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TERRAPOWER, LLC – FINAL SAFETY EVALUATION OF TOPICAL REPORT NATD-FQL-PLAN-0004, "FUEL AND CONTROL ASSEMBLY QUALIFICATION," REVISION 0 (EPID L-2023-TOP-0017)

SPONSOR AND SUBMITTAL INFORMATION

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Brief Description of the Topical Report: NATD-FQL-PLAN-0004, "Fuel and Control Assembly Qualification," Revision 0 [1] provides TerraPower, LLC's (TerraPower's) plan to qualify fuel and control assemblies for the Natrium sodium fast reactor (SFR). The topical report (TR) identifies acceptance criteria for fuel qualification and presents select fuel qualification results in addition to ongoing and planned fuel qualification activities. The TR also summarizes a notional fuel surveillance plan for the collection of data to address certain targeted gaps and help develop new fuel designs. The qualification plan is applicable to Natrium Type 1 fuel, a uranium-10 weight percent zirconium (U-10Zr) alloy fuel clad in HT9 steel, and control assemblies using boron carbide as a neutron absorber.

Following the initial TR submittal, TerraPower identified minor errors and submitted corrections [2]. The errata noted some minor changes to numbers in Table 6-7, "Type 1 Fuel Assembly Design Parameters," of the TR and stated that the report would be re-numbered because TerraPower's report numbering scheme had changed.

REGULATORY EVALUATION

The TR was submitted in support of TerraPower's license application under Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities." [3]

Enclosure 1

The U.S. Nuclear Regulatory Commission (NRC) regulations under 10 CFR Part 50 applicable to the Natrium reactor's fuel and control assemblies include:

- 10 CFR 50.43(e), which states that reactor designs that differ significantly from light-water reactor (LWR) designs licensed before 1997 will be approved only if there has been appropriate demonstration of their safety features. In particular, 10 CFR 50.43(e)(1)(i) and (ii) require demonstration of safety feature performance and interdependent effects through analysis, appropriate test programs, experience, or a combination thereof; and 10 CFR 50.43(e)(1)(iii) requires that sufficient data exist on the safety features to assess the analytical tools for safety analysis over a sufficient range of plant conditions.
- 10 CFR 50.34(a)(1)(ii)(D), which requires construction permit (CP) applicants to evaluate a postulated fission product release from the core into the containment.
- 10 CFR 50.34(a)(3)(i), which requires CP applicants to submit principal design criteria (PDCs) for the facility. The regulation notes that the general design criteria (GDCs) included in 10 CFR Part 50, Appendix A, "General Design Criteria for Nuclear Power Plants," provide guidance to CP applicants for establishing PDCs for facilities different in design and location to plants for which CPs have previously been issued by the NRC. TerraPower submitted a TR concerning PDCs for the Natrium design [4].

The guidance considered by the NRC staff in its review of the TR included the following:

Guidance on fuel qualification for non-LWRs is provided in NUREG-2246, "Fuel Qualification for Advanced Reactors" [5]. This NUREG builds on guidance for LWRs contained in NUREG-0800, Section 4.2, "Fuel System Design," Revision 3 [6]. Concepts in these guidance documents are also broadly applicable to the qualification of control assemblies.

Additional relevant technical information is available in NUREG/CR-7305, "Metal Fuel Qualification: Fuel Assessment Using NRC NUREG-2246, 'Fuel Qualification for Advanced Reactors,'" [7] which is a generic assessment of uranium-zirconium alloy metallic fuel following the NUREG-2246 process. While NUREG/CR-7305 assumes certain characteristics of the fuel for the purposes of its assessment, most of the discussion in that report is relevant to the Natrium Type 1 fuel.

Finally, TerraPower is following the Licensing Modernization Project (LMP) design and licensing approach outlined in Nuclear Energy Institute (NEI) 18-04, "Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development" [8]. The LMP approach was endorsed by the NRC staff in Regulatory Guide (RG) 1.233, "Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors" [9]. This guidance defines risk-informed, performance based, and technology-inclusive processes for the selection of licensing basis events; safety classification of structures, systems, and components (SSCs); and determination of defense-in-depth adequacy for non-LWRs. NEI 18-04 provides a frequency-consequence target curve that is used to assess events, SSCs, and programmatic controls. Because the fuel is the primary source of radionuclides in the reactor, its performance under both normal and off-normal conditions plays a key role in evaluating consequences for the NEI 18-04 process.

TECHNICAL EVALUATION

1.0 INTRODUCTION

TerraPower stated in TR Section 1, "Purpose," that the objective of the TR is to "confirm that all aspects of the fuel system design and fabrication process will provide reliable and safe operation of a commercial sodium-cooled, fast-neutron spectrum nuclear reactor."[1] The TR further requests specific NRC review and approval that:

- the identified acceptance criteria are adequate to support fuel qualification.
- the identified key fuel manufacturing parameters are adequate to support fuel qualification.
- the identified evaluation methods and models are adequate to support fuel qualification.
- the use of legacy data and the planned testing is adequate to provide the necessary information to qualify the fuel.
- the plans for inclusion of small subsets of fuel pins that operate outside the performance envelope of the bulk of the core, or that feature advanced design features, are acceptable.

The NRC staff considered TerraPower's overall objective and specific requests in the preparation of this safety evaluation (SE). In the executive summary of the TR, TerraPower presented the TR as a "plan to qualify fuel and control assemblies to support operation of the Natrium Reactor" containing "TerraPower's fuel qualification results to date as well as plans for future fuel qualification activities." Knowing that fuel qualification has not yet been completed, the NRC staff's SE focuses on the acceptability of the qualification plan, the acceptability of the qualification activities carried out thus far, and the specific items requested in the TR. Limitation and Condition (L&C) 1 highlights the scope of this TR as a fuel qualification plan that does not in and of itself demonstrate that the fuel is qualified and the future work that must be done to qualify Natrium Type 1 fuel.

To the extent possible, this SE assesses TerraPower's fuel and control assembly qualification plan against the fuel qualification assessment framework (FQAF) criteria provided in NUREG-2246. The FQAF provides a set of goals that, when satisfied, provide reasonable assurance that the fuel, fabricated in accordance with its specification, will perform as described in the safety analysis (i.e., the fuel is qualified for use). The FQAF is constructed using a top-down approach, in which the primary objective is stated as a goal. This goal is composed of subgoals which, if met, demonstrate that the higher-level goal is satisfied. Subgoals may be further composed of lower level subgoals, and so on, until the supporting subgoals are at the level where they can be directly verified by evidence. The NRC staff notes that NUREG-2246 is not a requirement but provides an acceptable means for an applicant or licensee to demonstrate that fuel has been appropriately qualified.

As discussed in the TR, TerraPower's strategy for fuel qualification is centered around the development of regulatory acceptance criteria (RAC), which represent acceptance criteria derived from regulatory requirements. These RAC were identified by TerraPower based on a review of relevant regulations and guidance prior to the issuance of NUREG-2246. However,

[1] Because the TR also covers control assemblies, the NRC staff assumes that a similar objective could also be applied to aspects of control assembly design.

TerraPower identified in Section 1 of the TR that the fuel qualification plan was informed by NUREG-2246, and that Section 2.2, "Regulatory Background," of the TR provides a mapping of the RAC discussed in the TR to the NUREG-2246 FQAF goals (Table 2-1, "TerraPower Identified/Developed RAC Mapped to NUREG-2246 Appendix A Goals in FQAF 14") and to the NUREG-2246 evaluation model assessment framework goals (Table 2-2, "TerraPower Identified/Developed RAC Mapped to NUREG-2246 Evaluation Model Assessment Framework Goals").

2.0 BACKGROUND

2.1 Natrium Type 1 fuel design

Section 5.2, "Fuel Assemblies," of the TR presents details on the Natrium Type 1 fuel design. The overall design is conceptually very similar to fuel operated in previous United States SFRs, particularly the metallic fuel irradiated in Experimental Breeder Reactor-II (EBR-II) and the Fast Flux Test Facility (FFTF).[2] The fuel consists of U-10Zr slugs inside HT9 fuel pins. The pins are wrapped with an HT9 wire to provide spacing and are assembled into a hexagonal bundle, which is inserted into an HT9 duct. The final assembly has an inlet nozzle that interfaces with the core support structure and a handling socket that allows the assembly to interface with fuel handling equipment. Additional details from the TR are provided in the sections that follow.

2.1.1 Fuel pin

The metallic fuel is composed of U-10Zr. The enrichment of the uranium in the Natrium Type 1 fuel varies depending on the fuel's intended location in the core, but peak enrichment is < 20% uranium-235. The fuel is formed into right cylindrical slugs via injection casting in quartz molds.

Following manufacturing and inspection, the fuel slugs are inserted into cladding tubes composed of HT9, a ferritic-martensitic steel. The cross-sectional area of the slugs is approximately 75% of the internal cross-sectional area of the cladding. A liquid metallic sodium bond is used to fill the space between the fuel and the cladding; this is necessary to improve heat transfer, particularly at beginning of life before the fuel swells to the point where it contacts the cladding. Below the fuel column within the pin, there is an axial shield section composed of [[ ]], while above the fuel column there is a fission gas plenum initially backfilled with inert gas. [[ ]]. The pin is sealed with end caps attached to the cladding using resistance pressure welding.

The fuel pins are then wrapped in HT9 wire to provide spacing between the pins when they are loaded into a fuel assembly. The wire is fixed at each end of the fuel pin by [[ ]].

[2] Though the FFTF was primarily an oxide-fueled reactor that was used to irradiate a series of metallic fuel assemblies, referred to in the literature as MFF (which is not a clearly defined acronym, according to the TR), towards the end of its operating life. These assemblies were part of a metallic fuel qualification campaign that was terminated when FFTF was shut down in 1994.

