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Effect of Hydrides on the Structural Integrity of Zirconium-alloy Fuel Cladding

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Abstract

Spent nuclear fuel (SNF) cladding made of zirconium alloys is susceptible to embrittlement due to hydrogen uptake and hydride formation during reactor operation and subsequent storage. When cladding containing hydrides is subjected to mechanical loads, hydride morphology and reorientation critically influence ductility and failure likelihood. This study investigates how changes in material properties and the inclusion or distributions of hydride affect the structural integrity of SNF cladding. Two typical zirconium alloys were examined across a range of temperatures and irradiation conditions. For each alloy and condition set, tensile response was characterized and parameterized as input for mesoscale simulations. Hydride were modeled in two complementary ways: (i) idealized distributions assuming constant hydride sizes, and (ii) image-based microstructure maps derived from microscopy. Representative volume element (RVE) models reflecting these hydride fields were incorporated into three-dimensional finite element (FE) simulations of a fuel rod to compute local and global mechanical responses under referenced dynamic loading paths. The uniform elongation obtained from FE analyses exhibited substantial variation depending on alloy type, operational history, and the hydride modeling approach. Using established failure criteria, structural performance was quantified in terms of safety margins as well as their sensitivity to hydride clustering and temperature. Key findings indicate that alloy-specific irradiation and thermal histories modulate susceptibility to hydride-driven failure. Image-based RVE representations effectively capture localized phenomena (e.g., strain localization and elevated triaxiality) that idealized models can underpredict ductility reduction. This systematic assessment provides quantitative guidance on how hydride characteristics translate into macroscopic integrity metrics for SNF cladding, and it supplies a basis for improved predictive models to support long-term storage and transport safety.

Keywords:

Finite element analysis Hydride reorientation Representative volume element Structural performance Zirconium alloys