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TERRAPOWER, LLC – DRAFT SAFETY EVALUATION FOR TOPICAL REPORT NAT-9393, “STABILITY METHODOLOGY TOPICAL REPORT,” REVISION 0 (EPID NO. L-2023-TOP-0057)

SPONSOR AND SUBMITTAL INFORMATION

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Project No.: 99902100

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Brief Description of the Topical Report: By letter dated November 30, 2023, TerraPower, LLC (TerraPower) submitted Topical Report (TR) TP-LIC-RPT-0006, “Stability Methodology Topical Report,” Revision 0, for the U.S. Nuclear Regulatory Commission (NRC) staff’s review. On February 21, 2024, the NRC staff found that the TR provided sufficient information for the NRC staff to begin its detailed technical review (ML23355A072). On April 24, 2024, the NRC staff transmitted an audit plan to TerraPower (ML24115A128) and subsequently conducted an audit of materials related to the TR from May 7, 2024, through July 16, 2024. The NRC issued the audit summary on December 12, 2024 (ML24233A294). On August 16, 2024, TerraPower submitted a revision of the TR (ML24232A231), which was renumbered from TP-LIC-RPT-0006 to NAT-9393, to clarify portions of the TR as discussed in the audit summary.

NAT-9393, Revision 0, describes the methodology used to characterize Natrium reactor stability. TerraPower states, “[n]uclear reactor stability analysis, as approached by this TR, 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.” Specific aspects addressed in the TR include (1) methodology requirements (e.g., important phenomena, constraints, criteria); (2) an overview of the methodology including Figure of Merit (FOM) calculation and associated uncertainty treatment; (3) the models that comprise the methodology; (4) the process steps to perform the calculations involved; (5) a benchmark calculation using historical reactor measurements to be used to construct an estimate of the model uncertainty; and (6) a discussion of plant-specific application, including a demonstration application to aid in understanding of how the methodology operates.

Enclosure

REGULATORY EVALUATION

TerraPower's licensing strategy includes the establishment of principal design criteria (PDCs) to comply with the regulations in Title 10 of the *Code of Federal Regulations* (10 CFR) 50.34(a)(3)(i) that require PDCs for construction permit applications. The Natrium PDCs are specified in TR NATD-LIC-RPRT-0002-A, "Principal Design Criteria for the Natrium Advanced Reactor," Revision 1 (ML24283A066).[1]

The NRC staff conducted its review considering Natrium PDC 12, "Suppression of reactor power oscillations." PDC 12, "Suppression of reactor power oscillations," states:

> 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 system radionuclide release design limits are not possible or can be reliably detected and suppressed.

Though applicable to boiling water reactors (BWRs), the NRC staff considered aspects of chapter 15.9, "Boiling Water Reactor Stability," of NUREG-0800, "Standard Review Plan [SRP] for the Review of Safety Analysis Reports for Nuclear Power Plants," dated March 28, 2007 (ML070550017), relevant to a reactor cooled with single-phase liquid sodium. The proposed Natrium reactor is a sodium-cooled fast reactor, which utilizes sodium as a coolant, in contrast to light water reactors that use water. For example, the staff considered the approach to characterization of a power-to-flow operating domain in SRP chapter 15.9 as applicable to the Natrium reactor. However, as this SRP chapter pertains to BWR behavior, adaptations were applied, such as considering stability behavior in terms of a Nyquist FOM in lieu of a parameter such as a decay ratio.

BACKGROUND AND SUMMARY OF TECHNICAL INFORMATION

1.0 INTRODUCTION

Reactor stability analysis is an evaluation of a reactor's response to cyclic perturbations in reactor power. In a given state, if the reactor is shown to dampen these perturbations, the reactor is considered stable. By contrast, if the reactor is shown to respond with power level fluctuations of increasing magnitude, the reactor is unstable. To comply with PDC 12, several options are available to reactor designers. If a credible analysis demonstrates stable performance at all permissible operating statepoints,[2] including those arising from anticipated operational occurrences, PDC 12would be considered met with regard to a stable reactor. However, if stable performance cannot be demonstrated, exclusion regions that preclude the entry into statepoints that are prone to instability can be defined, or systems can be designed to detect a forming instability and suppress it by changing the statepoint, such as by tripping the

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[1] The NRC staff notes that NAT-9393, Revision 0 (the TR that is the subject of this safety evaluation) references NATD-LIC-RPRT-0002, Revision 0 (ML23024A280). However, TerraPower submitted Revision 1 to NATD-LIC-RPRT-0002, which the staff subsequently approved. The NRC staff verified that PDC 12 is unchanged between NATD-LIC-RPRT-0002, Revision 0, and NATD-LIC-RPRT-0002-A, Revision 1. Thus, the out-of-date reference to NATD-LIC-RPRT-002, Revision 0 in NAT-9393, Revision 0, does not impact the NRC staff's determinations in this safety evaluation.

