Correlating Thermal and Mechanical Coupling Based Multiphysics Behavior of Nuclear Materials Through *In-Situ* Measurements

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ABSTRACT:

In the nuclear reactor environment, both the fuel and the fuel cladding evolve under the influence of various driving forces such as temperature, radiation damage, fission product creation, stress, corrosive environment, etc. Light-water reactors typically use zirconium alloy nuclear fuel cladding with burn up levels of up to 30–35 GWd/ton. However, driven by the need to minimize waste volume, increase capacity factors, and reduce fuel costs, the industry has increased the average discharge fuel burn up with a consequent increase in exposure time. Such increases take the fuel into an operation regime in which cladding degradation mechanisms are not well understood. The pivotal aspect of cladding reliability is thermo-mechanical response, which is a complex interplay of thermal conductivity (a parameter that influences thermal gradient and stress) and mechanical strength. Very often, the roles of microstructure and thermal transport in reactor environment are studied separately (either mechanical or thermal) or are primarily theory-based. The primary motivation of this proposal is to address this limitation by combining thermal transport and mechanics together through a unique set of in-situ experimental techniques. The anticipated outcome is a new set of fundamental insights on the coupling of thermal transport and mechanical properties moderated by reactor loading (radiation, temperature and chemical alteration such as oxidization and hydration) induced microstructural changes.

The work scope includes: (Task 1) Prediction of microstructure feature change as a function of irradiation energy using in-situ transmission electron microscopy (TEM) observation of the co-PI#1 in collaboration with Sandia National Lab and University of Huddersfield, (Task 2) Measurement of change in thermal properties (conductivity, diffusivity etc.) as a function of mechanical stress, irradiation, and temperature using in-situ TEM experiments of the co-PI#2, and (Task 3) Measurement of thermal properties as a function of change in loading, temperature (upto 1000 oC), and environment (gaseous/liquid/air under different electric potentials to induce electrochemical gradients) with an account of nanoscale to micron scale feature using nanomechanical and micromechanical surface enhanced Raman spectroscopy (SERS) measurements of the PI; and (Task 4) Establishment of microstructure-property correlation based on experimental data including uncertainty quantification in collaboration with Idaho National Lab. TEM measurements will supply visual and quantitative information regarding the role of bulk microstructure in measured properties. This information will be coupled to SERS based measurements that will reveal role played by oxides and hydrides at sample surfaces in coupled thermomechanics. The samples will be based on Zircaloy. Later with success the pellet-cladding system will be examined in collaboration with National Lab facilities.

Overall, focus is on establishing an elaborate in-situ experimental setup that can not only predict change in thermal properties and their correlation with mechanical properties as a function of stress, temperature, and environment, but also on correlating such changes to changes in microstructural and chemical features under the effect of irradiation. The measurement data will be incorporated into multiphysics models in the form of user subroutine as well as experimental database of separate effects to understand how length scale dependent microstructural factors affect thermomechanical failure of pellet-cladding systems. The data would incorporate uncertainty quantification information that can be used to verify and validate existing and new multiphysics models. In the end, the data set will also be supplied for inclusion into Idaho National Lab's BISON code.