differences between the 4S and Natrium designs, these tests are valuable for demonstrating that the EM is capable of modeling the phenomena, **[[** **]]**. As discussed in Limitation and Condition 2, if a future licensing submittal referencing this TR includes the **[[** **]]** tests in the code assessment matrix, the submittal will need to provide the scaling applicability of these tests.

3.2.3.14 Monju Decay Heat Removal Test

Monju was a loop-type SFR built and operated for a short period in Japan. Commissioned in 1995, it was shut down shortly afterwards due to a sodium leak. **[[**

]] [32] **[[**

]].

The NRC staff reviewed the document [32] referenced in the TR which discussed this experiment performed at the Monju facility. The NRC staff determined that TerraPower's potential inclusion of this experiment in the code assessment matrix is acceptable because of the similarities in the **[[** **]]**. However, the NRC staff notes that **[[**

]].

3.2.3.15 PNC 37-Pin Bundle Experiments

Power Reactor and Nuclear Fuel Development Corporation (PNC) constructed a multi-subassembly sodium experiment, the Plant Dynamics Test Loop with Direct Heat Exchanger (PLANDTL-DHX), to investigate thermal-hydraulics in an SFR core during natural circulation [33]. TR section 3.5.11, "PNC [misspelled as PCN] 37-Pin Bundle Experiments," discusses this experiment and its objectives.

PLANDTL-DHX was an IET scaled to the Japan Sodium-cooled Fast Reactor (JSFR), a proposed loop-type SFR design [34]. PLANDTL-DHX was designed to simulate the primary, intermediate, and decay heat transfer loops of the JSFR. It was used for both steady-state and transient experiments to gain data regarding a variety of thermal-hydraulic phenomena [34]. The simulated core consisted of seven subassemblies[5] with an inter-wrapper gap between them. The central subassembly contained 37 heater pins, surrounded by six subassemblies, each containing nine heater pins. **[[**

]].

[[

]]. The NRC staff reviewed the documents referenced in the TR regarding the PLANDTL-DHX [33, 34]. The NRC staff determined that TerraPower's inclusion of this experiment in the code assessment matrix is acceptable because of the similarities between **[[**
]].

[5] The subassemblies in the PLANTDTL-DHX are analogous to the fuel assemblies planned for the Natrium design. Both consist of rows of pins surrounded by a hexagonal duct.

3.2.3.16 WARD 61-Pin Bundle Test

Westinghouse Advanced Reactors Division (WARD) constructed an experimental facility consisting of a 61-rod assembly connected to a sodium loop [35]. **[[**

]].

TR section 3.5.12, “WARD 61-Pin Bundle Test,” discusses this experiment. **[[**

]]. The NRC staff reviewed the document [35] regarding this experiment referenced in the TR. The NRC staff determined that TerraPower’s inclusion of this experiment in the code assessment matrix is acceptable because of the similarities between the **[[**
]].

3.2.3.17 UIUC Natural Circulation Tests

The University of Illinois at Urbana-Champaign (UIUC) has conducted a series of single-phase water natural circulation tests. **[[**

]] [36].

TR section 3.5.13, “UIUC Natural Circulation Tests,” discusses using data from the UIUC facility in the code assessment matrix. TerraPower intends to select data from UIUC that most closely scales with liquid sodium at operational conditions expected in Natrium. **[[**

]].

The NRC staff reviewed the document [36] referenced in the TR which discusses the UIUC facility. The NRC staff determined that TerraPower’s inclusion of this experiment in the code assessment matrix is acceptable because it provides value in demonstrating that SAS is capable of modeling the phenomena present at the UIUC facility, **[[**
]].

3.2.3.18 Code Assessment Matrix

TR section 3.5.14, “Summary of Pedigree Evaluations,” provides TerraPower’s evaluations of the pedigree for the data from the legacy experiments discussed in TR section 3.5. TR table 3-5 lists each legacy IET and SET. The relevancy, availability, and expected data quality from each test is included in table 3-5. **[[**
]].

TR section 3.5.15, “Preliminary Code Assessment Matrix for Natrium EM,” outlines how TerraPower constructed its Preliminary Code Assessment Matrix shown in TR table 3-6. The table provides which experimental facilities will be used to assess the EM’s capability to predict the highly-ranked phenomena identified in Step 4. The scaling category for each facility is also included.

3.2.3.19 Staff Evaluation

The NRC staff determined that TerraPower’s approach to EMDAP Step 7 is acceptable because the experiments discussed in TR Section 3.5 are expected to provide adequate assessment data for the highly-ranked phenomena identified in Step 4. The NRC staff also determined that the initial pedigree evaluation and preliminary code assessment matrix are consistent with the guidance provided in RG 1.203. However, the NRC staff has not made a determination with respect to TerraPower’s execution of EMDAP Step 7 because the final scaling assessment has not been completed, the scaled IET and SETs still need to be performed, and, as TerraPower notes, the pedigree evaluation and the code assessment matrix have not been finalized. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that this step of the EMDAP has been appropriately addressed.

3.2.4 Step 8: Evaluate Effects of IET Distortions and SET Scaleup Capability

In Step 8 of the EMDAP, the effects of IET distortions and SET scaleup capability are evaluated. TR section 3.6, “Evaluation of IET Distortions and SET Scaleup Capability: EMDAP Step 8,” states that TerraPower’s evaluation of the IET and SET experimental scaling facilities will be performed based on the magnitudes of the ratios of the similarity criteria identified in Step 6.

The NRC staff determined that TerraPower’s approach to EMDAP Step 8 is adequate because it aligns with RG 1.203 guidance on evaluating the effects of IET distortions and SET scaleup capability. The NRC staff has not made a determination with respect to TerraPower’s execution of EMDAP Step 8 because evaluations of these effects have not yet been performed for the IET and SET experimental facilities discussed in this SE. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that this step of the EMDAP has been appropriately addressed.

3.2.5 Step 9: Determine Experimental Uncertainties as Appropriate

Step 9 of the EMDAP involves determining experimental uncertainties for the database. If quantified experimental uncertainties are too large compared to requirements for EM assessment, this particular data set or correlation should be rejected.

TR section 3.7, “Experimental Uncertainties Determination: EMDAP Step 9,” discusses TerraPower’s approach to this step. The uncertainties measured and reported in the TerraPower IET and SET experimental facilities will be scaled to the Natrium design and comply with the American Society of Mechanical Engineers (ASME) Nuclear Quality Assurance (NQA-1) standard, which is referenced in 10 CFR 50.55a(a)(1)(v)(B) under “ASME NQA-1 Quality Assurance Requirements for Nuclear Facility Applications.” The use of NQA-1 ensures new experiments used to validate EMs are of sufficient quality to be used in support of SR analyses. However, legacy experiments may not be consistent with NQA-1. In such instances, TerraPower stated that the experimental uncertainties associated with legacy data will be evaluated in part using engineering judgement to determine the degree of compliance with NQA-1. This is largely driven by limitations in how the uncertainties were reported. The NRC staff determined that the use of the legacy experiments cited in the TR is acceptable, even if they do not meet the entire NQA-1 standard, because TerraPower included a plan for how to assess uncertainties to ensure high quality data.

The NRC staff determined that TerraPower's approach to EMDAP Step 9 is acceptable because it presents a plan for quantifying uncertainties, consistent with RG 1.203, which indicates that uncertainties should be known and not too large. While a full assessment of the uncertainties in the experimental database has not been performed, TerraPower has qualitatively screened the expected quality of the data from the experiments selected for inclusion in the assessment matrix in table 3-5, "Results of Pedigree Evaluation of Legacy Test Data." The NRC staff has not made a determination with respect to TerraPower's execution of EMDAP Step 9 because it has not been completed. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that this step of the EMDAP has been appropriately addressed.

3.3 Element 3: Develop Evaluation Model

The third element of the EMDAP involves selecting or developing the calculational devices needed to analyze designated transients or events in accordance with the requirements determined in Element 1. The EM is the calculational framework for evaluating the behavior of a reactor system during a postulated transient or DBA. The EM may include one or more computer programs, special models, and all other information needed to apply the calculational framework to a specific event. This includes:

1. Procedures for treating the input and output information (particularly the code input arising from the plant geometry and the assumed plant state at transient initiation).

2. Specification of those portions of the analysis not included in the computer programs for which alternative approaches are used.

3. All other information needed to specify the calculational procedure.

TR chapter 4, "Evaluation Model Development: EMDAP Element 3," discusses TerraPower's approach to Element 3 and specifies the code used in the EM. For analyzing in-vessel DBA events without radiological release for the Natrium reactor, the EM is composed of the SAS systems code and required input and post-processing algorithms used to model the Natrium plant with capabilities and reliabilities of the SR SSCs to mitigate and prevent postulated event sequence consequences to within 10 CFR 50.34 dose limits per NEI 18-04.

3.3.1 Step 10: Establish an Evaluation Model Development Plan

Step 10 of the EMDAP involves creating an EM development plan based on the requirements established in Element 1. This plan should include development standards and procedures that apply throughout the development activity including:

1. Design specifications for the calculational device
2. Documentation requirements
3. Programming standards and procedures
4. Transportability requirements
5. QA procedures
6. Configuration control procedures

TR section 4.1, “EM Development Plan: EMDAP Step 10,” details TerraPower’s EM development plan. The discussion in the TR references NUREG-1737, which the NRC staff notes is not guidance to applicants or licensees but does represent a set of good practices for evaluation model development. TerraPower stated that it divides the EM’s design specifications into functional requirements, performance requirements, and validation requirements. TR section 4.1 provides a high-level overview of each of these requirements, which may be summarized as follows:

- TR section 4.1.1.1, “Functional Requirements,” specifies how functional requirements must be developed when adding or modifying functionality to the EM.
- TR section 4.1.1.2, “Performance Requirements,” specifies how to develop performance requirements for new or modified functions, including details on how to document software test plans.
- TR section 4.1.1.4, “Documentation Requirements,” discusses how code manuals will be produced and upgraded concurrently with the code development process.
- TR section 4.1.1.5, “Programming Standards and Practices,” provides good practices regarding programming of the EM.
- TR section 4.1.1.6, “Other Requirements,” summarizes the EM development plan’s approach to EM quality assurance, transportability requirements (i.e., requirements related to the use of the EM on different computers and operating systems), test requirements, and installation requirements.

The EM’s design specifications are discussed in further detail in **[[** **]]** a proprietary document. The NRC staff audited this document to confirm that it contained sufficient information regarding the EM’s design specifications and was consistent with the discussion in the TR. The design specifications as discussed in the TR appropriately address the six key focus areas of EMDAP Step 10, except for an explicit discussion on software configuration control. However, TerraPower’s approved quality assurance plan, as documented in TP-QA-PD-0001, “TerraPower Quality Assurance Program Description,” Revision 14 [37], commits computer programs used for design analyses to the requirements of NQA-1-2015, Part II, Subpart 2.7, “Quality Assurance Requirements for Computer Software for Nuclear Facility Applications.” This standard contains specific requirements for various activities related to safety analysis software, including configuration control.

TR section 4.1.2, “Status of EM Development Plan,” states that the EM development plan has been created by examining the EMDAP principles and twenty steps, identifying activities necessary to develop the EM, and specifying high-level descriptions for corresponding activities in each step. This is reasonable for providing an overall framework for developing the EM in accordance with the EMDAP.

The NRC staff determined that TerraPower acceptably completed EMDAP Step 10 because, as discussed above, TerraPower's software design specifications and quality assurance requirements appropriately address the six key focus areas discussed in RG 1.203 and the EM development plan provides an appropriate framework for EM development.

3.3.2 Step 11: Establish Evaluation Model Structure

In Step 11 of the EMDAP, the EM structure is established. This structure should be based on the principles and requirements established in Element 1, including the following six ingredients:

1. Systems and components: The EM structure should be able to analyze the behavior of all systems and components that play a role in the targeted application.

2. Constituents and phases: The code structure should be able to analyze the behavior of all constituents and phases relevant to the targeted application.

3. Field equations: Field equations are solved to determine the transport of the quantities of interest (usually mass, energy, and momentum).

4. Closure relations: Closure relations are correlations and equations that help to model the terms in the field equations by providing code capability to model and scale particular processes.

5. Numerics: Numerics provide code capability to perform efficient and reliable calculations.

6. Additional features: These address code capability to model boundary conditions and control systems.

TR section 4.2, "EM Structure: EMDAP Step 11," specifies SAS as the main system analysis computer code which will be used for the class of scenarios discussed in the TR. The six ingredients required in Step 11 are discussed at a high-level in TR section 4.2.1.2, "Structure of SAS4A/SASSYS-1," which references the publicly-available SAS Code Manual.

3.3.2.1 SAS4A/SASSYS-1 Structure

The basic geometric modeling element used in SAS is a channel which consists of a fuel pin, its cladding, and the associated coolant and structure around the channel. SAS has options for either a single-pin or multiple-pin model. This is discussed in section 2.2.1, "Code Structure Basis," of the SAS Code Manual, which states that "[i]n a single-pin model, a single average channel is used to represent the average of many pins in the reactor, and multiple channels are used to extend the model to all the pins in the reactor. In a multiple-pin model, each channel represents one or more pins in a subassembly, and multiple-pin subassembly models are joined with single-pin subassembly models to cover the whole reactor core" [16].

Appendix 2.2, "SAS4A/SASSYS-1 Input Data Blocks," of the SAS Code Manual states that an input file is uploaded to the program which establishes the design of the reactor and the reactor's operating conditions. This input file is then used to establish initial conditions for the code run. A steady-state calculation is then performed which serves as the starting point for transient calculations. In the TerraPower methodology, the final results from the transient calculation are assessed against the FOMs to see if any limiting values are violated as discussed in TR section 4.2.2, “EM Structure.”

3.3.2.2 Systems and Components

TR section 4.2.1.2(a), “Systems and Components,” outlines how SAS models SFR systems and components. Using the **[[ ]]**, an arrangement of components for a loop-type or pool-type system can be analyzed. TR table 4-1, “Geometric Components of SAS4A/SASSYS-1 EM,” provides the basic geometric components used. The code uses a modular approach with the user specifying the properties of these components and arranging them in an arbitrary manner. This module computes coolant pressures, flow rates, and temperatures in primary and IHT loops [16].

As discussed in section 5.2, “Hydraulic Calculations,” of the SAS Code Manual, the PHT and IHT systems are modeled using a number of compressible volumes (CVs) that are connected by liquid or gas segments. These segments can have multiple elements, each characterized by incompressible single-phase flow except for the core element. CVs include inlet and outlet plenums, pools with cover gas, and almost incompressible liquids with no cover gas. Components modeled by CVs include the hot and cold pools. Liquid flow element types include core subassemblies, pipes, IHX shell-and-tube sides, and pumps. As discussed in section 5.4.2, “Heat Exchangers: Detailed Options,” of the SAS Code Manual, SAS characterizes HXs with a shell, primary coolant channel, tube, and secondary coolant channel. **[[ ]]**.

As discussed in section 5.4.7, “RVACS [Reactor Vessel Auxiliary Cooling System]/RACS [Reactor Air Cooling System] Models,” of the SAS Code Manual, SAS can be used to model the RAC for SFRs. SAS has two built-in models for RAC: a simple model in which the user provides relevant information regarding the air side performance and a detailed air side model in which air temperatures and flow rates are calculated by the code. SAS can also couple with an external code for modeling the RAC. **[[ ]]**.

In EMDAP Step 3, TerraPower decomposed the Natrium reactor into constituent ingredients to help determine EM characteristics. The NRC staff reviewed the SAS Code Manual in conjunction with the EM’s constituent ingredients and verified that TerraPower’s implementation of SAS is capable of modeling all systems, subsystems, components, and geometric configurations.

3.3.2.3 Constituents and Phases

In EMDAP Step 3, TerraPower also identified that the EM must be capable of modeling liquid sodium, air, and argon gas. SAS is capable of modeling liquid sodium in both the primary and intermediate loops. Additionally, SAS allows for selecting parameters for the cover gas, including options for argon, discussed in appendix 2.2 of the SAS Code Manual [16]. Air and its interaction with the RAC are modeled in **[[   ]]**. Based on the review of the SAS Code Manual, the NRC staff verified that TerraPower, using SAS, can model the constituents and phases identified in Step 3.

3.3.2.4 Field Equations

As identified in EMDAP Step 3, the EM uses mass, momentum, and energy conservation equations to predict the transport of mass, momentum, and thermal energy of liquid sodium, argon gas, and air. SAS Code Manual chapter 3, “Core Thermal-Hydraulics,” applies the conservation of mass, energy, and momentum using field equations to describe phenomena in the reactor core. Conservation of energy is used to determine temperatures in the core for various components, such as the fuel pins and reflectors in each channel. Conservation of mass and momentum are applied to determine coolant flow rates through each channel. SAS Code Manual chapter 5, “Primary and Intermediate Loop Thermal Hydraulics Module,” applies the conservation of mass, energy, and momentum for plant components outside of the reactor core. These field equations are used for calculating temperatures, pressures, and flow rates throughout the PHT and IHT systems. The NRC staff reviewed the SAS Code Manual and verified that TerraPower can adequately use SAS to employ the field equations identified in Step 3.

3.3.2.5 Closure Relations

TR section 4.2.1.2(d), “Closure Relations,” states that correlations used in SAS are discussed in detail in the SAS Code Manual. The TR discusses specific closure relations included in SAS in EMDAP Step 12. The NRC staff’s review of the closure relations discussed by the TR is documented in SE section 3.3.3, “Step 12: Develop or Incorporate Closure Models.”

3.3.2.6 Numerics

TR section 4.2.1.2(e), “Numerics,” states that “[m]ost of the heat transfer calculations and flow rate calculations in SAS use semi-implicit time differencing to obtain stable solutions with reasonably long-time steps.” SAS Code Manual section 3.19.1, “Degree of Implicitness for Flow and Temperature Calculations,” provides a detailed overview of the semi-implicit approach used for these calculations. Additionally, each chapter in SAS provides the equations employed by the code. The NRC staff reviewed the TR and SAS Code Manual and determined that a semi-implicit differencing scheme is expected to give the analyst flexibility to provide an appropriate balance of accuracy and stability for a given transient and is thus acceptable. However, the NRC staff determined that the minimum degree of implicitness in the SAS calculations is a user input, and changing this value would affect the results when performing code verification activities (e.g., discretization studies, comparisons to exact analytical solutions, etc.). This is discussed further in section 3.4.4 of this SE, which addresses Step 16 of the EMDAP.

3.3.2.7 Additional Features

TR section 4.2.1.2(f), “Additional Features,” discusses SAS capabilities available to model control systems and boundary conditions. SAS Code Manual chapter 6, “Control System,” discusses the control system in detail. Users supply mathematical equations to describe their desired plant control system and identify plant variables that are to be measured and controlled.

These equations and variables are then transformed by the user into a block diagram where individual blocks are basic mathematical elements, such as an integrator or summer. The input card for SAS is prepared directly from this block diagram.

3.3.2.8 Software Limitations

TR section 4.2.1.2(g), "Software Limitations," discusses the limitations of SAS, including:

- SAS is not intended to analyze fuel failure and subsequent fuel relocation or fission product relocation in the sodium pool.

- SAS is limited to modeling single-phase liquid sodium, which is consistent with the approach taken in the EM[6].

- Nodalization refinement flexibility is limited.

- SAS is a one-dimensional code and thus cannot address any three-dimensional effects.

The NRC staff reviewed TerraPower's software limitation and determined that the software limitations of the code related to fuel failure/relocation and single-phase liquid sodium is consistent with the scope of the DBA without radiological release EM, in that the methodology is only used to analyze events where there is no fuel failure and no coolant boiling. The software limitation related to nodalization is also reasonable, because flexibility is retained for the nodalization in the core, where finer nodalization is needed most. The software limitation related to SAS not being able to model multi-dimensional effects is currently being investigated by TerraPower, as discussed in section 3.2.2.2 of this SE. The NRC staff expects that the results of that investigation will be used to inform code biases or uncertainties used in the DBA analysis, and should be discussed further in any future licensing submittal that uses the TR. This limitation is captured in Limitation and Condition 2, below.

3.3.2.9 EM Structure

TR section 4.2.2 discusses how SAS is integrated into the EM. Inputs into SAS include fuel performance, neutronics, thermal-hydraulics, design, materials, and safety analysis. In SAS, a steady-state calculation is first performed, followed by the desired transient calculation. The final results from the transient calculation are assessed to the FOMs to see if any limiting values are violated. TR figure 4.1, "EM Structure: Data Inputs, EM Program Flow, and Final Results," provides a flow diagram illustrating this process.

