Nuclear Energy University Program

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Mechanistic study and modeling of fission gas release in UO_2 and doped UO_2

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ABSTRACT:

Uranium dioxide fuel (UO_2), including its accident-tolerant variant, doped UO_2, is the most extensively used fuel in current nuclear reactors and is proposed for future fuels in several advanced reactor designs. The performance, longevity, and accident resilience of this fuel are significantly influenced by its fission gas release (FGR) behavior. Accurate modeling of FGR is essential for attaining higher burnup, designing novel fuel forms such as Cr_2O_3-doped UO_2, and extending their use to different fuel and reactor designs. Mechanistic models, preferred over empirical ones for their higher reliability and adaptability, cater to diverse fuel designs, materials, microstructures, and varying thermal and neutronic conditions in different reactors. The development of mechanistic models necessitates experimentally informed, microstructure-dependent mechanisms, which are challenging to deduce from conventional integral fuel irradiation tests due to the pronounced heterogeneity in high-burnup pellets and the steep temperature gradient. Consequently, the advanced fuel performance code BISON continues to rely on semi-empirical models for aspects of FGR simulations. To expedite the deployment of advanced nuclear technologies, the accelerated development of mechanistic models is crucial. This development hinges on well-designed separate-effect studies that can sidestep the intricacies of FGR phenomena and reveal the underlying physics essential for model formulation.

The objective of this project is to enhance the safety and performance of nuclear reactors by gaining a fundamental understanding of FGR mechanisms and developing mechanistic models for UO_2 and doped UO_2 fuels under high burn-up and transient conditions. Novel and low-cost separate-effect and semi-integral experiments will be conducted to inform mechanistic model development, which will then be validated by existing integral irradiation data. We will employ both advanced spark plasma sintering (SPS) and conventional powder metallurgy techniques to fabricate fission gas-bearing depleted-UO_2 samples with controlled grain and pore structures (Task 1). These samples, with minimal radioactivity, will then undergo multiple testing and characterization, including the novel applications of thermogravimetry (TG), differential scanning calorimetry (DSC), and mass spectroscopy (MS) to simultaneously obtain the time-resolved data of gas release and microcracking events (Task 2). Based on the experimental results, multi-physics models of FGR will be developed, implemented into BISON, and validated against a wide range of existing integral fuel data (Task 3). The mechanistic model is expected to predict the FGR behavior in UO_2 and doped UO_2 with material parameters obtained from the experiments and literature.

Upon completion, this project will establish new experimental approaches to studying FGR, which will benefit ongoing and future fuel programs. The mechanistic FGR model will be implemented in the BISON code and complement current capabilities, ready to be connected to microstructural evolution models to predict FGR behavior for new fuel designs. The project holds significant value for both the Advanced Fuels Campaign (AFC) and Nuclear Energy Advanced Modeling and Simulation (NEAMS) programs, and it will provide support to the U.S. nuclear industry by delivering a tool to extend the lifespan of current fuel designs and facilitate the design and licensing of doped UO_2.