March 26, 2024

TP-LIC-LET-0127
Project Number 99902100

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

Subject: Transmittal of TerraPower, LLC "Partial Flow Blockage Methodology," Revision 1

This letter transmits the TerraPower, LLC (TerraPower) Topical Report "Partial Flow Blockage Methodology," Revision 1 (enclosed). The report contains an overview and description of evaluation models developed for the Natrium™ Plant[1] to evaluate partial flow blockage events within a sodium fast reactor.

TerraPower requests the NRC's review and approval of the evaluation models presented in this report for use by future applications utilizing the Natrium design.

TerraPower requests that a nominal review duration of 12 months be considered.

The report contains proprietary information and as such, it is requested that Enclosure 3 be withheld from public disclosure in accordance with 10 CFR 2.390, "Public inspections, exemptions, requests for withholding." An affidavit certifying the basis for the request to withhold Enclosure 3 from public disclosure is included as Enclosure 1. Enclosure 3 also contains ECI which can be disclosed to Foreign Nationals only in accordance with the requirements of 15 CFR 730 and 10 CFR 810, as applicable. Proprietary and ECI materials have been redacted from the report provided in Enclosure 2; redacted information is identified using [[ ]]$^{(a)(4)}$, [[ ]]^{ECI}, or [[ ]]$^{(a)(4), ECI}$.

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

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

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If you have any questions regarding this submittal, please contact Ryan Sprengel at rsprengel@terrapower.com or (425) 324-2888.

Sincerely,

Ryan Sprengel
Director of Licensing, Natrium
TerraPower, LLC

Enclosure:
1. TerraPower, LLC Affidavit and Request for Withholding from Public Disclosure (10 CFR 2.390(a)(4))
2. TerraPower, LLC Topical Report, "Partial Flow Blockage Methodology," Revision 1 – Non-Proprietary (Public)
3. TerraPower, LLC Topical Report, "Partial Flow Blockage Methodology," Revision 1 – Proprietary (Non-Public)

cc: Mallecia Sutton, NRC
William Jessup, NRC
Nathan Howard, DOE
Jeff Ciocco, DOE

ENCLOSURE 1

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

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

I, George Wilson, hereby state:

1. I am the Vice President, Regulatory Affairs and I have been authorized by TerraPower, LLC (TerraPower) to review information sought to be withheld from public disclosure in connection with the development, testing, licensing, and deployment of the Natrium™ reactor and its associated fuel, structures, systems, and components, and to apply for its withholding from public disclosure on behalf of TerraPower.

2. The information sought to be withheld, in its entirety, is contained in Enclosure 3, which accompanies this Affidavit.

3. I am making this request for withholding, and executing this Affidavit as required by 10 CFR 2.390(b)(1).

4. I have personal knowledge of the criteria and procedures utilized by TerraPower in designating information as a trade secret, privileged, or as confidential commercial or financial information that would be protected from public disclosure under 10 CFR 2.390(a)(4).

5. The information contained in Enclosure 3 accompanying this Affidavit contains non-public details of the TerraPower regulatory and developmental strategies intended to support NRC staff review.

6. Pursuant to 10 CFR 2.390(b)(4), the following is furnished for consideration by the Commission in determining whether the information in Enclosure 3 should be withheld:

    a. The information has been held in confidence by TerraPower.

    b. The information is of a type customarily held in confidence by TerraPower and not customarily disclosed to the public. TerraPower has a rational basis for determining the types of information that it customarily holds in confidence and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application and substance of that system constitute TerraPower policy and provide the rational basis required.

    c. The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR 2.390, it is received in confidence by the Commission.

    d. This information is not available in public sources.

    e. TerraPower asserts that public disclosure of this non-public information is likely to cause substantial harm to the competitive position of TerraPower, because it would enhance the ability of competitors to provide similar products and services by reducing their expenditure of resources using similar project methods, equipment, testing approach, contractors, or licensing approaches.

I declare under penalty of perjury that the foregoing is true and correct.
Executed on: March 26, 2024

George Wilson

George Wilson
Vice President, Regulatory Affairs
TerraPower, LLC

ENCLOSURE 2

TerraPower, LLC Topical Report
"Partial Flow Blockage Methodology" Revision 1

Non-Proprietary (Public)

Topical Report

Document Number:	TP-LIC-RPT-0008		Revision:	1
Document Title:	Partial Flow Blockage Methodology			
Functional Area:	Licensing	Engineering Discipline:	N/A	
Effective Date:	3/26/2024	Released Date:	3/26/2024	
			Page:	1 of 197

Approval

Title	Name	Signature	Date
Originator, Licensing Engineer	Matthew Presson	Electronically Signed in Agile	3/26/2024
Reviewer, Licensing Manager	Nick Kellenberger	Electronically Signed in Agile	3/26/2024
Approver, Director of Licensing	Ryan Sprengel	Electronically Signed in Agile	3/26/2024

Export Controlled Content: **Yes** ☐ **No** ☒

SUBJECT TO DOE COOPERATIVE AGREEMENT NO. DE-NE0009054

REVISION HISTORY

Revision No.	Effective Date	Affected Section(s)	Description of Change(s)
0	3/25/2024	All	Initial Release
1	3/26/2024	All	Revised proprietary markings

Not Confidential

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EXECUTIVE SUMMARY

This report documents the partial flow blockage evaluation model (EM) development process for the Natrium™ reactor, a TerraPower & GE-Hitachi Technology. The resulting EM, and items identified which require further development, are described. Certain aspects of the EM adequacy demonstration remain in development and are noted throughout the report. It is acknowledged that this report contains preliminary technical information, and several sections within describe future actions that are planned to be taken by TerraPower. Information generated by these actions will be provided in future licensing submittals. These actions are expected to be complete prior to use of this EM in support of an operating license application.

As described in Regulatory Guide 1.203 [1], it is very important to determine the application envelope for an EM and to identify constituent phenomena, processes, and key parameters within that envelope. This EM is the calculational framework for evaluating the behavior of the reactor system during a postulated transient or Design Basis Accident (DBA).

This report summarizes Element 1 (EMDAP Steps 1 through 4), Element 2 (EMDAP Steps 6, 7, and 9), Element 3 (EMDAP Steps 10 through 12), and Element 4 (EMDAP Steps 13, 16, and 20) of the EMDAP where Element 1 is to establish the requirements of an EM capability, Element 2 is to provide the basis for EM development and assessment, Element 3 is for developing the desired EM, and Element 4 is to assess an adequacy of the EM; however, plans for all 20 steps are also considered. This plan supports efficient development of the EM according to its scope and schedule.

The desired result of the plan is to develop an EM that supports a conservative analysis for the DBA evaluation of partial flow blockage. The EM developed should meet the analytical requirements of the Licensing Modernization Project and support the Probabilistic Risk Assessment (PRA).

The report contains eight chapters and three appendices.

Chapter 1 discusses the overall objective of the report, a high-level description of the Natrium design, and identifies the safety systems and design basis accidents that pertain to the partial flow blockage EM development and how the DBAs fit within the overall identification of event types addressed.

Chapter 2 discusses the scope and regulatory requirements and guidance used in the EM development process.

Chapter 3 discusses assumptions made to define the scope of the EM, determine conservative boundaries, and to identify areas in which future work is planned.

Chapter 4 provides additional detail on how partial flow blockage events are characterized for evaluation.

Chapter 5 discusses the planned activities and the work that has been completed while following the guidance provided by the EMDAP.

Section 5.1 summarizes the EM capability requirements development. This includes how the development plan specifies analysis purpose, transient class, and power plant class; figures of merit (FOMs); identifies systems, components, phases, geometries, fields, and processes that must be modeled; and lists important key phenomena.

Section 5.2 discusses development of the EM assessment base and is generally focused on addressing applicable aspects of Element 2 of Regulatory Guide 1.203. This includes discussion of the assessment base objectives, scaling analysis and similarity criteria, existing data needed to complete the EM validation database, evaluation of integral effects test (IET) distortions and

separate effects test (SET) scaleup capability, and experimental uncertainties determination (where information is available).

Section 5.3 discusses EM development including the associated plan, a listing of computer codes considered for inclusion in the EM, computer codes upstream of the EM, code selection gaps, the EM structure, and the strategy for partial flow blockage modeling.

Section 5.4 discusses the EM adequacy assessment for evaluations made to support the Natrium Preliminary Safety Analysis Report (PSAR).

Chapter 6 discusses the overarching EM adequacy decision.

Chapter 7 describes the limitations of this partial flow blockage EM and identifies items related to limitations of the EM.

Appendix 9.1 provides sample derivation of governing equations for the EM. Appendix 9.2 provides a discussion on the geometric correction factors developed for use with the semi-empirical model implementation discussed in Section 5.3.3.1.3.2. And Appendix 9.3 provides a sample partial flow blockage analysis using this EM.

ACRONYMS

Acronym	Definition
ANL	Argonne National Laboratory
AOO	Anticipated Operational Occurrence
ASME	American Society of Mechanical Engineers
BDBE	Beyond Design Basis Event
BOEC	Beginning of Equilibrium Cycle
CFD	Computational Fluid Dynamics
CP	Construction Permit
CRBRP	Clinch River Breeder Reactor Project
DBA	Design Basis Accident
DBE	Design Basis Event
DID	Defense-In-Depth
DOE	Department of Energy
DRM	Distributed Resistance Model
EBR	Experimental Breeder Reactor
EM	Evaluation Model
EMDAP	Evaluation Model Development and Assessment Process
FCCI	Fuel-Cladding Chemical Interaction
FCMI	Fuel-Cladding Mechanical Interaction
FFM	Fuel Failure Mockup
FFTF	Fast Flux Test Facility
FOM	Figures of Merit
IAEA	International Atomic Energy Agency
IET	Integral Effect Test
INL	Idaho National Laboratory
LBE	Licensing Basis Event
LMFBR	Liquid Metal Fast Breeder Reactor
LMP	Licensing Modernization Project
LMR	Liquid Metal Reactor
LWR	Light Water Reactor
NEI	Nuclear Energy Institute
NGNP	Next Generation Nuclear Plant
NI	Nuclear Island
NPP	Nuclear Power Plant
NQA	Nuclear Quality Assurance
NRC	Nuclear Regulatory Commission
OL	Operating License
OQE	Other Quantified Event
ORNL	Oak Ridge National Laboratory
PCT	Peak Cladding Temperature

Acronym	Definition
PIRT	Phenomena Identification and Ranking Table
PNC	Power Reactor and Nuclear Fuel Development Corporation
PRISM	Power Reactor Innovative Small Module
PRA	Probabilistic Risk Assessment
PSAR	Preliminary Safety Analysis Report
PSER	Preapplication Safety Evaluation Report
PTP	Plant Transient Precursor
QA	Quality Assurance
QAPD	Quality Assurance Program Description
RCC	Reactor Core System
SAFR	Sodium Advanced Fast Reactor
SER	Safety Evaluation Report
SET	Separate Effect Test
SFR	Sodium-cooled Fast Reactor
SIMPLE	Semi-Implicit Method for Pressure Linked Equations
SMP	Software Management Procedure
SOK	State of Knowledge
SSC	Structures, Systems, and Components
TATNF	Time at Temperature No Failure
THORS	Thermal-Hydraulic Out-of-Reactor Safety
TWR	Traveling Wave Reactor
TWR-P	Traveling Wave Reactor - Prototype
V&V	Verification and Validation

1 INTRODUCTION

A partial flow blockage in a fuel assembly has been considered as one of the important safety issues of Sodium-cooled Fast Reactors (SFR), which are characterized by tight spacing of fuel pins, high power density and high burnup. The partial flow blockage may be initiated due to an accumulation of debris circulated in the primary sodium, a failure of wire-wrapped spacers, and from swelling or bowing of the fuel pins.

The consequences of partial flow blockage were categorized as a local fault Design Basis Accident (DBA) in the Clinch River Breeder Reactor Project (CRBRP) PSAR [2], Power Reactor Innovative Small Module (PRISM) PSER [3], Sodium Advanced Fast Reactor (SAFR) PSER [4], CRBRP SER [5], and IAEA-TECDOC-1157 [6]. As the local fault category is related to potential radiological release, this event should be analyzed, and adequate protection or mitigation be justified. If the blockage event can be detected before significant damage results, the limit of damage should be determined that can be accepted before shutdown and repair are required.

Flow blockage is discussed in Section 15.4, "Local Failure Events" of CRBRP PSAR [2] and may occur in three potential places: fuel assembly, control assemblies and radial blanket assemblies.

- Control Assemblies Flow Blockage: The impact of the flow blockage in a control assembly would be less significant compared to the flow blockage in fuel assemblies since temperatures are lower in the control rods.
- Radial Blanket Assembly Flow Blockage: Radial blanket assemblies have lower power, lower flow, and larger pitch to diameter ratios than those of fuel assemblies. Therefore, a large blockage is required to cause a reduction in flow rate and significant increase in the outlet temperature. It is noted that the Natrium core design contains fuel, control, standby shutdown, reflector, and shield assemblies. The radial blanket assembly of the CRBRP corresponds to reflector and shield assemblies of Natrium Reactor Core System (RCC) system.

Based on the conclusions from the CRBRP PSAR [2], the partial flow blockage occurring in a fuel assembly is only evaluated in this study as a bounding case. It is noted that this conclusion will be verified and demonstrated for the Natrium design by performing safety analysis using the partial flow blockage evaluation model (see assumption number 4.1).

The safety concern of the partial flow blockage is that the incident fuel assembly could be damaged or even become molten with consequent propagation to adjacent assemblies in the core. Pin-to-pin failure propagation could be either self-limiting, with damage confined to a region of the affected pin bundle, or severe if the blockage remains undetected. If the failure propagation occurs in a short time, plant protection systems may not prevent or mitigate the progress.

The U.S. Nuclear Regulatory Commission (NRC) required that reactor and core assembly designs incorporate features to minimize the potential of flow blockage for the CRBRP design [5] and the PRISM design [3]. The NRC reviewed the SAFR design [4] and concluded that an in-core flow blockage could go undetected until fuel failure propagation since there is no in-core fuel assembly temperature or flow instrumentation. If the blockage event proceeds undetected for a long-time during power operation, increased local cladding temperature around the blockage would reduce the burnup capability of the fuel rods. Metal fuel expands when it heats up. Overall thermal expansion causes increase of fuel average height and decrease of fuel smeared density. Consequently, the fuel region becomes more transparent, and this increases the probability of neutron leakage in radial direction.

The CRBRP safety evaluations [2] assumed 6-subchannel blockage as a DBA, in which all subchannels surrounding a particular pin are completely blocked. However, the 6-subchannel blockage did not result in a substantial change relative to the non-blockage regarding the overall coolant mass flow rate and mixed mean temperature at the exit of the fuel assembly. Particularly, it was demonstrated that such a partial blockage is an extremely low probability event because of engineering design features, inspection, and operation techniques.

An EM needs to be developed and approved prior to performing safety analyses of partial flow blockage. As described in Regulatory Guide 1.203 [1], an EM is the calculational framework for evaluating the behavior of the reactor system during a postulated transient or Design 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.

2 PURPOSE AND SCOPE

The safety objective of the flow blockage analysis is to maintain the fuel integrity within the incident assembly. The fuel integrity can be maintained if the cladding damage is avoided. Thus, a peak cladding temperature is important to determine safety limits preventing partial flow blockage fuel failures. Additionally, temperature distribution at the exit of the core provides important information for detecting the blockage event depending on its extent and severity.

The purpose of this document is to identify and establish a plan for developing an EM for partial flow blockage by complying with the basic principles of the Evaluation Model Development and Assessment Process (EMDAP). First, the basic principles and the 20 steps of the EMDAP are examined and activities are defined for each step under the conditions and assumptions described below. Activities that need to be performed to comply with the EMDAP activities for each step are also discussed.

The desired result of this plan is to develop an EM that supports a conservative analysis for the evaluation of DBA events which include a partial flow blockage. Conservative assumptions are informed by the prior best estimate evaluations. The EM developed should meet the analytical requirements of the Licensing Modernization Project (LMP) to support the Probabilistic Risk Assessment (PRA). The LMP is described in the Nuclear Energy Institute (NEI) 18-04 [7] and Regulatory Guide 1.233 [8].

This document describes the plan for the partial flow blockage EM using the Natrium Demonstration Reactor Project General Methodology Development and Assessment Guide to ensure that it is adequate for performing safety analysis and licensing of the Natrium design.

This document will be revised as necessary to reflect changes in the plan as methodology development, design, and project mature.

3 ASSUMPTIONS

As the plant design and safety methods are currently based on preliminary information, several assumptions have been made to define the scope of the EM, determine conservative boundaries, or to identify areas in which future work is planned.

3.1 Assumptions

[[

]](a)(4)

[[

]]$^{(a)(4),ECI}$

[[

]](a)(4)

4 PARTIAL FLOW BLOCKAGE EVENTS

4.1 Licensing Basis Events

The NEI 18-04 [7] provides definitions of licensing basis events for non-light-water reactors. Regulatory Guide 1.233 [8] endorses NEI technical report 18-04 [7] as one acceptable method for non-LWR designers to use when carrying out selection of LBEs classification and special treatments of SSCs, and assessment of DID and preparing their applications. Table 3-1 of NEI 18-04 [7] describing the LBE definitions is replicated as shown in Table 4-1.

Table 4-1 Definitions of Licensing Basis Events [7]

Event Type	Guidance Document Definition
Anticipated Operational Occurrence (AOO)	Anticipated event sequences expected to occur one or more times during the life of a nuclear power plant, which may include one or more reactor modules. Event sequences with mean frequencies of 1×10^{-2}/plant-year and greater are classified as AOOs. AOOs consider the expected response of all SSCs within the plant, regardless of safety classification.
Design Basis Event (DBE)	Infrequent event sequences that are not expected to occur in the life of a nuclear power plant, which may include one or more reactor modules, but are less likely than AOOs. Event sequences with mean frequencies of 1×10^{-4}/plant-year to 1×10^{-2}/plant-year are classified as DBEs. DBEs consider the expected response of all SSCs within the plant regardless of safety classification.
Beyond Design Basis Event (BDBE)	Rare event sequences that are not expected to occur in the life of a nuclear power plant, which may include one or more reactor modules, but are less likely than a DBE. Event sequences with mean frequencies of 5×10^{-7}/plant-year to 1×10^{-4}/plant-year are classified as BDBEs. BDBEs consider the expected response of all SSCs within the plant regardless of safety classification.
Design Basis Accident (DBA)	Postulated event sequences that are used to set design criteria and performance objectives for the design of Safety Related SSCs. DBAs are derived from DBEs based on the capabilities and reliabilities of Safety-Related SSCs needed to mitigate and prevent event sequences, respectively. DBAs are derived from the DBEs by prescriptively assuming that only Safety Related SSCs are available to mitigate postulated event sequence consequences to within the 10 CFR 50.34 dose limits.
Licensing Basis Event (LBE)	The entire collection of event sequences considered in the design and licensing basis of the plant, which may include one or more reactor modules. LBEs include AOOs, DBEs, BDBEs, and DBAs.

4.2 Other Quantified Events

For events below the LBE cutoff frequency, i.e., 5×10^{-7} per reactor year, there is still a requirement to calculate the integrated risk. These events are analyzed using the same methods and tools as the LBE analysis and are treated using best estimate methods, i.e., traditional PRA. However, the evaluation of these events is not dispositioned as an LBE in the safety analysis report.

