# Out-of-pile RandD on chromium coated nuclear fuel zirconium based claddings for enhanced accident tolerance in LWRs

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Title: **"Out-of-pile R&D on coated nuclear fuel zirconium based claddings for enhanced accident tolerance in LWRs"**

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In the framework of the CEA/AREVA/EDF French nuclear institute, coatings (with thicknesses of a few microns up to ~20µm) on zirconium alloy cladding have been studied with the objective to provide a significant reduction in the embrittlement of the cladding in accidental conditions, such as the loss-of-coolant accident (LOCA). Early studies performed at CEA on several types of coatings obtained by a physical vapor deposition (PVD) process, including ceramic nitride and metallic multi-layered coatings, are discussed in a first part of this paper. The results of this screening analysis showed that chromium coatings have exhibited the best compromise between oxidation resistance and adhesion of the coating. In a second part, the present paper gives an overview of out-of-pile results obtained so far on Cr-coated Zircaloy 4 cladding in both nominal and accidental (LOCA) conditions:

- As-received properties and behavior in nominal conditions: The Cr-coating forms a dense layer with no porosity at the interface leading to very good adherence to the underlying Zircaloy substrate, which is not affected by the PVD coating process. Additionally, the Cr-coated Zircaloy-4 samples exhibit significantly reduced corrosion kinetics during autoclave tests in representative 360°C PWR water chemistry conditions by forming a very thin oxide layer on the order of a few hundred nanometers.

- Accidental conditions: The behavior of chromium coated claddings during high temperature (HT) oxidation has been studied and shows significant reduction of oxidation kinetics in HT steam conditions. The Cr-coating serves as a barrier for the diffusion of oxygen in the underlying zirconium substrate, and this delays significantly the formation of the brittle ZrO2 and Zr-Alpha(O) layers and decrease the overall oxygen quantity diffusing into the remaining prior-β. Consequently, Cr-coated Zircaloy-4 cladding retains higher post-quench ductility and helps extend the margins to fuel rod (brittle) failure in accidental conditions. A model describing the HT oxidation kinetics of the Cr-coated cladding up to 1200°C and for typical Design Base Accident (DBA) cumulated time will be presented in this paper. The consequences of the oxidation at HT on the resulting post-quench mechanical properties (hardness, tensile properties…) will also be discussed.

Further investigations are ongoing and the next steps of coated Zr cladding evaluation as well as CEA/AREVA/EDF perspectives are also briefly presented in the paper. For example, the same deposition process was used to successfully deposit a Cr-coating on other zirconium alloys, such as M5® and some material irradiations have been performed or are planned to test this solution in more representative conditions. Additionally, high temperature creep and ramp tests are ongoing to obtain a full understanding of the LOCA behavior. To conclude, the current results on Cr-coated cladding suggest that it could provide significant benefits in accidental conditions, while allowing for a relative short term implementation time. Consequently, it appears as a very promising solution to enhance the accident tolerance of the fuel rod.