[2] A statepoint is a specific combination of core thermal power and coolant flow.

reactor. The scope of the TR is limited to the methodology only and does not provide a demonstration of stable performance for the Natrium reactor, nor does the TR address the matter of whether exclusion regions would be necessary or whether systems to detect and suppress unstable behavior would be required. A future licensing action (e.g., operating license application, standard design approval application) would need to address the actual stability performance of the reactor design and demonstrate that the stability performance is acceptable.

The TR includes a set of requirements the methodology must satisfy and an overview describing the use of the Nyquist criterion as the FOM and the treatment of uncertainties. The models and calculational process are described, followed by a comparison of calculated performance to data obtained from the Fermi Unit 1 reactor. The TR concludes with a demonstration application for the proposed Natrium reactor.

The TR is focused on demonstrating the adequacy of the stability analysis methods, but as suggested above, the methods are not applied in sufficient fashion to demonstrate whether the proposed Natrium reactor is stable in all states or whether exclusion regions or systems would be necessary to detect and suppress unstable oscillations. TerraPower notes in TR section 3.1, “Overview,” that the preferred means to address PDC 12 would be to demonstrate stable reactor performance in all states; however, this demonstration is outside the scope of the TR.

Chapter 2, “Method Requirements,” of the TR specifies methodology requirements, which are summarized in TR table 2-1, “Natrium Stability Methodology Requirements.” TerraPower also summarized important stability performance-related phenomena (rated medium or high) that it will address in the methodology (see table 2-2, “Phenomena Important to the Natrium Reactor System”). Finally, TR section 2.4, “Figure of Merit,” describes TerraPower’s basis for using the Nyquist FOM in its stability methodology.

The TR defines the Nyquist stability criterion in the following terms: “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).” A visual representation of this criterion is provided in figure 3-4, “Nyquist Results Used to Determine Input Frequency Domain Selection,” of the TR. The -1+0j point is also referred to as the singularity location.

1.1 Methodology Overview

TR chapter 3, “Methodology Roadmap,” provides a methodology roadmap. The methodology includes consideration of stability performance in an operating domain described by power level and coolant flow (power-to-flow operating domain). Each combination of achievable power level and coolant flow can be considered as a statepoint within the power-to-flow operating domain. The method will be used to generate a Nyquist stability criterion for each statepoint to demonstrate whether that statepoint can be considered stable.

TR figure 3-1, “Set of Initial Power and Flow Condition Statepoints to Characterize the Stability Map for the Natrium Sodium-cooled Fast Reactor,” provides an illustration of the power-to-flow operating domain with seven discrete statepoints. The operating domain establishes the initial conditions used in the calculation of the Nyquist criterion.

As described in TR section 3.2, “Nyquist Figure of Merit Calculation,” the Nyquist criterion is determined using an OLTF, which is calculated from the reactor’s full power transfer function (FPTF) and zero power transfer function (ZPTF). The FPTF and ZPTF differ in that the FPTF measures the reactor response to oscillatory reactivity input in the presence of reactivity feedback, while the ZPTF is a measure of the reactor response to the oscillatory input in the absence of reactivity feedback.

1.2 Models

TR chapter 4, “Models,” describes the modeling approach. **[[ ]]**

The important reactivity feedback phenomena identified for the Natrium reactor as defined in the TR include:

- **[[ ]]**

The TR states the **[[ ]]** TerraPower also notes that **[[ ]]**

The representation of each of these temperatures is provided in detail in TR section 4.1, “Reactor System Model.”

[[ ]]

1.3 System Representation Using Transfer Functions

TR figure 3-2, “Visual Representation of the Methodology’s Process for Calculating the Nyquist Figure of Merit,” provides a basic overview of the methodology, for which the theory is described in TR chapter 5, “Technical Evaluation Process Description.” The process involves calculating the FPTF and the ZPTF, then combining the two to obtain an OLTF. An OLTF is calculated in this manner over the range of frequencies. For the FPTF, **[[**

]] The parameters are then combined as described in TR section 5.1.3, “Open Loop Transfer Function Calculation,” to determine the OLTF.

