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TERRAPOWER, LLC – DRAFT 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

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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

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[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

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[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

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[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 **[[**

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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 **[[**

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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 **[[** **]]**.

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[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 **[[**

]].

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, **[[**

]].

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. **[[**

]].

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].

[[**]]**.

[[

]].

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. **[[**

]].

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]. **[[**

]].

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, **[[**

]].

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. **[[** **]]**.

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 **[[**

]].

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[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. **[[**

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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. **[[**

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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 **[[**

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

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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**[[**

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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.

REFERENCES

1. TerraPower, “Design Basis Accident Methodology for In-Vessel Events without Radiological Release,” TP-LIC-RPT-0004, Revision 0, September 2023. (ML23272A260)

2. U.S. Nuclear Regulatory Commission, “EMAIL - Completeness Determination for the TerraPower, LLC. Topical Report “Design Basis Accident Methodology for In-Vessel Events without Radiological Release,” Revision 0 (EPID L-2023-TOP-0050),” October 2023. (ML23303A168)

3. U.S. Nuclear Regulatory Commission, “TerraPower, LLC – Audit Plan for Topical Report “Design Basis Accident Methodology for In-Vessel Events without Radiological Release,” Revision 0 (EPID NO. L-2023-TOP-0050),” March 2024. (ML24064A195)

4. U.S. Nuclear Regulatory Commission, “TerraPower, LLC – Summary Report on the Regulatory Audit of Topical Report, TP-LIC-RPT-0004, “Design Basis Accident Methodology for In-Vessel Events without Radiological Release Topical Report,” Revision 0 (EPID NO. L-2023-TOP-0050,” November 2024. (ML24255A017)

5. TerraPower, LLC (TerraPower), “Design Basis Accident Methodology for In-Vessel Events without Radiological Release,” NAT-9390, Revision 2, October 2024. (ML24295A202)

6. U.S. Nuclear Regulatory Commission, “Transient and Accident Analysis Methods,” Regulatory Guide 1.203, December 2005. (ML053500170)

7. U.S. Nuclear Regulatory Commission, “Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs),” NUREG/CR-6944, Vol. 1, March 2008. (ML081140459)

8. U.S. Nuclear Regulatory Commission, “Software Quality Assurance Procedures for NRC Thermal Hydraulic Codes,” NUREG-1737, December 2000. (ML010170081)

9. Nuclear Energy Institute, “Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development,” NEI 18-04, Revision 1, August 2019. (ML19241A472)

10. U.S. Nuclear Regulatory Commission, “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,” Regulatory Guide 1.233, Revision 0, June 2020. (ML20091L698)

11. TerraPower, “Fuel and Control Assembly Qualification,” NATD-FQL-PLAN-0004, Revision 0, January 2023. (ML23025A409)

12. U.S. Nuclear Regulatory Commission, “Final Safety Evaluation of Topical Report NATD-FQL-PLAN-0004, “Fuel and Control Assembly Qualification,” Revision 0 (EPID L-2023-TOP-0017),” October 2024. (ML24220A154).

13. U.S. Nuclear Regulatory Commission, “Preapplication Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor,” NUREG-1368, February 1994. (ML063410561)

14. TerraPower, “Design Basis Accident Methodology for Events with Radiological Release,” TP-LIC-RPT-0007, Revision 0, March 2024. (ML24082A262)

15. TerraPower, “Partial Flow Blockage Methodology,” TP-LIC-RPT-0008, Revision 1, March 2024. (ML24085A822)

16. Argonne National Laboratory, “SAS4A/SASSYS-1 Code Manual, Version 5.7.1,” <https://wiki.anl.gov/sas/Code_Manual> (16 September 2024).

17. International Atomic Energy Agency (IAEA), “Benchmark Analysis of EBR-II Shutdown Heat Removal Tests,” IAEA-TECDOC-1819, August 2017.

18. Argonne National Laboratory, "BOP-301 and BOP-302R: Test Definitions and Analyses," ANL-GIF-SO-2018-2, December 2018.

19. Argonne National Laboratory, “SAS4A/SASSYS-1 Validation with the FFTF, LOFWOS Tests #10-12,” ANL/NSE-22/17, June 2022.

20. Wootan, D.W. et al., “Lessons Learned from Fast Flux Test Facility Experience,” *IAEA Proceedings of the International Conference on Fast Reactor and Related Fuel Cycles*, Yekaterinburg, Russia, 26-29 June 2017.

21. Lucoff, D.M., “Passive Safety Testing at the Fast Flux Test Facility,” WHC-SA-0046-FP, Westinghouse Hanford Company, September 1987.

22. IAEA, “Benchmark Analyses on the Natural Circulation Test Performed During the Phénix End-of-Life Experiments,” IAEA-TECDOC-1703, July 2013.

