DRAFT SAFETY EVALUATION, REVISION 2

URANIUM OXYCARBIDE (UCO) TRISTRUCTURAL ISOTROPIC (TRISO) COATED PARTICLE FUEL PERFORMANCE: TOPICAL REPORT EPRI-AR-1(NP)

DOCKET NO. 99902021

1.0 INTRODUCTION

By letter dated May 31, 2019, the Electric Power Research Institute (EPRI), the applicant, submitted for US Nuclear Regulatory Commission (NRC) staff review, “Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance, Topical Report EPRI-AR-1(NP)” (Agencywide Documents Access and Management System (ADAMS) Accession No. ML19155A173), hereafter referred to as the topical report (TR).

This TR provides a baseline set of data in order to establish a foundation for TRISO fuel performance, based on testing performed as part of the US Department of Energy (DOE) Advanced Gas Reactor (AGR) Fuel Development and Qualification Program. The TRISO fuel form has applications ranging across a variety of reactor designs. The use of a topical report to establish a well-understood baseline set of fuel performance data for TRISO particles that can be referenced by a variety of vendors presents an efficient means to provide early review in support of potential future applications.

2.0 REGULATORY EVALUATION

This TR does not have a specific regulatory requirement associated with it because how the TRISO fuel meets regulations will depend on how the design and other systems, structures and components (SSCs) are credited in the overall safety of the design. No matter the design, however, 10 CFR 50.34(a)(3)(i) requires, in part, that an applicant for a construction permit to build a power reactor provide principal design criteria (PDC) for the facility. Similar regulatory requirements exist for design certification applications, combined license applications, and standard design approvals (10 CFR 52.47(a)(3)(i), 10 CFR 52.79(a)(4)(i), and 10 CFR 52.137(a)(3)(i), respectively). The PDC establish requirements for SSCs, and based on other approaches proposed for advanced reactor designs utilizing TRISO fuel, including the Next Generation Nuclear Plant (NGNP) project, designs with TRISO fuel have used a safety strategy focused on the radionuclide retention capabilities of the TRISO particles.

General Design Criterion (GDC) 10, “Reactor design”, in Appendix A of 10 CFR Part 50 states that the reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences. Although GDC 10 applies only to light water reactor (LWR) designs, the staff expects non-LWR designs to have a similar PDC. Examples of substitute PDC can be found in Regulatory Guide (RG) 1.232 “Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors”, which provides guidance for developing PDC for non-LWR designs. Establishing fuel design limits and ensuring these limits are not exceeded represent a fundamental underpinning of the safety assessment of a nuclear power plant required by 10 CFR 50.34(a)(1). This TR forms the basis for establishing the design limits for TRISO fuel.

Further, 10 CFR 50.34(a)(1)(ii)(C) requires an applicant to describe the extent to which the reactor incorporates unique, unusual, or enhanced safety features having a significant bearing on the probability or consequences of accidental release of radioactive materials. TRISO fuel presents a unique safety case in using a "functional containment" approach for reducing the release of radioactive materials, and the mechanisms by which TRISO fuel restricts the release of radioactive materials are described in this TR. Such an approach would also likely impact any PDC proposed for containment, but this is outside the scope of this TR.

3.0 TECHNICAL EVALUATION

3.1 INTRODUCTION

Section 1 of the TR summarizes the intended purpose of the report: to establish a baseline set of fuel performance criteria related to TRISO particles, based on the AGR-1 and AGR-2 tests and the irradiation, safety testing, and post-irradiation examination (PIE) results of that testing. The applicant notes this TR could support TRISO development in some of the following areas: to provide for early acceptance and resolution of technical information and data for fuel performance validation; to identify open issues related to the fuel form that could be resolved in subsequent submittals; and to progress fuel performance demonstration in the context of other licensing areas, such as source term and functional containment.

The introduction also states that the applicant requests the staff agree with the following conclusions in the TR (further detailed in the conclusions section and Section 3.8 of this safety evaluation):

- Testing of UCO TRISO-coated fuel particles in AGR-1 and AGR-2 constitutes a performance demonstration of these particle designs over a range of normal operating and off-normal accident conditions. Therefore, the testing provides a foundational basis for use of these particle designs in the fuel elements of TRISO-fueled high-temperature reactor (HTR) designs (that is, designs with pebble or prismatic fuel and helium or salt coolant).
- The kernels and coatings of the UCO TRISO-coated fuel particles tested in AGR-1 and AGR-2 exhibited property variations and were fabricated under different conditions and at different scales, with remarkably similar excellent irradiation and accident safety performance results. The ranges of those variations in key characteristics of the kernels and coatings are reflected in measured particle layer properties provided in Table 5-5 from AGR-1 and AGR-2. UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by these measured particle layer properties in Table 5-5 can be relied on to provide satisfactory performance.
- Aggregate AGR-1 and AGR-2 fission product release data and fuel failure fractions, as summarized in this report, can be used to support licensing of reactors employing UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by measured particle layer properties in Table 5-5 from AGR-1 and AGR-2.

Finally, the applicant notes that "Sections 1–4 and Appendices A and B are included as historical background and context only" and the conclusions of this TR do not rely upon the historical pre-AGR data. This is important in evaluating the context of Sections 2 through 4 of the TR, which are not reviewed for approval as part of this submission.