5 EVALUATION MODEL ADEQUACY ASSESSMENT

As described earlier, the basic principles and the 20 steps of the EMDAP are examined to identify necessary activities to develop an EM for partial flow blockage within a fuel assembly. The EMDAP is an NRC-endorsed means of satisfying specific regulatory requirements and it is acceptable for developing an EM. The application of the EMDAP facilitates the EM development effectively. In Regulatory Guide 1.203 [1], the U.S. NRC has identified six basic and important principles to follow in the process of developing and assessing an EM. The six principles are:

1. Determine requirements for the evaluation model.
2. Develop an assessment base consistent with the determined requirements.
3. Develop the evaluation model.
4. Assess the adequacy of the evaluation model.
5. Follow an appropriate quality assurance protocol during the EMDAP.
6. Provide comprehensive, accurate, up-to-date documentation.

The regulatory guide discusses the evaluation model development and assessment process in detail. The six principles above are satisfied when an EM is developed by complying with the elements and steps discussed in the EMDAP. Using the EMDAP in developing an EM for partial flow blockage is a practical path to approval because the U.S. NRC considers the EMDAP acceptable for developing an EM. Figure 5-1 shows an overall diagram of the EMDAP [1].

A development plan for the partial flow blockage EM for the Natrium LBEs is established by the examination of the EMDAP principles and 20 steps with assumptions (see Section 3.1) identifying activities necessary to develop the EM and specifying high-level descriptions of corresponding activities in each EMDAP step.

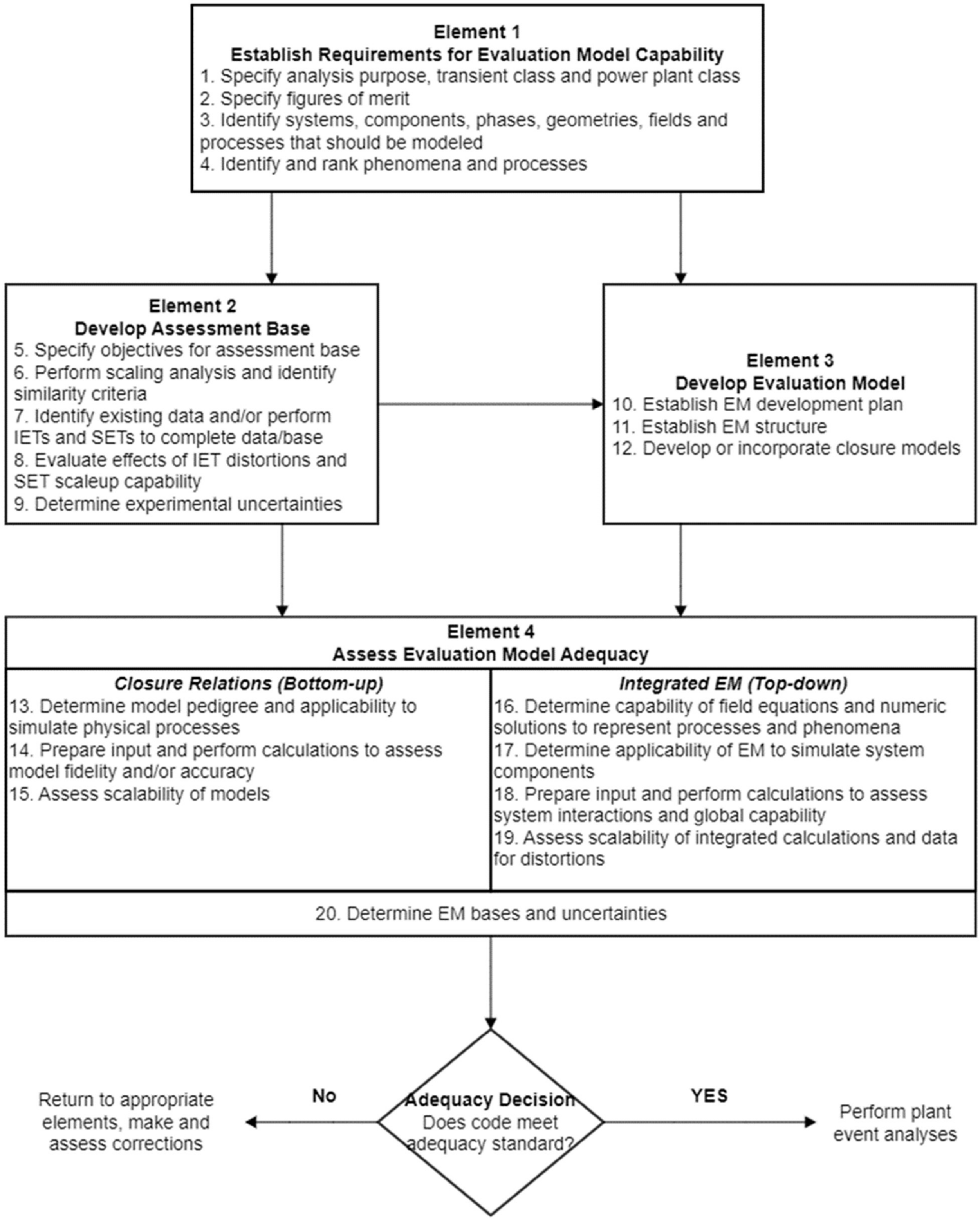

Figure 5-1 Overall Diagram of EMDAP and Relationships among Elements [1]

5.1 EMDAP Element 1: Establish Requirements for Evaluation Model Capability

Element 1 of the EMDAP provides guidance in determining the exact application envelope of the methodology. This first element also identifies and drives agreement on the importance of constituent phenomena, processes, and key parameters within that envelope. Figure 5-2 shows a diagram of EMDAP Element 1[1].

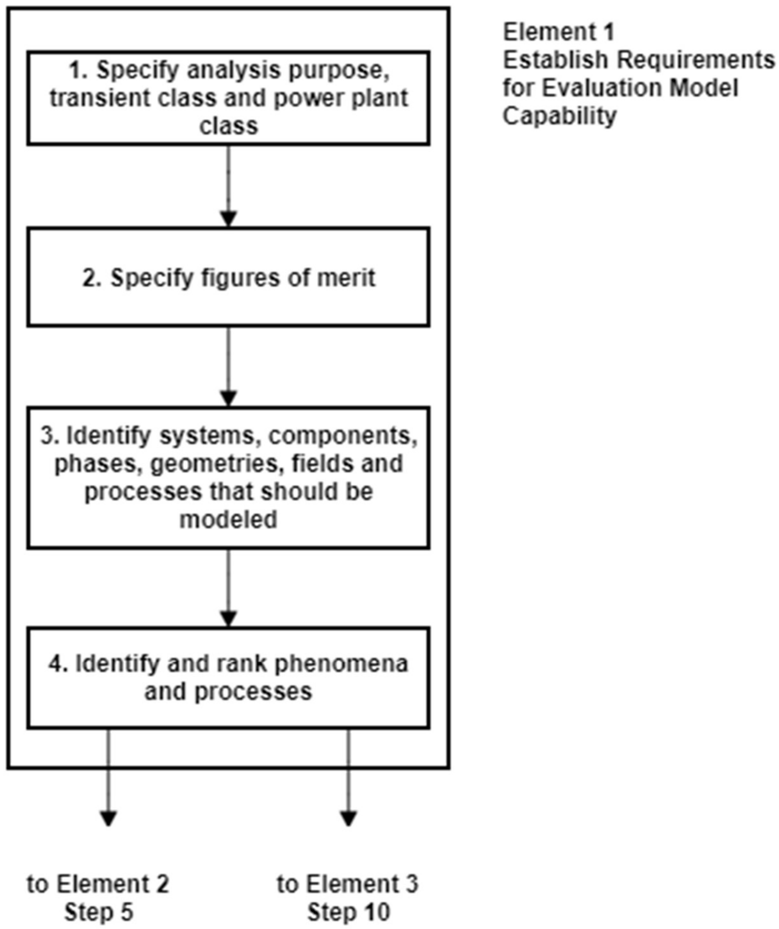

Figure 5-2 Steps in EMDAP Element 1 [1]

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

As the first step in the development of an EM, EM requirements and capabilities are established by specifying:

- Analysis purpose: Purpose of partial flow blockage analysis including such items as historical background and causes
- Transient class: Dominant phenomena and processes in transient scenarios
- Power plant class: Description of the Natrium plant

Activities for Step 1: Define partial flow blockage EM scope and initial list of important phenomena

Requirements for the capabilities of the principal analytical computer code have been established by specifying analytical purpose, transient class, and power plant class.

5.1.1.1 Analysis Purpose

The purpose of the partial flow blockage analysis is to demonstrate that the Natrium design satisfies the regulatory requirements of dose consequences for "LBE without fuel failure" and meets construction permit (CP) and operating license (OL) guidelines. This goal is achieved by confirming in the analyses that the system responses to LBEs with partial flow blockage within a fuel assembly satisfy all relevant acceptance criteria during normal operating conditions.

According to CRBRP PSAR [2], fuel assembly damage caused by blockage is extremely low probability event because of engineering design features, inspection, and operation techniques. For Natrium applications, design features to preclude flow blockage will be provided such as redundant flow paths in the inlet modules and assembly nozzles.

5.1.1.2 Transient Class

The transient class considered in the partial flow blockage analysis is "Local Fuel Faults".

There are two events identified for the partial flow blockage: 1) local blockage in [[ ]]^(a)(4) and 2) local blockage in [[ ]]^(a)(4). These are the two representative events for which phenomena and processes are considered to cover the other events' phenomena and processes and summarized in Table 5-1. [[ ]]^(a)(4)

If other events are identified to be representative as the Natrium design matures, discussions of those events will be added and the Phenomena Identification and Ranking Table (PIRT) will be updated for the operating license application.

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Table 5-1 Local Fault Events due to Partial Flow Blockage

[[

Event Name	Accident Type	Event Type	Event Initiation	Event Sequence

]](a)(4)

5.1.1.3 Power Plant Class

The power plant class is a Natrium pool-type SFR. Characteristics of the Natrium design relevant to this EM are discussed in Sections 5.1.3.1 and 5.1.3.2 below.

5.1.2 EMDAP Step 2: Specify Figures of Merit

Figures of merit (FOMs) are specified in this step by considering the following items.

- FOMs are quantitative standards of acceptance (e.g., peak cladding temperature) used to define acceptable answers for a safety analysis.
- During the evaluation model development and assessment, surrogate FOMs can be of value in assessing the importance of phenomena and processes.

Activities for Step 2: Define partial flow blockage EM scope and initial list of important phenomena

- FOMs for partial flow blockage analyses have been specified.

Report Discussion

The FOMs are one or more quantitative metrics related to a process or phenomena that can be used to characterize the importance of phenomena and/or systems relative to the acceptance criteria. NEI 18-04 [7] uses a set of frequency-consequence criteria (referred to as the F-C target in that report) to select LBEs. The F-C target is shown in Figure 5-3. As described in Table 4-1 and shown in Figure 5-3, LBE categories and the F-C target values are based on the mean event sequence frequency of occurrence per plant year and radiation exposure limits, respectively.

Even though the F-C target should not be used as a demarcation of acceptable and unacceptable results of the partial flow blockage within a fuel assembly analysis, it can be used as a general reference to assess the events and evaluate safety margins. Fuel performance, especially fuel failure phenomenon, becomes important in the deterministic safety analysis that challenges the top-level safety targets shown in Figure 5-3. Some parameters (or mechanisms) that can lead to fuel failure include:

- Fuel-Cladding Mechanical Interaction (FCMI) can impose limits on maximum burnup.
- Fuel-Cladding Chemical Interaction (FCCI) may place an operational limit on coolant outlet temperature for a metallic fuel core.
- Fission-gas pressure induced cladding strain can lead to thermal creep, which is accelerated by FCCI.

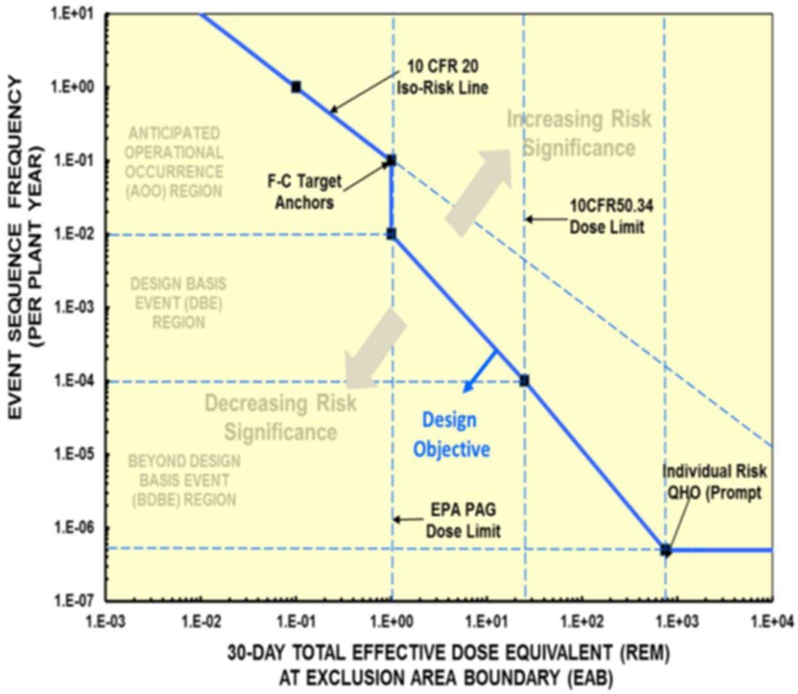

Figure 5-3 Frequency-Consequence Target [7]

Acceptance criteria based on fuel design limits have been established for use in the Natrium design as described in Table 5-2. Acceptance criteria for fuel failure are preliminary, and final results will be provided at the operating license stage. The Time at Temperature No Failure (TATNF) screening criteria is used for this method.

Table 5-2 TATNF Screening Criteria for LBE Analysis

[[

PCT	TATNF	Description

]](a)(4),ECI

The focus for selecting FOMs is in preserving the integrity of the fuel pins. They should also have characteristics of being directly related to key phenomena and easily comprehended, explicit, and measurable. The main FOMs established are both fuel and cladding temperatures because these are the measures of fuel melting and pin failure, respectively, which directly affect dose consequences. Another FOM that impacts the integrity of fuel pins is the coolant temperature (Table 5-3).

Table 5-3 Figures of Merit

Figures of Merit	Significance
Fuel temperature	A measure of fuel melting, directly affecting the fuel pin integrity and dose consequences. [[ ]]$^{(a)(4)}$
Cladding temperature	A measure of cladding failure, directly affecting the fuel pin integrity and dose consequences (see TATNF screening criteria described in Table 5-2).
Coolant temperature	A measure of coolant boiling. Coolant boiling degrades core heat transfer capability, leading to core damage. [[ ]]$^{(a)(4)}$

5.1.3 EMDAP Step 3: Identify Systems, Components, Phases, Geometries, Fields, and Processes that Must be Modeled

The purpose of this step is to identify the EM characteristics along with corresponding ingredients. Ingredients of the EM characteristics are as follows:

- System: Natrium plant
- Subsystems: Major components such as the RCC, fuel assemblies, etc.
- Modules: Physical components within the subsystem (e.g., fuel pin)
- Constituents: Chemical form of substance (sodium, molten-salt, argon gas, etc.)
- Phases: solid, liquid, or vapor
- Geometrical configurations: Geometrical shape (pool, drop, film, bubble, etc.)
- Fields: Properties (mass, momentum, and energy)
- Transport process: Mechanism that determines the transport of and interactions between constituent phases throughout the system

The activities of Step 3 specify the capabilities of the principal computer code which will become the basis of developing a PIRT. If any significant deficiency is discovered, the selected code needs to be revised to eliminate it. The above processes apply to existing computer codes and any new computer code under development or recently developed.

Activities for Step 3: Define partial flow blockage EM scope and initial list of important phenomena

The characteristics of the EM are identified by discussing systems, components, phases, geometries, fields, and processes that must be modeled. The identified EM characteristics are compared with the ingredients discussed in the main computer code (Mongoose++) manuals on theory, numerical methods, and assessment when the code selection is made.

- In addition, an initial list of important phenomena that are (or may be) observed in partial flow blockage are established in this step and activity.

Report Discussion

5.1.3.1 System

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

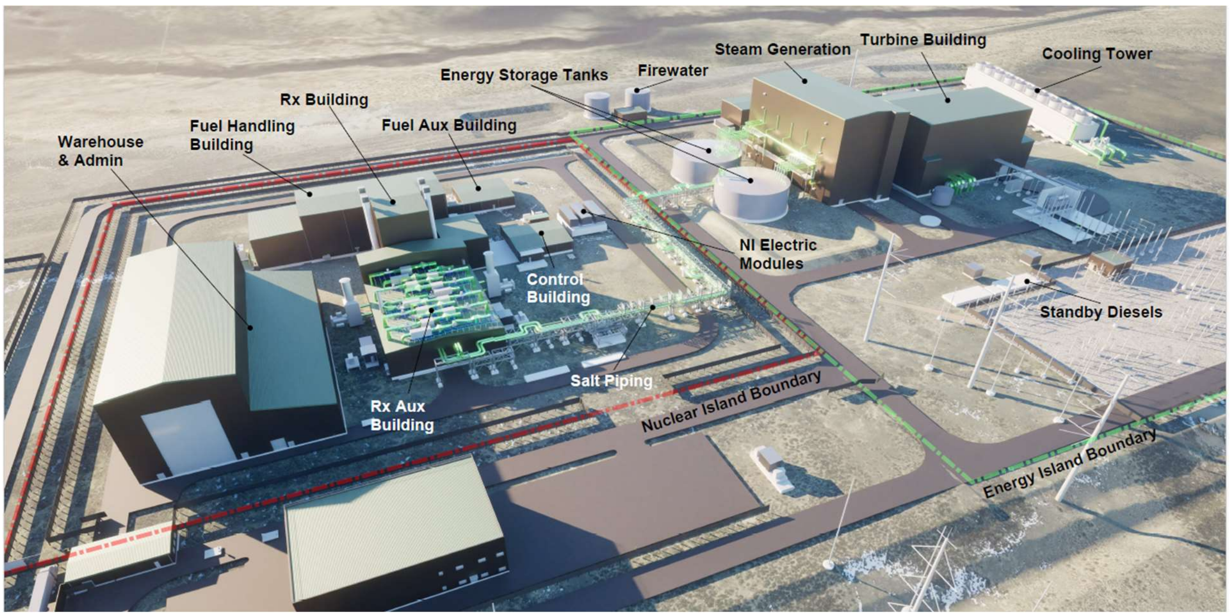

Figure 5-4 Natrium Plant Layout

The general plant layout is shown in Figure 5-4 and is made up of two basic areas; a Nuclear Island where the reactor and associated support facilities reside and an Energy Island where thermal storage tanks and turbine facilities for generating electricity reside. Safety functions are made integral to the reactor vessel and support equipment is moved to separate structures in the Energy Island, resulting in a simplified reactor building. Decoupling the Nuclear Island from the Energy Island from a nuclear safety perspective is central to simplifying the Natrium design. The Natrium design capitalizes on the proven metal fueled SFR safety characteristics to minimize the number of safety-related Structures, Systems, and Components (SSCs) needed to achieve safety goals. The necessary Nuclear Island systems that need to be analyzed are briefly described in the following Section 5.1.3.2.

