



Update on the Halden work on coatings

Performance of CrN coated claddings

PIE results of the first in-core test on coated fuel rods

Dr. Rudi Van Nieuwenhove

Head of Research and Development Department

Sector Nuclear Technology, Physics and Safety

Institutt for Energiteknikk (IFE)

Halden Reactor Project (HRP)

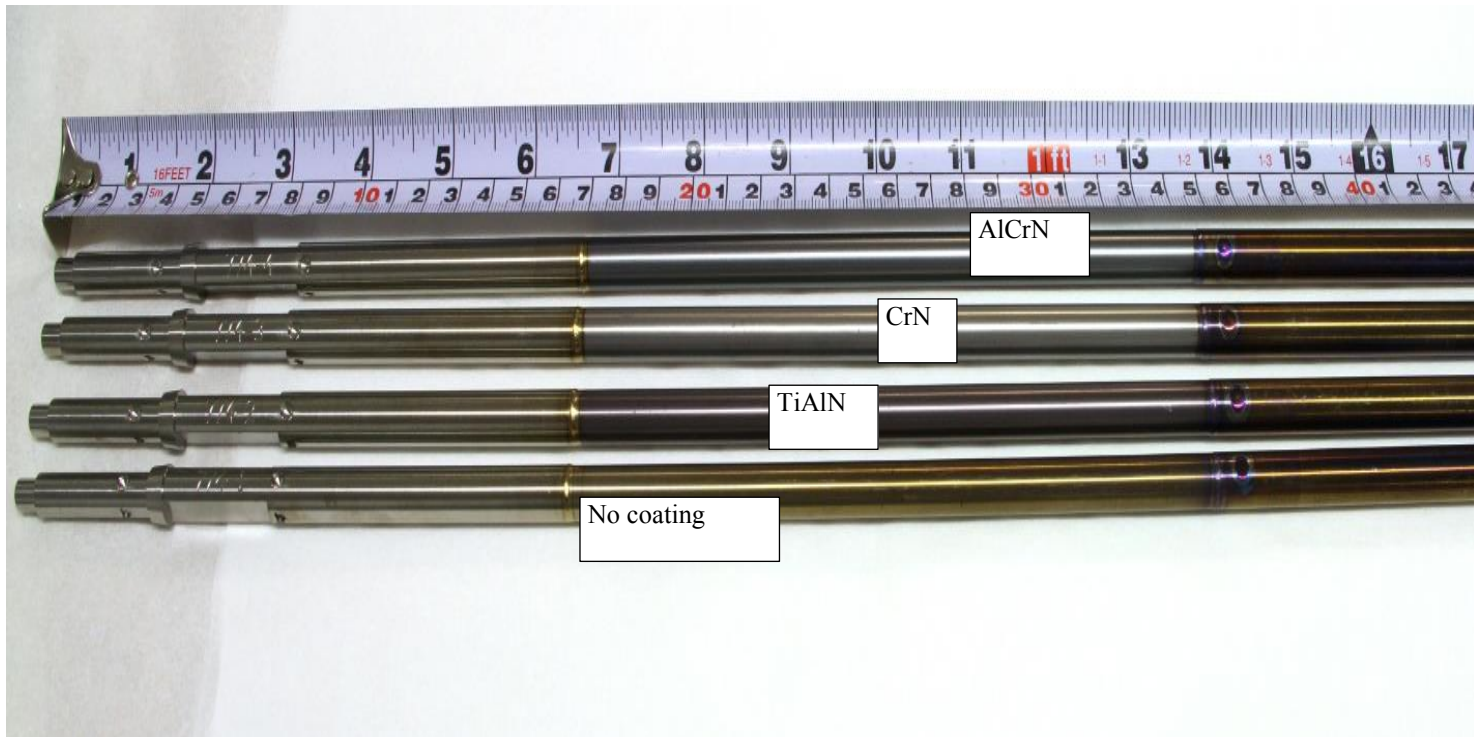
Email: rudivn@ife.no

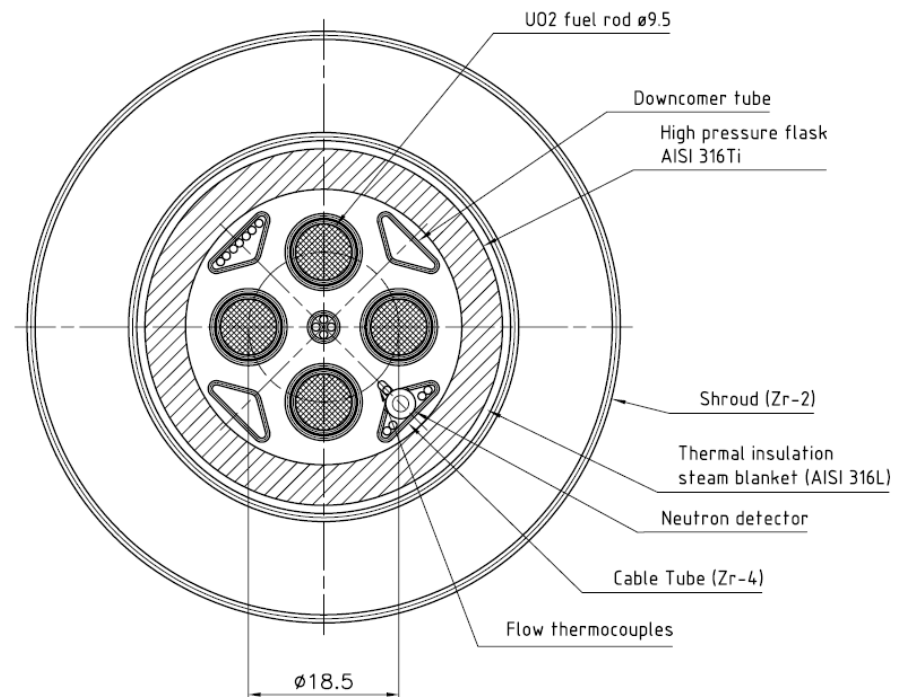
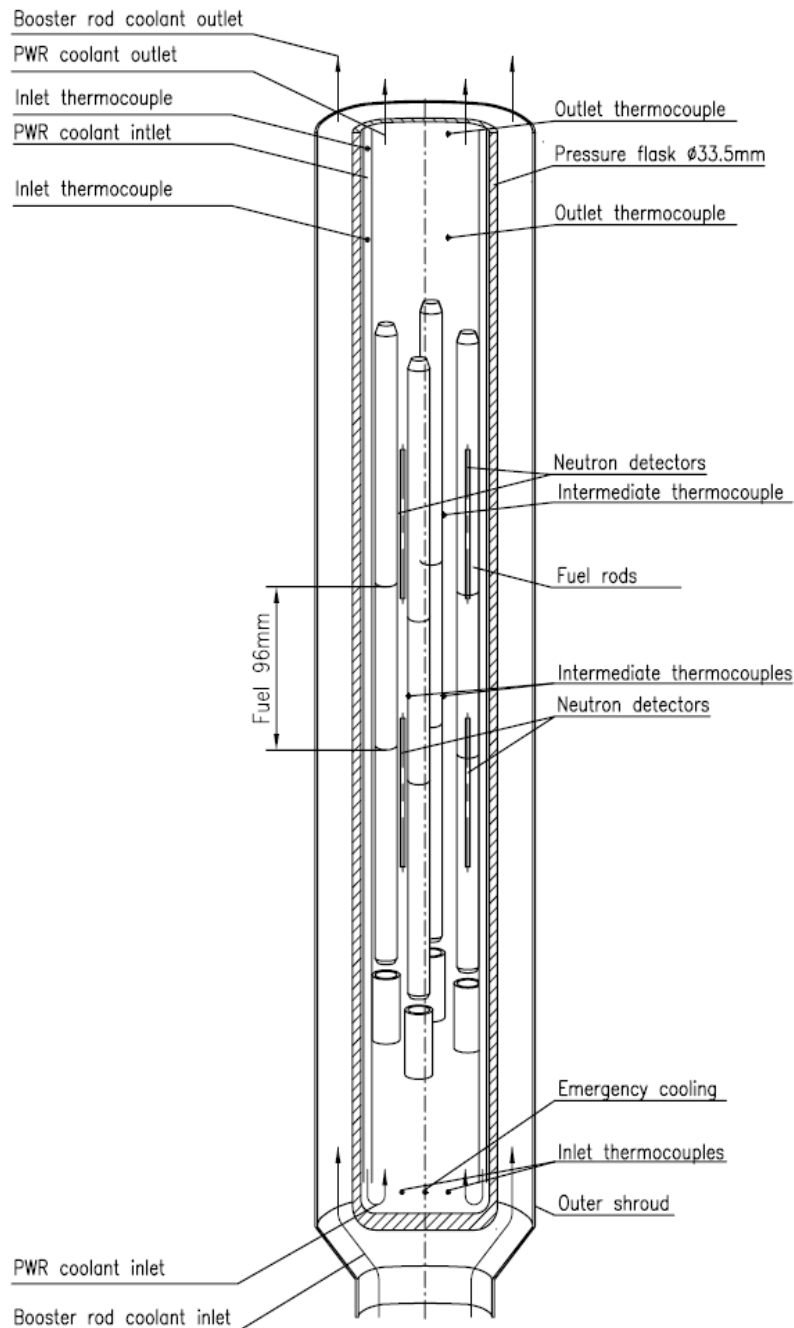
NEA- 5th EGATFL meeting, 12-14 April 2016 ,
Boulogne-Billancourt, Paris



