TerraPower

November 30, 2023

TP-LIC-LET-0106
Project Number 99902100

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

Subject: Transmittal of TerraPower, LLC "Stability Methodology Topical Report," Revision 0

This letter transmits the TerraPower, LLC (TerraPower) "Stability Methodology Topical Report," Revision 0 (enclosed). The report contains an overview and description of the model developed to evaluate reactor stability for the Natrium™ Plant[1].

TerraPower requests the NRC's review and approval of the evaluation model 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.

15800 Northup Way, Bellevue, WA 98008 www.TerraPower.com P. +1 (425) 324-2888 F. +1 (425) 324-2889

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, "Stability Methodology Topical Report," Revision 0 – Non-Proprietary (Public)
3. TerraPower, LLC Topical Report, "Stability Methodology Topical Report," Revision 0 – 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: November 30, 2023

George Wilson
____

George Wilson
Vice President, Regulatory Affairs
TerraPower, LLC

ENCLOSURE 2

TerraPower, LLC Topical Report
"Stability Methodology Topical Report" Revision 0

Non-Proprietary (Public)

Controlled Document - Verify Current Revision

TOPICAL REPORT

Document Number:	TP-LIC-RPT-0006	**Revision:**	0
Document Title:	Stability Methodology Topical Report		
Functional Area:	Licensing	**Engineering Discipline:**	Safety & Licensing
Effective Date:	11/30/2023	**Released Date:**	11/30/2023
		Page:	1 of 67

Approval

Title	**Name**	**Signature**	**Date**
Originator, Licensing Engineer	Matthew Presson	Electronically Signed in Agile	11/30/2023
Reviewer, Licensing Manager	Nick Kellenberger	Electronically Signed in Agile	11/30/2023
Approver, Director of Licensing	Ryan Sprengel	Electronically Signed in Agile	11/30/2023

Export Controlled Content: Yes ☐ No ☒

REVISION HISTORY

Revision No.	Effective Date	Affected Section(s)	Description of Change(s)
0	11/30/2023	All	Initial Issue.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Acronyms

Acronym	Definition
AOO	Anticipated Operational Occurrence
BOEC	Beginning of Equilibrium Cycle
BOL	Beginning-of-Life
CRDL	Control Rod Driveline
EOEC	End of Equilibrium Cycle
FOM	Figure of Merit
FPTF	Full Power Transfer Function
HFP	Hot Full Power
Hz	Hertz
IHX	Intermediate Heat Exchanger
LHS	Latin Hypercube Sampling
LTI	Linear Time-Invariant
LWR	Light Water Reactor
MOEC	Middle of Equilibrium Cycle
MWth	Megawatt Thermal
NRC	U.S. Nuclear Regulatory Commission
OLTF	Open Loop Transfer Function
PDC	Principal Design Criteria or Principal Design Criterion
RAC	Reactor Air Cooling System
SARRDL	Specified Acceptable Radionuclide Release Design Limit
SFR	Sodium-cooled Fast Reactor
ToR	Topical Report
U.S.	United States
ZPTF	Zero Power Transfer Function

1 INTRODUCTION

Nuclear reactor stability analysis, as approached by this Topical Report (ToR), is the study of a reactor's oscillatory power response to reactivity perturbations. Ensuring a stable (i.e., non-diverging) oscillatory reactor power response helps preclude controllability issues and limits the potential of failing to maintain design limits.

1.1 Purpose and Scope

This report is submitted for the following purposes, subject to the scopes described:

- Provide a description of the methodology developed to characterize Natrium™[1] Sodium-cooled Fast Reactor (SFR) stability, including the requirements established that such a methodology must satisfy (Section 2), an overview of the methodology including Figure of Merit (FOM) calculation and associated uncertainty treatment (Section 3), the models that comprise the methodology (Section 4), the process steps to perform the calculations involved (Section 5), a benchmark calculation using historical reactor measurements to be used to construct an estimate of the model uncertainty (Section 6), and a discussion around plant-specific application, including a demonstration application to aid in understanding of how the methodology operates (Section 7).
- Receive approval for the use of the developed methodology for performing calculations to characterize the stability behavior of Natrium reactor designs that fit the description provided over all cycle locations and initial power and flow operating conditions.
    - This requested approval scope is intended to be limited to the methodology itself and is not expected to include approvals regarding the stability behavior of the Natrium SFR presented as part of the demonstration application results (Section 7.2). These results are included only for illustrative purposes such that the methodology may be better understood.

