Quench Phenomena during Reflood of an Overheated Reactor Core

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Abstract

Results of the large-scale experiments being performed in the QUENCH test facility as well as results of accompanying single-rod and separate-effects tests are presented.

Introduction

The most important accident management measure to terminate a severe accident transient in a Light Water Reactor is the injection of water to cool the uncovered degraded core. The aims of the QUENCH experimental program at KIT are the investigation of the hydrogen source term resulting from emergency water injection, the examination of the behaviour of overheated fuel elements under different flooding conditions, the creation of a data base for model development and the improvement of Severe Fuel Damage code packages [1].

All phenomena occurring in the bundle tests have been additionally investigated in single-rod and separate-effects tests. Furthermore, hydrogen absorption by different zirconium alloys was investigated in detail, recently also using neutron radiography as non-destructive method for determination of hydrogen distribution in claddings [2].

Results of Bundle Tests

The large-scale experiments are being performed in the QUENCH test facility with test bundles with a total length of approximately 2.5 m. So far, 15 integral bundle QUENCH experiments with 21-31 electrically heated fuel rod simulators have been conducted. The following parameters and their influence on bundle degradation and reflood have been investigated: degree of pre-oxidation, temperature at initiation of reflood, flooding rate, influence of neutron absorber materials (B_4C, AgInCd), air ingress, and the influence of the type of cladding zirconium alloy.

All bundle tests without absorber rods and with water flooding rate above 2 g/s/rod showed immediate cooldown of the test bundle if the peak bundle temperature at the onset of reflood was below 2100 – 2200 K. Zirconium alloy melt formation at higher temperatures and melt release into the space between rod simulators with following exothermic melt oxidation in steam were indicated as main reason for observed sharp temperature escalation and increased hydrogen production by delayed reflood initiation. Presence of absorber rod materials and their eutectic interaction with the cladding material causes melt formation already at temperatures of ~1500 K (Fig. 1).

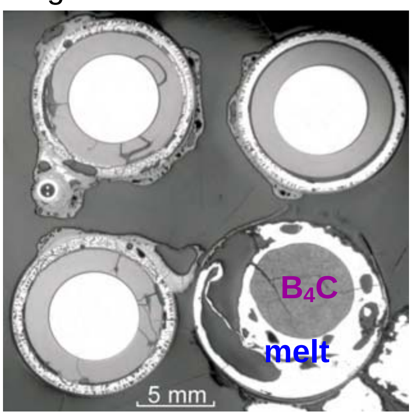

Fig. 1. Test Q-07: melt triggered by B_4C

Fig. 2. Test Q-12 with E110 alloy: breakaway oxidation

An oxide layer on the cladding tube surface delays the interaction of solid or molten zirconium alloy with steam. However, this layer can be destroyed or weakened by the following three mechanisms: (1) oxide scale degradation under steam starvation conditions, (2) oxide spalling due to breakaway oxidation (Fig. 2) [3], (3) ZrO_2 dissolution by molten materials. The presence of homogeneous intact oxide layer is very important during the reflood of an overheated bundle. Comparison of hydrogen production during the quench phase of three bundle tests with similar pre-reflood scenarios but with different Zr-alloys showed the highest hydrogen release during the QUENCH-12 test (Fig. 3). The oxide layer on the cladding tube surfaces of this bundle was intensively damaged during the pre-reflood phases due to breakaway oxidation. Thereby, on the one hand, oxidation kinetics is significantly accelerated and, on the other hand, molten Zr-alloy, developed at the hottest bundle elevations, is not anymore enclosed in the gap between pellet and oxide scale and rapidly oxidised during its relocation in the bundle.

