Bundle reflood tests QUENCH-14 and QUENCH-15 with advanced cladding materials: comparable overview

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Objective

Investigation of influence of different cladding materials on bundle oxidation and core reflood for following bundles:

- QUENCH-14 with niobium-bearing M5® cladding
- QUENCH-15 with tin-niobium-bearing ZIRLO™ cladding
- QUENCH-06 with Zircaloy-4 cladding (reference test)
- QUENCH-12 with niobium-bearing E110 cladding
Features of QUENCH-facility

Scaling
Height: 1:3 ... 1:2
Volume: 1:5000 ... 1:3000

Bundle
- PWR (21 rods M5 or 24 rods ZIRLO)
- VVER (31 Stäbe, E110)

Heating
- electric 70 kW (~1 m W-heaters inside fuel rod simulators)

Instrumentation
- ~80 TCs at 17 axial levels
- Mass spectrometer (incl. steam)
- Quench water level (Δp)
- Corner rods for “online” check of oxide scale
Different bundle compositions

Q-14 bundle with 21 rod simulators
M5® cladding with thickness 750 µm

Q-15 bundle with 24 rod simulators
ZIRLO™ cladding with thickness 570 µm
Comparison of geometrical parameters of the QUENCH-15 bundle with the QUENCH-14 bundle:

1) coolant channel area relationship $Q_{15}/Q_{14} = 1.16 \Rightarrow$ the fluid flow rate should be 16% higher for the Q15 bundle than for the Q14 bundle to provide the same flow velocity

2) metallic surface relationship $Q_{15}/Q_{14} = 1.09 \Rightarrow$ increased chemical energy production for the Q15 bundle due to exothermic steam-metal reaction
Performance of tests QUENCH-06, QUENCH-12, QUENCH-14 and QUNCH-15 under identical scenario

![Graph showing performance of tests QUENCH-06, QUENCH-12, QUENCH-14, and QUNCH-15 under identical scenario. The graph includes stages such as heatup, preoxidation, transient, and quenching. The x-axis represents time in seconds, ranging from 0 to 8000, and the y-axis represents temperature in Kelvin, ranging from 300 to 2100. The graph also shows power output with different markers and lines for each test.](image-url)
Comparison of bundle peak temperature evolution for QUENCH-06 (Zry-4), QUENCH-12 (E110), QUENCH-14 (M5) and QUENCH-15 (ZIRLO)

common characteristics: similar temperature escalation at the end of transient and similar cooling duration after reflood initiation
Axial distribution of cladding outer oxide thicknesses for the bundles QUENCH-06 (Zry4), QUENCH-12 (E110), QUENCH-14 (M5) and QUENCH-15 (ZIRLO)

- QUENCH-06 (Zry4)
- QUENCH-12 (E110)
- QUENCH-14 (M5)
- QUENCH-15 (ZIRLO)

Graph showing the axial distribution of cladding outer oxide thicknesses with bundle elevation and ZrO2 thickness as axes. The graph includes multiple lines representing different bundles, with a noted shift in the axial maximum.
Hydrogen uptake by ZIRLO cladding and different corner rods of QUENCH-15 bundle in comparison to M5 cladding of QUENCH-14. Corner rods were withdrawn from the bundle after the test.

![Graph](image)

- Q15 rod 24 (ZIRLO)
- Q14 rod 16 (M5)
- Q15 corner rod E110 (solid rod)
- Q15 corner rod E110 (tube / rod)
- Q15 corner rod Zry4 (tube / rod)

Hydrogen content in Zr, at%

Bundle elevation, mm

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QWS-16, Karlsruhe
Hydrogen production according to mass-spectrometer measurements

- **Q-06 (Zry-4)**
  - H₂ production before reflood (g): 32
  - H₂ production during reflood (g): 4

- **Q-14 (M5)**
  - H₂ production before reflood (g): 34
  - H₂ production during reflood (g): 6

- **Q-15 (ZIRLO)**
  - H₂ production before reflood (g): 41
  - H₂ production during reflood (g): 7

Increased H₂ production due to:
- Increased Q15 metallic surface
- Use of not prototypical corner rods

Peak hydrogen release from not prototypical E110 corner rods

Hydrogen production rate, g/s

Produced hydrogen, g

Time, s

J. Stuckert: QUENCH-14 (M5) and QUENCH-15 (ZIRLO)

QWS-16, Karlsruhe
QUENCH-14 bundle at elevations between 900 and 1000 mm (hottest zone): molten cladding metal between outer and inner oxide layers

rod #20 at elevation 900 mm
rod #11 at elevation 1000 mm
QUENCH-06 and QUENCH-14 at elevation 900 mm: cladding structure with partial oxidised metal melt, frozen between two oxide layers.