1.2 Event Definition

The event defined for analysis with this methodology starts from a steady-state initial condition in normal operation or as a result of an Anticipated Operational Occurrence (AOO). A small reactivity perturbation is introduced into this initial condition, which induces small fluctuations in the reactor power and primary system temperatures. Throughout this event, the secondary system operating conditions are assumed to be held constant. This event definition excludes scenarios where sodium boiling is present, as sodium boiling is neither part of an AOO nor part of any normal operating condition.

It is not expected that there will be AOOs where scrams are not initiated that result in a steady-state condition outside the conditions of the normal operating range (including uncertainties). Therefore, it is expected that the Natrium stability methodology may be applied only in this normal operating range while still accounting for the stability of the reactor system for all conditions of both normal steady-state operation and AOOs. However, these expectations are to be confirmed upon methodology application.

[1] a TerraPower & GE-Hitachi technology

2 METHOD REQUIREMENTS

2.1 Development Criteria

The methodology requirements are derived from regulatory criteria relevant to reactor stability. In a broad sense the regulatory criteria exist to guarantee that:

1. The reactor system is stable for all conditions of steady-state operation and for AOOs.
2. If potential instabilities cannot be eliminated or otherwise avoided, design proposals should detect and suppress them reliably and readily.
3. The methodology used when assessing reactor system stability is reliable.

These criteria are provided as generalized requirements such that they are applicable to a broad range of analyses. The requirements in this document were developed specifically for stability analysis of the Natrium reactor system.

The requirements identified pertain to the assessment and quantification of stability in the Natrium reactor system. These requirements satisfy the NATD-LIC-RPRT-0002, *Principal Design Criteria for the Natrium Advanced Reactor* [1] Principal Design Criterion (PDC) 12 that relates to stability:

- The reactor core; associated structures; and associated coolant, control, and protection systems shall be designed to ensure that power oscillations that can result in conditions exceeding specified acceptable radionuclide release design limits (SARRDLs) are not possible or can be reliably and readily detected and suppressed.

2.2 Developed Requirements

Requirements have been established to ensure the methodology used to evaluate the stability of the Natrium reactor system satisfies the criteria outlined in Section 2.1. These requirements provide specific guidance for the stability methodology including input specifications, output specifications, and how the methodology satisfies the criteria. Table 2-1 outlines the stability methodology requirements.

Table 2-1: Natrium™ Stability Methodology Requirements

ID	Requirement Title	Requirement
1	Stability Assessment	The reactor core; associated structures; and associated coolant, control, and protection systems shall be designed to ensure that power oscillations that can result in conditions exceeding SARRDLs are not possible or can be effectively detected and suppressed for all conditions of steady-state operation and for AOOs.
1.1	Automatic Controls	For operational configurations found to be unstable, where detect and suppress are not selected for use, the implementation of automatic controls is expected, unless sufficient justification is provided for a given configuration.
2	Method Roadmap	This methodology shall provide an overview of the evaluation model which provides a clear roadmap describing all parts of the evaluation model, the relationships between them, and where they are in the documentation.
3	Application Space	This methodology shall define the operational configurations necessary to develop a complete stability analysis for the Natrium reactor system.
4	Phenomena Capture	This methodology shall capture all phenomena that are important to the Natrium reactor's inherent power response to reactivity insertions.
5	Figures of Merit	This methodology shall use the figures of merit identified in this document when quantifying the stability of the Natrium reactor system.
6	Methodology Assessment	This methodology shall contain a number of assessments using available data to demonstrate method validity.
7	Uncertainty Assessment	This methodology shall include a process to assess and incorporate both input and methodological uncertainties.

2.3 Important Phenomena

The purpose of stability analysis is to understand the inherent oscillatory power response of a reactor system to reactivity changes. The inherent response of any reactor system to reactivity changes is generally a function of the input reactivity worth, inherent reactor kinetics, and multiple reactivity feedback mechanisms. All phenomena relevant to reactivity and core power must be captured by any analysis methodology if the analysis is going to return an accurate representation of the system's response to reactivity changes, as specified by Requirement 4 in Table 2-1. Phenomena relevant to the stability of the Natrium reactor were identified and ranked using a categorization of low, medium, and high importance, and all phenomena with an importance of medium or higher are identified as important phenomena and included in Table 2-2. All phenomena listed must be captured in some form by any methodology used to analyze the stability of the Natrium reactor system. Similarly, any methodology that acceptably represents the phenomena described in Table 2-2 is considered to satisfy Requirement 4 in Table 2-1.

