

Improving the Results of QUENCH-16 Experiment by Using New Models of MELCOR 2.1

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Abstract. The air ingress experiment Quench-16 was analysed with MELCOR 2.1. The code version of MELCOR 2.1 included oxidation model for air at low and high temperatures. This study explores the influence of oxygen concentration on the hydrogen generation and temperature escalation. The influence of the oxygen concentration on the kinetics behaviour was observed from the Separate Effect Test. In Steinbruek's work [1] there is an evidence for significant effect of composition and flow rates on oxidation of Zry-4 impact on cladding and the air oxidation kinetics. Oxidation of Zircaloy depends on the time, temperature, gas composition and cladding alloys. Additionally, the oxidation kinetics in air is much faster than in steam due to the formation of non-protective oxide (partially nitrated) scales.

The main purposes of QUENCH-16 test were to examine the oxidation of Zircaloy in air following a limited pre-oxidation in steam and to achieve a long period of oxygen starvation to promote the nitrogen interaction. The low concentration of the oxygen in QUENCH-16 might have resulted in lower rate of oxidation than would be expected. The studies were presented on oxygen consumption, hydrogen generation and temperature escalation during the whole experiment. Series of simulations using new models of MELCOR for QUENCH-16 were performed to examine influence of oxygen concentrations to improve the results of hydrogen generation during the quench phase. The QUENCH-16 test was conducted successfully at KIT (Karlsruhe Institute of Technology) on 27 July 2011[2,3].

Keywords: severe accident, Hydrogen generation, Oxygen consumption, Nitrogen consumption, quenching.

1 Introduction

The QUENCH-16 test has been investigated the hydrogen generation, behaviour of the fuel assembly in penetration on air and bundle degradation during reflooding in the early phase of a severe accident. The experiment is supported by separate-effects tests (SET) and code analyses. The QUENCH program provides experimental and analytical data for the development of quench and quench-related models and for the validation of SFD code systems [4,5]. In the presence of air ingress during a reactor fuel severe accident, the fuel rods will be exposed to air-containing atmospheres at high temperatures. As opposed to steam, the air ingress is expected to increase the damage of the fuel rods. The safety impacts of such air ingress have been studied for situations such as those in-vessel following hot-leg failure in a PWR severe accident with subsequent failure of the lower head of the vessel [6]. The QUENCH-16 test phases can be summarized as follows:

- 0 s – Pre-oxidation and heat up phases: Initial bundle temperature 871 K with injection of 3.4 g/s steam and 3 g/s Argon flow;
- 6301 s – Cooling phase: Reduction of el. power;
- 7307 s – Air ingress phase: Air flow 0.2 g/s and 1 g/s Argon flow, switch-off steam supply;
- 10350-10650 s – Transition of steam starvation and partial nitrogen consumption;
- 11341 s – Fast water injection. Stop of Argon and overheated gas supply;
- 11350 s – Initiation of 53 g/s quench water supply.

2 Description of Quench-16 Facility

The bundle [7] was equipped with 20 heated fuel rod simulators arranged in two concentric rings and one unheated central fuel rod simulator, each about 2.5 m long. The rods were heated by 1024 mm long and 6 mm diameter tungsten heaters located at the rod centres. Molybdenum and copper electrodes connected the tungsten heaters to the cables leading to the DC electrical power supply. The tungsten heaters were surrounded by annular ZrO_2 pellets to simulate the UO_2 fuel.

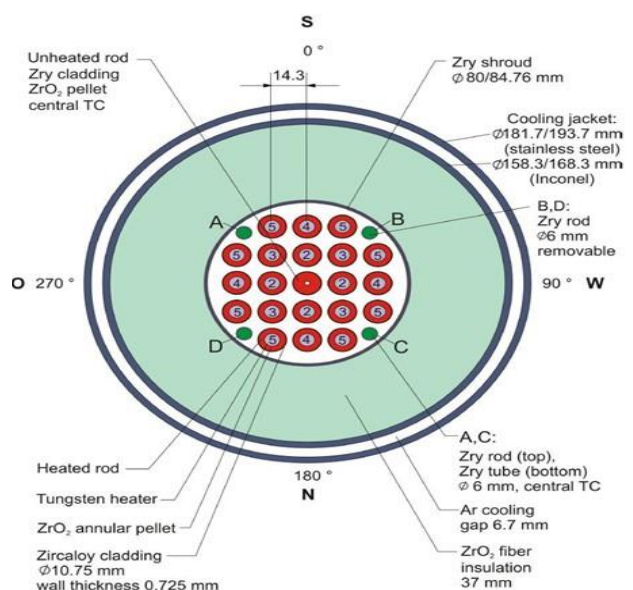


Figure 1. QUENCH-16 cross-section.

