High Temperature Expansion Due to Compression Test for the Determination of a Cladding Material Failure Criterion under RIA Loading Conditions

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Extended abstract

The increase of fuel burnup limits and the extension of operating cycles leading to optimize Pressurized Water Reactors (PWR) management have motivated numerous studies related to the behavior of high burnup fuel during design basis accidents. Reactivity Initiated Accidents (RIAs), caused by the inadvertent ejection of a control rod assembly, are amongst the most serious postulated scenarios. The very fast local power increase in the surrounding fuel assemblies (~50 ms) results in nearly adiabatic heating of the fuel pellets which expand due to thermal and fission gases expansion. This produces fast multiaxial straining of the surrounding cladding tube (typically 1 s^{-1}) through Pellet Clad Mechanical Interaction (PCMI) which, combined with the fairly low clad temperature at this early stage of the RIA (<600°C), may cause a partially brittle failure of the high burnup cladding, embrittled due to accumulation of irradiation damage and primarily to heterogeneous hydrides precipitation resulting from metal-water oxidation reactions during reactor exposure. In accordance with RIA full-scale tests results, which revealed rod failures with some fuel dispersal at a very low enthalpy level, the PCMI induced clad failure is commonly considered as the most restrictive for high burnup fuel rods. Post-test examinations indicated a two-stage process involving, first, the radial ductile propagation of incipient cracks initiated by brittle or nearly brittle fracture of hydride and oxygen rich external layers and, secondly, the axial propagation of these through-thickness defects.

In order to accurately predict cladding survivability during RIAs, the development of reliable failure models is essential. Accuracy of these criteria strongly depends on suitability and accuracy of the experimental data retained for their establishment. This paper is mainly dedicated to the development of an out-of-pile test reproducing the thermomechanical loading conditions encountered during the PCMI stage of RIAs. In particular, the high strain rate strain-controlled clad loading, combined with the high heating rate thermal loading, expected during the PCMI phase is simulated by an extended Expansion Due to Compression (EDC) test, initially developed at Studsvik AB. The EDC test consists in loading a cladding specimen thanks to the radial expansion of a pellet axially compressed inside the tube by a pair of pistons. The use of appropriate materials for the inner pellet, i.e. Teflon, pure aluminum or pure copper depending on temperature, made it possible to achieve tests from 20°C up to 900°C. Moreover, an appropriate device has been designed in order to reach a loading path biaxiality (combination of axial and hoop components) close to that expected during the PCMI stage (strain path between plane-strain and equal biaxial, depending on the fuel-clad contact friction).

The interpretation of the test data has been supported by Finite Element Analyses (FEA), including pellet mechanical properties and friction coefficients tuned using an inverse method coupling FEA and tests results. A deformation model, describing the anisotropic viscoplastic behavior of stress relieved Zircaloy-4 cladding alloys under typical RIA loading conditions, has been exploited. This law has mainly been identified upon the PROMETRA (TRAnsient MEchanical PROperties) experimental database, including axial tensile tests, hoop tensile tests and burst tests results. It provides a reliable description of the mechanical behavior of fresh as well as highly irradiated cladding materials (burnup up to 64 GWd/tU) within large temperature and strain rate ranges, 20°C up to 800°C and 10^{-4} s^{-1} up to 5 s^{-1} respectively. The combined analysis of experimental results and finite element simulations provides a deeper understanding of the deformation and failure modes that arise during the tests. These appear to be representative of those obtained on tubes during the PCMI stage of RIA experiments.

Due to the small size of the specimens, the test requires a limited amount of material and allows the study of localized cladding properties (in presence of hydride blisters for example). Moreover, simplicity of the experimental apparatus and ease of the tests achievement are appropriate for the analysis of failure mechanisms of irradiated cladding specimens under RIA characteristic loading conditions. At present, the implementation in CEA hot cells of the test described in this paper is envisioned.

A Gurson-Tvergaard-Needleman (GTN) type damage model is conjointly developed in order to represent the ductile fracture (i.e. void nucleation, growth and coalescence) of the hydrided substrate under the external brittle layers. The identification and determination of the model micromechanical parameters are performed by combination of EDC tests results and numerical simulations. This model should provide a better understanding of the failure mechanisms and aims at evaluating cladding integrity under RIA loading conditions.

Keywords: Zircaloy-4 fuel cladding, RIA, PCMI, EDC test, deformation model, failure mechanisms, failure criterion, irradiation, loading path biaxiality.