First results of the QUENCH-20 test with BWR bundle


Abstract

Experiment QUENCH-20 with BWR geometry simulation bundle was successfully conducted at KIT on 9th October 2019. This test was performed in the framework of international access SAFEST infrastructure with the users from Swedish Radiation Safety Authority (SSM) in cooperation with Westinghouse Sweden, GRS and KTH.

The test objective was the investigation of a BWR fuel assembly degradation including a B\(_4\)C control blade. The test bundle mock-up represents one quarter of a BWR fuel assembly. The 24 electrically heated fuel rod simulators were filled separately with krypton (overpressure of 4 bar).

According to the pre-test calculations performed with ATHLET-CD, the bundle was heated to a temperature of 1230 K at the cladding of the central rod at the hottest elevation of 950 mm. This pre-oxidation phase in steam lasted 4 hours. Towards the end of this phase, the reference rod was extracted from the test bundle for determination of the oxide thickness axial distribution.

During the transient stage, the bundle was heated to a maximal temperature of 2000 K. The cladding failures were observed at temperature about 1700 K and lasted about 200 s. Massive absorber melt relocation was observed 50 s before the end of transition stage.

The test was terminated with the quench water injected with a flow rate of 50 g/s from the bundle bottom. Fast temperature escalation from 2000 to 2300 K during 20 s was observed. The mass spectrometer measured release of CO\(_x\) and few CH\(_4\) during the reflood as products of absorber oxidation; corresponding production of B\(_2\)O\(_3\) should be about 97 g. Hydrogen production during the reflood amounted to 32 g (57.4 g during the whole test) including 10 g from B\(_4\)C oxidation.
First results of the QUENCH-20 test with BWR bundle


QWS-25, Karlsruhe
QUENCH-20 (SAFEST): Choice of BWR elements, which should be simulated during QUENCH-SAFEST

SSM proposal: study of high temperature degradation of BWR assembly mock-up in QUENCH facility (melt formation due to eutectic material interaction inside absorber cross)
QUENCH-20: suggested test bundle composition
(¼ SVEA-96 OPTIMA2 assembly)

- Heated rods (24): cladding Zy-2 with inner ZrSn-liner (10% of clad),
  ZrO₂ pellet OD 8.48±0.05 ID 5.45±0.1 mm, length 11 mm,
  W heater OD 5.25±0.025 mm
- Absorber blades with B₄C, side length 67 mm
- Advanced low tin ZIRLO fuel channel box, wall thickness 1.4 mm
- Inconel cooling jacket, inner tube ID=158.3 mm
- Corner rod (Zry-4, OD 6 mm)
- Water channel box (ZIRLO), side length 27.4 mm
- Water cross wing (ZIRLO), wall thickness 0.8 mm
- Zr shroud 90 mm x 114 mm (inner clearance dimensions), wall thickness 3 mm
- ZrO₂ porous thermal insulation

Geometrical parameters:
- Bundle pitch 12.898 mm;
- Outer diameter of claddings 9.84 mm;
- Thickness of claddings 0.605 mm;
- Absorber blades: thickness 8.05 mm
- Cladding length 2500 mm
- Absorber and cannell box lengths 1600 mm
- Water gap between channel box and absorber blade 2.5 mm (nominal inter-assembly gap in BWR-PROTEUS core is 13.8 mm -> water gap 2.875 mm)
QUENCH-20: delivered parts

Zr shroud

channel box (low tin ZIRLO)

absorber blade (stainless steel)

B₄C pin

sleeve type spacer grid
Inconel X750

horizontal holes for B₄C pins

claddings
(Zry-2 with inner ZrSn liner)
QUENCH-20: instrumentation and preparation of parts

Q20 bundle instrumented with TCs

low temperature TC at shroud surface

high temperature TC at clad surface

Zr shroud connected to bundle foot

absorber blades filled with B4C pins and prepared for filling with He, then welded
gas injection: Ar 3g/s during the whole test; superheated steam 3 g/s until the quench initiation
QUENCH-20: axial temperature profiles of outer cladding surfaces and outer shroud surface (temperatures averaged through the cross-section for each elevation)

on the end of pre-oxidation (14400 s)

on the end of transient (15880 s)
QUENCH-20: oxidation of Zry-4 corner rod withdrawn on the end of pre-oxidation

breakaway (spalled oxide layer)
QUENCH-20: failure of rods; first failures: inner rods 1, 4, 8; last failure: outer rod 12

ballooning and burst or cracks?
QUENCH-20: indication of rod failures by Kr release

7 Kr peaks ↔ 7 rod groups (conditioned by temperature)
QUENCH-20: shroud failure
QUENCH-20 bundle surrounded by shroud: post-test view