IFA-774: Description of experiment

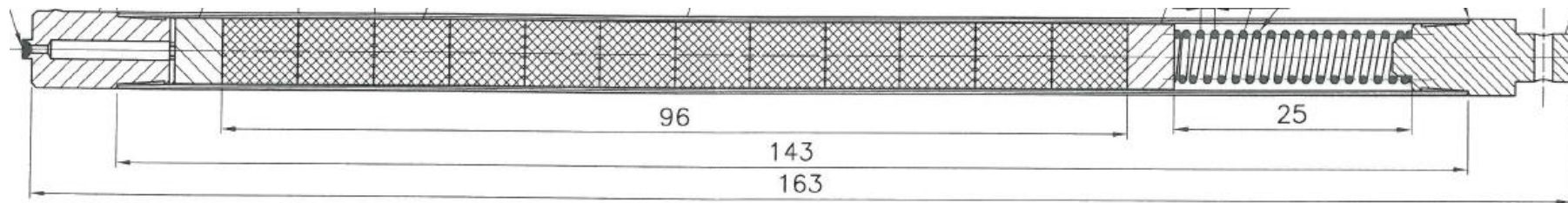
- First experiment with coated fuel rods
- PWR conditions at 320 °C (144 days)
- Three rods with of coating: TiAlN, CrN, AlCrN (PVD)
- One reference rod







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

Cladding nr	Marking (at one of the cladding)	Coating type	Coating thickness of original coating (μm)
1	1 mark	No coating	0
2	2 marks	TiAlN	2.6
3	3 marks	CrN	2.1
4	4 marks	AlCrN	3.7



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/cm²





After irradiation



1. No coating

2. TiAlN

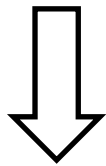
3. CrN

4. AlCrN

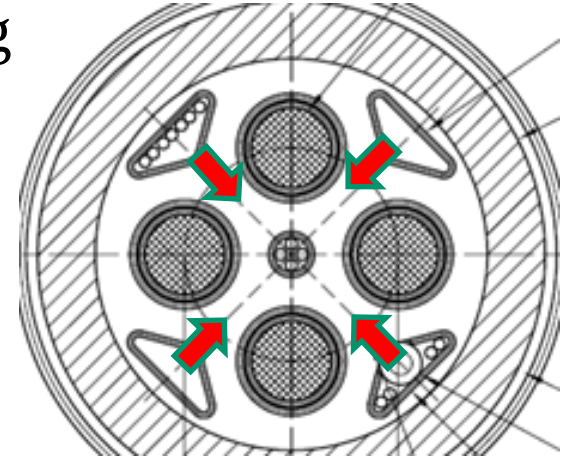


Bending of downcomer tubes towards fuel rods

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)

