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Experimental results of the QUENCH-16 bundle test on air ingress

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ABSTRACT

The out-of-pile bundle experiment QUENCH-16 on air ingress was conducted in the electrically heated 21-rod QUENCH facility at KIT in July 2011. It was performed in the frame of the EC supported LACOMECO program. The test scenario included the oxidation of the Zircaloy-4 claddings in air following a limited pre-oxidation in steam, and involved a long period of oxygen starvation to promote interaction with the nitrogen. The primary aim was to examine the influence of the formed oxide layer structure on bundle coolability and hydrogen release during the terminal flooding phase. QUENCH-16 was thus a companion test to the earlier air ingress experiment, QUENCH-10, which was performed with strongly pre-oxidized bundle. Unlike QUENCH-10, significant temperature escalation and intensive hydrogen release were observed during the reflood phase. Post-test investigations of bundle cross sections reveal residual nitride traces at various elevations. The nitrides were formed at upper bundle elevations characterized by steam starvation conditions. The external part of the oxide scale is of porous structure due to re-oxidation of nitrides during reflood. Relative thick internal oxide scales underneath this porous layer and residual nitrides were formed during reflood. At lower bundle elevations frozen partially oxidized melt was detected, relocated from upper elevations. Three contributors for the high hydrogen production during the reflood were recognized: re-oxidation of nitrides, secondary oxidation of residual cladding metal due to massive steam penetration through the porous oxide/nitride layer and melt oxidation.

1. Introduction

Air ingress issues have received considerable attention in recent years in view of the likely acceleration in cladding oxidation, fuel rod degradation, and the release of some fission products, most notable ruthenium. The Paks NPP cleaning tank incident (Paks Fuel Project, 2008) and the accidents at Fukushima Daiichi (NISA, 2011) drew attention to the possibility of overheated fuel assemblies becoming exposed to air outside of the reactor.

Experimental and analytical works on air ingress were performed within the EC 4th and 6th Framework Programs (Shepherd et al., 2000; Albiol et al., 2007). Numerous single effect tests on cladding oxidation in air were performed at ANL (temperatures 573–1173 K) (Natesan and Soppet, 2004), AEKI (temperatures 873–1773 K) (Matus et al., 2008), IRSN (temperatures 873–1773 K) (Duriez et al., 2008; Duriez et al., 2009) and KIT (temperatures 873–1873 K) (Steinbrück, 2009; Steinbrück and Böttcher, 2011). The current OECD/NEA project SFP investigates the performance of full-scale 17 × 17 PWR assemblies in air with regard to thermal-hydraulic and ignition phenomena (SFP, 2013). A number of previous bundle air ingress tests have been performed under a range of configurations and oxidizing conditions, namely CODEX AIT-1, AIT-2 with small 9-rod bundles (Hózer et al., 2003), QUENCH-10 with 21-rod strong pre-oxidized bundle (Stuckert et al., 2004), (Schanz et al., 2006) and PARAMETER-SF4 with finally molten 19-rod bundle (Konstantinov et al., 2007; Kiselev et al., 2010). The accumulated data have demonstrated that air oxidation of cladding is a quite complex phenomenon governed by numerous processes depending on the oxidizing conditions, the oxidation history and the details of the cladding material specification. The models for air oxidation do not yet cover the whole range of representative conditions. The main aims of new bundle tests should be the investigation of areas where data were mostly missing.

The QUENCH-16 bundle test was proposed by AEKI in the frame of the EC-sponsored LACOMECO program (Miassoedov et al., 2012) as part of the collective investigation of air ingress into overheated nuclear fuel assemblies. The experiment focused specifically on the following phenomena:

- air oxidation after rather moderate pre-oxidation in steam;
- slow oxidation and nitriding of cladding in high temperature air and transition to rapid oxidation and temperature excursion;
- role of nitrogen under oxygen-starved conditions;
- formation of oxide and nitride layers on the surface of cladding;

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- reflooding of the oxidized and nitrided bundle by water, release of hydrogen and nitrogen.

The proposal included a target scenario characterized by:

- a long period of oxygen starvation to promote the appearance of the above mentioned phenomena;
- reflood quench initiated at temperatures well below the melting point of the cladding to provide the opportunity of avoiding a major oxidation, to facilitate post-test inspection of the bundle.

Concerning the second objective, it was realized that avoiding such an excursion could not be guaranteed, especially in the light of previous experiments such as PARAMETER-SF4 which showed clearly how a starvation period can promote an excursion. The outcome would in any case yield valuable data on this phenomenon.

QUENCH-16 was successfully performed on 27 July 2011, according to a test protocol agreed following discussions among the participants and based on coordinated planning analyses by GRS, EDF and PSI using independent simulation tools. Different post-test calculations were performed to check the ability of new implemented models for description of oxidation in air to describe the processes in the bundle (Beuzet et al., 2012; Birchley and Fernandez-Moguel, 2012; Fernandez-Moguel and Birchley, 2013). The QUENCH-16 test was used recently also for performance of international benchmark (Fernandez-Moguel et al., 2013). Unfortunately, all codes have limitations concerning nitride formation and melt oxidation, although these phenomena were the main peculiarities of the QUENCH-16 test.

2. Test facility and instrumentation

The main goal of the QUENCH program at KIT is to investigate the core thermal response, the cladding oxidation with accompanying hydrogen release and the efficacy of water injection under accident conditions. The recent two bundle tests were performed with advanced cladding materials M5® (Stuckert et al., 2010) and ZIRLO™ (Stuckert et al., 2011), whereas thirteen previous tests were performed in the same facility with Zircaloy-4 claddings (Steinbrueck et al., 2010).