Q14, rod 20, 0°: homogeneous inner oxide layer.

Q06, rod 3, 0°: outer oxide, oxidised Zr-melt, epoxy resin.

Q14, rod 20, 90°: interrupt of inner oxide layer development.

Q06, rod 4, 0°: outer and inner oxides; oxidised Zr-melt.
QUENCH-14, elevation 1000 mm: structure of oxidised cladding of rod #11 with frozen and lost melt of metal layer

45°: transition from two oxide sub-layers to 1-phase oxide layer

90°: absence of cubic ZrO$_2$-x phase in oxide layer; melt relocated downwards

225°: transition from melt to completely oxidised cladding

270°: non homogeneous internal oxide layer
J. Stuckert: QUENCH-14 (M5) and QUENCH-15 (ZIRLO)

rod 3, 90°: outer and inner oxides; foamy Ta$_2$O$_5$-containing external layer from failed thermocouple

rod 7, 45°: outer oxide, local inner oxide from relocated melt

rod 12, 90°: void from downwards relocated melt

QUENCH-06: some fragments of cladding structures at elevation 1000 mm
QUENCH-06 and QUENCH-15 at elevation 1000 mm: cladding structure with partial oxidised metal melt, frozen between two oxide layers.

**QUENCH-15, rod #17**

- ext. ZrO₂
- int. ZrO₂
- melt
- pellet

**QUENCH-06, rod #13, 90°**

- foamy Ta₂O₅-containing external layer from failed thermocouple
- outer ZrO₂
- inner ZrO₂
- melt
- pellet
QUENCH-14, elevations 950 and 1100 mm: no interaction between cladding metal and ZrO$_2$ pellet

- rod #3 at elevation 1100 mm: solid cladding position
- rod #13 at elevation 950 mm
- ZrO$_2$ pellet
- no indications of oxygen diffusion outside pellet (no contact with cladding, absence of $\alpha$-Zr(O) precipitates at pellet grain boundaries)

Reason of inner oxide layer development is penetration of steam under cladding through the cladding ruptures at different elevations.

Mostly it is not the interaction between cladding and pellet.
QUENCH-14 at 900 mm: map of outer and inner oxide layer thicknesses

Thicknesses of inner oxide layer between 75 and 260 µm
QUENCH-14 at 1000 mm:
map of outer and inner oxide layer thicknesses

Thicknesses of inner oxide layer between 50 and 200 µm
SUMMARY

• The QUENCH-14 (M5) and QUENCH-15 (ZIRLO) experiments investigated the influence of different cladding materials and bundle geometry on bundle oxidation and core reflood, in comparison with test QUENCH-06 (Zircaloy-4).

• After pre-oxidation phase, which lasted ~3000 s, the electric power was ramped during ~1150 s to reach desired maximum bundle temperature of ~1800°C. Following fast water injection the reflood with ~1.3 g/s/(eff.rod) water was initiated, and the electrical power was reduced to decay heat level. The cooling duration of 300 s was measured for all three bundles.

• Two Zircaloy-4 corner rods withdrawn during the tests showed the following peak ZrO₂ thickness for QUENCH-14 / -15: 180 / 150 µm on the end of the pre-oxidation phase, 360 / 380 µm before reflood. The E110 corner rods extracted after the tests evident intensive breakaway effect.

• Average post-test oxide layer thickness at elevation 950 mm for QUENCH-14 / -15: 840 / 630 µm. These values correspond to 74 / 70% metal converted to ZrO₂.
SUMMARY (Cont.)

• Measured hydrogen production during the QUENCH-14 /-15 tests were \(34 / 41\) g in the pre-oxidation and transient phases and \(6 / 7\) g in the quench phase (in QUENCH-06: 32 g and 4 g, respectively). Reasons of higher hydrogen production for QUENCH-15 were increased bundle surface and usage of not prototypical corner rods.

• Post-test investigations of bundles QUENCH-06, -14 and -15 reveals significant cladding inner oxide layers with thickness up to 20% of outer oxide layers. This inner oxide layers were developed mostly due to penetration of steam through cladding cracks and are noticeable factor for hydrogen generation.

• The partially oxidised cladding melt was catch between outer and inner oxide layers for all three tests QUENCH-06, -14 and -15.

• Bundle tests QUENCH-06, -14 and -15 showed comparable behaviour of Zircaloy-4, M5® and ZIRLO™ materials during reflood.
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**Thank you for your attention**

http://quench.forschung.kit.edu/