3.3.2.10 Staff Evaluation

The NRC staff reviewed the SAS Code Manual as it relates to establishing the EM structure (EMDAP Step 11). The NRC staff determined that TerraPower's approach to Step 11 is acceptable because it appropriately addresses all six ingredients, as discussed in the preceding

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6 **[[**

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sections. The NRC staff notes that this step may need to be revisited as the EMDAP progresses if any software limitations are found to impact the EM's capabilities.

3.3.3 Step 12: Develop or Incorporate Closure Models

Step 12 of the EMDAP involves developing and incorporating closure models into the EM. Closure models or relationships are usually developed using SET data. Correlations may also be selected from existing database literature.

TR section 4.3, "Closure Models and Conservatisms – EMDAP Step 12," addresses the closure models and conservatisms used to simulate Natrium responses to postulated DBAs without radiological release. TR section 4.3 outlines the closure relations used in the EM. Sections 3.3.3.1 and 3.3.3.2 of this SE address closure models that currently exist in the version of SAS available from ANL. TerraPower has also developed additional closure models, which are discussed in section 3.3.3.3 of this SE.

3.3.3.1 SAS Thermal-Hydraulic Closure Models

SAS Code Manual section 5.4.2.2, "Basic Equations," outlines the IHX heat transfer correlations used by SAS. For these equations, users supply a variety of coefficients to reflect their specific IHX design. TR section 4.3 states that TerraPower's chosen coefficients come from historical work done for the PRISM model which was based on an EBR-II model benchmark. TerraPower stated that both PRISM and EBR-II were pool-type SFRs with similar designs to Natrium. TerraPower stated that final tuning of these coefficients will be based on data from the SETs and vendor-supplied details on the IHX design.

SAS Code Manual section 5.3.3.1, "Anisotropic Re-dependent Loss Coefficients," discusses anisotropic Reynolds' number-dependent pressure drops for liquid flow across a zone interface (defined as the boundaries between liquid segments and CVs or elements within liquid segments). SAS can model pressure drops for both forward and reverse flow as required.

Section 5.3.3, "Pipes and Intermediate Heat Exchangers," of the SAS Code Manual states that the Moody friction factor is used for frictional pressure losses in pipes and intermediate heat exchangers.[7]

SAS Code Manual section 5.4.7.2.1, "Basic Equations," outlines the Nusselt number correlation and friction factors used for air in the **[[ ]]**. TerraPower stated that the EM discussed in the TR is currently using default numbers provided in the SAS Code Manual for user supplied coefficients for these correlations. TerraPower stated that the default numbers are adequate for preliminary design as the accumulated heat removal is conservative compared to the RAC design performance envelope.

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[7] TR section 4.3 references section 7.2.2, "Analytical Equations," of the SAS Code Manual for the friction factor in pipes, but this section of the manual relates to the SAS balance-of-plant model which is not used in TerraPower's EM. Nonetheless, the Moody friction factor discussed in section 7.2.2 of the manual is identical to that used in SAS Code Manual section 5.3.3, "Pipes and Intermediate Heat Exchangers," for the primary and intermediate loops, and is a standard model for friction in pipes.

SAS Code Manual section 5.3.4.2.2, “Option 2,” outlines the option which TerraPower selected in SAS for modeling centrifugal pumps. For this option, homologous pump curves are used for predicting pump performance. TerraPower stated that EM will use the representative data provided by SAS, noting that the pump model will be calibrated to achieve the minimum flow halving coastdown time required based on the design specification of the pump.

SAS Code Manual section 5.4.6, “Component-to-Component Heat Transfer,” outlines the correlations used by SAS for heat transfer between components. In TR section 4.3, the **[[**

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3.3.3.2 SAS Reactivity Feedback Models

SAS allows users to select from various reactivity feedback models. TerraPower stated that the models it selected cover reactivity feedback from axial, radial, and control rod drive (CRD) expansion. Each model and its assumptions are discussed in SAS Code Manual section 4.5, “Net Reactivity.”

SAS Code Manual section 4.5.4.1, “Simple Axial Expansion Reactivity Model,” discusses the model chosen by TerraPower for axial expansion reactivity feedback. Fuel, cladding and structure expansion fractions are calculated based on temperature and user-provided thermal expansion coefficients. Reactivity worths per unit mass are applied to each expanded mass and summed to determine the total axial expansion reactivity feedback.

SAS Code Manual section 4.5.7, “Control Rod Drive Expansion Feedback Reactivity,” outlines the model chosen by TerraPower for CRD expansion reactivity feedback. As CRD temperatures rise, thermal expansion will cause control rods to be inserted further into the core, providing negative reactivity. If CRDs are supported by the vessel head and the core is supported by vessel walls, the heating of the vessel walls will either lower the core or raise the CRD supports, leading to positive reactivity feedback. As such, this model accounts for both CRD and vessel wall expansion. The CRD expansion is determined by the CRD temperature, which is calculated based on the CRD physical properties input by the user and on coolant temperature in the upper internal structural region. The vessel expansion is calculated by **[[ ]]**, based on temperatures of the walls for liquid elements or CVs representing the vessel wall. The SAS Code Manual states that the code then calculates the net movement of the CRDs and determines the total CRD expansion reactivity feedback.

TerraPower stated that SAS has a built-in control system, as discussed in SAS Code Manual chapter 6, “Control System,” that enables the user to model plant control systems. TerraPower stated that because of the ability to take any code parameter as input and provide outputs that influence the system model, the SAS control system can also be used to develop new ad hoc models for physical phenomena. TerraPower is using the SAS control system to model radial expansion reactivity feedback. TerraPower accomplished this by providing the control system with a user-specified reactivity to the point kinetic model in SAS. TerraPower’s radial expansion reactivity feedback model consists of a lookup table of reactivity insertion based on power and flow conditions within the reactor. **[[**
]], which is discussed at a high level in

TP-LIC-RPT-0011, “Core Nuclear and Thermal Hydraulic Design Technical Report” [38], which was submitted as part of the Kemmerer Unit 1 construction permit application [39].

3.3.3.3 New Closure Models Added to SAS

TR section 4.3.1, “Closure Models,” details three new closure relations added to SAS to perform calculations for the Natrium design. TR section 4.3.1.1, “Core Convective Heat Transfer,” discusses one of the new closure relations. **[[**

]] [40]. TerraPower stated that the **[[**
]]. The NRC staff audited **[[**

]].

TR section 4.3.1.2, “Reynolds-Dependent Pressure Drop,” discusses another new closure model added to SAS. **[[**

]].

TR section 4.3.1.3, “Wire-wrapped Pin-Bundle Pressure Drop,” discusses the third new closure model added to SAS. **[[**

]] [41]. The NRC staff audited
ECI**[[**

]].

3.3.3.4 Staff Evaluation

The NRC staff reviewed the SAS Code Manual regarding the existing closure models and the documents [40, 41] referenced in the TR regarding the three new closure models. The NRC staff additionally audited internal TerraPower reports to ensure TerraPower’s fuel assembly design parameters fell within the ranges of applicability for each correlation. The NRC staff determined that TerraPower’s approach to EMDAP Step 12 is acceptable based on this review. The NRC staff also determined that the closure models added to SAS by TerraPower are acceptable for use in the EM because, in general, they are expected to provide more accurate predictions of key parameters while remaining applicable to Natrium fuel. However, the NRC staff noted that TerraPower intends to **[[**

]]; this will be needed in order for the NRC staff to determine whether [[ ]]. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that this step of the EMDAP has been appropriately addressed.

3.4 Element 4: Assess the Adequacy of the Evaluation Model

Element 4 of the EMDAP revolves around evaluating the adequacy of the EM. It consists of two parts: a bottom-up evaluation of the closure relationships used and then a top-down evaluation of the governing equations, numerics, and integrated performance of the EM. After these two parts are completed, then the biases and uncertainties of the EM can be determined. A key feature of this adequacy assessment is the ability of the EM to predict appropriate experimental behavior. In Element 4, Steps 13 through 15 covers the bottom-up evaluation, while Steps 14 through 19 cover the top-down evaluation.

The introduction of TR chapter 5, “Evaluation Model Adequacy Assessment: EMDAP Element 4,” outlines that the code assessment matrix developed in Element 2 will be used in conjunction with the EM developed in Element 3 to determine the adequacy of the EM. This chapter addresses both bottom-up and top-down evaluations planned for the EMDAP. As discussed in Steps 13 through 20, final completion of Element 4 requires experimental data from the planned IET and SETs to compare against the EM.

3.4.1 Step 13: Determine Model Pedigree and Applicability to Simulate Physical Processes

In Step 13, the closure relationships used in the EM are evaluated based on their pedigree and applicability. The pedigree evaluation relates to the physical basis, assumptions and limitations, and adequacy characterization of the closure model. The applicability evaluation relates to whether the closure model is consistent with its pedigree or whether use over a broader range of conditions is justified.

TR section 5.1, “Closure Relations (Bottom-Up: Pedigree and Applicability): EMDAP Step 13,” details what is needed for a pedigree and applicability evaluation for an example closure relationship, discussing:

1. Documentation – summary of experimental work performed and description of experimental hardware and instrumentation.

2. Measurement of uncertainty of the instrumentation used to obtain the data.

3. Range of applicability of the data.

4. Types of hardware for which data is applicable, including scaling information.

TR section 5.1 stated that this approach will be applied for all the closure relationships used in the EM and documented in a Models and Correlations document. The NRC staff determined that TerraPower’s approach to EMDAP Step 13 is acceptable because it is consistent with the considerations discussed in RG 1.203. The NRC staff has not made a determination with respect to TerraPower’s execution of EMDAP Step 13 because it has not been performed. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that this step of the EMDAP has been appropriately addressed.

3.4.2 Step 14: Prepare Input and Perform Calculations to Assess Model Fidelity or Accuracy

In Step 14 of the EMDAP, a fidelity evaluation is performed by preparing the necessary input data for the EM and then performing calculations required to assess the fidelity or accuracy of the model. This can be done through validation efforts (comparing results to experimental data), benchmarking efforts (comparison to other standards or results obtained from other codes), or some combination thereof. SET input for component devices used in the model should be prepared to represent the phenomena and test facility being modeled. Nodalization convergence studies should be performed when practicable in both the test facility and plant models. Differences between the calculated results and experimental data for important phenomena should be quantified for bias and deviation.

TR section 5.2, “Closure Relations (Bottom-Up: Model Fidelity and Accuracy): EMDAP Step 14,” states that SAS calculations will be performed and compared against relevant data from experiments applicable to Natrium’s design as described in TR chapter 3. TerraPower stated that this will include convergence studies focused on nodalization representing the experiments that were built to generate data underlying the closure model. TR section 5.2 states that these calculations should be performed for all closure relations that are used within the EM. The section further states that model fidelity and accuracy is shown by reasonable or excellent agreement between experimental and calculated data for each closure relationship unless a conservative treatment was applied. TerraPower stated that in that scenario, the model should show calculated behavior with a conservative outcome. As discussed in Step 10, RG 1.203, appendix B, states that for highly-ranked phenomena identified in the PIRT, the minimum standard of acceptability with respect to fidelity is generally “reasonable agreement.” TerraPower notes that this step will be conducted once experimental data from Step 7 is available (i.e., the SETs are completed and legacy experimental data is acquired).

The NRC staff determined that TerraPower’s approach to Step 14 is acceptable because it aligns with RG 1.203 guidance in that it appropriately focuses on validation of the EM relative to experimental data, supported by numerical studies and benchmarks as needed. The NRC staff has not made a determination with respect to TerraPower's execution of EMDAP Step 14 because it has not been performed. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that this step of the EMDAP has been appropriately addressed.

3.4.3 Step 15: Assess Scalability of Models

Step 15 of the EMDAP requires a scalability evaluation to be performed, limited to determining whether the specific model or correlation is appropriate for application to the configuration and conditions of the plant and transient under evaluation.

TR section 5.3, “Closure Relations (Bottom-Up: Assess Scalability of Models): EMDAP Step 15,” discusses that TerraPower will conduct confirmatory calculations or justifications for the scalability of each closure relationship once the experimental data discussed in Step 7 becomes available. TerraPower stated that these will address the validity of using closure relationships developed using data from experiments that are a fraction of the size of the Natrium plant.

The NRC staff determined that TerraPower's approach to Step 15 is acceptable because it is consistent with the considerations discussed in RG 1.203. The NRC staff has not made a determination with respect to TerraPower's execution of EMDAP Step 15 because it has not been performed. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that this step of the EMDAP has been appropriately addressed.

3.4.4 Step 16: Determine Capability of Field Equations to Represent Processes and Phenomena and the Ability of Numeric Solutions to Approximate Equation Set

Step 16 of the EMDAP determines the capability of the field equations to represent processes and phenomena as well as the ability of numeric solutions to approximate the equation set. For the field equation evaluation, the acceptability of the governing equations in each code is examined to characterize the relevance of the equations for the chosen application. This evaluation should consider the pedigree, key concepts, and processes culminating in the equation set solved by each component code.

The numeric solution evaluation considers convergence, property conservation, and stability of code calculations to solve original equations when applied to the target application. This evaluation summarizes information regarding the domain of applicability of the numerical techniques and user options that may impact accuracy, stability, and convergence features of each component code.

TR section 5.4, "Integrated EM – Top-down: Field Equations/Numeric Solutions Capabilities – EMDAP Step 16," discusses TerraPower's approach to determining the capability of the EM's field equations and numeric solutions. For SAS, TerraPower derived partial differential equations (PDEs) to describe single-phase flow for liquids, covering conservation of mass, momentum, and energy. TerraPower stated that these conservation equations are discretized using finite difference equations (FDEs).

TR section 5.4 states that the EM's PDEs will be validated by performing calculations using data from experiments scaled to the Natrium plant. TerraPower stated that it intends to evaluate the momentum equation against the requirements for momentum equations discussed in 10 CFR 50 Appendix K. TerraPower stated the pedigree, key concepts, and processes culminating in the field equations used in SAS will be distilled from existing documentation and included in subsequent revisions of this TR as well as in additional code manuals.

For the numeric solution evaluation, TerraPower stated that it will consider consistency, property conservation, and stability of the SAS code and that consistency will be characterized by the extent to which the FDEs approximate the PDEs.

The NRC staff determined that TerraPower's approach to Step 16 acceptable because it is consistent with the considerations discussed in RG 1.203. The NRC staff has not made a determination with respect to TerraPower's execution of EMDAP Step 16 because it has not been performed. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that this step of the EMDAP has been appropriately addressed.

3.4.5 Step 17: Determine Applicability of Evaluation Model to Simulate System Components

In Step 17, an applicability evaluation is performed to consider whether the integrated code is capable of modeling plant systems and components. The various EM options, special models, and inputs should have the inherent capability to model major systems and subsystems required for the application.

TR section 5.5, "Integrated EM – Top-down: Assess Applicability of EM to Simulate System and Global Capability: EMDAP Steps 17 and 18," addresses both Steps 17 and 18. As such, the SE assesses them together in the next section.

3.4.6 Step 18: Prepare Input and Perform Calculations to Assess System Interactions and Global Capability

Step 18 of the EMDAP consists of a fidelity evaluation, where EM-calculated data is compared to measured test data from component and integral tests (and to plant transient data if available). For this, data from the EM is compared against the integral database selected in Element 2. Once IET simulations are completed, the differences between calculated data and experimental data should be determined for important processes and phenomena and be quantified for bias and deviation. The ability of the EM to model system interactions are evaluated in this step, and input decks are prepared for the EM's target applications.

TR section 5.5 addresses Steps 17 and 18 of the EMDAP. TerraPower plans to first evaluate the capability of the EM to simulate the systems and subsystems of the Natrium plant, and then assess the system interactions and global capabilities of the EM. Based on historic work and pedigree documentation, TerraPower stated that SAS is capable of modeling SFR components. TerraPower has additionally completed commercial grade dedication for SAS version 5.7.1. TR section 5.5 also provides a list of tasks which must be completed to assess system interactions and global capabilities of the EM, consisting of:

- Identification of the optimal model representation of Natrium plant components and systems.

- Confirmation that a nodalization gives convergent solutions for both the Natrium plant and models used to perform validation studies based on the experimental data sets which make up the code assessment matrix.

- Application of the same model options and nodalization in both the Natrium design and experiment validation calculations.

- Assessment and confirmation that all highly-ranked phenomena identified in the PIRT are calculated in either reasonable or excellent fashion for a best-estimate calculation, or are suitably conservative.

- Quantification of the biases and deviations of the validation calculations and subject validation data.

- Evaluation of the EM's ability to model system interactions.

- Qualification of the parameter ranges characteristic of the Natrium plant for the scenarios discussed in Step 1.

The NRC staff determined that TerraPower's approach to Step 17 and 18 is acceptable because the tasks planned are consistent with the considerations discussed in RG 1.203 and will sufficiently demonstrate the EM's ability to model Natrium and demonstrate the EM's fidelity. The NRC staff has not made a determination with respect to TerraPower's execution of EMDAP Steps 17 and 18 because they have not been performed. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that these steps of the EMDAP have been appropriately addressed.

3.4.7 Step 19: Assess Scalability of Integrated Calculations and Data for Distortions

Step 19 of the EMDAP involves performing a scalability evaluation limited to whether EM calculations and experimental data exhibit otherwise unexplainable differences among facilities or between calculated and measured data for the same facility. These differences may indicate experimental or code scaling distortions.

TR section 5.6, "Integrated EM – Top-down: Scalability Assessment of the Integrated EM: EMDAP Step 19," states that TerraPower intends to perform Step 19 in conjunction with Step 15, the scalability evaluation of closure models. For this step, TerraPower stated that it used the scalability assessment to ensure that the experimental data and EM calculations of the highly-ranked phenomena identified in Step 4 agree reasonably and demonstrate that the EM is sufficiently conservative. Additionally, TerraPower stated that it would perform an assessment of the distortion level of the measured data.

The NRC staff determined that TerraPower's approach to Step 19 is acceptable because it is consistent with the considerations discussed in RG 1.203. The NRC staff has not made a determination with respect to TerraPower's execution of EMDAP Step 19 because it has not been performed. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that this step of the EMDAP has been appropriately addressed.

3.4.8 Step 20: Determine Evaluation Model Biases and Uncertainties

Step 20 of the EMDAP involves determining EM biases and uncertainties. This includes determining whether the degree of overall conservativism or analytical uncertainty is appropriate for the entire EM.

TR section 5.7, "Determine EM Biases and Uncertainties: EMDAP Step 20," states that TerraPower is taking a conservative approach to its in-vessel DBAs without radiological release, and therefore does not perform uncertainty analyses. TerraPower stated that it has undertaken an effort to demonstrate that TerraPower's approach is "suitably conservative." The conservativism in the methodology is expanded on in TR section 4.3.2, “Conservatisms, Biases, and Hot Channel Factors” outlining that conservative DBA calculations are performed by revising the best-estimate model by:

1. Inserting conservative biases on the nominal inputs related to highly-ranked phenomena determined during Step 4.

2. Performing the calculation using the EM to obtain a calculational output.

3. Applying the safety HCFs and including the Hot Pin Ratio (HPR) to the output to obtain a conservative 2-sigma cladding temperature.

TR section 4.3.2 also includes a list of inputs to which biases will be applied. TerraPower stated that **[[**

]].

The NRC staff reviewed TerraPower’s approach and determined that it was appropriate to ensure that inputs will be biased conservatively and provide an overall conservative result, and is consistent with the principle discussed in RG 1.203, EMDAP Step 20, that suitably conservative transient analyses do not require a complete uncertainty analysis. Based on this, the NRC staff determined that the approach discussed in Element 3 and Step 20 of the TR is acceptable. However, as noted in RG 1.203, the appropriate degree of conservatism depends significantly on the purpose of the analysis, models used, etc. The NRC staff notes that the ultimate means of determining whether the EM is sufficiently conservative is to compare the prediction of the EM with applicable experimental data. Therefore, the NRC staff has not made a determination with respect to TerraPower’s execution of Step 20 because the application of this approach and its comparison to experimental results have not been performed. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to justify that this step of the EMDAP has been appropriately addressed.

3.5 Natrium Sample Analysis

TR chapter 6, “Natrium Sample Analysis Results,” states that TerraPower’s DBA analyses have not been performed in sufficient detail to warrant inclusion in the TR. TerraPower stated that sample DBA evaluations will be performed and documented prior to submitting a final update for this methodology.

3.6 Adequacy Evaluation

As discussed in section 1.5, "Adequacy Decision," of RG 1.203, "Throughout the EMDAP, questions concerning the adequacy of the EM should be asked. At the end of the process, the adequacy should be questioned once again to ensure that all the earlier answers are satisfactory and the intervening activities have not invalidated previous acceptable responses." If inadequacies are found, the issues should be corrected and appropriate portions of the EMDAP repeated to evaluate the correction. This process continues until EM adequacy is confirmed.