Bundle cross-section, top view

950 mm

550 mm

0°, 90°, 180°, 270°
Strong degradation of **absorber blades**, channel box and shroud between elevations 650 and 950 mm at angle positions 0° and 270°.
QUENCH-20: absorber melt formation at above 750 mm and relocation to lower elevations

He, ppm/10; CH4, mg/s

He
CH4
blade T at 450 mm, 0°
shroud T at 750 mm, 0°
shroud T at 750 mm, 270°

1st melt relocation
2nd melt relocation
quench
QUENCH-20: absorber melt relocation from hottest bundle elevations to elevations 250-450 mm

Temperature, K

Time, s

relocation of molten absorber at 0° at 270°

TBL 8/90 450 mm

TCH 8/90 450 mm

TCH 8/180 450 mm

TBL 7/180 450 mm

TCH 7/180 350 mm

TCH 7/90 350 mm

TBL 6/90 250 mm
QUENCH-20: reaction of B₄C with steam

\[
\begin{align*}
B_4C(s) + 7H_2O(g) &= 2B_2O_3(l) + CO(g) + 7H_2 \\
B_4C(s) + 8H_2O(g) &= 2B_2O_3(l) + CO_2(g) + 8H_2 \\
B_4C(s) + 6H_2O(g) &= 2B_2O_3(l) + CH_4(g) + 4H_2
\end{align*}
\]

only small release of CH₄ before quench;  CO and CO₂ formation firstly in the quench stage
QUENCH-20: reaction of $\text{B}_4\text{C}$ with steam, integral gas release

According to $\text{CO}_x$ and $\text{CH}_4$ release: corresponding mass of $\text{B}_2\text{O}_3$ is 96.8 g; $\text{H}_2$ is 10.0 g

$\text{B}_4\text{C}(s)+7\text{H}_2\text{O}(g)=2\text{B}_2\text{O}_3(l)+\text{CO}(g)+7\text{H}_2$

$\text{B}_4\text{C}(s)+8\text{H}_2\text{O}(g)=2\text{B}_2\text{O}_3(l)+\text{CO}_2(g)+8\text{H}_2$

$\text{B}_4\text{C}(s)+6\text{H}_2\text{O}(g)=2\text{B}_2\text{O}_3(l)+\text{CH}_4(g)+4\text{H}_2$
**QUENCH-20: hydrogen release**

**H₂ release during the whole test:** 57.4 g; before quench – interaction of steam with Zry, during quench – steam interaction with Zry and absorber

**H₂ release during quench:** 22 g (from Zry and molten steel) + 10 g (from B₄C)

- **before quench:** 25.4 g
- **during quench:** 32 g
QUENCH-20: steam production during the quench stage

![Graph showing steam production and temperature over time, with labels indicating various stages such as filling of thermal insulation by quench water through the shroud breach and oscillations during evaporation.](image-url)
QUENCH-20: filling of bundle with quench water and wetting of thermocouples

delayed cooling of the bundle (>450 s) due to filling of insulation annulus through the shroud breach at ≈550 mm
Summary and conclusions

- Experiment QUENCH-20 with BWR geometry simulation bundle was successfully conducted at KIT on 9th October 2019 in the framework of the international SAFEST project. The test bundle mock-up represented one quarter of a BWR fuel assembly with 24 electrically heated fuel rod simulators and B₄C control blade. The rod simulators were filled with Kr to inner pressure of 6 bar at peak cladding temperature of 900 K.

- The pre-oxidation stage in the flowing gas mixture of steam and argon (each 3 g/s) and system pressure of 2 bar lasted 4 hours at the peak cladding temperature of 1250 K. The Zry-4 corner rod, withdrawn at the end of this stage, showed the maximal oxidation at elevations between 930 and 1020 mm with signs of breakaway.

- During the transient stage, the bundle was heated to a maximal temperature of 2000 K. The cladding failures were observed at temperature about 1700 K and lasted about 200 s. During the period of rod failures also the first absorber melt relocation accompanied by shroud failure were registered. Massive absorber melt relocation was observed 50 s before the end of transition stage.

- The test was terminated with the quench water injected with a flow rate of 50 g/s from the bundle bottom. Fast temperature escalation from 2000 to 2300 K during 20 s was observed. The mass spectrometer measured release of CO (12.6 g), CO₂ (9.7 g) and CH₄ (0.4 g) during the reflood as products of absorber oxidation; corresponding production of B₂O₃ should be 96.8 g.

- Hydrogen production during the reflood amounted to 32 g (57.4 g during the whole test) including 10 g from B₄C oxidation.
Acknowledgment

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Thank you for your attention

http://www.iam.kit.edu/awp/666.php
http://quench.forschung.kit.edu/