3.2 REGULATORY BASES

Section 2 of the TR describes how the applicant perceives the TR fits in the broader regulatory framework. The applicant provides background on previous interactions regarding the TRISO fuel form under the NGNP project. Appendix A of the TR details the regulations and guidance that the applicant found to be related to TRISO fuel. The applicant notes that establishing PDC for a reactor is a key part of the licensing basis for a reactor design, but the GDC were developed for LWR designs. Due to this, to assist advanced reactor designers in developing PDC for non-LWR designs, the NRC issued RG 1.232. The applicant states this TR is intended to provide background for meeting Modular High-Temperature Gas-Cooled Reactor Design Criteria (MHTGR-DC 10), "Reactor Design" and MHTGR-DC 16, "Containment Design" for TRISO-fueled designs in Appendix C of RG 1.232.

Specifically, because TRISO fuel is expected to be a primary fission product barrier, it will both be the design feature restricting radioactive releases in accordance with MHTGR-DC 10 and play a large role in the functional containment concept as described in MHTGR-DC 16 and in SECY-18-0096, "Functional Containment Performance Criteria for Non-Light-Water-Reactors." The applicant notes the scope of this TR is foundational, addressing the performance data obtained in the AGR-1 and AGR-2 tests and focused on the TRISO particle. Further fuel qualification efforts for other aspects of the fuel or a broader scope of performance conditions could be within the scope of future submittals, as needed.

3.3 TRISO-COATED PARTICLE FUEL EXPERIENCE BASE

Section 3 of the TR provides a review of historical experience related to the development of TRISO particles, including in the UK, US, Germany, and Japan. Further experience from these nations and others is described in Appendix B of the TR. The data in Section 3 of the TR is presented for context and background, only to show that TRISO fuel meeting prismatic HTR fuel performance requirements can be fabricated, but this information is not used by the NRC staff as part of the evaluation in this document.

3.4 FISSION PRODUCT RETENTION, PARTICLE DESIGN, AND PERFORMANCE BASES

Section 4 of the TR describes the features of the TRISO fuel design that make up the design and performance envelope. In the TR, the applicant explains how the concept of functional containment applies to the TRISO fuel design. Functional containment is discussed both in RG 1.232 and SECY-18-0096, and the applicant uses the definition in RG 1.232: "a barrier, or set of barriers taken together, that effectively limit the physical transport and release of radionuclides to the environment across a full range of normal operating conditions, anticipated operational occurrences, and accident conditions."

Generally, a collection of barriers is relied upon to ensure offsite dose limits are not exceeded. For high-temperature reactors using TRISO fuel, the fuel particle will be the primary barrier credited, and so fuel performance established for the TRISO particles must demonstrate a low fuel defect and failure frequency. This is accomplished in large part through the design of the particles themselves – a series of coatings surrounding each of the individual fuel kernels act together to retain most fission products and transfer heat effectively, while the particles are compatible with a carbonaceous matrix that provides a structural form to contain a large number of the small particles. The TRISO particle layers include (sequentially from inner- to outer-most) an inner fuel kernel, a low-density pyrolytic carbon (PyC) buffer layer designed to accommodate

gaseous fission products, and a pair of higher-density PyC (inner pyrolytic carbon (IPyC) and outer pyrolytic carbon (OPyC)) layers that sandwich a silicon carbide (SiC) layer. The IPyC and OPyC act as “load-bearing” components of the particle’s effective pressure boundary, and are structurally supported by the SiC layer, which acts as the primary metallic fission product barrier. The SiC layer is compressed by the two higher-density PyC layers, which assists in maintaining the structural integrity of the SiC layer. Different designs use different values for the layer parameters in particle design; these are summarized in Table 4-2 of the TR.

Section 4.3 of the TR explores the different potential failure mechanisms for the TRISO particle; a visual representation of how these failures may occur is shown in Figure 4-4 of the TR. Each of the failure mechanisms identified can be controlled through a combination of manufactured particle properties (e.g. density and layer thicknesses) and reactor service conditions (e.g. temperature, burnup, fluence). One failure mechanism, discussed in more detail later, that can result in releases through even “intact” particles is diffusion-stimulated releases through intact layers, which is a function of time at temperature and burnup, among other parameters. The TR also notes that while as-manufactured heavy metal contamination is not an in-service failure mechanism, it may impact fission product releases.

NRC Staff Evaluation

Staff recognizes that the applicant does not request staff approval of Section 4 of the TR, addressing different potential failure mechanisms, and does not present any conclusions in Section 8 of the TR based solely on this section. However, information related to the fuel particle and performance envelope play an important role in defining the relation between the tested fuel and the requests in this TR. Conclusion 1 of the TR states that “testing of UCO TRISO-coated fuel particles in AGR-1 and AGR-2 constitutes a performance demonstration of these particle designs over a range of normal operating and off-normal accident conditions.” Discussions under the conclusion reference a compact-averaged burnup of 7.3-19.6% fissions per initial metal atom (FIMA) and time-averaged maximum temperatures of 1069-1360°C. Other relevant performance parameters that bound the data set, such as those referenced in Figure 4-6 of the TR (packing fraction, fluence, power density) could influence particle performance. In reviewing the TR and during audit discussions (ADAMS Accession No. ML19310F085) with Idaho National Laboratory (INL) experts, staff determined other key parameters include fluence, time-averaged power, kernel stoichiometry, kernel-to-buffer ratio, and particle microstructure. In a letter dated February 26, 2020, the applicant provided clarifications regarding the relevant additional parameters associated with the particle performance. These topics are discussed in subsequent sections of this evaluation as limits for TRISO particles. The conclusions of this TR are subject to these limits, supplemented by the limitations and conditions section of this TR.