1.4 Uncertainty Quantification

Separate treatments are applied to model uncertainties and input uncertainties. The uncertainty treatment is described conceptually in TR section 5.2, “Method Uncertainties Treatment Calculation,” and in more detail in TR section 3.3, “Uncertainties Treatment.” The **[[** **]]** is calculated as described in the analytic comparison to stability experiments performed in the Enrico Fermi Unit 1 reactor, which is presented in TR chapter 6, “Fermi-1 Benchmark Calculation.” The demonstration analysis in TR chapter 7, “Plant-Specific Application,” provides an example of the treatment of input uncertainties.

As a demonstration of the approach to address model uncertainties, a comparison is made using the Enrico Fermi Unit 1 stability experiments, which the applicant modeled using its methods. The applicant used the results to determine a **[[** **]]** However, as discussed further in section 2.4 of this SE, TerraPower considered this **[[** **]]** representative until validated upon application, as there are noteworthy differences between the proposed Natrium and Fermi 1 reactors.

Input uncertainties are generally those associated with modeling the various statepoint parameters, including the reactivity parameters. **[[** **]]** Figure 7-2, “Nyquist Results, Accounting for Input Uncertainties,” illustrates the results of the input uncertainty characterization for the Natrium reactor demonstration analysis; Figure 7-3, “Nyquist Results, Accounting for Input and Model Uncertainties,” provides a characterization of the input and model uncertainties.

1.5 Fermi Unit 1 Benchmark Comparison

The methodology was benchmarked against reactor stability tests performed in the Fermi Unit 1 reactor. Fermi 1 was a metallic fuel, sodium-cooled fast reactor that, according to NUREG-1350, was issued an operating license in 1963 and shut down in 1972 (ML23047A371). When the reactor was operating, a series of stability tests were performed that relied on rotating oscillator rods with one side composed of neutron poison to produce sinusoidal reactivity perturbations. A report describing these tests is available from the Department of Energy's Office of Science and Technical Information.[3]

The results for gain and phase shift, respectively, are depicted in figures 6-2, "Transfer Function Gain Plot," and 6-3, "Transfer Function Phase Shift Plot." **[[**

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1.6 Demonstration Analysis

The technical discussion in the TR concludes in chapter 7 with a demonstration of a Natrium-specific analysis. The demonstration includes a **[[**

]] these results conceptually demonstrate stable performance of the reactor at the full power state point.

TECHNICAL EVALUATION

2.0 EVALUATION SCOPE

This evaluation addresses several topics associated with the proposed stability analysis methodology. These topics include:

- Coverage of proposed Natrium reactor operating domain
- Coverage of frequency domain at a given statepoint
- Confirmation of theoretical approach

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[3] Klickman, A.E., *et al.*, Atomic Power Development Associates, Inc, "Enrico Fermi Atomic Power Plant Nuclear Test Series: Oscillator Tests in the Enrico Fermi Reactor," Michigan, August 1967. https://doi.org/10.2172/4505470.

- Treatment of uncertainties
- Adequacy of Fermi 1 benchmark evaluation

Because the TR proposes and demonstrates the stability methodology at a conceptual level, the staff did not assess or make any determinations on the acceptability of the demonstration analysis provided in chapter 7, including specific associated uncertainty values.

2.1 Operating Domain

The TR summarizes an analytic stability methodology to demonstrate PDC 12 is met for the Natrium reactor. Specifically, TR chapter 3 describes the selection of **[[**

]] The TR also states that **[[**

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The NRC staff considered whether this approach would provide adequate coverage of the operating domain. **[[**

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Importantly, the TR recognizes that if a demonstration of reactor stability is not possible throughout the operating domain, additional measures including identifying exclusion regions in the power-to-flow operating domain, monitoring hardware, and reactor protection system actuation will need to be considered; this material is considered outside the scope of the present review. Additionally, since the specific, quantitative operating range extrema statepoints will be identified in applications implementing the TR methodology, these statepoints will be specifically reviewed and approved therein.

2.2 Frequency Domain

At each statepoint, the methodology includes analysis of the effects of **[[**

]] These considerations assure that the licensing analysis will include OLTFs that span an acceptable range of frequencies such that the stability behavior of the reactor at a given statepoint will be well characterized. Based on these considerations, the NRC staff concludes that the applicant's treatment of the frequency domain is acceptable.

