UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, DC 20555-0001

June 27, 2024

Mr. Raymond V. Furstenau
Acting Executive Director for Operations
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: DRAFT SAFETY EVALUATION OF TERRAPOWER'S NATRIUM TOPICAL REPORT ON FUEL AND CONTROL ASSEMBLY QUALIFICATION

Dear Mr. Furstenau:

During the 716th meeting of the Advisory Committee on Reactor Safeguards, June 5 through 6, 2024, we completed our review of TerraPower's Natrium Topical Report NATD-FQL-PLAN-004 on Fuel and Control Assembly Qualification and the associated NRC staff safety evaluation report (SER). Our TerraPower Subcommittee reviewed this matter on May 15, 2024. During these meetings, we had the benefit of discussions with the Nuclear Regulatory Commission (NRC) staff and representatives of TerraPower. We also had the benefit of the referenced documents.

CONCLUSIONS AND RECOMMENDATIONS

1. The proposed operating envelope for Natrium fuel compared to the historical fast reactor metallic fuel performance database provides confidence that the fuel will perform with adequate margin under both normal operation and transient overpower conditions.

2. Quantitative fuel design limits that are tied to the regulatory acceptance criteria remain to be established as the design and safety analysis evolve.

3. The fuel surveillance program is important because it provides a way to safely manage the operation of Natrium fuel in light of any residual performance uncertainties once all the testing and code validation activities are complete.

4. The mechanical restraint system with the associated load pads is unique. The applicant has committed to monitoring during operation to validate the radiation effects in the modeling predictions of this system. Given this system's importance in reactivity control, a detailed plan for this activity is recommended for review and approval by the NRC prior to initial operation.

5. As recognized above, significant work remains to provide all of the information necessary to qualify the fuel assemblies, control assemblies and mechanical core restraint system in Natrium. These limitations are appropriately noted by the staff. The SER with its associated limitations and conditions should be issued.

BACKGROUND AND OVERVIEW

The topical report presents plans to qualify: (1) the fuel assembly design, (2) the control assembly design, and (3) the mechanical response of the Natrium fuel/core. The report establishes high level regulatory criteria that when satisfied support a finding that the fuel is qualified and will perform as described in the Natrium safety analysis. The specific regulatory criteria are:

- To prevent fuel system damage,
- To prevent fuel system failure,
- To ensure fuel coolability, and
- To ensure reactivity control insertability.

These criteria are translated into the following fuel design criteria:

- Fuel is not damaged during normal operation and anticipated operational occurrences,
- Number of fuel pin failures is not underestimated during postulated accidents,
- Coolability is maintained, and
- Fuel system is never so severely damaged to prevent reactivity control and control rod insertion when required.

These fuel design criteria impose requirements on the fuel system, its design, testing and inspection of new fuel assemblies, on-line fuel system failure monitoring, and post-irradiation surveillance. All of these are part of the fuel qualification program. Acceptance criteria must be established for applicable fuel, absorber pins, and assembly design limits (e.g., stress, strain, mechanical loads) and associated performance limits (e.g., internal pin pressure, rod bowing, maximum temperature).

The topical report also maps all important fuel qualification activities to those outlined in NUREG-2246, "Fuel Qualification for Advanced Reactors," providing confidence that the fuel qualification plan is adequate. In simpler terms, fuel qualification includes identifying key fuel manufacturing parameters, specifying a fuel performance envelope to inform testing, using an evaluation model in the fuel qualification process, and assessing the experimental data to develop and validate this evaluation model and quantitatively define empirical safety criteria in support of the Natrium safety analysis.

Fuel System Design and Evaluation

The metallic fuel pin consists of fuel slugs inserted into a steel cladding with sodium (Na) bonding between the fuel slug and the cladding. Fresh fuel slugs represent 75% of the internal cross-sectional area of the fuel pin. A liquid sodium bond between the fuel and the cladding promotes heat transfer. The plenum is filled with inert gas. As burnup progresses, fission gas is generated and induces swelling of the fuel slug that causes: (1) contact with the cladding early in life, and (2) interconnected porosity in the fuel slug which leads to venting of fission gasses to the upper plenum of the pin.

The cladding is HT9, a ferritic-martensitic steel that has a strong resistance to swelling with adequate microstructural stability at the peak doses proposed for Natrium. Each pin is helically wrapped with HT9 wire to provide lateral pin-to-pin and pin-to-duct spacing and promote coolant mixing throughout the assembly. Fuel assemblies may require rotation at selected irradiation times to balance out irradiation-induced geometrical distortions.

