A Comparative Analysis of CABRI CIP0-1 and NSRR VA-2 Reactivity Initiated Accident tests

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Abstract:
Zirlo™ is an improved fuel cladding material that was developed to accommodate constraints associated with increasing burn-ups in a more severe duty operation. The behavior of Zirlo™ irradiated above 75 GWd/t under RIA conditions was studied in CABRI CIP0-1 and NSRR VA-2 tests. The samples were initially similar but VA-2 failed at relatively low enthalpy whereas CIP0-1 did not fail. Because test conditions were different in terms of initial temperature, coolant nature and power pulse width, it is necessary to use a transient fuel code to compare the two results. Using SCANAIR and CLARIS it was shown that the concentration of hydrogen precipitates at the temperature of the test is of primary importance to assess both experiments in a consistent manner. The analysis demonstrated that room temperature is a testing condition much more severe than that expected at typical PWR conditions.

1 INTRODUCTION

Economic considerations have lead utilities to propose burn-up increases of the fuel used in Light Water Reactors. However, experiments performed during the 90’s to simulate Reactivity Initiated Accidents (RIA), in particular in the experimental reactors CABRI in France and NSRR in Japan, have shown that Zr-4, the cladding material most commonly used in Pressurized Water Reactor, has a resistance to the loadings resulting from Rod Ejection Accidents that decreases with increasing burn-ups [1, 2, 3]. It was then commonly admitted that Zr-4 was not suitable for the targeted burn-up levels. During reactor operation, fuel clads are submitted to a high temperature water environment. Under these conditions, the cladding material oxidizes and a zirconia layer forms on the outer part of the clads. Part of the hydrogen generated during oxidation diffuses into the clad base metal and then precipitates as zirconium hydrides if the solubility limit is reached. Different typical hydride morphologies, i.e. hydride distribution and orientation are observed. When the hydrogen mean concentration is low, below the solubility limit during

![Figure 1: Zr-4 and Zirlo oxidation versus burnup (from R.L. Kesterson et al. TOPFUEL 2006)](image-url)
irradiation, the hydrides observed at room temperature are more or less randomly distributed through the clad thickness. When the mean concentration increases, under the thermal gradients existing during operation, the soluble hydrogen migrates to the cooler clad outer diameter and accumulates as hydrides below the zirconia layer, to form a hydride rim. Besides, if a cold spot exists on the clad, for example resulting from zirconia layer spalling, hydrogen can move towards this cold spot resulting in an hydride blister, which is a massive zirconium hydride.

It is well known that hydrogen embrittles metals. This deleterious effect of hydrogen was confirmed on Zr-4 as failures were observed in RIA experiments with clads containing hydride blisters (e.g. CABRI REP-Na1, Na8 and Na10) or hydride rims (e.g. NSRR HBO-1 and HBO-5). New zirconium alloys were then developed with better resistance to water corrosion and hydriding. Zirlo™ is one of these new alloys [4]. Figure 1 shows that corrosion resistance of Zirlo™ is globally better than that of Zr4 [5].

The objective of the CABRI CIP0-1 and NSRR VA-2 tests was to characterize the behavior of Zirlo™ rods under RIA conditions. It can be seen in Figure 1 that both tested samples were taken from fuel rods that were representative of higher corrosion values observed on Zirlo™ rods.

2 DESCRIPTION OF THE TEST RODS

Both CIP0-1 and VA-2 rodlets were refabricated from the fifth (from bottom) span of fuel rods that were inserted in a fuel assembly irradiated in the Vandellos 2 reactor in Spain in the frame of a joint Japanese-Spanish R&D program [6]. This program aimed at studying the behavior of UO₂ fuel at high burn-up.

The power histories of both rodlets were quite similar as shown in Figure 2. They had a low power 4th cycle, even lower for CIP0-1 than for VA-2.

![Figure 2: Power histories of CIP0-1 and VA-2](image)

The maximum local burn-up was respectively 75 and 79 GWd/t for CIP0-1 and VA-2. The fissile length was respectively 54 and 11 cm. The mean zirconia thickness was 80 µm for CIP0-1, varying between 50 and 100 µm over the length of the sample. For VA-2, the mean value was 70 µm and variation was +/-20 µm.

The state of the rods before test was characterized by examining radial cuts on the father rod. Typical metallographies are show in Figure 3.
The hydrogen content of the rods was relevant, with a mean hydrogen concentration of about 1000 ppm for CIP0-1 and about 800 ppm for VA-2. The hydrides were long and oriented in the circumferential direction, as expected for Zirlo™. In both cases, no hydride blisters were found and hydride rims with a similar thickness of 50 µm were observed. In conclusion, with respect to hydrogen content, the two rods were very similar. Thus their mechanical properties are also expected to be close to each other.

