UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

December 19, 2025

WESTINGHOUSE EVINCI[TM] - SAFETY EVALUATION OF THE "TRISO FUEL DESIGN METHODOLOGY TOPICAL REPORT." EPID: L-2024-TOP-0028

SPONSOR AND SUBMITTAL INFORMATION

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Docket/Project No.: 99902079

Submittal Date: July 31, 2024

Submittal Agencywide Documents Access and Management System (ADAMS) Accession No.: ML24214A277

Brief Description of the Topical Report:

By letter dated July 31, 2024 (ML24214A277), Westinghouse Electric Company (Westinghouse) submitted the topical report (TR), EVR-LIC-RL-003-P/NP, "Westinghouse TRISO Fuel Design Methodology Topical Report," Revision 0, for the U.S. Nuclear Regulatory Commission (NRC) staff's review. This subject TR describes the general methodology and introduces analytical tools that will be employed to design, assess, and qualify uranium oxycarbide (UCO) tristructural isotropic (TRISO) fuel for the eVinci[TM] microreactor core design. It includes the consideration of the TRISO fuel lifecycle, including the fuel manufacturing process, quality control measures, operational envelope, performance analysis through simulation, transient testing to validate the behavior of the proposed TRISO fuel, technical specifications (TS) framework, and failed fuel monitoring. The proposed process plans to follow regulatory guides for fuel qualification and model benchmarking and validation.

REGULATORY EVALUATION

The following regulatory requirements are applicable to the NRC staff's review of TR EVR-LIC-RL-003-P/NP:

- Title 10 of the *Code of Federal Regulations* (10 CFR) Section 50.43, "Additional standards and provisions affecting class 103 licenses and certifications for commercial power," contains performance demonstration requirements that are applicable to commercial power facilities as described therein. Paragraph 50.43(e) of 10 CFR requires that, applications for a design certification, combined license (COL), manufacturing license (ML), operating license or standard design approval that propose nuclear reactor designs that differ significantly from light-water reactor designs that were licensed before 1997, or use simplified, inherent, passive, or other innovative means to accomplish their safety functions will be approved only if:

Enclosure 1

- (1)(i) The performance of each safety feature of the design has been demonstrated through either analysis, appropriate test programs, experience, or a combination thereof;

- (ii) Interdependent effects among the safety features of the design are acceptable, as demonstrated by analysis, appropriate test programs, experience, or a combination thereof; and

- (iii) Sufficient data exist on the safety features of the design to assess the analytical tools used for safety analyses over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions; or

- (2) There has been acceptable testing of a prototype plant over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions. If a prototype plant is used to comply with the testing requirements, then the NRC may impose additional requirements on siting, safety features, or operational conditions for the prototype plant to protect the public and the plant staff from the possible consequences of accidents during the testing period.

- Paragraph 52.47(a)(2)(iv) of 10 CFR requires:

(a) The application must contain a final safety analysis report (FSAR) that describes the facility, presents the design bases and the limits on its operation, and presents a safety analysis of the structures, systems, and components and of the facility as a whole, and must include the following information:

(2) A description and analysis of the structures, systems, and components (SSCs) of the facility, with emphasis upon performance requirements, the bases, with technical justification therefore, upon which these requirements have been established, and the evaluations required to show that safety functions will be accomplished. It is expected that the standard plant will reflect through its design, construction, and operation an extremely low probability for accidents that could result in the release of significant quantities of radioactive fission products. The description shall be sufficient to permit understanding of the system designs and their relationship to the safety evaluations. Such items as the reactor core, reactor coolant system, instrumentation and control systems, electrical systems, containment system, other engineered safety features, auxiliary and emergency systems, power conversion systems, radioactive waste handling systems, and fuel handling systems shall be discussed insofar as they are pertinent. The following power reactor design characteristics will be taken into consideration by the Commission:

(iv) The safety features that are to be engineered into the facility and those barriers that must be breached as a result of an accident before a release of radioactive material to the environment can occur.

> Special attention must be directed to plant design features intended to mitigate the radiological consequences of accidents. In performing this assessment, an applicant shall assume a fission product release from the core into the containment assuming that the facility is operated at the ultimate power level contemplated. The applicant shall perform an evaluation and analysis of the postulated fission product release, using the expected demonstrable containment leak rate and any fission product cleanup systems intended to mitigate the consequences of the accidents, together with applicable postulated site parameters, including site meteorology, to evaluate the offsite radiological consequences. The evaluation must determine that:
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> A) An individual located at any point on the boundary of the exclusion area for any 2-hour period following the onset of the postulated fission product release, would not receive a radiation dose in excess of 25 rem total effective dose equivalent (TEDE);
>
> B) An individual located at any point on the outer boundary of the low population zone, who is exposed to the radioactive cloud resulting from the postulated fission product release (during the entire period of its passage) would not receive a radiation dose in excess of 25 rem TEDE;

- Similarly, 10 CFR 52.157(d) is relevant for an ML application, 10 CFR 50.34(a)(1)(ii)(D) is relevant for a CP application, and 10 CFR 52.79(a)(2)(iv) is relevant for a COL application.

The NRC guidance documents that are applicable to the review of this TR are described below.

- DANU-ISG-2022-01, "Review of Risk-Informed, Technology-Inclusive Advanced Reactor Applications - Roadmap" (ML23297A158).

- Regulatory Guide (RG) 1.203, "Transient and Accident Analysis Methods," (ML053500170) provides the evaluation model (EM) development and assessment process (EMDAP) as an acceptable framework for developing and assessing EMs for reactor transient and accident analyses.

- RG 1.253, "Guidance for a Technology-Inclusive Content of Application Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors" (ML23269A222).

