
Radiation-induced swelling in advanced nuclear fuel

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ABSTRACT:

Nuclear fuels are subject to extreme conditions including high temperatures (with steep gradients), stress, evolving chemical composition, and intense energetic particle irradiation. Such exposure results in substantial microstructural evolution, characterized by defect accumulation and material degradation. The deceleration of fission fragments with high kinetic energies (~100 MeV) produces primarily ionizations along their ~10 μm range and is responsible for most of the radiation damage within the fuel pellet, leading to significant microstructural modifications in current nuclear fuel (e.g., rim effect). Fission fragment radiation will occur in next-generation fuel materials but at significantly higher doses. One of the key factors that limits the development of advanced reactor technology is the current knowledge gap concerning microstructural evolution related to fission-fragment damage in next generation fuel materials under normal operation and accident scenarios and its consequence on material performance.

We propose an innovative research project that directly addresses how the microstructure evolves in advanced fuel materials under intense fission-fragment type irradiation utilizing a successful, recently developed experimental approach. In collaboration with fuel experts at Oak Ridge National Laboratory (ORNL) we will synthesize a range of uranium carbide (UC) and uranium nitride (UN) compounds, which are currently being considered for advanced fuel forms. These materials will be irradiated with energetic ions under well-controlled conditions, simulating the effects induced by fission-fragment projectiles. We will utilize state-of-the-art ion-beam experiments coupled with synchrotron X-ray characterization at DOE user facilities, requiring only microgram quantities of the samples, to obtain detailed nanoscale information on the defect formation that results in volumetric swelling and microstrain, as well as defect kinetics and recovery at high temperatures. Neutron total scattering experiments at the Spallation Neutron Source will be utilized to obtain additional insight into the short-range defect structure that forms in these advanced fuel materials as a result of ion irradiation. These efforts will be complemented by reactivity tests on irradiated materials, exposing them to water/steam at high temperatures, in order to further understand their behavior under severe accident conditions.

A detailed understanding of UC and UN under intense irradiation and operating/off-normal conditions is an important requirement for their use as fuel forms in advanced reactor systems. Unlike traditional UO_2 based fuel, these materials will be subjected to extreme amounts of ionization from exposure to a more intense radiation field of fission fragments due to the much higher uranium density. Radiation stability of the advanced fuel materials will be needed for safe use in a reactor. The atomic-scale behavior of radiation damage and its impact on fuel performance must be fully understood to overcome this significant technological challenge. This project will involve several graduate and undergraduate students who will perform research at both contributing institutions to create a unique opportunity for collaboration as well as training and education of next generation nuclear engineers in the development of advanced fuel forms.