2.3 Theoretical Approach

The TR states that the Nyquist FOM has been widely applied for stability analysis of engineered systems. The NRC staff identified and confirmed that several references include frequency-domain techniques relying on transfer functions to determine gain and phase shift and determine a Nyquist FOM to characterize reactor stability behavior. Some examples include journal articles, graduate theses, and textbooks.[4,5,6]

In the TR analysis, nuclear feedback is modeled using **[[**

]] the NRC staff concludes that this modeling representation is acceptable for the stability analysis of this reactor.

The FPTF is determined by evaluating the gain and phase shift associated with **[[**

]] The NRC staff independently analytically derived the ZPTF to verify the TR results. The NRC staff also observed that the ZPTF is also consistent with the work of Oka and Suzuki. The OLTF is then determined using the FPTF and ZPTF results as conceptually illustrated in figure 5-1, "Single Loop Feedback System Diagram."

The NRC staff concludes that the approach using the Nyquist FOM obtained from the OLTF is acceptable because it is consistent with the state-of-practice for stability analyses, including for liquid metal cooled and molten salt cooled and fueled systems.

2.4 Uncertainty Treatment

The TR applies **[[**

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[4] Cammi, A., et al., "Transfer Function Modeling of Zero-Power Dynamics of Circulating Fuel Reactors," Journal of Engineering for Gas Turbines and Power, Volume 133, May 2011.

[5] Oka, Y. and Suzuki, K., Nuclear Reactor Kinetics and Plant Control, Springer, New York, 2013.

[6] March-Leuba, J., University of Tennessee – Knoxville, "Dynamic Behavior of Boiling Water Reactors," Ph.D. Dissertation, Knoxville, Tennessee, 1984.

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[7] **[[**

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[8] **[[**

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[9] **[[**

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[10] **[[**

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2.5 Fermi 1 Benchmark Comparison

The TR states that, **[[**

]] The effect was addressed in the TR by **[[**

]] and the resulting OLTF is shown in figure 6-7, “Nyquist Plot of the Fermi Measured Data, as Compared to Calculated Sensitivity Data.” The NRC staff observed that applying **[[**

]] brought the Fermi 1 benchmark results into closer agreement with the Fermi 1 data; however, the results remain unacceptably discrepant to establish that this is the most likely cause for disagreement between the experimental and calculated results.

In addition to the above sensitivity study, the TR considered **[[**

]] Based on this improved agreement, and because the damping reflects a more realistic representation of the Fermi 1 reactor, the NRC staff concludes that this investigation, along with the radial feedback evaluation described above, provides an acceptable comparison between Fermi 1 data and calculated Nyquist results, such that the comparison establishes that the model provides a credible estimation of the Natrium stability behavior.

LIMITATIONS AND CONDITIONS

The NRC staff imposes the following Limitations and Conditions with regard to the use and approval of the subject TR:

1. 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.

2. The topical report develops a **[[ ]]** for the purpose of describing how such a **[[ ]]** may be obtained and for the purpose of describing how such a **[[ ]]** is subsequently applied as part of the methodology's calculation steps. In application, a **[[ ]]** must be developed and appropriately justified for the use described in this methodology. Any applied **[[ ]]** must be reviewed and approved by the NRC.

Additional discussion for both Limitations and Conditions is provided in section 2.4 of this SE.

CONCLUSION

The NRC staff concludes that TerraPower TR NAT-9393, Revision 0, "Stability Methodology Topical Report," provides an acceptable methodology for assessing the stability characteristics of the Natrium reactor based on the following considerations:

1. The TR proposes an acceptable means to characterize and discretize the power-to-flow operating domain, including characteristics to indicate when a more detailed discretization would be necessary.
2. An applicant implementing the methodology will justify the selection of analyzed frequencies at each state point.
3. The TR methodology reflects a theoretical approach that has been used to evaluate stability in similar reactor system designs;
4. The TR methodology includes an acceptable means to characterize input and model uncertainty, and to justify these means; and
5. The TR includes an acceptable evaluation of a benchmarking exercise comparing its analytic methods to stability experiments in the Fermi 1 reactor.

These review conclusions are subject to the two limitations and conditions discussed above. Accordingly, the NRC staff concludes that TerraPower TR NAT-9393, Revision 0, "Stability

Methodology Topical Report," can be used for assessing the stability characteristics of the Natrium reactor.

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Date: 1/31/2025

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