- NUREG-2246, "Fuel Qualification for Advanced Reactors," (ML22063A131) discusses a framework for use in qualification of nuclear fuels. The framework discusses the identification of key fuel manufacturing parameters, the specification of a fuel performance envelope to inform testing requirements, the use of EMs in the fuel qualification process, and the assessment of the experimental data (ED) used to develop and validate models and empirical safety criteria. The framework outlines a set of goals that, when met, can be used to justify that a nuclear fuel design is qualified for use.

Principal Design Criteria

Westinghouse TR EVR-LIC-RL-001-P/NP-A, Revision 1, “Principal Design Criteria Topical Report,” (ML24353A097) dated December 17, 2024, provides principal design criteria (PDC) for the eVinci™ Microreactor design that were reviewed and approved by the NRC staff in the associated safety evaluation (SE) (ML24283A133). The PDCs below are identified as relevant per TR EVR-LIC-RL-003-P, “Westinghouse TRISO Fuel Design Methodology Topical Report”:

- PDC 1, “Quality Standards and Records” - Safety significant structures, systems, and components (SSCs) shall be designed, fabricated, erected, and tested to quality standards commensurate with the safety significance of the functions to be performed. Where generally recognized codes and standards are used, they shall be identified and evaluated to determine their applicability, adequacy, and sufficiency and shall be supplemented or modified as necessary to assure a quality product in keeping with the safety significant function. A quality assurance program (QAP) shall be established and implemented in order to provide reasonable assurance that these SSCs will satisfactorily perform their safety significant functions. Appropriate records of the design, fabrication, erection, and testing of safety significant SSC’s shall be maintained by or under the control of the nuclear power unit licensee for an appropriate period of time.

- PDC 10, “Reactor Design” - The reactor system and associated heat removal, control, and protection systems (along with any SSCs supporting the reactor system and associated heat removal, control, and protection system’s safety function(s)) shall be designed with appropriate margin to ensure that specified acceptable system radionuclide release design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences (AOOs).

- PDC 12, “Suppression of Reactor Power Oscillations” - The reactor core; associated structures; and associated coolant, control, and protection systems shall be designed to ensure that power oscillations that can result in conditions exceeding specified acceptable system radionuclide release design limits are not possible or can be reliably and readily detected and suppressed.

- PDC 16, “Functional Containment” - A functional containment shall be provided to control the release of radioactivity to the environment and to ensure that the safety significant functional containment design conditions are not exceeded for as long as licensing basis event (LBE) conditions require.

- PDC 26, “Reactivity Control” - Reactivity control shall be provided. Reactivity control shall provide:

  (1) A means of inserting negative reactivity at a sufficient rate and amount to assure, with appropriate margin for malfunctions, that the specified acceptable system radionuclide release design limits and the reactor helium pressure boundary design limits are not exceeded and safe shutdown is achieved and maintained during normal operation, including AOOs.
  (2) A means, which is independent and diverse from the other(s), shall be capable of controlling the rate of reactivity changes resulting from planned, normal limits and the reactor helium pressure boundary design limits are not exceeded.

(3) A means of inserting negative reactivity at a sufficient rate and amount to assure, with appropriate margin for malfunctions, that the capability to cool the core is maintained and a means of shutting down the reactor and maintaining, at a minimum, a safe shutdown condition following a LBE.

(4) A means for holding the reactor shutdown under conditions that allow for interventions such as fuel loading, inspection, and repair.

- PDC 64, "Monitoring Radioactive Releases" - Means shall be provided for monitoring the functional containment performance, effluent discharge paths and facility environs for radioactivity that may be released from normal operations and LBEs.

TECHNICAL EVALUATION

Scope of NRC Review

Westinghouse intends to follow NUREG-2246 for accelerated fuel qualification, relying on modeling and simulation to inform fuel performance where deviations in the fuel design depart from the historic irradiation testing. Westinghouse states that the methodology for the modeling and simulation follows the EMDAP outlined in RG 1.203.

As requested in TR section 1.4, "Request for NRC," this SE covers the entire Westinghouse TRISO fuel design methodology for the eVinci™ microreactor core under normal operation, AOOs, and design basis accidents (DBAs) with the understanding that further development and licensing activities will occur. Westinghouse has identified key elements to software and analysis methods described in TR section 4.1, "Bison Governing Equations," section 4.2, "Bison TRISO Fuel Particle Material Properties," section 4.3, "Bison TRISO Physical Models," and section 5.0, "TRISO FUEL PERFORMANCE ANALYSIS METHODOLOGY,"; the code validation and verification plan described in TR section 4.4, "Verification and Validation Plan"; the uncertainty quantification plan described in TR section 4.5, "Uncertainty Quantification"; and the transient fuel capsule testing described in TR section 3.5, "Transient Fuel Capsule Testing."

The SE is structured in alignment with TR table 1.3-1, "Mapping of NUREG-2246 Goals," wherein each goal from NUREG-2246 is cross-referenced to the section(s) or information in the TR that is intended to support the accomplishment of that goal. The information provided by Westinghouse in TR section 6.0, "Technical Specifications Framework and Failed Fuel Monitoring," and appendix A, "Physical Constants and Conversion Factors," was also considered by the NRC staff to inform aspects of the review but is not part of the NRC staff's evaluation. The methods described in the TR are preliminary and V&V of these models has not been completed at the time of this review. As such, the NRC staff imposes Limitation 1, which withholds staff findings on the sufficiency of the results from testing, modeling, and analyses performed in accordance with the methodology to demonstrate conformance with PDCs or regulations. The NRC staff will review those, as requested, as part of future TRs or license applications. The NRC staff further imposes Condition 1, which requires an applicant referencing this TR to provide justification that parameters affecting the fuel performance, including the composition, dimensions, and operating envelope are within the scope of those to which the methodology can be applied and its results validated.

eVinci™ Design Overview

As discussed in TR section 2.0, the proposed conceptual design for the eVinci™ is a high-temperature, heat pipe-cooled, thermal spectrum, 15 MWth reactor. The reactor core is fueled with high-assay, low-enriched uranium TRISO fuel and consists of horizontal hexagonal graphite blocks with channels for fuel, burnable absorbers, alkali metal heat pipes, and shutdown rods. The core is surrounded by a radial reflector that houses control drums designed to manipulate core reactivity and allow the otherwise subcritical core to achieve criticality when the drums are specifically oriented. The control drums and shutdown rods provide independent, diverse means of achieving sub-criticality (shutdown).