Table 2-2: Phenomena Important to the Natrium Reactor System

Category	Phenomena	Notes
[[		
		]](a)(4)

Table 2-2: Phenomena Important to the Natrium Reactor System

Category	Phenomena	Notes
[[		
		]](a)(4)

2.4 Figure of Merit

The methodology must incorporate an FOM and associated criterion sufficient for demonstrating that the Natrium reactor system is stable. Furthermore, the methodology's calculation of this FOM must be able to be validated. The ability to validate a methodology is largely dependent on the availability of existing data relevant to the methodology in question. The Nyquist FOM has been selected as the FOM for stability assessment due to its ability to quantitively capture reactor system stability, including a clear stability criterion, and the availability of experimental data to validate the methodology. This FOM was selected because it has been used to assess stability in historically operated reactors. (Refer to APDA-NTS-11, *Oscillator Tests in the Enrico Fermi Reactor* [2], HEDL-SA-2417, *USA/FBR Program Fast Flux Test Facility Startup Physics and Reactor Characterization Methods and Results* [3], and ANL-7542, *A Catalog of Rod-Drop and Transfer-Function Data from EBR-II Runs 25 through 30A* [4] for additional details.) The Nyquist stability criterion states that a linear system with feedback is unstable when the system's open loop transfer function (OLTF) encircles or passes through the -1+0j point, as determined by visual inspection of the plot on the complex plane (also referred to as a Nyquist plot). The Nyquist FOM for a reactor system is derived from the power response of the system when subject to oscillating reactivity input, both in the absence and in the presence of reactivity feedback.

A process for identifying methodological uncertainties and input sensitivities for the FOM must be part of the stability assessment methodology. The Nyquist stability criterion must be evaluated inclusive of the treatment of these uncertainties to adequately demonstrate whether the reactor is stable.

3 METHODOLOGY ROADMAP

3.1 Overview

The methodology described in this ToR was developed with a focus on satisfying the first development criterion from Section 2.1: demonstrate that the reactor system is stable for all conditions of steady-state operation and AOOs. The methodology seeks to satisfy this first development criterion without needing recourse to the second development criterion, which states: if potential instabilities cannot be eliminated or otherwise avoided, design proposals should detect and suppress them reliably and readily.

The stability of the Natrium reactor is characterized using the Nyquist stability criterion. The FOM associated with this criterion is calculated for a range of discrete operating initial conditions to draw a stability map that characterizes the stability behavior of the reactor as a function of power on the y-axis and flow on the x-axis. At each discrete power/flow location on the map, the reactor is classified as either stable or unstable based on the Nyquist stability criterion. This stability determination also includes a treatment for method uncertainties (both model uncertainties and input uncertainties). A stable result is only declared at any initial condition statepoint if the Nyquist stability criterion indicates stability when taking these uncertainties into account.

It is expected that the reactor will be marked stable at every location on the stability map. If, however, a location is marked as unstable, operational controls are to be put in place to preclude experiencing an instability event. These operational controls may include the specification of exclusion zones where immediate operator action is required if the reactor enters a condition marked unstable on the stability map, or other appropriate controls. The operational controls must be justified at the time of application if a location is marked unstable. This is expected to be sufficient. However, in the unlikely event that this approach is not sufficient, namely if it is not possible to develop appropriate operational controls, a methodology to satisfy the second development criterion (detect and suppress) must be developed.

The initial conditions selected to characterize the stability map will cover the range of initial power and flow conditions where steady-state operation is expected or allowed, [[

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

[[

]][(a)(4)]

Figure 3-1: Set of Initial Power and Flow Condition Statepoints to Characterize the Stability Map for the Natrium Sodium-cooled Fast Reactor

At each initial condition on the stability map, the process for calculating the Nyquist FOM is applied, as described in Section 3.2, including uncertainties treatment. The treatment of uncertainties in the calculation of the Nyquist FOM is described in Section 3.3.

[[

]][(a)(4)]

3.2 Nyquist Figure of Merit Calculation

The Nyquist stability criterion, as evaluated using the Nyquist FOM, has been widely applied for stability analysis of engineered systems. The Nyquist FOM is characterized by plotting the OLTF of the reactor on the complex plane (referred to as a Nyquist plot). The Nyquist stability criterion states that if the OLTF crosses or encircles the (-1,0) location, the reactor is unstable. The OLTF, in turn, is calculated from the reactor's full power transfer function (FPTF) and zero power transfer function (ZPTF). The FPTF is a measure of the reactor's power response to an oscillatory (sinusoidal) reactivity input in the presence of reactivity feedbacks, while the ZPTF is a measure of the reactor's power response to an oscillatory reactivity input in the absence of reactivity feedbacks.