Staff notes that the above discussion relates to particle performance only, not any effect related to the compact. Compact performance could be credited as an additional fission product retention mechanism, or potentially require additional considerations due to key parameters related to the final fuel form such as particle packing fraction or material properties. Accordingly, staff-imposed **Limitation 1** as stated in the Limitations and Conditions section of this evaluation (Section 4.0), related to the scope of this TR covering the TRISO particle only.

In 2005, the DOE established the NGNP project at INL to support near-term commercial deployment of a high-temperature gas-cooled reactor technology demonstration plant. The design and licensing strategy of the NGNP centered on radionuclide retention capabilities of TRISO particle fuel, which included the INL AGR Fuel Development and Qualification Program.

The EPRI TR covers foundational fuel performance testing from the AGR-1 and AGR-2 tests including the irradiation, safety testing, and PIE results. The NRC staff assessment of "Next Generation Nuclear Plant Quality Assurance Program Description [QAPD]," dated September 12, 2012 (ADAMS Accession No. ML12241A157), found that the QAPD was acceptable for use during the technology development and high-level design phase of the NGNP project. Because the TR did not describe the scope of quality assurance (QA) activities performed by INL to obtain and submit the data used in the EPRI TR, the staff sought additional clarification in draft request for additional information (RAI) 5. In a letter response dated March 9, 2020 (ADAMS Accession No. ML20071D143), EPRI stated that these research and development activities are associated with "technology development" activities, and that the QA standards reflected in the NGNP QAPD and assessed by the NRC staff were implemented during the performance of those activities. The staff reviewed EPRI's response and concludes that the activities involved in developing the data referenced in this report performed by INL are bound by the NRC approved QAPD in that the activities were associated with technology development and high-level design activities.

3.5 ADVANCED GAS REACTOR FUEL DEVELOPMENT AND QUALIFICATION PROGRAM

Section 5 of the TR summarizes the AGR program and its relation to the TRISO particle design envelope discussed in the TR. Design specifications for the fuel and operational campaign were informed by US and international experience and expected industry performance requirements, and the AGR program was intended to provide for fuel qualification data in support of HTR designs. As a whole, the program focused on the following topical areas related to fuel qualification: fuel fabrication, fuel and material irradiation, fuel PIE and safety testing, fuel performance modeling, fission product transport, and source term development.

The AGR program consists of a series of campaigns, which cover a range of conditions from initial fuel scoping, to fuel performance, to fission product transport, to safety performance and accident condition testing. The TR provides a brief discussion related to TRISO fuel fabrication methods used to produce the particles for the AGR-1 and AGR-2 tests; the TR emphasizes that the conclusions outlined in the TR are intended to be fabrication method independent, and that only the fuel specifications (provided in Table 5-5 of the TR) constrain the performance as demonstrated in the AGR tests. Data related to the particles produced for these tests can be found in Tables 5-1, 5-2 and 5-3 of the TR.

The TR provides a brief discussion related to particle characterization, including methodology and particle makeup. Values obtained from whatever set of characterization methods (for the AGR-1 and AGR-2 tests) is used then fall within the particle property bounds in Table 5-5. The TR notes that the final step in fuel preparation is fabrication of the final fuel form – in the case of the AGR program, a cylindrical compact. The final fuel form is generally composed of a graphite binder due to satisfactory material properties and compatibility with the outer TRISO layer.

The TR also provides a supplementary discussion related to particle carbon content of the UCO particles. The particles used in the AGR testing targeted a uranium carbide content of approximately 30% to achieve burnups of 20% FIMA without exceeding acceptable CO gas formation. The TR provides an extended discussion from the literature on the relative effects of carbon content on gas formation.

NRC Staff Evaluation

The primary conclusions included as part of the TR center around Table 5-5, which is implied to provide an exclusive set of properties that, if determined to be satisfied, ensure that the manufactured TRISO fuel will perform to the same standards as the particles tested in AGR-1 and AGR-2. Based on the AGR-1 and AGR-2 tests and the consequential information provided in the TR, particles behaved similarly even with different manufacturing methods. International experience with a broader set of manufacturing methods lends further credence to the assertions in Section 5.3.6 of the TR, which states, “there is not a unique set of kernel specifications that are critical to successful TRISO fuel.” Based on the information provided in the TR, staff agrees that it is reasonable and possible to establish a set of measurable performance criteria independent of the manufacturing process based on the AGR experience and informed by historic TRISO development.

