RESULTS OF THE QUENCH-12 EXPERIMENT ON REFLOOD OF A VVER-TYPE BUNDLE

J. Stuckert, L. Sepold, M. Steinbrück

Forschungszentrum Karlsruhe GmbH, Institut für Materialforschung
Postfach 3640, 76021 Karlsruhe, Germany
juri.stuckert@imf.fzk.de

Introduction

The QUENCH experiments are aimed at investigating the hydrogen source term resulting from water injection into an uncovered core of a Light-Water Reactor (LWR), examining the physico-chemical behavior of overheated fuel elements under different flooding/cooling conditions, and at creating a database for model development and improvement of Severe Fuel Damage computer codes. The QUENCH-12 experiment was carried out to investigate the effects of VVER materials (niobium-bearing alloys) and bundle geometry on core reflood, in comparison with test QUENCH-06 (ISP-45, [1]) using western PWR materials (Zircaloy-4) and geometry. While the PWR bundle uses a single unheated rod, 20 heated rods, and 4 corner rods arranged on a square lattice, the VVER bundle consists of 13 unheated rods, 18 heated rods, and 6 corner rods arranged on a hexagonal lattice.

The test was conducted successfully at the Forschungszentrum Karlsruhe on 27 September 2006 within the framework of the ISTC project 1648.2. The test protocol covered numerous calculations with SCDAP/RELAP5, SCDAPSIM, and ICARE/CATHARE, with adaptation being based on the QUENCH-12 pre-test with short bundle heating to 800 °C. The main test was conducted with largely the same protocol as QUENCH-06, such that the effects on the VVER characteristics could be observed more easily.

Test Conduct and Results of QUENCH-12

The main test phases of the QUENCH-12 experiment are shown in Fig. 1 and summarized below.

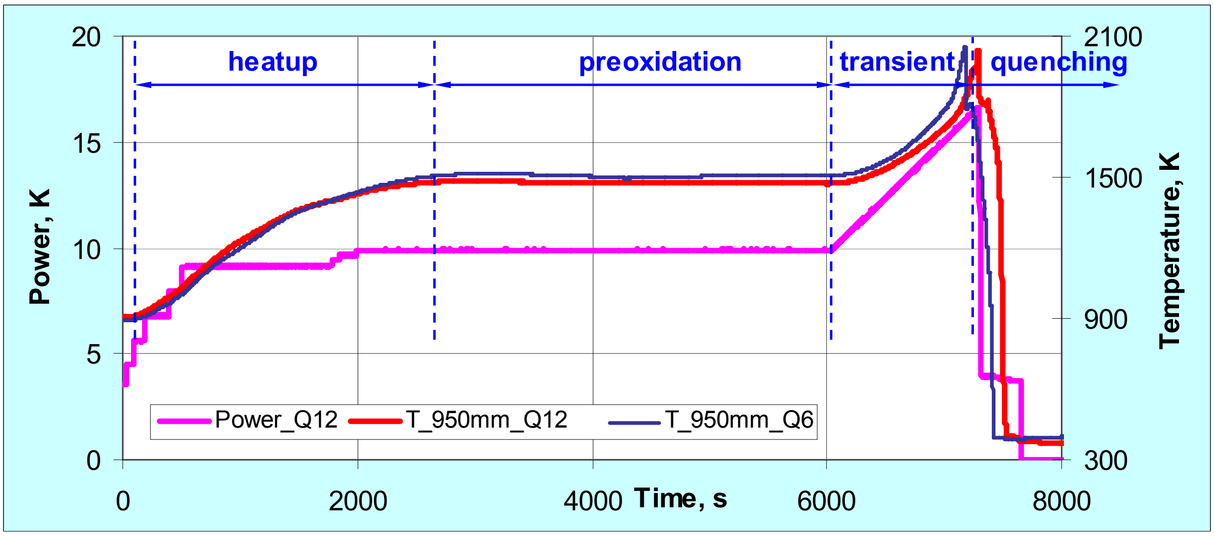

Figure 1. Temperature on the 950 mm level (Q12: TFC 1/13; Q6: TIT A/13) and electric power vs. time together with an indication of the QUENCH-12 test phases.

Phase I Stabilization at ~900 K. Facility checks.

Phase II Heatup by ~0.3-0.7 K/s to ~1473 K for ~48 min (first transient).

Phase III **Pre-oxidation** in a flow of 3.3 g/s of superheated steam and 3.3 g/s argon for ~53 min at a relatively constant temperature of ~1473 K.