The main component of the QUENCH test facility is the test section with the test bundle (Fig. 1). The facility can be operated in two modes: a forced-convection mode (typical for most QUENCH experiments) and a boil-off mode. QUENCH-16 was conducted in forced-convection mode, in which superheated steam from the steam generator and superheater together with argon as a carrier gas for off-gas measurements enter the test bundle at the bottom. The system pressure in the test section is around 0.2 MPa absolute. The test section has separate inlets at the bottom to inject water for reflood (bottom quenching) and synthetic air (80% N_2 + 20% O_2) during the air ingress phase. The argon, the steam and gases not consumed, and the hydrogen produced in the zirconium-steam reaction flow from the bundle outlet at the top through a water-cooled off-gas pipe to the condenser where the steam is separated from the non-condensable gases. The water cooling circuits for bundle head and off-gas pipe are temperature-controlled to guarantee that the steam/gas temperature is high enough so that condensation at the test section outlet and inside the off-gas pipe is avoided.

The test bundle is approximately 2.5 m long and is made up of 21 fuel rod simulators (Fig. 2). The fuel rod simulators with the Zircaloy-4 (Zry-4) claddings are held in position by five grid spacers, four are made of Zry-4 and the one at the bottom of Inconel 718. Except the central one all rods are heated. Heating is electric by 6 mm diameter tungsten heaters of length 1024 mm installed in the rod center (lower edge of heaters corresponds to bundle elevation 0 mm). Electrodes of molybdenum (length 300 + 576 mm; Ø 8.6 mm) and copper (length 390 + 190 mm; Ø 8.6 mm) are

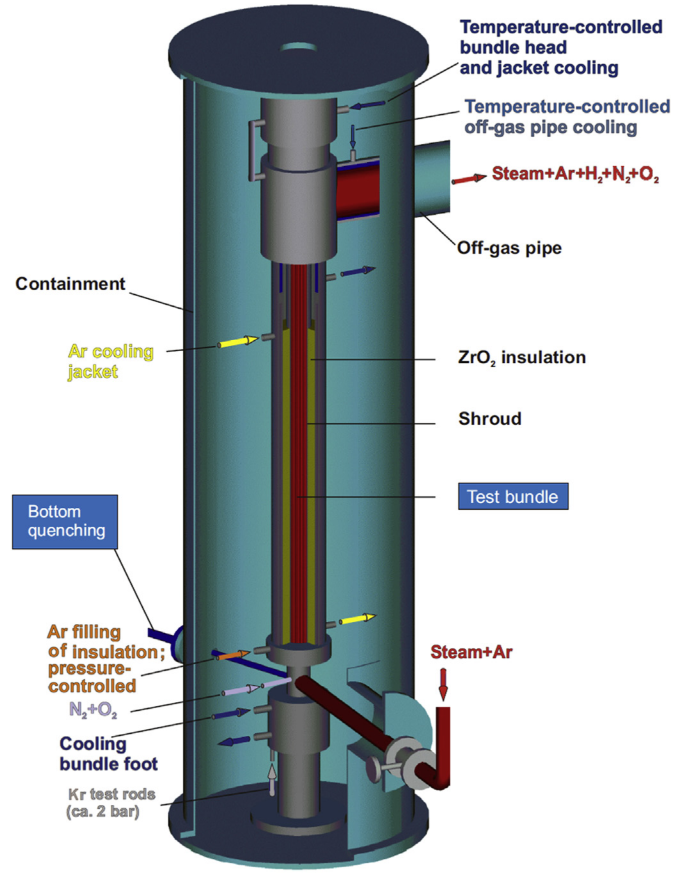

Fig. 1. QUENCH Facility: Containment and test section.

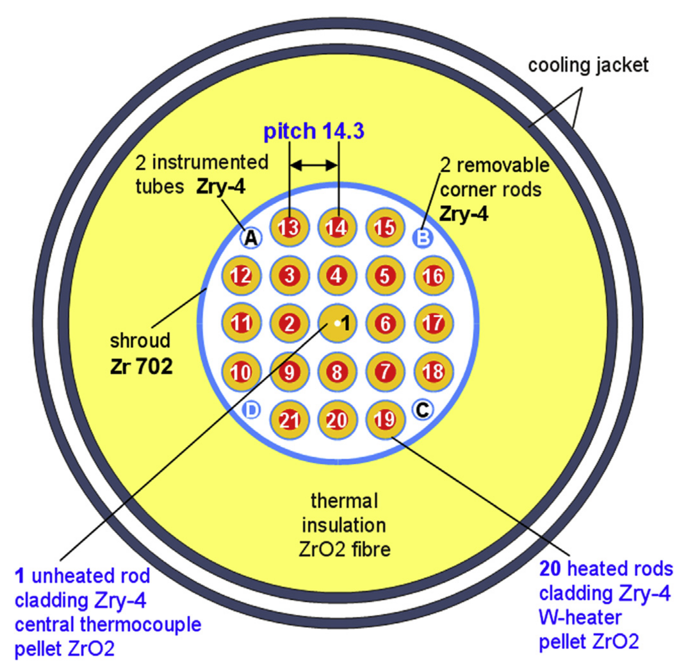

Fig. 2. Bundle cross-section with marked rods.