The historical experience with metallic fuel and a Phenomena Identification and Ranking Table (PIRT) developed as part of the topical report preparation indicate that the key fuel performance criteria include fuel swelling and axial growth, fission gas release, cladding irradiation creep and swelling, fuel-clad chemical interaction (FCCI), and constituent redistribution in the fuel. Transient performance is determined by fuel melting, formation of low melting point fuel/clad eutectics, and thermal creep and total strain in the cladding.

Fuel Qualification Approach

The topical report notes that three methods will be used to qualify the fuel and demonstrate that the fuel system design bases are met: (1) historical operating experience, (2) testing, and (3) analytical predictions. To help bridge the gap between historical experience/designs and the Natrium fuel design, the applicant plans to use analytical predictions to evaluate fuel system compliance with design basis limits combined with operating experience.

Historical Database. Metallic fuel has been used in historic U.S. sodium cooled fast reactors, namely the Experimental Breeder Reactor (EBR)-II and the Fast Flux Test Facility (FFTF).[1] The fuel qualification program leverages this historical operating experience and data. Initial operation of Natrium will begin with U-10Zr fuel that is similar to that used in EBR-II and FFTF at temperatures, loads, and burnups within the historical operating envelope.[2] About 130,000 metallic fuel pins are part of the historical database. Most have burnups less than 10% fissions per initial metal atom (FIMA) but some as high as 20% FIMA. Many have different cladding alloys than that proposed for Natrium fuel. There is no direct commercial reactor operating experience with Natrium fuel, but the fuel is modeled after successful operation of similar fuel in EBR-II and FFTF.

Irradiated fuel similar to Natrium fuel has undergone overpower transient testing and demonstrated good performance at about four times the nominal power of historical sodium fast reactor designs. It appears that cladding failure under such transient conditions requires extensive fuel melting which may be delayed in U-10Zr fuel because of its higher melting point relative to other historical metallic fuels. Cladding failure is due to a combination of overpressure and thinning of the clad due to FCCI and low melting point eutectic formation. At low burnup significant eutectic penetration is necessary to cause failure; at modest burnup modest penetration is required; and at high burnup little penetration is necessary to cause failure. At high burnup, the type of cladding did not influence failure.

Performance Testing. Post-irradiation Examination (PIE) of a limited number of irradiated fuel pins from EBR-II and FFTF are of most interest to support qualification of Natrium fuel. PIE is also planned on FFTF fuel qualification assemblies and will provide independent validation (by withholding a subset of fuel pins from the model development/calibration activities).

Additional testing is planned: (1) to supplement historical operating experience for verification of consistent (or improved) performance between newly fabricated materials and historical

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[1] FFTF used predominantly oxide fuel in its core. There were some special fuel assemblies that contained metallic fuel. In this letter, comments made about FFTF fuel refer to these special assemblies and not the oxide fueled core.

[2] U-10Zr is an alloy of uranium metal with 10 weight percent zirconium.

materials, (2) to cover extrapolations of conditions beyond the historical database (e.g., long duration creep testing), (3) to reduce uncertainties or improve fundamental understanding, (4) to evaluate prototypic bundle or fuel pin geometries, and (5) to address gaps in historical operating experience due to differences in fuel pin/assembly design features and geometries. Collectively, this testing is intended to validate fuel damage limits and coolability.

Other Testing, Monitoring and Surveillance. Testing is planned to supplement the HT9 material property database, including thermal properties, unirradiated and irradiated mechanical properties, and chemical interactions. Testing and inspection of fabricated fuel will be important to establish cladding integrity, fuel system dimensions, fuel enrichment, fuel chemical composition, and absorber composition. On-line fuel system monitoring for fuel pin failure is also planned and will be accomplished by monitoring the reactor cover gas for fission gas, as was proven in FFTF, and correlating the gas release with a specific fuel assembly.