Effectively, the TR ties the property specification envelope to the performance demonstration of the AGR-1 and AGR-2 tests as discussed in Sections 6 and 7 of the TR. However, it was not clear in the TR that the exclusive set of parameters referenced in Table 5-5 was sufficient to demonstrate that manufactured fuel was sufficiently similar to the tested AGR fuel. Table 5-5 of the TR listed only kernel layer properties and thicknesses, along with properties related to relative uniformity of the particle (IPyC and OPyC anisotropy and particle aspect ratio). Other elements that the TR highlights as important, but that are not directly referred to in Table 5-5, include kernel-to-buffer ratio for the fuel particle (and potentially its associated size), columnar grain structure of the SiC, and carbon content of the UCO.

In the letter response dated February 26, 2020, the applicant added a number of additional areas of discussion related to key aspects of the tested TRISO particles. Section 5.3.2.4 of the TR provides additional context related to the SiC microstructure (**Confirmatory item**). Although the AGR program did not include quantitative limits on grain size, testing experience has shown that grains that are sufficiently large or columnar in nature (effectively those that provide for less torturous pathways for fission product escape) could fail to perform as intended. Because it would be challenging to establish a limit value, no restriction has been included in Table 5-5, but the TR provides a visual example of what constitutes approximate upper bound on an acceptable grain size in Figure 5-2, and the expectation is that an applicant referencing this TR would institute a similar control on manufactured TRISO particles.

Section 4.2 and Section 4.3 of the TR highlight the importance of SiC stresses in the mechanical fuel performance of the TRISO particles. Stresses are captured in a stress metric (σ in the TR, used as a proxy for tensile stress in the SiC layer), which encapsulates kernel stresses as a function of kernel and buffer volume, as well as burnup, SiC radius, and SiC thickness. Using the AGR data and Monte Carlo simulation techniques, the applicant calculated the value for σ and examined the distribution of stresses for the tested particles. This distribution is provided in Table 5-6 of the TR and is similar to the values used for historical fuel tests. Because σ includes considerations related to different particle sizes and layer parameters, it is a reasonable value for demonstrating the mechanical efficacy of potentially dissimilar particles (similar to non-dimensional values used in scaling analysis).

The values in Table 5-6 of the TR are not indicated as limits on the applicability of the TR. Although most of the parameters in σ are effectively derived from other limits cited in the TR (e.g. Table 5-5 plus burnup), kernel size itself is not. Staff recognizes this TR demonstrates TRISO fuel particle performance over a range of fabrication and operation conditions captured within the AGR-1 and AGR-2 data. The staff expects that Table 5-5 of the TR adequately captures the coating properties that bound acceptable particle performance based on the

provided data. However, staff notes that fuel kernel size can differ among different designs (see Table 4-2 of the TR), and this is not captured in the TR. Accordingly, the staff imposed **Condition 1** (discussed in Section 4.0 of this evaluation) on the TR, related to ensuring the AGR particle sizes sufficiently envelope those used by applicants or licensees referencing this TR. Staff notes this discussion in the TR also captures the considerations related to kernel-to-buffer ratio discussed earlier in the TR.

The TR states that "fuel particles tested in AGR-1 and AGR-2 exhibited property variations…with remarkably similar excellent irradiation and accident safety performance results. The ranges of those variations in key characteristics of the kernels and coatings are reflected in measured particle layer properties provided in Table 5-5 from AGR-1 and AGR-2." Table 5-5 provides a set of characteristics for "acceptable" TRISO particles, accounting for the bulk of the particle sample and the tolerance extremes for particles at the tails of the distribution. Staff audited (ADAMS Accession No. ML19310F085) the data and documentation supporting the values found in the TR. The staff issued RAI 3 on January 2, 2020, requesting the applicant provide, in part, a table with a clear requested range for each property for approval to be referenced in the conclusions. The staff reviewed the RAI response, dated February 26, 2020, and found the values in the revised Table 5-5 of the TR accurately reflect the data gathered. Based on the provided data, there is a clear basis for use of the measured values in Table 5-5.

In the response to RAI 3 (ADAMS Accession No. ML20058A040), the applicant added Appendix C of the TR to provide further context for the fuel manufacturing specifications used for the AGR program. The specification range is larger than the tested fuel range (from Table 5-5), sometimes substantially. This is an important consideration and a notable distinction of TRISO fuel as opposed to traditional previously licensed fuel designs – in TRISO fuel, there are many orders of magnitude more individual fuel elements, a very small fraction of which will be statistically expected to fail. The net effect of this small number of expected failures, as part of a broader functional containment approach for the full design (as described in SECY-18-0096), allows for a more granular performance-based approach (because these "anticipated" failures can be quantified directly and accounted for) with potentially larger margins of safety. Because this design philosophy for TRISO fuel differs dramatically from existing practice, staff recognizes and agrees with the statement in the TR that (**Confirmatory item**):

> "The values in Table 5-5 are not intended to define a comprehensive envelope of TRISO fuel that is expected to have acceptable performance. The data characterize the range of properties for particles that performed well during the AGR-1 and AGR-2 irradiations, but do not define the only ranges or combination of ranges that would perform well under these irradiation conditions or under service conditions proposed by fuel fabricators and reactor designers."