The reactor core and reflector are contained within a canister that makes up an element of the functional containment design, with the layers of the TRISO fuel particles representing the other physical barriers. The vessel is filled with helium gas to enhance decay heat removal, which can be accomplished through the core block, radial reflector, core containment system (vessel), and shielding. Reactor heat produced for power generation (15 MWth) will be removed through alkali metal heat pipes and a primary heat exchanger and will be converted to electric power (~5MWe) through an open-air Brayton cycle power conversion system (PCS).

The eVinci™ microreactor concept is designed such that the reactor canister and core, and the support and PCS, can be transported in shipping containers by truck, rail, or waterway to an approved reactor site that has been appropriately constructed and prepared. Following installation at the site, criticality testing and subsequent operation will commence and continue, under remote monitoring with limited on-site operations, maintenance, and security staff, until the core reaches end-of-life. Following a reactor's operation, a replacement reactor can be shipped to and installed at the site in its place, while the spent reactor is allowed to cool until it is ultimately removed from the site for refurbishment, refueling, and/or decommissioning, as appropriate.

TRISO Fuel Design

Section 3.1 of the TR, "TRISO Fuel Design," provides a description of the eVinci™ fuel, which comprises TRISO-coated particles cast into cylindrical compacts with a graphite matrix. A TRISO-coated particle has a fissile material fuel kernel surrounded successively by four coating layers, including a porous carbon buffer layer, an inner pyrolytic carbon layer (IPyC), a Silicone Carbide (SiC) layer, and an outer pyrolytic carbon layer. The eVinci™ fuel design includes [[redacted] as described in TR table 3.2-1, "eVinci Microreactor TRISO Fuel Particle Parameters." The proposed design uses a TRISO fuel kernel [[redacted] Westinghouse is proposing a burnup [[redacted] fission per initial metal atom (FIMA) with benchmarking and validation and verification of BISON, a finite element-based nuclear fuel performance code developed through Idaho National Laboratory, to ensure nominal fuel performance is achieved [[redacted] Following benchmarking, Westinghouse will model its fuel system, perform a beginning of life transient test of the design in the Transient Reactor Test (TREAT) facility at Idaho National Laboratory, develop in-pile monitoring, and impose technical specification limits to achieve appropriate radionuclide release limits and fuel performance.

G1 - Fuel Manufacturing Specification

NUREG-2246 Goal G1, "Fuel Manufacturing Specification," states that licensing documentation should contain fuel manufacturing specifications sufficient to ensure that parameters affecting fuel performance are controlled during normal operation and accident conditions. These specifications help verify that the fuel will meet safety requirements throughout its operational life. Fuel manufacturing specifications are provided in TR section 3.1, section 3.2, "Westinghouse TRISO Fuel Design," and section 3.3, "Fuel Manufacturing and Quality Control." The eVinci™ TRISO fuel specifications are guided by AGR UCO TRISO specifications. The load-bearing SiC layer acts as the primary structural fission product retention boundary within the kernel, and PyC layers ensure SiC structure while acting as a bonding surface to the graphite matrix and final fission product barrier in the particle. Table 3.2-1, "eVinci Microreactor TRISO Fuel Particle Parameters," and table 3.2-2, "eVinci Microreactor TRISO Fuel Compact Parameters," outline the eVinci™ TRISO particle parameters such as composition, impurity limits, geometries, densities, and anisotropy. The elements of G1 in NUREG-2246 are: key dimensions and tolerances for fuel components that affect performance should be specified (G1.1, "Dimensions"), key constituents of fuel components should be specified, along with allowances for impurities (G1.2, "Constituents"), and end state attributes for the materials within fuel components should be specified or otherwise justified (G1.3, "End state attributes"). These elements are addressed in the following subsections.

G1.1 - Dimensions

The dimensions of the TRISO particles and the compact are included in tables 3.2-1 and 3.2-2. The specification of the dimensions meets goal G1.1 of NUREG-2246. The NRC staff noted that the TRISO fuel particle coating geometries being proposed by Westinghouse are largely in agreement with historic tests, particularly the AGR program. [[redacted]]. The NRC staff makes no findings on the qualification of fuel with these specific dimensions. Qualification of fuel with these specific dimensions will be addressed, as requested by Westinghouse, in the review of future submittals, consistent with Limitation 1 and Condition 1.

G1.2 - Constituents

G1.2 specifies that the material constituents of the fuel, including acceptable impurity levels, must be documented. This ensures that the chemical makeup of the fuel will not degrade performance or interact negatively with reactor materials. Impurities can affect both the fuel stability and cladding integrity, making it critical to control these elements within prescribed limits. TR sections 3.1, "TRISO Fuel Design," and section 3.2, "Westinghouse TRISO Fuel Design," discuss generalities and specifics of TRISO fuel design, respectively. Table 3.2-1 specifies parameters for eVinci™ Microreactor TRISO Fuel Particles, including acceptable impurity levels. Table 3.2-2 specifies parameters for eVinci™ Microreactor TRISO Fuel Compacts. The specification of the material constituents and associated impurity levels meets goal G1.2 of NUREG-2246. The NRC staff makes no findings on the qualification of fuel with these specific constituents. The qualification of fuel with these specific constituents will be addressed, as requested by Westinghouse, in the review of future submittals, consistent with Limitation 1 and Condition 1.