Lead demonstration assemblies (LDAs) will be exposed to higher burnups and for longer resident time than the fuel used in the core. There are also plans for lead test assemblies (LTAs) for more advanced fuel designs. This is a good starting approach to fuel qualification given the lack of fast reactor testing capability in the U.S. The topical report proposed a fuel surveillance program starting with a number of LDAs in the core and removing some of them after each cycle to perform PIE to verify fuel is performing consistently. The focus of the examinations will be on the high-importance fuel phenomena identified in the PIRT. The testing will also address fuel performance uncertainties associated with the current understanding of these phenomena from the existing historical database. This fuel surveillance program is an important part of the fuel qualification program. It provides a way to safely manage the operation of Natrium fuel in light of any residual uncertainties in fuel performance once all the testing and code validation activities are complete.

Analytical Predictions. Fuel performance models are an integral part of the fuel qualification program. The applicant will use these models to evaluate if fuel meets design criteria and to determine whether a fuel pin is damaged or failed. Validated models are required to assess fuel pin performance, fuel damage failure, and fuel coolability. Many of these evaluations also rely on neutronic and thermal hydraulic tools.

Control Assembly Design and Qualification

Control assembly absorber pins contain cladded helium bonded boron carbide. There are some geometric differences between the secondary and primary control assembly designs to provide defense in depth relative to common cause failure of absorber bundle to duct binding. Similar control assembly designs have had success in fast reactors around the world. HT9 cladding is used in Natrium rather than earlier austenitic stainless steels and the design lifetime is within the historical database. Validation comparisons to absorber pin data including plenum pressure, gas release fraction, B_4C swelling, absorber-clad chemical interaction (ACCI) and B_4C temperature will be performed. Additional testing will follow the initial fuel testing as necessary.

Fuel and Core Mechanical Response

A core restraint system is incorporated into the design to control radial expansion reactivity feedback. During operation, core-wide assembly movement can occur that can cause reactivity changes affecting power. Complex distortions must be accounted for due to assembly/assembly interactions caused by thermal and flux gradients. An above core load pad that maintains inter-assembly spacing and the top load pad along with the core support structure comprise the core restraint system. Historically, inelastic strains develop including thermal creep, irradiation creep, and void swelling. Inelastic deformations limited assembly lifetimes at both EBR-II and FFTF and made refueling difficult.

Fuel motion during seismic events must also be considered because it induces important reactivity feedback effects in sodium fast reactors. The design must ensure a mechanically locked core when inter-assembly contact is established. The locked core tends to insert negative reactivity with increases in core power. Tradeoffs exist between tight gaps to achieve a locked core early in life versus larger gaps needed for ease of core management.

A significant amount of mechanical testing of the core restraint system is planned over a range of physical sizes from subcomponents to single assemblies and multiple assemblies. Proof of concept tests to validate important design aspects are also planned. The results of these tests will support core assembly mechanical behavior estimates using finite element analysis. The core mechanical analysis considers both the core assembly distortion and the core restraint system response. These tools will also be used to support fuel assembly drop events to compare the stresses and strains to structural material limits.

Staff Safety Evaluation

The staff determined that the topical report provides an acceptable approach for qualifying fuel and control assembles for the Natrium reactor in large part based on their assessment of the plan compared to the goals established in NUREG-2246. The approval is subject to the following five limitations and conditions:

1) The approach described in the topical report does not in and of itself demonstrate that the fuel and control assemblies are qualified. Additional activities must be completed to appropriately justify that the fuel and control assemblies are qualified.

2) Materials other than U-10Zr and HT9 used in the fuel must be demonstrated to be manufactured according to standard specifications and used consistent with their qualification.

3) The report does not provide a means of demonstrating that the proposed specified acceptable system radionuclide release design limits (SARRDLs) are satisfied during normal operation and anticipated operational occurrences for the Natrium plant.

4) Other standards that have not been subject to previous NRC review must be appropriately justified if they are used to develop design criteria and associated limits for fuel and control assemblies.

5) The report does not address the extent to which the fuel system is expected to retain radionuclides following a breach of the clad. If the fuel is anticipated to be a fission product barrier, models for fuel system radionuclide retention and release must be proposed and appropriately justified by comparison to experimental data.

ACRS Assessment

The topical report presents an expansive plan covering fuel assembly qualification, control assembly qualification, and mechanical core response testing. In some cases, such as historical fuel pin examinations, the topical report provides details, while in other areas, such as specific testing that is currently planned, much less detail is provided. The staff noted this in their SER and provided an appropriate limitation and condition.

The plan is complex. Numerous regulatory acceptance criteria flow down to fuel design criteria that impose requirements on separate effects and integral irradiation testing, surveillance and monitoring requirements, and PIE. In addition, demonstrating that the fuel design criteria are met requires information on the reactor design and safety analysis. As appropriately noted by the staff, in some cases the plan lacks the quantitative fuel design limits that are necessary for the fuel design to support the high-level regulatory acceptance criteria.