Figure 3-2 provides a visual overview of the process by which the calculation of the OLTF from the ZPTF and the FPTF proceeds to ultimately produce a Nyquist plot.

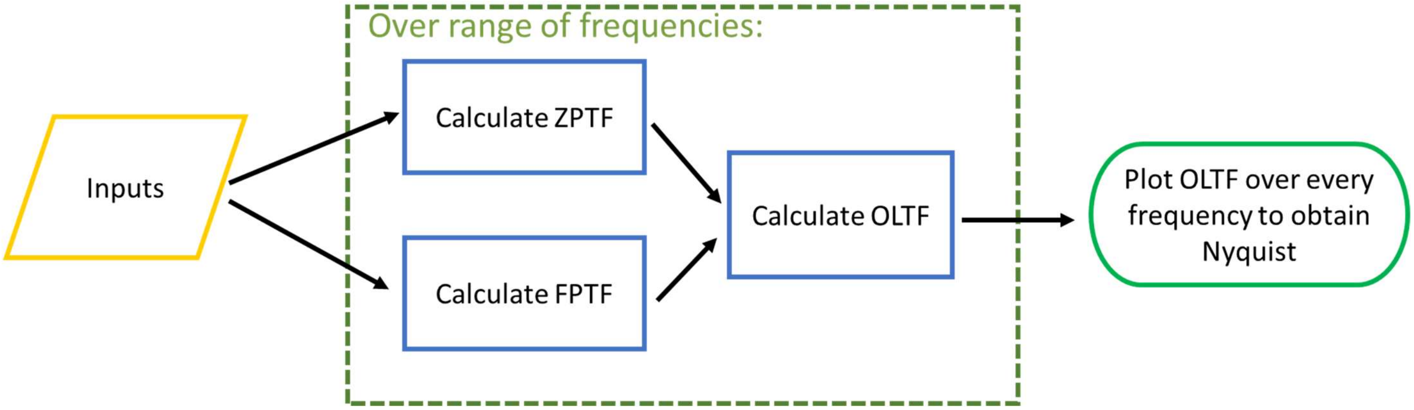

Figure 3-2: Visual Representation of the Methodology's Process for Calculating the Nyquist Figure of Merit

The Nyquist FOM requires linear time-invariant (LTI) behavior (or nonlinear behavior that converges to LTI). LTI behavior is expected [[
]]$^{(a)(4),ECI}$ with small reactivity perturbations for the event definition of interest to this methodology (Section 1.2): the stability analysis seeks to understand the stability behavior at any condition of normal operation and AOOs. Non-LTI behavior is expected to be associated with events outside of the event definition, namely events beyond normal operation and AOOs that are thus not included in PDC 12 and are addressed with the safety methodology that seeks to satisfy PDCs 10 and 11.

However, the Natrium stability methodology is still able to account for non-LTI responses if they are encountered, [[

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

The steps to implement the FPTF calculation are summarized in Section 3.2.1. The ZPTF calculation is summarized in Section 3.2.2. The OLTF is calculated from the FPTF and the ZPTF as summarized in Section 3.2.3.

The full detailed calculational procedural descriptions are provided in Section 5.

3.2.1 Calculating the Full Power Transfer Function

The most calculation-intensive aspect of the described methodology for Natrium stability is the means by which the FPTF is obtained. [[

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

3.2.2 Calculating the Zero Power Transfer Function

Because obtaining the ZPTF involves calculating the reactor's power response to a sinusoidal reactivity input in the absence of reactivity feedback effects, [[

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

3.2.3 Calculating the Open Loop Transfer Function

Once the FPTF and ZPTF have been obtained [[ ]]$^{(a)(4),ECI}$, the OLTF is calculated [[ ]]$^{(a)(4),ECI}$. Also referred to as the system's "characteristic equation," the complex-valued OLTF result is then plotted on the complex plane to obtain the Nyquist FOM.

3.3 Uncertainties Treatment

3.3.1 Method Uncertainties Overview

The two principal categories of uncertainties considered in the Natrium stability method uncertainties treatment are:

1. Model-driven uncertainties
2. Input-driven uncertainties

Model-driven uncertainties (henceforth referred to as model uncertainties) arise from the limitations of the developed mathematical representation of the physical system. No mathematical representation can ever perfectly describe the behavior of a physical system, thus computational modeling of any system's particular behavior suffers from uncertainty in how well the selected model is capturing the system's actual performance. This is typically manifested in the form of model bias, a systematic difference between the model's calculated results and measured results obtained from the actual system.

