Results of the QUENCH-DEBRIS bundle test

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Objectives

• investigation of debris bed formation for bundle with completely oxidised Zry-4 claddings filled with segmented pellet simulators

• investigation of cooling of degraded bundle during the water reflood from bottom
Quench single rod test with completely oxidized cladding filled with segmented pellets.
Oxidation at 1773 K during 11600 s, quench with water 80 g/h

sample inside inductive furnace during quench

ZrO₂ powder reacted with clad metal

oxide

pellet segment

sample was destroyed during handling
Zry cladding filled with ZrO$_2$ pellet segments and ZrO$_2$ powder

12 heated rods with Hf cladding

9 unheated rods with Zry-4 cladding

Hf shroud
Two features of unheated test rods

load 100 – 1000 N

check of through going oxidation
Bundle composition

positions of grid spacers

top of corner rod C (1300 mm)

positions of upper W/Re thermocouples

TFS 17/17 (1350 mm)
TFS 16/16 (1250 mm)
TFS 15/15 (1150 mm)
TFS 14/14 (1050 mm)
Bundle elements at bundle bottom

- Bottom of six Zry-4 rods: -420 mm
- Bottom of Zry-4 rods #4, 6, 8: -590 mm
- Zr-wires of indicator rods #4, 6, 8
- Fastening of NiCrNi thermocouple

bundle bottom

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Post-test: overview of mostly intact Hf-shroud (only several cracks) after dismounting of heat insulation
Test scenario: el. power and TC readings at different elevations

1) pre-oxidation stage with 2 g/s steam and 2 g/s Ar. Complete oxidation of Zry-4 clads between 650 and 1150 mm

2) Test termination: reflood from bottom with water flow rate 10 g/s.
Failures of Zry claddings and Hf shroud

1st failure of Zry cladding: 5235 s

shroud failure: 25245 s

no failure of Hf claddings was registered

FM 406: Ar through shroud damage

MS: He (Zry claddings)

MS: Kr (Hf claddings)
Integral criterion of bundle oxidation progression: hydrogen release during oxidation of Zry and Hf parts

the course of the experiment closely followed the pre-test prediction
Indication of complete oxidation at 650 mm by el. resistance measurement

3 welded joints:
  R1 at 550 mm for rod #8,
  R2 at 650 mm for rod #2,
  R3 at 650 mm for rod #4

Resistance decrease during annealing

Complete oxidation at 650 mm
Indication of debris relocation to GS#2
(reaction of thermocouples TGS installed at the top of GS#2)

Temperature, K

Time, s

TC (TGS)
Reflood simulation with pellet debris inside 21-rod-bundle. Cold water flow rate 10 g/s

δt=27 s: v = 5 mm/s

δt=28 s: v = 3 mm/s
Quench phase:
collapse water level and TC wetting

TC wetting at high elevation by 2-phase fluid
Quench phase: water level oscillations and evaporation rate

- Mass spectrometer: steam
- L 501 gauge: water level

Debris

Quench water at bundle inlet

Stagnant evaporation rate: region of debris bed
Quench phase: measured and calculated water level

- Calculated water level
- Measured by L501

Averaged good agreement between pre-calculated and measured results, but no prediction for water level oscillations.

Filling of annulus between cracked shroud and cooling jacket.

Water level oscillations inside debris bed.
Withdrawn grid spacer #4 (1350 -1390 mm) and remnant of cladding

remnant of rod #8: significantly oxidised

GS #4: completely oxidised
Structure of oxidized Zry cladding remnant at 1328 mm, $T \approx 1000$ K

-$\alpha$-Zr(O)
- prior $\beta$-Zr
- thick inner oxide layer (breakaway)
- gap
- upper not segmented pellet
- thin outer ZrO$_2$ (starvation, spalling?)

Temperature, K
Time, s
Top view of grid spacer #3 (1090 mm)

pellet segments between heated rods

completely oxidised GS #3

cladding filled with pellet segments

empty cladding
Endoscope observation of debris relocated under GS #3

- Sintered pellets at 950 mm
- Pellet segments at 920 mm between Zry and Hf claddings
- Blockage at elevation 910 mm
Debris collected at the top of grid spacer #3 (1090 mm)
Structure of claddings at elevations 1050 mm

- completely oxidized Zry cladding (segment of tube debris)

- partially oxidized Hf cladding (deleted segment of cladding)
### Structure of Zry claddings between 450 and 750 mm

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Composition</th>
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<tbody>
<tr>
<td>450 mm</td>
<td>outer ZrO$_2$ 75 µm, inner ZrO$_2$ 25 µm, $\alpha$-Zr(O) 70 µm (outer and inner), prior $\beta$-Zr rest</td>
</tr>
<tr>
<td>550 mm</td>
<td>outer ZrO$_2$ 250 µm, inner ZrO$_2$ 75 µm, $\alpha$-Zr(O) rest</td>
</tr>
<tr>
<td>650 mm</td>
<td>completely oxidised</td>
</tr>
<tr>
<td>750 mm</td>
<td>completely oxidised</td>
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The QUENCH-17 bundle test with 9 unheated internal rods (Zry-4 claddings) and 12 heated external rods (Hf claddings) was performed in two stages: 1) long pre-oxidation stage (78000 s) at T_pct=1750 K with complete oxidation of Zry-4 claddings between about 650 and 1150 mm, maximum oxidation of Hf claddings about 30%; 2) reflood stage with slow flooding from bottom (10 g/s, or about 3 mm/s through the debris bed).

Hf claddings of heated rods were intact during whole test, Hf shroud was failed at 850 mm after 25000 s. First failure of Zry-4 cladding was registered at 5500 s. Noticeable internal oxidation was observed at upper bundle elevations.

Mechanical impact on the end of pre-oxidation caused debris relocation to grid spacers at 1050 mm and 350 mm. Some Zry-4 claddings were not significantly damaged; the pellet segments relocated from the failed rods were captured between corresponding neighbour rods. Ceramics debris collected at the top of grid spacers consist of separate pellet segments and relatively large cladding segments.

The porosity of debris bed is significant, no dense packing of debris particles was observed. Large empty volumes formed due to bending of rods. The maximum bundle blockage was about 85%.

Steam production rate was stagnated during propagation of flooding water through the debris collected above grid spacers at 350 mm.

Despite additional gas flow from breaches in the shroud and unheated rods, the course of the experiment closely followed the pre-test prediction, indicating that those events did not impact the test conduct.

Impact of debris bed on reflooding remains open question. Detailed analysis of the reflood is planned in the near future to examine the latter question.

Summary
Acknowledgment

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**Thank you for your attention**

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