TR chapter 7, "Adequacy Decision," states that once the EMDAP is complete, the adequacy of the EM will be examined again to ensure that the EM meets its objectives. TerraPower stated that if an EM inadequacy is found, the issue will be corrected and the appropriate steps of the EMDAP will be repeated. TerraPower stated that this task will be performed last and documented prior to a final update to this methodology.

The NRC staff reviewed TerraPower's adequacy decision and observed that TerraPower's plan for its final adequacy decision appears to be consistent with the guidance in RG 1.203. The NRC staff is not making any determinations on TerraPower's adequacy decision because this step is incomplete. As discussed in Limitation and Condition 2, future licensing submittals referencing this TR will need to provide the status of the adequacy decision and justify that it has been appropriately addressed.

LIMITATIONS AND CONDITIONS

The NRC staff imposes the following limitations and conditions on the use of this TR:

1. The NRC staff's determinations in this SE are limited to the Natrium design described in Section 1.2 of the TR and this SE, including the use of Natrium Type 1 fuel. An applicant or licensee referencing the methodology developed in this TR must justify that any departures from these design features do not affect the conclusions of the TR and this SE. Additionally, this methodology was developed to analyze certain design basis accidents as discussed in TR section 2.1 and this SE (and as defined in NEI 18-04 [9]); use of this methodology for other kinds of analyses must be justified.

2. The NRC staff noted that execution of the steps 6, 7, 8, 9, 12, 13, 14, 15, 16, 17, 18, 19, and 20 of the EMDAP, as well as sensitivity studies discussed in section 2.5 of the TR and section 3.1.4 of this SE, have not been completed. An applicant or licensee referencing the methodology developed in this TR must submit documentation and justify that these steps of the EMDAP have been completed to a state that is appropriate for the intended licensing application.

CONCLUSION

The NRC staff has determined that Revision 2 of TerraPower's TR, "Design Basis Accident Methodology for In-Vessel Events without Radiological Release," provides an acceptable approach to develop a methodology for use by future applicants utilizing the Natrium design as described in the TR and this SE to evaluate in-vessel DBA events without radiological release because its approach is consistent with RG 1.203. This approval is subject to the limitations and conditions discussed in the previous section of this SE.

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REVISION HISTORY

Revision No.	Affected Section(s)	Description of Change(s)
0	All	Initial Release – Supersedes TP-LIC-RPT-0004 Rev. 0, Incorporates changes made to address NRC questions during audit review. Changes from previous information marked via change bars.
1	4.2.1.2, 4.3.2	Prop markings revised
2	9	Prop markings revised

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EXECUTIVE SUMMARY

This report summarizes the approach taken to satisfy the guidance outlined in Regulatory Guide (RG) 1.203 Evaluation Model Development and Assessment Process (EMDAP) for in-vessel design basis accident (DBA) events without radiological release in the Natrium™ reactor, a TerraPower & GE-Hitachi Technology.

Within RG 1.203, six basic principles are identified as important to follow in the process of developing an EM. The first four principles deal with the EMDAP itself, whereas the remaining two principles focus on the quality assurance protocol and the need for comprehensive, accurate, and up-to-date documentation. The content of this topical report is summarized by briefly outlining the approach for satisfying the requirements of the four principles that deal with EMDAP in the subsequent paragraphs.

An adequacy decision is achieved when Regulatory Positions 1.1 through 1.4 have been satisfactorily addressed (see RG 1.203, Section 1.5, p. 20). Regulatory Positions 1.1 through 1.4 are discussed below from the perspective of achieving this objective.

It is noted that the strategy to follow the EMDAP defined in RG 1.203 is still under development for the DBA methodology for in-vessel events without radiological release. The objective is to develop a conservative methodology to determine the Natrium EM adequacy; therefore, an uncertainty methodology will not be discussed in this report. Instead, the conservative methodology which is still under development will be shown to be suitably conservative.

Regulatory Position 1.1 (RP 1.1) concerns the determination of the requirements for the EM. RP 1.1 is addressed in EMDAP Element 1. Key events and scenarios relevant to in-vessel DBAs without radiological release were identified together with the Figures of Merit (FOMs) and phenomena which are highly-ranked in importance in the five Phenomena Identification and Ranking Table (PIRT) studies that were conducted (see Chapter 2). [[ ]](a)(4) highly-ranked phenomena were identified and qualitatively described. Based on historically successful sodium-cooled fast reactor (SFR) experiments, design and deployment of measurement diagnostics, and subsequent analyses, successful mathematical modeling methods have been identified. The SAS4A/SASSYS-1 (SAS) code serves as the basis for the EM.

RP 1.2 focuses on the development of an assessment base consistent with the determined requirements. RP 1.2 is addressed in EMDAP Element 2 (Chapter 3). The assessment base forms the content of the Natrium EM code assessment matrix. The required data sets that will characterize the highly-ranked phenomena and populate the Natrium code assessment matrix will be obtained from:

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]](a)(4)

Data from the above planned and vintage experimental facilities are presently included in the preliminary EM code assessment matrix.

Regulatory Position 1.3 (RP 1.3) concerns the development of the EM. RP 1.3 is addressed in EMDAP Element 3 (Chapter 4). The EM is based on the SAS code that was developed and is being maintained and revised to accommodate the needs of this EM development effort by Argonne National Laboratory (ANL). The ingredients that distinguish the Natrium EM from earlier versions of the SAS are:

- [[

]](a)(4)

Regulatory Position 1.4 (RP 1.4) concerns the assessment of the EM adequacy: RP 1.4 is addressed in Element 4 (Chapter 5). The calculations and evaluations performed demonstrate the closure relationships and the integrated EM are satisfactory. The calculations will demonstrate that the analyses are “suitably conservative” and thus demonstrate that the Natrium EM is adequate. The selection of conservative assumptions will be informed by the quantitative uncertainty analysis of consequences that will be performed for the corresponding Design Basis Event (DBE) – consistent with the NEI 18-04 methodology.

This report documents the Natrium In-Vessel DBA EM adequacy. Certain aspects of the EM adequacy demonstration remain in development and are noted throughout the report. It is acknowledged that this report does not contain the complete technical basis that would be expected in a full transient and safety analysis methodology report. Several sections describe actions that are planned to be taken by TerraPower, and information generated by these actions will be provided through revisions to this report, supplemental documents, or future engagements prior to the method's use with an operating license.

TerraPower requests NRC review and approval of the proposed DBA methodology documented in this report for use by future applicants utilizing the Natrium design as an appropriate and adequate means to evaluate in-vessel DBA events without radiological release.

ACRONYMS

Acronym	Definition
AHX	Sodium-Air Heat Exchanger
ANL	Argonne National Laboratory
AOO	Anticipated Operational Occurrences
BDBE	Beyond Design Basis Events
BOL	Beginning of Life
BOP	Balance of Plant
CDF	Cumulative Damage Fraction
CGD	Commercial Grade Dedication
CPA	Construction Permit Application
CRD	Control Rod Drive System
DBA	Design Basis Accident
DBE	Design Basis Event
DID	Defense-in-Depth
DOE	Department of Energy
EBR	Experimental Breeder Reactor
EM	Evaluation Model
EMDAP	Evaluation Model Development and Assessment Process
EOC	End of Cycle
F-C	Frequency-Consequence
FDE	Finite Difference Equation
FFTF	Fast Flux Test Facility
FOM	Figure of Merit
FSAR	Final Safety Analysis Report
GEH	GE-Hitachi
GV	Guard Vessel
HCF	Hot Channel Factor
HPR	Hot Pin Ratio
IAC	Intermediate Air Cooling
IET	Integral Effects Test
IHT	Intermediate Heat Transport System
IHX	Intermediate Heat Exchanger
IRACS	Intermediate Reactor Auxiliary Cooling System
ISP	Intermediate Sodium Pump
IVS	In-Vessel Storage
IVTM	In-Vessel Transfer Machine
KAERI	Korea Atomic Energy Research Institute
LBE	Licensing Basis Event
LMR	Liquid Metal Reactor

Acronym	Definition
LOFWOS	Loss of Flow Without Scram
LOHS	Loss of Heat Sink
LOOP	Loss of Offsite Power
LWR	Light Water Reactor
NEI	Nuclear Energy Institute
NQA	Nuclear Quality Assurance
NRC	Nuclear Regulatory Commission
NSRST	Non-Safety-Related with Special Treatment
NSS	Nuclear Island Salt System
NST	Non-Safety-Related with No Special Treatment
PCT	Peak Cladding Temperature
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PDE	Partial Differential Equation
PHT	Primary Heat Transport System
PIRT	Phenomena Identification and Ranking Table
PNC	Power Reactor and Nuclear Fuel Development Corporation
PRISM	Power Reactor Innovative Small Module
PSAR	Preliminary Safety Analysis Report
PSP	Primary Sodium Pump
RAC	Reactor Air Cooling
RAC	Reactor Vessel Air Cooling
RCC	Reactor Core and Core Components System
RES	Reactor Enclosure System
RG	Regulatory Guide
RP	Regulatory Position
RSF	Required Safety Functions
RV	Reactor Vessel
RVACS	Reactor Vessel Auxiliary Cooling System
RVH	Reactor Vessel Head
RWAP	Rod Withdrawal at Power
RXB	Reactor Building
SAS	SAS4/SASSYS-1
SET	Separate Effects Test
SFR	Sodium-Cooled Fast Reactor
SHRT	Shutdown Heat Removal Test
SHX	Sodium-Salt Heat Exchangers
SR	Safety-Related
SRP	Standard Review Plan
SSC	Structures, Systems, and Components

Acronym	Definition
TATNF	Time-at-Temperature No-Failure
TWR	Travelling Wave Reactor

1 INTRODUCTION

This report documents the evaluation method developed for in-vessel DBA events without radiological release which are associated with the Natrium™ Reactor Plant, the EM development process, the resulting EM, and identifies items which require additional development. Certain aspects of the adequacy demonstration for the EM remain in development and are noted throughout the report. Overarching TerraPower methodology development guidance and RG 1.203, *Transient and Accident Analysis Methods* [2] were used to guide the EM development process.

1.1 Regulatory Requirements and Guidance

DBA postulated accidents "… are used to set design criteria and limits for the design and sizing of safety-related systems and components." per the Standard Review Plan (SRP) (NUREG-0800) 15.0[1]. Further, as noted in NUREG-2122: A DBA "…is a postulated accident that a nuclear facility must be designed and built to withstand without loss to the systems, structure, and components necessary to ensure public health and safety." The definition put forth in Nuclear Energy Institute (NEI) 18-04 is: [1]

> "Postulated event sequences are used to set design criteria and performance objectives for the design of Safety Related SSC. DBAs are derived from DBEs based on the capabilities and reliabilities of Safety-Related SSCs needed to mitigate and prevent event sequences, respectively. DBAs are derived from the DBEs by prescriptively assuming that only Safety Related SSCs are available to mitigate postulated event sequence consequences to within the 10 CFR 50.34 dose limits."

As shown in Figure 1-1, DBAs are derived from DBEs and have no frequency assigned. The DBAs meet the definition given in NEI 18-04 and were obtained using the NEI 18-04 processes as noted in the next paragraph.

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[1] See NEI 18-04, Table 3-1, p. 6.

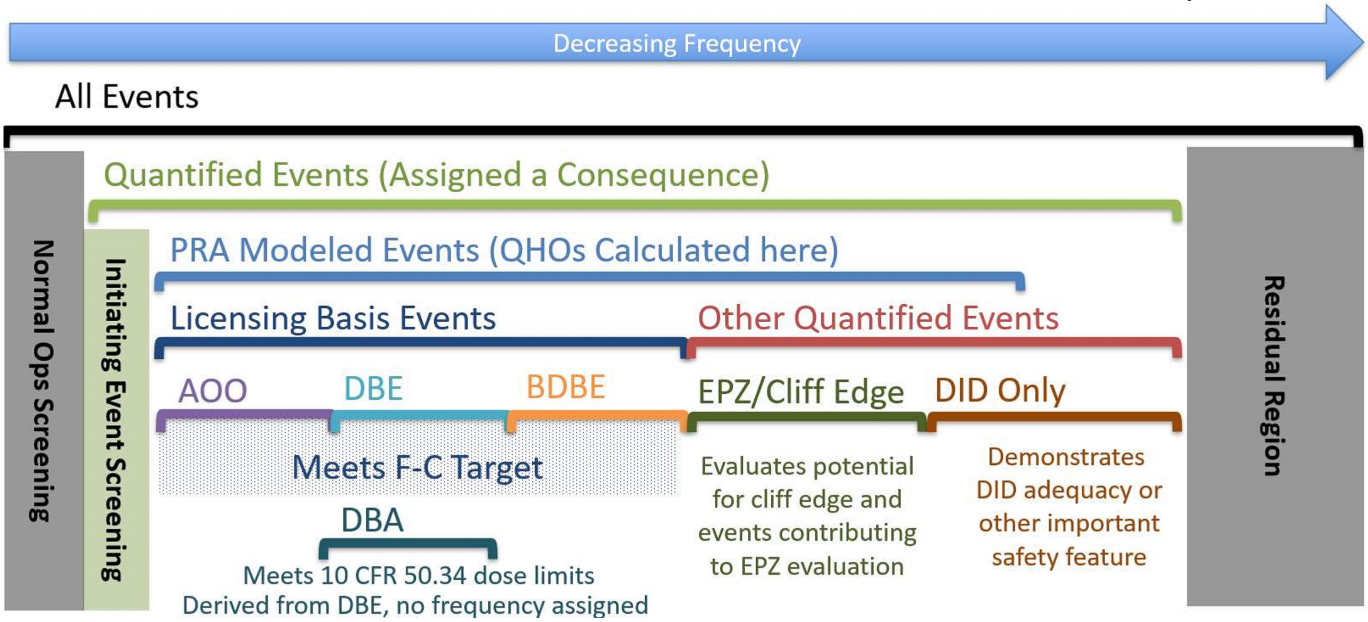

Figure 1-1. Event Type Line Diagram by Frequency.

NEI 18-04 & 21-07: Methodologies developed to identify the postulated events associated with in-vessel events without radiological release have been performed to define the DBAs considered in this report. These methodologies conform to the "…technology-inclusive, risk-informed, and performance-based process for the selection of Licensing Basis Events (LBEs); safety classification of SSCs and associated risk-informed special treatments; and determination of Defense-in-Depth (DID) adequacy for non-light water reactors." [1] The processes described in NEI 18-04 are "…acceptable processes for selection of LBEs; safety classification of SSCs and associated risk-informed special treatments; and determination of DID adequacy applicable to a technology-inclusive array of advanced non-Light Water Reactor (LWR) designs." [1] By following the guidance in [1] and NEI 21-07: Technology Inclusive Guidance for Non-LWRs: Safety Analysis Report Content for Applicants Using the NEI 18-04 Methodology [3], TerraPower has developed the basis for evaluations that can be used to demonstrate compliance with 10 Code of Federal Regulations (CFR) 50.34 for both a Preliminary Safety Analysis Report (PSAR) for a Construction Permit application and the Final Safety Analysis Report (FSAR) for an Operating License application.

Content of This Report: The following topics are addressed:

- DBA events selected for analysis (Chapter 1.4),
- Required EM capabilities for performing in-vessel DBAs without radiological release (Chapter 2)
- EM assessment base development for the selected DBAs (Chapter 3)
- EM development for the analysis of the selected DBA events (Chapter 4)
- Bottom-up and Top-down EM adequacy assessment for the DBA events (Chapter 5)

- Sample analysis results (Chapter 6)
- EM adequacy decision (Chapter 7)

The report structure given above describes how the EMDAP methodology has been applied to the development, assessment, and the determination of adequacy of the EMs used to analyze the DBAs for in-vessel events without radiological release.

The Evaluation Model Concept: as defined in RG 1.203[2], "…establishes the basis for methods used to analyze a particular event or class of events. This concept is described in 10 CFR 50.46 for loss-of-coolant analyses but can be generalized to all analyzed events described in the SRP." As such:

> "An evaluation model (EM) is the calculational framework for evaluating the behavior of the reactor systems during a postulated transient or design-basis accident. As such, the EM may include one or more computer programs, special models, and all other information needed to apply the calculational framework to a specific event, as illustrated by the following examples:
>
> 1. procedures for treating the input and output information (particularly the code input arising from the plant geometry and the assumed plant state at transient initiation)
> 2. specification of those portions of the analyses not included in the computer programs for which alternative approaches are used
> 3. all other information needed to specify the calculational procedure.
>
> The entirety of an EM ultimately determines whether the results are in compliance with applicable regulations. Therefore, the development, assessment, and review processes must consider the entire EM.
>
> The reader should note that this regulatory guide also uses the term "model," which should be distinguished from the evaluation model or EM. In contrast to the EM as defined here, "model" (without the "evaluation" modifier) is used in the more traditional sense to describe a representation of a particular physical phenomenon within a computer code or procedure."

The EM used to evaluate postulated in-vessel DBAs without radiological release is centered on the use of the SAS code.

The adequacy of the EM is achieved by following the EMDAP as shown in flow chart form in RG 1.203, Figure 1[3]. Note that EMDAP consists of four elements followed by an "Adequacy Decision" when the contents of the four elements are completed:

Element 1	Establish requirements for EM capability (Chapter 2)
Element 2	Develop assessment base (Chapter 3)
Element 3	EM development (Chapter 4)
Element 4	EM adequacy assessment (Chapter 5)

Element 1 focuses on establishing the exact application envelope for the EM and identifying the importance of constituent phenomena, processes, and key parameters within that envelope.

[2] See Section B, Discussion, p. 3.
[3] See Section B, Discussion, p. 6.

Chapter 2 documents the determination of: (i) the necessary capabilities of the EM by identifying the physics that should be contained in the EM for the transient scenarios, (ii) the geometries of the subject nuclear system that must be evaluated with the EM, (iii) the safety margin of the subject nuclear system using key measurable physical parameters that are closely associated with the plant operational and accident limits—commonly labeled “figures-of-merit”, and (iv) the adequacy of the EM that is to be developed in Element 3. Element 1 consists of the first four steps of EMDAP.

Element 2 encompasses the effort required to obtain an adequate assemblage of experimental data for use as the reference for determining the adequacy of the EM. The data captured in Element 2 must be relatable to the full-sized nuclear system using a hierarchical scaling law approach that contains a way to measure the geometrical correspondence, physical properties, representative events, representative sequences of events, and transient timing of events with respect to the full-sized nuclear system. Element 2 consists of Steps 5 through 9 of EMDAP.

Element 3 contains the central activities of (i) establishing the EM development plan and (ii) constructing the EM. The action of creating the EM development plan (identified as Step 10 in EMDAP) is the central key activity of EMDAP. Within the EM development plan are the following ingredients (see RG 1.203, Appendix B, pp. B-9 to B-10): (a) the software quality assurance plan, (b) the software requirements specification, (c) the documentation of the software design and implementation, (d) the source code verification test report, (e) validation testing report, and (f) the installation package and program upgrade documentation. Therefore, these sections and their associated documentation contain the descriptions of phenomena that must be contained within the EM, the means for demonstrating closure for both code verification and solution verification of the EM, and the measures that are to be used to determine whether or not the EMs are capable of calculating all the key phenomena within all the nuclear reactor components and within the system as a whole for all the transients listed in Element 1. Based on these parameters, the plan will develop the specifications of the experiments and their required measurement uncertainties, the acceptable distortion levels of the experiments to be used to generate validation data, the scale-up of experimental data recorded in experimental facilities much smaller than the full-sized plant, the validation metrics, and the limits within which the determination of EM adequacy. In a sense, all activities in both Elements 1 and 2 are inputs to the EM development plan and the remainder of Element 3 and all of Element 4 are steps that direct the execution of the EM development plan. Element 3 consists of Steps 10 through 12 of EMDAP.

Element 4 describes the performance of the EM development plan via (i) bottom-up considerations, i.e., model pedigree and performance of calculations to enable validation studies to be performed through model scalability, and (ii) via top-down considerations, i.e., ultimately demonstration of the scalability of integrated calculations for the transient class under consideration. Element 4 consists of Steps 13 through 20 of EMDAP.

EM Adequacy Decision, the final step in EMDAP, is performed by comparing the results obtained throughout EMDAP to the measures of success prescribed in the EM development plan (Step 10 within Element 3). Successful completion of the EM development plan as demonstrated by meeting all requirements of the EM development plan enables the plant event analyses to be performed for licensing purposes.

1.2 Sample Plant Description

The Natrium reactor is an SFR that uses a fuel design and an operating environment that are significantly different from LWRs currently utilized in the United States. The Natrium reactor is an innovative design that facilitates rapid construction and achieves cost competitiveness and flexible operations through the adoption of new technology and a reimagined plant layout. Many of these advances are enabled through inherent safety features of pool-type SFRs with metal fuel. The design is based on early reactor technology developed in the US by the Department of Energy (DOE) and was developed from decades of research, design, and development from GE-Hitachi's (GEH) Power Reactor Innovative Small Module (PRISM) technology and TerraPower's Traveling Wave Reactor (TWR®) technology.

