RECENT DATA ON M5™ ALLOY UNDER LOCA CONDITIONS

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Experience feedback from irradiation in PWRs has confirmed the M5™ possesses all the properties required for upgraded reactor operation under normal conditions. Several papers recently reported Nb based alloys may have a worse behavior under LOCA conditions than Zr-4. To address this issue, Framatome-ANP and EDF started in CEA labsa number of full-scale tests and comprehensive analyses on both M5™ and SRA low-tin Zircaloy-4.

We will focus hereafter on the behavior of pre-hydrided M5™ cladding in LOCA conditions as compared to the Zircaloy-4 behavior.

We first present the recent research on phase transformation kinetics, mechanical behavior (creep and temperature ramp tests), oxidation kinetics and quench behavior of pre-hydrided sample as compared to as-received material.

It is noticed that the phase transformation kinetics and mechanical behavior of both virgin alloys are very similar and are not affected by pre-hydriding for hydrogen content (150 ppm) greater than the value obtained at EOL for elevated burnups for M5™.At high-temperature the M5™ cladding exhibits oxidation kinetics and quench behavior at least equivalent to Zircaloy-4.

The oxidation kinetics fits well with the Cathcart-Pawel correlation and the Baker-Just correlation is still overly conservative. No breakaway of the oxidation reaction has been detected up to 1400°C for LOCA prototypical time ranges. No effect of hydriding on the oxidation kinetics of the two alloys is noted, in particular the Baker-Just correlation remains conservative up to an hydrogen content of 450 ppm.

The M5™ cladding failure threshold upon quench doesn't vary much from 1100 to 1300°C: the physical failure limit upon quench is greater than 27% ECR or 38% ECR when calculated with the Baker-Just correlation. To take into account the influence of high- burnup conditions, quench tests were performed on pre-hydrided samples for a testing temperature of 1200°C. Hydrogen content has only a little influence on their resistance to quenching after oxidation at 1200°C.

Then, the post-quench mechanical properties, for different high temperature oxidation levels, between 1000 and 1200°C, have been investigated for both M5™ and Zircaloy-4 alloys. The residual ductility properties at R.T. were determined using impact, bending and compression tests.

After single face oxidations giving weight gains ranging from ~4 mg/cm² up to ~38 mg/cm² and according to the measured residual ductility/toughness properties at R.T., we can observe that the M5™ and Zy-4 alloys have comparable properties. Also, it is worth noticing that, even for the M5™ alloy, no hydrogen pick-up is observed after oxidation at 1100°C and 1200°C. We only measured hydrogen pick-up at 1000°C for both alloys (Zy4 and M5™), after the beginning of the break-away phenomenon occurring for times much higher than the prototypical LOCA times range (less than 30 min). Besides, it was found that there is a residual ductility for both alloys even at the maximum oxidation within the range of the tested conditions. All these results are different from previously published data on Zr-1%Nb alloy.

For Nb-containing alloys, recent studies suggest that the impurity content in the metal (Ca, Hf), the SPP's size and distribution and the surface finish (chemistry and roughness) may play a significant role on the oxidation and the quench performances.

In the second part of this paper we present the study performed before 1996 by Framatome-ANP within the scope of the optimization of the M5™ cladding tubes. The various possible factors and potential causes of variability have been thoroughly analyzed from the point of view of their impact on the finished product properties (corrosion, phase transformation kinetics,…).

In this way, all the chemical composition variabilities of the alloying elements and impureties (Fe,O,S,Hf,Al,N,C, Ca,…) have been investigated. Also, a number of manufacturing process variants (Zircon, ore, Zr sponge, ß-quench, heat treatments, ID and OD surface preparations) has been studied. And finally, the impact of the microstructure (SPPs chemical composition size and distribution) on the heterogeneous corrosion has been investigated.

It has been shown that most of these parameters have little or no impact on the high temperature oxidation and quench behavior of the Nb based alloys tested and selected.