U.S. NUCLEAR REGULATORY COMMISSION STAFF FEEDBACK AND OBSERVATIONS REGARDING TERRA INNOVATUM WHITE PAPER LTR-TINN-25-012, "DESIGN CONSIDERATIONS ON REACTOR CORE (FUEL) AT NOMINAL CONDITIONS," REVISION 0 (EPID: L-2025-LRO-0037)

By letter dated June 8, 2025 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML25159A003) Terra Innovatum s.r.l (Terra Innovatum) submitted for the U.S. Nuclear Regulatory Commission (NRC) staff's review the white paper (WP) LTR-TINN-25-012, "Design Considerations on Reactor Core (Fuel) at Nominal Conditions," Revision 0. The WP outlines the integration of standard pressurized water reactor (PWR) fuel rods into the SOLO reactor design and evaluates the conditions under which the fuel operates. It provides a technical assessment of fuel performance within the distinct SOLO environment, which differs significantly from conventional light water reactors (LWRs) due to its use of graphite as a moderator and a different operational envelope (e.g., lower linear heat generation rates, lower burnup, lower fission gas release, inert helium atmosphere) compared to traditional PWR systems. In addition to assessing the technical information in the WP and providing feedback, Terra Innovatum requested that the NRC staff focus and respond to the following specific aspects:

1. The use of LWR fuel in SOLO considering baseline and stretched nominal conditions[1].
2. The possibility of relying on LWR fuel qualification studies.
3. The sufficiency of justifications provided to demonstrate the applicability of LWR fuel products pre-existing licensing basis for SOLO implementation.

Observations

The feedback and observations are based on the information provided in this WP and are not regulatory findings on any specific licensing matter, nor are they official agency positions. The feedback and observations on this WP are also not intended to be comprehensive; a lack of feedback or observations should not be interpreted as NRC staff agreement with Terra Innovatum's position.

The NRC Staff's Response to Terra Innovatum's Questions

1. Assessment of the use of LWR fuel in SOLO considering baseline and stretched nominal conditions: Terra Innovatum requested NRC staff feedback on the acceptability of using standard LWR fuel in the SOLO reactor, under both baseline and stretched operating conditions.

   Based on the information provided in the WP, the NRC staff observed that the proposed use of standard LWR fuel within graphite slots in the SOLO reactor is generally consistent with applicable regulatory frameworks for power reactors in Title 10 of the *Code of Federal Regulations* (10 CFR). However, the implementation of this concept and its safety demonstration may warrant additional validation to demonstrate its suitability under the specific operating conditions of the SOLO design. Additional staff perspectives and technical observations are provided in the General Observations section below.

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[1] Terra Innovatum uses the term "stretched nominal condition" to describe an operating state in which the nominal cladding temperature is increased by approximately 100 Kelvin (K) above the baseline value. This approach aims to incorporate additional conservatism into the evaluation.

2. The possibility of relying on LWR fuel qualification studies: Terra Innovatum requested feedback on the feasibility of leveraging existing qualification studies and operational data for LWR fuel in support of its use in the SOLO design.

   While many aspects of existing LWR fuel qualification data may be applicable to the SOLO environment, certain areas may fall outside the established LWR operational envelope. Specifically, steady-state fuel temperatures in SOLO are well-bounded by those observed in LWRs, suggesting that temperature-dependent fuel qualification data from LWR applications is likely transferable.

   However, for the cladding, the prolonged residence at elevated temperatures in SOLO, particularly under stretched nominal conditions, exceed those typically encountered in LWR service. As such, additional justifications for acceptable fuel performance under those conditions may be warranted, particularly to address thermo-mechanical response under irradiation, including creep, dimensional growth, and other time-dependent deformation mechanisms at the relevant temperature and fast neutron fluence levels. Additional NRC staff observations are provided in the General Observations section below.

3. The justifications provided demonstrate the applicability of LWR fuel products as a pre-existing licensing basis for SOLO implementation: Terra Innovatum requested NRC staff feedback on whether the justifications provided in the WP are sufficient to support the applicability of the pre-existing licensing basis for standard LWR fuel products in the SOLO reactor.

   The NRC staff noted that justifications in the WP are partially sufficient. While certain specified acceptable fuel design limits (SAFDLs) established for LWRs—such as those related to temperature and strain limits—may be applicable to the SOLO reactor, others may not be directly transferable due to the distinct chemical environment (helium versus water) and differing irradiation conditions, including temperature, neutron flux, and spectrum. In a future submittal, a comprehensive assessment of SAFDL applicability is warranted to determine which limits remain valid for SOLO and to establish a clear path for addressing those that do not.

   The provided justification is more robust for the fuel pellet, as the steady-state fuel temperatures in SOLO are bound by those in LWRs and the helium coolant environment significantly reduces the potential for corrosion-related degradation. As a result, temperature-dependent fuel qualification data from LWR applications are likely applicable to the SOLO design.

   In contrast, the cladding operating conditions in SOLO, particularly under stretched nominal conditions, exceed those typically encountered in LWRs. These include higher cladding temperatures, potentially greater fast neutron fluence, and prolonged in-reactor residence times. Such deviations may impact cladding creep, irradiation-induced growth, and long-term mechanical integrity, which are not fully bound by existing LWR qualification data. Therefore, additional validation or targeted demonstration efforts may be necessary, particularly to confirm the cladding's mechanical behavior under SOLO-specific conditions.

