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Hydrogen Generation in Reflood Experiments with LWR-type Rod Bundles (QUENCH Program)

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INTRODUCTION

Cooling of an uncovered, overheated LWR (Light-Water Reactor) core with water is a prime accident management measure to terminate a severe accident transient. The initiation of quenching/cooling does, however, not necessarily mean a sudden drop of bundle temperature and hydrogen generation as was demonstrated by analysis of the TMI-2 accident [1] and results of out-of-pile (CORA [2,3]) and in-pile LWR bundle experiments (LOFT [4]) because of the extensive exothermal zirconium-steam reaction.

The QUENCH experimental program at the Karlsruhe Research Center is to investigate the hydrogen source term that results from water injection into an uncovered core, to examine the physico-chemical behavior of overheated fuel elements under different flooding conditions, and to create a data base for model development and code improvement.

The test bundle consists 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. 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. After an optional pre-oxidation phase and a transient test phase to 2000 K and above cooling of the test bundle is accomplished by injecting water or saturated steam at the bottom of the test section.

DESCRIPTION OF THE ACTUAL WORK

At the end of 2002 eight QUENCH tests have been performed (see Table I). In particular, experiments QUENCH-07 and -09 are being evaluated including posttest metallographic examinations of the test bundles, and preparations for the QUENCH-08 experiment are under way.

RESULTS

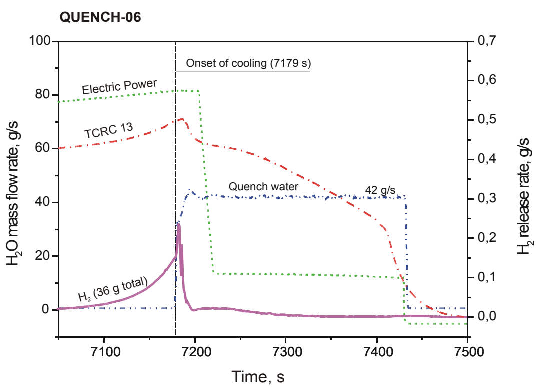
The temperature response on cooldown initiation and thus the hydrogen release rate are determined by the heat transfer from the rods to the coolant and by the heat release from the exothermic zirconium oxidation with help of an increased supply of water or steam.

In the QUENCH experiments it was found that with cooldown the hydrogen generation either stops almost immediately, or continues, or even increases. In the tests QUENCH-01, -04, -05, and -06 the major part of the hydrogen was formed during the transient heatup, i.e. before cooldown. An enhanced hydrogen release in connection with a temperature excursion was found in tests QUENCH-02, -03, -07, and -09 (see Table I and Fig. 1).

TABLE I. QUENCH hydrogen release.

Test	Max. Temp. [K]	Melt formation	Max. H_2 release rate [g/s]	H_2 total (before/ during cooldown) [g]
QUENCH-01 (Water)	≈ 1830	No	0.08	39 (36/3)
QUENCH-02 (Water)	≈ 2500	Yes	2.5	192 (20/172)
QUENCH-03 (Water)	≈ 2500	Yes	3.3	123 [a)] (18/105)
QUENCH-04 (Steam 50 g/s)	≈ 2340	No	0.31	12 (10/2)
QUENCH-05 (Steam 50 g/s)	≈ 2270	No	0.33	27 (25/2)
QUENCH-06 (Water)	≈ 2150	No	0.24	36 (32/4)
QUENCH-07 (Steam 15 g/s)	≈ 2300	Yes	2.3	198 (62/136)
QUENCH-09 (Steam 50 g/s)	≈ 2500	Yes	5.6	468 (60/408)

The high amounts of hydrogen generated in the QUENCH-02, -03, -07, and -09 tests (and earlier in the CORA and LOFT experiments) might be explained by the oxidation of zirconium-containing melt. Posttest examinations of the QUENCH-02, -03, and -07 bundles confirmed earlier observations made in the CORA out-of-pile experiments with UO_2 fuel pellets that besides the oxide scale growth at the peripheries of the solid bundle components, fragments, and melt lumps, ZrO_2 particles can be found precipitated in the bulk of the Zr-containing melt. At temperature the oxygen contents lie in the two-phase region, i.e. between the liquidus and the solidus line in the Zr-O phase diagram, and thus indicate that oxidation continues beyond oxygen saturation of the melt. Precipitation of (a new) ceramic phase is accompanied with an enhanced Zr oxidation kinetics which leads to an enhanced hydrogen production [5,6]. Special attention to this phenomenon is paid in the QUENCH program.



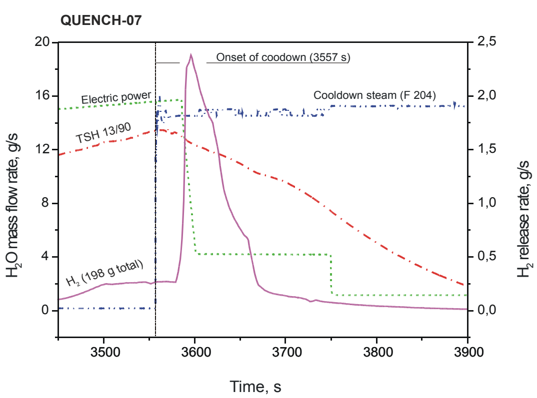


Fig. 1: Time dependence of the electric bundle power input, characteristic bundle temperature, quench water or steam flow, and of the hydrogen release rate measured by the mass spectrometer (solid line), at the initiation of cooling in tests QUENCH-06 (with no enhanced H_2 generation), top, and QUENCH-07 resulting in an enhanced H_2 production, bottom. (Note: Electric power and temperature are not to scale!).

Under similar test conditions the hydrogen release in the flooding/cooldown phase of all QUENCH experiments performed so far seems to be independent of the cooling medium, i.e. water or steam.

CONCLUSION

Based on the results of the first eight experiments the following conclusion is meant as an information for power reactor operators. In severe accident scenarios, particularly under the formation of melt in a LWR fuel element, an enhanced H_2 generation during reflood of the core is possible which then must be accounted for in accident mitigation procedures.

ACKNOWLEDGMENT

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