G1.3 - End State Attributes

G1.3 states that the final attributes of the manufactured fuel should be specified or otherwise justified. These attributes may include microstructure, thicknesses, sphericity, coating coverage, or phase composition of the fuel after fabrication. Examples of how historic TRISO fuel has defined end state attributes can be found in Electric Power Research Institute (EPRI)-AR-1(NP)-A, "Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance" (ML20336A052). TR section 3.2.2, "TRISO Fuel Compact Specification," discusses nominal TRISO fuel compact parameters including **[[**[redacted].**]]** TR section 3.3 discusses fuel manufacturing quality control. Westinghouse is using an end state specification adherence that will rely upon out-of-pile testing to ensure quality, rather than a process-based adherence. This testing includes **[[**[redacted].**]]** Westinghouse identifies the primary manufacturing defects and plans to assess each in a statistical manner through sampling and analysis of batches. The identification of end state attributes and the end state testing meets goal G1.3 of NUREG-2246 through a combination of specification and justification. NRC staff makes no findings on the qualification of fuel with these specific end state attributes, nor on the conclusions to be drawn from the tests, but these will be addressed in the NRC staff's review of future submittals, consistent with Limitation 1 and Condition 1.

G2 - Safety Criteria

The elements of G2, "Safety Criteria," involve design limits and the performance of the fuel under both normal and accident conditions to assess how safety criteria are satisfied. To adequately assess safety criteria, fuel failure mechanisms should be clearly defined and understood. TR section 3.4.1, "Failure Mechanisms," recounts fuel failure mechanisms from PNNL-31427 in TR table 3.4-1, "A Brief Summary of Failure Mechanisms." The elements of NUREG-2246 goal G2 are to ensure a margin to design limits can be demonstrated under normal operation and AOOs (G2.1, "Design Limits During Normal Operation and AOO's"), to demonstrate a margin to radionuclide release limits under accident scenarios (G2.2, "Radionuclide Release Limits"), and to demonstrate the ability to achieve and maintain safe shutdown (G2.3, "Safe Shutdown"). Portions of these may reference or require an EM or ED. The associated NUREG-2246 goals for EMs and EDs are covered below.

G2.1 - Design Limits During Normal Operation and AOOs

G2.1 establishes that the fuel is expected to remain intact or adhere to Specified Acceptable System Radionuclide Release Design Limits (SARRDLs) under conditions of normal operation, including the effects of AOOs. This goal comprises two sub elements: defining a fuel performance envelope (G2.1.1, "Definition of Fuel Performance Envelope"), and the specification of means of evaluating fuel for performance, failure, and degradation (G2.1.2, "Evaluation Model"). TR section 3.4.2, "AGR TRISO Qualification Envelope vs. eVinci Microreactor Operating Conditions," covers operating conditions including temperatures, burnups, fast fluence, and power density. The section also states that it is the design goal for eVinci™ to have an operational envelope bounded by the AGR test data. The intended operating envelope for eVinci™ is summarized in figure 3.4-2, "**[[**[redacted]

[redacted]]] and table 3.4-2, "Comparison of eVinci Microreactor Fuel Performance Key Parameters to the AGR TRISO Qualification Envelope." The specification of fuel performance envelope meets G2.1.1 of NUREG-2246. The TR states that because the design is preliminary, the design parameters are subject to change. Westinghouse has not requested approval of, and therefore the NRC staff makes no findings on, the acceptability of this specific qualification envelope. Consistent with Limitation 1 and Condition 1, the acceptability of this specific qualification envelope will be addressed in the NRC staff's review of future submittals, once Westinghouse finalizes the design parameters.

As discussed in TR section 3.0, "Background on the TRISO Fuel Design," and section 5.0, "TRISO Fuel Performance Analysis," a four-step approach is proposed to demonstrate performance of the fuel design in accordance with G2.1.2, including fuel performance analysis using the BISON code and transient fuel capsule testing. This approach is a technical specification framework that will set limits on the amount of fission products released from failed fuel and an online monitoring system that will be capable of detecting fission product release due to manufacturing defects or in-service fuel failure.

The specification of an evaluation model meets G2.1.2 of NUREG-2246, subject to Condition 2, that applications referencing this TR must quantify manufacturing tolerances in a manner that can demonstrate adherence to potential SARRDLs or otherwise specified radionuclide release limits. The approach in the TR leverages an EM to assess fuel performance, meaning NUREG-2246 goals EM G1, "Evaluation Model Capabilities," and EM G2, "Evaluation Model Assessment," are also applicable. EM G1 addresses the model's capabilities through three sub elements that ensure that the EM is capable of modeling geometry (EM G1.1, "Geometry Modeling"), materials EM (EM G1.2, "Material Modeling"), and physics (EM G1.3, "Physics Modeling"). These sub elements are described in the following sections of this SE.

EM G1.1 - Modeling Geometry of the Fuel System

EM G1.1 states that the model should accurately represent the geometry of TRISO fuel particles and their arrangement within the reactor core. TR section 5.2, "[[redacted]]]

TR section 5.3, "TRISO Fuel Compact Model," discusses how the fuel compact model [[redacted].]] This fuel compact model is then used in the integrated model and simulation of a subsequent core, beyond the scope of a fuel qualification.

NUREG-2246 goal EM G1.1 states that the EM should be able to capture geometric changes due to irradiation and exposure to the in-reactor environment (e.g., fuel swelling, cladding creep, oxide layer growth). TR section 4.4.2, "Verification and Validation," discusses [[redacted]

[redacted]]], which will aid in assessing the ability of the model to capture appropriate geometries throughout irradiation.

The approach given in the TR meets the intent of EM G1.1, but adherence to the EM goals will require methodology execution and successful benchmarking, verification, and validation to demonstrate that BISON is capable of modeling irradiation induced changes, consistent with Limitation 1.