23. IAEA, “Profile SFR-40, SADHANA,” Catalogue of Facilities in Support of Liquid Metal-cooled Fast Neutron Systems. <https://nucleus.iaea.org/sites/lmfns/Facility%20Country%20Profiles1/Profile%20SFR-40%20India%20-%20SADHANA.pdf> (19 September 2024).

24. Padmakumar, G. et al., “SADHANA Facility for Simulation of Natural Convection in the SGDHR System of PFBR,” *Progress in Nuclear Energy,* Vol. 66, pp. 99-107, July 2013.

25. IAEA, “Profile SFR-55, STELLA-1,” Catalogue of Facilities in Support of Liquid Metal-cooled Fast Neutron Systems. <https://nucleus.iaea.org/sites/lmfns/Facility%20Country%20Profiles1/Profile%20SFR-55%20Korea%20-%20STELLA-1_rev2.pdf> (19 September 2024).

26. Hong, Jonggan et al., "Heat transfer performance test of PDHRS heat exchangers of PGSFR using STELLA-1 facility," *Nuclear Engineering and Design*, Vol. 313, pp. 73-83, March 2017.

27. Lee, J. et al., "Design of large-scale sodium thermal-hydraulic integral effect test facility, STELLA-2," *Nuclear Engineering and Technology*, Vol. 54, no. 9, pp. 3551-3566, September 2022.

28. Lee, J. et al., "Design evaluation of large-scale sodium integral effect test facility (STELLA-2) using MARS-LMR," *Annals of Nuclear Energy*, Vol. 120, pp. 845-856, October 2018.

29. IAEA, "Status Report – 4S (Toshiba Energy Systems & Solutions Corp./Japan)," October 2018. <https://aris.iaea.org/PDF/Toshiba-4S_2020.pdf> (19 September 2024).

30. Namekawa, F. et al. "Buoyancy Effects on Wire-Wrapped Rod Bundle Heat Transfer in an LMFBR Fuel Assembly," American Institute of Chemical Engineers, Symposium Series No. 236, Vol. 80, pp. 128-133, 1984.

31. Toshiba Corporation, "Validation of 4S Safety Analysis Code SAEMKON for Loss of Offsite Power Event," Toshiba Corporation, US Nuclear Regulatory Commission, September 2012. (ML12278A087)

32. Mochizuki, Hiroyasu and Takano, Masahito, "Heat Transfer in Heat Exchangers of Sodium Cooled Fast Reactor Systems," *Nuclear Engineering and Design*, Vol. 239, No. 2, pp. 295 - 307, February 2009.

33. Kamide, H. et al., "Multi-Bundle Sodium Experiments for Thermohydraulics in Core Subassemblies During Natural Circulation Decay Heat Removal Operation," *International Atomic Energy Agency International Working Group on Fast Reactors Specialists' Meeting on Evaluation of Decay Heat Removal by Natural Convection*, Oarai, Japan, 22-23 Feb 1993.

34. Ono, A. et al., "An Experimental Study on Natural Circulation Decay Heat Removal System for a Loop Type Fast Reactor," *Journal of Nuclear Science and Technology* Vol. 53, No. 9, pp. 1385-1396, February 2016.

35. Engel, F. et al., Westinghouse Electric Corporation, Advanced Reactors Division, "Buoyancy Effects on Sodium Coolant Temperature Profiles Measured in an Electrically Heated Mock-Up of a 61-Rod Breeder Reactor Blanket Assembly," TID-28746, 1978.

36. Zhang, T. et al., "Validation of SAS4A/SASSYS-1 for Predicting Steady-State Single-Phase Natural Circulation," *Nuclear Engineering and Design*, Vol. 377, June 2021.

37. TerraPower, "TerraPower Quality Assurance Program Description," TP-QA-PD-0001, Revision 14-A, July 2023. (ML23213A199)

38. TerraPower, “Core Nuclear and Thermal Hydraulic Design Technical Report,” TP-LIC-RPT-0011, Revision 0, March 2024. (ML24088A085)

39. G. Wilson, TerraPower, Document Control Desk, U.S. Nuclear Regulatory Commission, “Submittal of the Construction Permit Application for the Natrium Reactor Plant, Kemmerer Power Station Unit 1,” TP-LIC-LET-0124, March 28, 2024. (ML24088A060)

40. Mikityuk, K., “Heat transfer to liquid metal: review of data and correlations for tube bundles,” *Nuclear Engineering and Design*, Vol. 239, No. 4, pp. 680–687, April 2009.

41. Pacio, J. et al., “Analysis of pressure losses and flow distribution in wire-wrapped hexagonal rod bundles for licensing. Part I: The Pacio-Chen-Todreas Detailed model (PCTD),” *Nuclear Engineering and Design,* Vol. 388, March 2022.

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