2.1.2 Fuel assembly

Once the HT9 wire wrap is completed, the fuel pins are arranged into a tight triangular pitch and attached together into a hexagonal bundle. This fuel pin bundle is then inserted into the fuel assembly. The fuel assembly consists of an inlet nozzle, hexagonal duct, handling socket, and the fuel pin bundle. [[ ]].

The handling socket [[ ]], and is attached to the top of the duct. The duct is the principal structural member of the fuel assembly and provides vertical support during fuel handling operations and horizontal support during power operations. The inlet nozzle is attached to the bottom of the duct and is inserted into the core support structure, supporting the fuel assembly vertically during power operations. The inlet nozzle [[ ]].

2.1.3 Core restraint system

The handling socket functions as the top-core load pad and the duct includes an above-core load pad. These load pads are important components of the core restraint system, which positions the fuel assemblies horizontally within the core while allowing for limited bowing due to neutronic and thermal effects. Geometric distortion of the fuel has a significant effect on core reactivity due to changes in neutron leakage; this effect contributes to the inherent reactivity feedback characteristics of the fuel.

2.1.4 Lead demonstration assemblies and lead test assemblies

TerraPower states in TR Section 9, "Fuel Surveillance," that it intends to include lead demonstration and lead test assemblies (LDAs and LTAs, respectively) in the Natrium reactor core beginning with the first cycle of operation. LDAs and LTAs are discussed in Section 5.2.3, "Lead Demonstration Assembly," and Section 5.2.4, "Lead Test Assemblies / Type 1B Fuel," of the TR, respectively, and the fuel surveillance program, which is supported by the LDAs, is discussed in Section 9, "Fuel Surveillance," of the TR.

LDAs are intended to [[ ]]. The LDAs will be as similar as possible to standard Natrium Type 1 fuel assemblies, but will include up to [[ ]] removable pins that will be examined following irradiation to confirm fuel performance. These removable pins will be very similar to the standard fuel pins, with the following exceptions: the length of the pins will extend beyond the top of the standard pins with a feature on the upper end cap to enable them to be removed with a pin removal tool, [[ ]].

LTAs are intended to test new fuel design features in support of the eventual qualification and use of future Natrium fuels. The overall design concept for the LTA is similar to that of the LDA; however, the LTA uses a different fuel duct material and a different fuel pin design. The LTA fuel duct is composed of [[ ]]. The LTA fuel pin [[ ]].

2.2 Natrium control assemblies

Section 5.3, "Control Assemblies," of the TR provides details on the control assembly design. As noted in the TR, the main function of the control assemblies is to position neutron absorber material to appropriately control and terminate the nuclear chain reaction. This absorber material is composed of boron carbide which, like the fuel rods, is inserted into HT9 absorber pins. Also like the fuel pins, the absorber pins are wrapped with HT9 wire for spacing and packed into a hexagonal bundle. The bundle is assembled into what TerraPower refers to as a control rod assembly. This assembly consists of the pin bundle, upper and lower guide plates, a coupling head that connects to the control rod drive, and an HT9 control rod duct that surrounds the absorber rods. This whole control rod assembly moves up and down within the control assembly duct, which occupies its own space within the core. The control assembly duct, load pads, and handling socket are identical to the fuel assembly duct, though the inlet nozzle is slightly different. At the bottom of the control assembly duct, sitting on top of the inlet nozzle, is an axial shield block. During a reactor scram, the control rod drive disconnects at the coupling head and the control rod assembly drops into the core via gravity.

TerraPower is also developing a secondary control rod assembly that features some design differences relative to the primary control rod assembly to ensure a diverse means to control and terminate the nuclear chain reaction. The main differences between the primary and secondary assemblies are that ECI [[

]]. The intent of these changes is to reduce the likelihood of mechanical binding of the control rod assembly within the control assembly duct for the secondary control rod assembly. Mechanical binding is considered to be the main mechanism that could inhibit control rod insertion.

3.0 FUEL QUALIFICATION PLAN EVALUATION USING THE NUREG-2246 FUEL QUALIFICATION ASSESSMENT FRAMEWORK

3.1 Manufacturing specifications

FQAF Goal 1 (G1) states that "licensing documentation should include sufficient information to ensure the control of key parameters affecting fuel performance during the manufacturing process." This goal is comprised of three supporting goals: that key dimensions and tolerances of fuel components are specified (G1.1); that key constituents are specified with allowance for impurities (G1.2); and that end state attributes for materials within the fuel component are specified or otherwise justified (G1.3).

Table 2-1 of the TR indicates that G1, including G1.1, G1.2, and G1.3, is addressed by RAC 4.2-5. The TR does not state the acceptance criterion associated with RAC 4.2-5. However, a description of all RAC was previously submitted to the NRC staff by TerraPower in a white paper (WP) entitled "Advanced Fuel Qualification Methodology Report" [10]. In this document, RAC 4.2-5 states that "the fuel system description and design drawings shall provide information necessary to verify that the fuel system design bases are met." The NRC staff evaluated the information provided in the TR in this context to ensure that it is consistent with G1 and its supporting subgoals, as discussed below.

3.1.1 Key dimensions and tolerances

FQAF G1.1 states that key dimensions and tolerances of fuel components that affect performance should be specified. Table 2-1 of the TR indicates that this goal is fulfilled by providing references to design drawings that specify relevant key dimensions and tolerances of fuel components, as identified by RAC 4.2-5. The applicable specifications and the primary sources for this information are summarized in Section 5.6, "Verification of the Fuel System Design Basis," of the TR, particularly in Table 5-3, "Summary of Completed and Planned Activities to Satisfy Fuel System Design Description Requirements (RAC 4.2-5)."

The NRC staff reviewed Table 5-3 and determined that the documents referenced are expected to cover all key dimensions and tolerances of the fuel, including dimensions for the fuel, cladding, and assembly components. Additionally, the NRC staff verified during the audit that the documents contain the appropriate information (ML24043A155). Therefore, the NRC staff concluded that the TR provides an acceptable approach to demonstrate that G1.1 is satisfied.

3.1.2 Key constituents

FQAF G1.2 states that key constituents should be specified with allowance for impurities. Table 2-1 of the TR indicates that relevant key constituents with allowance for impurities, as identified by RAC 4.2-5, are specified in design drawings. The applicable specifications and the primary sources for this information are summarized in Section 5.6 of the TR, particularly in Table 5-3.

Section 5.5.1, "HT9," of the TR provides details on the HT9 alloy, which is used for various components in the fuel assembly, including the cladding. Section 5.5.1.1, "Composition," provides details on the material composition, particularly in Table 5-1, "Nominal Composition of HT9 Steel." Table 5-3 references a document that provides information on the "type and metallurgical state of the cladding." The NRC staff determined that the information referenced in the TR appropriately specifies the key constituents of HT9. Section 5.5.2, "U-10Zr Fuel," of the TR provides a brief overview of the fuel slug materials and manufacturing process. Table 5-3 additionally references a document containing information on the "slug alloy composition for metallic fuel" and "allowable slug impurities," which the NRC staff reviewed during the audit. The NRC staff determined that the information referenced in the TR appropriately specifies the key constituents of the fuel slug.

Section 5.5.3, "Other Core Materials," refers to the potential use of other materials for some components of the fuel system, including Type 304 and Type 316 stainless steel and Inconel 718. The TR does not specifically state where these materials would be used, except for [[ ]]. As discussed in the TR, these materials are commonly used in the nuclear industry. TerraPower stated in the TR that design inputs, such as material performance and properties, would be considered pre-qualified for these materials if they are obtained from NRC-accepted standards.

The NRC staff determined that the TR provides an acceptable approach for demonstrating that G1.2 is satisfied, particularly for HT9 and U-10Zr, because key material constituents and impurities are appropriately specified in the documentation referenced in the TR. If other materials are used in the fuel system, TerraPower should demonstrate that these materials are manufactured according to standard specifications and used consistent with their qualification under relevant NRC-accepted codes and standards, or otherwise appropriately justified. This is documented as L&C 2, below.

3.1.3 End-state attributes

FQAF G1.3 states that end-state attributes for materials within the fuel component should be specified or otherwise justified, particularly to the extent that these end-state attributes influence key properties of the fuel during operation. NUREG/CR-7305 Section 2.1.3, “End-State Attributes,” provides some end-state attributes considered to be important for a U-Zr/HT9 fuel system, as they relate to the fuel slugs, sodium bond, and the cladding. These attributes can be summarized as:

- the fuel should be manufactured using an injection molding process with controls on the formation of oxides and the fuel density
- the sodium bond needs to have limited voids and the height of the sodium bond in the plenum must be appropriate
- the cladding plenum needs to be appropriately sized and the welds need to meet certain criteria

Some details on the manufacturing process for HT9 are provided in TR Section 5.5.1.2, “Manufacturing Process,” while the fuel slug manufacturing process is discussed in Section 5.5.2.1, “Manufacturing Process,” of the TR. Additionally, Table 5-3 of the TR provides references to documents that provide further details on the fuel cladding and slug specifications, including manufacturing processes. Based on the information provided in the TR and referenced in Table 5-3, which the NRC staff verified during the audit, the NRC staff found that the desired end-state attributes provided for Natrium Type 1 fuel are consistent with (i.e., they meet or exceed) the key desired end-state attributes discussed. Thus, the NRC staff determined that the TR provides an acceptable approach to demonstrate that G1.3 is satisfied.