EM G1.2 - Modeling Material Properties of the Fuel System

EM G1.2 focuses on ensuring that the model accounts for the material properties of TRISO fuel, including changes in those properties due to irradiation and high-temperature exposure. TR section 4.1, "Bison Governing Equations," discusses the coupled partial differential equations for energy, species, and momentum conservation. TR section 4.2, "Bison TRISO Fuel Particle Material Properties," discusses the material property models including kernel properties, buffer layer properties, gas gap properties, pyrolytic carbon properties, silicon carbide properties, and overall compact properties.

The material properties specific to kernels include thermal conductivity, specific heat capacity, molar mass, density, elastic properties, thermal expansion, and volumetric swelling. The TR includes both UCO and UO_2 thermal conductivity models, with the primary difference being irradiation induced changes to thermal conductivity being accounted for only in the UO_2 model. Both models are valid over the temperature and burnup ranges proposed in the TR. The specific heat capacity for the kernel is a UO_2 model. The equations for molar mass, theoretical density, and elastic modulus are sourced from relevant peer-reviewed literature. Thermal expansion models exist for both UCO and UO_2 fuels. The NRC staff identified that the conservative model should be used for thermal expansion. The same model availability is true for volumetric swelling: the TR discusses both UCO and UO_2 volumetric swelling models.

The material properties specific to the buffer layer, presented in TR section 4.2.2, "Buffer (Low-Density Pyrolytic Carbon) Properties," include thermal conductivity, specific heat capacity, elastic properties, thermal expansion, irradiation induced dimensional changes, irradiation induced creep, and density. For the gas gap properties, the TR covers thermal conductivity. All these properties are sourced from relevant literature.

Section 4.2.4, "Pyrolytic Carbon Layer," covers thermal conductivity, specific heat capacity, elastic properties, irradiation induced creep, irradiation induced dimensional changes, characteristic strength and Weibull modulus, thermal expansion, Bacon Anisotropic Factor, and density. TR section 4.2.5, "Silicon Carbide Properties," covers the thermal conductivity, specific heat capacity, thermal expansion, elastic properties, irradiation induced creep, characteristic strength and Weibull modulus, and density for the SiC layer. Section 4.2.6, "Compact Material Properties," discusses thermal conductivity and specific heat capacity for graphite. TR section 4.2.6.2, "Homogenized Compact Thermal Conductivity," discusses the effective thermal conductivity of the homogenized system and references established practices and TR section 4.2.6.4, "Homogenized Compact Specific Heat Capacity," which introduces the model for homogenized specific heat capacity. As the models depend upon the aforementioned material properties, they will inherently incorporate the same conservatisms. The TR identifies no novelty in these layers or graphite.

The NRC staff finds that Westinghouse has identified the necessary models to meet EM G.1.2 following benchmarking and code validation and verification. The NRC staff imposes Limitation 2, that the application of the BISON framework will be limited to UCO TRISO fuels encompassed by experimental data, both in design and operational envelopes, used for validation of the model, or to where the scalability of both the UCO TRISO fuel system and the model has been adequately demonstrated.

EM G1.3 - Modeling Relevant Physics

EM G1.3 emphasizes that the model must simulate the key physical processes affecting TRISO fuel, such as fission product migration, chemical interactions with coolant, and mechanical stresses.

TR section 4.3, "Bison TRISO Physical Models," covers the relevant physical models including burnup, fission gas release, fission product recoil, Booth model for diffusion, fission gas production, internal gas pressure, fission product transport, fission product release and birth ratios, carbon monoxide production, kernel migration, and Palladium penetration.

Historical data, particularly those identified in the TR for benchmarking and validation assessment, are capable of informing the validity of burnup and fission gas release models included in the topical report. Direct recoil of **[[**[redacted]**]]** are fundamental physics equations derived from literature and are not easily, nor expected to be, benchmarked and validated directly in full scale testing. However, a benchmarking and validation process consistent with EMDAP and RG 1.203 would be capable of quantifying model sensitivities. Similarly, TR section 4.3.2.2, "Booth Model," proposes a model to simulate diffusive release of fission products through the kernel.

Fission product diffusivity will impact internal pressures and subsequent fuel kernel swelling, which may be directly analyzed in the test data, likely limiting the impact that this model directly has on fuel performance prediction. Coupling this with the model for fission gas production, pressure, and fission product transport in TR section 4.3.3, "Fission Gas Production," section 4.3.4, "Internal Gas Pressure," and section 4.3.5, "Fission Product Transport," it is possible for an assessment to be made against the identified data sets.

Westinghouse intends to submit future licensing documentation on the eVinci™ microreactor mechanistic source term that will further support conformance with this goal. As such, the NRC staff finds the identified physical models and identified test base to be sufficient to formulate a mechanistic source term assessment and demonstrate that the modeling efforts conform to EM G1.3 from RG 1.203, subject to Limitation 1 and Condition 1.

EM G2 - Evaluation Model Assessment

EM G2 states that the EM should be rigorously assessed to ensure it produces reliable predictions. This includes validating the model against ED to confirm its accuracy, as proposed in TR section 4.4. EM G.2 is subdivided into the assessment of ED and the fuel performance prediction over test envelope, which includes quantification of model error, data coverage of performance envelope, justification of sparse data regions, and restricted application domain. EM G2.1, "Experimental Data," is further divided into ED goals. EM G2.1 states that the model should be validated using data relevant to the proposed TRISO fuel, ensuring that predictions match observed performance. Westinghouse has identified data for such a validation in TR section 3.5, "Transient Fuel Capsule Testing" and section 4.4.2 "Verification and Validation." These tests and their purposes are discussed in a later section of the SE "ED Experimental Data Goals," pertaining to the ED goals. Thus, the NRC staff finds the approach to satisfy EM G2.1 acceptable subject to Limitation 1 of this SE.