The conceptual plant layout is shown in Figure 1-2 and is made up of two basic areas; a Nuclear Island where the reactor and associated support facilities reside and an Energy Island where thermal storage tanks and turbine facilities for generating electricity reside. Safety functions are made integral to the Nuclear Island and equipment supporting energy production is moved to separate structures in the Energy Island, resulting in a simplified Reactor Building (RXB). The design leverages the legacy of 40 reactor-years of EBR-II and FFTF operation. These two predecessor reactors demonstrated how SFRs can passively accommodate severe transients. The design capitalizes on the proven metal-fueled SFR safety characteristics to minimize the number of SR SSCs needed to achieve safety goals.

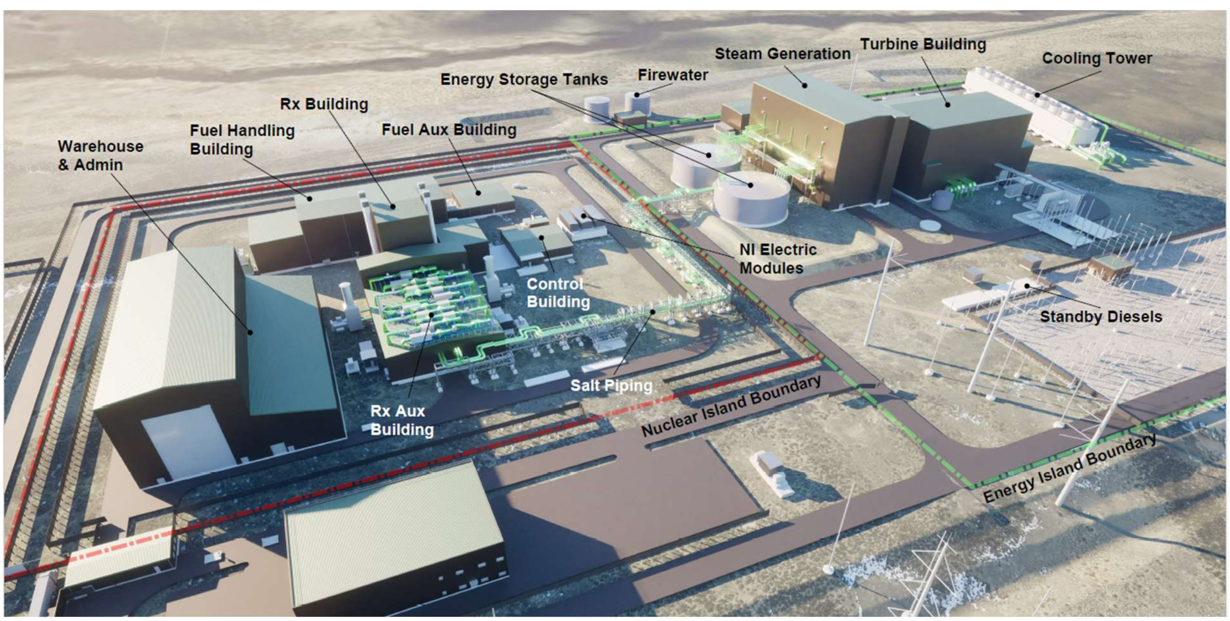

Figure 1-2. Plant Layout

The Natrium plant uses a pool-type design with the reactor core and primary coolant pumps located within a large pool of primary sodium coolant and no penetrations through the sides of the Reactor Vessel (RV), thereby eliminating loss of coolant accidents involving primary pumps and piping. The primary sodium pool operates near atmospheric pressure. Heat is transferred from the hot primary sodium pool to an intermediate sodium piping loop by means of two Intermediate Heat Exchangers (IHXs). The intermediate piping loop uses sodium to transport reactor heat from each IHX to Sodium-Salt Heat Exchangers (SHXs). These SHXs in the Nuclear Island heat salt received from the cold salt tank(s) in the Energy Island. The heated salt is then returned to the Energy Island for storage in the hot salt tank(s), which serves as thermal energy storage. The salt stored in the hot tank is used to generate steam for use in steam turbine generators, eliminating the need for generating steam directly from reactive sodium metal. The Natrium plant can vary its supply of energy to the grid through its energy storage system. The reactor operates at a thermal power of 840 MW while the plant produces 336 MWe steady-state and 500 MWe peak power.

The Natrium plant has been designed to accomplish reactivity control with multiple layers:

- The NSRST reactor control system acts as a buffer to prevent the need for a scram. It detects abnormal operation and initiates a runback via motor driven insertion of neutron absorbing control rods to achieve a softer shutdown than a scram.
- The SR reactor protection system initiates a scram if the reactor control system fails, or a runback fails to prevent the reactor from reaching a scram setpoint. The scram function is initiated by removing electrical power to an electromagnet, resulting in insertion of all control and standby rods into the reactor core.

The reactor core is designed with a negative temperature and power coefficient that is strong enough such that the reactor can accommodate anticipated transients without scram for events such as loss of primary flow, or loss of heat sink.

The high boiling point of sodium allows reactor operation at atmospheric pressure. A close-fitting Guard Vessel (GV) surrounding the RV stops the loss of coolant should the RV develop a leak. Furthermore, the reactor cover gas operates at essentially atmospheric pressure so there is little driving force for a release.

The Natrium plant is designed to accomplish residual heat removal with multiple layers of protection.

The Intermediate Air Cooling (IAC) transfers heat to the atmosphere (the final heat sink) from the Sodium-Air Heat Exchangers (AHXs). Forced flow heat removal via IAC serves as the normal shutdown cooling system for outages. There are two trains, one for each primary heat exchanger. The IAC can also operate in a passive flow mode. Simple operation of a fail-open electromagnetic damper initiates passive cooling. Use of active forced circulation through the IAC supports normal controlled cooling operations (such as during a refueling outage) and provides a response to anticipated transient events. Forced flow is provided by air blowers and the Intermediate Sodium Pumps (ISPs). The IAC's natural draft arrangement permits passive operation of the system as a diverse alternative if power to support forced cooling is not available. These functions supplement the SR RAC system and enable the IAC and its support systems to be non-safety-related.

The RAC removes decay heat using natural circulation of air around the exterior of the GV. The RAC does not have any dampers. The RAC is always operating and requires no power, people, or control action to perform its function. The RAC heat removal function relies on the natural circulation of the primary sodium and conductive/convective heat transfer to the RV wall. Thermal radiation heat transfer then dominates heat transfer to the GV. Natural draft air inlets provide ambient outside air to cool the GV outer wall via a combination of radiative and convective heat transfer. This air is then returned to atmosphere.

Figure 1-3 provides an illustration of how heat may be removed by both the IAC and RAC.

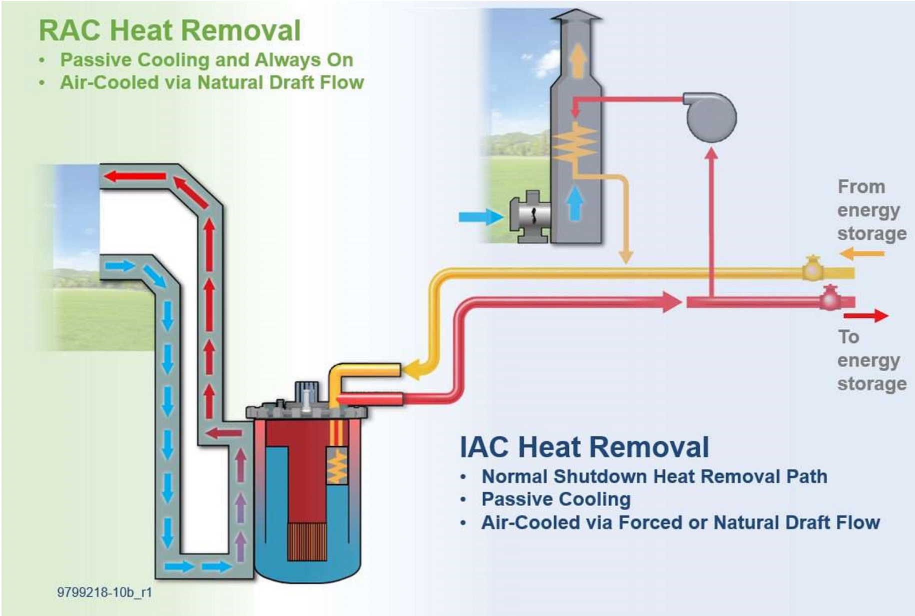

Figure 1-3. IAC and RAC Heat Removal

The Nuclear Island is composed of six major buildings: reactor, fuel handling, control, electrical, reactor auxiliary, and fuel auxiliary buildings. The RXB, see Figure 1-4, houses two major components: the reactor and RAC air ducts. The reactor is located below grade to protect it from natural hazards (e.g., earthquakes, tornadoes, etc.) and other hazards. There are only two rooms in the RXB, the refueling access area, where refueling and maintenance takes place, and the head access area where limited maintenance takes place. Intermediate sodium piping exits the RXB below ground to the reactor auxiliary building.

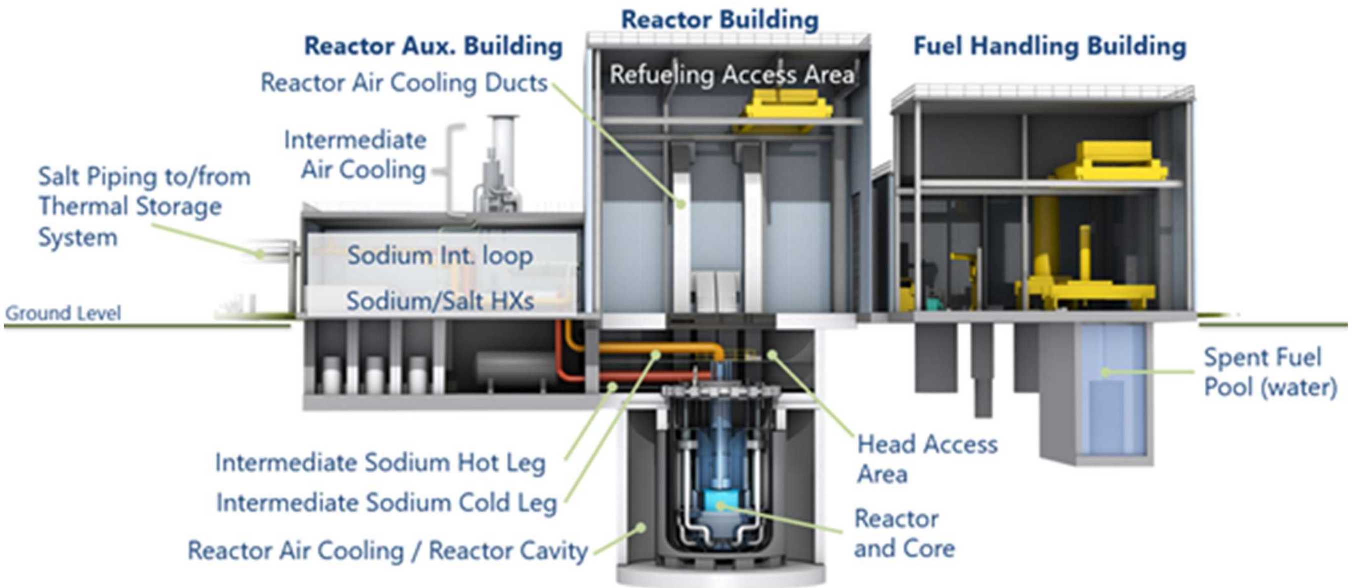

Figure 1-4. Conceptual Elevation View

The Primary Heat Transport System (PHT) is contained within the RV and consists of the IHX, the Primary Sodium Pumps (PSPs), the hot pool, and the cold pool. The PHT sodium flows up through the core where the fuel assemblies heat the sodium. The hot sodium enters the hot pool and flows downward through the shell side of the two IHXs. The sodium, cooled by the Intermediate Heat Transport System (IHT) sodium coolant transferring heat from the PHT to the Nuclear Island Salt System (NSS), exits the bottom of the IHXs and enters the cold pool. Cold pool sodium flows downward to the PSP inlet plenums which are located near the bottom of the vessel to maximize coolant inertia. The PSPs drive the cold pool sodium downward from the inlet and discharge it into a series of core supply pipes, which return the sodium to the core inlet. The sodium then enters the core through the core support and distribution structure, completing this flow circuit.

The Fuel Handling Building (FHB) houses fuel receipt equipment, refueling equipment, fuel storage equipment, and the fuel storage pool. Casks are used to transport fuel and in-reactor components from the RXB to the FHB. The buildings are connected by a rail system at ground level to support movement of the fuel handling cask. The FHB also contains the mechanical handling equipment which moves assemblies and provides access to the fuel pool. A bridge crane supports movement of dry storage fuel casks and equipment within the facility.

The Reactor Vessel Head (RVH) supports the rotatable plug for refueling operation. This plug is essential for the initial fueling of the reactor and for all subsequent fuel transfer operations during refueling and decommissioning. The plug is configured such that the In-Vessel Transfer Machine (IVTM) can access all core components, the In-Vessel Storage (IVS) locations, and the fuel elevator. The plug rotates via a bearing and drive assembly and is equipped with sealing mechanisms to isolate the primary fluid and cover gas from the atmosphere during normal, accident, and refueling operations. The GV surrounds the RV and is designed to contain sodium leakage in the event of an

RV breach, ensuring sufficient coolant inventory is maintained in the RV for residual heat removal through level equalization and preventing a sodium reaction with the surrounding RXB concrete.

The IVTM moves core assemblies between the core, in-vessel fuel storage racks, and transfer station for removal from the RV. It is mounted on the reactor rotatable plug, which is centered within the reactor top plate. The IVTM consists of two subassemblies: the above-head drive assembly and the in-vessel fuel handling mechanism. The latter extends to reach all removable core assembly locations when used in conjunction with the rotatable plug. Core assemblies are transferred into and out of the RV with the fuel transfer lift operating through the reactor transfer adapter. Fresh core assemblies are transferred into the fuel transfer lift and are then lowered into the pool region by the fuel transfer lift to core level to be transferred into the core using the IVTM. Used core assemblies are transferred out of the core to the in-vessel storage for decay or directly to the fuel transfer lift for assemblies which do not require in-vessel decay. The IVTM and fuel transfer lift are installed at the beginning of a refueling outage, the IVTM installed on the rotating plug assembly, and the fuel transfer lift penetrating the reactor vessel head. They make up part of the functional containment boundary during refueling operations and are removed after refueling is complete.

1.3 Safety Classification

The Natrium plant uses three safety classification levels: Safety-Related (SR), Non-Safety-Related with Special Treatment (NSRST), and Non-Safety-Related with No Special Treatment (NST). Explanations for each of the three classifications are provided below.

Safety-Related

SSCs selected from those that are available to perform the Required Safety Functions (RSFs) to mitigate the consequences of DBEs to within the LBE Frequency-Consequence (F-C) target, and to mitigate DBAs that only rely on the SR SSCs to meet the dose limits of 10 CFR 50.34 using conservative assumptions.

SSCs selected from those that are available and relied on to perform RSFs to prevent the frequency of Beyond Design Basis Events (BDBE) with consequences greater than the 10 CFR 50.34 dose limits from increasing into the DBE region and beyond the F-C target.

Non-Safety-Related with Special Treatment

Non-safety-related SSCs relied on to perform risk-significant functions. Risk-significant SSCs are those that perform functions that prevent or mitigate any LBE from exceeding the F-C target or make significant contributions to the cumulative risk metrics selected for evaluating the total risk from all analyzed LBEs.

Non-safety-related SSCs relied on to perform functions requiring special treatment for DID adequacy. These SSCs are safety-significant even if they are not risk-significant.

Non-Safety-Related with No Special Treatment

All other SSCs (with no special treatment required)

1.4 In-Vessel Design Basis Accidents Without Radiological Release

Accident sequences evaluated within the PRA identify three categories of LBEs: AOOS, DBEs, and BDBEs. The events are categorized by frequency, consistent with the guidance outlined in NEI 18-04, as follows:

AOOs are events with mean frequencies of $1x10^{-2}$ / plant-year or greater

DBEs are events with mean frequencies from $1x10^{-4}$ / plant-year to $1x10^{-2}$ / plant-year

BDBEs are events with mean frequencies from $5x10^{-7}$ / plant-year to $1x10^{-4}$ / plant-year

DBAs are not categorized by a mean frequency and are instead derived from the DBEs determined above by only crediting safety-related SSCs. The EM presented in this report is used to evaluate DBAs that occur within the reactor vessel, and which do not involve the release of radioactive material.

2 EVALUATION MODEL CAPABILITY REQUIREMENTS: EMDAP ELEMENT 1

A four-step process was undertaken to define the capabilities of the in-vessel DBA EM. These steps included:

1. Specify analysis purpose, transient class, and power plant class (Section 2.1)
2. Specify FOMs (Section 2.2)
3. Identify systems, components, phases, geometries, fields, and processes that must be modeled (Section 2.3)
4. Identify a list of important key phenomena (Section 2.4)

The following subsections describe the content of EMDAP Steps 1 through 4. A preliminary evaluation of the highly ranked phenomena is also presented in Section 2.5.

2.1 Analysis Purpose: EMDAP Step 1

The analysis purpose is to demonstrate that the plant operates such that all relevant acceptance criteria are satisfied under normal operational conditions, and continue to be satisfied during in-vessel DBAs without radiological release. The phenomena and processes inherent to the occurrence of in-vessel DBAs without radiological release are identified as inputs to define the physics, models, and calculational capabilities of the EM.

Three scenarios were selected as representative of the potential events included in the in-vessel DBA envelope, and include the Loss of Offsite Power (LOOP), Rod Withdrawal at Power (RWAP), and Loss of Heat Sink (LOHS). These scenarios were reviewed as part of the PIRT development process.

The EM used for these analyses is conservative, and not best-estimate. Therefore, calculational uncertainties are not calculated in the DBAs. However, as noted in Appendix A of RG 1.203 (see p. A-3) [2] the predictions of the EM, or portions thereof, shall be compared with applicable experimental information to the extent practicable.

2.2 Figures-of-Merit: EMDAP Step 2

FOMs give quantitative standards of acceptance with respect to the safety analysis. Adherence to the limits prescribed by the FOMs provides general requirements for maintaining the Natrium reactor in a safe condition during normal operation and during transients and accidents in terms of quantitative fuel and reactor system design limits. Fuel performance-centered acceptance criteria have been established for in-vessel DBA events.

To identify FOMs for EM development associated with DBAs without radiological release, it is helpful to examine event acceptance criteria for its LBEs.

NEI-18-04 provides guidance for selecting LBEs, safety classification of SSCs and associated risk-informed special treatments, and determination of DID adequacy for non-LWRs. NEI-18-04 uses a set of frequency-consequence criteria (referred to as the F-C Target in that report) to select LBEs. The F-C Target values are based on mean event sequence frequency of occurrence per plant-year and radiation exposure limits, respectively.

The F-C Target values provide a general reference to assess events and evaluate safety margins. Fuel performance, especially fuel failure phenomenon, becomes important in deterministic safety analyses that challenge the F-C target. Key parameters (or mechanisms) that can lead to fuel failure are fuel and cladding temperatures and cladding strain. Coolant temperature was considered in the PIRT process for RV integrity.

Natrium Type 1 fuel has a considerable margin to strain limit (even under the conservative analysis conditions involving thinning the initial cladding thickness by 25%, applying a Fuel-Clad Chemical Interaction model which includes uncertainty in the model fit, using 2σ Hot Channel Factor (HCF) temperatures, and including the creep damage model). The large margin to cladding strain limits provides confidence that transient analysis will also meet design limits. The peak cladding temperature (PCT) is used as a surrogate for the cladding strain limit. The fundamental intent of in-vessel DBA without release analysis is intended to show compliance with the above statement.

The parameters (temperatures of coolant, clad, and fuel center) serve as FOMs. The severity of consequences of a DBA can be evaluated by investigating those parameters. The FOMs and their significances are summarized in Table 2-1. Cladding temperature limits are set to prevent fuel pin failure and to maintain a coolable geometry and ensure fuel pin reliability preventing cladding failure by fuel-clad eutectic reaction. The peak cladding temperature limit is applied to the inner cladding wall surface that may be in contact with fuel.

Table 2-1 Figures of Merit for In-Vessel DBAs Without Radiological Release.