3.2 Safety criteria

FQAF Goal 2 pertains to safety criteria that support evaluation of the fuel’s safety performance. This goal is comprised of three subgoals in the following areas: design limits during normal operations and anticipated operational occurrences (AOOs) (G2.1); radionuclide release limits under accident conditions (G2.2); and safe shutdown (G3.3).

In addressing fuel safety performance safety criteria for Natrium, the NRC staff notes that TerraPower’s proposed PDCs [4] include specified acceptable system radionuclide release design limits (SARRDLs) and a functional containment, rather than the specified acceptable fuel design limits (SAFDLs) included in the GDCs. As discussed in RG 1.232, “Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors” [12], the SARRDLs are not a generically acceptable replacement for the SAFDLs but are instead a necessary complement to the use of a functional containment approach. The SARRDLs limit the amount of radionuclide inventory released by the system (i.e., in this case, the fuel, primary coolant system, and all unisolated connected systems that may contribute to dose, such as the cover gas and primary sodium purification systems).

Section 1 of TerraPower’s TR states that one key objective of the fuel design criteria and associated limits is to ensure that the fuel system is not damaged as a result of normal operations and AOOs. The NRC staff determined that the fuel design criteria and associated limits are appropriate as supporting criteria for the SARRDLs because, if the fuel system is not damaged from normal operations and AOOs, a substantial increase in circulating radionuclides from normal operations and AOOs is not expected. Therefore, SARRDLs could be satisfied with respect to releases from the fuel. The NRC staff's evaluation of the fuel design criteria for normal operations and AOOs is included below in SE Section 3.2.1.

However, fuel performance criteria are necessary but not sufficient to evaluate the SARRDLs. Based on operating experience, while random fuel pin failures from various mechanisms (e.g., manufacturing defects, cladding fretting) are expected to be rare, they are not completely preventable so some radionuclide release from the fuel must be assumed and accounted for in the evaluation of the SARRDLs. The relationship between the SARRDLs and fuel design limits is discussed in L&C 3.

3.2.1 Design limits during normal operations and anticipated operational occurrences

FQAF G2.1 states that margin to design limits should be demonstrated under conditions of normal operation, including the effects of AOOs. This goal is further divided into two subgoals, which are discussed below.

3.2.1.1 Fuel performance envelope for normal operations and AOOs

FQAF G2.1.1 states that the fuel performance envelope for normal operations and AOOs should be defined. The fuel performance envelope defines the conditions under which the fuel is expected to perform and informs various aspects of a plant's licensing basis, including the safety analysis, technical specifications, and operating limits. As discussed in NUREG-2246, the fuel performance envelope is typically provided in terms of parameters such as temperature, power, and exposure.

To demonstrate that G2.1.1 is satisfied, Table 2-1 of the TR refers to RAC that TerraPower identified for a number of mechanisms. The intent of these acceptance criteria is to provide an envelope in which it can be demonstrated that the fuel system is not damaged as a result of normal operations and AOOs, consistent with FQAF G2.1.1. While damage was not clearly defined in the TR, TerraPower provided the following definition in [10] for RAC 4.2-1: "Fuel system damage means that fuel system dimensions are outside operational tolerances or the functional capabilities of the fuel system are reduced below those assumed in the safety analysis." This is a conservative definition of "damage" below which it would be reasonable to assume that the fuel would not fail, but beyond which additional evaluation would be needed to ensure that the fuel is still capable of fulfilling its functional requirements and the safety analysis remains valid. TerraPower provided damage criteria for both the fuel pin and for the whole fuel assembly, which are discussed in more detail in the following sections.

Fuel Pin Damage Criteria

Specific RAC for fuel system damage are provided in TR Table 4-1, "Design Criteria to Prevent Fuel System Damage." The criteria applicable to fuel pin damage are summarized as follows:

- RAC 4.2-1.1 – stress, strain, and loading
- RAC 4.2-1.2 – fatigue
- RAC 4.2-1.3 – fretting wear
- RAC 4.2-1.4 – erosion and corrosion

- RAC 4.2-1.5 – cladding internal damage due to fuel-cladding chemical interaction (FCCI)
- RAC 4.2-1.6 – dimensional changes, such as bowing or swelling
- RAC 4.2-1.8 – fuel pin internal pressure
- RAC 4.2-1.12 – fuel and cladding temperatures

The NRC staff notes that these criteria do not in and of themselves establish a fuel performance envelope as envisioned by NUREG-2246. In comparison, Section 2.3, "Fuel Performance Envelope," of NUREG/CR-7305 provides a proposed steady-state envelope for U-10Zr/HT9 fuel meeting certain geometric considerations approximately equivalent to Natrium Type 1 fuel and the metallic fuel operated at EBR-II and FFTF. This envelope includes a peak fuel rod burnup of 10%; a beginning of life peak linear heat generation rate of 40 to 55 kilowatts per meter (kW/m); a peak steady-state fuel cladding temperature of 650 degrees Celsius (°C); total radial strain and deformation of 2%, or a limiting cumulative damage fraction; and peak fuel temperature below the local fuel composition solidus temperature (that is, no fuel melting). NUREG/CR-7305 additionally specifies that a limit should be established for eutectic penetration of the cladding for AOOs.

NUREG/CR-7305 Section 2.3.1, "Behaviors, Phenomena, and Properties," also discusses key behaviors of metallic fuel that impact safety. These include the geometric evolution of the cladding, which is heavily influenced by fuel swelling and cladding creep behavior; fuel properties, including the melting or solidus temperature, which are influenced by fuel constituent migration; cladding properties, including yield stress, solidus temperature, thermal properties, and irradiation effects; cladding rupture due to overpressure; and the overarching effect on all of these mechanisms of the cladding thinning caused by FCCI. While TerraPower did not fully establish a fuel performance envelope as noted above, the NRC staff determined that the pin damage acceptance criteria provided by TerraPower are consistent with the key phenomena discussed in NUREG/CR-7305 for normal operations and AOOs and, therefore, provide an acceptable approach to qualifying Natrium Type 1 fuel.

The NRC staff notes that future fuel qualification work would be expected to establish and appropriately justify limits on fuel pin design criteria used to demonstrate that the acceptance criteria are satisfied. While TR Table 6-8, "Comparison of Fuel System Operational Parameters," appears to document much of the operating envelope for normal operations, these design limits are necessary to fully understand the conditions in which the fuel is expected to operate. The development of design limits and the definition of an associated operating envelope is in many cases also intrinsically tied to the analytical approaches used to evaluate the limits. For example, Section 3.2, "Fuel Constituent Migration," of NUREG/CR-7305 discusses the significance of fuel constituent redistribution on thermal properties, but notes that the effect is captured in post-irradiation experiment (PIE) data below 10% burnup. If the fuel is to be used within the burnup envelope and evaluated using empirical fuel property models developed based on these PIE data, fuel constituent redistribution is included implicitly and is not a particular concern.

However, if the fuel is used significantly beyond the burnup envelope or it is analyzed with mechanistic models, fuel constituent redistribution should be modeled explicitly and one might expect a different set of limits to be developed, possibly on different parameters. Relatedly, the NRC staff also notes that in developing and evaluating these fuel performance limits, consideration should be given to ensuring that appropriate phenomena are included in the evaluation (e.g., evaluations of cladding stress and strain should account for any residual stresses in the cladding from manufacturing, residual stresses and changes in material properties from end cap welding, compressive stress imposed by the wire wrap). The NRC staff also expects future qualification work to characterize the AOOs that the fuel is expected to experience without damage. See L&C 1 for a discussion of future work needed to qualify the fuel.

Fuel Assembly Damage Criteria

In addition to effects on the fuel pin alone, the TR also provides additional design criteria for the fuel assembly in Table 4-1. The RAC and associated phenomena applicable to the fuel assembly include:

- RAC 4.2-1.1 – stress, strain, and loading
- RAC 4.2-1.2 – fatigue
- RAC 4.2-1.3 – fretting wear, [[ ]]
- RAC 4.2-1.4 – erosion and corrosion, [[ ]]
- RAC 4.2-1.6 – dimensional changes such as duct bowing and dilation
- RAC 4.2-1.9 – hydraulic loads exceeding the hold-down capability of fuel, reflector, or shield assemblies
- RAC 4.2-1.12 – assembly component temperatures (which must be either limited or explicitly assessed in analyses demonstrating compliance with other fuel system damage criteria)

As discussed in Section 5.2.2, “Fuel Assembly,” of the TR, the purposes of the fuel assembly are to position the fuel in the core, provide passages to guide and control sodium for heat removal, provide shielding for components of the core support structure, provide features for proper interfacing with other core components [[ ]], and to provide a physical barrier between fuel pins to minimize the effect of one assembly on adjacent assemblies. The NRC staff finds that the criteria presented above adequately encompass the phenomena that would degrade these functions and, therefore, determined that they provide an acceptable approach to qualifying Natrium Type 1 fuel. The NRC staff notes that as with the pin acceptance criteria, the actual limits were not provided; the development and justification of these limits is expected to be part of future fuel qualification work (see L&C 1).

The NRC staff additionally notes that the applicable fuel assembly design criteria in TR Table 4-1 reference [[ ]]. L&C 4 therefore states that if these design criteria are to be used to establish fuel assembly design limits, additional justification must be provided.

3.2.1.2 Evaluation model

FQAF G2.1.2 states that evaluation models (EMs) should be available to assess fuel performance against design limits to protect against fuel failure and degradation mechanisms. The NRC staff notes that Natrium fuel EMs are discussed in Section 6.4, “Analytical Predictions,” of the TR. However, the EM itself is assessed against a separate framework and is, therefore, discussed in Section 3.3, below.