Particles from the AGR tests fall within the ranges delineated by the statistical ranges laid out in the TR (specifically, the specification ranges reflected in Table 5-5). As such, no limitation or condition need be imposed on an applicant directly referencing this TR. However, staff notes that this TR does not provide for the only set of parameters for acceptable TRISO performance, and that TRISO particles sharing many but not all of the characteristics of the particles tested in the AGR program could easily be shown to perform adequately. An applicant could have particles exceeding boundary values in areas and continue to have acceptable performance, but an applicant-specific demonstration would need to be provided. Staff is receptive to reviewing applications that reference this TR with supplemental justification for limited discrepancies from the performance envelope described here, and the review of that supplemental justification would be incorporated as part of any future licensing submittal.

As stated previously, the conclusions in this TR are limited to the TRISO particle. Performance of the final fuel form, including fission product retention and any other functional performance of the fuel itself is not within the scope of this TR and would need to be the subject of a future submittal.

As presented in the TR and supplemented by the response to RAI 2, the staff agrees that the tested carbon content during the AGR program does not represent a lower (or upper) bound on the amount of carbon that could be used in an acceptable TRISO particle. There is a lower bound, based on testing and the literature presented, and the precise value of that bound is based on burnup (and potentially temperature at elevated temperatures) and cannot be clearly established. Staff agrees with the assertion in the TR that there is a "wide range of UO_2/UC_2 ratios that maintain effectiveness at (a) limiting CO gas formation and (b) promoting the formation of rare earth oxides over the formation of rare earth carbides in order to increase retention of rare earths in the kernel." Due to the difficulty in establishing a clear boundary value, staff expects an applicant referencing this TR to provide a target burnup and carbon content range within the boundaries provided for in Figure 5-4 of the TR. This is reflected in **Limitation 2** as stated in the Limitations and Conditions section of this evaluation (Section 4.0).

3.6 AGR-1 AND AGR-2 IRRADIATIONS

Section 6 of the TR provides an extended discussion of the AGR-1 and AGR-2 irradiation programs. The TR outlines the experimental setup, layout including instrumentation and gas lines for cooling and fission product monitoring, and calculated power profiles over the course of the irradiation. Figure 6-6 and Figure 6-7 of the TR show the calculated capsule-average heat generation rate in the experimental compacts versus time. Many of the capsules showed an increase in power during the first half of the experiment; the applicant explains this is due to the depletion of the boron burnable poison added to the graphite fuel holders. The applicant states "capsule-average burnups [for AGR-1] ranged from 13.4% FIMA in Capsule 6 to 18.6% FIMA in Capsule 3" and "for AGR-2… capsule-average burnups ranged from 9.3% FIMA in Capsule 6 to 12.2% FIMA in Capsule 2 for UCO".

Further data is provided for power density, burnup, fluence, temperature, and other parameters for both the AGR-1 and AGR-2 campaigns. Direct fuel performance can be assessed through use of fission product release over birth (R/B) ratios measuring a collection of krypton and xenon isotopes. Calculated R/B ratios showed an "extremely low" gas release for AGR-1 and indicated zero fuel failures experienced out of 300,000 particles. AGR-2 had slightly higher R/B ratios (partially due to higher uranium contamination in the compacts), such that some small number of particle defects or failures cannot be precluded. Up to four failures were present out of 114,000 UCO particles in the AGR-2 tests, a failure fraction still below the design specification. Based on the results presented, the TR concludes that the AGR-1 and AGR-2 tests demonstrate excellent performance of UCO TRISO-coated particles with significant margin. These particles were fabricated using different conditions and properties (confined to the values provided in Section 5 of the TR).

NRC Staff Evaluation

Staff agrees that TRISO particles were tested over a range of fluxes, temperatures, and burnup values during the AGR-1 and AGR-2 testing. Based on the above discussion related to Section 5 of the TR, the data collected is applicable to the particles manufactured to the specifications in Table 5-5 of the TR. Data presented in the TR is difficult to summarize with a

single bounding value due to the nature of the fuel form and experimental setup (many individual particles located throughout a series of different test environments), but the temperature data presented in Figures 6-26 through 6-28 of the TR provide a reasonable effective temperature profile to reference. Further, power density over time for the tests is presented in Figures 6-6 and 6-7 of the TR, and burnup and fluence are captured in Figures 6-9 through 6-11 of the TR. Ultimately, the performance boundaries for the scope of this TR are provided in Table 6-6 and Figure 6-30 (**Confirmatory item**). The discussion related to Conclusion 1 in the TR accurately reflects these bounds. These data provide a "performance envelope" for the collection of AGR-1 and AGR-2 tests.

Staff reviewed the values provided as part of the TR and audited (ML19310F085) the underlying test results and methods for examining the test specimens and found them to be without issue. Staff compared the parameters used to historical fuel performance parameter thresholds for both traditional reactor fuel forms and for previous TRISO fuel experiments. Due to the nature of the TRISO particles and the substantial differences in form from most previously licensed fuel designs, staff agreed that the parameters chosen (burnup, fluence, and time-averaged temperature, power density, and particle power) represent an adequate set for evaluating TRISO fuel performance. This does not represent a complete datum for evaluating fuel performance in all operational modes – as noted earlier, performance of the final fuel form remains the responsibility of a future license applicant, and staff expects some transient and accident conditions may exhibit behavior that yields values that exceed the envelope presented in the TR. Nevertheless, staff agrees that the testing provides a foundational basis (and a valid data set) for use in future licensing submittals using TRISO particles.