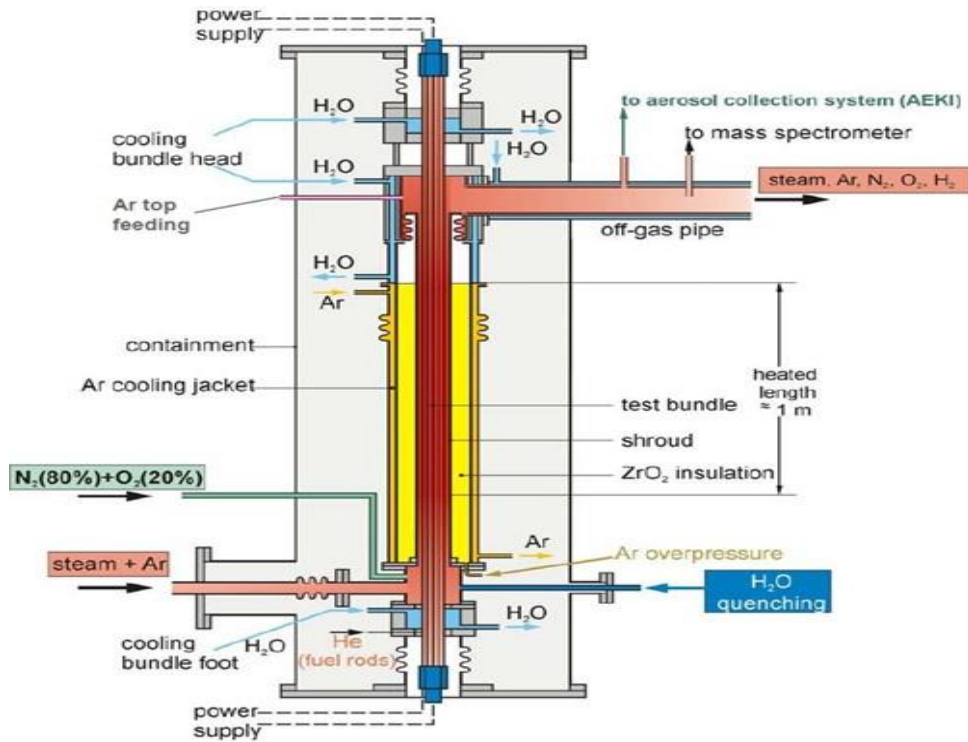


Figure 2. QUENCH-16 facility.

The geometry and most other bundle components were prototypical for Western-type PWRs. The fuel rod simulators were held in position by five grid spacers, four were made of Zircaloy-4 and the one at the bottom of Inconel 718. Four 6 mm diameter corner rods were installed to mount additional thermocouples. The bundle was surrounded by a Zircaloy-4 shroud to provide encasement, a 37 mm thick ZrO_2 fibre insulation and a double-walled cooling jacket of Inconel 600/stainless steel within which a flow of argon was maintained to remove excess heat. The whole set-up was enclosed in a steel containment. The facility bundle cross-section and the schematic of the facility are shown in Figures 1 and 2.

3 Quench-16 Facility MELCOR 2.1 Model

MELCOR 2.1 computer code [8] has been used for the analysis. The model of computer code MELCOR 2.1 has been developed at INRNE-BAS for analyses of QUENCH-16 test on the base of the older model [9] and has been improved [10]. The bundle was divided in twenty-two axial levels and four rings. The innermost ring contained the single unheated fuel rod simulator, the second ring contained eight heated rod simulators, and the third ring contained twelve heated rod simulators and four corner rods. The outermost ring contained the shroud. Sixteen hydrodynamic volumes were used to represent the core. The cooling systems were represented as a fixed temperature boundary. Additional volumes were used to represent the lower and upper plenum, the water-filled sinks at the extremes of the bundle, and the isolated region between the top of the bundle outlet plenum and the upper heat sink. The model is represented as shown in Figure 3.

The MELCOR 2.1 was used for this analysis. This code version allows to model oxidation in air and for the Zircaloy-oxygen reaction is used breakaway model. The notable feature of the model is a transition from parabolic to linear kinetics. The metal oxidation is calculated using standard parabolic kinetics, with appropriate rate constant for Zircaloy and steel oxidation, limited by gaseous diffusion considerations.

For the Zircaloy-steam reaction, the oxidation constant is evaluated using the Urbanic-Heidrich constants, which are implemented (along with the transition temperatures of 1853 K and 1873 K), as sensitivity coefficients.