5.1.3.2 Subsystems

5.1.3.2.1 Reactor Core System

The reactor core of the Natrium design provides approximately 840 MW_{th} of heat generation for the Nuclear Island. The core is designed as a fast reactor cooled by liquid sodium. The coolant flows upward through the core, which is composed of fuel, control rod, reflector, shield, and standby assemblies. The fuel assembly produces heat and provides the neutron flux environment. Initial operation of the Natrium plant will consist of Type 1 fuel featuring a U-10Zr fuel column with a sodium bond to HT9 cladding as shown in Figure 5-5.

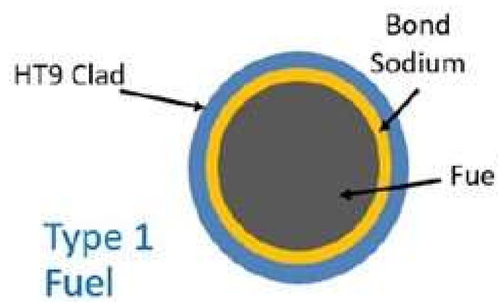

Figure 5-5 Natrium Type 1 Fuel

The Natrium Type 1 fuel assembly rod parameters are given in Table 5-28. The initial loading and first few years of operation of the Natrium fuel system is based on the fuel systems of past SFRs, i.e., EBR-II and FFTF used Type 1 sodium-bonded metallic U-Zr fuel.

The RCC contains 13 control rod assemblies (9 primary, 4 secondary) that function to position neutron absorber material and provide reactivity control. These are positioned by the control rod drive mechanism system. The reflector assemblies surround the active fuel assemblies radially, improving neutron efficiency and limiting radiation damage to permanent reactor structures. Shield assemblies make up the outermost portion of the reactor core, directly adjacent to the reflector assemblies. These function to absorb neutron leakage outside of the reflector assemblies, limiting activation to intermediate sodium while also contributing to prevent radiation damage to permanent reactor structures.

5.1.3.2.2 Fuel Assemblies

The fuel assembly is the primary nuclear power-generating component of the Natrium reactor core. It contains the fuel, produces heat, and provides the neutron flux environment. It can be removed from and replaced or shuffled in the core during the reactor refueling. The Natrium fuel assembly has a hexagonal cross section as shown in Figure 5-6. It has approximately [[ ]]$^{(a)(4),ECI}$ total length and is comprised of an inlet nozzle, a hexagonal duct tube with above core load pads, a handling socket with top load pads, and a fuel pin bundle with its attachments.

[ ] (a)(4),ECI

Figure 5-6 Natrium Fuel Assembly Design

5.1.3.2.3 Fuel Pin

The Natrium fuel pin is comprised of a cladding tube, an upper and lower end cap, wire wrap, sodium-bonded fuel column, fission gas plenum, and axial shield as shown in Figure 5-7. The cladding tube and end caps provide the structural supports and hermetic sealing for the contained components.

[ ] (a)(4),ECI

Figure 5-7 Natrium Type 1 Fuel Pin Design

The Natrium Type 1 fuel is metallic uranium alloyed with 10 wt. % zirconium (U-10Zr). The fuel column section of the pin consists of a stack of right circular cylinder fuel slugs. The individual fuel slug lengths are partially influenced by the manufacturer and their optimal process efficiency and capability. The as-manufactured fuel slugs have cross sectional dimensions that represent 75% of the internal cross-sectional area of the cladding (i.e., 75% smear density). Radiation-induced swelling of the fuel slug will increase its volume such that it contacts the cladding tube inner surface within the first few percent of burnup. The extra space is provided to preclude undue strain on the cladding from fuel-clad mechanical interaction as the fuel continues to swell and generate fission products.

A liquid metal sodium bond is employed in the Natrium fuel pin and is initially located in the space between the fuel and cladding. The sodium bond enables adequate heat transfer and prevents unacceptable temperatures during operation, especially at beginning of life when the fuel is not in physical contact with the cladding tube. Once the fuel swells, the liquid metal sodium bond is pushed into the upper plenum although a small amount remains in the porosity of the fuel slug.

Each fuel pin is helically wrapped with an annealed HT9 wire to provide lateral pin-to-pin and pin-to-duct spacing along its length and to promote coolant mixing throughout the assembly. The wire is wrapped under a tensile load. The wire is terminated at each end of the pin by pulling it through a through-hole feature in the end caps and welding a fused ball at the end of the wire to restrain it in place as shown in Figure 5-8.

[[ ]](a)(4),ECI

Figure 5-8 Natrium Wire Wrap Fused Ball Termination

5.1.3.2.4 Fuel Pin Bundle

The fuel pin bundle is shown in Figure 5-9 with its hexagonal cross section.

[[ ]](a)(4),ECI

Figure 5-9 Fuel Pin Bundle Cross Section in Fueled Region

Type 1 fuel assemblies contain [[ ]](a)(4),ECI sealed fuel pins packed with triangular pitch spacing. The pins extend from their primary attachment point near the top of the inlet nozzle to just below the handling socket at the top of the assembly. The upper and lower end caps of the wire-wrapped fuel pins in the strip layers are oriented identically to ensure uniform coolant flow across the bundle and proper fit with all attachment hardware. A very tight fit of the fuel pin bundle in the duct is important to achieve such that proper coolant flow is guided to the bundle internals and a minimum amount of coolant flows through the bypass region between the bundle periphery and inner duct wall. Accordingly, the bundle is fixtured and slightly compressed during manufacturing prior to assembling the duct over the bundle.

5.1.3.3 Modules

Physical components within the subsystems are described in Section 5.1.3.2.

5.1.3.4 Constituents

The chemical form of substance during the partial flow blockage event is sodium.

5.1.3.5 Phases

[[

]]$^{(a)(4)}$

5.1.3.6 Geometrical Configurations

The geometrical configuration of sodium during the partial flow blockage event is [[

]]$^{(a)(4)}$

5.1.3.7 Fields

The properties that are being transported during the partial flow blockage event are mass, momentum, and thermal energy of liquid sodium. Thermal energy within the solid structures such as fuel rods (i.e., power generation) and an assembly duct should also be considered.

5.1.3.8 Transport Processes

The following transport and interaction mechanisms need to be considered.

- Heat transfer between solid structures and liquid sodium.
- Properties defining energy transport between constituents and heat structures.

5.1.4 EMDAP Step 4: Identify and Rank Phenomena and Processes

The PIRT is developed by identifying and ranking all processes and phenomena that occur during partial flow blockage. It consolidates expert subjective judgement and objective recommendations from experimentation, analysis, and experience with respect to the FOMs through each phase of a transient.

The PIRT developed in this step is a basis for building and assessing the EM for the partial flow blockage within a fuel assembly. The analyses or assessments that benefit from the PIRT include but not limited to:

- Code capability evaluation
- Code improvements
- Computer code V&V
    - Assessment database evaluation
    - Scaling analysis

- Uncertainty quantification
- Reactor core modeling and calculation

Activities for Step 4: Formalize PIRT for partial flow blockage EM

- The PIRT is examined and documented in a PIRT report.

5.1.4.1 Historical PIRTs for SFRs

Historical PIRTs that have been developed for SFRs or similar liquid metal reactors were reviewed for the Natrium design and are discussed below.

5.1.4.1.1 PIRT for TerraPower Traveling Wave Reactor - Prototype (TWR-P)

Reference [13], "Evaluation of Licensing Basis Events for Analytical Requirements: Pilot Application to Local Flow Blockage Event," summarizes PIRTs for a selected set of AOOs and DBAs occurring in the TWR-P design, which is a pool-type SFR. The importance ranking, State of Knowledge (SOK) ranking, and risk determination were performed for the identified phenomena.

5.1.4.1.2 PIRT for Toshiba 4S (Super-Safe, Small and Simple) Reactor

Reference [14], "Phenomena Identification and Ranking Tables for 4S Beyond-Design-Basis Accidents - Local Faults and Sodium-Water Reaction," summarizes the PIRTs in the Toshiba 4S reactor, which is a pool-type SFR. It considers events of loss of offsite power, sodium leakage from intermediate piping, and failure of a cavity can. The phenomena importance, state of knowledge, as well as the tests and analyses to be implemented in the future are summarized in this report. The PIRTs in the report reflected the experience and knowledge of SFRs in Japan. Design basis events in the PIRT also included local blockage in a fuel assembly.

5.1.4.1.3 PIRT for Initial Important Phenomenon Study on Liquid Metal Reactors

Reference [15], "Phenomena Important in Liquid Metal Reactor Simulations," focused on SFRs because there was more information on those designs. Lists of important phenomena to model to simulate normal operation and transients/accidents were generated. The study leveraged experience from EBR-II that ran for 30 years in Idaho National Laboratory (INL), PRISM concepts, and technology-gap studies from the U.S. Department of Energy. The important phenomena identified in this study are in the PIRT format with rankings. They could be used as the foundation to generate formal PIRTs for the Liquid Metal Reactors (LMRs).

5.1.4.2 PIRT Process

The U.S. NRC used a nine-step PIRT process in developing PIRTs for the Next Generation Nuclear Plant (NGNP) in NUREG/CR-6944 [16]. A PIRT for the partial flow blockage within a fuel assembly is developed following the guidance of this nine-step process.

5.1.4.2.1 PIRT Process Step 1: Issue Definition

- Define the issue that is driving the need for a PIRT.
- An evaluation model is being developed to analyze the partial flow blockage within a fuel assembly. The analysis supports the Natrium construction permit and operating license application.

5.1.4.2.2 PIRT Process Step 2: PIRT Objective

- Define the specific objectives for the PIRT.

- The PIRT objective is to identify safety-relevant phenomena and processes, rank their importance based on pre-established figures of merit, and rank the status of knowledge for each of the phenomena to build a technical base for developing the evaluation model.

5.1.4.2.3 PIRT Process Step 3: Hardware and Scenarios

- Define the hardware and the scenario for the PIRT.
- Hardware is identified in this step as the Natrium systems and components. Two representative event scenarios, [[ ]]$^{(a)(4)}$ are chosen to develop a PIRT. High-level discussions on the event scenarios are provided in Table 5-1 of Section 5.1.1.2.

5.1.4.2.4 PIRT Process Step 4: Evaluation Criteria

- Define the evaluation criterion.
- Evaluation criteria are established in this step to help judge the importance of the phenomena and processes identified in the PIRT process Step 6. The main evaluation criterion is fuel/cladding temperature because it is the measure of fuel failure that directly affects dose consequences. Another evaluation criterion is the sodium coolant temperature in the subchannel. Coolant boiling degrades heat transfer capability leading to core damage. Discussions on how to establish the evaluation criteria are provided in Table 5-2 and Table 5-3 of Section 5.1.2. As the project moves forward, the evaluation criteria are expected to be reviewed to ensure that the Natrium design acceptance criteria are reflected in the PIRT processes.

5.1.4.2.5 PIRT Process Step 5: Current Knowledge Base

- Identify, compile, and review the current knowledge base.
- The PIRT panel members review the supporting materials (the results of PIRT process step 1 through PIRT process step 4), licensing basis events, relevant experimental data, and partial flow blockage analysis results, if available. Especially, the review focuses on phenomena/processes associated with the Natrium design and technology, and the event scenarios identified in PIRT process step 3.

5.1.4.2.6 PIRT Process Step 6: Phenomena Identification

- Identify plausible phenomena, that is, PIRT elements.
- The plausible phenomena and processes are identified in this step.

5.1.4.2.7 PIRT Process Step 7: Importance Ranking

- Develop importance ranking for phenomena.
- Importance rankings of phenomena/processes identified in PIRT process Step 6 are made by the panel members according to a three-level scale shown in
- Table 5-4. This ranking assesses the level of modeling fidelity required to predict the evaluation criteria, identified in PIRT process Step 4, reasonably well based on the current knowledge of the phenomena. The importance ranking, therefore, may be regarded as the relative sensitivity of the evaluation criteria to variability of the parameters associated with the phenomenon being considered.

Table 5-4 Phenomena/Processes Importance Rankings

Ranking	Description
High (H)	The sensitivity of the evaluation criteria to the phenomenon is large.
Medium (M)	The sensitivity of the evaluation criteria to the phenomenon is medium.
Low (L)	The sensitivity of the evaluation criteria to the phenomenon is little or negligible.
The sensitivity of the evaluation criteria is with respect to the expected variability of the expected values.	

5.1.4.2.8 PIRT Process Step 8: Knowledge Level

- Assess knowledge level for phenomena.
- Rankings of the knowledge level of phenomena/processes are made by the panel members according to a three-level scale. The three-level scale is shown in Table 5-5. The knowledge level is determined in an absolute sense that is independent of the associated importance ranking. A knowledge level of high (H) implies additional research on this phenomenon is not necessary even if the importance level is high. Conversely, a knowledge level of low (L) implies that this phenomenon is a priority for additional research, particularly if the importance level is high. A knowledge level of medium (M) implies that research is suggested if the phenomenon is of high importance.

Table 5-5 Knowledge Level Rankings

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

5.1.4.2.9 PIRT Process Step 9: Documentation

- Document PIRT results.
- The activities and results of all the previous steps (PIRT process Step 1 through PIRT process Step 8), including tables of ranked phenomena/processes with their rationales, are documented in this step.

5.1.4.3 Natrium Systems and Components Description

A high-level description of the key systems and components of the Natrium design is included in Sections 5.1.3.1 and 5.1.3.2. Because the plant is still in the preliminary design phase, changes to the system and components are expected. Any changes to these components are planned to be complete prior to TerraPower's submittal of an operating license application, and information will be included in a future licensing submittal.

5.1.4.4 Phenomena Identified for PIRT Meeting

Table 5-6 shows the initial list of important phenomena and description identified for the partial flow blockage within a fuel assembly in the Natrium design.

5.1.4.5 PIRT with Consensus Rankings and Rationales

Table 5-7 summarizes consensus rankings with rationales.

[[

]](a)(4) PIRT items where the SOK is below the Importance Rankings (IRs). Ongoing work in this area due to design review is planned to be complete prior to TerraPower's submittal of an operating license application, and that information will be included in a future licensing submittal.

Table 5-6 Phenomena Identification and Description for Partial Flow Blockage within a Fuel Assembly

[[

]](a)(4),ECI

[[

]]$^{(a)(4)}$

[[

]](a)(4)

[[

]](a)(4)

Table 5-7 PIRT Rankings with Rationales for Partial Flow Blockage within a Fuel Assembly

[[

]](a)(4),ECI

[[

]]^(a)(4)

[[

]](a)(4)

[[

]](a)(4)

[[

]](a)(4)

[[

]](a)(4)

5.2 EMDAP Element 2: Develop Assessment Base

The purpose of this element is to provide a basis for EM development and assessment by acquiring appropriate experimental data relevant to the scenario being considered and ensuring the suitability of experimental scaling. Figure 5-10 shows a diagram of the EMDAP Element 2 [1].

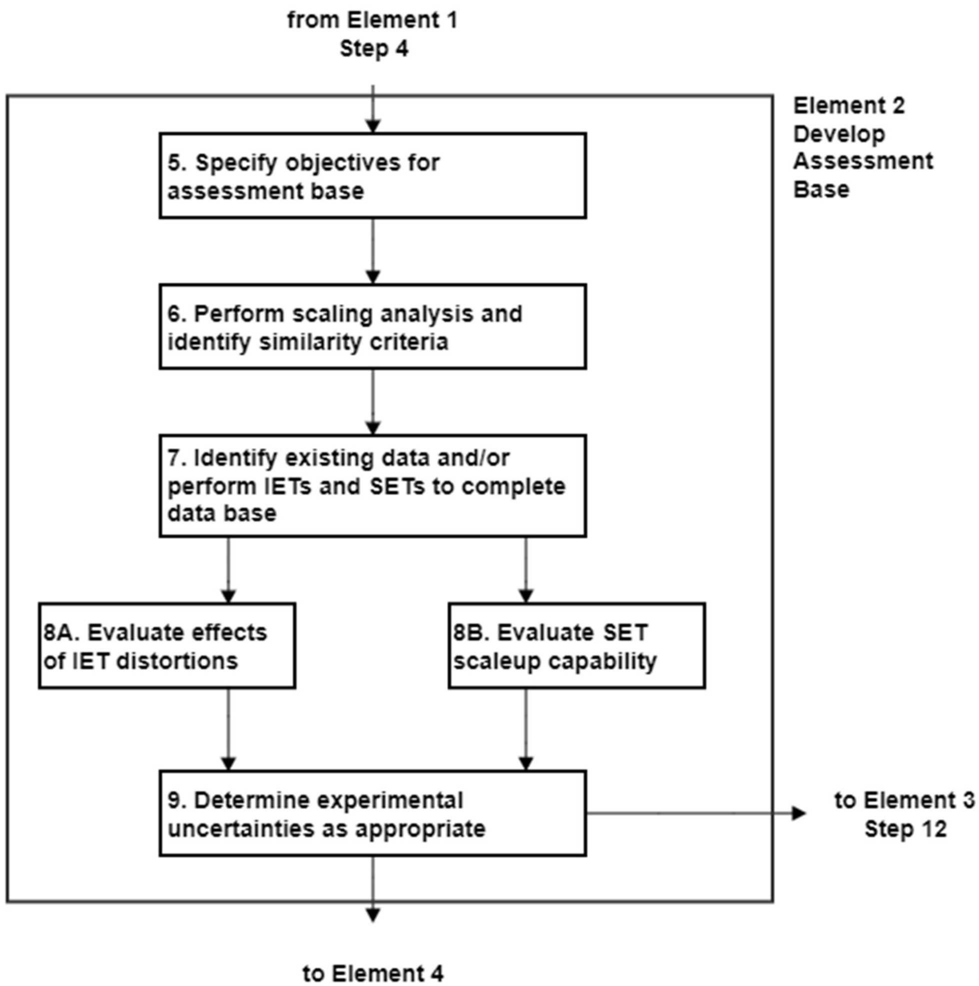

Figure 5-10 Steps in EMDAP Element 2[1]

5.2.1 EMDAP Step 5: Specify Objectives for Assessment Base

The principal need for a database is to provide a basis to assess the EM and develop correlations for numeric, flow anomalies, and field equations (mass, momentum, and energy). This supports the relationships needed to define analytical solutions, time step limitations, consistency, and numerical precision.

A database is developed at this step by obtaining appropriate experimental and plant transient data through the activities of Step 7. A database should include:

- Separate Effect Tests (SETs), Integral Effect Tests (IETs), benchmarks with other codes, plant transient data, and simple test problems.
- New experiment(s) to validate the EM based on the PIRT if needed.

Activities for Step 5: Identify existing data and testing needs for partial flow blockage validation data

- The principal needs for an assessment database are specified in this step.

Report Discussion

The results of this step are summarized in Table 5-14 Phenomena Validation for Partial Flow Blockage within a Fuel Assembly.

5.2.2 EMDAP Step 6: Perform Scaling Analysis and Identify Similarity Criteria

Top-down and bottom-up scaling analyses are conducted to ensure that the data and the models based on those data are applicable to the full-scale analysis of plant transients. Optimum similarity criteria are identified based on important phenomena and processes identified in the PIRT (EMDAP Step 4) and scaling analysis.