Input-driven uncertainties (henceforth referred to as input uncertainties) arise from limitations in the measurements and calculations used to derive the inputs to the model used in estimating Natrium reactor stability. The nature of these limitations depends on the type of input. Regardless of the source, the uncertainties [[

]](a)(4)

The treatment applied to each of these method uncertainties is described in subsequent sections. Section 3.3.2 describes the method used to estimate model uncertainty from the Fermi-1 methodology assessment. Section 3.3.3 describes the method for quantifying and propagating the input uncertainties through to obtain a characterization of the stability behavior of the Natrium design.

Note that the described treatment for including the effects of method uncertainties in the estimation of reactor stability is to be performed at each initial condition identified for characterization in the stability map, as introduced in Section 3.1.

3.3.2 Model Uncertainties Treatment Method

The treatment for model uncertainties utilizes a benchmark with the historic Fermi-1 sodium-cooled fast-spectrum commercial power reactor to perform a methodology assessment. This assessment [[

]](a)(4)

The Fermi-1 benchmark calculation is described in Section 6, and the calculations by which [[

]](a)(4) are described in Section 5.2.3. If Natrium reactor-specific data or other benchmark data becomes available, modification of the [[

]](a)(4) may be performed and justified appropriately at the time of application without needing to revise this methodology, provided that once the [[

]](a)(4) is obtained, it is applied consistent with the approach described herein.

3.3.3 Input Uncertainties Treatment Method

3.3.3.1 Description of Selected Approach

To capture the effect of uncertainty in input parameters on the calculation results, [[

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

Calculational efficiencies are obtained by [[

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

Note additionally that this approach inherently assumes that the [[

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

[[

]]^(a)(4),ECI

[[

]](a)(4),ECI

3.3.3.2 Input Parameters to be Evaluated

The input parameters to the model are directly used in modeling the identified important phenomena (which the model is built to represent). For the input uncertainty treatment, [[

]](a)(4),ECI

Table 3-1: Input Parameters to be Examined via Uncertainty Analysis

Parameter	Symbol	Units	Related important phenomena category
[[			
			]](a)(4),ECI

Table 3-1: Input Parameters to be Examined via Uncertainty Analysis

Parameter	Symbol	Units	Related important phenomena category
[[			
			]]$^{(a)(4),ECI}$

[[

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

[[

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

Note that the approach taken by this methodology is to assume that each input parameter is [[

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

Input values that are [[

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

Table 3-2: Input Parameters Only Implicitly Included in the Uncertainty Analysis

Parameter	Symbol	Units	Reason for not explicitly including
[[			
			]]$^{(a)(4),ECI}$

Table 3-2: Input Parameters Only Implicitly Included in the Uncertainty Analysis

Parameter	Symbol	Units	Reason for not explicitly including
[[			
			]](a)(4),ECI

Note that if alternative representations of the [[

]](a)(4),ECI for the input uncertainty treatment that is consistent with the one described here, but adapted for the alternative representations, may be used with sufficient justification at the time of application. In this situation, [[

]](a)(4),ECI

3.3.3.3 Input Frequency-Domain Selection Method

The extent of the [[

]](a)(4),ECI

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

[[

]](a)(4),ECI

[[

]](a)(4),ECI

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

[[

]](a)(4),ECI.

[[

]](a)(4),ECI

Figure 3-3: Nyquist Results Used to Determine Input Frequency Domain Selection

[[

]](a)(4),ECI

[[

]](a)(4),ECI

4 MODELS

The models constructed for the [[ ]](a)(4),ECI calculation (used to calculate the FPTF) fall into two overarching categories: models that [[ ]](a)(4),ECI and the model constructed to represent the input reactivity. Reactivity feedback [[ ]](a)(4),ECI models are described in Section 4.1, and the input reactivity model is presented in Section 4.2.

Note that for all the developed models presented in this section, the inputs incorporated into calculations applying these models must be developed consistent with their use. Where these inputs are provided by other methodologies, the details of their calculation must be referenced sufficiently at time of application to justify their use in this methodology (see limitation in Section 8.2).

