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An Approach to an Alternative LOCA Embrittlement Criterion

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ABSTRACT

The current oxidation criterion of 17% ECR has been based on the results of high-temperature oxidation of Zry-4 (normal composition and with the original surface) and was intended to ensure that the FE cladding would not suffer damage even if cooled rapidly or when handled during the removal of damaged fuel from the reactor. The purpose of this criterion was to safely separate cladding material samples that had been damaged during rapid cooling (or routine handling) from undamaged samples. Oxidation properties, including mechanical tests, have been evaluated and the oxidation criterion of 17% ECR has been proposed. This criterion simplified the results and, at the same time, took account of ductility, which remained preserved at 17% ECR. The assumption of residual ductility was warranted by the behaviour of Zry-4 during high-temperature oxidation, where no increase in the hydrogen content of the alloy occurs at roughly 17% ECR. During the deployment in the reactor, however, absorption of hydrogen by the alloy takes place, and the hydrogen content is seriously high particularly at a high burnup. It is a well known fact that hydrides cause brittleness of the cladding material.

High-temperature experiments with the E 110 alloy have shown that the oxide peels off during oxidation and absorption of hydrogen takes place to a considerable extent, bringing about loss of ductility of the exposed samples roughly at 5% ECR. The samples, however, suffered damage during rapid cooling at ECR π 30 % (much later that zircaloy-4 or ZIRLO alloys). Assessing the oxidation behaviour of alloys during high-temperature transitions based on results obtained with Zr-alloys with the original surface (without pre-oxidation at low temperatures) can be misleading.

Experiments performed by UJP PRAHA a.s. with pre-oxidized Zr-alloy samples (425 °C/2, 10, 50 ℓm, 360 °C water VVER/1600d) gave evidence that pre-oxidation and the associated hydridation affect substantially the mechanical properties of the alloys following high-temperature transitions. The correlations between the mechanical properties and the ECR, hydrogen content, thickness of the original ↕Zr, chemical composition and/or the cladding tube thickness are highly complex and depend on temperature and time of exposure.

We decided to distinguish between ductile and brittle samples based on pressure testing of annular samples. The boundary lies at residual ductilities between > 0 and < 1 %. Based on the dependence t = f (1/T) (where t is time in seconds, T is absolute temperature) for four Zr-alloys over the temperature range of 800 °C – 1200 °C with both-sided pre-oxidation of 2 - 50 ℓm with hydrogen content of 50 ppm – 1200 ppm as well as without pre-oxidation, we propose an alternative oxidation criterion, which is intended to ensure ductility of the cladding tube and only depends on the temperature and time of transition:

$$\boldsymbol{K = A.\exp\left(\frac{-B}{T}\right).\, t^{1/2}}$$

where A, B are constants to be determined experimentally.

If K [1, the cladding tube retains its ductility. If $K > 1$, the cladding tube can be brittle.

This alternative oxidation criterion has been tested with success on simulated conservative LOCA type transitions (1st peak at 1000 °C, 2nd peak at 1050 °C).

Currently the A and B constants are being refined and the boundary conditions (maximum temperature) established. Based on preliminary results of the criterion, the temperature of 1200 °C is unsuitable.

When the LOCA develops normally, K is lower than 1.

Several laboratories should be engaged in the testing and refining of the criterion.