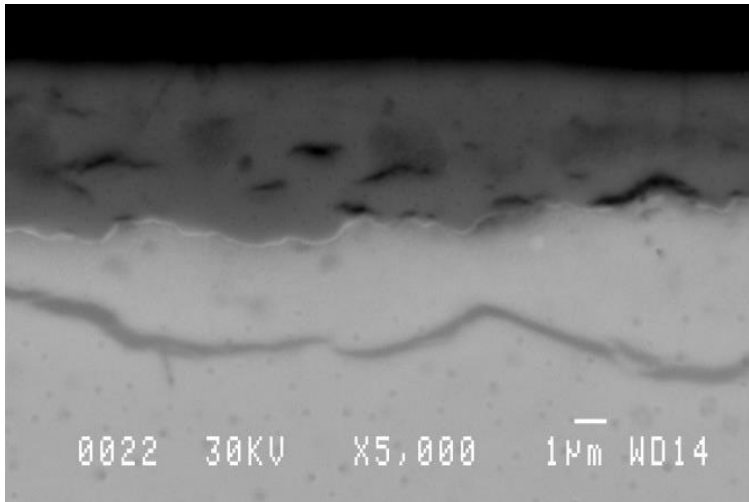
General observations:

- 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.

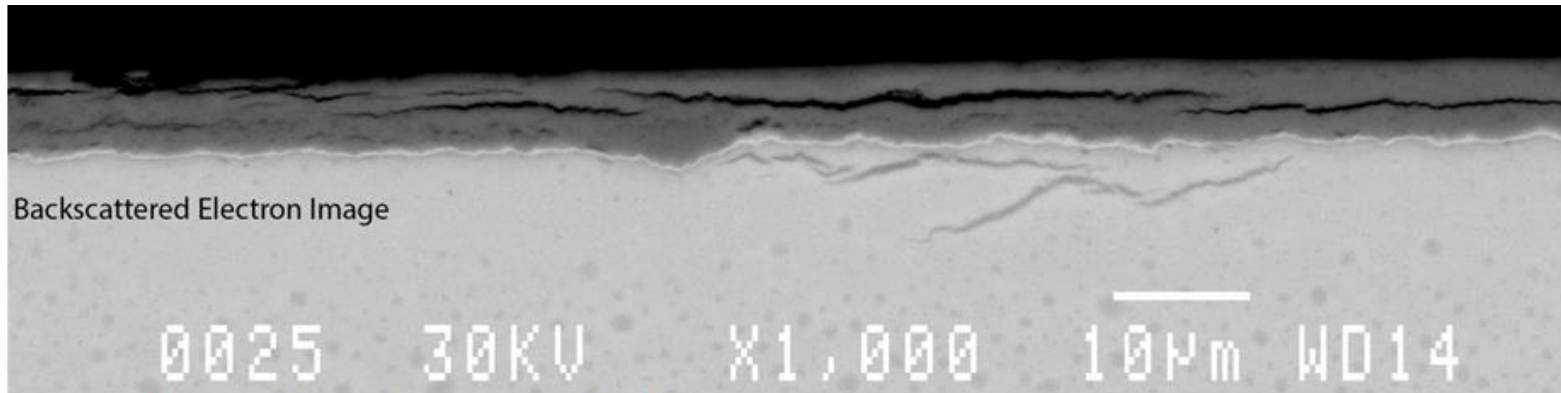
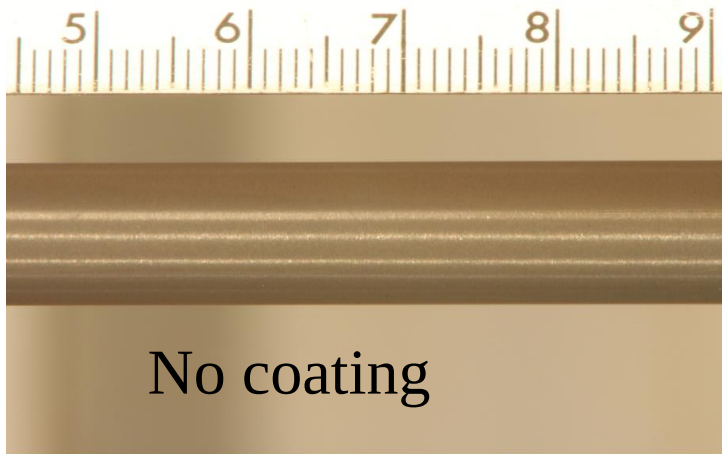


