Update on the Halden work on coatings
Performance of CrN coated claddings
PIE results of the first in-core test on coated fuel rods

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NEA- 5th EGATFL meeting, 12-14 April 2016, Boulogne-Billancourt, Paris
IFA-774: Description of experiment

- First experiment with coated fuel rods
- PWR conditions at 320 °C (144 days)
- Three rods with coating: TiAlN, CrN, AlCrN (PVD)
- One reference rod
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Fuel rod characteristics

Double cladding: In view to ease PIE examination of the coated cladding

- Outer, coated cladding (Zr-4): 9.5/8.36 mm
- Inner cladding, not coated (Inconel 600): 8 / 7 mm
- Pellet outer diameter: 6.83 mm
- Fuel rod enrichment: 5%
- Fill gas: He
- Designed to reach a linear heat rate of 20 kW/m
## Matrix

<table>
<thead>
<tr>
<th>Cladding nr</th>
<th>Marking (at one of the cladding)</th>
<th>Coating type</th>
<th>Coating thickness of original coating (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 mark</td>
<td>No coating</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2 marks</td>
<td>TiAlN</td>
<td>2.6</td>
</tr>
<tr>
<td>3</td>
<td>3 marks</td>
<td>CrN</td>
<td>2.1</td>
</tr>
<tr>
<td>4</td>
<td>4 marks</td>
<td>AlCrN</td>
<td>3.7</td>
</tr>
</tbody>
</table>
Installed in rig, before irradiation

1. No coating
2. TiAlN
3. CrN
4. AlCrN
Irradiation history

144 FPD (69+29+47)
BU = 6.5 MWd/kgUO2
Fast fluence: 1.8 E20 n/cm^2

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After irradiation

1. No coating
2. TiAlN
3. CrN
4. AlCrN

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Bending of downcomer tubes towards fuel rods

increased temperature of cladding

«Accident conditions» over 144 days!

CrN rod
Look into SEM analysis on un-coated Zircaloy-4 cladding in order to find an indication of insufficient cooling

IFA-774 Tube 1 Zircaloy-4 (reference, no coating)

General observations:

- The oxide has high porosity/circumferential cracks that locally create oxide layers
- Porosity/cracks were observed both close to the cladding and throughout the oxide thickness
- Oxide spallation/delamination has occurred at several locations

Porosity/cracks in the oxide and delamination/spallation are more severe than expected for low burnup PWR conditions.

Porosity/cracks in the oxide and delamination/spallation were observed in specimens taken from 30mm and 60mm from the lower end of the fuelled region however the presence is higher in the 60mm specimen i.e. in the middle of the fuelled segment. The top of the fuelled segment and the plenum segment have not yet been examined.

These features could be an effect of higher temperature of the cladding.
Oxide thickness:
About 5.5 µm

SEM backscattered mode – IFA-774, Zry-4, 60mm –
High porosity/circumferential cracks divide the oxide into several layers.
From visual inspection, the CrN seemed to survive

Note: Due to bending of downcomer tubes, the temperature of the rods increased substantially
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Visual inspection of CrN coated Zr-4 tube from IFA-774 – 0 degree

Visual inspection of CrN coated Zr-4 tube from IFA-774 – 180 degree
CrN coated Zr-4 tube from IFA-774 before irradiation at 30mm

CrN coated Zr-4 tube from IFA-774 after irradiation at 30mm
CrN coated Zr-4 tube from IFA-774 before irradiation at 30mm

CrN coated Zr-4 tube from IFA-774 after irradiation at 30mm

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CrN coated Zr-4 tube from IFA-774 - After irradiation at 30mm Oxide under coating
SEM analysis performed on the CrN coated cladding

Approximately 20% of circumference is damaged coating and/or contain oxide under coating.

Coating area: 109 μm²
Coating length: 57 μm
Average thickness: 1.9 μm
SEM analysis of TiAlN coated rod

Coating disappeared.
Optical investigation AlCrN coated rod

Coating disappeared.
Testing in steam (+ air) up to 1000 °C

Log system

Sample holder + thermocouples

Steam generator

Pump

Distilled water

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Some results (for Zr-2 substrate):

- 750 °C, 60 minutes: CrN coating survives
- 1000 °C, 15 minutes: CrN coating survives
- In the presence of cracks, oxide starts forming and can grow under the coating, pushing the coating outwards

Example:
750°C, 60 minutes
With machined scratch
Planned test IFA-796 (PWR) in the Halden reactor (Joint Halden Program)

<table>
<thead>
<tr>
<th>Segment</th>
<th>CEA</th>
<th>KAERI</th>
<th>IFE</th>
<th>ORNL</th>
<th>EPRI</th>
<th>REF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rod 1</td>
<td>Rod 2</td>
<td>Rod 3</td>
<td>Rod 4</td>
<td>Rod 5</td>
<td>Rod 6</td>
</tr>
<tr>
<td>Top*</td>
<td>~5 μm Cr</td>
<td>~80 μm Cr</td>
<td>CrN</td>
<td></td>
<td>Mo-LCAC FeCrAl</td>
<td>Zry-4</td>
</tr>
<tr>
<td>Top-mid</td>
<td>~15 μm Cr</td>
<td>ODS</td>
<td>FeCrAl-2</td>
<td>FeCrAl-1</td>
<td>Mo-LCAC Zry</td>
<td>Zry-4</td>
</tr>
<tr>
<td>Bot-mid</td>
<td>~5 μm Cr</td>
<td>~80 μm Cr</td>
<td>CrN</td>
<td></td>
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Planned irradiation duration: 4-5 years
Expected loading: Autumn 2016
Conclusions

- TiAlN and AlCrN coatings disappeared
- CrN coating chemically stable (BRW and PWR)
- No reduction in coating thickness
- Despite «accident like» conditions, most of the coating still intact after 144 days
- When a crack occurs, oxide forms underneath and the expansion leads to further cracking