A proof test of actual fuel to be used in Natrium cannot be performed because of the lack of a domestic fast neutron source. Any thermal reactor irradiations of metallic fuel will result in “old” fuel (high burnup) and “young” cladding (low radiation fluence). This may be acceptable for some testing where the focus is on the fuel but is not acceptable to assess cladding performance or integral effects in a prototypic environment at high fluence. As a result, to close any gaps, the proposed qualification approach includes numerous post-irradiation examinations of historic EBR-II and FFTF fuel pins, surveillance and monitoring during operation of Natrium, and analytic assessments of fuel performance. There will be no high fluence Natrium fuel available for transient safety testing; thus, additional testing of FFTF irradiated metallic fuel is planned.

The operating envelope for Natrium fuel and the historical fast reactor metallic fuel performance database provide confidence of acceptable fuel performance with reasonable margin under both normal operation and transient overpower conditions. However, the limited number of actual relevant fuel pins (U-10Zr in HT9 cladding) in the historical database makes statistical estimates of low failure rates difficult to support or validate. The planned fuel surveillance program is an important part of the overall fuel qualification approach. The use of the Natrium reactor as a test bed for qualifying subsequent more advanced fuels is a pragmatic approach to qualifying those future fuels, but the plan lacks details about the testing of those advanced fuels at this time.

The mechanical restraint system with the associated load pads is unique. The planned mechanical restraint testing may be insufficient especially in regard to its importance in demonstrating the overall negative reactivity response of the core with increases in power and temperature. Because of the mechanical complexity and the uncertainties in the relevant phenomena, it appears that obtaining distortion information on all core components may be needed during pre-startup testing and operation of Natrium at different points in the reactor’s lifetime. The applicant has committed to surveillance during operation to validate the modeling predictions. A detailed plan for this surveillance is recommended prior to actual operation, for review and approval by the NRC. For a plant of this size, negative reactivity feedback (e.g., neutron leakage) is of paramount importance for inherently stable and safe operation and acceptable transient performance.

Beyond the data that is planned to be acquired, analytic model estimates of the performance of the fuel assembly, control assembly, and core restraint system determine ultimate acceptability. Given the verification and validation burden associated with these models, it is unclear if the results will provide the necessary assurance relative to the regulatory acceptance criteria, especially when uncertainties are considered. The plan lacks details on the level of precision needed in these analytic results. The staff will need to carefully assess the modeling results given their role in demonstrating these systems meet the established design criteria.

Review of state-of-the-art models in the open literature confirm that a better understanding of axial and radial fuel swelling, fission gas release, and HT9 creep is needed, consistent with TerraPower's PIRT. The complexity associated with modeling physical contact between the fuel and the cladding, coupled with the potential for anisotropic swelling and growth, results in unresolved uncertainty.

There are also concerns about the repeatability and uniformity of the fuel fabrication process since pilot scale production of metallic fuel has not occurred in over 50 years. Moreover, how changes in fabrication affect material properties of the fuel system in both the unirradiated and irradiated state, especially swelling and creep in both fuel and cladding, remains an open question. Recent literature suggests that the onset of swelling in HT9 could be accelerated by high stress, that the swelling rate could be influenced by heat treatment during fabrication, and that HT9 experiences low temperature irradiation embrittlement.

Finally, it is important to provide assurance based on all the planned testing (some of which is confirmatory) that there is sufficient margin to conditions under which fuel-clad chemical interaction would cause fuel failure. Further, it should be confirmed that the associated fuel element constituent redistribution will not change the assumed melting temperature of the fuel due to the various low melting point eutectics that would form.

SUMMARY

The proposed operating envelope for Natrium fuel compared to the historical fast reactor metallic fuel performance database provides confidence that the fuel will perform with adequate margin under both normal operation and transient overpower conditions. The applicant has identified a number of technical gaps that will be addressed as part of the qualification program. The fuel surveillance program is important because it provides a way to safely manage the operation of Natrium fuel in light of any residual uncertainties in fuel performance once all the testing and code validation activities are complete.

We are not requesting a response to this letter.

Sincerely,

Walter L. Kirchner Signed by Kirchner, Walter on 06/27/24

Walter L. Kirchner
Chair

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