Figure of Merit	Descriptions and Significance
Fuel centerline temperature	The fuel centerline temperature must stay below the fuel solidus temperature to avoid fuel damage. [[ ]][(a)(4),ECI] SAS calculates the fuel centerline temperature utilizing Hot Channel Factors (HCF), or safety factors that quantify the extent of temperature perturbations caused by manufacturing and analytical variability or uncertainty. A 2-sigma statistical uncertainty is assumed for the HCFs applied.
Coolant temperature	High coolant temperature may cause sodium boiling in the reactor core, which can result in positive reactivity feedback. In addition, this phenomenon can be used to examine the primary boundary integrity. This FOM is tracked, however the acceptance criteria for time-at-temperature no-failure (TATNF) for peak cladding temperature is designed to preclude boiling.

Figure of Merit	Descriptions and Significance
Time-at-temperature for PCT	The design basis approach and limit values of the PCT were evaluated for application to the Natrium design. For mechanical fuel pin cladding failure criteria, the main options include strain, cumulative damage fraction (CDF), stress, and temperature as primary or dependent criteria parameters. The Natrium design basis has adopted response parameters such as strain, wastage, and temperature rather than CDF and stress criteria because they have a historic precedent, are defensible by existing data, are readily analyzed, and can be measured to validate. These attributes allow for monitoring and surveillance that can confirm analysis predictions and assess remaining life of the fuel system. The time-at-temperature no-failure acceptance criteria incorporate cladding wastage and thermal creep criteria in assessing potential failure. [[ ]](a)(4)

Following development of the above FOMs and the corresponding PIRT review, development of fuel pin cladding temperature criteria for failure analysis proceeded.

The resulting TATNF criteria above were developed after the initial PIRT, however they are consistent with the FOM used within the PIRT. The temperature ranges used for the PIRT have been updated with the addition of time-dependent acceptance criterion for PCT. Evaluation of the time dependent criteria's potential impact on the PIRT must still be performed.

2.3 Systems, Components, Phases, Geometries, Fields, and Processes Modeled: EMDAP Step 3

The hierarchical system decomposition of the Natrium design follows:

- System: Natrium Plant
- Subsystems:
    - Reactor core and core components system
    - Reactor enclosure system
    - Primary heat transport system
    - Intermediate heat transport system
    - Intermediate air cooling system
    - Control rod drive system
    - Reactor air cooling system
- Modules: physical components, including the following
    - Reactor vessel
    - Intermediate heat exchanger
    - Other heat exchangers (e.g., IAC, SHX[4])
- Constituents:
    - Liquid sodium
    - Air
    - Argon gas
- Phases: Liquid sodium and gases
- Geometrical configurations
    - Liquid sodium flow direction governed by physical structures.
    - Air flowing through the riser of the RAC and IAC
    - Argon gas in stagnant condition above hot pool
- Fields: composed of constituents
    - Mass

[4] See supporting information in Appendix A.

- Momentum
- Energy

- Transport processes
  - Inter-component transport of constituents
  - Energy transport from:
    - Fuel to liquid sodium
    - Liquid sodium to structures
    - Components (e.g., ISP and PSP) to liquid sodium
    - Structures to surroundings

There is no transient scenario resulting in two-phase (sodium and argon) flow in a pipe under the in-vessel DBA/LBE events without radiological release[5].

2.4 Identification and Ranking of Phenomena and Processes: EMDAP Step 4

The final step (Step 4) of Element 1 is the identification and ranking of phenomena and their knowledge states concerning these phenomena—obtained by performing a PIRT for each scenario of interest within a selected event type, e.g., a loss-of-offsite power. PIRTs for DBAs without radiological consequence for the Natrium reactor were generated using historically-approved protocols and procedures. Although many DBAs without radiological consequence need to be considered, it is impractical to develop a PIRT for each scenario within each event. The DBAs were scrutinized to select three events as representative scenarios, which includes Loss of Off-site Power (LOOP), Rod Withdrawal at Power (RWAP) and Loss of Heat Sink (LOHS) as described in the paragraphs below. The phenomena and processes of the selected three representative accidents are considered to encompass the other in-vessel events without radiological release. The three representative events are:

1. LOOP—where two scenarios were examined and PIRTs were performed,
2. RWAP—where two scenarios were examined and PIRTs performed, and
3. LOHS.

The sequences in these representative events used to support the PIRT development, as described in the paragraphs below, may not be identical to those analyzed in the safety analysis.

One of the representative scenarios considered within the LOOP event [[ ]](a)(4) has a sequence of events that includes automatic reactor scram, pump coastdown behavior, reactor transitions to natural circulation, and decay heat removal via the RAC during a long-term cooling period. The LOOP event is initiated with power loss to the scram solenoid valves, the PSPs, and

[5] See supporting information in Appendix A.

ISPs, causing all control rods to be released and the PSPs and ISPs to coastdown. The NSS isolation valve is closed on loss of power. The RAC system passively removes heat from the reactor.

One of the representative scenarios considered within the RWAP event [[ ]](a)(4) has a different sequence of events that includes positive reactivity insertion, temperature increase in the primary and intermediate loops, and normal heat removal via the intermediate loop. Control rods are assumed to be sequentially withdrawn continuously at the maximum withdrawal rate. It is assumed in this event that the NSS isolation valve is not closed, and the PSPs and ISPs do not trip.

The representative scenario considered within the LOHS event [[ ]](a)(4) is initiated by the loss of power to all ISPs due to a spurious signal. It should be noted that the event sequence is different from the LOOP scenario discussed above. The LOHS event sequence is proposed to represent more appropriate responses as the LOHS event evolves. The ISP pumps are turned off at time zero of the transient. A reactor scram signal is generated on a low ISP flow trip. The PSPs are tripped with the reactor scram to prevent the pump heat from being added to the sodium in the PHT. Natural circulation is initiated in the PHT, and the RAC is operational, removing the decay heat.

A LOOP scenario and an additional RWAP scenario were considered by an internal TerraPower expert panel. The PIRTs for the three scenarios summarized above were performed using an expert panel that was external to TerraPower. The results of these PIRTs are also included in the composite PIRT results.

The five scenarios considered as representative of the above three events were analyzed using the results of representative SAS calculations. For example, the analyses of the scenarios considered by the external expert panel are based on the sequences of events as calculated by the SAS code.

The PIRTs will be updated prior to the FSAR if other events are identified to be representative, or as significant design changes occur.

The protocols and procedures used to develop PIRTs for the above events are described in detail in [4] where the necessary PIRTs were developed as a primary ingredient to Element 1 of RG 1.203. [2] The PIRTs generated are applicable to Anticipated Operational Occurrences (AOOs), DBEs, DBAs, and BDBEs without fuel failure.

The results of these PIRT studies are captured in high-level summary in the identification of the:

- Phenomena and processes importance rankings
- Knowledge level rankings for the phenomena or processes

The evaluation criteria used to obtain the importance rankings of the phenomena and processes are tied to the FOMs specified in Section 2.2. The FOMs are expected to be re-evaluated as assessment data is collected and evaluated based on the important phenomena and processes identified in the PIRT to ensure that Natrium design acceptance criteria are reflected.

Importance rankings of phenomena/processes identified using their relationships to the FOMs identified above were quantified using the three-level scale shown in Table 2-2. [5] The importance ranking quantifies the level of modeling fidelity required to predict the FOM values as reasonable, as defined in RG 1.203. The importance ranking, therefore, may be regarded as the relative sensitivity of the FOM with respect to the expected variability of the parameters associated with the phenomenon being considered.

Table 2-2. Phenomena/Processes Importance Rankings

Ranking	Description
High (H)	The sensitivity (1) of FOMs to the phenomenon is large.
Medium (M)	The sensitivity of FOMs to the phenomenon is medium
Low (L)	The sensitivity of FOMs to the phenomenon is little or negligible

Note (1): The sensitivity of the FOM is with respect to the expected variability of the expected values.

Three characteristic time periods are considered in evaluating the importance of phenomena/processes. The three time periods are described below.

- Phase 1 (P1, Initiation Phase): from event initiation until the control rods start to drop.
- Phase 2 (P2, Transition Phase): from the time the control rods start to drop, through pump coastdown, until stable natural circulation is attained.
- Phase 3 (P3, Post-scram Cooling Phase): from the time of reaching stable natural circulation flow until decay heat removal by RAC, ambient losses, and/or other systems exceeds generated decay heat, and the long-term cooling stability is sufficiently maintained.

The PIRT panel members identified the phenomena/processes ranking using a defined vote process. [5]

Rankings of the knowledge level of phenomena/processes are made using a three-level scale as shown in Table 2-3. The knowledge level is determined in an absolute sense, independent of the associated importance ranking.

Table 2-3. Knowledge Level Rankings

Ranking	Description
High (H)	The phenomenon is well known. Data uncertainties are relatively low and well characterized.
Medium (M)	The phenomenon is partially known. Data are available but the uncertainties are relatively large.
Low (L)	There is little knowledge regarding the phenomenon. There are high modeling uncertainties.

A knowledge level of high (H) implies additional research on this phenomenon is not necessary even if the importance level is high. Conversely, a knowledge level of low (L) implies that this phenomenon is a priority for additional research, particularly if the importance level is high. A knowledge level of medium (M) implies that research is suggested if the phenomenon is of high importance.

Table 2-4 describes the phenomena and processes identified in the postulated events of the Natrium reactor. The importance and knowledge level rankings of these phenomena are identified in Table 2-5

Table 2-4. PIRT Phenomena and Processes

[[

System	Component	Phenomena ID	Phenomenon/ Process	Phenomena description

]](a)(4)

Not Proprietary
Controlled Document - Verify Current Revision

[[

System	Component	Phenomena ID	Phenomenon/ Process	Phenomena description

]](a)(4)

Not Proprietary
Controlled Document - Verify Current Revision

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System	Component	Phenomena ID	Phenomenon/ Process	Phenomena description

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System	Component	Phenomena ID	Phenomenon/ Process	Phenomena description

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System	Component	Phenomena ID	Phenomenon/ Process	Phenomena description

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System	Component	Phenomena ID	Phenomenon/ Process	Phenomena description

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System	Component	Phenomena ID	Phenomenon/ Process	Phenomena description

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[[

System	Component	Phenomena ID	Phenomenon/ Process	Phenomena description

]](a)(4)

The details of the internal PIRTs and external PIRTs are documented [[ ]](a)(4) The internal PIRTs were prepared in 09/2021 with subject matter experts in TerraPower and GEH. Two representative events (LOOP and RWAP) were considered in the internal PIRTs [[

]](a)(4) Three representative events were considered in the external PIRTs: LOOP, RWAP, and LOHS. The first two events (LOOP, RWAP) are similar as the ones used in the internal PIRTs, however, there were differences in the sequence of events that were better aligned with PRA.

A combined PIRT was generated based on the results of the individual PIRTs for five scenarios while adopting the most conservative ranking among the 5 rankings among individual PIRTs. For the phenomena importance ranking, the higher ranking is more conservative (High > Medium > Low). For the level of knowledge ranking, the lower ranking is considered as more conservative (Low > Medium > High). The combined PIRT (shown in Table 2-5) gives the phenomena/processes rankings together with the knowledge rankings since these items are the basis for determining key physics that must be captured by the EMs and also measured in the experiments designed to generate data for code assessment of the EMs. The PIRT phenomena/processes that are ranked with high importance in phases 1, 2, or 3 are in bold as an indication of their relevance to EM development and assessment.

The Natrium project plans to have further updates and revisions to the PIRTs to reflect the plant design and analysis progress. One revision is planned to reflect the preliminary plant design completion (around the end of 2024), and another revision is planned to reflect the detailed plant design completion. It is expected that a final PIRTs report will be prepared before the FSAR.

Table 2-5: Combined PIRT for LOOP, RWAP, and LOHS Licensing Basis Events without Fuel Failure

[[

System	Component	Phenomenon ID	Phenomenon/Process	Importance Ranking			State-of-Knowledge (SOK) Ranking		
				P 1	P2	P3	P 1	P2	P3

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Not Proprietary

Controlled Document - Verify Current Revision

[[

System	Component	Phenomenon ID	Phenomenon/Process	Importance Ranking			State-of-Knowledge (SOK) Ranking		
				P 1	P2	P3	P 1	P2	P3

]](a)(4)

[[

System	**Component**	**Phenomenon ID**	**Phenomenon/Process**	**Importance Ranking**			**State-of-Knowledge (SOK) Ranking**		
				P 1	P2	P3	P 1	P2	P3

]](a)(4)

2.5 Preliminary Evaluation of Highly-Ranked Phenomena

The highly-ranked phenomena identified in the combined PIRT and shown in Table 2-5 may be divided into two groups dependent on whether additional experimental data are required or not. The highly-ranked phenomena for which adequate data already exist are:

- [[

]](a)(4)

Because the effect of the above eight highly-ranked phenomena can be quantified using sensitivity studies that envelope the range of interest via input to the EM[6], these highly-ranked phenomena are input boundary conditions to Element 3 regarding the EM development.

The remaining highly-ranked phenomena are input for consideration of available data from vintage experimental data sets and the design of the TerraPower IET and SETs that are tasks within Element 2.

3 ASSESSMENT BASE DEVELOPMENT: EMDAP ELEMENT 2

The task objectives for Element 2 are focused on obtaining the experimental data necessary "…to provide the basis for development and assessment…" of the EM as described in RG 1.203. The input to Element 2 is that output from Step 4 of Element 1, i.e., the results of the PIRT analysis for scenarios of interest for the Natrium design—as summarized in Chapter 2 of this report.

The output of Element 2 is input to:

- Step 12 of Element 3 to develop and incorporate closure models in the EM and
- Steps 13 through 19 of Element 4 to assess the EM adequacy.

The Element 2 objectives to provide input to Element 3, Step 12 and Element 4 are similar but different as described in Sections 3.1 and 3.2.

3.1 Developmental Assessment: Input to Element 3, Step 12

[6] For supporting information see Appendix A

Step 12 of Element 3 focuses on closure model development and therefore is aimed at ensuring the EM closure models match the physics of the original closure models given in the literature. In addition, the closure models must be demonstrated to properly interact and complement the conservation equations that form the fundamental framework of the EM. Therefore, the input from Element 2 to Element 3, Step 12 is the Development Assessment matrix for the EM. The EM Development Assessment matrix is collection of existing data and calculational assessment problems. The existing developmental assessment matrix is not specific to the Natrium reactor as the matrix addresses a wide operational envelope composed of IETs, SETs, and fundamental physics experiments with a wide range of scales and types; the matrix range is wider than required and defined by the operational and accident envelopes of the Natrium design.

In the process of enhancing the SAS code to include closure relationships required to model the reactor, i.e., the process of creating the EM, the existing Development Assessment matrix will have to be expanded to include data or calculational assessment problems to address the validity of any revisions to the original closure models of the SAS code to create the EM specified to accommodate the required calculational design specific phenomena and processes. [[

]](a)(4)

3.2 Code Adequacy Assessment Matrix: Input to Element 4

The input to Element 4 is the code adequacy assessment matrix and is composed of data sets that are:

- Satisfactory and available in the literature. Satisfactory data sets have a pedigree that describes the experimental facility and test section such that a scalability relationship may be determined (see discussion on data scalability Categories 1, 2, and 3 in Section 3.3), have a data range applicable to the Natrium design, and have measurement uncertainties that are quantified and acceptable.
- Obtained from the IET and SET experimental facilities that are scaled to the Natrium plant. It is noted that plans for the IET are presently being formulated. The IET scaled to Natrium will be defined to provide data that characterize key highly-ranked phenomena, e.g., natural circulation, in combination with applicable data available from both the Stella-2 and Phenix facilities. Data from the scaled facilities have the same attributes as described in the previous bullet plus a geometrical scalability with an acceptably low distortion level and compliance with NQA-1 standards.

A flow chart of this process is shown in Figure 3-1.

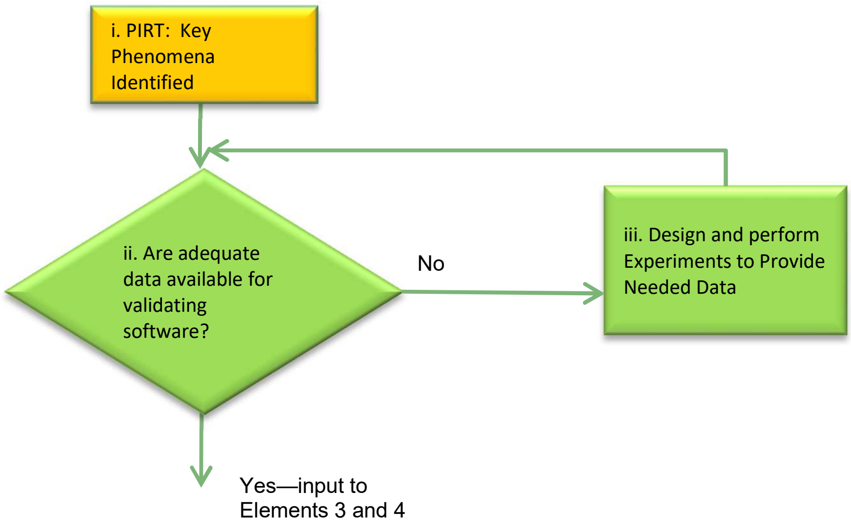


Figure 3-1. Distilled Element 2 flow path.

Sections 3.3 through 3.7 summarize the application of EMDAP Steps 5 through 9 to the EM.

3.3 Assessment Base Objectives: EMDAP Step 5

To determine whether available data are adequate to perform the EMDAP protocols on the Natrium EM, the scalability of the data is considered within 3 categories:

1. Geometry and phenomena: The physical geometry of the experimental facility used to generate data relevant to the Natrium design, including unique features, is assessed considering both the design of the system components and the comparison to experimental facility similarity criteria. All the highly-ranked phenomena defined by the relevant PIRTs must be provided with an acceptable distortion level as defined in the scaling analysis, protocol, and metrics. The working fluid may not be the same as the Natrium working fluid, but if an experiment has a different working fluid than the Natrium plant, then the scaling relationships must accommodate the differences in the working fluid between design and the experiment.

2. Properties: The physical properties (e.g., the thermodynamic state and a variant[7] of the working fluid) are either the same or else have no significant differences that would result in a noticeable scaling distortion, and

[7] In dealing with liquid sodium, it is envisioned that there is "reactor grade" liquid sodium and there are also variations of liquid sodium that are not of the same quality, i.e., they may have a larger fraction of impurities of some kind.

3. Phenomena character, event timing, and order: The presence of key phenomena that are projected to be present in the Natrium plant together with similar event timings, ranges, and the order of event progression. Such data may be found in counterpart tests performed in facilities that have many of the characteristics of the Natrium plant and have different scales from one another including the scaled IET and SET experimental facilities.

It is noted that only an IET and SETs that have been specifically scaled to match geometrically with an acceptably small distortion are able to meet the requirements of Category 1. However, because other IETs, which may be built to achieve other objectives such as proof-of-principle concepts but not to specifically match the Natrium design geometrically with acceptably small distortions, may have scalability from the perspective of Categories 2 and/or 3. For example, if an IET has phenomena and processes that are in some ways similar to the phenomena and processes in the Natrium design, then even though such a facility does not meet the requirements of Category 1 scalability, the data may be used for code assessment because agreement of the EM calculations with the experimental data demonstrates the capability of the EM to calculate the type of phenomena and processes that are projected to be present. A number of counterpart tests that were performed in a variety of scales for similar scenarios and transient conditions satisfy the Category 3 scalability requirements. Examples are data from the EBR-II, FFTF, and Phenix facilities. It is noted that there is historical precedent for including experimental data not only from Category 1 experimental facilities but also Categories 2 and 3 in the EM code assessment matrix.

The objective of the Step 5 tasks is to identify sufficient experimental data to form a complete assessment base for assessing the adequacy of the EM. A complete assessment base has the following characteristics:

- Experimental data from at least one Category 1 IET and the supporting Category 1 SETs deemed necessary are available to support assessment of all the highly-ranked phenomena identified in Element 1[8].
- Experimental data from other, often legacy, IETs and SETs that may not have an acceptable distortion level to achieve Category 1 scalability requirements, but have many of the geometrical, behavioral characteristics, phenomena, and processes sufficient to qualify as Categories 2 and 3 scalable facilities—provide a medium for establishing credibility for the EM at a variety of scaling factors and conditions that are somewhat different from the typical operational and accident envelope. Using data from such facilities with scaling factors that may differ from that of the Category 1 IET and SETs adds confirmatory evidence of the capability of the EM to perform the required calculations for scenario classes under consideration.

Therefore, the ingredients of the assessment base are obtained from two sources:

[8] No IETs are planned for RAC since it is anticipated that all highly-ranked phenomena can be validated using data from the planned RAC validation tests.

- Data from IET facilities and SET facilities scaled to the Natrium plant with acceptable distortion levels and designed specifically to generate data for the highly-ranked phenomena identified in the PIRT.
- Vintage data that may be shown to be similar to the Natrium design.

Figure 3-2 shows the 16 highly-ranked phenomena/processes identified in the PIRT discussed in Section 2.4 relative to the region of interest.