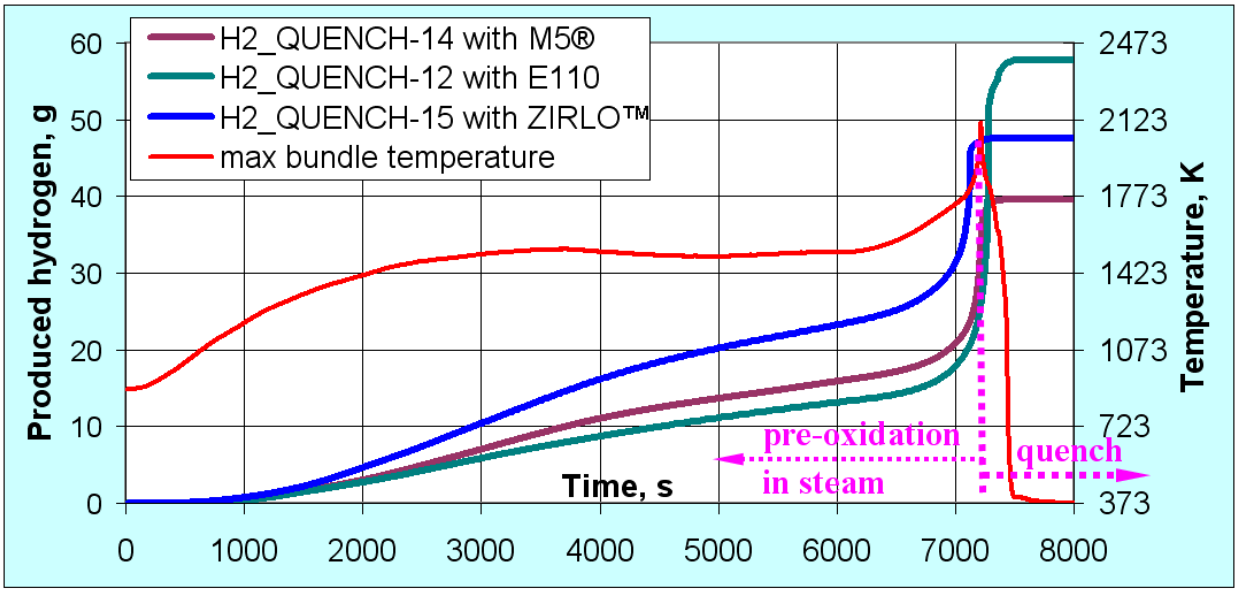

Fig. 3. Comparison of H_2 production during bundle tests with different Zr-alloys

Results of Single-Effect Tests

Extensive single-effect tests were performed to determine oxidation kinetics and to investigate special oxidation effects of different Zr-alloys in different oxidising atmospheres. The oxidation kinetics for oxidation in steam can change from cubic law at lower temperatures ($T < 800$ K) to linear kinetics for intermediate temperature range (800 K $< T < 1400$ K) to parabolic law at high temperatures ($T > 1400$ K). The mechanism of linear oxidation kinetics is connected with the breakaway effect, whose intensity is depending on temperature, oxidation duration and material. Different alloys show intensive breakaway oxidation in different temperature ranges. Whereas typical breakaway temperature range for the E110 alloy is between 950 and 1200 K, Zircaloy-4 alloy shows most intensive spalling of oxide scales at temperatures between and 1200 and1300 K (Fig. 4).