Activities for Step 6:

Assess individual model fidelity, accuracy, and scaling for partial flow blockage EM

- Scaling analysis consists of top-down and bottom-up approaches. The top-down scaling analysis evaluates the global system behavior and systems interactions from integral test facilities shown to represent the Natrium design. The top-down scaling analysis is performed by deriving the non-dimensional groups governing similitude between facilities, showing that these groups scale the results among the experimental facilities, and determining whether the ranges of group values provided by the experiment set encompass the corresponding plant- and transient-specific values. The bottom-up scaling analysis is conducted by focusing on localized process behaviors and deriving non-dimensional groups governing similitude between the Natrium plant and the test facility.

Develop similarity criteria for partial flow blockage validation data

- It is difficult to design test facilities that preserve a total similitude between the Natrium plant and the experiments because of many processes and phenomena. Hence, the optimum similarity criteria are identified based on the important processes and phenomena documented in the PIRT and the scaling analysis.
- The experimental facilities providing validation data are identified, and their geometry dimensions, material properties, initial and boundary conditions, and instrumentation recordings are prepared. The related information from the Natrium design is also obtained. Once the required data become available, the mathematic representation (e.g., governing equations) of physical process employed in the evaluation model (computer code) are identified for scaling analysis. For physical processes where distortions are inevitable, it is important to ensure the dimensionless groups for key phenomena fall within a reasonable range. This allows for a

determination on if the distortions are acceptable and the similarities between the experiment and the Natrium design are maintained. In general, these distortions are required to be evaluated for IET data.

5.2.2.1 Scaling Analysis Purpose

Scaling analysis for partial flow blockage is performed to determine non-dimensional parameters and quantify scaling distortions. Data from Oak Ridge National Laboratory (ORNL) [17] and Power Reactor and Nuclear Fuel Development Corporation (PNC) [18] are used for the validation of the partial flow blockage analysis for the Natrium design. Geometric and fluid property differences between the historical data and the Natrium design require scaling analysis to justify the applicability of the data.

5.2.2.2 Scaling Analysis Scope and Overview

The central FOM is the peak cladding temperature (PCT). The PCT is expressed as the summation of three surrogate FOM:

- [[

]](a)(4)

Scaling relations are derived for each of the surrogate FOM, as opposed to the PCT itself, to expand the applicability of the available experimental data.

Four sets of non-dimensional equations are analyzed to determine their associated non-dimensional parameters:

- [[

]](a)(4)

Consistent geometry indicates the geometric ratios are treated as constant. Most critically, the pitch to diameter ratio is held constant. Additionally, the geometric ratios of the wire wrapping are held constant (see Section 5.2.2.3.5 for further discussion). [[

]](a)(4)

5.2.2.3 Scaling Analysis Background Information

This section summarizes supporting information for the scaling analysis.

5.2.2.3.1 Fundamental Units

There are our fundamental units present in this scaling analysis: time(s), length (m), mass (kg), and temperature (K). Consequently, there should be four less non-dimensional parameters than independent variables for each set of non-dimensional relations.

5.2.2.3.2 Reference Values

The reference values provided in Table 5-8 are used to nondimensionalize all equations. [[

]]$^{(a)(4)}$

Table 5-8 Reference Values used for Nondimensionalization

[[

]]$^{(a)(4)}$

5.2.2.3.3 Nomenclature Used for Scaling Analysis

[[

]]$^{(a)(4)}$

[[

]](a)(4)

5.2.2.3.4 Geometric Differences

The key geometric difference between the Natrium design and assessment data is [[ ]](a)(4) (see Equation 5-1). This analysis reports a best estimate and bounding set of scaling distortions. [[ ]](a)(4) as is the case for Natrium configurations when compared to the historical tests as shown in Table 5-9.

[[

]](a)(4)

Table 5-9 Pitch to Diameter and Diameter to Gap Ratios for ORNL, PNC, and Natrium Configurations

[[

]]$^{(a)(4),ECI}$

5.2.2.3.5 Effects of Wire Wrap Pitch on Partial Flow Blockage

The wire wrap pitch also varies among the configurations of interest as shown in Table 5-10. Note the PNC experimental setup used straight wires without a helical pitch.

Table 5-10 Wire Wrap Pitches for ORNL, PNC, and Natrium Configurations

[[

]]$^{(a)(4),ECI}$

[[

]]$^{(a)(4)}$

5.2.2.4 Non-dimensional Independent Parameters

This section contains non-dimensional equations for consistent geometry with diffusion terms, consistent geometry without diffusion terms, variable geometry with diffusion terms, and variable geometry without diffusion terms. Nondimensional parameters are reported for each set of equations.

5.2.2.4.1 Consistent Geometry with Viscous and Conduction Terms

[[

]]$^{(a)(4)}$

[[

]](a)(4)

The boundary conditions for a rod bundle with adiabatic conditions at the duct wall are summarized in Equation 5-7 through Equation 5-14.

[[

]](a)(4)

[[

]]^(a)(4)

5.2.2.4.2 Consistent Geometry without Viscous and Conduction Terms

[[

]]^(a)(4)

[[

]]^(a)(4)

5.2.2.4.3 Variable Geometry with Viscous and Conduction Terms

[[

]]^(a)(4)

(a)(4)

Figure 5-11: Control Volume Used for Variable Geometry Scaling Analysis

[[

]]$^{(a)(4)}$

[[

]](a)(4)

5.2.2.4.4 Variable Geometry without Viscous and Conduction Terms

[[

]](a)(4)

[[

]](a)(4)

5.2.2.5 Scaling Distortion

[[

]](a)(4)

[[ ]](a)(4)

Figure 5-12: Geometric Representation for the Heat Balance of a Subchannel [[ ]](a)(4)

[[

]](a)(4)

[[

]](a)(4)

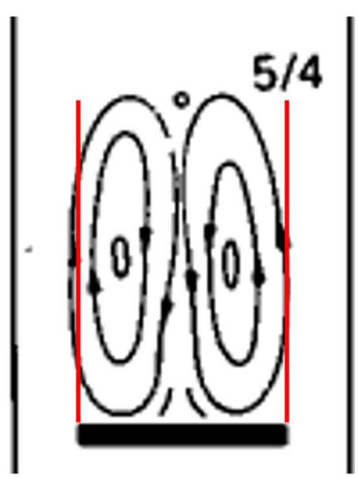

Figure 5-13: Streamlines from 169 Pin SNR Bundle [17] with Red Lines added to Represent Gap Faces

[[

]](a)(4)

[[

]]$^{(a)(4)}$

5.2.2.5.2 Outer Clad Temperature Distortion

The temperature difference between the wake average temperature and the peak outer clad temperature [[

]]$^{(a)(4)}$

(a)(4)

Figure 5-14: Nusselt Number in the Wake behind the Blockage [[

]]$^{(a)(4)}$

[[ ]]$^{(a)(4)}$

ORNL experimental data also shows [[

]](a)(4)

5.2.2.5.3 Inner Clad Temperature Distortion

[[

]](a)(4)

5.2.2.6 Scaling Analysis Conclusions

A summary of the independent variables and non-dimensional parameters is given in Table 5-11.

Table 5-11 Summary of Independent Variables and Non-dimensional Parameters for Sets of Non-dimensional Equations

[[

Set of Non-dimensional Equations	Independent Variable	Non-dimensional Parameters

]](a)(4)

[[

]](a)(4)

[[

]](a)(4)

Table 5-12 Scaling Distortions between the Natrium design and ORNL/PNC Data

[[

]](a)(4)

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

A database is completed by fulfilling the following items:

- Identifying and selecting available experimental, plant, and benchmark data.
- Performing IETs and SETs to complete the database depends on data collection.
- A correlation(s) is developed based on experimental data, if necessary.
- This step can be done in EMDAP Step 5 or in parallel with EMDAP Step 5.

<u>Activities for Step 7</u>: Identify existing data and testing needs for partial flow blockage validation data

- The EM assessment currently intends to focus on the phenomena/process that have high importance ranking with any knowledge ranking (H-H/M/L) and medium importance ranking with low knowledge ranking (M-L). Other medium-ranked phenomena/process are expected to be further examined to determine if additional assessment is needed in conjunction with the assessment to the high importance phenomena.

- Lists of IETs, SETs, and component experimental data were assembled when verification and validation test plans were developed for the Natrium design, and these lists included consideration for partial flow blockage events. The lists present various historical SETs and IETs that were performed at different facilities that are available for validating the partial flow blockage methodology. The available experimental data is examined to see whether the experiments represent some part(s) or the whole of transient scenarios that simulate the important phenomena. If some important phenomena are not covered by the available experimental data, requirements for experiments are developed for the appropriate validation of this evaluation model. A complete assessment matrix is created as part of the maturation work for this methodology.

Based on a review of the tests assembled for those initial test plans, a series of additional tests may be needed to support the validation of this EM. The results of this review are discussed in Section 5.2.3.3.

[[

]](a)(4)

5.2.3.1 Experimental Data Available for Benchmarking Analysis

Available experimental data to support EMDAP Step 7 have been identified for the partial flow blockage methodology applied to Natrium fuel designs. Experiments are matched to the important phenomena identified from the PIRT report that provides context and rationale for the importance rankings (see Sections 5.1.4.4 and 5.1.4.5).

Substantial flow blockage testing was performed to support the Fast Flux Test Facility (FFTF) and Clinch River Breeder Reactor (CRBR) projects that use similar wire-wrapped hexagonal fuel assembly designs along with other overseas Liquid Metal Fast Breeder Reactor (LMFBR) designs. Most of the experimental data is not directly available in the public domain because they were withheld for commercial purposes.

Available assembly and flow blockage experiments for code benchmarking are listed in this section. Data is either partially available in the public domain, within available literature or being pursed through the DOE. Tests from these experiments may be used to assess TerraPower's Mongoose++ subchannel code, which is being developed for the partial flow blockage methodology.

5.2.3.1.1 ORNL 19-Pin Bundle Sodium Experiments

A large-scale sodium flow facility, originally called the Fuel Failure Mockup (FFM) facility, was built in 1970 at ORNL. In 1976, the name of the facility was changed to the Thermal-Hydraulic Out-of-Reactor Safety (THORS) facility. Several experiments have been carried out to assess the effect of partial flow blockages on the local temperature distributions in LMFBR fuel assemblies. These are the most extensive experiments on flow blockage with sodium.

The assemblies were based on FFTF and CRBR designs using hexagonal and scalloped ducted assemblies with 19-pins for unblocked and blocked configurations. Scalloped ducts were used to represent rods within an infinite array and include the wire on the edge rods. The 0.230-inch diameter heater rods are arranged in a tridiagonal configuration using 0.056-inch diameter wire wrapped at a 12-inch axial pitch to maintain rod spacing. The rod pitch to diameter ratio is 1.24. [[

]][(a)(4),ECI]

A wide variety of bundle configurations were tested with sodium coolant as shown in Table 5-13. Blocked and unblocked tests in hexagonal and scalloped duct assemblies were performed over a range of rod powers, flow rates and radial power distributions. An extensive set of tests were performed to determine the effects of partial flow blockages (ORNL-TM-4324 [11] and ORNL-TM-5839 [17]. CFD studies (Reference [23]) of ORNL Bundle 2A tests confirmed results from a subchannel code and identified uncertainties. A summary of the blockage configurations and key findings follow.

Table 5-13 THORS Facility 19-Pin Flow Blockage Configuration

Bundle Identification	Blockage Configuration	Reference
1A	Unblocked scalloped duct assemblies (not used due to several heater failures, rod warping and shifted wire wrap)	ORNL-TM-4670 [24]
1B	Unblocked scalloped duct assemblies	ORNL-TM-4939 [25]
2A	Unblocked hexagonal duct	ORNL-TM-4113 [26]
2B	13- and 24-channel inlet blockage hexagonal duct	ORNL-TM-4324 [11]
3A	6-channel internal blockage scalloped duct	ORNL-TM-5101 [27]
5A	14-channel edge blockage hexagonal duct (rebuilt as Bundle 5B due to early failure of important thermal elements)	ORNL-TM-5003 [28]
5B	14-channel edge blockage hexagonal duct (with and without bypass flow at the duct wall)	ORNL-TM-5003 [28]
5C	Unblocked and power skew hexagonal duct tests	ORNL-TM-5003 [28]

5.2.3.1.1.1 13- and 24-Channel Inlet Blockage in FFM Bundle 2B

FFM Bundle 2 is a 19-rod bundle in a hexagonal duct. The dimensions and configurations of the bundle are similar to those of the FFTF fuel subassembly except that the heated length is 21-inch rather than 36-inch. There is a 3-inch unheated length below the heated section of the rod. The bundle in its original orientation is designated FFM Bundle 2A (ORNL-TM-4113 [26]). The bundle in the inverted orientation for inlet blockage tests is designated FFM Bundle 2B (ORNL-TM-4324 [11]). Testing was conducted with (1) no inlet blockage, (2) 13 channels blocked (channels 1 to 6 and 13 to 19), and (3) 24 channels blocked (channels 1 to 24: all but the peripheral channels).

With the 24-channel inlet blockage plate installed, approximately half of the net flow cross-sectional area was covered. Inlet blockages were centrally located.

[[

]](a)(4)

5.2.3.1.1.2 6-Channel Internal Blockage in FFM Bundle 3A

Bundle 3A of the FFM program was also a FFTF configuration with a scalloped duct. It had six central channels blocked by a non-heat-generating stainless steel device, ¼-inch long, brazed to the central rod.

[[

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5.2.3.1.1.3 14-Channel Edge Blockage in FFM Bundle 5B

Bundle 5B (ORNL-TM-5003 [28]) contained a blockage along one of the hexagonal sides that blocked one-third of the flow area in a 19-pin sodium-cooled electrically heated bundle, which simulates the fuel assemblies of the CRBR. The objective of Bundle 5B was to experimentally determine if an edge blockage will result in sodium boiling. Bundle 5B tests quantitatively assessed the effect of a built-in leak, between the blockage plate and the duct wall on the temperature rises in the wake behind the blockage.

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5.2.3.1.1.4 Recommended Benchmarks

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5.2.3.1.2 ORNL 19-Pin Bundle Water Experiments

The ORNL 19-pin water mockup tests (ORNL-TM-5839 [17] and ORNL-TM-4324 [11]) were performed to determine the effect of blockage geometries on 1) heat transfer coefficient along the rod surface, 2) the extent of the recirculation wake behind the blockage, 3) mass exchange between the wake and the free stream, and 4) the pressure drop in the bundle. Water and a transparent Plexiglass hexagonal shroud allowed for flow visualization. One of the 19-rods is electrically heated, and the others were Plexiglass. The axial length of the wake was determined by introducing air bubbles. Mass exchange rates were based on salt injection as a tracer and conductivity probes. Tests were conducted for 5-, 14- and 24-channel edge blockages as well as 6- and 24-channel central blockages. [[

]][(a)(4)]

Phenomena:

- [[

]][(a)(4)]

5.2.3.1.3 PNC 37-Pin Bundle Sodium Experiments

Sodium tests in a 37-pin assembly with a 24-channel central blockage and 50% edge blockage by Uotani were reported by PNC (Reference [18]). Heated rods were used within the blockage boundary with unheated rods outside the blockage. The blockages were located below a grid spacer. Pressure and temperature distributions were measured at radial and axial locations above the blockage. Miyaguchi (Reference [18]) also presents analytical models for residence time, mass exchange and maximum temperature in the wake region.

Phenomena:

- [[

]][(a)(4)]

5.2.3.1.4 Existing Mongoose Benchmarks

Several unblocked experiments were assessed at TerraPower using Mongoose, and include evaluations of experiments performed by ORNL [26], Toshiba [29], and Westinghouse [30]. Mongoose is the predecessor to Mongoose++, which is selected for the Natrium partial flow blockage methodology.

5.2.3.2 Phenomena Validation Matrix for Existing Data

The above experiments are listed for each phenomenon validated in Table 5-14 below. A basis is provided for conservative modeling or phenomena that are potentially beyond the scope of the methodology. The first four columns are from Table 5-6 and Table 5-7.

Table 5-14 Phenomena Validation for Partial Flow Blockage within a Fuel Assembly

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5.2.3.3 Test Needs

The significant number of experiments conducted to support FFTF, CRBR and other LMFBRs provide sufficient data to validate Mongoose++ for the partial flow blockage method. The tests are sufficient to validate the range of blockages anticipated for the method [[

]]^(a)(4)

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

IET distortions and SET scaleup capability are evaluated in this step.

- IET distortions may arise from scaling compromises (missing or atypical phenomena) in sub-scale facilities or atypical initial and boundary conditions in all facilities. The effects of the distortions are evaluated in the context of the experimental objectives determined in EMDAP Step 5.
- SET scaleup capability is evaluated based on important phenomena and processes identified in the PIRT (EMDAP Step 4).
- Scaleup capability of an analysis code is evaluated by comparing modeling requirements and code capabilities.
- This step can be done in or parallel to EMDAP Step 6.

Activities for Step 8: Assess individual model fidelity, accuracy, and scaling for partial flow blockage EM

- To assess the individual model (typically derived from scaled-down SET) fidelity, the scale-up capability and the data applicability to full-scale conditions are required. The individual models, such as closure correlations, that are adopted and programmed in the evaluation model are identified. A technical rationale and justification of using these closure correlations are provided to confirm that the dominant parameters represented by the individual models and correlations reflect the ranges expected in the Natrium design and transient scenarios.
- The effect of IET distortions is evaluated in this step through this activity.

Report Discussion

Portions of this activity are described in the work performed for EMDAP Step 6, Section 5.2.2. Ongoing work in this area is planned to be complete prior to TerraPower's submittal of an operating license application, and that information will be included in a future licensing submittal.

5.2.5 EMDAP Step 9: Determine Experimental Uncertainties as Appropriate

Uncertainties arise from measurement errors, experimental distortions, and other aspects of experimentation. Based on the experimental uncertainties, it is determined whether the experimental data is qualified to be used in model assessment. Discussions about how to evaluate uncertainties are included when the uncertainties in the experiments (especially legacy experiments in 50's or 60's) are unknown or difficult to determine.

Activities for Step 9: Establish experimental uncertainties for partial flow blockage EM

- Experimental uncertainties arise from measurement errors, experimental distortions, etc. Available experimental data (IETs, SETs, and component experiments) are reviewed and experimental uncertainties are determined based on the review.
- The absolute magnitudes (and the relative magnitudes) of experimental uncertainties are identified for key experimental data, such as FOMs. The magnitudes of the experimental uncertainties are used to determine whether the experimental data is still appropriate for model assessment. Some experimental data should be eliminated from the EM development and evaluation if their quantified uncertainties are too large compared to the requirements.