(a)(4)

Figure 3-2. Highly-ranked Phenomena–Relative to the Natrium Design

3.4 Scaling Analysis and Similarity Criteria: EMDAP Step 6

3.4.1 Hierarchical Two-Tiered (H2TS) Scaling

The H2TS scaling methodology serves as the basis to: (a) specify and design the IET and SET experimental facilities with acceptable distortion levels for the specified highly-ranked phenomena and (b) determine the distortion levels, if necessary, for data recorded in legacy experimental facilities. Presently both activities are ongoing and not ready for release. The following discussion summarizes the H2TS methodology to give an example of how it is being used for items (a) and (b). A complete summary of the results of the ongoing scaling analyses will be provided in a later revision to this report.

The challenges associated with hierarchically organized complex thermal hydraulic systems associated with safety issues for nuclear power plants were recognized during the development of the scaling methodology for severe accident analyses in the early 1990s. The hierarchical scaling approach is introduced to combine the system response viewpoint (holistic) and process viewpoint (reductionist) by first describing the hierarchical structure associated with the unique time scales related to the mass/volume ratios, temporal, spatial, and energetics. Two tiers of the methodology are (1) top-down approach to focus on the system response as an aggregate of various processes that take place within a hierarchical level and (2) bottom-up approach to focus on a particular process (prioritized based on their contribution to the system level response). Therefore, a two-tiered scaling approach as part of methodology development guidance addresses the top-down/system-response by efficiency and bottom-up/process-description by sufficiency. Four key elements of the H2TS methodology are described as follows:

(a) System Decomposition, by providing the hierarchical structure of the complex system down to process level description as consistent with the PIRT items.

(b) Identification of Scales (energetic, temporal, spatial scales within each level in the hierarchy)

(c) Top-down/System Scaling Analysis by providing appropriate form of the averaged balance equations for given representative region (or hierarchical level) and deriving the time-ratio groups to determine the scaling hierarchy down to the process-level description.

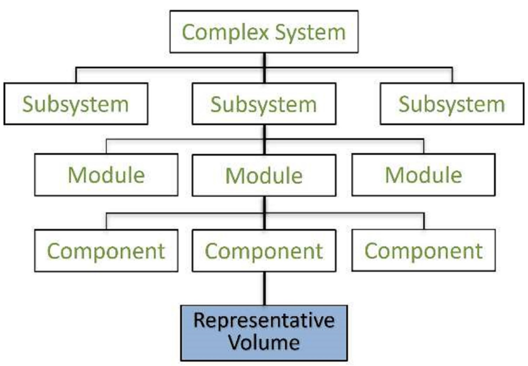
(d) Bottom-up/Process Scaling by focusing on the processes that have large contributions to the FOM or surrogate FOM such that pedigree, fidelity, and scalability of the models/correlations for the processes are addressed.

The hierarchical decomposition of a given complex system is done first based on the structural/functional description of the system/subsystem/module/components down to a particular volume for which the top-down analysis is to be performed and based on state/process description of the selected volume down to processes contributing to the rate of change in different field variables described by balance equations, i.e., conservation of mass, momentum, and energy. Both decompositions are illustrated in Figure 3-3.

The top-down description of a given hierarchical level to quantify the processes contributing to the rate of change in a given FOM is frequently done through control volume analysis due to its value and flexibility in engineering analysis. Therefore, the rate of change in a given field variable can be determined from the balance equations describing the conservation of mass, momentum, energy, and charge. The control volume analysis is done through averaging of the balance equations over a control volume bounded by a surface across which several transfer or flow paths can be identified by which the communication with other hierarchical levels is established. The averaged general balance can be obtained by deriving the volume-average balance from the local balance such that the rate of change in a specific field variable can be written as follows:

$$\mathcal{M}\frac{d\varphi}{dt} = \sum_m A_m J_m + \sum_j \dot{m}_j \Delta\varphi_j + \sum_n \mathcal{M}_n\, \varphi_n \tag{1}$$

where the volume-averaging symbols are omitted for clarity.



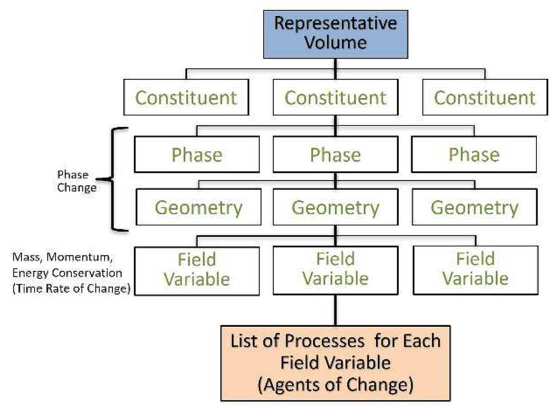


Figure 3-3. Hierarchical Decomposition

In Equation (1) the first term on the right-hand-side of the balance represents the transfer processes that do not involve mass crossing the transfer area, e.g., viscous shear, the second term represents the advection/convection of the conserved property across the flow path or junction, and the last term represents the distributed source/sink mechanisms, e.g., body force (gravity). The control volume balance is written for single-phase material; however, the similar balance can be written for an individual phase/field in a mixture of materials present within the volume. In H2TS methodology, the hierarchy within the volume down to process level is characterized in terms of time-ratio groups which are derived based on the dimensionless form of the balance such that the dimensional analysis is performed on the balance by selecting appropriate reference quantities appearing in the balance. For the field variable, the dimensionless form can be introduced by considering the initial and final values of the variable during the time-interval of interest such that

$$\phi^+ \equiv \frac{\phi - \phi_\infty}{\phi_0 - \phi_\infty} = \frac{\phi - \phi_\infty}{\Delta\phi_\infty}$$

All other quantities appearing in the control volume balance equation are normalized via corresponding reference quantities denoted by subscript (o) such that the dimensionless balance becomes

$$\mathcal{M}^+ \frac{d\phi^+}{dt^+} = \sum_m \Pi_m \cdot \mathrm{J}_m^+ + \sum_j \Pi_j \cdot \dot{m}_j^+ \, \Delta\phi_j^+ + \sum_n \Pi_n \cdot \mathcal{M}_n^+ \Phi_n^+ \tag{2}$$

where Π appears as coefficients for each process contributing to the rate of change in the field variable, ϕ. If the reference quantities are chosen such that $f^+ \equiv f/f_{\text{o}} \approx 1$, the dimensionless rate of change in the field variable can be written as the summation of these Π groups or time-ratio groups such that

$$\frac{d\phi^+}{dt^+} \approx \sum_{i=m,j,n} \Pi_i = \Pi_1 + \Pi_2 + \Pi_3 + \cdots \tag{3}$$

The time-ratio groups can be written for each process as

$$\Pi_i \equiv \omega_i \cdot \tau_{\text{o}} = \frac{\tau_{\text{o}}}{\tau_i} = \frac{\text{System (Control Volume) Time Constant}}{\text{Process } i \text{ Time Constant}} \tag{4}$$

In other words, a time-ratio group compares the individual process time constant to that system to generate the hierarchical structures among the various processes. Furthermore, the processes can be ranked quantitatively according to their importance in the aggregated system response. Therefore, the most dominant process would be the one with

$$\Pi^{\text{o}} \equiv \max_i |\Pi_i|$$

and all the other processes are ranked according to the absolute magnitude of their corresponding time-ratio groups.

3.4.2 Top-down Description of PHT Loop Flow Dynamics

The hierarchical decomposition of the PHT system is performed as shown in Figure 3-4 for the scaling purposes. This decomposition is consistent with the system decomposition discussed in Section 2.3. The first level in the hierarchy considers all the components within the PHT except warm pool and cover gas such that the closed single-phase flow loop is considered. The PHT System is designed to safely remove the heat generated in the core during normal steady-state operation, AOOs, and other off-normal events. The PHT system consists of coolant flow through the reactor core with multiple parallel channels, two identical IHXs, and two identical mechanical pumps. Liquid sodium is discharged from the pumps into the high-pressure plenum, then into multiple core channels composed of fuel, reflector, shield, and control assemblies surrounded by interstitial region. The orifice design at the channel inlets provides flow distribution such that the temperature distribution at the channel exits is fairly uniform.

(a)(4)

Figure 3-4. The Hierarchical Decomposition of the PHT System

The hot liquid sodium from these core channels is mixed in the lower plenum of the hot pool region where the majority of the sodium flows into the region below the bottom of the Upper Internal Structure (UIS) where the control drive mechanisms and fuel handling machine are located. The top hot pool and UIS communicate both thermally and hydraulically. The hot sodium below the sodium/argon interface is fed through the perforated walls into the shell side of the IHX where the heat is transferred into the secondary sodium flowing through the tubes via a counter-current flow configuration between the primary and secondary sides of the heat exchanger. The heat is transferred into the warm sodium pool surrounding the IHX and from the hot pool to the warm pool through the inner vessel liner. The warm pool (listed as “Intermediate Pool” in Figure 3-4) is hydraulically isolated from the hot and cold pools; however, there is a small amount of leakage through the thermal baffles at the top and bottom of the warm pool. The cold sodium exiting the IHX shell-side flows into the cold pool, through the suction pipe into the PSP, and is pumped into the high-pressure plenum through the discharge pipe, completing the flow loop.

The top-down description of the PHT loop dynamics is given based on the closed flow loop schematically shown in Figure 3-5. The flow loop consists of different sections with unique geometry such as flow length (ℓ_i), orientation ($sin\,\theta_i$), flow area ($\mathcal{A}_i$), hydraulic diameter (D_i), and irreversible loss coefficient (K_i). The section orientation angle (θ_i) is defined such that vertically upward sections ($sin\,\theta_i \equiv 1$), vertically downward oriented sections ($sin\,\theta_i \equiv -1$), and horizontal sections ($sin\,\theta_i \equiv 0$) can be defined.

Since the flow loop is a closed loop, the following loop integral should resolve to zero along the flow path, i.e.,

$$\oint_{\text{loop}} sin(\theta)d\ell = \sum_{i} \ell_i \, sin\, \theta_i = 0$$

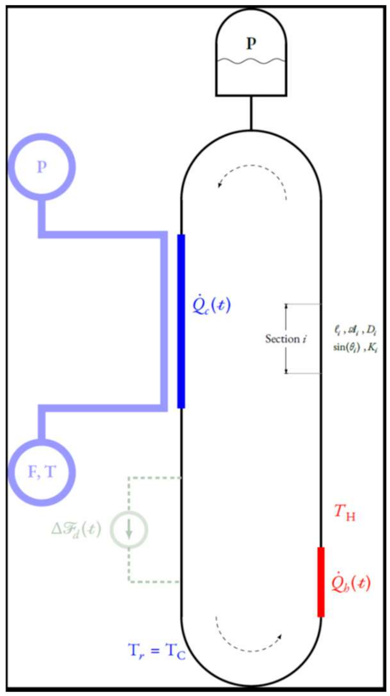


Figure 3-5. Schematic View of a Closed Forced/Natural Circulation Flow Loop

One-dimensional (area-averaged) mass, momentum, and thermal energy equations are assumed applicable in characterizing the single-phase flow around the flow loop depicted in Figure 3-5. This is a valid assumption especially for flow geometries associated with large length-to-diameter ratios, i.e., small aspect ratio. Furthermore, the covariance terms for the velocity-velocity and velocity-temperature are neglected assuming the flow is turbulent with flat velocity/temperature distributions. The one-dimensional characterization of the large pool sections needs to be reevaluated via CFD calculations to represent multi-dimensional effects in the flow/temperature distribution.[9]

[9] In developing the similarity criteria for the SET and IET design requirements, the governing equations in one-dimensional form are used to represent the dynamics of the PHT flow loop, i.e., momentum integral coupled with the one-dimensional energy equation in various sections of the loop. It is recognized that the one-dimensional approach does not fully capture the phenomena/processes in large pool sections, i.e., sections associated with large diameter-to-length ratios. Scoping calculations which use CFD as a higher fidelity computational tool are being used to provide a first-look at the potential distortions on highly-ranked phenomena in these pool sections [[
]](a)(4)

The wall heat transfer is coupled to the solution of the heat conduction equation with appropriate boundary and initial conditions in the heated and cooled sections. The one-dimensional mass, momentum, and thermal energy equations are summarized as follows: [[

]][(a)(4)]

[[

]][(a)(4),ECI] CFD scoping calculations, as a higher-fidelity calculational tool are used to inform the tests and to study the potential distortions. CFD is not used as an ingredient in the EMDAP code assessment data base.

[[

]](a)(4)

3.4.3 Establishing Similarity Criteria based on Closed Flow Loop

The governing equations describing the flow loop dynamics coupled with energy balances in each flow segments are described in the previous section. In this section, the governing dimensionless groups are derived by normalizing the balance equations by selecting appropriate reference values for each quantity appearing in the equations. [[

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]](a)(4)

Table 3-1. Summary of Dimensionless Groups and Their Definitions

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Table 3-2. Similarity Criteria for a Closed Forced/Natural Circulation Flow Loop

[[

Similarity	Criteria

]](a)(4)

3.5 Existing Data and SET/IET Needed to Complete Data Base: EM Code Assessment Matrix—EMDAP Step 7

Step 7 consists of three tasks:

1. Construct and perform experiments in the IETs and SETs experimental facilities to create the required database,
2. Identify existing data, and
3. Construct the EM Assessment Matrix.

The following subsections summarize:

- The expectations for obtaining data in IET and SETs scaled to the Natrium design, and the planning that is in progress for them to be designed, built, and operated. The facilities scaled specifically to provide assessment data on the highly-ranked phenomena will provide the backbone of the assessment matrix.

- The vintage reactor facilities and experimental facilities that are candidates for providing assessment data for evaluating the EM adequacy.

Although the scaled IET and SET experimental facilities will provide key assessment data to evaluate the EM adequacy, the data obtained from vintage facilities are essential ingredients to the EM adequacy assessment matrix. The scaled IET and SET facilities are discussed in Section 3.5.1. The vintage IET and SET experimental facilities, from which data sets are presently being considered for inclusion in the EM assessment matrix, are discussed in Sections 3.5.2 through 3.5.12. The pedigrees of the various vintage experimental data sets are discussed in Section 3.5.13. The preliminary EM assessment matrix is given in Section 3.5.14.

3.5.1 Scaled IET and SET Facilities: Category 1 Data

The outputs of Step 6 in Element 2 are scaling analyses and the resulting similarity criteria for IET and SET facilities scaled to the Natrium design with an acceptable distortion level. Such facilities are designed to have the capability to provide data for most of the highly-ranked phenomena and processes that occur in the DBA scenarios identified in this report. A Thermal Hydraulic Testing Roadmap was developed to plan and execute the test campaign, supporting the Natrium plant design and licensing. Some of those test data are used to assess the EM for in-vessel events without radiological release by filling the gap of the phenomena not covered by the historical tests. Presently a single IET is being considered for construction and operation. [[

]](a)(4)

Presently four SET facilities are under consideration to obtain data sets related to eight highly-ranked phenomena:

- [[

]]^(a)(4)

3.5.1.1 [[ ]]^(a)(4)

[[

]]^(a)(4),ECI

3.5.1.2 [[ ]]^(a)(4)

[[

]](a)(4)

3.5.1.3 [[ ]](a)(4)

[[

]](a)(4)

3.5.1.4 [[ ]](a)(4)

The RAC is a passive air-cooling open system during normal and off-normal plant operations. The RAC operates continuously as it is an open system. It requires no power supply and no operator actions as there are no moving parts. RAC heat removal varies with respect to the surface temperature of the GV of the RES. The RES is the heat source that thermally drives air circulation through the RAC system from and to the surrounding environment atmosphere. Since the RAC is an open system, the surrounding environment is both the ultimate coolant source and heat sink for the RAC system.

[[

]](a)(4)

[10] See Appendix A for additional information.

3.5.2 EBR-II Tests: SHRT-17, SHRT-45R, and BOP[11]

EBR-II began operating in 1964 and ran until the reactor was shut down in 1994. [10] [11] [12] [13] EBR-II was designed, built, and operated by Argonne National Laboratory. The EBR-II Shutdown Heat Removal Test (SHRT) program was carried out between 1984 and 1986. The objectives of this program were to support U.S. Liquid-Metal Reactor (LMR) plant design, provide test data supporting the validation of computer codes for the design, licensing, and operation of the LMRs, and demonstrate passive reactor shutdown and decay heat removal in response to various transient initiators for both protected and unprotected transient conditions. Among the SHRT tests was a variety of loss of primary and/or intermediate flow tests, loss of heat sink tests, tests to examine the response of the system to changing conditions in the balance of the plant, and tests to characterize reactivity feedbacks.

SHRT-17 was performed during Run 129C and was a protected loss of flow test where a loss of electrical power to all sodium coolant pumps (initiated by a simultaneous trip of the primary and intermediate sodium pumps and control rod scram) was simulated to demonstrate the effectiveness of natural circulation cooling characteristics. SHRT-45R was performed during Run 138B and was an unprotected loss of flow test where the control rod scram function of the plant protection system was disabled to demonstrate the effectiveness of EBR-II's passive reactivity feedbacks. The Balance of Plant (BOP) series of tests were conducted at EBR-II as part of the SHRT Program. Where the SHRT tests typically examined intentional variations in primary system flow conditions, the BOP tests examined the impact of intermediate system heat removal or core power oscillations on primary system behavior. Table 3-3 shows the evaluation results of the EBR-II tests.

Table 3-3. Pedigree of EBR-II Tests Data

Test	Conducted Under Documented QA Program	Testing Procedure Available	Measured Data Publicly Available	Known Issues With Data	Measurement Uncertainty Quantified
SHRT-17	Unknown, but reference to testing procedures in Reference [11]	Yes, in Reference [12]	Yes, plotted data in Reference [12]	[[	No
SHRT-45R	See above	Yes, in Reference [12]	Yes, plotted in Reference [12]		No
BOP-301	See above	Mostly, defined in	Yes, plotted in	]](a)(4)	No

[11] See discussion in Appendix A.

Test	Conducted Under Documented QA Program	Testing Procedure Available	Measured Data Publicly Available	Known Issues With Data	Measurement Uncertainty Quantified
		Reference [13]	Reference [13]		
BOP-302R	See above	Mostly, defined in Reference [13]	Yes, plotted in Reference [13]	[[ ]](a)(4)	No

3.5.3 FFTF Tests: LOFWOS Test #10-12[12]

The Loss of Flow Without Scram (LOFWOS) Test series was conducted at FFTF in 1986 as part of the Passive Safety Testing Program. The LOFWOS test series included thirteen unprotected tests where the plant protection system was intentionally disabled. The goals of the LOFWOS tests were confirming the safety margins of FFTF, providing data for computer code validation, and demonstrating the inherent and passive safety benefits of several of FFTF's design features, such as the limited free core restraint system and the gas expansion modules. [[

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3.5.4 FFTF Cycle 8A Type 1 through Type 7 Tests

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Table 3-4 Cycle 8A Individual Reactivity Feedback Types [14]

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[12] For supporting information see Appendix A

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]](a)(4)

3.5.5 Phenix Tests: Natural Circulation Tests[13]

The Phénix Natural Circulation Test was conducted in 2009 during the End-of-Life Tests Campaign and was designed to represent a protected loss of heat sink with a delayed loss of primary flow with a resumption of secondary system heat rejection. The natural circulation Test was the focus of a large IAEA Coordinated Research Project and is well-documented in reference [16].

13 For supporting information see Appendix A

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3.5.6 STELLA-2 Safety Systems Integral Effects Tests

The STELLA-2 facility was designed to investigate the integral effect of safety systems, including the comprehensive interaction among PHTS (Primary Heat Transfer System), IHTS (Intermediate Heat Transfer System), and DHRS (Decay Heat Removal System). Of particular interest are the various combinations of interaction between the passive DHRS and active DHRS with the PHTS. Characterization of these phenomena interactions is the main focus of STELLA-2. The long-term transient behaviors are to be observed to evaluate the overall safety characteristics of the Prototype Generation IV Sodium-cooled Fast Reactor (PGSFR). The database of STELLA-2 is used for the assessment of the evaluation model [17]. The STELLA-2 consists of a main system, auxiliary system, I&C system, and data processing system. In the main system, there are the core simulator system, the PHTS, the IHTS, and the DHRS. The auxiliary system includes the purification system, the Reactor Vessel Cooling System (RVCS), sodium charging & drain system, heat loss compensation system, fire protection system, power supply, and gas supply & vacuum system. The I&C system and the data processing system are also included [18]. [[

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3.5.7 SADHANA Scaled Sodium-Sodium Heat Exchanger Tests

SADHANA Scaled Sodium-Sodium Heat Exchanger Tests. Reference [19] provides a general description of the SADHANA test loop operated by the Indira Gandhi Centre for Atomic Research and mentions scaled sodium-to-sodium heat exchanger tests performed there sometime between 2009 and 2013 to support the design of Indira Gandhi Centre for Atomic Research Prototype Fast Breeder Reactor. References [20] [21] [22] [23] further describe the test facility and present some experimental results.