3.2.2 Radionuclide release limits

Complementing FQAF G2.1 criteria for normal operations and AOOs, FQAF G2.2 states that margin to radionuclide release limits under accident conditions should be demonstrated for the fuel. This goal is supported by four subgoals regarding the fuel performance envelope for accidents (G2.2.1); requirements for radionuclide retention within the fuel system (G2.2.2); barrier degradation and failure criteria (G2.2.3); and radionuclide retention and release (G2.2.4). In developing these goals and subgoals, NUREG-2246 states that “as radionuclide inventory originates from the nuclear fuel, fuel qualification should include characterizing the behavior of the fuel under accident conditions, so that its contribution to the accident source term can be determined in a suitably conservative manner.”

3.2.2.1 Fuel performance envelope for accidents

FQAF G2.1.1, which was discussed previously in Section 3.2.1.1 of this SE, also covers the fuel performance envelope for accidents. TerraPower stated in the TR that the fuel performance envelope for accidents is defined by the fuel system failure criteria in TR Table 4-2, “Design Criteria to Prevent Fuel System Failure,” the fuel coolability criteria in TR Table 4-3, “Design Criteria to Ensure Fuel Coolability,” and the reactivity control insertability criteria in TR Table 4-4, “Design Criteria to Ensure Reactivity Control Insertability.”

While the NRC staff acknowledges that the fuel performance envelope for accidents is defined by the fuel failure criteria to some degree, the criteria that must be considered and what constitutes appropriate limits are also driven by the transients that may occur in the reactor. The overall system transient response is, in turn, driven by the design of the plant, including SSCs such as reactivity control systems and pumps. This ultimately results in effects that can be applied to the fuel, such as power ramp rates, coolant flow rates, seismic loads, etc. However, because these transients are defined by the system design rather than the fuel, TerraPower did not define the types or magnitudes of transients that the fuel is expected to experience in the TR.

Although the present approach does not currently include a discussion on the system transients that the fuel is expected to experience, the NRC staff expects that these transients would be defined in other licensing submittals that address transient safety analysis. In the TR, TerraPower performed a review of historical transient test data and proposed additional testing that addresses transient behavior of the fuel, as is discussed in Section 3.4 of this SE. The NRC staff finds TerraPower’s approach to identifying the fuel performance envelope acceptable because of this planned testing that will be informed by transient safety analyses. This represents additional work needed to qualify the fuel (see L&C 1).

3.2.2.2 Radionuclide retention requirements

FQAF G2.2.1 states that the radionuclide retention requirements for the fuel – that is, the extent to which radionuclides are expected to be retained within the fuel system – should be specified. While the TR implies (see Section 8, "Online Fuel System Monitoring for Fuel Pin Failure," of the TR, for example) that the fission gases in the plenum would be expected to be released into the primary coolant upon cladding breach, TerraPower did not include specific radionuclide retention requirements. Instead, TerraPower stated that these requirements would be described in the Natrium preliminary safety analysis report (PSAR).

The NRC staff understands that the retention requirements would be addressed in a separate submittal covering TerraPower's approach to analyzing design basis accidents that result in releases of radionuclides from the fuel. As with the transient fuel performance envelope discussed above, this is reasonable considering that more than just the fuel system itself plays a role in defining these requirements. However, in addressing transient fuel behavior, TerraPower identified relevant historical test data and discussed plans for future testing and analysis, demonstrating an appropriate path forward. By contrast, no similar path forward was presented for radionuclide retention and release, which plays a key role in the source term expected from the fuel. As such, the NRC staff imposed L&C 5, which states that radionuclide retention and release requirements must be specified.

3.2.2.3 Barrier degradation and failure criteria

FQAF G2.2.2 states that the criteria for barrier degradation and failure under accident conditions must be understood and suitably conservative when the design credits some retention of barrier integrity. In the case of Natrium Type 1 fuel, these criteria are for the radionuclide barriers represented by the fuel matrix and fuel cladding. This goal is supported by two subgoals: that the criteria must be conservative as demonstrated by comparison to data (G2.2.2(a)) and that the data used for validation are appropriate (G2.2.2(b)).

Barrier degradation and failure criteria (G2.2.2(a))

Barrier degradation is discussed in the context of the fuel performance criteria for normal operations and AOOs in Section 3.2.1.1 of this SE. Therefore, this section will focus on the criteria for accidents (i.e., failure). Table 2-1 of the TR identifies that RAC 4.2-2.1 through 4.2-2.5 represent the criteria for fuel pin failure. These acceptance criteria are discussed further in TR Table 4-2, which includes the following:

- RAC 4.2-2.1 – Fuel cladding overheating
- RAC 4.2-2.2 – Fuel slug overheating
- RAC 4.2-2.3 – Fuel cladding deformation due to mechanical loads, up to and including cladding rupture
- RAC 4.2-2.4 – Fuel system mechanical fracturing caused by externally applied forces
- RAC 4.2-2.5 – Fuel cladding wastage

While the TR indicates that TerraPower plans to identify the melting point of the cladding and protect against fuel cladding melting for the purposes of ensuring a coolable geometry, the RAC 4.2-2.1 fuel cladding temperature criterion is primarily to protect against [[

]]. The fuel slug temperature criterion (RAC 4.2-2.2) is to prevent against [[

]].

RAC 4.2-2.3 and 4.2-2.4 both cover mechanical limits on the cladding. RAC 4.2-2.3 relates to failure caused by deformation; this deformation could be driven by natural phenomena, such as cladding thermal creep and rod internal pressurization, or by externally applied forces. According to the RAC, either a cladding deformation limit should be developed at which cladding failure is assumed, or deformation should be explicitly addressed in evaluations of other criteria that could be affected by cladding deformation. RAC 4.2-2.4 specifically relates to mechanical fracturing from externally applied forces, like seismic loading or dropping during a fuel handling accident.

Finally, RAC 4.2-2.5 applies to cladding wastage, stating that either a total cladding wastage limit should be developed at which cladding failure is assumed, or that cladding wastage should be explicitly addressed in evaluations of other criteria that could be affected by cladding wastage. Cladding wastage is caused by various mechanisms including fretting wear, erosion, corrosion, FCCI, and eutectic formation, all of which have been discussed previously. These mechanisms can occur on various time scales and as such this criterion is a complement to the RAC 4.2-2.1 and 4.2-2.2 temperature-based criteria, which specifically address [[
]].

The NRC staff compared these proposed criteria against the design criteria presented in NUREG/CR-7305 Section 2.2.2, "Design Limits During Anticipated and Accident Transients." The NUREG/CR indicates that the primary fuel failure mechanisms in a U-Zr/HT9 fuel system would be expected to be failure due to low-melting-point eutectics between the fuel and cladding, and cladding overpressure due to fission gas release. The recommended design criteria for postulated accidents are thus that fuel melting is precluded, and cumulative eutectic penetrations should be maintained below a specified limit to account for its effects as wastage. Additional criteria are proposed for core coolability, but since TerraPower discussed its coolability criteria separately, these will be addressed in SE Section 3.2.3.1, below.

The criteria proposed by TerraPower for fuel pin failure are consistent with the criteria proposed in the NUREG/CR, with additional criteria that specifically account for fuel cladding deformation/rupture and mechanical fracturing caused by external loads. The NRC staff therefore determined that the identified fuel failure criteria are appropriate. The NRC staff notes that future fuel qualification work would be expected to develop and appropriately justify limits supporting these acceptance criteria (see L&C 1).

FQAF G2.2.2(a) supports G2.2.2, stating that the criteria used to determine barrier degradation and failure should be suitably conservative as demonstrated by comparison to transient testing and irradiated fuel samples. As noted above, TerraPower did not propose or justify limits on the acceptance criteria for fuel damage or failure and, as such, the NRC staff has not made a determination on whether these criteria are conservative. This is expected to be part of the future fuel qualification work (see L&C 1).

Experimental data (G2.2.2(b))

The TR contains information on fuel testing, both historical and planned, that supports the criteria discussed above. The data used to demonstrate the adequacy of the barrier degradation and failure criteria are nominally covered by FQAF G2.2.2(b). However, NUREG-2246 states that these data should be addressed using the data assessment framework. Therefore, discussion of the data used to assess the barrier criteria is provided in Section 3.4 of this SE.

3.2.2.4 Radionuclide retention and release

FQAF G2.2.3 states that radionuclide retention and release behavior of the fuel matrix under accident conditions should be modeled conservatively. As discussed in Section 3.2.2.2 of this SE, TerraPower did not propose radionuclide retention requirements for Natrium Type 1 fuel in the TR and, therefore, the NRC staff did not assess whether TerraPower met this goal. It is the NRC staff's understanding that models of radionuclide retention in the fuel matrix and release out into the coolant following fuel failure will be covered in future Natrium licensing submittals. The NRC staff therefore imposed L&C 55 on the use of this TR, which states that appropriate models for radionuclide retention and release must be proposed and justified.

In Table 2-1 of the TR where FQAF G2.2.3 is referenced, TerraPower included a statement that evaluations of the fuel system design will ensure that the design bases are met for normal operations, AOOs, and accidents, and that these evaluations will be supported by test data discussed in Section 6, "Fuel System Design Evaluation," of the TR. The NRC staff evaluated the extent to which the available data and planned testing discussed in the TR support the development of radionuclide retention and release models; this discussion is included in Section 3.4 of this SE.

