Multi-physics fuel performance modeling of TRISO-bearing fuel in advanced reactor environments

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ABSTRACT:

The overarching objective of this project is to develop and validate accurate and computationally efficient multi-physics TRISO fuel performance models for advanced pebble bed fluoride cooled, and gas cooled, high temperature reactor concepts currently being pursued by industry partners. BISON-based fuel performance models will be informed by reactor core simulator and dynamic plant modeling tools, and focus on predicting the thermal-mechanical response of TRISO fuel compacts during operation of advanced, fluoride high temperature reactors (FHR) and the radionuclide source term released from the fuel during anticipated reactor transients and design basis accident conditions. The tools we enhance and develop will be relevant to normal operation, anticipated operational occurrences (AOO), and design basis accident (DBA) conditions. Solid fueled FHRs benefit directly from years of research and development focused on TRISO fuel, nuclear grade graphite, and fission research and development programs.

There is a need to answer key questions related to reactor performance during operating, transient and accident scenarios including the trade off in ability to achieve reactor overpower conditions versus the susceptibility of the fuel particle to damage from the irradiated state due to accumulation of burnup and neutron fluence. Among the key questions this project aims to answer include:

- What are the most extreme fuel conditions that lead to significant failure?
- Does power cycling progressively damage the fuel particles?
- How do these impact the specified acceptable radionuclide release design limits (SARRDLs), which define limits for facility licensing?
- What are the safety margins to be used in fuel design based on the sensitivities and sources of uncertainty about TRISO fuel performance and fission product release source term?

Thus, the objectives of the proposed work are to:

1. Develop an accurate and computationally efficient fuel performance model for TRISO fueled advanced nuclear reactors that will assess the thermal mechanical fuel response,

specifically focused on the Kairos pebble bed FHR and to a lesser extent, modular HTGRs and advanced reactor concepts of interest to General Atomics (GA). The fuel performance tool is based on transformational enhancements to BISON.

2. Develop multi-physics neutronics and thermal-hydraulics models to determine fuel operational conditions in normal operation (including power cycling), AOOs and DBA conditions, and use these data and related uncertainties as input in fuel performance models.
3. Validate these development efforts using separate effects experiments in the literature, from the Advanced Gas Reactor (AGR) program, ongoing high-power irradiations of AGR-like TRISO in the NSUF program, from other historical irradiation experiments, and through performing targeted diffusion couple measurements to assess fission product transport and corrosion in the silicon carbide layer of TRISO particles, and mechanistically assess the resulting fission product diffusion behavior using lower length scale material modeling that leverages our connection to the Nuclear Energy (NE) Scientific Discovery through Advanced Computing (SciDAC) Project on improving the mechanistic understanding of fission gas behavior and release in UO_2 nuclear fuel.
4. Use the models we develop and validate to predict fuel behavior and radionuclide release during Kairos FHR normal operation (including power cycling), AOOs and DBA conditions. We will inform the model predications using a systematic uncertainty quantification study as well as multi-physics boundary conditions from core and plant simulator tools, which are similar to those in use by the industry partner.
5. Use information about fuel failure fraction and radionuclide release inventory to quantify the acceptable limits during normal operation, AOO, and DBA conditions. This will enable us to better define the performance requirements for TRISO in an FHR application.

This project involves a very strong and diverse team of nuclear engineers, nuclear fuel and materials specialists and has a strong connection to other DOE NE modeling and analysis programs, including the Nuclear Energy SciDAC project. The research team is lead by the University of Tennessee, Knoxville (UTK) and involves the University of California, Berkeley (UCB), University of Texas at San Antonio (UTSA), and General Atomics, in addition to funded national laboratory partners of Idaho National Laboratory (INL) and Los Alamos National Laboratory (LANL). Kairos Power, L.L.C. (Kairos) is our (unfunded) industrial partner. Our team has extensive experience with the development and use of BISON, first-principles based materials modeling of fission gas and fission product diffusion in nuclear fuel and silicon carbide, experience with neutronics modeling of heterogeneous fuel geometries involving TRISO, the experimental assessment of the fuel performance of TRISO, and experience applying uncertainty quantification to nuclear fuel and materials problems. Furthermore, UTSA is certified as both a minority serving institution (MSI) and a hispanic serving institution (HSI).