An initial list of parameters and uncertainties that might require confirmation (to be obtained using qualified existing data, fuel and material development, qualification programs, manufacturing data and/or new tests) if considered significant follows):

- Assembly flow uncertainty: Accounts for uncertainties in the assembly flow due to flow maldistribution in the lower and upper plena, internal structure tolerances, orificing uncertainties, and flow rate uncertainties.
- Reactor physics modeling: Accounts for uncertainties in power distribution by neutronic modeling approximations. This is expected to be informed by analysis and validation effort under neutronics methodologies.
- Wire wrap orientation: Accounts for flow uncertainty induced by variations in wire wrap orientation.
- Film heat transfer coefficient: Accounts for uncertainty in film heat transfer coefficient.
- Fuel-cladding eccentricity: Accounts for uncertainty in fuel pin and cladding concentricity which can result in elevated cladding temperature gradients (impact of uncertainties is likely to be evaluated through analysis but the eccentricity used in these analyses should be informed by tolerance data and specifications).
- Cladding thickness and fuel pin pitches: Accounts for effects on the cladding temperature due to manufacturing tolerances.
- Fuel heat capacity and conductivity: Accounts for uncertainty in fuel heat transport.
- Fissile fuel maldistribution: Accounts for fuel fissile manufacturing tolerances (local inhomogeneity, fuel pin and assembly misload).

Uncertainty quantification may be conducted in collaboration with Argonne National Laboratory (ANL).

5.2.5.1 Experimental Uncertainties for ORNL FFM Tests

Experiments to support FFTF and CRBR such as those at the ORNL FFM facility in the 1970s were performed prior to EMDAP from Regulatory Guide 1.203 (Reference [1]) and best-estimate plus uncertainty methods. They also pre-date ASME NQA-1-2015 quality assurance guidance although 10 CFR 50 Appendix B existed, and quality assurance was applied (Reference [31]). These vintage experiments typically reported uncertainties for each measurement type with instrument and acquisition system accuracy information. They did not quantify other contributors to total uncertainty such as the impact of potential experimental distortions. Therefore, engineering judgement is used to assess the impact of experimental distortions and decide whether total uncertainty is acceptable for each test series.

Experimental uncertainties are evaluated for ORNL FFM test series for Bundle 3A with a six-channel, central blockage (Reference [27]) and Bundle 5B with a 14-channel, edge blockage (Reference [28]).

All the high and medium ranked phenomena from the PIRT are evaluated to determine related parameters in the experiments affecting the figures of merit. These related parameters are used later to quantify the experimental uncertainties and impact on the figures merit. This approach provides results consistent with Regulatory Guide 1.203 Appendix B Section 1.2.5 (Reference [1], Page B-8).

5.2.5.1.1 Phenomena Related Parameters for ORNL FFM Tests

Table 5-15 evaluates PIRT phenomena (Table 5-6) for the ORNL FFM Bundle 3A and 5B experiments to determine related parameters affecting the figures of merit. Only one table is needed because the test series primarily differ by the blockage size and location. The same phenomena and related parameters apply to each test.

Table 5-15 Phenomena and Related Parameters for ORNL FFM Bundle 3A and 5B Tests

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[[

]](a)(4)

5.2.5.1.2 ORNL FFM Bundle 3A with a Six-Subchannel Center Blockage

Experimental uncertainties for the ORNL FFM Bundle 3A tests with a six-subchannel center blockage are shown in Table 5-16 for three runs with varying power and flow. [[

]](a)(4)

Table 5-16 Experimental Uncertainty for ORNL FFM Bundle 3A with a Six-Subchannel Center Blockage[1]

[[

]](a)(4)

The maximum experimental uncertainties from the three sampled runs above are listed in Table 5-17 for each related parameter. [[

]](a)(4)

Table 5-17 Experimental Uncertainty Impact for ORNL FFM Bundle 3A with a Six-Subchannel Center Blockage

[[

Parameter	Maximum Uncertainty	Figure of Merit

]](a)(4)

[1] Temperature data was measured in Fahrenheit and converted to Celsius.

[[

Parameter	Maximum Uncertainty	Figure of Merit

]](a)(4)

5.2.5.1.3 ORNL FFM Bundle 5B with a 14-Subchannel Edge Blockage

Experimental uncertainties for the ORNL FFM Bundle 5B tests (Reference [28]) with a 14-subchannel edge blockage are shown in Table 5-18 for three runs with varying power and flow. [[

]](a)(4)

Table 5-18 Experimental Uncertainty for ORNL FFM Bundle 5B with a 14-Subchannel Edge Blockage[2]

[[

]](a)(4)

[2] Temperature data was measured in Celsius.

[[

]](a)(4)

The maximum experimental uncertainties from the three sampled runs above are listed in Table 5-19 for each related parameter. [[

]](a)(4)

Table 5-19 Experimental Uncertainty Impact for ORNL FFM Bundle 5B with a 14-Subchannel Edge Blockage

[[

Parameter	Maximum Uncertainty	Figure of Merit

]](a)(4)

5.2.5.1.4 Experimental Distortions for the ORNL FFM Tests

The total uncertainty includes the impact of experimental distortions in addition to measurement uncertainties. As noted above, these vintage experiments did not quantify other contributors to total uncertainty such as experimental distortions. Therefore, engineering judgement is used to assess the impact of experimental distortions and decide whether total uncertainty is acceptable for each test series. The following potential distortions were identified:

- [[

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[[

]][(a)(4)]

5.2.5.2 Conclusion

The measurement uncertainties for the figures of merit [[ ]][(a)(4)] therefore, the ORNL FFM tests series are acceptable for validating the partial flow blockage method. This conclusion is also supported by use of ORNL FFM tests for CRBRP and FFTF licensing and FFTF operation.

5.3 EMDAP Element 3: Develop Evaluation Model

An EM is a collection of calculational devices (codes and procedures) developed and organized to meet the requirements established in EMDAP Element 1. This element describes the steps for developing the desired EM. As described earlier, Mongoose++ is used as the principal analytical computer code to assess partial flow blockage. Hence, the steps of Element 3 for developing the computer code are skipped or simplified. Figure 5-15 shows a diagram of EMDAP Element 3 [1].

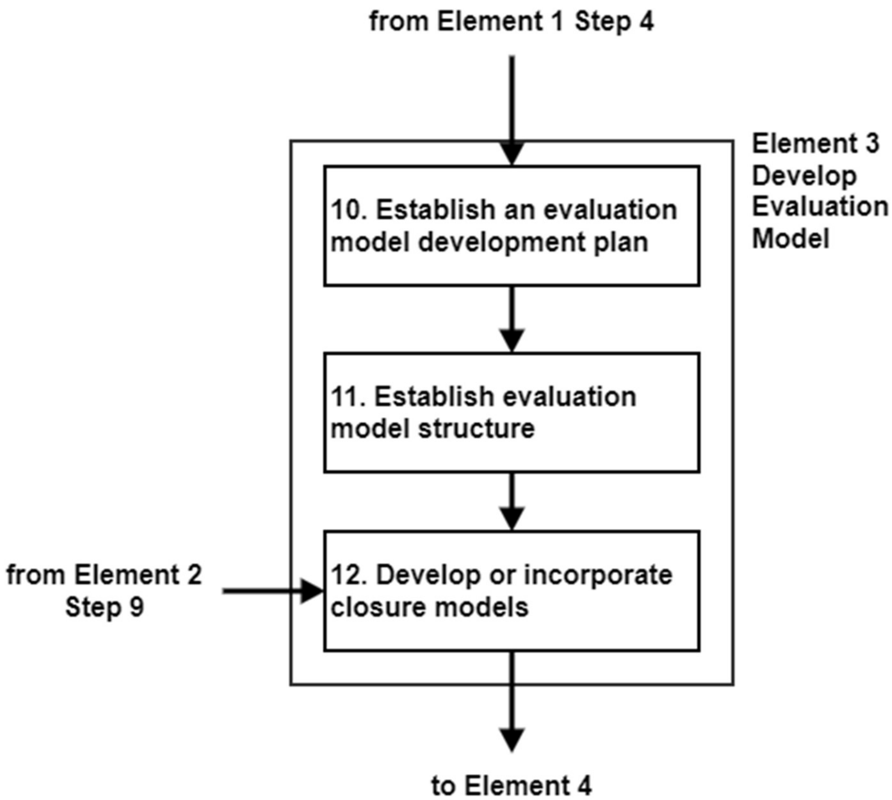

Figure 5-15 Steps in EMDAP Element 3 [1]

5.3.1 EMDAP Step 10: Establish an EM Development Plan

The following aspects are considered in establishing an EM plan for partial flow blockage.

- Since TerraPower's Mongoose++ is used as the subchannel analysis computer code to assess partial flow blockage, establishing a development plan for the main analytical code is skipped and this task is replaced with code selection.
- If any significant deficiency is discovered, the selected code is revised to eliminate it. For example, subchannel crossflow assumptions may need to be addressed for the more dominate lateral flows in the wake zone behind the flow blockage.
- Quality assurance and configuration control procedures for Mongoose++ that meet EMDAP requirements are established in TerraPower's Software Management Procedure (SMP).

<u>Activities of Step 10</u>:

Establish partial flow blockage EM development plan

- Internally developed software uses the approved TerraPower procedures for software development and Quality Assurance (QA). The source code for Mongoose++ is maintained under a revision control system and checks are performed prior to accepting changes to the software. Formal processes for automating the build and test methods are implemented and the scope of automated testing and benchmarking will be extended.

It is possible that some other code(s) will be run alone or coupled with the main analytical computer code to simulate the 3D fluid behavior in the pool and/or near the partial flow blockage. Development plans are not necessary for the other codes because already existing codes [[ ]](a)(4) can be used for this purpose if necessary. Further discussion regarding the possible use of other codes is provided in EMDAP Step 11.

However, a general development plan of the EM for partial flow blockage analysis is established and this plan specifies basic principles of the EM including:

1. Design specifications for the main analytical computer code,
2. Documentation requirements,
3. Programing standards and procedure,
4. Transportability requirements,
5. Quality assurance procedure,
6. Configuration control procedures, and
7. Associated general criteria/principal design criteria to be demonstrated by this method.

This plan establishes the link between QA level, commercial grade dedication, code selection, development specifications, and deliverables.

Perform code(s) selection for partial flow blockage EM

As mentioned above, the main analytical computer code will be Mongoose++. Four major criteria are considered in the main analytical computer code selection as shown below:

1. Requirements for code capabilities,
2. Software quality assurance pedigree,
3. Code experience, and
4. Potential additional usage.

<u>Report Discussion</u>

The Quality Assurance Program Description (QAPD) TP-QA-PD-0001 [32] and the SMP establish the generic QA requirements and processes for the Natrium design and they comply with the applicable requirements of ASME NQA-1-2015, 10 CFR 50 Appendix B, 10 CFR Part 21, and Regulatory Guide 1.28 [33]. The existing TerraPower QA programs are sufficient to establish QA controls for computer codes that perform safety-related or non-safety-related applications. Should any deficiency be found in these existing QA documents or further elaborated procedures are required, they can be developed to meet the practical needs.

A manual for Mongoose++ is available and will be updated to describe models and inputs implemented for partial flow blockage.

5.3.1.1 Modeling Choices

The safety analysis of partial flow blockage is performed with respect to the consequences and detectability of the flow blockages. Thus, calculations of the peak cladding temperature within the incident fuel assembly and temperature distribution at the exit of the fuel assembly are important parameters. In general, the following steps are considered for the partial flow blockage analysis:

- Evaluate effects of location, size, shape, and porosity of local blockage to identify the limiting case resulting in the highest peak cladding temperature.
- Investigate thermal-hydraulic characteristics for the limiting case with respect to the peak cladding temperature, coolant temperature, and temperature rise at the exit of the fuel assembly.

Many computer codes have been developed for predicting the behavior of SFR core with wire-wrapped rod bundles under normal and abnormal transient conditions. The subchannel approach is mainly used in this type of analysis.

5.3.1.1.1 Subchannel Approach

It is recognized that the subchannel analysis technique can be used to provide reasonable, three-dimensional representation of the thermal-hydraulics and heat transfer conditions within a pin bundle. [[

]]$^{(a)(4)}$

TerraPower used the Mongoose code based on the subchannel approach for thermal-hydraulic design of Traveling Wave Reactor® (TWR) core. [[

]]$^{(a)(4)}$

Mongoose has been revised to Mongoose++ and is being modified for flow blockage analysis application by [[

]]$^{(a)(4)}$

Mongoose++ benchmark and validation analysis are being performed with existing experimental data sets of the partial flow blockage. Ongoing work in this area is planned to be complete prior to TerraPower's submittal of an operating license application, and that information will be included in a future licensing submittal.

5.3.1.2 Code Selection for the Partial Flow Blockage Evaluation Model

There are many code candidates designed for liquid metal cooled reactor applications. Code modeling capabilities are summarized with regards to the partial flow blockage PIRT. Code availability and computational workload are also considered. Mongoose++ was selected as the primary code for the partial flow blockage analysis.

5.3.1.2.1 Code Identification, Description, and Comparison

The codes identified in Table 5-20 represent all subchannel analysis candidates that could either fully or partially model the partial flow blockage phenomena.

Subchannel analysis codes: Subchannel analysis codes are among the TH codes that focus specifically on the subassembly analysis including the meshing and boundary conditions. The subchannel analysis framework allows for a straightforward incorporation of a variety of specialized closure relations, [[
]]$^{(a)(4)}$ The subchannel analysis codes listed in Table 5-20 are the potential candidates for the partial flow blockage evaluation model. Although there are a variety of subchannel analysis codes in the literature, the listed codes in Table 5-20 are developed specifically for SFR subassembly analysis [[

]]$^{(a)(4)}$

5.3.1.2.2 Evaluation Matrix

An evaluation matrix is constructed in Table 5-21 to summarize the codes modeling capabilities of the pertinent phenomena. The phenomena/process in Table 5-21 follow the formalized PIRT. As described in Table 5-22, "X" indicates the code can effectively and efficiently model the corresponding phenomena, while "N" entry signifies the code is unable to model the phenomena. Due to a variety of nuances, a binary evaluation of each codes ability to model a phenomenon would fail to capture key details and likely be misleading. The use of qualitative descriptors such as “low fidelity” and “mid fidelity” are based upon code documentation and engineering judgement. The "unknown" label is used for older codes where some of the more obscure features are not readily available.

Table 5-20 Summary and Description of Codes for Modeling Subchannel Analysis in SFR

[[

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Table 5-21 Evaluation* of Code Ability to Model Phenomena within PIRT for Partial Flow Blockage

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]][(a)(4),ECI]

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]](a)(4)

* Evaluation labels used in this table are described in Table 5-22.

Table 5-22 Evaluation Label Used in Table 5-21

Label	Description
X	Able to calculate the phenomena accurately and efficiently.
N	Not able to model the phenomena.
Low fidelity	Uses reduced order model. Often used to streamline calculations by simplifying lower length scale calculations.
Mid fidelity	A reasonable model is present but is lacking in fidelity compared to other codes.
Computationally cumbersome	The code can model the phenomena, but at high computational cost, such as the modeling of full assemblies using CFD codes.
Unorthodox	The phenomena can technically be modeled by an unorthodox application of the code, but such methods are often outside the original scope of the code making verification and validation difficult.
Unknown	For codes long out of development, the documentation is scarce for more some of the more obscure phenomena.
Unnecessary	The phenomena are not necessary to be modeled according to the EM structure. For instance, in terms of porosity, the limiting condition is an impermeable blockage. Hence permeability and porosity modeling will not be undertaken.
N/A	Not Applicable. While all potentially impactful phenomena need to be considered in the PIRT, many will be justified as negligible prior to analysis and will not require modeling.

5.3.1.2.3 Code Availability and Computational Workload

In addition to modeling capabilities, the code selection process is governed by code availability (Table 5-23). The code availability is based on executable accessibility. Many subchannel codes historically used for subchannel blockages in LMFBR applications are not available. Computational resources are also considered in the code selection process.

Table 5-23 Code Availability and Computational Workload

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5.3.1.2.4 Mongoose++ Selection

Based on the outcome of the evaluation matrix in Table 5-21, Mongoose++ is the recommended code. Stated concisely, the partial flow blockage analysis requires a liquid metal based subchannel analysis code with the ability to model blockages. Due to code availability, Mongoose++ is the obvious choice. [[

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Table 5-21 also shows Mongoose++ to have [[

]]^(a)(4)

5.3.1.2.5 Mongoose++ Code Development in Support of Partial Flow Blockage

General development of Mongoose++ is ongoing, with specific attention being devoted to [[ ]]^(a)(4) The following phenomena are being investigated. [[

]]^(a)(4)

5.3.1.2.5.1 Cross Flow at Wake Boundary Edge

[[

]]^(a)(4)

5.3.1.2.5.2 Enthalpy Mixing within or near the Wake Region

[[

]]^(a)(4)

5.3.1.2.5.3 Heat Transfer Coefficients within the Wake Regions

[[

]]^(a)(4)

5.3.1.2.5.4 Local Cladding Temperature Variations within a Subchannel

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]]^(a)(4)

[[

]](a)(4)

5.3.1.2.5.5 Wire Forces/Imposed Sweeping Flow

[[

]](a)(4)

5.3.1.2.5.6 Axial Insulation within Blockage

At present, Mongoose++ allows heat to pass via axial conduction through the blockage. [[ ]](a)(4)

5.3.2 EMDAP Step 11: Establish EM Structure

The following aspects are considered in establishing the EM structure:

- Including the structure of the individual component calculational devices, as well as the structure that combines the devices into the overall EM.
- Integrating the calculational codes into the overall EM. This work is discussed and documented to determine a safety analysis computer system.

Mongoose++ is used as the computer code to assess partial flow blockage. The six ingredients are available in the code manual and are discussed in the next subsection. As mentioned above, however, the selected code is revised to eliminate any significant shortcoming(s).

The structure of the safety analysis computer code system is established by specifying in detail how the analytical code interacts with other codes in other methodologies. Figure 5-16 shows key interfaces between this EM and other methodologies that are necessary to assess [[ ]](a)(4) which are beyond the scope of this EM. The partial flow blockage methodology provides steady state assembly temperatures and flows for the flow blockage to the LBE with fuel failure methodology, which also receives inputs from other methodologies.

The interactions between this EM and other methodologies described in Figure 5-16 are not final and they will be updated as the Natrium design and methodologies mature.

The selection of the main analytical computer code, determination of the safety analysis computer code system, and determination of the coupled codes are made in this EMDAP step and updated as the Natrium design and the EM mature.

Ongoing work in this area is planned to be complete prior to TerraPower's submittal of an operating license application, and information will be included in a future licensing submittal.

Activity of Step 11 Establish partial flow blockage EM structure

- Two kinds of EM structures are considered, the structure of the analytical code and the structure of the safety analysis computer code system. The structures of the analytical code have already been established for Mongoose++.

Report Discussion

A theory manual for Mongoose++ is available for discussion of the six ingredients. The structure of the safety analysis computer code system and the interactions between the main analytical computer code and other codes in other methodologies are discussed in detail in this topical report.