3.2.3 Safe shutdown

FQAF G2.3 states that a safe shutdown condition (i.e., a subcritical condition with adequate decay heat removal) must be assured in any scenario. This goal is supported by two subgoals, which state that the fuel must maintain a coolable geometry under accident conditions (G2.3.1) and that negative reactivity insertion can be demonstrated (G2.3.2). Consistent with the overall objective of this goal, Section 1 of the TR states that the fuel design limits are established, in part, to ensure that "[fuel] coolability is always maintained" and "fuel system damage is never so severe during postulated accidents as to prevent reactivity control and control rod insertion when it is required." The two sets of criteria supporting these objectives are discussed below.

3.2.3.1 Coolable geometry

FQAF G2.3.1 relates to maintaining a coolable geometry. This goal is supported by two subgoals: that the phenomena that could cause a loss of coolable geometry are identified (G2.3.1(a)) and that there are evaluation models available to assess margin (G2.3.1(b)).

Phenomena that could cause a loss of coolable geometry (G2.3.1(a))

TerraPower's criteria to ensure fuel coolability are discussed in Table 4-3 of the TR and, like the criteria for fuel system damage and failure, are established as RAC with acceptance criteria that are supported by design criteria for the fuel pin and fuel assembly. The RAC identified by TerraPower are:

- RAC 4.2-3.1 – cladding stress and strain, which must be kept below the point where cladding damage might prevent adequate core cooling or, alternatively, cladding stress and strain must be accounted for in analyses demonstrating compliance with fuel coolability criteria
- RAC 4.2-3.2 – cladding temperature, which must be kept below the melting temperature of the cladding
- RAC 4.2-3.3 – coolability evaluations must include the effects on core flow distribution or potential core blockage caused by ballooning of the cladding
- RAC 4.2-3.4 – fuel slug temperature must be lower than the melting temperature of the fuel
- RAC 4.2-3.5 – structural deformation of fuel assemblies due to combined loads must not prevent the ability to adequately cool the core
- RAC 4.2-3.6 – hydraulic loads combined with loads from natural phenomena must not unseat a fuel, reflector, or shield assembly and cause a reduction in flow that could prevent the ability to cool the fuel assembly

NUREG/CR-7305 Section 2.2.2, "Design Limits During Anticipated and Accident Transients," proposes a criterion to ensure that core coolability is maintained under all conditions, including beyond design basis accidents, by requiring that there is no clad melting. Other portions of the NUREG/CR also indicate that coolability is primarily influenced by fuel dimensional changes. In addition, fuel thermal conductivity is degraded as a function of burnup due to buildup of gaseous and solid fission products. Fuel swelling combined with property degradation can lead to cladding deformation if unconstrained. However, these are long-term phenomena that are particularly relevant to normal operations; other coolability issues that could result from transients, such as cladding ballooning (dilation) and debris ejection from breached fuel rods, should also be studied.

TerraPower's RAC explicitly preclude clad melting, ballooning, and the effects of fuel pin/assembly deformation that would affect coolability. The issue of whether debris ejected by a breached fuel rod could block an assembly is not explicitly covered by these criteria, but the NRC staff does not anticipate substantial debris generation provided that the fuel slug does not melt. As such, the criterion provided by RAC 4.2-3.4 is likely sufficient to preclude this issue. Beyond the criteria identified in NUREG/CR-7305, the TerraPower criteria related to mechanical deformation and hydraulic loads on the fuel are necessary and sufficient to ensure that coolability can be adequately maintained following accidents, including events initiated by external hazards such as earthquakes.

In consideration of the above, the NRC staff determined that the acceptance criteria for core coolability provided in the TR provide an acceptable approach to qualify Natrium Type 1 fuel. As with the criteria for fuel system damage and failure, future work is needed to propose and appropriately justify specific limits needed to ensure that the criteria are met (see L&C 1).

Evaluation models supporting coolable geometry demonstration (G.2.3.1(b))

In support of the overall demonstration that coolable geometry is maintained under accident conditions, NUREG-2246 FQAF G2.3.1(b) states that EMs should be available to assess margin to fuel coolability limits. In coolability assessments, it is typical that thermal-hydraulic or system transient EMs are needed to identify key parameters that affect the fuel. These EMs must be coupled with or otherwise inform the fuel performance evaluation (discussed in Section 6.4, "Analytical Predictions," of the TR) to ensure that combined thermal-hydraulic and thermo-mechanical effects are appropriately captured. The NRC staff notes that detailed thermal-hydraulic evaluations are outside the scope of the TR. However, Section 3.3 of this SE discusses the capabilities of the fuel performance codes in support of an overall coolability demonstration.

3.2.3.2 Negative reactivity insertion

FQAF G2.3.2 relates to negative reactivity insertion. This goal is supported by two subgoals: that criteria are provided to ensure that the means to insert negative reactivity is not obstructed during conditions of normal operation or accidents (G2.3.2(a)) and that an EM is available to assess geometry changes that could inhibit reactivity insertion during normal operation and accidents (G2.3.2(b)).

Criteria to demonstrate negative reactivity insertion (G2.3.2(a))

As discussed in Section 2.2 of this SE, control assemblies are responsible for providing negative reactivity insertion in the Natrium design. Each control assembly includes an absorber pin bundle that moves up and down within a control assembly duct. As such, the primary concern relative to negative reactivity insertion is that distortion of the pin bundle or duct could increase friction and impact the ability to insert the control rods into the core. This distortion could take place due to natural phenomena (e.g., bowing due to uneven thermal or irradiation creep) or accident conditions (e.g., external loading on the fuel assembly). Because the control assembly ducts are in physical contact with the other core assemblies in the core restraint system, control assembly distortion may be driven by forces imposed by adjacent fuel assemblies as they themselves distort (again, due to either natural phenomena or accident conditions). Additionally, because the control assemblies interface with the core support structure through inlet nozzles that provide coolant flow through the control assemblies, the control assemblies are subject to similar considerations for hydraulic loading as fuel assemblies.

TerraPower's criteria to ensure the capability to insert negative reactivity are included in Table 4-4 of the TR and, like the fuel system damage and failure and coolability criteria discussed above, are established as RAC with acceptance criteria that are supported by design criteria for the pin and fuel assembly. The RAC identified by TerraPower include:

- RAC 4.2-4.1 – structural deformation of control assemblies due to combined loads will not prevent the ability to insert control rods during postulated accidents
- RAC 4.2-4.2 – hydraulic loads will not unseat a reactivity control assembly that could prevent the complete insertion of control rods during postulated accidents

Table 4-4 of the TR indicates that these RAC are supported [[ ]]. The NRC staff additionally identified other RAC specified elsewhere in the TR that support control rod insertability, including RAC 4.2-1.6, 4.2-1.7, 4.2-1.8, 4.2-1.10, and 4.2-1.11, which relate to fuel and control assembly distortion, fuel and absorber pin internal pressure, hydraulic loads on control assemblies, and mechanical/neutronic design of control assemblies, respectively.

The NRC staff finds that TerraPower's acceptance criteria provide an acceptable approach to justify Natrium Type 1 fuel because these criteria address the possible mechanisms that could inhibit control assembly insertion discussed above. As with other criteria discussed in this SE, future work is needed to propose and appropriately justify specific limits needed to ensure that the criteria are met (see L&C 1).

Evaluation models supporting negative reactivity insertion demonstration (G2.3.2(b))

In support of the overall demonstration that negative reactivity insertion can be achieved even during accident conditions, NUREG-2246 FQAF G2.3.2(b) states that EMs should be available to assess geometry changes resulting from normal operation and accident conditions in order to ensure that the negative reactivity insertion path is not deformed. Section 6.4 of the TR identifies that the OXBOW computer code (and in particular the OXBOW.CASS module) is used to perform these evaluations. However, the EM for evaluating control rod insertability was not assessed in detail in the TR. Section 3.3 of this SE provides further discussion on EMs.

3.3 Evaluation model

Analytical prediction of fuel performance is a critical and complex portion of the fuel qualification process. Accordingly, NUREG-2246 provides a separate, generalized framework for assessing fuel performance EMs used to perform such analyses. However, the discussion on analytical capabilities provided in Section 6.4 of the TR contains only a high-level description of the proposed methods, with an overview of how the overall modeling approach intends to satisfy the FQAF EM goals provided in Table 6-28, "Fuel Performance Models for FQAF Goals," of the TR. The NRC staff understands that a detailed fuel performance methodology TR, which would seek to satisfy the FQAF EM goals, is planned for future submittal. Nonetheless, the NRC staff assessed the high-level TR information on the planned EM codes and structure against the FQAF EM framework.

Analyses performed at the fuel pin level are relevant to the assessment of barrier performance as discussed in Section 3.2 of this SE. The TR identified three computer codes that are used for various fuel pin predictions: ALCHEMY, a TerraPower in-house finite element model built on top of the commercial finite element code ABAQUS; [[ ]]; and CRUCIBLE, another TerraPower in-house code. ALCHEMY is [[ ]], while [[ ]]. Conversely, CRUCIBLE is not used to evaluate fuel design parameters but instead is a part of TerraPower's steady-state core design and analysis suite that helps to determine fuel parameters affecting steady-state temperatures and evaluate uncertainties. Tables 6-24, "Fuel Performance Prediction Capabilities to Assess Fuel Damage," through 6-27, "Fuel Performance Prediction Capabilities to Assess Phenomena Related to Fuel Temperatures," of the TR detail the specific modeling capabilities of these (and other) codes in support of predicting fuel pin damage and failure, fuel coolability, and fuel temperatures.

Beyond fuel pin behavior, it is important to consider fuel assembly distortion in SFRs, since it plays a significant role in inherent reactivity feedback effects. This is applicable to the Natrium plant design due to its core restraint system, which is discussed briefly in Section 5.4, "Core Restraint System," of the TR. Fuel assembly-level deformations are calculated using various modules of the OXBOW code, a TerraPower in-house finite element model built on top of the commercial finite element code ABAQUS. OXBOW is used to analyze the core restraint system, perform core assembly distortion analyses, analyze the overall mechanical response of fuel assemblies under seismic conditions, determine fuel assembly withdrawal and insertion loads, conduct control bundle insertability and scram time analyses, and analyze fuel bundle-duct interactions.

