Fundamental Understanding of Coupled Irradiation and Corrosion Effects on ZrNb Fuel Cladding

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Niobium is a common alloying element for zirconium fuel cladding alloys with enhanced oxidation and hydrogen pickup resistance. This study specifically aims at understanding how irradiation affects Nb redistribution and precipitation in the matrix and the subsequent effects on ZrNb in-reactor corrosion mechanism. Indeed, it has been shown recently that pre-irradiation reduces ZrNb corrosion kinetics in subsequent high-temperature water autoclave corrosion. However, the mechanism behind this potential beneficial effect of irradiation on corrosion is still unknown. To investigate the coupled effects of corrosion and irradiation on fuel cladding, this study aims at precisely characterizing the microstructure and microchemistry of proton irradiated Zr-xNb alloys at 1dpa and 350°C, with different Nb contents below and above the theoretical solid solubility limit (x=0.2,0.5,1.0wt%), before and after corrosion in pure water autoclave. This study uses Atom Probe Tomography to characterize the Nb solute content in the pre-irradiated, post irradiated/pre-corroded and post irradiated/post-corroded matrix. State of the art High-Resolution Scanning Transmission Electron Microscopy (HR-STEM) and novel 4D-STEM techniques were also performed at every sample stages to characterize the chemistry and interface of irradiated induced precipitates at the atomic scale. Findings include a clear decrease of solute Nb content in the matrix after irradiation. In addition, the semi-coherency of irradiation induced Nb-rich precipitates interfaces, showing local high tensile stresses at the platelet's ends, led to the development of a precipitate growth model using rate theory formulation under irradiation, such that a clear understanding of the irradiated alloys was achieved. Then, corrosion kinetics of the pre-irradiated alloys after high-temperature water autoclave exposure were obtained at different exposure times via Focused Ion Beam lift-outs and the fate of irradiation-induced redistributed Nb was investigated. Specific attention was given to the Nb embedded in the oxide as the oxide grows into the pre-irradiated matrix. The results shed light on the mechanism behind the beneficial effect of irradiation on corrosion kinetics of ZrNb alloys using the framework of the "coupled-current charge compensation" corrosion model previously developed by the authors.