(a)(4)

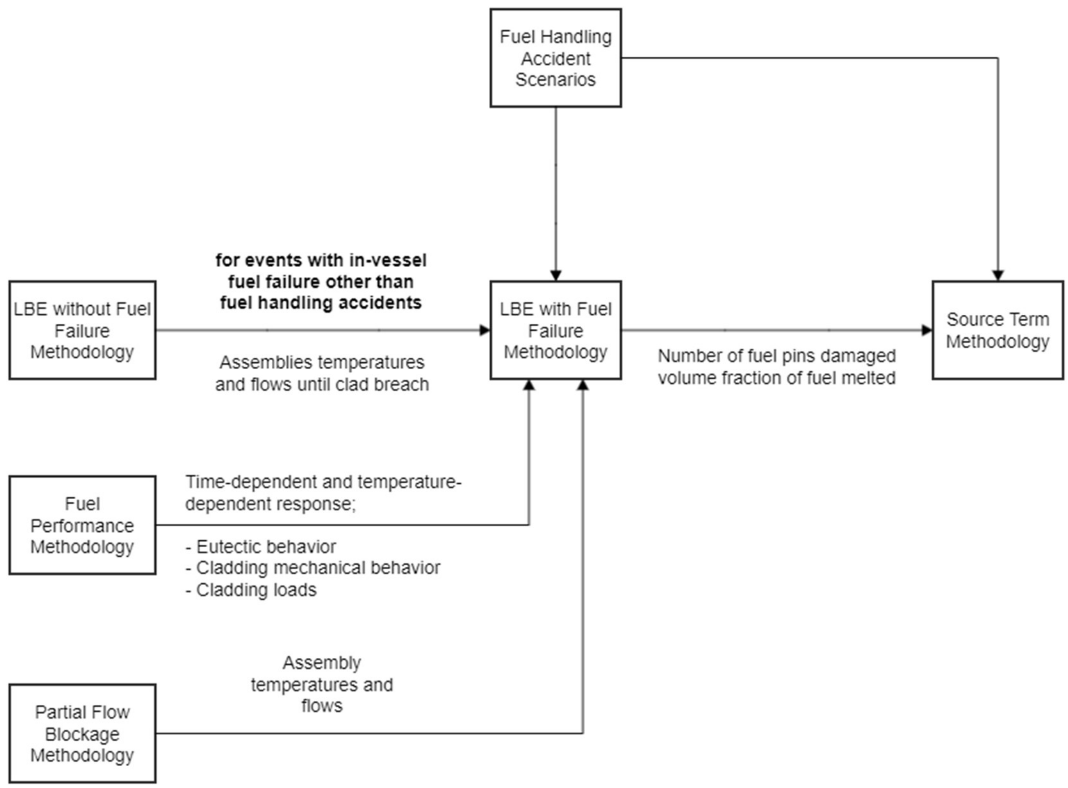

Figure 5-16 Interfaces of Partial Flow Blockage Methodology with Other Important Methodologies

5.3.2.1 Structure of Mongoose++

The Mongoose++ subchannel code is described here according to the six ingredients specified in Regulatory Guide 1.203 (Reference [1]). A more granular description is available in the Mongoose++ theory manual. The definitions of the six ingredients according to Regulatory Guide 1.203 (Reference [1]) are given below.

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.

5.3.2.1.1 System Components

The partial flow blockage scope is limited to a single assembly. All proposed blockages [[

]](a)(4) The assembly is selected to be limiting from a PCT perspective, specifically regarding assembly power, assembly mass flow, and inlet temperature. [[

]](a)(4)

The pertinent components of the single assembly for subchannel analysis are given in Table 5-24. Components outside the typical spatial domain of subchannel analysis, such as inlet nozzles and shield slugs, are excluded. When the excluded components operate properly (i.e., no structural damage), they do not have significant impact on flow structures in blocked fueled regions. Any failure to these component (i.e., blockage in the inlet nozzle) is outside the scope of the partial flow blockage EM.

Table 5-24 System Components for Partial Flow Blockage Evaluation Model

Component	Description
Fuel slug	U-10Zr fuel rod with standard thermal conductivity and volumetric heat capacity properties. The fuel is subject to enforced linear heat generation rates.
Sodium bond	Sodium bond is modeled as a conductivity parameter between fuel and cladding.
Cladding	HT9 cladding with standard thermal conductivity and volumetric heat capacity properties.
Rod plenum	Rod plenum is modeled as a section of rod without fuel and the accompanying heat generation rate.
Wire wrap	Helical wire wraps are incorporated to increase thermal transport via sweeping and mixing crossflow.
Inner subchannel	Inner subchannels are comprised of all subchannels that do not share a boundary with the assembly duct.
Edge subchannel	Adjoined to assembly duct but exclude corner subchannels.
Corner subchannel	Reside in the six corners of the hexagonal assembly.
Assembly duct	Surrounding structure which houses the assembly.

5.3.2.1.2 Constituents and Phases

The scope is limited to liquid sodium, fuel, and cladding. [[

]](a)(4) The subassembly requirements

establish a subcooled margin during normal operation. [[

]](a)(4)

5.3.2.1.3 Field Equations

The field equations for the coolant include conservation of mass, axial and lateral momentum, and energy applied to axial control volumes within each subchannel for single phase sodium. In addition, all relations include temporal terms to allow for transient modeling. Conservation of mass includes axial and lateral mass transfer. Conservation of axial momentum contains axial and lateral transfer of axial momentum, turbulent eddy momentum transfer between subchannels, wall friction, gravity, and the axial pressure gradient. Conservation of lateral momentum includes axial transfer of lateral momentum, gap resistance, and the lateral pressure gradient. Conservation of energy contains convective heat fluxes, axial and transverse heat conduction, sweeping and mixing crossflow energy transfer, and volumetric heating for gamma heating.

The fuel and cladding are governed by [[

]](a)(4)

5.3.2.1.4 Closure Relations

Mongoose++ is a subchannel code and thermal hydraulic system code (high reliance on closure relations) in terms of the use of closure relations to assist in solving the mechanistic physics. Closure relations used in Mongoose++ are described in Table 5-25.

Table 5-25 Closure Relations within Mongoose++

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]](a)(4)

[[

]](a)(4)

5.3.2.1.5 Numerics

The field equations are implemented into a finite volume scheme. Conservation of mass and energy are integrated over an axial control volume comprised of an axial segment of a subchannel. Conservation of axial momentum is applied to a similar axial control volume that is axial offset by one half of the volume axial length, in accordance with a staggered grid. Conservation of transverse momentum is applied to a smaller gap centered axial control volume that is axially aligned with the axial control volume used for conservation of axial momentum.

[[

]]$^{(a)(4)}$

5.3.2.1.6 Additional features

[[

]]$^{(a)(4)}$

5.3.2.2 Supporting Reactivity Feedback Calculations

A blockage near the axial center of selected assembly near the core center may cause an increase in net reactivity. [[

]]$^{(a)(4)}$

[[

]](a)(4)

5.3.2.3 Mongoose++ Partial Flow Blockage EM within a Natrium Assembly

The active fuel region of Natrium assembly is modeled for the partial flow blockage EM. In accordance with assumptions stated in Section 3.1, a planar type of blockage is enforced. The key phenomena outlined in the PIRT for partial flow blockage are modeled with sufficient fidelity in the Mongoose++ simulations. The model entails enforcing a blockage in the blocked subchannels and obtaining the maximum cladding temperature rise at equilibrium or steady state conditions. Analyses are performed for DBEs, BDBEs, DBAs, and OQEs. These events vary in the number of blocked subchannels and in the level of conservatism as shown in Table 5-26.

Table 5-26 PTP1/DBE/BDBE/DBA/OQE Problem Specifics

[[

Event Type	Number of Blocked Subchannels	Level of Conservatism

]](a)(4)

Since the EM must be bounding for all assemblies within the Natrium core, a limiting assembly is constructed from fuel design limits. [[

]](a)(4),ECI

The aim of the partial flow blockage EM is to determine whether the PCT remains below the screening criteria as provided in Table 5-2. The assembly parameters are specified in Table 5-27. The Natrium assembly rod parameters and assembly schematic are given in Table 5-28 and Figure 5-9, respectively.

Table 5-27 Natrium Assembly Parameters

[[

Parameter	Value

]](a)(4),ECI

[[

]](a)(4)

Table 5-28 Natrium Assembly Rod Parameters

[[

Parameter	Type 1 Fuel

]]$^{(a)(4),ECI}$

5.3.3 EMDAP Step 12: Develop or Incorporate Closure Models

Closure relationships or models describe a specific process during a plant transient and are developed and/or incorporated in the principal analytical computer code, if needed.

- Closure models are developed mostly based on the results of SETs as well as on the results of IETs on rare occasions.
- The developed models are incorporated into the main analytical computer code(s).
- Closure models or relationships within Mongoose++ subchannel code are provided in Table 5-25 above.

Activity of Step 12: Perform code(s) selection for partial flow blockage EM

- Closure models used in Mongoose++ are described in Table 5-25. Although the title of the activity does not explicitly mention closure models, the additional closure models or relationships are developed and incorporated into the main analytical computer code of Mongoose++, if needed, through this activity.

5.3.3.1 Conservative Modeling of Heat Transfer in the Wake Region behind the Blockage

The partial flow blockage semi-empirical model will be incorporated within Mongoose++ [[

]]$^{(a)(4)}$ The model is comprised of four components:

[[

]]$^{(a)(4)}$

5.3.3.1.1 Nomenclature Used for Developing Conservative Heat Transfer Model

[[

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5.3.3.1.2.1 Historical Analysis of Wake Region

The length of the wake region, which is defined as the distance from the blockage plate to the rearward stagnation point, has been one of the focuses of past research by ORNL [17], PNC [18], and Westinghouse [19]. The results are reported in terms of the ratio of the wake length to the blockage diameter as shown in Table 5-29.

Table 5-29 Experimentally Measured Wake Lengths to Blockage Diameter Ratio

Study	**Wake Length to Blockage Diameter Ratio**		
	Central Single-subchannel Blockage	Central Blockage	Edge Blockage
ORNL (Reference [17], Page 71)	N/A	1.5 - 4	2 - 5
PNC (Reference [18], Page 62)	N/A	2	4
Westinghouse (Reference [19], Page 2)	2.7	2.4	N/A

The ORNL data determined the wake length to be a function of the blockage Reynolds number and blockage diameter, as shown in Equation 5-48 (Reference [22], Page 163). The wake length is generally understood to be independent of the blockage plate thickness, provided the plate is relatively thin. Wake length to diameter ratios versus blockage Reynolds number for a variety of blockage sizes and types are shown in Figure 5-17.

Equation 5-48
$$\frac{L}{D_b} \propto \left(\frac{D_b u_\infty}{\nu}\right)^{0.28}$$

- L is the wake length, D_b is the equivalent blockage diameter defined as $\sqrt{l_a l_w}$, and l_a and l_w are characteristic lengths of the blockage cross section defined in ORNL documentation (Reference [17], Page 68).
- u_∞ (V in Figure 5-17 from ORNL documentation) is the free stream velocity.
- ν is the kinematic viscosity.

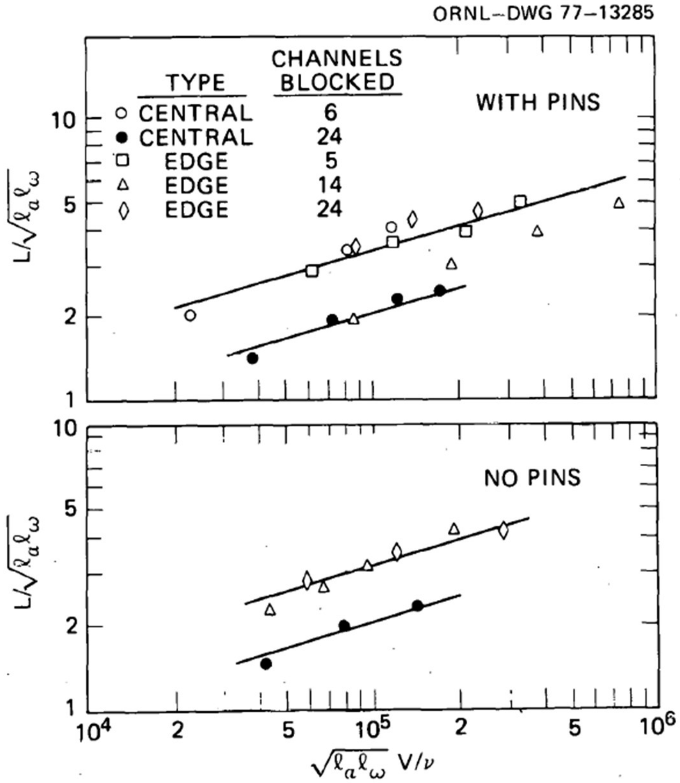

Figure 5-17 Wake Length to Blockage Diameter Ratio versus Blockage Reynolds Number from ORNL (Reference [17], Page 71)

5.3.3.1.2.2 Semi-Empirical Model Implementation on Wake Region

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(a)(4)

Figure 5-18 [[

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5.3.3.1.3 [[

]]$^{(a)(4)}$

5.3.3.1.3.1 Historical Analysis to the Energy Transport

The relevant historical analysis to the energy transport via mixing in the semi-empirical model includes the "negative bundle" analysis by Kirsch (Reference [10], Page 50), the ORNL residence time model (Reference [17]), and local flow blockage experiments by PNC (Reference [18]).

Kirsch Negative Bundle

Kirsch (Reference [10], Section 4.1.1) performed a scaling analysis [[

]]$^{(a)(4)}$

The "negative bundle" experiment included a flowing tube of sodium with an internal object that was shaped to mimic a fuel bundle. The outer surface of the bundle was heated, and four of the six subchannels were blocked. The temperature difference between the blocked and unblocked channels were then used to quantify the mixing coefficients between channels.

Calculations within the "negative bundle" experiment [[

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ORNL Residence Time Model

A derivation of the ORNL residence time model is presented that is similar to the theoretical framework outlined in ORNL documentation (Reference [17], Page 76). [[

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]](a)(4)

PNC Mixing Mass Exchange Per Wake Interfacial Area

As shown in Figure 5-19, PNC (Reference [18]) performed an [[

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(a)(4)

Figure 5-19 [[

]]$^{(a)(4)}$ PNC Experimental Analysis [18]

5.3.3.1.3.2 Semi-Empirical Model Implementation on the Energy Transport

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]][(a)(4)]

Table 5-30 Mixing Coefficients and Accompanying Relevant Information from Salt Concentration Measurements from ORNL THORS Water Mockup

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5.3.3.1.4 [[

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Figure 5-20 Nusselt Number in the Wake behind the Blockage [[
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5.3.3.1.5 Local Wake Spatial Factor

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5.3.3.1.5.1 Historical Analysis on Local Wake Spatial Factor

The ORNL THORS 3A experiments (References [11], [17], and [27]) noted a wide variation in the cladding temperatures within the wake region as shown in Figure 5-21. [[

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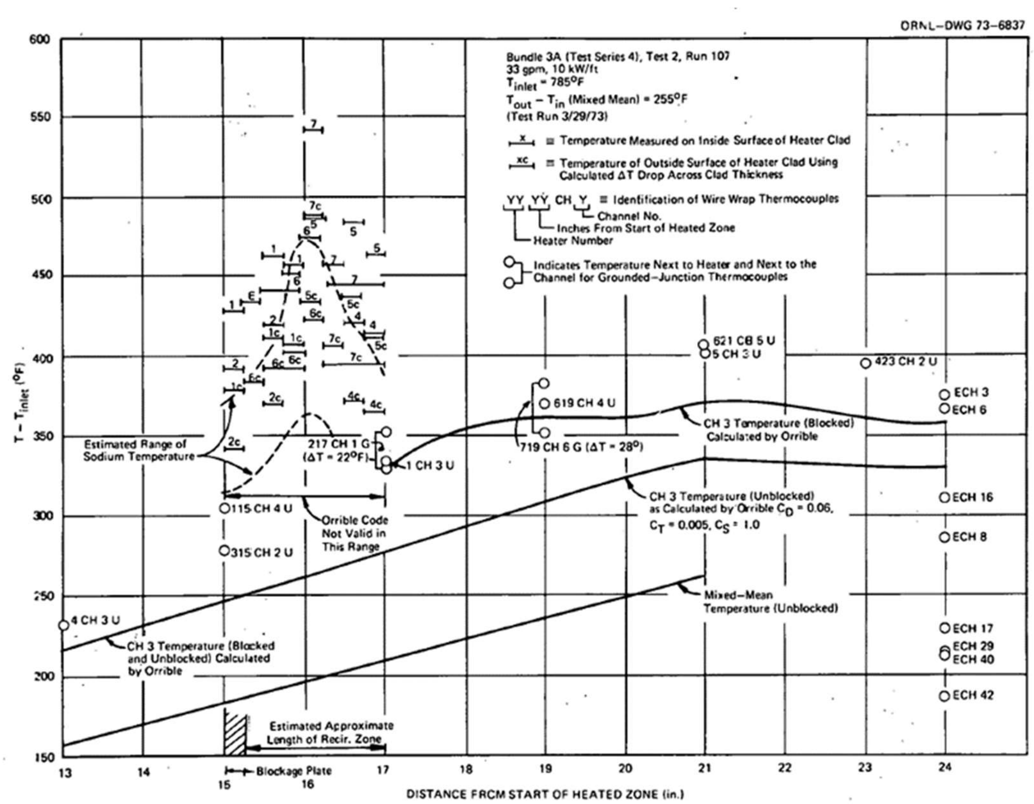

Figure 5-21 Measured Cladding and Coolant Temperature from ORNL 3A Experiments (References [11], [17], and [27]) with 32.8 kW/m and 33 gpm

As previously noted, the [[

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5.3.3.1.5.2 Semi-Empirical Model Implementation on Local Wake Spatial Factor

[[

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5.3.3.1.7 Results

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(a)(4), ECI

Figure 5-22 Comparison of Mongoose++ Results [[

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5.3.3.1.7.2 Sample Results of Central 6-Subchannel Blockage from ORNL 3A

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Figure 5-23 Comparison of Measured Cladding and Coolant Temperatures to Calculated Values from Mongoose++ [[ ]]$^{(a)(4)}$

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[[ ]](a)(4),ECI

Figure 5-24 Comparison of Measured Cladding and Coolant Temperatures to Calculated Values from Mongoose++ [[ ]](a)(4)

[[ ]](a)(4),ECI

Figure 5-25 Comparison of Measured Cladding and Coolant Temperatures to Calculated Values from Mongoose++ [[ ]](a)(4)

5.3.3.1.7.3 14-Subchannel Edge Blockage from ORNL 5B

The experimental setup for the 14-subchannel edge blockage (including the subchannel and rod numbering convention) is given in Figure 5-26.