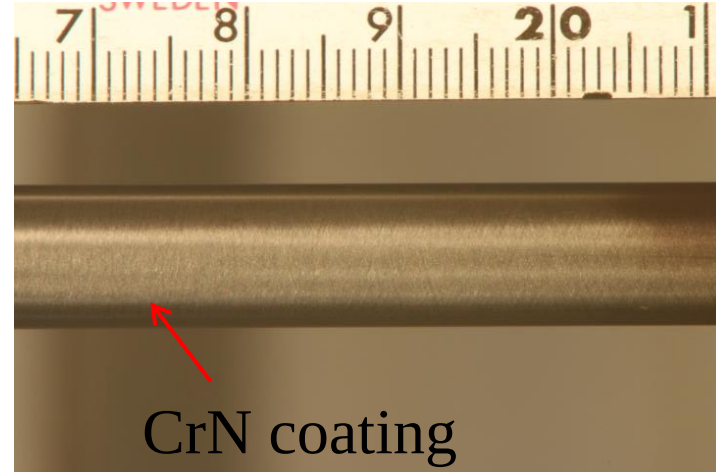
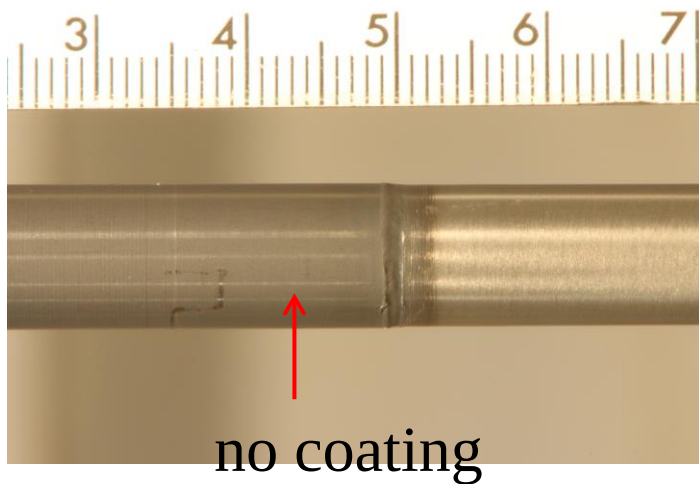
Fig. 2 SEM SEI + BEI – IFA-774, Zry-4, 60mm – Zirconia delamination

