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Neutron Imaging of Nuclear Fuel Cladding Tubes

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The employment of neutron radiography and tomography allow non-destructive visualization of hydrogen distribution in cladding tubes due to the strong neutron attenuation by hydrogen compared to the weak attenuation by zirconium. The excellent spatial resolution of neutron radiography and sensitivity enable a precise characterization of hydride morphology and hydrogen gradients in 2D and 3D. Experiments allow for hydrogen studies under various thermal and mechanical loading conditions, but also for hydrogen diffusion tests within different cladding tubes and different metallic structure directions. Post-test hydrogen quantification can always be performed additionally via carrier gas hot extraction (CGHE) and validated against the neutron imaging results using calibration samples of a known hydrogen content.

Zirconium alloys are widely employed as cladding materials for nuclear fuel rods due to their low neutron absorption cross-section, high corrosion resistance, and adequate mechanical strength during and after reactor operation. However, during operation, hydrogen is absorbed by cladding corrosion processes involving reactor coolant. The hydrogen influence on the claddings is investigated by means of neutron imaging referring to different scenarios: loss-of-coolant accident (LOCA) conditions and dry storage similar conditions. The LOCA scenario includes a rapid temperature rise that causes ballooning of the cladding tubes and may lead to bursting. Further, the influence of secondary hydriding phenomena on the applicability of cladding embrittlement criteria is tested during this scenario. The formation of ballooning regions, cladding wall thinning and hydrogen enrichments can be revealed by 3D neutron tomographies, where local hydrogen concentrations up to 1800 wt.ppm were measured. On the other hand, dry storage related hydrogen effects arise after operation upon cooling, when the hydrogen solubility limit is exceeded and hydrogen precipitates. These hydrides have a profound impact on the mechanical integrity of the cladding, particularly due to their orientation, morphology, and distribution. In dry storage conditions, hydrogen redistribution and hydride precipitation continue to evolve over time, influenced by temperature gradients and residual mechanical stresses. Understanding this behavior is essential for long-term safety assessments of SNF in interim storage.

This paper presents the diverse neutron imaging possibilities to investigate zirconium based nuclear fuel cladding tubes with regard to hydrogen/ hydrides.

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