4.1 Reactor System Model

4.1.1 Reactivity Feedbacks

As described in Section 2.3, the important reactivity feedback phenomena identified for the Natrium reactor include:

- [[

]](a)(4),ECI

[[

]](a)(4),ECI

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

[[

]](a)(4),ECI

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

[[

]](a)(4),ECI

[[

]](a)(4),ECI

[[

]](a)(4),ECI

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

[[

]](a)(4),ECI

[[

]](a)(4),ECI

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

[[

]](a)(4),ECI

[[

]](a)(4),ECI

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

[[

]](a)(4),ECI

[[

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

[[

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

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

[[

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

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

[[

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

[[

]](a)(4),ECI

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

[[

]](a)(4),ECI

[[

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

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

[[

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

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

[[

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

[[

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

4.2 Reactivity Insertion Model

The calculation of the Nyquist FOM requires an oscillating (sinusoidal) reactivity insertion be applied to the reactor. The amplitude of the reactivity insertion is selected to be small, on the order of cents, consistent with the assumptions around LTI behavior as described in Section 3.2. [[

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

5 TECHNICAL EVALUATION PROCESS DESCRIPTION

The process steps to perform the calculations involved in applying the methodology are described in this section.

5.1 Nyquist Figure of Merit Calculation

5.1.1 Full Power Transfer Function Calculation

5.1.1.1 [[
]]$^{(a)(4),ECI}$

1. [[

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

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

1. [[

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

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

1. [[

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

[[

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

[[

]](a)(4),ECI

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

5.1.2 Zero Power Transfer Function Calculation

[[

]](a)(4),ECI

5.1.3 Open Loop Transfer Function Calculation

To evaluate the Nyquist FOM, the reactor is treated as a single loop feedback system. Figure 5-1 depicts a high-level single loop feedback system diagram. The equations for evaluating the system are listed below.

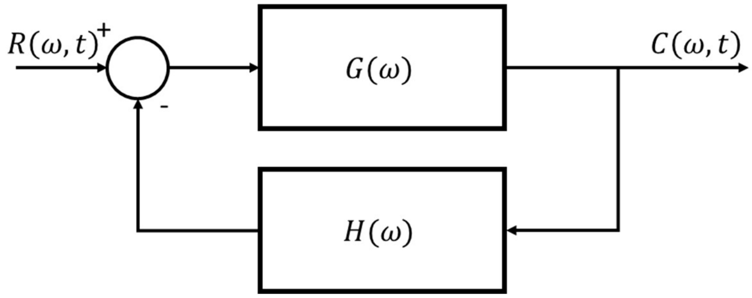

Figure 5-1: Single Loop Feedback System Diagram

$$\left.\frac{C(\omega,t)}{R(\omega,t)}\right\|_{with\ feedback} = \frac{G(\omega)}{1 + G(\omega)\cdot H(\omega)}$$	(5-12)
$$\left.\frac{C(\omega,t)}{R(\omega,t)}\right\|_{no\ feedback} = G(\omega)$$	(5-13)
$$L(\omega) = G(\omega)\cdot H(\omega)$$	(5-14)

Where:

ω: Reactivity insertion frequency $\left(\frac{rad}{s}\right)$

t: Time (s)

$R(\omega, t)$: Input signal: reactivity input $(\$)$

$C(\omega, t)$: Output signal: normalized power response $(unitless)$

$G(\omega)$: Forward loop transfer function

$H(\omega)$: Feedback transfer function

$L(\omega)$: OLTF (also referred to as the system's characteristic equation)

$\left.\frac{C(\omega,t)}{R(\omega,t)}\right|_{with\ feedback}$: FPTF

$\left.\frac{C(\omega,t)}{R(\omega,t)}\right|_{no\ feedback}$: ZPTF

1. [[

]](a)(4),ECI

[[

]](a)(4),ECI

5.2 Method Uncertainties Treatment Calculation

5.2.1 Model Uncertainty Treatment Calculation

[[

]](a)(4),ECI

5.2.2 Input Uncertainties Treatment Calculation

1. [[

]](a)(4),ECI

5.2.3 Final Combined Method (Input and Model) Uncertainties Treatment Calculation

1. [[

]](a)(4),ECI

[[

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

5.3 Stability Map Construction

1. Identify the initial power and flow condition pairs to be plotted on the stability map, following the guidance in the method description (Section 3.1).
2. For each initial power and flow condition pair (referred to as a stability map location), perform the calculation of the Nyquist FOM including the method uncertainties treatment, as detailed in Section 5.2.
   a. Examine the resulting Nyquist FOM [[
   ]]$^{(a)(4),ECI}$ If the Nyquist FOM, including the correction for model uncertainty, crosses or encircles the singularity location on the complex plane at (-1,0), mark that stability map location as unstable per the Nyquist stability criterion. Otherwise, mark it as stable.
3. Report the final stability map, including results for all analyzed power and flow condition pairs, to characterize the Natrium reactor's stability behavior.