3.5.8 STELLA-1 Scaled Sodium-Sodium Heat Exchanger Tests

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3.5.9 Toshiba 4S Test Facility Tests

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3.5.10 Monju Decay Heat Removal Test

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3.5.11 PCN 37-Pin Bundle Experiments

Multi-subassembly sodium experiments, using the Power Reactor and Nuclear Fuel Development Corporation (PNC) loop PLANDTL-DHX, were performed by PNC in Japan (References [34] and [35]). [[

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3.5.12 WARD 61-Pin Bundle Test

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3.5.13 UIUC Natural Circulation Tests

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3.5.14 Summary of Pedigree Evaluations

The evaluations of the pedigree of historical test data (Non-TerraPower Tests) are summarized in Table 3-5. The first column indicates the test names. The relevancy of the test data to the Natrium reactor, the availability of the data to the public, and the expected data quality are described in the second, third, and fourth columns, respectively. Scales of high (H), medium (M), and low (L) are used for the second and fourth columns. The fifth column provides information on what documentation is available.

Table 3-5 Results of Pedigree Evaluation of Legacy Test Data

[[

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[14] Request for data in progress = RDIP

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3.5.15 Preliminary Code Assessment Matrix for Natrium EM

Many vintage test cases have been examined, but only a few of them (see Sections 3.5.2 through 3.5.14) have been selected to perform EM adequacy calculations. Also, the plans for designing and constructing scaled IET and SET experimental facilities (see Section 3.5.1) are presently being formulated. Consequently, only a preliminary Natrium EM code assessment matrix is available (see Table 3-6).

Table 3-6. Preliminary Natrium Code Assessment Matrix[15]

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[15] [[

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3.6 Evaluation of IET Distortions and SET Scaleup Capability: EMDAP Step 8

The evaluation of IET and SET experimental facilities scaling distortions will be performed based on the magnitudes of the ratios of the similarity criteria identified in Section 3.4.

3.7 Experimental Uncertainties Determination: EMDAP Step 9

Experimental uncertainties associated with vintage data sets were determined by the experimentalists associated with each experimental facility—and as such may not be consistent from one experimental program to another. Also, vintage measurement uncertainties may not be consistent with the NQA-1 standards. Generally, the reported measurement uncertainties for vintage data consist of uncertainties for each measurement type together with approximations of the uncertainties associated with the data acquisition system. No attempts are generally made to separate the uncertainties into aleatory and epistemic components. Therefore, engineering judgement will be applied to the measurement uncertainties of vintage data that are documented to determine the degree of compliance with NQA-1.

The uncertainties of the diagnostics measured and reported for the TerraPower IET and SET experimental facilities scaled to the Natrium design are to be determined in compliance with the NQA-1 standard.

4 EVALUATION MODEL DEVELOPMENT: EMDAP ELEMENT 3

As noted in RG 1.203 [2] (see p. 3):

> "An evaluation model (EM) is the calculational framework for evaluating the behavior of the reactor system during a postulated transient or design-basis accident. As such, the EM may include one or more computer programs, special models, and all other information needed to apply the calculational framework to a specific event as illustrated by the following examples:
>
> 1. Procedures for treating the input and output information (particularly the code input arising from the plant geometry and the assumed plant state at transient initiation).
> 2. Specification of those portions of the analysis not included in the computer programs for which alternative approaches are used.
> 3. All other information needed to specify the calculational procedure.
>
> The entirety of an EM ultimately determines whether the results are in compliance with applicable regulations. Therefore, the development, assessment, and review processes must consider the entire EM."

The EM in context of the effort described in this report "is a collection of calculational devices (codes and procedures) developed and organized to meet the requirements established in Element 1" for analyzing in-vessel DBA events without radiological releases. The EM is composed of:

- The SAS4/SASSYS-1 systems code [41] and
- The required input ingredients and post-processing algorithms (e.g., HCF/HPR used to conservatively assess the PCT) that are arranged to model the Natrium plant with the capabilities and reliabilities of the SR SSCs to mitigate and prevent postulated event sequence consequences to within the 10 CFR 50.34 dose limits per NEI-18-04 [1].

Finally, because this report addresses a DBA methodology where a conservative approach is used, an uncertainty methodology is not considered—analogous to the approach defined by the original conservative Appendix K option in 10 CFR 50.46 (see p. A-3 of RG 1.203). Instead, the conservative methodology to be followed is designed to provide sufficient conservatisms without the need for an uncertainty analysis. Therefore, as noted in Appendix A of RG 1.203, "To the extent practicable, predictions of the EM, or portions thereof, shall be compared with applicable experimental information." but without application of an uncertainty methodology.

The above considerations are reflected in the ingredients and requirements defined in the EM development plan (Section 4.1), the EM structure (Section 4.2), and in the development and incorporation of the necessary closure models (Section 4.3).

4.1 EM Development Plan: EMDAP Step 10

The EM development plan includes development standards and procedures that are applied throughout the developmental process per RG 1.203 and in conformance with NUREG-1737: Software Quality Assurance Procedures for U.S. Nuclear Regulatory Commission Thermal-Hydraulic

Codes. [42] In essence, the EM development standards and procedures fall within six areas as identified and summarized below (see RG 1.203 Section 1.3.1, p. 15 and pages B-9 and B-10).

4.1.1 Design Specifications

The specifications are divided into functional requirements, performance requirements, and validation requirements per NUREG-1737. [[

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4.1.1.1 Functional Requirements

Functional requirements consist of the following items:

- The theoretical basis and mathematical models for each phenomenon are shown to be consistent with the subject phenomenon.
- The range of variables over which the model is applied is specified.
- All figures, equations, and references necessary to specify the functional requirements for the design of the software are documented.

4.1.1.2 Performance Requirements

Performance requirements are codified in a software test plan that contains the following considerations:

- The number and type of qualification problems to be performed.
- The rationale for the specification for each qualification problem.
- The specific range of parameters and boundary conditions for which successful execution of the problem set will qualify the code to meet the specific functional requirements.
- Each code input test problem will be described.
- The measure used to determine whether the code results are acceptable will be defined.
- Significant features that will not be tested are identified and the justification for these decisions will be documented.
- The acceptance criteria for each item will be defined.
- The scalability of the qualification problem to the prototype will be identified if applicable.

4.1.1.3 Validation Requirements

All highly-ranked phenomena identified in the PIRT specific to the scenarios of interest must be found to be conservative as measured by reducing the margin of the FOMs.

4.1.1.4 Documentation Requirements

As noted in RG 1.203, p. B-10 “The software design and implementation documentation shall describe the logical structure, information flow, data structures, the subroutine and function calling hierarch, variable definitions, identification of inputs and outputs, and other relevant parameters. It shall include a tree showing the relationship among the modules and a database describing each module, array, variables, and other parameters used among code modules.”

Also, the existing program documentation shall be revised and enhanced to provide a complete description of the program. Code manuals will be produced and upgraded concurrently with the code development process. The set of code manuals, or together with other supplemental documents, will cover the following subjects: Theory, Models & Correlations, User’s Manual, Programmer’s Manual, and Developmental Assessment Manual.

4.1.1.5 Programming Standards and Practices

The source code listing or update listing shall have the following attributes. Sufficient explanations will be documented in the listing to permit review of these attributes:

- Traceability between the source code and the corresponding design specification to enable analysis of the coding for correctness, consistency, completeness, and accuracy.
- Functionality: Evaluate the coding for correctness, consistency, completeness, accuracy, and testability. Also, evaluation of the design specifications should be enabled for compliance with established standards, practices, and conventions and to enable evaluation of the source code quality.
- Interfaces: Evaluate the coding with hardware, operator, and software interface design documentation for correctness, consistency, and accuracy. At a minimum the ability to analyze data items at each interface will be present.

4.1.1.6 Other Requirements

Transportability requirements, quality assurance procedures, test requirements, and installation requirements.

- Transportability requirements: Thought to be interchangeability between computers and their operating systems.
- Quality assurance procedures: see RG 1.203, Section 2, pp. 20-21.
- Test requirements: All testing activities shall be documented and shall include information on the date of the test, code version tested, test executed, discussion of the test results, and whether the software meets the acceptance test criteria.
- Installation requirements: The program installation package shall consist of program installation procedures, files of the program, selected test cases for use in verifying installation, and expected output from the test cases.

4.1.2 Status of EM Development Plan

The EM development plan has been developed. The EM plan is established by examination of the EMDAP principles and 20 steps, identifying activities necessary to develop the EM, and specifying high-level descriptions of corresponding activities in each EMDAP step. The EM development plan will be updated along with the Natrium reactor's development.

4.2 EM Structure: EMDAP Step 11

The main system analysis computer code of the Natrium EM for the class of scenarios addressed in this report is the SAS code. The structure of the code has already been defined by the SAS development group at the Argonne National Laboratory (ANL). Therefore, this report presents a high-level discussion of the code in Section 4.2.1, and its detailed descriptions can be replaced by referring to the SAS manuals. [41]

4.2.1 SAS4A/SASSYS-1 Code Overview

SAS4A/SASSYS 1 is a physics simulation software developed to perform deterministic analysis of anticipated events as well as DBAs in SFRs.

The process to use the SAS code in the form needed to analyze the required DBA analysis scenarios consists of the following:

- Literature research
- Control System Development
- Sensitivity Studies
- Code and Model Benchmarks
- Event Specific Application Methodology
- Sample Events

This approach provides a path that takes advantage of the research and industry experience, yet still allows the development of EM models and nodalization schemes. Therefore, a methodology is devised that meets the requirements of being simple to model yet detailed enough to benchmark against the required experimental data to be used for code assessment.

4.2.1.1 EM Modeling Scope and Limitations

The objective of the EM simulation typically is to quantify accident consequences as measured by the transient behavior of system performance parameters, such as fuel and cladding temperatures, sodium coolant temperatures, pressure, fluid velocities, reactivity, cladding strain, etc. The EM is to perform the safety analysis of the PHT system with heat generation, hydraulic conditions, and thermal conditions for in-vessel DBA scenarios without radiological release. The FOMs that serve as the basis for defining the margin of safety are listed in Table 2-1 and include the fuel centerline temperature, the bulk coolant temperature, and the time-at-temperature criteria.

4.2.1.2 Structure of SAS4A/SASSYS-1

The structure of SAS must contain the following six RG 1.203 ingredients. [2]

- System and components: The SAS structure is designed to enable the analysis of the behavior of all systems and components that describe the physical system of interest.
- Constituents and phases: The models for all the constituents and phases relevant to the required analyses are included in the EM.
- Field equations: The conservation equations that, when solved, calculate the mass, momentum, and energy distribution within the physical system of interest.
- Closure relations: Closure relations are correlations and equations that describe the characteristics of the physical problem that are introduced to obtain a closed solution describing the state of the physical system.
- Numerics: The discretizations of the partial differential equations and closure relationships; the numerical discretizations must be consistent, stable, and convergent.
- Additional features: These address code capability to model boundary conditions and control systems.

High-level discussions of the six constituents of the EM are provided in the following sections. It should be noted that EM is a one-dimensional code (with some zero-dimensional components) and composed of two computer codes, SAS4A and SASSYS-1. SAS4A contains detailed, mechanistic models of transient thermal, hydraulic, neutronic, and mechanical phenomena to describe the response of the reactor core, its coolant, fuel elements, and structural members to accident conditions. SASSYS-1 provides the capability to perform a detailed thermal/hydraulic simulation of the primary and secondary sodium coolant circuits and the balance-of-plant steam/water circuit. Although they are generally portrayed separately, they have always shared a common code architecture, the same data management strategy, and the same core channel representation. The six constituents of the EM are explained in more detail in the code user manual and are expected to be detailed further in a separate report.

a) System and Components

The EM structure was designed to model SFR geometries and thus the systems and components of the Natrium plant. The EM computes coolant pressures, flow rates, and temperatures in the core and heat transport systems. An arbitrary arrangement of components in either a loop-type or a pool-type system can be analyzed. Table 4-1 lists the major components in SAS that are necessary for analyzing the DBA scenarios addressed in this report.

Table 4-1. Geometric Components of SAS4A/SASSYS-1 EM [41]

No.	Component
[[	
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The compressible volume (CV) is defined by the CV pressure, volume, mass, and temperature. CVs can accumulate liquid or gas by compressing the cover gas or the liquid, and it is the pressure in the compressible volumes that drives the flows through the liquid and gas segments. CVs are used to model hot pool, cold pool, warm pool, etc. The element, especially the liquid element, is characterized by incompressible single-phase flow, with the exception of the core element. Detailed explanations of the components presented in Table 4-1 including the CV and element are provided in the EM manuals.

In the core models, the basic geometric modeling element is a fuel pin, its cladding, and the associated coolant and structure, with the structure field representing wire wraps, and/or hex cans. In SAS terminology, the term "channel" is used to denote collectively the element consisting of fuel, cladding, coolant, and structure. In a single-pin model, a single average channel is used to represent the average of many pins in the reactor, and multiple channels are used to extend the model to all the pins in the reactor. In a multiple-pin model, each channel represents one or more pins in a subassembly, and multiple-pin subassembly models are joined with single-pin subassembly models to cover the whole reactor core. A single SAS channel may therefore represent either one pin or a large number of pins in many subassemblies. In either case, the elementary unit from a code structure and data management stand-point is an individual channel.

The code structure of SAS is also the result of the programming language employed and the functional requirements of the phenomenological models. The programming language used for SAS4A/SASSYS-1 is ANSI FORTRAN, and the organization of the code follows the FORTRAN convention of the MAIN program with a number of subroutines and functions. For the purpose of this discussion, the subroutines and functions of SAS are grouped according to purpose into one of the modules listed in Table 4-2. These modules are aligned in a one-to-one fashion with the phenomenological models of SAS, each of which is described in the code manuals [41] in detail.

[16] [[ ]](a)(4)

It should be noted that the six modules identified in Table 4-2 are used in DBA in-vessel analyses without radiological release analysis.

Table 4-2. Applicable SAS4A/SASSYS-1 I Modules and Phenomenological Models [41]

[[

Module	Purpose/Phenomenological Models

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b) Constituents and Phases

The chemical forms of substance included in the DBA analyses are sodium, air, and argon gas. The sodium for the DBA analysis is in liquid phase. As shown in Table 4-2, the EM has the capabilities to analyze the behavior of all constituents and phases as described in Chapter 2.3. [[ ]](a)(4)

c) Field Equations

To predict the transport of mass, momentum, and thermal energy of liquid sodium, argon gas, and air present, the EM uses the mass, momentum, and energy conservation equations. Chapter 5 of the SAS4A/SASSYS-1 manuals [41] provides a description of the field equations for the transport of mass, momentum, and thermal energy systems and components except for the core assemblies. Chapter 3 of the manual discusses the field equations used to predict the thermal-hydraulics and thermal conductions of core assemblies separately.

Reactor point kinetics, decay heat, and reactivity feedback models are described in Chapter 4 of the SAS4A/SASSYS-1 manuals and are used to provide an estimate of the reactor power level to be used in the prediction of energy deposition in the fuel. A time-independent reactor power spatial shape is assumed, along with a space-independent (point) reactor kinetics model. The ANS decay heat standard with 23 exponential terms can be used to evaluate decay heat, but SAS uses decay power obtained by curve-fitting the decay power calculated by another code (Burnx). First-order perturbation theory is used to predict reactivity feedback effects associated with material density changes. Fuel temperature (Doppler) effects are calculated assuming a logarithmic dependence on the local absolute temperature ratio, with a linearly dependent variation of the local Doppler coefficient on the coolant void fraction. Besides Doppler and sodium density reactivity feedbacks, axial expansion of the fuel and cladding, core radial expansion, and control rod driveline expansion are also used to calculate reactivity feedback.

d) Closure Relations

Heat transfer correlations (within the fuel pin, between subassemblies, pipe, etc.) and pressure loss are defined by user-supplied coefficients depending on the working fluid and geometry. Thermophysical property correlations of metal fuel, structural metal, sodium, and gas are discussed in the SAS4A/SASYSS-1 manuals in detail.

e) Numerics

Most of the transient heat transfer calculations and flow rate calculations in SAS use semi-implicit time differencing to obtain stable solutions with reasonably long time-steps. Detailed discussions of the numerical solution techniques are presented in the code user manuals Part II, Chapter 3.19 [41].

f) Additional Features

Additional capabilities are available to model control systems. Boundary conditions, steady-state and transient characteristics of special components (pump, valve, etc.), reactor scram, reactivity insertion rate, etc. are modeled using the control system. The control system of SAS consists of four types of signals which are “measured signal”, “demand signal”, “block signal”, and “control signal”. A measured signal makes available to the block diagram the present value of a referenced SAS variable. A demand signal makes available to the block diagram the product of the current value of a time-dependent function defined by the user through a demand table and an initial condition value. A demand table is a set of ordered pair values supplied by the user. A block signal makes available to the block diagram the value at the output of a block. A control signal is used to set the value of a SAS variable equal to the value of a block signal. Again, detailed discussions of the SAS structure are provided in its manuals [41].

g) Software Limitations

The SAS4A/SASSYS-1 is a system analysis computer code developed to model the steady-state and transient system behavior in a pool-type SFR. The usage of the EM for the Natrium design has the following limitations:

- The SAS code is not intended for analyzing the fuel failure and subsequent in-pin or ex-pin fuel relocation, as well as the fission products transport in the sodium pool.
- The application of SAS is limited to single-phase liquid sodium. For sodium boiling, only its impact on reactivity feedback is analyzed, and the impact on fuel/clad heat transfer is not modeled. Sodium freezing is beyond the code capability.
- The software nodalization capability is considered sufficient to model the Natrium plant design, however, nodalization refinement flexibility is limited stemming from some component nodalizations that are hard-wired into the code.
- The software is a 1D system analysis computer code, and thus it is not able to address any 3D effect in the analysis.

4.2.2 EM Structure

The structure of the EM is composed of:

- SAS4A/SASSYS-1
- Data is input to the SAS code that describe fuel performance, neutronics, thermal-hydraulics, design, and safety analysis characteristics are completed.
- A steady-state calculation is performed and a converged solution is obtained.
- The steady-state results are analyzed and a determination is made regarding whether the converged solution is acceptable.
- The desired transient calculation is performed.
- The results of the transient calculation are reviewed and the fidelity of the calculation is assessed.
- The final results are assessed from the perspective of limiting values of the figure-of-merit. Conclusions are formulated.
- The calculation is documented.

This structure is generally illustrated in Figure 4-1.