4 Analysis of the Results

SET test involving air oxidation of zirconium alloys preoxidised in steam at high temperature and their reaction in mixed air-steam atmospheres. With increasing temperature up to 1300–1400°C there was a progressively stronger degrading effect of even lower air concentrations in the mixture. As could be expected from chemical thermodynamics, the oxidation in oxygen is favoured in comparison with the oxidation in steam [8]. Figure 4 shows the oxidation of Zircaloy with different Ar/Air compositions. It is observed that at low concentrations of oxygen the kinetics are significantly slower than at higher O_2 concentration.

Series of calculations using new models of MELCOR for QUENCH-16 were performed to examine influence of oxygen consumption to improve the results of hydrogen generation during the quench phase. During the air phase the hottest temperature location had changed from the 950 mm to lower elevations due to the early oxygen consumption (Figures 5 and 6). Early oxygen consumption was

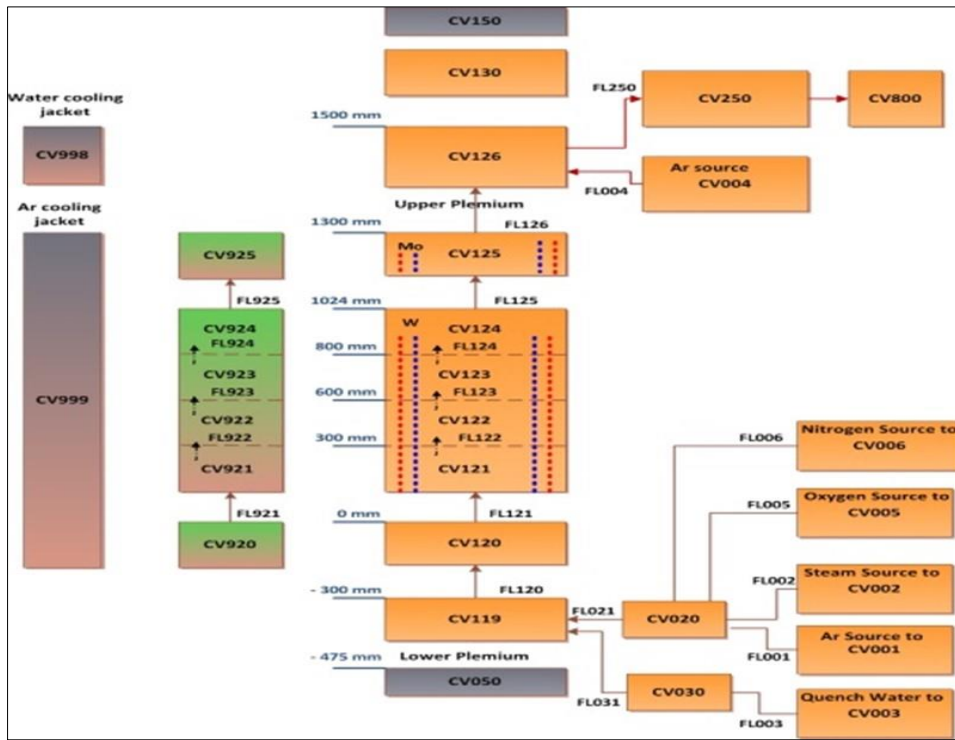


Figure 3. Nodalization scheme of QUENCH-16 facility for MELCOR 2.1 model.

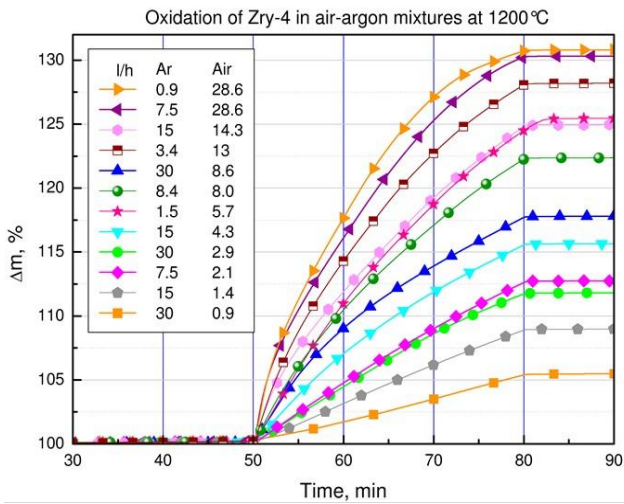


Figure 4. Oxidation of Zry-4 in air-argon mixtures.

