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A QUENCH Experiment Including an Air Ingress Phase Prior to Flooding

L. Sepold, Z. Hózer*, G. Schanz, U. Stegmaier, M. Steinbrück, J. Stuckert

*Forschungszentrum Karlsruhe (Karlsruhe Research Center), Institute for Materials Research, P.O. Box 3640, 76021 Karlsruhe, Germany (e-mail leo.sepold@imf.fzk.de)   * KFKI Atomic Energy Research Institute, Budapest, Hungary*

INTRODUCTION

The QUENCH experimental program at the Karlsruhe Research Center is to investigate the hydrogen source term that results from water injection into an uncovered LWR (Light-Water Reactor) core, to examine the behavior of overheated fuel elements under different flooding conditions, and to create a data base for model development and improvement of Severe Fuel Damage codes [1].

Large-scale experiments are being performed in the QUENCH test facility with test bundles consisting of 21 rods, 20 of which are electrically heated over a length of 1024 mm. The central rod is either an unheated one or an absorber rod [2]. The Zircaloy-4 rod cladding and the grid spacers are identical to those used in Pressurized Water Reactors whereas the fuel is represented by ZrO_2 pellets.

Test QUENCH-10 was performed in the frame of the EC-sponsored LACOMERA program [3], proposed by AEKI Budapest. The main objective of this test was to examine the oxidation and nitride formation of Zircaloy during air ingress, before flooding the bundle with water. The test should also support understanding of the consequences of a possible failure of heat removal in a spent fuel pool.

DESCRIPTION OF THE ACTUAL WORK

Posttest metallographic examinations of the QUENCH-10 bundle are continued as well as pertinent separate-effects tests (laboratory scale) in well defined atmospheres, i.e. steam, air, and N_2.

TEST CONDUCT

The main QUENCH-10 test phases were:

- I **Pre-oxidation** in 3 g/s of of both superheated steam and argon for ~113 min at ~1620-1690 K.
- II **Intermediate cooling** from ~1690 to 1190 K in 3 g/s of both superheated steam and Ar for ~38 min.
- III **Air ingress** from ~1190 to 2200 K with an initial heating rate of ~0.3 K/s in 1 g/s of air for ~30 min (steam flow turned off, Ar flow kept constant).
- IV **Quenching** by a water injection rate of 50 g/s → Zr oxidation in steam.

The change from steam to air had the immediate effect of reducing the heat transfer from the bundle so that the temperatures began to rise (see turnaround in temperature at 11629 s in Fig. 1). At 2073 K flooding was initiated.

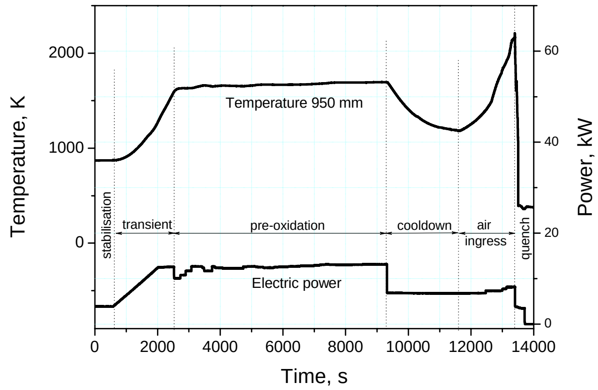

Fig. 1. Temperature at the 950 mm level (TIT A/13) and electric power vs. time together with designations of the QUENCH-10 test phases.

RESULTS

Off-gas Analysis: H_2, O_2, and N_2

During air ingress the total uptakes by Zircaloy were about 84 of O_2 and 8 g of N_2 (supplied were 302 g of O_2 and 1312 g of N_2). Towards the end of air ingress, i.e. after ~27 of ~30 min, oxygen was completely consumed (see Fig. 2). O_2 starvation is significant because it allows pure nitrogen not only to react with residual Zr (with access to the atmosphere) but also to severely attack a protective Zr oxide scale formed in steam atmosphere as was learned from the separate-effects tests [4].

As expected, no hydrogen was generated during most of the air ingress phase except ~0.3 g toward the end of this phase, i.e. during O_2 starvation. (The evaluation of the total hydrogen release amounts to 53 g and the maximum H_2 rate to ~0.57 g/s.) During quenching the release of hydrogen was small (~5 g) compared to experiments with melt formation (up to ~400 g in QUENCH-09). This result indicates the competitive bundle behavior of melting and oxidation.

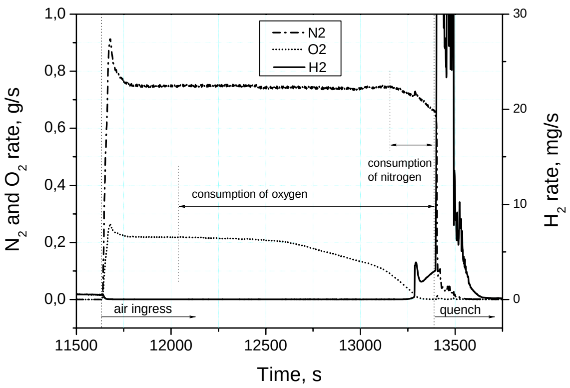

Fig. 2. Mass spectrometer measurements of H_2, N_2, and O_2 during the air ingress and quenching phase of QUENCH-10. A small amount of H_2 (note: scale is mg/s!) is released when O_2 is almost completely consumed, at the end of air ingress. More conspicuous is the H_2 response to steam oxidation upon flooding.

Test Bundle Oxidation and Degradation

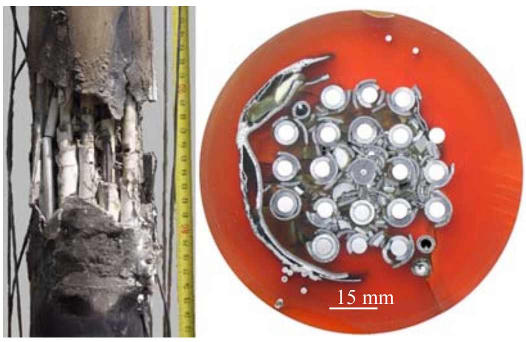

Fig. 3. Posttest appearance of the QUENCH-10 bundle between elevations 730 and 950 mm, at 90° orientation (left), and cross section at 835 mm depicting debris formation (right). Pieces of bundle and shroud fell off during dismantling due to an extreme brittleness caused by Zr oxidation in steam, then in air, and again in steam.

The posttest examination showed an extremely oxidized (degraded) bundle in the hot region, i.e. between 750 and 1000 mm (Fig. 3, left). An inspection by videoscope additionally revealed formation of zirconium nitride phases within the sub-layers of the inner oxide scale. Local defects, e.g. welding seams, seem to favor the formation of colored specks that contain ZrN phases.

In addition to rubble retained in the bundle (Fig. 3, right), large amounts of ceramic particles were carried to the off-gas pipe. The particle size analysis demonstrated that the majority of those particles (95 % ZrO_2) had a diameter of ~25 µm.

Conclusions

The QUENCH bundle experiment on air ingress, demonstrates in accordance with ongoing separate-effects tests the importance of nitrogen during Zr oxidation in air leading to severe bundle degradation, i.e. strong cladding and shroud embrittlement and fragmentation in the hot region. The small H_2 release in the quench phase compared to experiments with melt formation is the consequence of the especially strong oxidative metal consumption.

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