As stated previously, staff found that the activities performed by INL are bound by the NRC approved NGNP QAPD in that the activities were associated with technology development and high-level design activities. As such, staff finds that the data referenced in the TR can be used to inform fuel performance for TRISO particles for those referencing this TR, subject to the parameter envelope in Table 5-5 of the TR.

NRC staff notes that fission product release measurements are limited to fission gas release during irradiation (discussed in Section 6.7 of the TR) and long-lived post-irradiation fission product release data (discussed throughout Section 7 of the TR). No data is obtained on short-lived radioisotopes during post-irradiation examination, because decay reduces their inventory to undetectable levels by the time PIE is initiated. Fuel performance criteria related to short-lived non-gaseous fission products are not captured by the test program described in the TR and are therefore not part of the scope of the TR. Accordingly, staff imposed **Condition 3** (discussed in Section 4.0 of this evaluation), and an applicant referencing this TR will need to consider the impact, if any, of non-gaseous short-lived fission products.

3.7 ASSESSMENT OF FUEL PERFORMANCE FROM POST-IRRADIATION EXAMINATION AND SAFETY TESTING

Section 7 of the TR characterizes the data obtained from the PIE following the AGR-1 and AGR-2 tests as well as the safety testing performed where the irradiated compacts were heated to higher temperatures. The TR summarizes the different methods that are used to quantify fission product releases (by either quantifying the fission product inventory remaining in the fuel, or the inventory that has been released from the fuel).

The primary longer-lived fission products that are of concern are Silver-110 m, Cesium-134, Europium-154 and -155, and Strontium-90. Cerium-144 and palladium are also discussed in

the TR but were generally not indicative of large amounts of release. Results show that cesium was released from some particles in the event of SiC failures, and much better retained for compacts where no SiC failures were observed. Europium and strontium were generally detected to a higher degree (more than an order of magnitude in terms of fractional release) in compacts as compared to capsules, indicating these isotopes release from the particle as a function of time at temperature but are largely retained in the compact material (dependent on irradiation and temperature conditions). Silver showed higher releases to the capsule, and "at the individual particle level, Ag [silver] release could range from complete retention to complete release."

Evaluation of the individual irradiated particles indicate most particles experienced debonding of the buffer and IPyC layer, and some particles (roughly a quarter in AGR-1) experienced fracture of the buffer layer. However, failure of the SiC layer (the primary TRISO barrier) occurred very rarely – approximately one per 52,000 particles in the irradiation testing and one per 15,000 particles at 1600°C testing following irradiation. Failure of the TRISO particle itself was even less common than the SiC failure. Examination of the particles for SiC failure mechanisms showed one primary mechanism for failure: buffer shrinkage leading IPyC fracture. The TR states this failure mechanism is likely to be difficult to model.

Testing at elevated temperatures following irradiation was conducted (referred to in the TR as "safety testing"); the results from this testing are shown in Figures 7-6 through 7-8 of the TR. Testing was conducted at hundreds of hours at temperatures ranging from 1600°C to 1800°C. Results related to cesium showed that cesium was unlikely to be released except in the case of SiC failure, where particles could release a relatively large fraction of contained cesium. Nearly all safety tests showed a large initial release of silver as the compact was heated, followed by a leveling off of the silver release; this was attributed to the "depletion" of the silver inventory in the compact outside of intact SiC layers. Europium and strontium behaved similarly, and generally releases of these two elements increased with increases in temperature and time at temperature.

A statistical summary of SiC and total TRISO failure is provided in Table 7-2 and Figure 7-15 of the TR. The TR reports the AGR-1 failure fraction as $\leq 1.1 \times 10^{-5}$ at 95% confidence and a conservative failure fraction for AGR-2 as $\leq 8.1 \times 10^{-5}$. Failure fractions increased at increasing temperatures beyond 1600°C in the safety testing. SiC failures were still rare, though more common: the total (95% confidence upper bound) SiC failure fractions across the AGR-1 and AGR-2 tests were $\leq 3.6 \times 10^{-5}$ during irradiation and $\leq 1.7 \times 10^{-4}$ and $\leq 1.3 \times 10^{-3}$ during safety testing at 1600°C and 1800°C, respectively. The applicant states these data provide for a performance demonstration across a range of conditions, and can be used to support the licensing of UCO TRISO-fueled reactors, subject to the parameters discussed in Section 5 of the TR.

NRC Staff Evaluation

NRC staff agrees with the above summary. The testing referenced above was performed under an adequate QA program, and the data gathered is sufficient to draw the conclusions that are within the scope of this TR. As such, NRC staff finds the collected data is valid for use in qualifying TRISO particles subject to the property specification and performance envelope outlined in the TR. Failure data for irradiated TRISO particles meeting the envelope described can be used directly in referencing this TR.