The NRC staff has not previously reviewed or approved any of these codes. However, the NRC staff reviewed the information provided in the TR to determine the extent to which the codes may be capable of supporting future fuel qualification work. Section 6 of the TR, and in particular Table 6-3, “Summary of Identified High-Importance Phenomena and Associated Design Limits and RAC for Fuel and Absorber Pins,” provides details on a phenomena identification and ranking table (PIRT) assessment TerraPower performed to identify key phenomena[3] that must be modeled to evaluate fuel performance under a range of conditions. Tables 6-24 through 6-26 contain further information on which models are used to calculate specific high-ranked PIRT phenomena. All the fuel pin models referenced would at least be able to represent the fuel pins appropriately in a 1-dimensional axisymmetric geometry (as is typical of fuel performance models for operating reactors), although ALCHEMY would have the flexibility to represent distorted fuel geometries and other off-normal conditions since it is based on the finite element method. For that same reason, the OXBOW code would similarly be able to have a flexible representation of geometries at the fuel assembly scale. Based on this information, the NRC staff anticipates that these codes may be able to appropriately model key geometries, material properties, and relevant physics per FQAF EM G1.

Based on the above, the NRC staff concludes that the preliminary work on the EMs that support fuel qualification is acceptable. However, consistent with FQAF EM G1 and EM G2, additional work must be done to demonstrate that the proposed EMs contain all necessary material and physics models and to verify the EMs and validate them against appropriate experimental data (see L&C 1). This is echoed by TR Table 6-28, which notes that “detailed validation plans and assessments are under development to demonstrate that validation assessment criteria have been met”; “qualification of fuel performance data is being performed to qualify existing experiment data”; and “new experiments are being performed.” While an explicit assessment of the proposed methodologies against experimental data was not performed in the TR, the TR explained how both historical and planned testing supports the overall Natrium fuel qualification effort. These data are discussed in Section 3.4, below.

3.4 Data

NUREG-2246 states that the assessment of experimental data is the largest area of review for fuel qualification. This is because various goals of the fuel qualification assessment framework, including the development of acceptance criteria and limits and the validation of EMs for fuel performance analyses, require comparison to data. Section 3.4, “Assessment Framework for Experimental Data,” of NUREG-2246 provides an assessment framework for experimental data, which is supported by several goals: that any assessment data are independent of data used to develop or train the EM (Experimental Data (ED) G1), that the data have been collected over a test envelope that covers the fuel performance envelope (ED G2), that the experimental data are accurately measured (ED G3), and that the tests are representative of prototypic conditions (ED G4).

[3] Note that Table 6-3 identifies only high-ranked PIRT phenomena. The full PIRT results are detailed in [12], which was submitted to the NRC staff as a WP in 2021.

Because TerraPower stated in the TR that the qualification of historical data and development of new tests to support fuel qualification is ongoing, the NRC staff did not fully utilize the NUREG-2246 data assessment framework. However, the NRC staff assessed the data provided in the TR and referenced the ways in which the TR discussion supports the FQAF data evaluation goals.

3.4.1 Historical fuel operating experience

The TR contains numerous references to the testing of metallic fuel performed at EBR-II and FFTF, stating in Section 6.3, "Testing," that "the intention is to rely heavily on this basis for the safety case and validation of methods for Type 1 fuel pins." Section 6.2, "Historic Operating Experience," of the TR justifies the applicability of this historic data to Natrium Type 1 fuel, with details provided in several tables. Table 6-5, "Summary of Fuel Pin Parameters Including Comparison to FFTF/MFF and EBR-II," compares the Type 1 fuel parameters to certain selected fuel assemblies that operated at FFTF and EBR-II. Table 6-7 provides a comparison of Type 1 fuel assembly design parameters to fuel that operated at FFTF and proposed fuel for Power Reactor Innovative Small Module (PRISM) and Versatile Test Reactor (VTR). Table 6-8, "Comparison of Fuel System Operational Parameters," provides a comparison of the Type 1 bounding fuel system operating parameters. Finally, Table 6-9, "Relevant Historic Fuel Assemblies to Support Validation Activities," provides a detailed overview of all historical fuel assemblies operated at FFTF and EBR-II that TerraPower identified as relevant to the Type 1 fuel design.

From a geometric standpoint, Type 1 fuel has a ECI/Prop[[ ]] than all the comparison fuel assemblies, except for several assemblies used at EBR-II, which come very close. The cladding is ECI/Prop[[ ]] than all the comparison assemblies. The fuel column length is ECI/Prop[[ ]]. The plenum length is ECI/Prop[[ ]]. In an assembly, the fuel pin pitch to diameter ratio and assembly pitch are ECI/Prop[[ ]]. The fuel pin wire wrap axial pitch is ECI/Prop[[ ]]. Compared to the FFTF fuel, ECI/Prop[[ ]].

From an operating parameter standpoint, the peak enrichment is ECI/Prop[[ ]]. The peak burnup is ECI/Prop[[ ]], but the peak damage is ECI/Prop[[ ]]. Maximum residence time is ECI/Prop . The fast fluence is ECI/Prop [[ ]]. However, the linear heat generation rate is ECI/Prop[[ ]] [[ ]] – this would lead to ECI/Prop[[ ]].

The NRC staff notes that while the Type 1 fuel peak burnup provided in Table 6-8 of the TR is ECI/Prop[[ ]] than that of the comparison assemblies and generally well within the operational database, ECI/Prop[[

]]. However, [[ ]].

TerraPower additionally has proposed a surveillance program in Section 9 of the TR, and the NRC staff finds it highly likely that any issues with ECI/Prop[[ ]] – which are themselves unlikely based on a review of the historical data – will be identified by this surveillance program. As such the NRC staff considers a peak burnup limit of ECI/Prop[[ ]] to be consistent with the acceptance criteria discussed previously and, therefore, acceptable for the purposes of qualifying Natrium Type 1 fuel.

Because ECI/Prop[[ ]] all exceed the historical database, these phenomena are assessed below in more detail.

With respect to ECI/Prop[[ ]]. The NRC staff determined that this approach is acceptable, but notes that ECI/Prop[[ ]] (see L&C 1).

For ECI/Prop[[ ]]. Nonetheless, TerraPower also proposed additional testing and further PIE of historical fuel assemblies to confirm and reduce uncertainties. NUREG/CR-7305 notes that there is a complex relationship between ECI/Prop[[ ]]. The NRC staff therefore determined that TerraPower's proposed path to address EC/Prop[[ ]]

using historical data and supplemental additional testing is acceptable to support Natrium Type 1 fuel qualification.

The NRC staff also noted the potential that fuel constituent redistribution in Type 1 fuel, which contributes to FCCI, would not be appropriately captured by the reference fuels. This is because constituent migration is driven by thermal gradients, and the Type 1 fuel ECI/Prop[[

]]. However, the Type 1 fuel operates at ECI/Prop[[

]], which would result in the reference assemblies bounding Natrium Type 1 fuel with respect to constituent redistribution behavior.

In summary, the NRC staff finds the fuel assemblies detailed in Table 6-9 of the TR appropriate to provide qualification data for the Natrium Type 1 fuel because of their similarity to the Natrium Type 1 fuel design and relevance to the Natrium operating envelope. All assemblies presented are metallic fuel clad in stainless steel alloys that operated in SFRs. While some assemblies are more representative of Natrium Type 1 fuel than others, the NRC staff expects each assembly in the proposed database to be able to provide applicable insights for at least select mechanisms. The choice of a particular assembly to validate a certain model or behavior must be appropriately justified. The data that are planned to assess the various criteria and PIRT phenomena are discussed in Section 3.4.2, below.

3.4.2 Testing used to address acceptance criteria

The TR includes details on the historical and contemporary testing that will be used to support the determination and qualification of design basis criteria. TerraPower noted in TR Section 6.2.1, "Quality of Historic Data," that the quality of the historical test data needs to be addressed per NUREG-2246 ED G3. Because legacy test data have varying degrees of quality, additional effort may be needed to qualify these data for use at present. The methods that TerraPower proposed are: (1) demonstrate the equivalency of the quality program under which the data were collected to an NRC-approved quality assurance program that meets the requirements of 10 CFR Part 50 Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," (2) corroborate the data by comparison to other independent datasets, (3) perform confirmatory testing, or (4) perform a peer review of the data. TerraPower has developed a qualification plan for legacy data from FFTF and EBR-II, which involves qualification by Argonne National Laboratory using an NRC-approved quality process. The NRC staff, therefore, determined that this approach for the historical data from FFTF or EBR-II is generally acceptable. Other legacy data will be discussed below.

3.4.2.1 Cladding strain

As provided in the TR, cladding strain assessments will be supported by a combination of data from [[

]]. These data are supplemented by [[

]]. The effect of rod internal pressure on strain will be further addressed by [[

]].

Planned testing in the area of cladding strain includes [[ ]]. The [[ ]]. Mechanical assessments will be supported by planned [[ ]]. Rod internal pressure will also be addressed by [[ ]].

Cladding failure due to thermal creep will be addressed by [[ ]]. Future testing includes planned [[ ]].