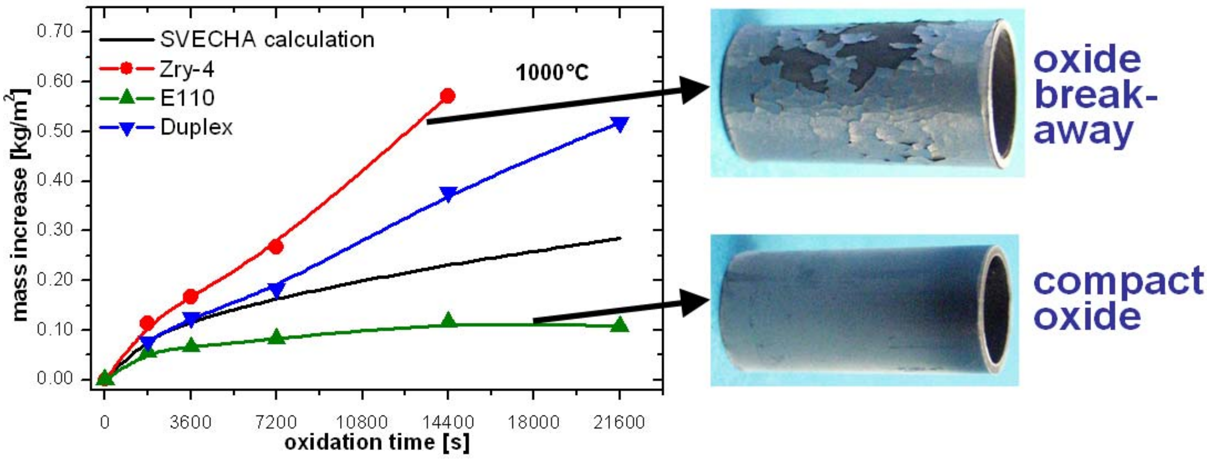

Fig. 4. Oxidation in steam at 1273 K for different alloys

The total microscopic neutron cross section of hydrogen is much higher than the cross section of zirconium. This provides the possibility to determine the hydrogen concentration in zirconium and zirconium alloys by quantitative analysis of neutron radiographs. This non-destructive method allows in-situ observations of hydrogen absorption during oxidation in steam (Fig. 5). Corresponding measurements showed large differences in hydrogen absorption depending on the quality of the oxide layer on the cladding surface.

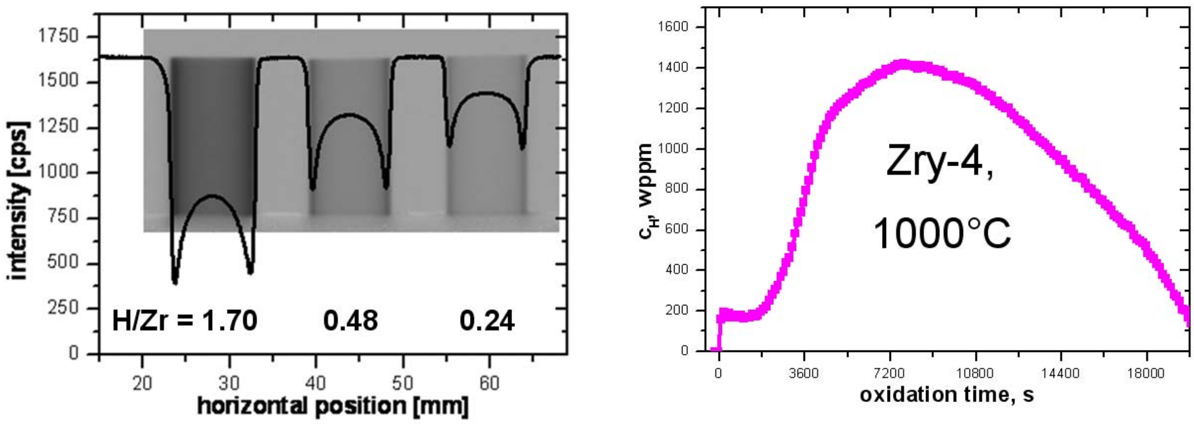

Fig. 5. Neutron radiography method (left) for determination of hydrogen content during oxidation in steam (right).

References

[1] Steinbrück, M., Große, M., Sepold, L., Stuckert, J. Synopsis and outcome of the QUENCH experimental program. Nuclear Engineering and Design (2010), doi: 10.1016/j.nucengdes.2010.03.021.

[2] Grosse, M., Lehmann, E., Vontobel, P., Steinbrueck, M. Quantitative determination of absorbed hydrogen in oxidised zircaloy by means of neutron radiography, Nucl. Instr. & Methods in Phys. Res. A 566 (2006), 739

[3] Stuckert, J., Birchley, J., Grosse, M., Haste, T., Sepold, L., Steinbrück, M., 2009. Experimental and Post-Test Calculation Results of the Integral Reflood Test QUENCH-12 with a VVER-type Bundle. Annals of Nuclear Energy, Vol. 36, Issue 2 (March 2009), 183–192.