Phase IV **Transient** heatup from ~1473 to 2063 K with a heating rate of ~0.3-2.5 K/s for 20.5 min.

Phase V **Quenching** of the bundle by a flow of 48 g/s of water from the bottom.

Pre-oxidation of the bundle was carried out to achieve the target cladding oxidation of around 200 µm at the upper end of the heated zone. The first corner rod (D, Fig. 2), which was withdrawn at the end of pre-oxidation phase, revealed an extensive breakaway effect along the complete hot zone. It was not possible to measure the oxide layer thickness due to spallation of the oxide scales. The second corner rod (F, Fig. 2) was withdrawn during the transient phase before starting the moderate temperature escalation. This rod also exhibited an extensive spallation of oxide scales.

Figure 2. The withdrawn corner rods D (lower), F (middle), B (upper) revealed an extensive breakaway effect and spallation of oxide scales.

The power was ramped after pre-oxidation at a rate of 5.1 W/s in order to increase the temperature until the desired maximum temperature before quench was reached. Then, reflood with 48 g/s water at room temperature was initiated, by a rapid filling of the lower plenum of the test section. The electrical power was reduced to 4 kW during the reflood phase, thus approximating effective decay heat levels. Following the initiation of reflood, a moderate temperature excursion of about 50 K was observed for 15 s, i. e. over a longer period than in QUENCH-06. The third corner rod (B, Fig. 2, two pieces) was pulled after the test. At the positions of rod rupture at the bundle elevations of 880 mm and 1010 mm, melting of the inner β-Zr structure was observed.

Failure registration of heated and unheated rods was performed separately for each type of rod by filling the rods with He gas (unheated rods) and Kr as an additive inside the heated rods. Cladding failure was detected for both rod groups towards the end of the transient phase. Shroud failure was observed at around the initiation of reflood.

Hydrogen Generation

Preliminary figures for hydrogen production are 34 g in the pre-oxidation and transient phases and about 24 g in the quench phase; the amount released in the quench phase being six times higher than in QUENCH-06 with ~4 g (Fig. 3). This may be attributed partly to the longer excursion time. Other reasons for the increased hydrogen production may be extensive damaging of the cladding surfaces due to the breakaway effect and local melt development with subsequent melt oxidation.

Hydrogen uptake by the corner rods was measured by neutron radiography at the Paul Scherrer Institute. The hydrogen content in the corner rods reached 35 at% at the bundle elevation of about 1100 mm.

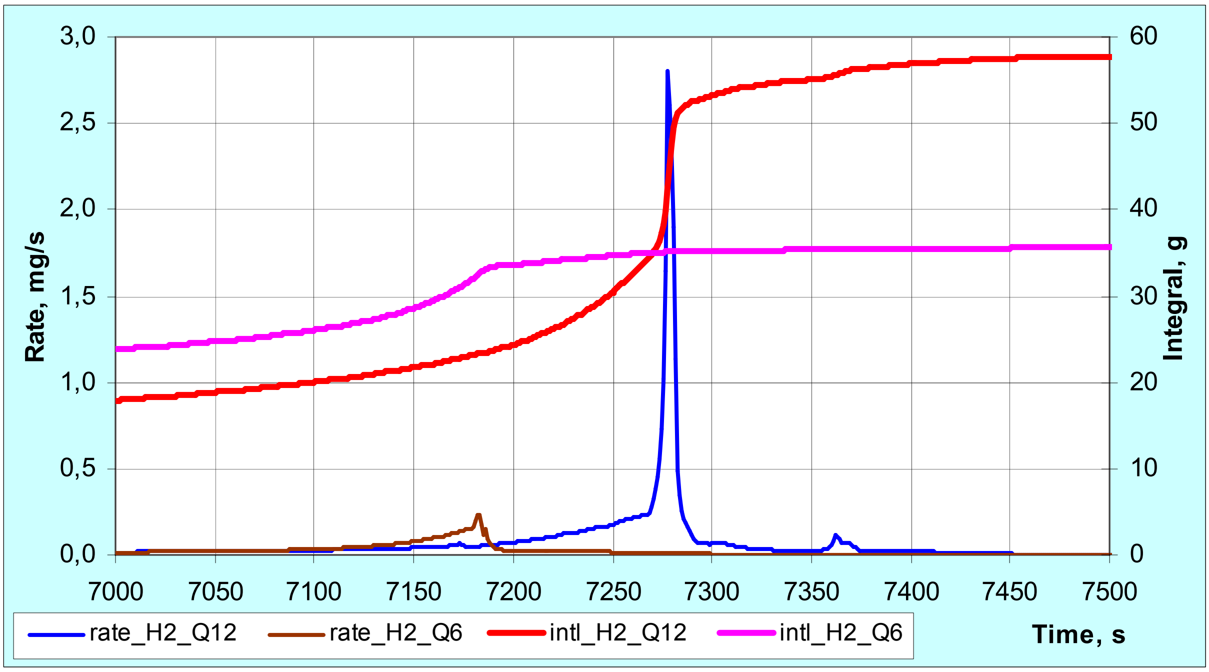

Figure 3. Comparison of hydrogen release during QUENCH-12 and QUENCH-06.