EM G2.2 "Demonstrated Prediction Ability over Test Envelope" states that the model's predictions should be demonstrated across the full range of operational and accident conditions to assess fuel failure and degradation. TR section 3.4.2, "AGR TRISO Qualification Envelope vs. eVinci Microreactor Operating Conditions," covers the test envelope and the envelope proposed by Westinghouse. TR section 4.5, "Uncertainty Quantification," covers the model uncertainty with respect to **[[**[redacted].**]]** EM G2.2 has four sub elements that include: quantification of model error against ED (EM G2.2.1, "Quantification of Evaluation Model Error"), error is determined throughout the fuel performance envelope (EM G2.2.2, "Validation Data Covers Performance Envelope"), sparse data regions are justified (EM G2.2.3, "Justification of Sparse Data Regions"), and the model is restricted to use within its test envelope (EM G2.2.4, "Restricted Application Domain"). The NRC staff finds the approach to satisfying EM G2 acceptable subject to Limitations 1 and 2 and Conditions 1 and 2.

G2.2 - Radionuclide Release Limits

G2.2 sets radionuclide release limits for accident conditions, ensuring that fission products are retained within the fuel. TRISO fuel's multi-layered coatings are designed to act as barriers, containing radionuclides even under extreme temperatures. G2.2.1, "Radionuclide Retention Requirements," specifies that fuel must demonstrate sufficient radionuclide retention during accident conditions, with performance evaluated at high temperatures. TRISO fuel's SiC layer is especially critical in retaining fission products during severe accidents. TR section 4.3.6, "Release/Birth Ratios," and section 4.4.2.2, "**[[**[redacted]**]]**," document Westinghouse's conformance with G2.2.1.

G2.2.2, "Criteria for Barrier Degradation," (a) states that there should be suitably conservative criteria for evaluating the degradation of the fuel's retention barriers, ensuring safety margins are maintained. TR section 3.5, section 4.4.2, and section 5.4.2, "Coupled Multiphysics Analysis," document Westinghouse's conformance with the G2.2.2(a). G2.2.2, "Criteria for Barrier Degradation," (b) states that barrier degradation mechanisms under accident conditions should be understood. This may be satisfied by demonstrating conservative prediction for barrier degradation and failure or through ED. The methodology for model V&V outlined in this TR informs the barrier degradation mechanisms and underlying phenomena; however, since this is a novel fuel geometry, Westinghouse has included transient testing to bridge this gap, as recommended in NUREG-2246.

G2.2.3, "Conservative Modeling of Radionuclide Retention and Release," states that modeling approaches to predict radionuclide retention and release under accident conditions should be conservative. This includes accounting for potential failure modes in TRISO fuel's coatings and ensuring the models provide a high degree of safety assurance. As discussed in this SE, Westinghouse has considered a reasonable interpretation of failure modes. Conformance with these goals relies on the execution of this TR and completion of model V&V as well as executing the proposed transient testing and characterization, consistent with Limitation 1. The transient testing data may also contribute to validation of fuel performance modeling and inform conservative input assumptions. The benchmarking of modeling, V&V, and transient testing supports conformance with the conservative criteria outlined in G2.2 of NUREG-2246.

Additionally, TR section 6.0, "Technical Specifications Framework and Failed Fuel Modeling," describes proposed active monitoring and associated TS to limit the release of fission products from failed fuel particles during normal and off-normal conditions. This will include the development and implementation of an online monitoring system, capable of detecting potential fission product releases from in-service fuel failures or manufacturing defects. As the fuel design is not directly correlated with historical TRISO fuel designs, this active monitoring is a critical component of the eventual fuel qualification efforts. As such, the NRC staff imposes Condition 3, that any application of this methodology will rely on the development of a failed fuel monitoring system that is capable of monitoring for adherence to radionuclide release limits and associated quantifiable TS.

G2.3 - Safe Shutdown

G2.3 addresses the ability of the reactor to achieve and maintain safe shutdown following an accident, ensuring that the fuel maintains a coolable geometry and does not compromise core cooling. G2.3.1, "Maintaining Coolable Geometry," states that the fuel's structural integrity should allow it to maintain a coolable geometry during and after an accident. For TRISO fuel, this means ensuring that fuel particle integrity is maintained, preventing the release of fission products that could impede cooling. Westinghouse has stated that there are no phenomena that could cause the loss of coolable geometry because fuel channels are physically isolated from coolant channels (i.e., heat pipes). As such, there are no applicable EMs necessary to assess the coolable geometry margin. The NRC staff will assess this during the review of future submittals, consistent with Limitation 1.

G2.3.2, "Negative Reactivity Insertion," states that the reactor design should ensure that negative reactivity can be inserted during an accident. TRISO fuel's behavior under such conditions must support this reactivity control, contributing to safe shutdown. This goal has two supporting subgoals: G2.3.2(a) states that, in part, "Criteria should be provided to ensure that the means to insert negative reactivity is not obstructed during conditions of normal operation or accident conditions."

The TR EVR-LIC-RL-001-A, Revision 1, "Principal Design Criteria Topical Report," (ML24353A097) dated December 17, 2024, provides PDCs for the eVinci™ Microreactor design that were reviewed and approved by the NRC staff in the associated SE (ML24283A133).

PDC 26 states, in part, that, "Reactivity control shall be provided. Reactivity control shall provide a means of inserting negative reactivity at a sufficient rate and amount to assure, with appropriate margin for malfunctions, that the specified acceptable system radionuclide release design limits and the reactor helium pressure boundary design limits are not exceeded, and safe shutdown is achieved and maintained during normal operation, including AOOs. Reactivity control shall provide a means of inserting negative reactivity at a sufficient rate and amount to assure, with appropriate margin for malfunctions, that the capability to cool the core is maintained and a means of shutting down the reactor and maintaining, at a minimum, a safe shutdown condition following a licensing basis event." G2.3.2(b) states, "An evaluation model is available to assess geometry changes as a result of normal operation and accident conditions." The NRC staff notes that the execution of this methodology will inform geometric evolution sufficient to assess negative reactivity insertion. Moreover, negative reactivity insertion is design dependent and, subsequently, cannot be assessed on a generic basis. The NRC staff will assess this during the review of future submittals, consistent with Limitation 1.