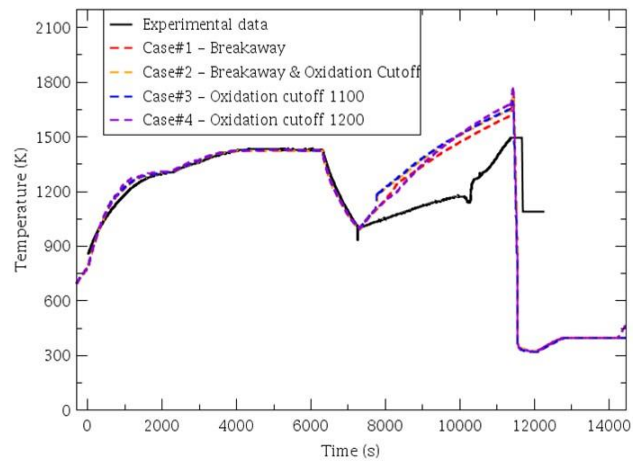


Figure 5. Temperature inner rod at elevation 950 mm.

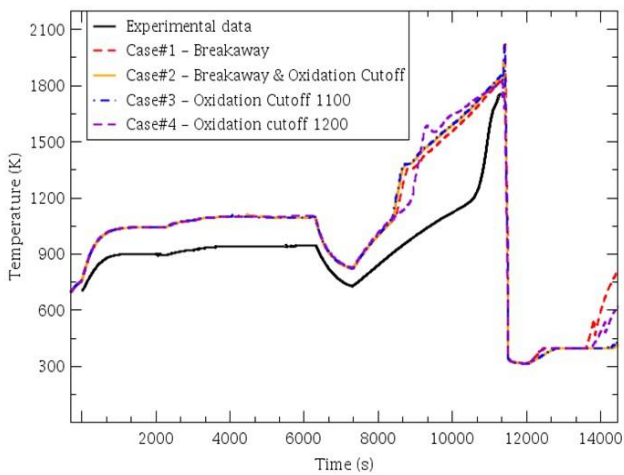


Figure 6. Temperature inner rod at elevation 350 mm.

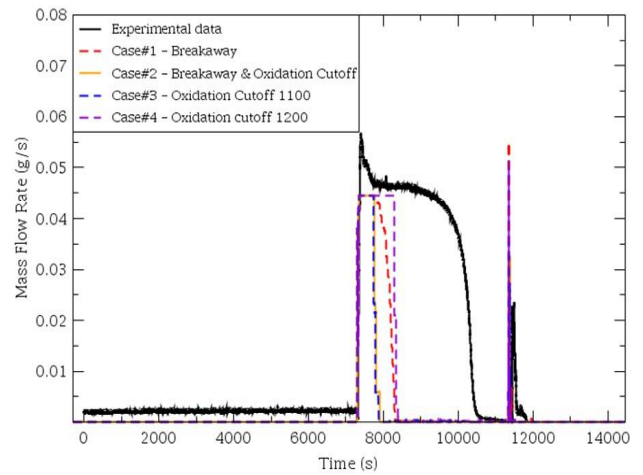


Figure 7. Oxygen consumption.

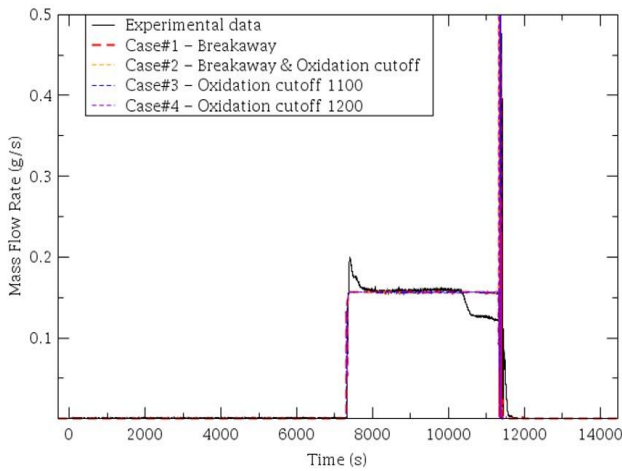


Figure 8. Nitrogen consumption.