6 FERMI-1 BENCHMARK CALCULATION

This section presents the results of a benchmark calculation using Fermi-1 reactor data performed for the purposes of methodology assessment. Fermi-1 was selected as a benchmark because it was a few hundred Megawatt thermal (MWth) metal-fueled SFR (as is the Natrium reactor) that performed oscillator experiments that generated measured Nyquist data. This measured Nyquist data is compared to calculations performed by applying this methodology to Fermi-1. The calculations here seek to:

1. Provide additional context and illustration of how the methodology operates.
2. [[

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

6.1 Nyquist Assessment for Fermi-1

A sample assessment of the gain, phase shift, and OLTF [[

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

6.1.1 Example Assessment [[ ]]$^{(a)(4),ECI}$

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

[[

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

Table 6-1: Example Values

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

[[

]](a)(4),ECI

Figure 6-1: Reactor Dynamic Response

[[

]](a)(4),ECI

Table 6-2: Example Gain and Phase Shift

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

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

[[

]](a)(4),ECI

Table 6-3: Gains and Phase Shifts for Evaluating the Characteristic Equation

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

[[

]](a)(4),ECI

Table 6-4: Summary of Example Calculation

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

6.1.2 Assessment Results [[ ]](a)(4),ECI

[[

]](a)(4),ECI

Table 6-5: Nyquist Summary

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

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

[[

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

Figure 6-2: Transfer Function Gain Plot

[[

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

Figure 6-3: Transfer Function Phase Shift Plot

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

[[

]](a)(4),ECI

Figure 6-4: Nyquist Plot of Calculated and Measured Data

The calculated response of the reactor matches the measured response best for reactivity insertions of higher frequencies. At lower frequencies the model tends to predict higher full power gain and lower zero power gain. The effect of these differences in gains can be seen in the Nyquist plot as increases in the magnitude of the OLTF. However, even with these differences, the calculated OLTF is still similar to the measured OLTF. The average distance between the measured and calculated OLTF is [[ ]](a)(4),ECI Additionally, the calculated Nyquist plot conservatively trends closer to the point of instability than the measured data.

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

[[

]](a)(4),ECI

[[

]](a)(4),ECI

Figure 6-5: Comparison between Measured and Calculated Open Loop Transfer Functions from the Fermi Methodology Assessment

[[

]](a)(4),ECI

[[

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

Figure 6-6: Close-up of Comparison between Measured and Calculated Open Loop Transfer Functions from the Fermi Methodology Assessment

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

6.2 Sensitivity Study on Fermi-1

The comparison between the measured and calculated data reported in Section 6.1.2 displays close agreement between OLTF values at higher frequencies, and reduced agreement between OLTF values at lower frequencies.

[[

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

[[

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

[[

]](a)(4),ECI

Figure 6-7: Nyquist Plot of the Fermi Measured Data, as Compared to Calculated Sensitivity Data

[[ ]](a)(4),ECI the lowest frequency OLTF locations shift furthest on the Nyquist plot. Quantitative values for the reduction in the differences between the calculated and measured OLTF results are shown in Table 6-6.

Table 6-6: Measured vs. Calculated Open Loop Transfer Function Sensitivity

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

It is key to note in this table that the low-frequency [[ ]]$^{(a)(4),ECI}$ average difference decreases significantly from a value [[

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

7 PLANT-SPECIFIC APPLICATION

7.1 Plant-Specific Application Requirements

This methodology's application is limited to an SFR inclusive of the Natrium reactor design. As part of applying this methodology, inputs and associated uncertainties as well as relevant initial condition descriptions must be known. Plant-specific application of the methodology may be performed using [[

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

7.2 Demonstration Application

This section provides an example application of the Natrium stability methodology, including uncertainties treatment, at a single initial condition, which would characterize the stability behavior of the Natrium system at a single location on the stability map. This example calculation is provided solely to illustrate the functioning of the methodology; the results included are meant to be illustrative, not definitive. Additionally, presentations of the detailed calculations of the Nyquist FOM are not included in this demonstration, with the focus instead placed on the calculations associated with the method uncertainties treatment. For an example of detailed Nyquist FOM calculations, please refer to Section 6, which provides these for the Fermi-1 benchmark.

7.2.1 Demonstration of Model Uncertainties Treatment

Section 5.2.1 describes the process utilized and results obtained [[
]]$^{(a)(4),ECI}$ using Fermi-1 benchmark data.