“Safety testing” values for testing at elevated temperatures, however, should not be used directly. Staff agrees the data is valid, but it may or may not directly apply to the specific scenarios calculated for any given design. A conservative assessment of the statistical failure data presented in this TR at lower temperatures (roughly less than 1600°C) may be directly used empirically. Once particles reach the temperature condition that shows failures may occur (that is, roughly greater than 1600°C), an applicant or licensee referencing this TR would need to justify how transient accident conditions were bounded by the data provided in the TR or provide additional analyses or testing to justify fuel performance in the specific accident scenario. Further, transient conditions (like sharp power ramp rates) are not generally within scope of this TR and would again require justification.

Staff further notes that this TR provides for an empirical, experimental data set pertaining to particle failure in a limited temperature and power regime. The data do not enable a deterministic prediction of individual particle failure; instead, based on an assessment of the fuel operating conditions (e.g., temperature) outlined in the TR, a statistical failure probability for a population of particles can be projected. Thus, the TR provides a reasonable data set to establish a performance envelope for particles that will not be expected to fail at rates exceeding the statistically calculated values. The results discussed in Section 7.4 of this TR provide for an understanding of TRISO particle failure mechanisms. The dominant SiC failure mechanism in the AGR-1 and AGR-2 tests is different from the failure mechanisms observed in past TRISO fuel irradiations and from mechanisms currently embedded in fuel performance models. Thestaff emphasizes that this TR does not provide sufficient data to evaluate simulated individual particles directly. The TR, can, however, be used to empirically evaluate failure probabilities of general populations of TRISO particles manufactured to the specifications outlined in Table 5-5 and subject to the performance envelope defined by Table 6-6 and Figure 6-30 of the TR. Accordingly, staff imposed **Condition 2** (discussed in Section 4.0 of this evaluation) related to the use of particle failure data based on the information presented in this TR.

With respect to the quantitative effects of the SiC microstructure discussed in Section 5.3 of the TR and in the above evaluation, the applicant found no pronounced differences in performance up to 1700°C due to differing SiC microstructures subject to the visual controls discussed earlier. Based on the data, staff agrees with that assessment and it supports the conclusions made above regarding the applicability of the AGR data.

3.8 SUMMARY/CONCLUSIONS

The applicant requests the NRC approve the following conclusions, based on the information presented in Sections 5 through 7 of the TR:

- Testing of UCO TRISO-coated fuel particles in AGR-1 and AGR-2 constitutes a performance demonstration of these particle designs over a range of normal operating and off-normal accident conditions. Therefore, the testing provides a foundational basis for use of these particle designs in the fuel elements of TRISO-fueled HTR designs (that is, designs with pebble or prismatic fuel and helium or salt coolant).
- The kernels and coatings of the UCO TRISO-coated fuel particles tested in AGR-1 and AGR-2 exhibited property variations and were fabricated under different conditions and at different scales, with remarkably similar excellent irradiation and accident safety performance results. The ranges of those variations in key characteristics of the kernels and coatings are reflected in measured particle layer properties provided in Table 5-5 from AGR-1 and AGR-2. UCO TRISO-coated fuel particles that satisfy the parameter

envelope defined by these measured particle layer properties in Table 5-5 can be relied on to provide satisfactory performance.

- Aggregate AGR-1 and AGR-2 fission product release data and fuel failure fractions, as summarized in this report, can be used to support licensing of reactors employing UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by measured particle layer properties in Table 5-5 from AGR-1 and AGR-2. (**Confirmatory item**)

NRC Staff Evaluation

Conclusion 1 of the TR requests acceptance that the AGR-1 and AGR-2 tests constitute a performance demonstration of AGR TRISO particles such that the testing forms a foundational basis for use in future TRISO fuel designs. The associated discussion under Conclusion 1 provides the performance ranges of the subject particles in terms of burnup, time-averaged temperatures, fast neutron fluence, and power density. Coupled with the time-averaged particle power – important because it accounts for differences in compacts and thus focuses on the particles themselves – discussed in Section 6 of the TR, staff agrees this set of performance parameters adequately captures the envelope of the AGR-1 and AGR-2 test conditions, as discussed above. Subject to the conditions laid out in the limitations and conditions discussed in this evaluation, staff finds Conclusion 1 to be applicable and acceptable.

Conclusion 2 of the TR requests broader approval: particles manufactured consistent with the limits identified in Table 5-5 of the TR, which are based on the calculated AGR-1 and AGR-2 particle parameters, can be relied on to provide satisfactory performance. Satisfactory performance, in this case, is aligned with the empirical performance demonstration described in Sections 6 and 7 of the TR. The discussion supporting Conclusion 2 further highlights the differences in coating conditions and manufacturing methods, with the exception that coating in all cases was carried out using an uninterrupted process to ensure high coating quality. As discussed above, the applicant provided a clear basis for use of the values in Table 5-5, and the values in Table 5-5 are not representative of an exclusive set of parameters for acceptable TRISO performance. However, the values in Table 5-5 serve to tie the empirical data discussed in this TR to the tested AGR-1 and AGR-2 particles, and so the staff finds the scope of Conclusion 2 acceptable. Subject to the limitations and conditions discussed in this evaluation, staff finds Conclusion 2 to be applicable and acceptable.