ED - Experimental Data Goals

The ED goals ensure that the EM is supported by accurate, reliable, and representative data, covering a comprehensive range of conditions.

ED G1 - Independence of Validation Data

ED G1 states that validation data must be independent from the data used to develop the model. Independent data ensures the objectivity and reliability of model validation. This goal is further subdivided into ED G1.1, "Data Origin," which states that validation data should come from a variety of independent sources, including experimental tests, historical data, and peer-reviewed studies, to provide a robust validation base. The element also includes ED G1.2, "Relevance to Model," which states that the data used for validation must be relevant to the conditions modeled for TRISO fuel performance, ensuring it covers operational and accident scenarios.

Westinghouse has identified tests for validation and benchmarking of BISON. These tests are discussed in TR section 4.4.2, "Verification and Validation." The NRC staff understands that Westinghouse may incorporate additional data for benchmarking and validation as deemed appropriate during the execution of the methodology. The ED referenced in this TR includes [redacted]]. This group of data originates from multiple sources independent of BISON development and encompasses the operational envelope found in the TR. As such, the NRC staff finds that the proposed test data in this TR satisfies NUREG 2246 goal ED G1.

ED G2 - Test Envelope

ED G2 focuses on ensuring that the ED spans the full test envelope of expected fuel behavior, including both normal and accident conditions. This goal is subdivided into additional subgoals. These include ED G2.1, "Operational Conditions," which states that data should cover the expected operational range, including temperatures, pressures, and neutron flux levels typical for TRISO fuel and ED G2.2, "Accident Conditions," which states that ED should include accident scenarios, such as loss-of-coolant accidents and high-temperature transients, to ensure the model predicts fuel performance under severe conditions.

The first ED referenced is the [[redacted],]] the fundamental behaviors and failure mechanisms captured in these benchmarks are also applicable to UCO fuels, which are expected to exhibit improved performance due to reduced CO production and enhanced fission product retention. As such, the benchmarking results versus the [[redacted]] data sets would be conservative for a direct comparison of UO_2 to UCO. Moreover, [[redacted]], aligning with much of the design proposed in this TR. The benchmarks encompass irradiation temperatures ranging from [[redacted]

[redacted]]], providing a comprehensive data set for validating models under various operational conditions. While the TR does not establish which test cases will be used or how, the NRC staff determined that the [[redacted]] data would support informative benchmarking and validation activities.

The second data set identified for validation is the [[redacted]]. The [[redacted]] testing included both UO_2 and UCO fuels. [[redacted]] Additionally, Westinghouse has identified that there are limited accident scenarios tested for UCO TRISO fuel particles and compacts. While earlier AGR program tests qualified TRISO fuel for slow heat-up transients typical of High-Temperature Gas-Cooled Reactor (HTGR) depressurized loss-of-forced-cooling accidents (~1800°C for extended durations), the proposed methodology employs transient testing to simulate reactor-specific transient conditions, such as [[redacted].]] The transient conditions are stated to be conservatively selected to bound all credible DBAs for the eVinci™ microreactor. The ED sets identified by Westinghouse in TR section 4.4.2 cover the normal operational envelope proposed in the TR, including burnups, fast fluence, time-average temperatures, and power density. A combination of historical data and transient testing will be used to assess AOOs. As such, the NRC staff finds the approach to satisfy NUREG goal ED G.2 acceptable, subject to Limitation 1.

ED G3 - Data Measurement

ED G3, "Data Measurement," outlines how ED should be collected, ensuring accuracy and reliability in data used for validation. ED G3.1, "Test Facility Quality Assurance," states that ED should be collected under a QAP, following appropriate standards such as American Society of Mechanical Engineers (ASME) NQA-1 to ensure accuracy. ED G3.2, "Measurement Techniques," focuses on ensuring that established, validated measurement techniques are used to collect data, thereby providing confidence in the accuracy of the results. The benchmarking and validation data identified in this SE satisfy this goal. The NRC staff will review the detailed documentation of the eVinci™ microreactor fuel performance code V&V in a future submittal.

How the data proposed by Westinghouse in TR section 4.4.2, "Verification and Validation" meets these criteria is beyond the scope of this review; however, the NRC staff notes that data used to satisfy EM G2 will also be assessed under ED goals. Additionally, Westinghouse intends to perform transient testing as described in TR section 3.5, "Transient Fuel Capsule Testing." The transient fuel testing program proposed by Westinghouse, including the design, fabrication, and execution, is to be conducted under a QAP that conforms with ASME NQA-1. This ensures that the ED generated is collected under controlled conditions, consistent with regulatory expectations for data integrity and traceability. In support of ED G3.2, Westinghouse has committed to using established and validated measurement techniques for both pre- and post-transient examinations. These techniques include characterization of the fuel capsules and compacts before and after irradiation. The use of inert gas environments to prevent chemical alteration during testing and the detailed control of transient heating conditions further support the accuracy of the data collected.

Together, these practices demonstrate potential conformance with ED G3 by ensuring that the ED used for model validation and fuel performance assessment are accurate, repeatable, and collected under appropriate quality assurance controls subject to Condition 1 and Limitations 1 and 2 of this SE.