7.2.2 Demonstration of Input Uncertainties Treatment

To perform the treatment of input uncertainties for the Natrium stability methodology, the process described in Section 5.2.2 is followed. Particularly informative components of this process' implementation are described in detail in the following sections.

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

[[

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

Table 7-1: Summary of Input Parameters to be Examined via Uncertainty Analysis

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

Table 7-1: Summary of Input Parameters to be Examined via Uncertainty Analysis

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

7.2.2.1.1 [[
]](a)(4),ECI

[[

]](a)(4),ECI

7.2.3 Method Uncertainty Characterization Results

This result section is split into two subsections. The first describes the Nyquist result for the BOL 100% rated power and flow condition with nominal values. This power and flow condition is also referred to as HFP. The second describes the Nyquist results at this initial power/flow condition [[

]](a)(4),ECI provides the stability characterization at a single point on the stability map.

7.2.3.1 Nominal Beginning-of-Life Hot Full Power Result

The OLTF result for the nominal BOL HFP condition over all [[

]](a)(4),ECI

Table 7-2: Nominal Beginning-of-Life Hot Full Power Open Loop Transfer Function Result and Distances from Singularity

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

[[

]](a)(4),ECI

Figure 7-1: Nyquist Plot for the Beginning-of-Life Hot Full Power Nominal Case

As can be observed in Table 7-2, the distance from the OLTF result and the singularity point at (-1+0j) only increases with decreasing frequency, indicating a stable response and associated trend. Lower frequency OLTF values [[ ]](a)(4),ECI further corroborating the significant distance from the singularity shown in the table. These conclusions remain even after adjusting for the model uncertainty as estimated from the Fermi assessment, [[ ]](a)(4),ECI

7.2.3.2 Uncertainty Characterization Results

The Nyquist plot [[

]](a)(4),ECI

Figure 7-2: Nyquist Results, Accounting for Input Uncertainties

[[

]](a)(4),ECI

[[

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

Figure 7-3: Nyquist Results, Accounting for Input and Model Uncertainties

[[

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

[[

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

Table 7-3: Limiting Open Loop Transfer Function Result and Distances from Singularity

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

Placed in the context of developing the stability map, this demonstration application would indicate that the reactor is stable at the HFP location. A similar process would then be applied at each selected initial power and flow condition to develop the full stability map.

8 CONCLUSIONS AND LIMITATIONS

8.1 Conclusions

In this ToR, a methodology for evaluating the stability of the Natrium reactor is presented. The proposed methodology evaluates the ZPTF and FPTF of the reactor in order to calculate the Nyquist FOM. A treatment of both model and input uncertainties is also applied. The uncertainty-adjusted Nyquist FOM is calculated at a set of power and flow conditions to create a stability map, where the reactor is declared stable or unstable at every location according to the Nyquist stability criterion. The methodology is intended to be applicable to the Natrium reactor, both the initial demonstration design, reloads, and all possible subsequent designs (with appropriate adjustments applied as noted). U.S. Nuclear Regulatory Commission (NRC) approval is requested for the use of this methodology for this purpose, subject to the limitations described below.

8.2 Limitation

This section describes the limitation associated with the application of the Natrium stability methodology described in this report. This limitation must be addressed upon time of application for analyses that utilize this methodology to characterize the stability behavior of the Natrium reactor.

Limitation: Inputs provided to the methodology calculated by other methodologies are to capture the higher-fidelity behavior of the identified important phenomena in a manner consistent with their incorporation into this methodology.

SUBJECT TO DOE COOPERATIVE AGREEMENT NO. DE-NE0009054

9 REFERENCES

Reference Number	Reference
1	NATD-LIC-RPRT-0002, "Principal Design Criteria for the Natrium Advanced Reactor," TerraPower, Inc., 2023.
2	APDA-NTS-11*, Oscillator Tests in the Enrico Fermi Reactor*, Atomic Power Development Associates, Inc., 1967.
3	R. A. Bennett, R. A. Harris and J. W. Daughtry, "HEDL-SA-2417, USA/FBR Program Fast Flux Test Facility Startup Physics and Reactor Characterization Methods and Results," in *International Atomic Energy Agency Seminar*, Julich, 1981.
4	I. A. Engen and R. W. Hyndman, ANL-7542*, A Catalog of Rod-Drop and Transfer-Function Data from EBR-II Runs 25 through 30A*, Argonne National Laboratory, 1970.
5	[[ ]](a)(4)
6	[[ ]](a)(4)
7	[[ ]](a)(4)

END OF DOCUMENT