Conclusion 3 requests the ability to use the AGR-1 and AGR-2 fuel failure and fission product release data to support licensing TRISO-fueled reactor designs that satisfy the parameter envelope defined in Table 5-5 of the TR. The supporting discussion notes this conclusion is limited to the isotopes discussed in Section 6.7, 6.8, 7.1 and 7.3 of the TR – that is, short-lived fission gases and longer-lived isotopes (Cs, Eu, Sr, Ag, Kr) discussed in greater detail in Section 7 of the TR. Based on the provided data, 95% confidence interval failure fractions for the irradiation testing are provided, and staff finds these values can be used by applicants referencing this TR. Relative values for radionuclide releases are confined to intact particles, and demonstration of any retention within the fuel form outside the particle is the responsibility of the applicant or licensee referencing this TR, as stated in Limitation 1 of this evaluation.

As discussed in the above evaluation, safety testing data post-irradiation should only be used considering the context of the specific design and the applicability of the data to the expected fuel conditions. The data itself is valid, but transient and accident conditions may or may not match the conditions experienced by the tested AGR particles. Thus, justifying the applicability of the safety testing data is an exercise left to an applicant or licensee referencing this TR.

4.0 LIMITATIONS AND CONDITIONS

The staff imposes the following limitations and conditions with regard to the TR and its conclusions:

(1) Limitation 1: The scope of this TR applies only to the UCO TRISO particles themselves. How the final fuel form is qualified and any impacts of the fuel form or other influences of the specific reactor design beyond the fuel form on the holistic fuel performance (for instance, any uranium contamination in the compact material) is the responsibility of the vendor or designer referencing this TR.

(2) Limitation 2: This TR applies only to UCO TRISO particles that fall within the ranges discussed in Section 5.3 of the TR. If an applicant chooses to use UO_2/UC_2 ratios or burnup values that differ meaningfully from those used in the AGR program, the applicant must provide a justification for how the burnup and carbon content ratios conform to the performance ranges discussed in Section 5.3 of the TR.

(3) Condition 1: An applicant or licensee referencing this TR must evaluate any discrepancies between their fuel particles and the TRISO particles used in the AGR program - specifically, reviewing the ranges specified in Table 5-6 for stress values to capture any effects from different kernel sizes to ensure the data in the TR remain applicable.

(4) Condition 2: The performance limits in Table 6-6 and Figure 6-30 of the TR are the result of different tests with distinct samples, not all of which had the maximum bounds occur during the same test. The test results include considerations for uncertainty discussed in Sections 6.4 and 6.5 of the TR. Further, when failures may occur, the data supporting the TR provides empirical evidence of failure based on aggregate test conditions rather than evidence of individual particle failure. Applicants referencing this TR must ensure that they either remain within the tested bounds or justify how their proposed operating conditions remain applicable, considering uncertainty in both the AGR test results as described in the TR and any analytical uncertainty resulting from the proposed analytical method.

(5) Condition 3: Data discussed in this TR does not consider the impacts of short-lived fission products beyond those captured in the gas phase during experiments. Any applicant or licensee referencing this TR must disposition the impacts, if any, of short-lived fission products on the safety analyses and operational dose considerations, or any other regulatory considerations resulting from short-lived fission products, in addition to the data discussed in the TR.

5.0 CONCLUSION

Based on the evaluation above, staff has concluded that the applicant has demonstrated that TRISO particles produced to the specifications and limited to the performance parameters documented in the TR can be used to satisfy a portion of the requirements associated with GDC 10 or an equivalent PDC, subject to the Limitations and Conditions in Section 4.0 of this evaluation. More specifically, TRISO particles produced to the specifications within the TR (including Table 5-5) and limited to the performance parameters in the TR (including Table 6-6) will perform in accordance with the AGR data presented in Sections 6 and 7 of the TR. This data can be used (subject to the performance thresholds of the AGR tests discussed in the TR) to support safety analyses referencing the unique design features of TRISO particle fuel. Staff

notes, as discussed in this evaluation, that performance of the particle represents only part of the justification needed to support qualification of TRISO-fueled designs – performance characteristics of the final fuel form and how any given design copes with transient scenarios outside the scope of the data presented in the TR will be needed to support any future licensing submittal referencing this TR.

6.0 REFERENCES

1. Transmittal of “Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance: Topical Report EPRI-AR-1(NP)” dated May 31, 2019 (ADAMS Accession No. ML19155A173).

2. Audit Report for the Regulatory Audit of EPRI Topical Report, Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance, dated November 19, 2019 (ADAMS Accession No. ML199310F085).

3. Request for Additional Information (RAI) Transmittal for Topical Report EPRI-AR-1(NP), Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance, dated January 2, 2020 (ADAMS Accession No. ML20009E065).

4. 12/09/2019 Summary of Public Meeting with EPRI regarding Topical Report EPRI-AR-1(NP), Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance, dated February 10, 2020 (ADAMS Accession No. ML20029E871).

5. EPRI – Responses to Requests for Additional Information (RAIs) on Topical Report EPRI-AR-1(NP), “Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance,” dated February 26, 2020 (ADAMS Accession No. ML20058A040).

6. EPRI – Response to Requests for Additional Information (RAI) on Topical Report EPRI-AR-1(NP), “Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance,” dated March 9, 2020 (ADAMS Accession No. ML20071D143).