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]](a)(4)

ORNL Test 12 Run 108 of the ORNL THORS 5B test (Reference [28], Pages 26 and 157-161) [[

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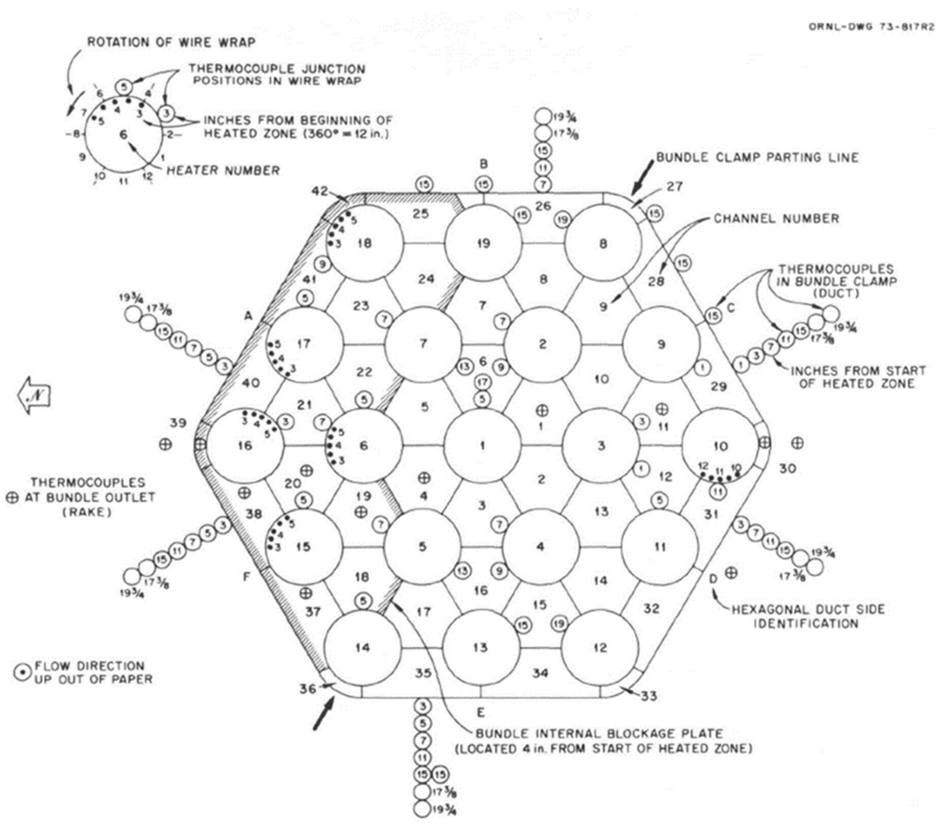

Figure 5-26 Schematic of ORNL THORS 5B 14-Subchannel Edge Blockage [28]

(a)(4)

Figure 5-27 Comparison of Measured Coolant Temperatures to Calculated Values from Mongoose++ [[ ]]$^{(a)(4)}$

(a)(4)

Figure 5-28 Comparison of Measured Cladding Temperatures to Calculated Values from Mongoose++ [[ ]]$^{(a)(4)}$

[[ ]](a)(4)

Figure 5-29: Comparison of Measured Coolant Temperatures to Calculated Values from Mongoose++ [[ ]](a)(4)

[[ ]](a)(4)

Figure 5-30 Comparison of Measured Cladding Temperatures to Calculated Values from Mongoose++ [[ ]](a)(4)

5.3.3.1.8 Conclusion

The basis for the individual components of the semi-empirical model have been described. The semi-empirical model [[

]](a)(4)

5.4 EMDAP Element 4: Assess Evaluation Model Adequacy

Figure 5-31 shows a diagram of the EMDAP Element 4 (Reference [1]).

The first part of Element 4 (Steps 13 through 15) applies to the bottom-up evaluation of the closure relations for each code by examining important closure models and correlations.

The second part of Element 4 (Steps 16 through 19) applies to the top-down evaluation of code-governing equations, numerics, the integrated performance of each code, and the integrated performance of the overall EM by assessing the field equations, numerics, applicability, fidelity to component or integral effects data and scalability.

After the bottom-up and top-down evaluations, it is important to determine whether the degree of overall conservatism or analytical uncertainty is appropriate for the entire EM (Step 20).

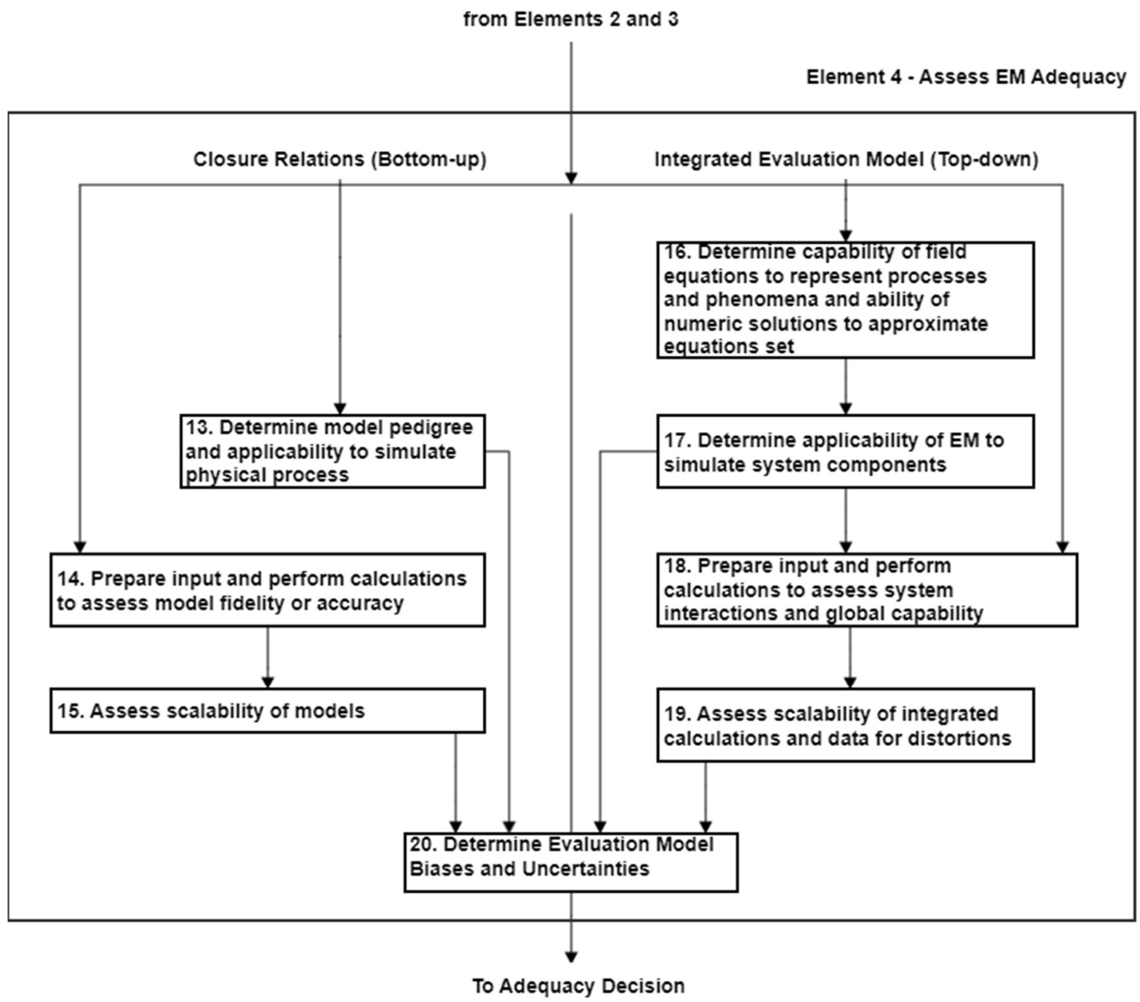

Figure 5-31 Steps in EMDAP Element 4[1]

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

The pedigree evaluation relates to the physical basis of a closure model, assumptions and limitations attributed to the model, and details of the adequacy characterization at the time the model was developed. The applicability evaluation relates to whether the model, as implemented in the code, is consistent with its pedigree or whether use over a broader range of conditions is justified.

Activity of Step 13: Establish partial flow blockage EM pedigree

- The developed EM for partial flow blockage is reviewed and compared to historical methodologies and historical uncertainties. The applicability evaluation is conducted by examining whether the model, as implemented in the code, is consistent with its pedigree or whether use over a broader range of conditions is justified.

5.4.1.1 Partial Flow Blockage Evaluation Model and Constitutive Models

Constitutive models in Mongoose++ include the fluid flow models, energy exchange models, wire wrap models and wake region models. The closure models in Mongoose++ are described in the following sections with their basis, application ranges, assumptions, and validation.

5.4.1.1.1 Fluid Flow Models

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(a)(4)

Figure 5-32 [[ ]](a)(4)

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5.4.1.1.1.1.2 Friction Factor Formulations for Different Flow Regimes

The friction factors can be formulated for laminar and turbulent flow regimes. [[

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(a)(4)

Figure 5-33 [[ ]](a)(4)

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(a)(4)

Figure 5-34 [[

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(a)(4)

Figure 5-35 [[

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(a)(4)

Figure 5-36 [[

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5.4.1.1.1.2 Cross Flow Resistance: Gap Resistance Factor, K_g

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(a)(4)

Figure 5-37 [[**]]**(a)(4)

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(a)(4)

Figure 5-38 [[ ]]$^{(a)(4)}$

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Figure 5-39 [[ ]](a)(4)

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Figure 5-40 [[ ]]$^{(a)(4)}$

[[ ]]$^{(a)(4)}$

Figure 5-41 [[ ]]$^{(a)(4)}$

5.4.1.1.3.2 [[

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(a)(4)

Figure 5-42 [[ ]](a)(4)

(a)(4)

Figure 5-43 [[

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5.4.1.1.4.2 [[

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(a)(4)

Figure 5-44 [[ ]](a)(4)

[[

]](a)(4)

5.4.1.2 Summary

The Mongoose++ code is selected as the evaluation model for the partial flow blockage methodology. The existing models in Mongoose++ have been discussed in addition to the newly added models [[ ]](a)(4) Based on the information discussed above, Table 5-31 summarizes the applicability of each model for partial flow blockage application and supports the EM validation assessment.

Table 5-31 Mongoose++ Constitutive Models

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]](a)(4),ECI

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]](a)(4),ECI

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]](a)(4),ECI

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

SET input for component devices used in model assessment are prepared to represent the phenomena and test facility being modeled, as well as the characteristics of the Natrium design. The following items are performed in this step.

- Validation efforts: Comparison of the calculation results to data.
- Benchmarking efforts: Comparison of the calculation results to other standards, such as a closed-form solution or results obtained with another code.
- Nodalization and time step convergence studies are performed to the extent practicable for the test facility.
- When the calculations of the SETs are completed, the differences between calculated results and experimental data for important phenomena are quantified for bias and deviation.

Activities of Step 14:

Establish base SSC modeling strategies for partial flow blockage events

- Base SSC modeling strategies for partial flow blockage are established in collaboration with safety analysts, design transient analysts, system design lead, and operational transient analysts. The strategies include SSC representation in the code, nodalization, time step, and various user options. Independent assessment of choices is performed during the EM assessment task. The base model is adapted for each end-use application as needed. Some preliminary modeling is included but most of the modeling work is accounted for under safety analysis. Important modeling strategies include nuclear core system modeling as well as reactor protection and plant control system modeling if they apply to partial flow blockage. In addition, SET input for component devices used in model assessment are prepared to represent the phenomena and test facility being modeled, as well as the characteristics of the Natrium design.

Evaluate numerical techniques and user options in partial flow blockage EM

- Nodalization and time step convergence studies are performed to the extent practicable in both the test facility and plant models. However, some models are essentially lumped parameter models and, in those cases, a nodalization convergence study cannot be performed but a time step convergence study is performed for stability. In such cases, care is taken to ensure that the model is applicable to both the test facility and the plant.

- Effects of user options that may impact the accuracy, stability, and convergence features of the EM are evaluated and selected during the EM development and should be codified into automation for licensing analyses.
- This activity is discussed in Section 5.4.4.

Perform benchmark and validation analysis for partial flow blockage EM

- Benchmark and validation analysis for partial flow blockage is conducted basically after developing the assessment base, establishing plant characteristics (and, if needed, modeling strategies of the SSC), and performing the nodalization, time step, and user option studies. This analysis work is performed in parallel with this EM development to provide appropriate feedback.
- The inputs of computer codes are developed to model the test facilities in the assessment base previously identified. The principle used to develop computer code inputs for the test facilities is to model the test facilities as the Natrium design is modeled. This means consistency of inputs, such as nodalization, model options selection, time-step control is maintained between the test facilities and the Natrium model. The phenomena, components, and characteristics of test facility designs modeled in the test facilities are applicable to the Natrium design.

<u>Report Discussion</u>

Portions of this activity are captured in the discussion of EMDAP Step 16 in Section 5.4.4. Ongoing work in this area is planned to be complete prior to TerraPower's submittal of an operating license application, and that information will be included in a future licensing submittal.

5.4.3 EMDAP Step 15: Assess Scalability of Models

The scalability evaluation is limited to whether the specific model or correlation is appropriate for application to the configuration and conditions of the Natrium design, and transient scenarios under evaluation based on the simulation results.

<u>Activity of Step 15</u>: Assess individual model fidelity, accuracy, and scaling for partial flow blockage EM

- To assess the individual model (typically derived from scaled-down SET) fidelity, the scale-up capability and the data applicability to full-scale conditions are required. The individual models, such as closure correlations, that are adopted and programmed in the evaluation model are identified. A technical rationale and justification for using these closure correlations are provided to confirm that the dominant parameters represented by the individual models and correlations reflect the ranges expected in the Natrium design and transient scenarios.

<u>Report Discussion</u>

Ongoing work in this area is planned to be complete prior to TerraPower's submittal of an operating license application, and that information will be included in a future licensing submittal.

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

The following items are considered in this EMDAP step:

- The field equation (partial differential equation) evaluation considers the acceptability of the governing equations in each component code.
- The numeric solution evaluation considers convergence, property conservation, and stability of code calculations to solve the original equations when applied to the target application.
- Effects of user options that may impact the accuracy, stability, and convergence features of the EM are evaluated during the EM development and minimized by codifying them into automation for licensing analyses.
- A complete assessment within this step can only be performed after completing a sufficient foundation of assessment analyses.

Activity of Step 16: Evaluate numerical techniques and user options in partial flow blockage EM

- As in the SET assessments, nodalization and time step convergence studies are performed to the extent practicable in both the test facility and plant models. However, some models are essentially lumped parameter models and, in those cases, a nodalization convergence study cannot be performed but a time step convergence study is performed for stability. In such cases, care should be taken to ensure that the model is applicable to both the test facility and the plant.
- Effects of user options that may impact the accuracy, stability, and convergence features of the EM are evaluated during the EM development and minimized by codifying them into automation for licensing analyses.
- The field equations (partial differential equations) are evaluated through this activity to ensure that the governing equations in each component code are acceptable.

Report Discussion

The following subsections provide guidelines for the numerical schemes, variable axial discretization, and convergence criteria to be used by Mongoose++ for partial flow blockage analysis. They establish the appropriate user input options to obtain adequate performance from the numerical techniques used by Mongoose++. The investigation into numerical techniques is limited to steady state simulations within Mongoose++ consistent with the method. The key figure of merit is the PCT.

5.4.4.1 Sample Fuel Assembly Parameters

Geometric parameters for the sample fuel assembly are shown in Table 5-32. [[

]](a)(4)

Table 5-32 Geometric Parameters for Evaluation of Numerical Techniques of Mongoose++ for Partial Flow Blockage

[[

Geometric Parameters	Value

]](a)(4),ECI

Table 5-33 Blockage Parameters for Evaluation of Numerical Techniques of Mongoose++ for Partial Flow Blockage

[[

Blockage Parameters	Value

]](a)(4)

The material properties of fuel are given in Table 5-34. The fuel properties use constant approximations of U-10Zr. The coolant and cladding material use pre-defined material properties of sodium and HT9 which are available in Mongoose++.

Table 5-34 Fuel Properties for Evaluation of Numerical Techniques of Mongoose++ for Partial Flow Blockage

[[

Fuel Properties	Value

]](a)(4),ECI

The operating parameters are given in Table 5-35. [[

]](a)(4)

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Table 5-35 Operating Parameters for Evaluation of Numerical Techniques of Mongoose++ for Partial Flow Blockage

[[

Operating Parameters	Value									

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[[

Operating Parameters	**Value**									

]](a)(4),ECI

5.4.4.2 Mongoose++ Residuals

A Mongoose++ simulation of the example case was executed [[

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Table 5-36 [[

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[[

]](a)(4)

5.4.4.3 Grid Refinement

Grid refinement is discussed to provide guidance for proper meshing.

5.4.4.3.1 Limitation in Radial Refinement

Mongoose++ uses the standard radial discretization scheme for subchannel solvers, where 1 radial element is used per subchannel as well as one radial element per gap for transverse quantities. [[

]](a)(4)

5.4.4.3.2 Axial Refinement

An axial grid refinement study was performed [[

]](a)(4)

(a)(4),ECI

Figure 5-45 Maximum Inner Cladding Temperature vs Axial Position [[ ]](a)(4)

Table 5-37 Axial Grid Refinement Results

[[

Axial Element Length (cm)	PCT (°C)

]](a)(4)

[[

]](a)(4)

5.4.4.4 Schemes

A description of the transverse flux schemes is documented in the Mongoose++ theory manual. [[

]](a)(4)

(a)(4),ECI

Figure 5-46 Radial Profiles for Subchannel Bulk Coolant Temperature [[

]](a)(4)

(a)(4),ECI

Figure 5-47 Radial Profiles for Subchannel Bulk Coolant Temperature [[

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[[ ]](a)(4),ECI

Figure 5-48 Radial Profiles for Subchannel Bulk Coolant Temperature [[ ]](a)(4)

Table 5-38 PCT for Transverse Axial Scheme

[[

Scheme	PCT (°C)

]](a)(4)

5.4.4.5 Conclusion

[[ ]](a)(4) These recommendations apply to the method and are used in the sample problem and benchmarks.

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

This EM applicability evaluation considers whether the integrated code (the safety analysis computer code system) can model the Natrium systems and components that apply to partial flow blockage. Before performing integrated analyses, the various EM options, special models, and inputs are determined to have the inherent capability to model the major systems and subsystems required for partial flow blockage analysis.

Activity of Step 17: Perform code(s) selection for partial flow blockage EM

- As discussed in Section 5.3.1.2, determination of the safety analysis computer code system including selection of the principal analytical computer code is made through this activity. The applicability of this EM is evaluated in this EMDAP step.

Report Discussion

Ongoing work in this area is planned to be complete prior to TerraPower's submittal of an operating license application, and that information will be included in a future licensing submittal.

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

The following aspects are considered in this EMDAP step:

- The EM input for IETs should best represent the facilities and characteristics of the Natrium design.
- This fidelity evaluation considers the comparison of EM-calculated and measured test data from component and integral tests and, where possible, plant transient data.
- Nodalization and time step convergence studies are performed to the extent practicable in the test facility and plant models.
- The difference between calculated results and experimental data for important processes and phenomena are quantified for bias and deviation.
- The ability of the EM to model system interactions are evaluated in this step.
- Plant input decks are prepared for the target applications.

Activities of Step 18:

Establish base SSC modeling strategies for partial flow blockage events

- As in SET assessments, base SSC modeling strategies for partial flow blockage are established in collaboration with safety analysts, design transient analysts, system design lead, and operational transient analysts. The strategies include SSC representation in the code, nodalization, time step, and various user options. Independent assessment of choices is performed during the EM assessment task. The base model is adapted for each end-use application as needed. Some preliminary modeling work can be included but most of the modeling work is accounted for under safety analysis. Important modeling strategies include nuclear core system modeling, reactor protection and plant control system modeling.

