Development of a Mechanistic Hydride Behavior Model for Spent Fuel Cladding Storage and Transportation: IRP-FC-1: Modeling of Spent Fuel Cladding in Storage and Transportation Environments

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ABSTRACT:

BACKGROUND & OBJECTIVES

The goal of this project is to develop a macroscale modeling capability that can be used to computationally assess the impact of hydride behavior on cladding integrity in commercial spent nuclear fuel during pool storage, drying, transportation, and long-term dry cask storage. This capability will be implemented in the BISON fuel performance code, as well as in FRAPCON.[1] To develop this capability, the research team will investigate both experimentally and with computational modeling the hydride behavior relative to three critical phenomena in various zirconium alloy cladding materials:

1. Migration and redistribution of hydrogen
2. Precipitation and dissolution of hydride particles
3. The impact of hydride microstructure on mechanical properties of the cladding

The approach will employ both experiments and modeling/simulation at the mesoscale, to inform the development of the macroscopic hydride models. In addition, the meso- and macroscale models will be validated with targeted separate effects experiments on artificially hydrided cladding. This approach is illustrated in the Figure 1 below.

WORK AND TASKS TO BE PERFORMED

Project objectives will be met by quantifying the hydrogen migration process, including the Soret effect as well as Fickian diffusion, through targeted experiments that can provide subsidies to the model implemented into BISON. These advances also include the description of the hydride precipitation and dissolution process which leads to a given hydride microstructure (density, orientation and connectivity) and which depends on temperature history, applied stress and material microstructure.

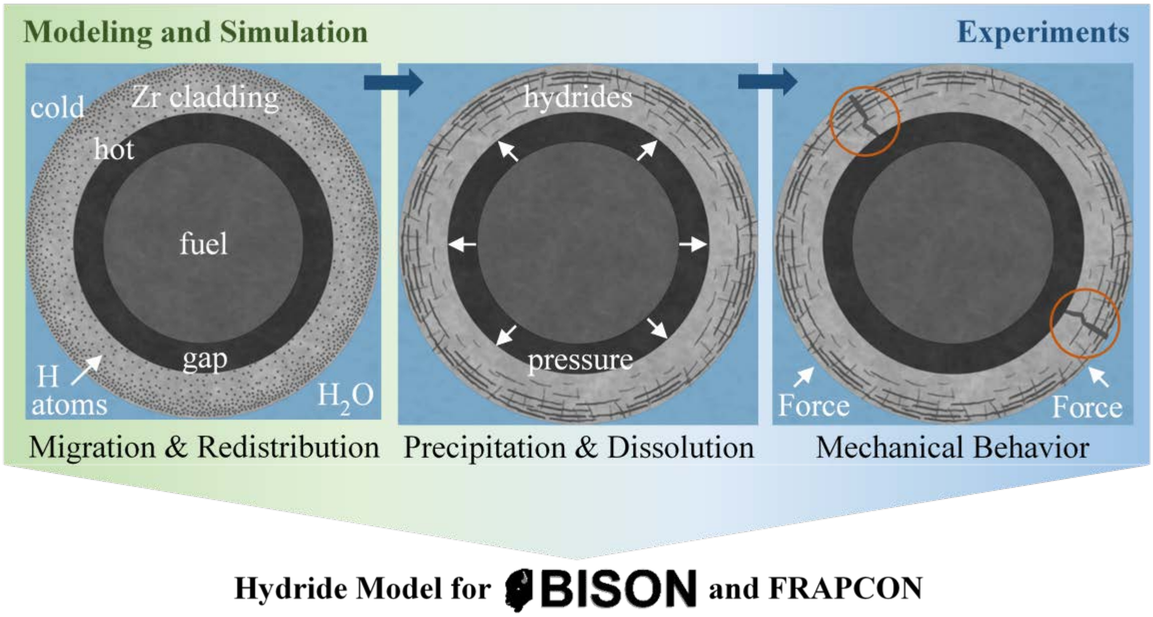

Figure 1. During normal reactor operation, hydrogen is absorbed into the zirconium nuclear fuel cladding as a result of the corrosion reaction. This hydrogen migrates and redistributes within the cladding and when the local hydrogen concentration is high enough it forms brittle hydride particles. The hydride particles orient around the circumference of the cladding tube during normal operation. In used fuel, due to temperature changes and elevated pressure, the hydrides can dissolve and reform with a radial orientation, increasing the likelihood of cladding failure during transportation and storage.

These parameters affect the hydride precipitation temperature, the critical stress for hydride reorientation, and the increased hydride connectivity with increasing cycles due to sympathetic nucleation. These phenomena will be investigated with separate effects experiments using synchrotron radiation diffraction in situ, as well as focused ion beam 3D reconstruction of the hydride microstructure in the SEM. Such data will be obtained as a function of alloy, temperature and material texture/microstructure and compared directly with the calculations performed using phase field modeling. Being a mesoscale tool, phase field modeling is the ideal tool for modeling hydride behavior as its calculations can be directly benchmarked and validated with the experiments proposed. Finally, failure of the hydrided cladding will occur through a process of hydride induced crack propagation, and the combination of mechanical testing and mesoscale simulations of fracture as a function of the hydride microstructure will provide a physically based failure criterion that can predict the susceptibility of the cladding to failure. In this project the final **deliverable** will be a mechanistic model within the BISON fuel performance tool of the impact of hydrides on spent fuel cladding, which will be benchmarked and validated by experiments.

[1] BISON is a fuel performance suite of codes developed by Idaho National Laboratory (INL) while FRAPCON is a Nuclear Regulatory Commission (NRC) maintained fuel performance code.