### 3 TESTS CHARACTERISTICS

The main differences between CIP0-1 and VA-2 are the test conditions. CIP0-1 was tested on November 29, 2002, in the former sodium loop of the CABRI reactor. Typical conditions in CABRI are: sodium at 280°C, flowing at 4 m/s under a 0.3 MPa pressure. These are close to PWR hot zero power PWR conditions, except for the nature of the coolant and the channel pressure.

VA-2 was performed on August 2, 2005, in the test capsule of the NSRR reactor. In this case, the coolant was stagnant water at 20°C and 0.1 MPa pressure. Because of their different designs, CABRI and NSRR have quite different characteristics with respect to energy injection into the test rodlet. For CIP0-1, the injected energy after 1.2 s was 99 cal/g. The full width at half maximum (FWHM) of the power pulse was 32.4 ms. In the VA-2 test, the 4.4 ms FWHM pulse resulted in an injected energy after 0.2 s of 138 cal/g. The core power traces and injected energy as a function of time are shown in Figure 4.

Because safety criteria for RIA are usually expressed in terms of fuel enthalpy or fuel enthalpy variation, it is usual to characterize RIA tests by these values. However, these values are not measurable and must be computed with a fuel code.
The SCANAIR code [7], developed by IRSN for RIA applications, was used to determine fuel enthalpies versus time for both tests. Enthalpy evolutions are plotted in Figure 4. In CIP0-1, the maximum fuel enthalpy $H_{\text{max}}$ was 93 cal/g (enthalpy increase $\Delta H=76$ cal/g). In VA-2, $H_{\text{max}}=\Delta H=128$ cal/g because $H$ is conventionally equal to 0 at 20°C.

4 TESTS RESULTS

Results from the CIP0-1 [8] and VA-2 [9] were already reported. They are briefly recalled below.

4.1 Results from CIP0-1

On-line measurements recorded during the CIP0-1 test did not show any noticeable event before reactor power shut down. However, one of the two microphones recorded a late event that remains unexplained to date. It was later confirmed, based on posttest exams that this late event did not correspond to a clad failure.

Posttest exams also revealed important features of the test. The clad permanent hoop strain remained quite low, with a maximum value of 0.5%. Visual exams also showed that the rodlet experienced extensive zirconia spalling during the test, as exemplified in Figure 5.

On metallographies of the clad performed on a radial cut (see Figure 6), one can see that part of the hydrides are oriented in the radial direction, whereas before test all hydrides were circumferential. This implies that a fraction of the hydrides were dissolved during the test and reprecipitated under sufficient hoop stress to form radial hydrides. Also visible on metallographies are radial cracks at the outer surface of the clad in spalled areas. These cracks extend through the hydride rim.

Figure 5: Spalling in CIP0-1

Figure 6: Metallographies of CIP0-1 after test. Left: hydrides morphology in the clad. Right: Detail showing radial cracks in the hydride rim in spalled areas.
4.2 Results from VA-2

On-line measurements during the VA-2 test did record the failure of the rodlet at a time corresponding to a fuel enthalpy of 55 cal/g. The total uncertainty on this value was evaluated to be +/-10 cal/g. This event is clearly seen in Figure 7, which depicts the coolant pressure inside the capsule as a function of time.

Visual examinations after test (see Figure 8) showed that a crack propagated all along the rodlet.

A SEM examination of the fracture surface was performed at a location defined in Figure 8. SEM images are given in Figure 9. The appearance of the fracture surface reveals that the outer half of the clad experienced a brittle failure, whereas the crack propagated in a ductile manner in the inner half.

Figure 7: Capsule internal pressure versus time

Figure 8: Visual appearance of VA-2 after test

Figure 9: SEM examinations of VA-2. Left: Clad thickness. Right: details showing a brittle fracture in the outer half (top) and a ductile fracture in the inner part (bottom)
5 ANALYSIS WITH SCANAIR-CLARIS

Because test conditions in CIP0-1 and VA-2 are quite different in terms of initial temperature, it is not possible to make a direct comparison between both results. It is then necessary to make use of a computer code to assess whether it is possible to analyze both tests with a consistent set of hypotheses.

The SCANAIR code was used for that purpose. It has been shown previously that SCANAIR modeling is adequate to reproduce the thermal and mechanical behavior of the CIP0-1 rodlet as calculation results in terms of coolant temperature and permanent strain were in very good agreement with experimental results.

