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

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ABSTRACT:

There is a need to inform the licensing process regarding reactor performance and safety characteristics, fuel performance, and fuel safety during operating, transient and accident scenarios for high-temperature gas cooled reactors and prismatic microreactors. This includes the performance of the tristructural isotropic (TRISO) fuel particles and their failure probability due to the concomitant impacts of power history and burnup during normal operation, anticipated operational occurrences, and accidents.

The focus of this project is to develop and validate coupled multi-physics TRISO fuel performance models for high temperature gas cooled reactors, including both pebble bed modular high temperature gas cooled reactors (mHTGRs) and microreactors (μHTGRs), as well as prismatic microreactors similar to eVinci. This builds upon our recent NEUP IRP project (20-22094) that was focused on pebble bed fluoride salt cooled high temperature reactors FHRs and historical prismatic mHTGR designs. The multi-physics models will be used to evaluate reactor performance and safety characteristics, and feed an envelope of operational and accident conditions to the fuel performance modeling using the BISON code to predict fuel behavior and to identify operational safety margins for fuel design that supports reactor licensing. Particular emphasis will be placed on the X-Energy pebble bed mHTGR Xe-100 design, as well as the μHTGRs design of HTR-10 for validation, and heat pipe based microreactors similar to eVinci.

The finite-element based nuclear fuel performance code, BISON, will be used to conduct an accurate analysis of fuel behavior during both steady-state and transient conditions. The boundary conditions for these BISON models will be established through realistic neutronics and thermal hydraulics (TH) models, utilizing relevant tools (including Serpent, OpenMC, MELCOR, Griffin, and Pronghorn). OpenMC has been utilized within NEAMS, and MELCOR is part of the NRCs suite of confirmatory analysis tools. This undertaking will explore the use of the Department of Energy's Nuclear Energy Advanced Modeling and Simulation (NEAMS) tools of Griffin and Pronghorn, for neutronics and thermal hydraulic analyses. Notably, these NEAMS tools are developed on the MOOSE platform, facilitating a seamless coupling approach with BISON, which is MOOSE software as well. Additionally, the SCALE toolkit, part of the NRCs accident analysis suite, will be used to inform source term and for code-to-code verification.

The primary objectives encompassed within this project include:

- The validation and application of dynamic multi-physics models for TRISO fuel within pebble bed mHTGRs (e.g. Xe-100), μHTGRs, and micro reactors similar to eVinci. This includes realistic steady state operational, transient, and accident conditions.

- The development of a mechanistic model to assess the palladium corrosion of SiC and impact on SiC layer failure probability.
- The identification of the most extreme fuel conditions, including whether those conditions are expected to lead to fuel failure, along with the quantitative assessment of the probability of such occurrences.
- The quantification of sensitivity and uncertainty involving diverse designs and operational parameters of TRISO fuel in pebble bed mHTGRs (e.g. Xe-100), μHTGRs, and micro reactors similar to eVinci to delineate the requisite safety margins and TRISO fuel failure probabilities, thereby quantifying any potential fuel failures that may result in the release of fission products.

Notably, our prior assessments of TRISO fuel performance for anticipated operation and accident scenarios for the Kairos fluoride high temperature reactor (FHR) provide further confidence on the robustness of the TRISO fuel form, and we anticipate further demonstrating this safety attribute as a part of the project. The project benefits from the extensive expertise of the team in several key areas, including the development and utilization of BISON, modeling of fission products diffusion in fuel elements, neutronics and TH simulations of heterogeneous fuel geometries, experimental assessment of TRISO fuel performance, uncertainty quantification and sensitivity analysis of nuclear fuel safety metrics.