The NRC staff considers the use of historical cladding strain data acceptable for qualifying Natrium Type 1 fuel, as the [[ ]] strain data would be expected to envelope expected Type 1 operating conditions. However, the NRC staff notes that [[ ]] are necessary to provide confidence in [[ ]]. The same is true for the [[ ]]. Also, while the historical data from [[ ]] are applicable and important to consider, the NRC staff notes that the planned testing [[ ]]. Similarly, the NRC staff considers the planned [[ ]] tests to be essential for providing a thorough understanding of cladding creep failure behavior under a variety of conditions, including transients. In summary, the NRC staff determined that the combination of historical and planned testing provides an acceptable approach for qualifying Natrium Type 1 fuel because it appropriately addresses strain in unirradiated and irradiated material in a wide range of operating conditions for both steady-state operation and transients.

3.4.2.2 Fatigue

As provided in the TR, fatigue lifetime assessments will be supported by [[ ]]. TerraPower also plans to conduct additional [[ ]]. The NRC staff finds this to be an acceptable approach for fuel qualification purposes because it is consistent with past assessments that ensured the appropriate treatment of nuclear fuel fatigue.

3.4.2.3 Fretting

As provided in the TR, fretting will be addressed by [[ ]]. Planned work includes [[ ]]. While the [[ ]] may not be fully applicable due to geometric and flow parameter differences relative to Type 1 fuel, [[ ]] would be expected to address any differences. The NRC staff also notes that fretting is a highly localized phenomenon and even a significant amount of fretting would likely only result in a small numbers of fuel leaks. The NRC staff determined that the approach to address fretting is acceptable because it supplements applicable historical data (which includes irradiated materials) with testing using prototypical materials and environments.

3.4.2.4 Corrosion

As provided in the TR, corrosion will be addressed by [[ ]]. Some [[ ]] has been performed, while additional assessment of [[ ]] is planned. These data will be supplemented by [[ ]]. The NRC staff determined that the approach to address corrosion is acceptable because corrosion in SFRs is generally considered a minor issue and the data are expected to bound in-reactor corrosion.

3.4.2.5 FCCI

As provided in the TR, FCCI will be addressed by [[ ]]. Planned and ongoing assessments include further [[ ]].

The NRC staff determined that the approach to address FCCI is acceptable because [[ ]].

3.4.2.6 Fuel and cladding temperature

As provided in the TR, damage to the fuel cladding caused by increased temperatures is assessed through [[ ]]. The NRC staff determined that this approach is acceptable because it is consistent with past approaches that ensured the appropriate assessment of fuel cladding damage due to elevated temperatures.

For cladding failure temperatures, the historical data include [[ ]]. TerraPower plans to perform various [[ ]]. The NRC staff determined that the approach to address cladding failure temperatures is acceptable because it starts from the [[,]] and supplements that data with [[ ]].

For fuel melting temperatures, TerraPower stated that the work completed to this point includes [[ ]]. This will be supplemented by various [[

]]. This approach is generally acceptable to the NRC staff because the tests involving [[ ]] will appropriately capture [[-]] and [[ ]].

3.4.2.7 Assembly mechanical behavior

Section 6.3.1, "Fuel Assembly Mechanical Test Plans," of the TR provides an overview of planned fuel assembly mechanical tests. These tests range from sub-component tests to multiple-assembly tests. The proposed tests address mechanical behavior of specific key components (fuel ducts, inlet nozzles), combinations of components (pin bundles, bundles and ducts), full fuel assemblies, and combinations of assemblies. Both static and dynamic behaviors are considered, including important component or assembly interactions. Proof-of-concept tests are also planned to demonstrate certain novel components or mechanisms. In Table 6-19, "Example Fuel & Control Assembly Mechanical Test Matrix," of the TR, TerraPower categorized the tests according to which effects are tested and the critical characteristics expected to be addressed by each test.

The NRC staff determined that the proposed testing appropriately encompasses the necessary mechanical behavior, particularly when coupled with the testing noted above supporting acceptance criteria and the testing noted below concerning material properties. A footnote on Table 6-19 of the TR indicated that irradiation effects are accounted for by using pre-deformed ducts to simulate dilation or bowing induced by irradiation creep and growth, but that irradiation effects will be treated conservatively in analyses and will be validated by surveillance programs. The NRC staff determined that the approach is acceptable because it is generally consistent with how mechanical behavior has been adequately tested and validated historically.

3.4.2.8 Material properties

TerraPower's approach to material property data is provided in Section 6.3.2, "Materials Property Data and Testing," of the TR. Data are taken from a variety of property handbooks, and if the data were not initially collected under an NRC-approved quality assurance program that meets the requirements of 10 CFR Part 50 Appendix B, the data are subsequently subjected to further qualification to ensure that the data meet a minimum quality standard.

HT9

As provided in the TR, thermal properties of HT9 appear to be readily available and can be qualified by [[ ]]. The NRC staff determined that this is acceptable because it is consistent with standard industry practice for thermal properties of cladding materials, which do not vary significantly for materials that fall within a given specification.

As provided in the TR, unirradiated material properties of HT9 also appear to be readily available. However, TerraPower is more constrained in the data that are available because the material must meet TerraPower's HT9 specification. It appears that TerraPower generally expects to be able to adopt unirradiated material properties based on [[ ]] with the potential for [[ ]] if necessary. The NRC staff determined that this is acceptable because the [[ ]] will identify those unirradiated material properties that may be expected to be affected by TerraPower's HT9 manufacturing process, which can then be addressed by [[ ]].

As provided in the TR, irradiated HT9 material properties are further constrained. As TerraPower notes in Section 6.3.2.1.3, "Irradiated Mechanical Properties," of the TR, some irradiated HT9 material properties have been measured historically and others have not. TerraPower is currently conducting mechanical testing of irradiated samples to determine these properties. Because the samples are likely to not be fully prototypical, other tests, testing methods, or analysis techniques may be included to corroborate the data and confirm expected behavior. TerraPower similarly notes that HT9 chemical interaction data are also not likely to be fully prototypical due to irradiation conditions and, as such, plans a similar approach as that for obtaining irradiated material properties. The NRC staff notes that while it is always prudent to assess chemical compatibility between the cladding and coolant, corrosion is not expected to play a significant role in the cladding safety case. The NRC staff determined that the approaches for characterizing irradiated and chemical interaction properties of HT9 are acceptable because TerraPower will characterize these properties under conditions approximating in-reactor conditions, with further testing and analyses to address any gaps between tested conditions and fully prototypic conditions.

Metallic fuel

TerraPower stated that the only high-importance property of the metallic fuel identified in the PIRT was the fuel thermal conductivity because it plays a key role in the thermal response of the fuel, especially during transient conditions. However, TerraPower also stated that other analyses are highly dependent on fuel properties and "having reliable materials property data is essential to characterizing the beginning of life conditions of the fuel system." All thermal and unirradiated properties are taken from the literature and qualified with [[ ]]. The NRC staff determined that the treatment of unirradiated fuel properties is acceptable because they can be measured relatively easily.

For irradiated fuel properties, TerraPower states in Section 6.3.2.3, "Metallic Fuel Properties Data for Qualification," of the TR that these properties are assessed by the fuel performance modeling tools. The NRC staff expects that some analysis work would be necessary to support the development of these properties, because irradiated properties would be highly dependent on local composition, temperature, etc., all of which depend on the processing and irradiation history of the material. However, the fuel performance models are themselves based on data and must be appropriately validated (see L&C 1). The NRC staff notes that this validation has not yet occurred, as discussed in Section 3.3 of this SE.

3.4.3 Conclusion regarding TerraPower fuel qualification data plans

Based on the considerations discussed above, the NRC staff determined that the overall approach to developing fuel qualification data is acceptable. However, the NRC staff notes that details of planned testing were not provided and, as such, the NRC staff is not capable of assessing the extent to which the planned testing appropriately envelopes the planned operating conditions for Natrium Type 1 fuel. Additionally, there is a clear tie between the data used for assessment and the EMs which will be validated against that data. Since the EMs (as discussed in Section 3.3 of this SE) have not been fully presented or validated, this represents an area of future work for TerraPower. Future work to qualify the fuel is addressed by L&C 1.

4.0 CONTROL ASSEMBLY QUALIFICATION PLAN EVALUATION

Like fuel assemblies, control assemblies must also be qualified for use in a reactor. Despite operating in the same environment, being similar in design, and being subject to similar phenomena, control assemblies fulfill a different safety role from fuel assemblies.
As discussed in Section 2.2 of this SE, the control assemblies' purpose is to ensure that neutron absorbing materials are positioned appropriately within the reactor to control or shut down the nuclear chain reaction. Because of this difference in the high-level safety objectives of the control assemblies versus the fuel assemblies, the full NUREG-2246 fuel qualification framework is not applicable to control assemblies. However, the high-level principles are applicable; specifically, that the control assemblies should be manufactured in accordance with an appropriate specification and that margin to appropriate design criteria can be demonstrated using EMs assessed against data. This section of the NRC staff's SE evaluates TerraPower's plans relative to the qualification of control assemblies considering NUREG-2246 high-level principles.

4.1 Manufacturing specifications

As with the fuel assemblies, detailed design information for control assemblies was referenced in TR Table 5-3. These documents were audited by the NRC staff and the NRC staff confirmed in the audit that these documents contain sufficient detail to cover all key dimensions and tolerances of a control assembly.

Most components of the control assembly are composed of HT9, except for a few components that may be composed of code-qualified materials as discussed in Section 5.5.3 of the TR, and the boron carbide absorber pellets. HT9 manufacturing is discussed in Section 3.1 of this SE and that discussion is applicable to the control assemblies. Manufacturing specifications for boron carbide absorber pellets are referenced in Table 5-3 of the TR. The NRC staff reviewed the referenced documents in the audit and confirmed that the relevant information was appropriately included in the referenced documents.