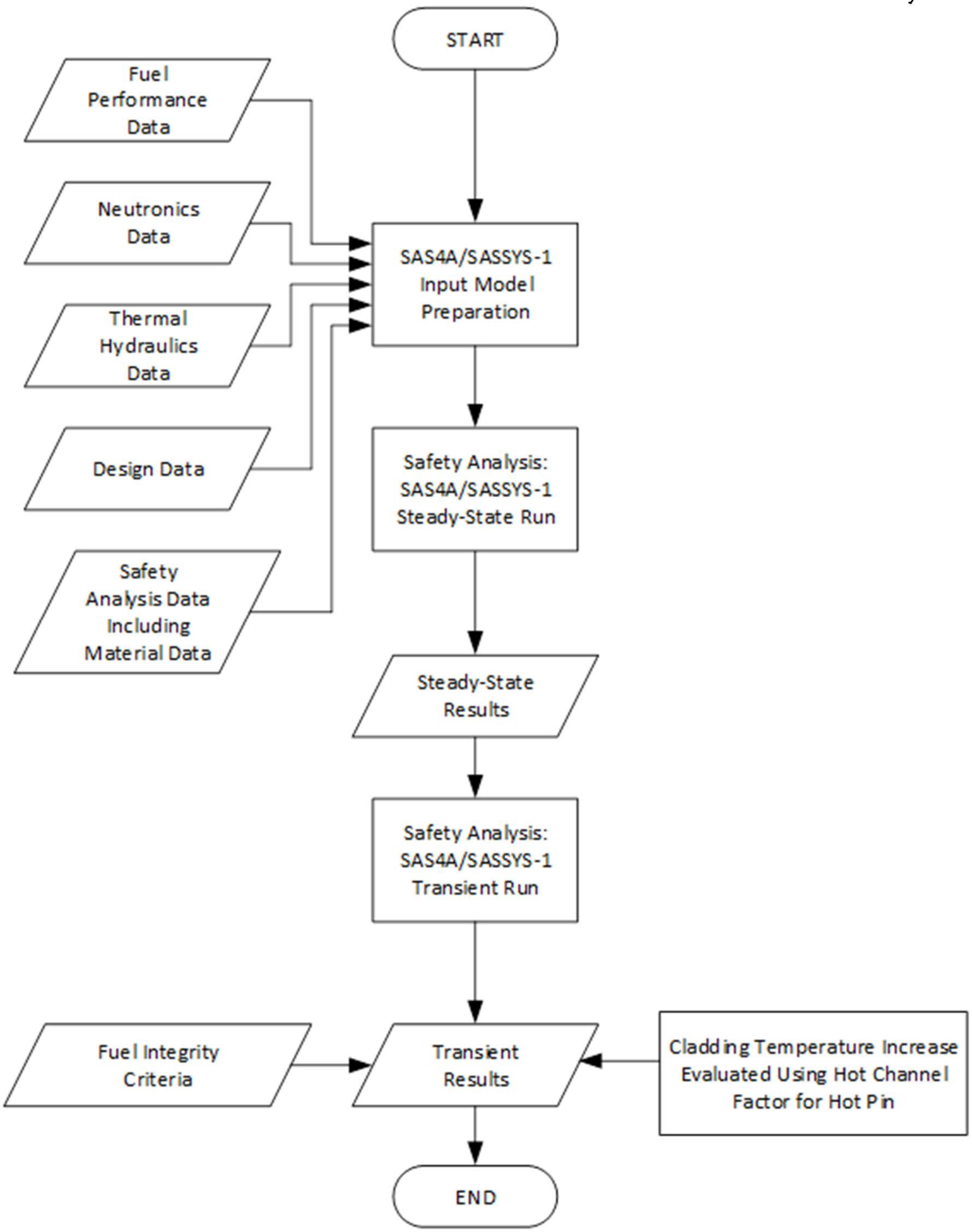

Figure 4-1. EM Structure: Data Inputs, EM Program Flow, and Final Results

4.3 Closure Models and Conservatisms—EMDAP Step 12

Many closure models and conservatisms are used to simulate Natrium responses to postulated DBAs without radiological release. The theory manual of SAS4A/SASSYS-1 [41] discusses the closure models in detail. Specifically, the closure relations used for the EM are summarized in the following seven items [[

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[[

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Three new closure correlations are implemented in SAS4A/SASSYS-1 to improve the capability of predicting Natrium behavior under normal operational and transient conditions. This section summarizes the conservatisms that are part of the EM.

4.3.1 Closure Models

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RAC is a critical heat sink in many DBAs, especially when the IHX is not fully functioning with the NSS isolation valve closure.

4.3.1.1 Core Convective Heat Transfer

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4.3.1.2 Reynolds-Dependent Pressure Drop

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The Reynolds-dependent pressure drop correlation is introduced to add the capability to model Reynolds-dependent core assembly inlet and outlet coefficients. Previously, inlet and outlet coefficients could not be defined as a function of the Reynolds number in SAS. [[
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4.3.1.3 Wire-wrapped Pin-Bundle Pressure Drop

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[17] [[

]](a)(4)

[[

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4.3.2 Conservatisms, Biases, and Hot Channel Factors

Conservatisms are required when performing DBA calculations. Although conservatisms are not closure models, conservative assumptions do affect the outcome of calculations performed using closure relationships and conservatisms are an integral ingredient in the EM. Thus, the conservatisms used for DBA calculations are summarized.

In essence, conservative DBA calculations are performed by revising the input to the nominal best-estimate Natrium model by:

- Inserting conservative biases on the nominal input related to the highly ranked phenomena listed in the PIRT (Table 2-5). Modeling conservatisms are also included directly in the DBA EM such as isolating NSS or tripping the pumps.
- Performing the calculation using the EM to obtain the calculational output.
- Applying the Safety HCF and including the HPR to the output on the channel to obtain conservative 2-sigma cladding temperature.

This process is shown in Figure 4-2 in flow chart form.

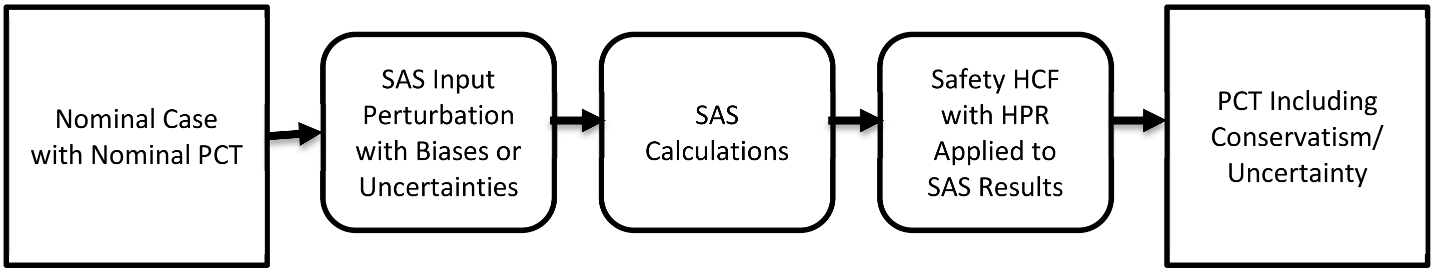

Figure 4-2. Flow chart illustrating methodology for performing conservative calculation of FOM.

EM input biases are applied to the following inputs:

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5 EVALUATION MODEL ADEQUACY ASSESSMENT: EMDAP ELEMENT 4

The information processed in Elements 2 and 3 are used as inputs to Element 4 wherein the adequacy of the EM is assessed. In particular, the specification and implementation of the plans established in
Element 3 (Step 10) provide the necessary information to begin the work that comprises Element 4, i.e.:

- A code assessment base was developed (in Element 2) that is consistent with the requirements defined in Element 1. The assessment base consists of already existing experiments or new experiments that serve as a means to determine the adequacy of the EM.
- The EM was developed (in Element 3) to approximate the physical behavior for the postulated events (DBAs for in-vessel events without radiological release) and is consistent with the requirements developed in Element 1. As a part of this task, the proper code options were chosen, the boundary conditions were defined as well as the temporal and spatial relationships among the components.

Element 4 consists of two broad topics:

1. A bottom-up evaluation of the EM (Steps 13 through 15) closure relationships where the closure models and correlations are examined by considering their pedigree, applicability, fidelity to appropriate fundamental or SET data, and scalability and
2. A top-down evaluation of the code (Steps 16 through 19): the governing equations, numerics, and integrated performance of the EM. Within these stages the EM is evaluated by examining

the field equations, numerics, applicability, fidelity to the component and/or IET data, and scalability.

The final step (Step 20) is a consideration of all the outputs of the bottom-up and top-down evaluations performed to determine the EM biases and uncertainties. Each of these steps is described in the subsequent sections.

5.1 Closure Relations (Bottom-up: Pedigree and Applicability): EMDAP Step 13

Step 13 focuses on the pedigree and applicability of the closure relationships used in the EM. A typical closure relationship is the use of a friction factor to approximate the irreversible pressure losses that occur as fluid moves through a pipe—where the magnitude of the friction factor is a function of the roughness of the pipe wall and whether the flow is laminar, in transition from laminar to turbulent, or turbulent. The pedigree and applicability of the friction factor closure relationship consist of the following: (i) documentation: a detailed summary of the experimental work performed to quantify the friction factor including a description of the experimental hardware and instrumentation, i.e., a report or paper available in the literature, (ii) the measurement uncertainty of the instrumentation used to obtain the data, (iii) the range of applicability of the data including the types of fluids for which the data are applicable, e.g., Newtonian fluids, and (iv) the types of hardware for which the data are applicable including how the data may be scaled to different sizes and configurations—in this case, the ratio of the roughness to the pipe diameter, i.e. the relative roughness.

The above approach must be applied and available for all the closure relationships that are used in the EM and the results of the pedigree and applicability studies will be documented in the Models and Correlations document for the EM.

The conclusions and documentation completed in Step 13 are inputs to Step 20 - to determine EM biases.

5.2 Closure Relations (Bottom-up: Model Fidelity and Accuracy): EMDAP Step 14

The model fidelity and accuracy confirmations required in Step 14 are performed by inserting the required input in the SAS code using the guidance given in the Code User's Guide and by performing calculations to demonstrate that the code calculations using the closure relationship match relevant data recorded in experiments that qualify as applicable to the Natrium design for validation purposes—as described in Chapter 3.

To accomplish the objectives inherent to determining the model fidelity and accuracy, the calculations performed to study the closure models should include convergence (discretization) studies that focus on the nodalization (sometimes identified as mesh) that represents the experiments that were built to generate the data underlying the closure model. The discretization studies demonstrate convergence to the calculated results that show agreement with the closure relationship.

Such calculations should be performed for all the closure relationships that are used in the EM when applied to Natrium scenarios. Demonstration of model fidelity and accuracy is shown by reasonable or excellent agreement with the closure relationship predicted results—or if the closure relationship is subjected to a conservative treatment as described in Step 12 then the model should show calculated behavior that demonstrates a conservative outcome, as described in Chapter 4, see discussion regarding Step 10.

This work will be conducted when the experimental data discussed in Section 3.5 become available to TerraPower through performing tests and purchasing tests data and all necessary information. The conclusions and documentation completed in Step 14 are inputs to Step 15 - to assess the scalability of the models.

5.3 Closure Relations (Bottom-up: Assess Scalability of Models): EMDAP Step 15

The scalability of the closure relationships addressed in Step 15 concerns the validity of using closure relationships developed using data from experiments that are a fraction of the size of the Natrium plant. Again, using the example of the friction factor, the use of the relative roughness enables the application of the Moody friction factors [2] over a wide range of pipe sizes. Similar types of scaling relationships should be available and applied for the other closure models, if required, that are used in the SAS4/SASYS-1 code.

Confirmatory calculations or justifications will be conducted when the experimental data discussed in Section 3.5 become available to TerraPower through performing tests and purchasing test data and all necessary information and must be provided for every closure relationship used for calculations.

The conclusions and documentation completed in Step 15 are inputs to Step 20—to determine EM biases.

5.4 Integrated EM - Top-down: Field Equations/Numeric Solutions Capabilities - EMDAP Step 16

The objective of Step 16 is to determine the capability of the field equations to represent processes and phenomena as well as the ability of the numeric solutions to approximate the equation set. The SAS4A/SASSYS-1 code field equations, i.e., the conservation equations of mass, momentum, and energy are discretized using finite difference equations (FDEs). The partial differential equations (PDEs) themselves have been derived, in general, to describe single-phase flow and the EM may be used to analyze the behavior of systems with both water and liquid sodium working fluids.

Based on 10 CFR 50.46 Appendix K, the momentum equation needs to have accommodations to satisfy the need to calculate the following effects: (1) temporal change of momentum, (2) momentum convection, (3) area change momentum flux. It needs to be capable of accommodating the need to determine the energy transfer and distribution within the fuel as well as from the fuel to the working fluid, to the reactor components and structures, and to the environment. The SAS code will be evaluated against the above requirements.

The validity of the PDEs will be demonstrated by performing validation calculations using data from experiments that are scaled as well as experiments that have partial scalability to the Natrium plant.

In general, the scalability of the data to the Natrium design is considered within 3 categories:

1. Geometry & phenomena: The physical geometry of an experimental facility used to generate data relevant to the Natrium design including unique features of the Natrium design assessed considering both the design of the system components and the comparison to experimental facility similarity criteria. Data for all of the highly-ranked phenomena defined by the relevant PIRTs must be provided with an acceptable distortion level.

2. Properties: The physical properties (e.g., the thermodynamic state and a variant of the working fluid) are either the same or else have no significant differences that would result in a noticeable scaling distortion, and

3. Phenomena character, event timing and order: The presence of key phenomena that are projected to be present in the Natrium plant together with relevant event timing and the order of event progression.

Only an IET facility scaled to represent the Natrium design with an acceptable distortion level can satisfy all 3 scalability categories. Other experimental facilities, e.g., EBR-II may satisfy scalability categories 2 and 3. Similarly, SET facilities will consist of vintage facilities that satisfy particular data needs as well as newly designed SET facilities built to satisfy specific data needs.

The relevance of the field equations in the SAS code is shown by the pedigree, key concepts, and processes that are characteristic of the SAS computer code. In essence, the SAS code was developed specifically to analyze the behavior of SFRs. Consequently, the historical development and evolution of the code reflect the creation of specific components designed to represent a pool-type SFR. These characteristics will be distilled from the existing documentation and included in subsequent revisions of this topical report as well as in the manuals being written to satisfy the RG 1.203 requirements for computer code manuals (see Appendix B, p. B-9 and B-10) such as the Theory Manual and the Developmental Assessment manual. The validation cases in the Developmental Assessment manual of interest are those that specifically satisfy Categories 2 and 3 of the scalability requirements described above.

The numeric solution evaluation considers consistency, property conservation, and stability of the SAS code. In essence, consistency is characterized by the extent to which the discretized equations approximate the partial differential equations. An FDE representation of a PDE is considered consistent if it can be shown that the difference between the PDE and the FDE and its difference representation vanishes as the mesh is refined, that is:

$$\lim_{h \to 0}[PDE - FDE] = \lim_{h \to 0}[TE] = 0$$

as the spatial mesh interval h approaches zero for both [PDE – FDE] and the truncation error [41].

The conclusions and documentation completed in Step 16 are inputs to Step 17—to determine the capability of the EM to simulate system components.

5.5 Integrated EM - Top-down: Assess Applicability of EM to Simulate System and Global Capability: EMDAP Steps 17 and 18

Steps 17 and 18 of RG 1.203 are specified to first evaluate the inherent capability of the EM to model the major systems and subsystems of the Natrium design and second to assess the system interactions and global capabilities of the EM. The historic work described in the pedigree documentation—reported upon and considered in Section 5.4—demonstrates the capabilities of the SAS4A/SASSYS-1 code to reasonably model SFRs. The commercial grade dedication (CGD) for the SAS4A/SASSYS-1 is performed following the guidance of the EPRI report 3002002289 [55]. Software technical evaluation [43], acceptance test plan [56], acceptance test report [57], and the final summary and conclusion of CGD is documented in the SAS4A/SASSYS-1 Software Dedication

Report [58]. CGD has been completed [[ ]](a)(4) for SAS code version 5.7.1 as used in the PSAR. The conclusions and documentation to be completed in Step 17 are inputs to Step 20—to determine EM biases.

The assessment of the system interactions and global capabilities of the EM focus on the fidelity of calculations performed using the EM. The demonstration of the EM fidelity is accomplished by satisfactory completion of the following tasks:

- Identification of the optimal model representation of Natrium plant components and system.
- Confirmation of a nodalization (mesh) that gives convergent solutions for both the Natrium plant and the models used to perform the validation studies using the experimental data sets that make up the validation matrix.
- Application of the same model options and nodalization in both the Natrium design and experiment validation calculations.
- Assessment and confirmation that all the highly-ranked phenomena identified in the PIRT are calculated in either a reasonable or excellent fashion for a best-estimate calculation, or are suitably conservative.
- Quantification of the biases and deviations of the validation calculations and the subject validation data.
- Evaluation of the ability of the EM to model system interactions, e.g., between the loops inherent to the heat exchangers. This objective is achieved by comparing the calculated interactions between system components that are present in the scaled IET experiments.
- Quantification of the parameter ranges characteristic of the Natrium plant for the scenarios under consideration.

Upon satisfactory completion of the above tasks, the final step of the integrated EM adequacy may proceed. The conclusions and documentation completed in Step 18 are inputs to Step 19—to assess the scalability of the integrated calculations and the distortion level of the experimental data.

5.6 Integrated EM - Top-down: Scalability Assessment of the Integrated EM: EMDAP Step 19

The scalability assessment of the integrated EM is performed in conjunction with the scalability assessment of the closure models (Step 15). The results of the two scalability assessments are integrated and conclusions are formed for consideration in Step 20.

From an integrated EM perspective, the scaling assessment consists of ensuring that the agreement between the experimental data and the EM calculations of the highly-ranked phenomena identified in the Natrium PIRT studies (considered in Element 1 of RG 1.203) is reasonable at a minimum, i.e. sufficiently conservative—together with an assessment of the distortion level of the measured data. Provided the distortion levels are acceptable, following evaluation viz-a-viz the plan requirements (Step 10), the conclusions formulated are one of the primary input ingredients to Step 20.

5.7 Determine EM Biases and Uncertainties: EMDAP Step 20

Because the methodology used for the evaluation of DBAs for in-vessel events without radiological release is conservative, no uncertainty analyses are required. Instead, a conservative approach is being defined and an effort is underway to demonstrate that it is "suitably conservative."

6 NATRIUM SAMPLE ANALYSIS RESULTS

At the time of this writing, the majority of DBA analyses have not been performed in sufficient detail to warrant inclusion in this report. Sample DBA evaluations will be performed and documented prior to submitting a final update of this evaluation methodology.

7 ADEQUACY DECISION

The adequacy decision provides documentation of the adequacy demonstration process. Questions concerning the adequacy of the EM will be addressed throughout the entire EMDAP. At the end of the process, the adequacy will be questioned again to ensure that all earlier answers are satisfactory and that intervening activities have not invalidated previous acceptable responses. If unacceptable responses indicate significant EM inadequacies, the code deficiency will be corrected and the appropriate steps in the EMDAP will be repeated to evaluate the correction.

This will be the last task to be performed and documented prior to submitting a final update of the DBA evaluation methodology in support of the Natrium application submittal to the NRC.

8 CONCLUSIONS AND LIMITATIONS

8.1 Conclusions

TerraPower is requesting NRC approval of the DBA methodology documented in this report for use by future applicants utilizing the Natrium design as an appropriate and adequate means to evaluate in-vessel DBA events without radiological release. This approval is subject to the limitations described below.

8.2 Limitations

This section describes the limitations of the methodology presented in this report. Each limitation must be addressed in safety analysis reports associated with licensing application submittals which use this methodology, or justification provided for why the limitation may remain open.

1. The methodology is limited to a Natrium design that has a pool-type, SFR design with metal fuel and sodium bond as described in Sections 1.3 and 2.3. Changes from these design features will be identified and justified in Safety Analysis Reports of Natrium license applications.

2. Adequate verification and validation assessment information should be made available to the NRC staff as part of future submittals supporting the codes that make up the EM. This verification and validation information should be justified to reasonably bound the operational envelope for the design for any applicant referencing the in-vessel DBA EM methodology.

3. An applicant utilizing the topical report needs to justify the use of the model for the design. This justification must discuss the capability of the model in the context of what is needed to appropriately represent the design and discuss how the model is applicable to the design,

including consideration of system interactions occurring in the design, system conditions (which may affect the applicability of models or validation data). If the design requesting use of this model shows significant change from the design described in this report, a revised PIRT (or functionally similar tool) should be made available to facilitate review of the final validation model. Demonstration of the use of suitably conversative methods will be provided, or uncertainties associated with the evaluation model and the validation data should be discussed in accordance with RG 1.203.

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Appendix A. SUPPORTING INFORMATION REGARDING ASSUMPTIONS AND MODELING PRACTICES

The information given in this appendix supports the narrative given in the main body of the report. The supporting information is arranged according to the report main body section in ascending order. As such, each appendix item is labeled according to the pertinent main body section number.

A.1 Section 2.3: Systems, Components, Phases, Geometries, Fields, and Processes Modeled: EMDAP Step 3

A.1.1 Regarding the Sodium Salt Heat Exchanger

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A.1.2 Regarding Two-Phase Liquid Sodium-Argon Gas Flow

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A.2 Section 2.5: Preliminary Evaluation of Highly-Ranked Phenomena—Regarding Quantification of the Effect of the Highly-Ranked Phenomena Using Sensitivity Studies to Envelope the Range of Interest

The table below discusses the high-level input sources and SAS implementation of the eight phenomena listed in Section 2.5.

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Sensitivity Analysis

For each of the phenomena, the related SAS input parameters were identified and preliminary sensitivities were performed to assess the ranking of the parameters impact on PCT as the FOM. Parameters were perturbed only one at a time for a specific subset of PIRT defined transients.

Future sensitivities will be done to complete the preliminary assessments. Parameters with negligible or no contribution to the system response could be removed in future studies. Parameters with significant contribution will be areas of focus for future research on consolidating the input uncertainty. Some detailed sensitivities related to these phenomena will also be performed outside of the SAS EM such as uncertainties attached to the HCF assessment.

The final method for these sensitivity analyses is under development at this time and different methods like scatterplots, Person and Spearman Correlation Coefficients, Partial Correlation Coefficients or Sobol Indices are considered.

A.4 Section 3.5.3--Regarding the IHX Geometry and Heat Transfer Coefficient Modeling

The IHX is within the preliminary design phase and with that representative data is used for geometry and heat transfer coefficients. [[

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A.5 Section 3.5.2-- EBR-II Tests: SHRT-17, SHRT-45R, and BOP

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A.5 Section 4.2.1.2-- Structure of SAS4A/SASSYS-1

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