ED G4 - Test Conditions

ED G4, "Test Conditions," describes how test data are representative of prototypical conditions. This goal is subdivided into two sub elements that ensure test specimens are fabricated consistently with the manufacturing specification (G4.1, "Manufacturing of Test Specimens") and ensures that test distortions arising from differences between the test and the actual conditions under which the fuel is expected to perform are evaluated (G4.2, "Evaluation of Test Distortions").

As discussed in SE sections regarding NUREG-2246 goal G1, and in section 3.0 of the TR, the TRISO fuel particle coatings, composition, and fabrication specifications being proposed by Westinghouse are largely in agreement with historical tests, particularly the AGR program. **[** [redacted] **]**. G4.1 relies upon the development of a fabrication process and testing, which will be reviewed as part of a future submittal, consistent with Limitation 1.

ED G4.2, states that test distortions should be evaluated and that "the test specimens should be fabricated consistent with fuel manufacturing specifications and any test distortions, such as differences in test dimensions or conditions, should be adequately justified." An additional consideration is that nuclear reactor fuel is generally considered a safety feature subject to the requirements of 10 CFR 50.43(e) which states, in part, that the performance of the safety feature (fuel) must be demonstrated through "either analysis, appropriate test programs, experience, or a combination thereof" and that sufficient data exist to assess the safety feature to assess tools used for safety analysis (BISON) "over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions."

The NRC staff finds that the methodology proposed in this TR is well represented in terms of operational conditions. The time-average fuel temperature for the eVinci™ microreactor is expected to be **[[** [redacted] **]]** with a corresponding time-average compact power density of **[[** [redacted] **]]**. Burnup is limited to **[[** [redacted] **]]** FIMA [redacted] **)]]** with a time-average particle power of **[[** [redacted] **]]** mW/particle. The fast fluence is targeted at a maximum of **[[** [redacted] **]]**. All of these characteristics are bounded by historical test data. For context, historical UCO TRISO fuel in the AGR program includes kernels reaching 5.7-19.6 percent FIMA, time-average fuel temperatures between 467°C and 1432°C, and fast fluence ranging between 1.6×10^{25} n/m^2 and 5.6×10^{25} n/m^2. **[** [redacted] **]**.

The TR refers to transient testing of its design to bridge the gap between historical testing and the novel geometry being proposed in the TR. While the NRC staff cannot make a finding on the acceptability of this approach as it relies on the outcome of the execution of the entire methodology, the methodology found within the TR does indicate a plan to assess relevant ED and to satisfy ED G4 subject to Limitation 1, Condition 1, and Limitation 2 of this SE.

LIMITATIONS AND CONDITIONS

The NRC staff imposes the following limitations and conditions on this TR:

Limitation 1:

The NRC staff's approval of the methods in this TR is limited to the general use of BISON, the described model assumptions, and verification and benchmarking approaches. Staff make no findings on the sufficiency of the results from testing, modeling, and analyses performed in accordance with the methodology to demonstrate conformance with PDCs or regulations.

Condition 1:

An applicant referencing this TR must provide justification that parameters affecting the fuel performance, including the composition, dimensions, and operating envelope, are within the scope of those to which the methodology can be applied and its results validated.

Condition 2:

Future submittals referencing this TR must quantify manufacturing tolerances in a manner that can demonstrate adherence to potential SARRDLs or otherwise specified radionuclide release limits.

Limitation 2:

Application of the BISON framework will be limited to UCO TRISO fuels encompassed by experimental data, both in design and operational envelopes, used for validation of the model or to where the scalability of both the UCO TRISO fuel system and the model has been adequately demonstrated.

Condition 3:

Any application of this methodology will rely on the development of a failed fuel monitoring system that is capable of monitoring for adherence to radionuclide release limits and associated quantifiable technical specifications.

CONCLUSION

The NRC staff has determined that Westinghouse's topical report, EVR-LIC-RL-003-P/NP, "Westinghouse TRISO Fuel Design Methodology," Revision 0 (ML24214A277), provides an acceptable approach for TRISO fuel qualification, subject to the limitations and conditions discussed above, by outlining a methodology that follows NUREG-2246 and RG 1.203. The NRC staff notes that while the fuel design and operating conditions provided in the TR are relatively mature, as is the current modeling framework proposed in the TR, the methodology is preliminary, and this TR defers significant technical details to future submittals. Successful implementation of this methodology will rely on the benchmarking and validation used to evaluate test distortions, an activity that is deferred to future submittals.

REFERENCES

1. U.S. Nuclear Regulatory Commission (NRC), EVR-LIC-RL-003 P/NP “Westinghouse TRISO Fuel Design Methodology Topical Report,” Revision 0 (ML24214A277), July 31, 2024.

2. U.S. NRC, EVR-LIC-RL-001-A, Revision 1 “Principal Design Criteria Topical Report,” (ML24353A097), December 17, 2024.

3. U.S. NRC, Final Safety Evaluation for eVinci™ Principal Design Criteria Topical Report, (ML24283A133), October 16, 2024.

4. U.S. NRC, “Regulatory Audit Report regarding Westinghouse Electric Company’s TRISO Fuel Design Methodology Topical Report,” (ML25190A670), August 21, 2025.

5. U.S. NRC, Regulatory Guide (RG) 1.203, “Transient and Accident Analysis Methods,” (ML053500170), December 2005.

6. U.S. NRC, DANU-ISG-2022-01, “Review of Risk-Informed, Technology-Inclusive Advanced Reactor Applications – Roadmap,” (ML23297A158), March 2024.

7. U.S. NRC, NUREG-2246, “Fuel Qualification for Advanced Reactors,” (ML22063A131), March 2022.

8. U.S. NRC, EPRI (2020) Transmittal of Published Topical Report EPRI-AR-1(NP)-A, “Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance,” (ML20336A052), November 30, 2020.

9. U.S. NRC, Final Safety Evaluation for “Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance” Topical Report EPRI-AR-1(NP) (ML20210M241), August 4, 2020.

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Date: December 19, 2025