Based on the above, the NRC staff determined that information provided in the TR provides an acceptable approach to demonstrate that control assembly manufacturing will be appropriately controlled.

4.2 Control assembly design criteria

In choosing appropriate control assembly design criteria, it is important to consider that the function of the control assemblies is to ensure that neutron absorbing materials are positioned appropriately within the reactor to control the nuclear chain reaction. Thus, it is reasonable to expect that the criteria will be defined such that the neutron absorbing materials will remain in the absorber pins and the control assembly will be able to insert into the reactor.

Acceptance criteria that TerraPower identified as applicable to control assemblies include:

- Damage:
    - RAC 4.2-1.1 – stress, strain, or loading

  - RAC 4.2-1.2 – fatigue
  - RAC 4.2-1.3 – fretting
  - RAC 4.2-1.4 – erosion and corrosion
  - RAC 4.2-1.5 – absorber-cladding chemical interaction (ACCI)
  - RAC 4.2-1.7 – dimensional changes, such as bowing, swelling, or dilation; these must be limited to prevent interference that could impact control rod insertability
  - RAC 4.2-1.8 – absorber pin internal pressure
  - RAC 4.2-1.11 – mechanical and neutronic lifetime, to ensure reactivity and insertability are maintained
  - RAC 4.2-1.12 – absorber material and cladding temperatures
- Failure:
  - RAC 4.2-2.1 – absorber cladding overheating
  - RAC 4.2-2.4 – mechanical fracture caused by externally applied forces
- Reactivity Control Insertability:
  - RAC 4.2-4.1 – structural deformation of control assemblies due to combined accident loads and natural phenomena
  - RAC 4.2-4.2 – hydraulic loads combined with loads from natural phenomena, which must not unseat a reactivity control assembly in a way that prevents complete control rod insertion

The NRC staff determined that the absorber pin RAC provide an acceptable approach to support qualification of Natrium control assemblies because these criteria ensure that absorber materials will: (1) remain neutronically effective (by RAC 4.2-1.11); (2) will stay enclosed within the absorber pin (by inhibiting absorber pin cladding damage or failure by various mechanisms); and (3) will not deform in a manner that inhibits their proper insertion in the core. Additionally, the negative reactivity insertion RAC are discussed in more detail in Section 3.2.3.2 of this SE.

4.3 Evaluation model for control assemblies

Section 6.4.1.1, "Alchemy," of the TR indicates that ALCHEMY can model boron carbide in place of fuel within pins, giving it the flexibility to model absorber pin performance. This is generally consistent with other approaches that have been shown to adequately model absorber pin performance. As discussed in Section 3.3 of this SE, TerraPower intends to use a module of the OXBOW code to analyze control rod assembly insertability criteria, which are related to control assembly distortion. Both of these codes are discussed in more detail in Section 3.3 of this SE. Specifically, while the work presented in the TR is acceptable at this stage, as with the fuel performance methodologies, these methodologies require further work to appropriately validate them against experimental data (see L&C 1).

4.4 Data for control assemblies

Table 6-6, "Summary of Absorber Pin Parameters Including Comparison to FFTF and JOYO," of the TR includes a detailed comparison of absorber pin parameters between the proposed Natrium absorber pin design, three designs that were operated at FFTF, and a design from the Joyo reactor in Japan. The Natrium absorber pins are generally comparable to or within the envelope of comparison pins, except that they have ECI/Prop[[ ]]. Additionally, ECI/Prop[[ ]]. Additional reference pins are presented in Table 6-10, "Relevant Historic Absorber/Control Pin Test Assemblies to Support Validation

Activities," of the TR, which includes absorber pins from FFTF, Joyo, EBR-II, and the Engineering Test Reactor. These pins appear to cover a reasonably wide range of designs and operating conditions.

In general, the historical data appear applicable for qualifying Natrium control assemblies. While there are ECI[[ ]], there is a wealth of data on ECI[[ ]]. Additionally, the fact that the absorber pin data come from a fairly diverse set of designs and operating conditions means that the data will include features, like differences in neutron spectra between metallic- and oxide-fueled SFRs, that are needed to fully qualify the absorber pin performance.

As noted in Section 3.4 of this SE, TerraPower is conducting or plans to conduct additional tests to assess HT9 behavior. These are expected to be generally applicable to HT9 performance in absorber pins as well. The main gap with respect to absorber pin qualification is ACCI; TerraPower noted in TR Table 6-11, "Design Basis Criteria and Supporting Information to Prevent Fuel Pin Damage," that [[ ]], but plans to conduct [[ ]] to confirm this. The NRC staff determined that this approach is appropriate because it includes testing that addresses potential information gaps, especially in light of the fact that ECI[[ ]].

5.0 FUEL MONITORING

Section 8 of the TR provides a description of the method by which TerraPower plans to detect fuel failures during operation. Cover gas will be monitored continuously and the detection of fission products in the cover gas is indicative of a fuel failure. TerraPower notes that [[ ]].
The NRC staff determined that this approach for detecting failures is acceptable because it will allow failed fuel assemblies to be identified and appropriately managed. The NRC staff notes that [[ ]].

6.0 FUEL SURVEILLANCE AND LEAD DEMONSTRATION AND TEST ASSEMBLY PROGRAM

As discussed in Section 2.1.4 of this SE, TerraPower plans to collect additional data on fuel performance by using LDAs and LTAs. The purpose of the LDA program is to [[ ]].
TerraPower also stated that LDAs may be designed such that they [[ ]]. The notional surveillance plan for the first several cycles of operation is presented in TR Table 9-1, "Notional Fuel Surveillance Plan for Initial Cycles of Operation." Additional detail on LTAs beyond the purpose and the notion of [[ ]] was not provided.

The NRC staff notes that there is a long history of similar LTA programs in the operating nuclear reactor fleet and, as such, there is ample precedent for a program conceptually similar to what TerraPower has proposed. However, because the LDA and LTA programs as presented in the TR are notional, the NRC staff cannot reach a final determination regarding the acceptability of LDAs or LTAs for the purposes discussed in the TR. In particular, the TR lacks details on how LDAs or LTAs would be evaluated to ensure that their impact on the co-resident fuel is minimized, and that any uncertainties in performance due to [[ ]] remain appropriately bounded or can otherwise be tolerated in safety analyses. Further, it is not clear to the NRC staff how [[ ]]. These issues should be addressed in future licensing submittals.

LIMITATIONS AND CONDITIONS

1. This TR represents an acceptable approach for qualifying Natrium Type 1 fuel and control assemblies for use in a reactor but does not in and of itself demonstrate that the fuel and control assemblies are qualified. Additional activities, including those discussed in the NRC staff's SE, must be completed to execute this plan and appropriately justify that the fuel and control assemblies are qualified.
2. This TR addresses the material properties and performance of U-10Zr and HT9 in fuel. If other materials are used in the fuel system in licensing applications, the applicant or licensee must demonstrate that they are manufactured according to standard specifications and used consistent with their qualification under relevant NRC-accepted codes and standards, or otherwise appropriately justified.
3. This TR does not provide a means for demonstrating that proposed SARRDLs are satisfied during normal operations and AOOs for the Natrium plant. The role of the fuel acceptance criteria is to demonstrate that the fuel system is not damaged as a result of normal operations and AOOs; if these criteria are satisfied, then the fuel system need not be further assessed against the SARRDLs. However, the SARRDLs must still be evaluated against other sources of radionuclides, including circulating radionuclides resulting from an appropriate number of random fuel failures.
4. The [[ ]] have not been subject to previous NRC review or approval. If they are to be used to develop design criteria and associated limits that support fuel assembly acceptance criteria, these design criteria and associated limits must be appropriately justified.
5. This TR does not address the extent to which the fuel system is expected to retain radionuclides following a cladding breach. If an applicant or licensee wishes to qualify Natrium Type 1 fuel with an expectation that radionuclides are expected to remain within the fuel following a cladding breach, models for fuel system radionuclide retention and release must be proposed and appropriately justified by comparison to experimental data.

CONCLUSION

The NRC staff determined that the TR, subject to the limitations and conditions discussed above, provides an acceptable approach for qualifying fuel and control assemblies for the Natrium reactor based on (1) the inclusion of sufficient information to demonstrate that fuel and control assemblies are manufactured in a process that provides adequate control over key parameters, (2) the identification of appropriate safety criteria for both fuel and control assemblies, (3) the development and justification of a significant applicable historical test database, (4) the development of a test plan that appropriately fills gaps in the historical test database, and (5) a robust fuel monitoring program. Accordingly, the NRC staff concludes that the qualification plan provided in the TR can be used to support compliance with 10 CFR 50.43(e) and proposed Natrium PDCs.

REFERENCES

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4. TerraPower, "Principal Design Criteria for the Natrium Advanced Reactor," NATD-LIC-RPRT-002, Revision 0, dated January 24, 2023 (ML23024A281)

5. U.S. Nuclear Regulatory Commission, "Fuel Qualification for Advanced Reactors," NUREG-2246, Revision 0, dated March 2022 (ML22063A131)

6. U.S. Nuclear Regulatory Commission, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," Section2, "Fuel System Design," Revision 3, dated March 2007 (ML070740002)

7. U.S. Nuclear Regulatory Commission, "Metal Fuel Qualification: Fuel Assessment Using NRC NUREG-2246, 'Fuel Qualification for Advanced Reactors,'" NUREG/CR-7305, dated August 2023 (ML23214A065)

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14. TerraPower, "Type 1 Fuel Pin Qualification Plan," AFQMG-ENG-PLAN-0001R, Revision 0, dated February 26, 2021 (ML21057A008)

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