Establish plant characteristics modeling assumptions for partial flow blockage events

- It is important to model plant characteristics appropriately. The main plant characteristics include power distribution in the core, core inlet temperatures, mass flow rates, core outlet temperature, etc. The analyses of LBEs use a conservative bounding approach. [[

]]$^{(a)(4)}$

Evaluate numerical techniques and user options in partial flow blockage EM

- Nodalization and time step convergence studies are performed to the extent practicable in both the test facility and plant models. However, some models are essentially lumped parameter models and, in those cases, a nodalization convergence study cannot be performed but a time step convergence study is performed for stability. In such cases, care should be taken to ensure that the model is applicable to both the test facility and the plant.
- Effects of user options that may impact the accuracy, stability, and convergence features of the EM are evaluated during the EM development and errors minimized by codifying them into automation for licensing analyses.
- This activity is discussed in Section 5.4.4.

Perform benchmark and validation analysis for partial flow blockage EM

- Benchmark and validation analysis for partial flow blockage is conducted basically after developing the assessment base, establishing modeling strategies of the SSC and plant characteristics, and performing the nodalization, time step, and user option studies. This analysis work is performed in parallel with EM development to provide appropriate feedback.
- The inputs of computer codes need to be developed to model the test facilities in the assessment base previously identified. The principle used to develop computer code inputs for the test facilities is to model the test facilities as the Natrium design is modeled. This means consistency of inputs, such as nodalization, model options selection, time-step control is maintained between the test facilities and the Natrium design. The phenomena, components, and characteristics of test facility designs modeled in the test facilities are applicable to the Natrium design.

<u>Report Discussion</u>

Portions of this activity are captured in the discussion of EMDAP Step 16 in Section 5.4.4. Ongoing work in this area is planned to be complete prior to TerraPower's submittal of an operating license application, and that information will be included in a future licensing submittal.

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

This scalability evaluation is limited to whether the assessment calculations and experiments exhibit otherwise unexplainable differences among facilities, or between calculated and measured data for the same facility, which may indicate experimental or code scaling distortions.

<u>Activity of Step 19</u>: Perform benchmark and validation analysis for partial flow blockage EM

- The scalability evaluation is performed by analyzing the code results according to the specified acceptance criteria. If distortions are present, the scalability of the integral calculations is assessed by investigating their impacts and consequences for the Natrium transient situation considered.

Report Discussion

Ongoing work in this area is planned to be complete prior to TerraPower's submittal of an operating license application, and that information will be included in a future licensing submittal.

5.4.8 EMDAP Step 20: Determine Evaluation Model Biases and Uncertainties

The objective of the uncertainty analysis is to provide a singular statement of uncertainty, with respect to the acceptance criteria, when using the best-estimate option in that rule. This singular uncertainty statement is accomplished when the individual uncertainty contributions are determined.

The EM uncertainty analysis is not required with suitably conservative input parameters. This suitability determination may involve a limited assessment of biases and uncertainties.

As an alternative to using “suitably conservative” input parameters, the EM may choose to perform an uncertainty analysis of the safety limit with an evaluation at the nominal technical specifications and setpoints being considered as the base case. The safety limit can then be analyzed with uncertainties in both phenomena and setpoints evaluated in a probabilistic manner.

The last part of this step is to determine whether the degree of overall conservatism or analytical uncertainty is appropriate for the entire EM. A hybrid methodology (where some parameters are treated in a bounding manner, and others are treated in a probabilistic manner) may also be acceptable.

Activity of Step 20: Establish partial flow blockage EM preliminary biases and uncertainties

- The EM biases and uncertainties are evaluated when the validation analysis is conducted using the best-estimate option. Simulation results will show distributions of predictions of important parameters (figures of merit) which compose probability density functions. The EM bias can be defined as the ratio of prediction (mean value) of important parameter value to its measured value. The statement of total uncertainty for the code is given as an error band or a statement of probability for the limiting value of the primary safety criteria.
- A singular statement of uncertainty, with respect to the acceptance criteria, is evaluated based on the probability density function. The individual uncertainties result from code limitations, scale effects, Nuclear Power Plant (NPP) input variations, etc. The desired combined uncertainty with its probability density function is determined through an acceptable statistical approach that represents the combined code output. Given a fast-running code, the probability density function is generated directly from large amount of code runs.
- When suitably conservative input parameters are prepared, rather than a full implementation of uncertainty quantification, the evaluation of the EM biases and uncertainties are not required. Perhaps a limited assessment of biases and uncertainties are conducted.
- If a great number of runs is not feasible or the effect of uncertainty contributors cannot be quantified with distribution because the data are limited or because it is not economical, then it could be quantified as separate biases based on bounding sensitivity calculations with the NPP model. These separate biases are then included in the total uncertainty as a hybrid method. A

hybrid methodology (where some parameters are treated in a bounding manner, and other are treated in a probabilistic manner) may also be acceptable.

Report Discussion

A suitably conservative approach is defined in the following subsections to support EMDAP Step 20 for the partial flow blockage method; therefore, a complete uncertainty analysis is not required. [[

]]$^{(a)(4)}$ Significant parameters based on the PIRT results and sensitivity analyses are treated in a bounding manner and preliminary biases are determined.

5.4.8.1 Sensitivities for DBA Six-Subchannel Blockage

Plant sensitivities for key parameters are evaluated [[

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Table 5-39 Plant Sensitivities and Biases by PCT Impact for DBA [[ ]](a)(4)

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Table 5-40 Disposition of High and Medium Ranked Phenomena

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5.4.8.2 Major Conservative Biases

This section discusses the major conservative biases for the partial flow blockage method.

5.4.8.2.1 Semi-Empirical Model

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Table 5-41 [[ ]](a)(4) for Bounding Initial Temp Distribution

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5.4.8.3 Results

Table 5-42 summarizes the conservative PCT biases for the partial flow blockage method [[

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Table 5-42 Summary of Conservative PCT Biases for DBA

Parameter	PCT Bias (°C)
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5.5 Adequacy Decision

The EMDAP process of 20 steps discussed in Regulatory Guide 1.203 (Reference [1]) is a systematic approach that the U.S. NRC considers acceptable for developing an evaluation model. However, questions concerning the adequacy of the EM are asked throughout the EMDAP. At the end of the process, the adequacy is questioned again to ensure that all the earlier answers are satisfactory and that intervening activities have not invalidated previous acceptable responses. If unacceptable responses indicate significant EM inadequacies, the code deficiency is corrected and the appropriate steps in the EMDAP repeated to evaluate the correction. It is helpful to develop a list of questions to be asked during the process and again at the end. To answer these questions, standards should be established by which the capabilities of the EM and its composite codes and models can be assessed. The question list may include the following:

- Is a safety analysis computer system developed and interactions among the codes clearly established?
- Is the EM suitable enough to meet the analysis purpose?
  - Does the EM have appropriate and enough systems and components to simulate the Natrium design?

    - Are the field equations and individual models, and correlations accurate and covering the full range of the analysis?

- Do the PIRT and assessment base include all important phenomena and processes of the Natrium plant and experimental data?
- Are the scaling and experimental uncertainty analyses in compliance with the basic principles discussed in the EMDAP?
- Are the validation cases conducted appropriately to examine the capabilities of the EM to simulate the important phenomena and processes of the Natrium design?
    - Are initial conditions, boundary conditions, options, time step size, nodalization, etc. appropriately prepared without unacceptable distortions?
    - Can the results of the SET calculations be used to assess scalability of models?
    - Are the results of the IET simulations appropriate to determine the capability of the field equations and the ability of numeric solutions to approximate equation set?
    - Are the results of the IET simulations appropriate to determine the applicability of the EM to simulate system components and to assess system interactions?
- Are the evaluated EM biases and uncertainties acceptable?

This question list is preliminary and will be updated as the evaluation model matures. Ongoing work in this area is planned to be complete prior to TerraPower's submittal of an operating license application, and information will be included in a future licensing submittal.

6 SUMMARY

This document describes the plan for developing a partial flow blockage EM, to ensure that it is adequate for performing safety analysis for the Natrium design. It describes the methodology specific activities and preliminary results needed to develop a methodology for the PSAR, as well as its interfaces within the Natrium testing program. The desired result of the plan is to develop an EM that supports a conservative analysis for the DBA evaluation of partial flow blockage.

This report describes the four EMDAP elements where Element 1 establishes the requirements for EM capability, Element 2 provides the basis for EM development and assessment, Element 3 develops the EM, and Element 4 assesses EM adequacy. An initial EM has been developed to support the PSAR and Construction Permit Application; however, plans have been developed for completion of the remaining steps and review of the method as the design matures. Ongoing work in this area is planned to be complete prior to TerraPower's submittal of an operating license application, and information will be included in a future licensing submittal.

Steps that have been completed to support the preliminary design include the following:

Requirements for EM capability have been established as follows:

- EMDAP Step 1: The application envelope of the EM has been established by specifying the analysis purpose, transient class, and power plant class.
- EMDAP Step 2: Figures of merit have been identified based on the established application envelope.

- EMDAP Step 3: The EM characteristics have been identified by describing systems, components, phases, geometries, fields, and processes that should be modeled.
- EMDAP Step 4: The EM phenomena and processes have been established by developing a PIRT.

The basis for EM development and assessment are provided by acquiring appropriate experimental data and ensuring the suitability of experimental scaling and uncertainties as follows:

- EMDAP Step 6: Scaling analysis has been performed to determine non-dimensional parameters and quantify scaling distortions using the data from ORNL and PNC.
- EMDAP Step 7: Available experimental data have been identified and are matched to the important phenomena from the PIRT. Substantial flow blockage testing was performed to support the FFTF and CRBRP that use similar wire-wrapped hexagonal fuel assembly designs along with other overseas LMFBR designs.
- EMDAP Step 9: Experimental uncertainties have been evaluated for two ORNL FFM test series. [[ ]]$^{(a)(4)}$ the partial flow blockage method and supported by use of ORNL FFM tests for CRBRP and FFTF licensing and FFTF operation.

The EM has been developed as follows:

- EMDAP Step 10: Establishing a code development plan has been replaced by code selection. TerraPower's Mongoose++ is used as the subchannel analysis computer code to assess partial flow blockage with new models to supplement predictions within the wake.
- EMDAP Step 11: An EM structure has been established for Mongoose++ according to the six ingredients specified in Regulatory Guide 1.203.
- EMDAP Step 12: Closure models have been incorporated within Mongoose++ using the semi-empirical model [[ ]]$^{(a)(4)}$

The EM adequacy has been assessed as follows:

- EMDAP Step 13: The EM pedigree and applicability to simulate the physical processes for partial flow blockage has been assessed for Mongoose++ models. The applicability evaluation has been conducted by examining whether the model, as implemented in the code, is consistent with its pedigree and whether use over a broader range of conditions is justified.
- EMDAP Step 16: The numerical schemes, variable axial discretization, and convergence criteria have been investigated to establish user options and input values needed to obtain adequate performance from the numerical techniques used by Mongoose++.
- EMDAP Step 20: Plant sensitivities for key parameters have been evaluated using a suitably conservative approach; therefore, a complete uncertainty analysis is not required. Table 5-42 summarizes the conservative PCT biases. [[

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7 CONCLUSIONS AND LIMITATIONS

7.1 Conclusions

TerraPower is requesting NRC approval of the Partial Flow Blockage EM documented in this report for use by future applicants utilizing the Natrium design as an appropriate and adequate means to evaluate the peak cladding temperature of partial flow blockage events. This approval is subject to the limitations described below.

7.2 Limitations

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

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

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

8 REFERENCES

[1] U.S. Nuclear Regulatory Commission, "Transient and Accident Analysis Methods," Regulatory Guide 1.203, December 2005.

[2] "Clinch River Breeder Reactor Project Preliminary Safety Analysis Report," Volume 10, June 1975.

[3] U.S. Nuclear Regulatory Commission, "Preapplication Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor," NUREG-1368, February 1994.

[4] U.S. Nuclear Regulatory Commission, "Preapplication Safety Evaluation Report for the Sodium Advanced Fast Reactor (SAFR) Liquid-Metal Reactor," NUREG-1369, December 1991.

[5] U.S. Nuclear Regulatory Commission, "Safety Evaluation Report Related to the Construction of the Clinch River Breeder Reactor Plant," NUREG-0968, March 1983.

[6] International Atomic Energy Agency, "LMFR Core Thermohydraulics: Status and Prospects," IAEA-TECDOC-1157, June 2000.

[7] Nuclear Energy Institute, "Risk-informed Performance-based Technology Inclusive Guidance for Non-light Water Reactor Licensing Basis Development," NEI Technical Report 18-04, August 2019.

[8] 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, June 2020.

[9] [[

]](a)(4)

[10] Kirsch, D., "Studies on Flow and Temperature Distribution in the Region of Local Channel Blockages in Bundle Fuel Elements," KFK-1794 (EURFNR-1106), Karlsruhe Nuclear Research Center, May 1973.

[11] Fontana, M. H., Kress, T. S., Parsly, L. F., Thomas, D. G., and Wantland, J. L., "Effect of Partial Blockages in Simulated LMFBR Fuel Assemblies," ORNL-TM-4324, Oak Ridge National Laboratory, December 1973.

[12] Toshiba Corporation, "Phenomena Identification and Ranking Tables for 4S Beyond-Design-Basis Accidents: Local Faults and Steam Generator Tube Failure," AFT-2012-000103rev.000(0), April 2012.

[13] Todd, D. R., "Evaluation of Licensing Basis Events for Analytical Requirements: Pilot Application to Local Flow Blockage Event," SDS-000142, March 2015.

[14] ML121290607, "Phenomena Identification and Ranking Tables for 4S Beyond-Design-Basis Accidents - Local Faults and Sodium-Water Reaction," April 2012.

[15] Brookhaven National Laboratory, "Phenomena Important in Liquid Metal Reactor Simulations," Prepared for U.S. Nuclear Regulatory Commission, BNL-207816-2018-INRE, August 2018.

[16] ML081140459, "Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)," Volume 1, NUREG/CR-6944, March 2008.

[17] Han, J. T., "Blockages in LMFBR Fuel Assemblies – A Review of Experimental and Theoretical Studies," ORNL-TM-5839, September 1977.

[18] Miyaguchi, K. and Takahashi, J., "Thermal-Hydraulic Experiments with Simulated LMFBR Sub-Assemblies Under Nominal and Non-Nominal Operating Conditions," International Working Group on Fast Reactors Specialists' Meeting, Power Reactor and Nuclear Fuel Development Corporation, February 1978.

[19] Vegter, B. J., Roidt, R. M., Pechersky, M. J. and Markley, R. A., "Measurement of Velocities Downstream of Blocked Subchannels in a Model Reactor Rod Bundle," Westinghouse Research Laboratories, December 1974.

[20] [[

[21]

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[22] Tang, Y. S., Coffield, R. D. and Markley, R. A., "Thermal Analysis of Liquid Metal Fast Breeder Reactors," 1978.

[23] Fricano, J. W. and Baglietto, E., "A quantitative CFD benchmark for Sodium Fast Reactor fuel assembly modeling," *Annals of Nuclear Energy,* vol. 64, pp. 32-42, February 2014.

[24] Fontana, M. H., MacPherson, R. E., Gnadt, P. A., Parsly, L. F., Kress, T. S., and Wantland, J. L., "Temperature Distribution in a 19-Rod Simulated LMFBR Fuel Assembly in a Scalloped Duct (Fuel Failure Mockup Bundle 1A) - Record of Experimental Data," ORNL-TM-4670, Oak Ridge National Laboratory, Janurary 1975.

[25] Fontana, M. H., MacPherson, R. E., Gnadt, P. A., Parsly, L. F., Kress, T. S., and Wantland, J. L., "Temperature Distribution in a 19-Rod Simulated LMFBR Fuel Assembly in a Scalloped Duct (Fuel Failure Mockup Bundle 1B) - Record of Experimental Data," ORNL-TM-4939, Oak Ridge National Laboratory, November 1975.

[26] Fontana, M. H., MacPherson, R. E., Gnadt, P. A., Parsly, L. F., and Wantland, J. L., "Temperature Distribution in a 19-Rod Simulated LMFBR Fuel Assembly in a Hexagonal Duct (Fuel Failure Mockup Bundle 2A) - Record of Experimental Data," ORNL-TM-4113, Oak Ridge National Laboratory, September 1973.

[27] Fontana, M. H., Gnadt, P. A., Kress, T. S., MacPherson, R. E., Parsly, L. F., and Wantland, J. L., "Temperature Distribution in a 19-Rod Simulated LMFBR Fuel Assemblies with a Six-Channel Internal Blockage (Fuel Failure Mockup Bundle 3A) - Record of Experimental Data," ORNL-TM-5101, Oak Ridge National Laboratory, March 1976.

[28] Fontana, M. H., Gnadt, P. A., Kress, T. S., MacPherson, R. E., Parsly, L. F., and Wantland, J. L., "Temperature Distribution in 19-Rod Simulated LMFBR Fuel Assemblies with and without an Edge Blockage (Out-of-Reactor Tests for ANL SLSF P1 Experiment) - Record of Experimental Data for Fuel Failure Mockup Bundles 5B and 5C," ORNL-TM-5003, Oak Ridge National Laboratory, January 1976.

[29] F. Namekawa, A. Ito, and K. Mawatari, "Buoyancy effects on wire-wrapped rod bundle heat," AIChE Symposium Series, vol 80(236), pp 128-133, 1984.

[30] F. C. Engel, B. Minushkin, R. J. Atkins, and R. A. Markley, "Characterization of heat transfer and temperature distributions in an electrically heated model of an LMFBR blanket assembly," Nuclear Engineering and Design, no. 62, pp 335-347, 1980.

[31] Grindell A. G. and MacPherson, R. E., "Final Systems Design Descrription of the Failed Fuel Mockup (FFM) of the Liquid-Metal Fast Breeder Reactor," ORNL-TM-3656, September 1972.

[32] TP-QA-PD-0001, "TerraPower QA Program Description," Revision 14, September 2022.

[33] U. S. Nuclear Regulatory Commission, "Quality Assurance Program Criteria (Design and Construction)," Regulatory Guide 1.28, October 2017.

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[42] Patankar, S. V. and Spalding, D. B., "A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows," *International Journal of Heat and Mass Transfer,* vol. 15, no. 10, p. 1787–1806, October 1972.

[43] Schleisiek, K., "Sodium Experiments for the Investigations of Local Cooling Disturbances in Test Assemblies Similar to Fuel Elements," KFK-1914 (EURFNR-1156), Karlsruhe Nuclear Research Center, February 1974.

[44] [[

]](a)(4)

[45] NAT-2806, "TerraPower, LLC (TerraPower) Natrium Topical Report: Fuel and Control Assembly Qualification," Revision 0, TerraPower, April 2023.

9 APPENDICES

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Table 9-1 [[ ]](a)(4)

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Table 9-2 [[ ]](a)(4)

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9.2.2.3 [[

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Figure 9-1 [[ ]](a)(4)

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9.2.2.3.2 [[

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Figure 9-2 [[ ]](a)(4)

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9.2.2.3.3 [[ ]](a)(4)

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Figure 9-3: [[ ]](a)(4)

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9.2.3 [[

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Table 9-3 [[ ]](a)(4)

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Table 9-4 [[ ]](a)(4)

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Table 9-5 [[ ]](a)(4)

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9.3 Sample Natrium Partial Flow Blockage Analysis

Several partial flow blockage LBEs have been analyzed, and sample results are summarized below. These evaluations are performed based on a preliminary design for a Natrium pool-type, sodium-cooled, fast reactor. [[

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Figure 9-4: [[ ]](a)(4)

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Figure 9-5: [[

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Figure 9-6: [[ ]](a)(4)

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