Post-test Appearance of the QUENCH-12 Test Bundle

After the experiment the QUENCH-12 bundle was investigated with a videoscope (OLYMPUS IPLEX). The optical tube of the videoscope was successively inserted at the positions of three withdrawn corner rods. The observation of bundle bottom showed the accumulation of spalled oxide scales (Fig. 4). The appearance of spalled oxide scales on the surface of claddings and shroud was observed from elevation 400 mm upwards. The intensive breakaway effect for the cladding material E110 was also observed by separate effect tests in Russia [2] and FZK single rod tests [3].

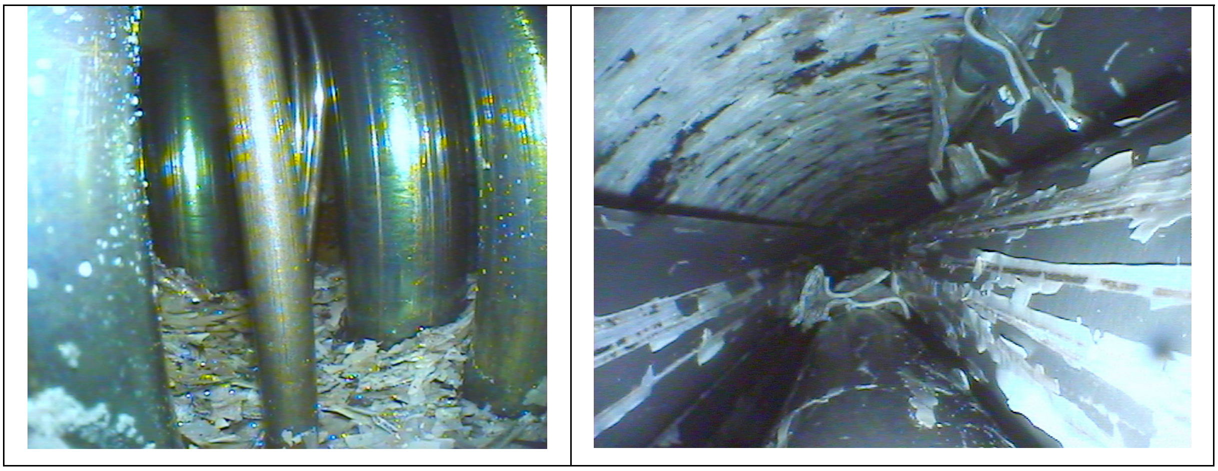

Figure 4. Spallation of oxide scales due to the breakaway effect: Spalled oxides on the bundle bottom (left); oxide spallation on cladding and shroud surfaces (right).

Summary and conclusions

- The QUENCH-12 experiment was carried out to investigate the effects of VVER materials and bundle geometry on core reflood, in comparison with the test QUENCH-06 (ISP-45) with western PWR geometry.
- A pre-test was performed at a maximum temperature of 800 °C. The corresponding oxidation was negligible: Less than 5 µm. The results of this test were used for the fine adjustment of pre-test modelling.
- The electrical power history during the test was in complete agreement with the values calculated up to the reflood phase. The temperature history during pre-oxidation is almost identical to the QUENCH-06 temperature history.
- Three corner rods were withdrawn: At the end of pre-oxidation, upon the completion of the transient phase, and after the test. The surface of all rods exhibited extensive traces of the break-away effect. A typical thickness of spalled oxide scale is about 100 µm.
- Following the initiation of reflood, a moderate temperature excursion of about 50 K was observed over a longer period than in QUENCH-06. For a short time, the temperatures at elevations between 850 mm and 1050 mm exceeded the melting temperature of β-Zr.
- The total hydrogen production was 58 g (for QUENCH-06: 36 g), 24 g hydrogen were released during reflood (for QUENCH-06: 4 g).
- Post-test videoscope observations showed an extensive spallation of oxide scales at elevations higher than 400 mm.

Acknowledgments

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