Because hydrided rods fail due to the induced embrittlement of the clad, a post-processing module called CLARIS was developed for SCANAIR. CLARIS is based on elastic plastic fracture mechanics theory and enables to evaluate a critical crack size (the size at which the crack propagates) evolution during RIA transients.

The critical crack size evaluated as a function of fuel enthalpy for CIP0-1 and VA-2 is plotted in Figure 10.

For CIP0-1, the minimal critical crack size equals to 100 µm. Assuming that the crack size is equal to the hydride rim thickness of 50 µm, it gives a result consistent with experimental observation that the rod did not fail.

With regards to VA-2, the critical crack size of 50 µm is reached for a fuel enthalpy value of 90 cal/g, which is far beyond the enthalpy at failure of 55 cal/g. Experimental uncertainty on enthalpy at failure can not explain this discrepancy because is amounts to +/- 10 cal/g only.

If one looks at the enthalpy of 55 cal/g, SCANAIR-CLARIS calculation indicates that the critical crack size at that moment was about 280 µm. This is consistent with the result of SEM examination that revealed brittleness extending over half of the clad thickness (see Figure 9). Although the tested rods were nearly identical, the VA-2 result suggests that the apparent rim thickness to be considered in the fracture analysis is 280 µm instead of 50 µm as in CIP0-1.

This difference in behavior cannot be explained only by a difference in fracture toughness because the same fracture toughness model that includes the influence of temperature was used in both analyses. This toughness model, based on a large review of the literature is presented in
The difference can neither be explained by a substantial difference in the mechanical loading of the clad. The Figure 12 presents the mechanical strain at the outer part of the clad as a function of enthalpy increase computed by SCANAIR. At the time of VA-2 failure, the mechanical loading in both rodlets was not different. It is then necessary to look at the temperature evolution in the rodlets into more details. Radial temperature profiles at different times are plotted in Figure 13. It is important to note that at the time of failure of VA-2, the temperature of the outer half of the clad was still close to the initial temperature of 20°C. On the contrary, in CIP0-1, the clad temperature goes very rapidly above 400°C, because of the initial temperature of 280°C, the “large” (compared to VA-2) pulse width and the good thermal conductivity of the sodium, which induces high thermal fluxes from the rod to the coolant.

This difference in temperature has an impact on the hydride content in the clad during the test. Referring to curves defining hydrogen solubility limits versus temperature in zirconium alloys (see Figure 14), one can evaluate that between 200 and 1000 ppm were dissolved during the CIP0-1 transient (consistent with the fact that radial hydrides were evidenced after the test, see 4.2 above). Consequently, apart from the 50 µm outer rim, few hydrides precipitates remained. On the contrary, at the time of failure of VA-2, no hydrogen dissolution had occurred in the
outer part of the clad. In this situation, the VA-2 results indicates that the length to be compared to the critical crack size is not only the depth of the hydrogen rim but must also include the underlying zone containing significant hydrogen concentration. This is represented in a schematic way in Figure 15.

![Figure 15: Schematic representation of hydrides morphology at time of maximal mechanical loading Left: CIP0-1, Right: VA-2](image)

As a conclusion, the comparative analysis of CIP0-1 and VA-2 shows that both temperature and hydrogen repartition have a strong impact on the clad resistance during RIA transients. The absence of hydrogen dissolution at room temperature as in the VA-2 test implies that the testing conditions were much more severe than those expected at typical PWR conditions.

6 CONCLUSION

The behavior of Zirlo™ irradiated up to more than 75 GWd/t was tested under fast thermo mechanical loading representative of RIA in the CABRI CIP0-1 and NSRR VA-2 tests. Examinations on the father rods showed that the two tested samples were very similar. The CIP0-1 rod reached a 93 cal/g enthalpy without failure; the VA-2 rod failed at 55 cal/g, which is a relatively low value. Because test conditions were different in terms of initial temperature, coolant nature and power pulse width, it is necessary to use a transient fuel code to compare the two results. Using SCANAIR and CLARIS it was shown that the concentration of hydrogen precipitates at the temperature of the test is of primary importance to assess both experiments in a consistent manner. At low temperature, the initial crack length to be used in failure analysis is much wider than only the hydride rim. Room temperature is thus a testing condition much more severe than that expected at typical PWR conditions. New experiments on Zirlo™ foreseen in both the CIP program in CABRI and the ALPS program in NSSR will help to refine this analysis.

REFERENCES