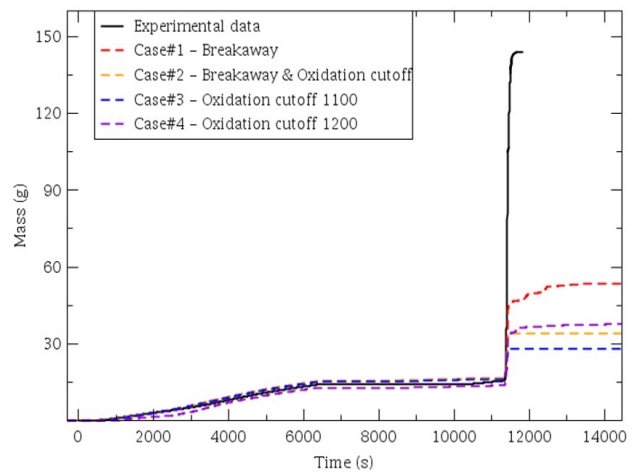


Figure 9. Total hydrogen generation.

corresponding on increasing in the temperature. All of the calculations showed an earlier than measured oxygen consumption with MELCOR 2.1 (with or without breakaway modelled) is presented in Figure 7. Since oxidation kinetics depends on temperature, one may conclude that the calculations began to oxidize earlier at the lower elevations due to the sharply increase in temperature. In all calculated cases is not observed the nitrogen consumption during air phase. While in experiment was noticed partial nitrogen consumption (Figure 8). In the next Figure 9 is shown total hydrogen generation. The calculations gave a closer prediction on the time when the hydrogen started to be generated (during the heat-up phase). The hydrogen generation during reflood was underestimated by all cases.

5 Conclusion

The calculations of temperature progression showed a good agreement with the experimental data. The measured hydrogen generation at the end of the reflooding is higher than the calculated in all cases after a long period of oxygen starvation

However, one or more of the following process may have led to a possible mechanism for triggering the strong oxidation excursion during reflood: ZrN formation, reoxidation of the ZrN and nitrogen release during reflood, dissolution of the oxide. Concerning impacts on reactor safety, the presence of air can lead to accelerated oxidation of Zircaloy is that in steam, owing the faster kinetics.

The study opens questions about dynamics of air oxidation and nitriding processes, and impact of nitriding on subsequent reflooding.

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Bibliography

- [1] Steinbrück M., Gerhards U., Große M., Leiste H., Prestel S., Stegmaier U. (2011) Recent results of KIT separate-effects tests on oxidation of zirconium alloy cladding. In 17th QUENCH Workshop, Karlsruhe, 22-24 November 2011.
- [2] Stuckert J., Steinbrück M. (2012) Experimental Results of the QUENCH-16 Bundle Test on Air Ingress. Proceedings of ICAPP '12, Chicago, USA, June 24-28, 2012, Paper 12049.
- [3] Stuckert J., Große M., Hozer Z., Steinbrück M. (2013) Results of the QUENCH-16 Bundle Test on Air Ingress. Scientific report KIT-SR 7634.
- [4] Steinbrück M., Große M., Sepold L., Stuckert J. (2010) Synopsis and outcome of the QUENCH experimental program. *Nuclear Engineering and Design* **240** 1714-1727.
- [5] Fernandez-Moguel L., Bals C., Beuzet E., Bratfisch C., Coindreau O., Hózer Z., Stuckert J., Vasiliev A., Vryashkova P. (2014) SARNET2 benchmark on air ingress experiments QUENCH-10, -16. *Annals of Nuclear Energy* **74** 12-23.
- [6] Powers D.A., Kmetyk L.N., Schmidt R.C. (1994) A Review of Technical Issues of Air Ingression during Severe Reactor Accidents. NUREG/CR-6218, September 1994.
- [7] Sepold L., Hering W., Schanz G., Scholtyssek W., Steinbrück M., Stuckert J. (2007) Severe fuel damage experiments performed in the QUENCH facility with 21-rod bundles of LWR-type. *Nuclear Engineering and Design* **237** 2157-2164.
- [8] MELCOR Code Manuals – Version 2.1 September 2011, NUREG/CR-6119, Vol. 1, Rev 3179, SAND2011.
- [9] Durieza C., Steinbrück M., Ohaic D., Melegc T., Birchley J., Hasted T. (2009) Separate-effect tests on zirconium cladding degradation in air ingress situations. *Nuclear Engineering and Design* **239** 244-253.
- [10] Vryashkova P., Groudev P., Stefanova A. (2014) Investigation of Quench-16 Experiment With MELCOR Computer Code. In Proceedings 22nd International Conference on Nuclear Engineering, Paper No. ICONE22-30979, pp. V005T17A060; doi:10.1115/ICONE22-30979.
- [11] Vryashkova P.I., Groudev P.P. (2015) Preliminary analysis of quench 16 experiment with MELCOR 2.1 computer code. *Comptes Rendus de l'Academie Bulgare des Sciences* **68** 455-462.