General Observations

1. Deviations from LWR operational experience: While the WP asserts the SOLO environment is less challenging than that of a typical PWR, particularly due to the lower linear heat generation rates and the inert helium atmosphere, the NRC staff identified several key exceptions that may warrant further evaluation in a future submittal, including:
    - Higher cladding temperatures in SOLO compared to conventional LWRs
    - A potentially harder (i.e., more neutrons at higher energies) fast neutron spectrum, which could lead to higher fast fluence at equivalent burnups, resulting in more detrimental effects on cladding performance
    - A considerably longer in-reactor fuel residence relative to the typical fuel cycle of a PWR
    - Potential Zircaloy-4 (Zry-4) and graphite chemical and mechanical interaction

    Such factors could influence cladding performance, particularly with respect to irradiation-enhanced creep and mechanical deformation. Moreover, the prolonged exposure to elevated temperatures may alter the cladding's mechanical response, while the harder neutron spectrum could further degrade its ductility, fracture toughness, and ultimately, its long-term structural performance.

2. Possible microstructural evolutions: The NRC staff noted that the cladding operating temperatures are closer to **[[**

    ]]. Therefore, the reactor design should ensure that the adequate margin to **[[** **]]** during normal operation is maintained if much of the existing cladding performance models and qualification data are to be employed.

3. Failure modes and effect analysis: The NRC staff anticipates that the unique design and operational envelope of the SOLO reactor may introduce fuel failure modes not typically observed in LWRs. Therefore, a comprehensive identification of all potential failure mechanisms specific to the SOLO configuration and its conditions of operation is important to support accurate safety assessments and would be expected in a future licensing submittal.

    The WP primarily addresses normal operating conditions, with limited evaluation of transient or accident scenarios. Understanding fuel behavior, including failure modes and thresholds, under such conditions is essential for safety demonstration. Given that SOLO's transients are likely to differ from those in LWRs, existing licensing bases may not apply, and new design-specific criteria may be needed. Future licensing submittals are expected to include safety analyses that capture all relevant physical phenomena and reflect SOLO-specific conditions. Developing SAFDLs tailored to SOLO would further support fuel integrity assessments under both normal and off-normal conditions.

4. Material properties and behavioral models: For future licensing actions, the NRC staff expects more detailed information on the material properties used, behavioral models incorporated, and the governing physics considered in the modeling and simulation activities. This includes, where applicable, identifying each model to simulate fuel behavior in the SOLO reactor, the validation range based on available LWR data (e.g., temperature,

burnup, fluence, displacements per atom), the intended application range in SOLO, and a technical basis and justification for any deviations from the validated range.

5. Potential chemical interaction: The NRC staff determined that there is a potential for interactions between Zry-4 and graphite if the cladding-to-graphite gap during irradiation is not maintained. Although appendix 1 of the WP provides some information, the assessments provided were limited. Additional justification and evaluation may be warranted to address potential interactions between Zry-4 and graphite, particularly regarding their impact on overall fuel performance during prolonged in-reactor residence times.

6. Effect of potential gap closures: The technical evaluations presented in the WP assumed that the gap between the fuel and the cladding remains open throughout the entire irradiation period of the fuel cycle (15 years with a one year extension, 16 years total). The analysis also explicitly assumed that the fuel cladding does not come into contact with the surrounding graphite at any point during the reactor's operation.

   The WP asserts that continuous separation between the cladding and the graphite moderator is achieved by design, through the inclusion of a **[[ ]]** gap. However, the proposed gap presents a tight fabrication tolerance that may be difficult to consistently achieve. Even if such precision is met during manufacturing, maintaining this separation throughout operation is expected to be challenging due to in-reactor mechanical loads and dimensional tolerances within the graphite slots. If contact between the cladding and graphite occurs, in addition to possible chemical reactions, it will also result in a different mechanical response from the fuel elements than currently assumed.

   This observation is particularly important since the WP indicates very low total cladding creep strain, with no plastic deformation and minimal thermal creep, primarily attributed to the low mechanical stresses. The NRC staff acknowledges that these results are consistent with the design assumption that the cladding remains physically separated from both the fuel and the graphite, and that the external pressure consistently exceeds the internal pressure, keeping the cladding in a continuous compressive state. However, if gap separation is not maintained, accuracy of all of these calculated variables and the conclusions based on those calculations will be impacted.

7. Prolonged in-reactor time at higher temperatures: The NRC staff also observed that, in the SOLO design, the fuel system experiences a longer in-reactor residence time at elevated temperatures compared to a typical PWR fuel rod. While creep behavior is influenced by multiple factors, including stress, temperature, fission density, neutron fluence, and time, the extended exposure duration alone can lead to distinct creep behavior, even under similar thermal and mechanical conditions.

   Furthermore, irradiation creep can still occur under constant low stress due to neutron-induced microstructural changes such as dislocation loop formation, void swelling, and irradiation hardening. While the WP presents near-zero total creep strain, it does not explicitly isolate or quantify the irradiation creep component. In future licensing submittals, further clarification is expected to understand how irradiation creep is modeled and whether the assumptions are supported by validation data for the relevant fluence and temperature ranges.

8. Verification, Validation and Uncertainties: The WP references several computational codes used in the analyses. The NRC staff emphasizes the importance of robust verification and validation (V&V) activities, particularly given that Terra Innovatum identifies modeling and simulation (M&S) as a primary means of evaluating performance and demonstrating safety. Given the technical considerations discussed in this feedback, the ability to accurately predict thermo-mechanical response of behavior using fuel performance codes is essential. The credibility of these M&S activities could be enhanced through the use of applicable concepts in NRC Regulatory Guides and industry standards.

Principle Contributors: Joseph Messina, NRR
Chris Van Wert, NRR
Hakan Ozaltun, NRR