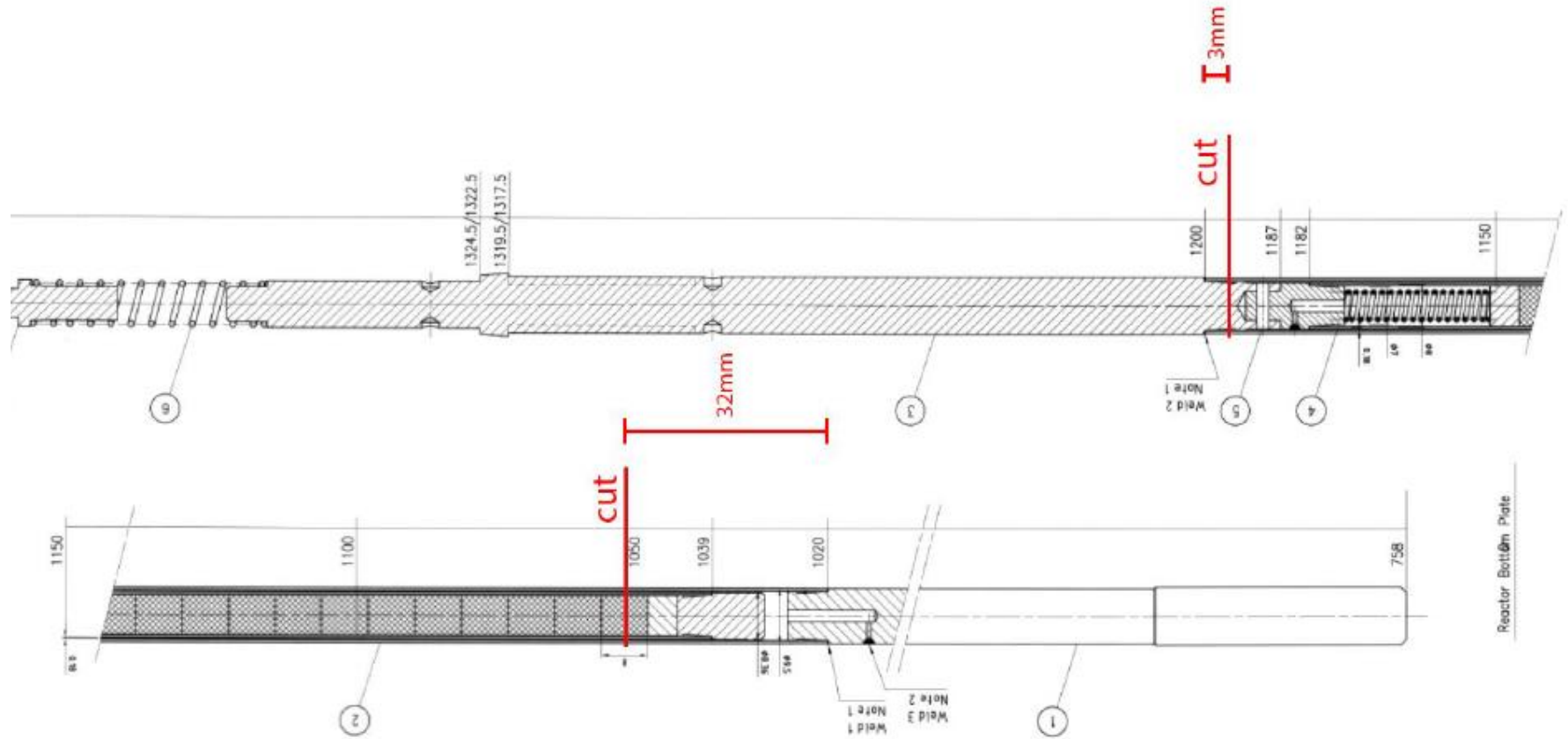


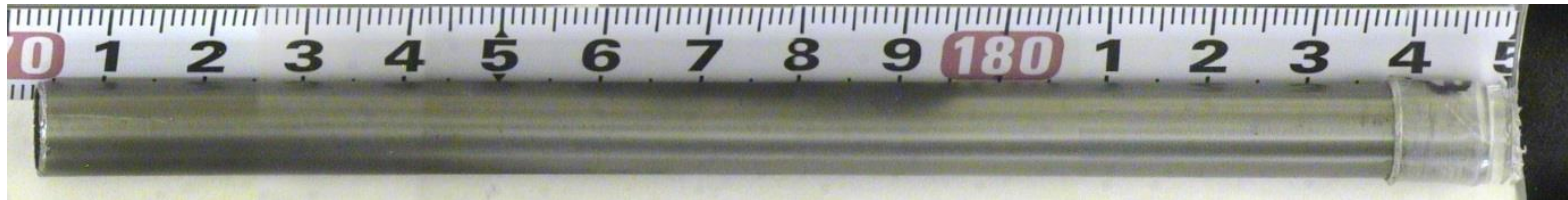
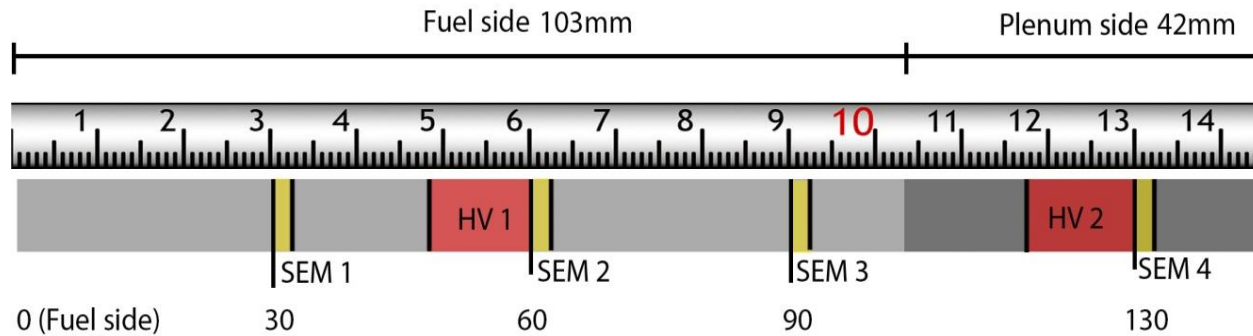
From visual inspection, the CrN seemed to survive



Note: Due to bending of downcomer tubes, the temperature of the rods increased substantially



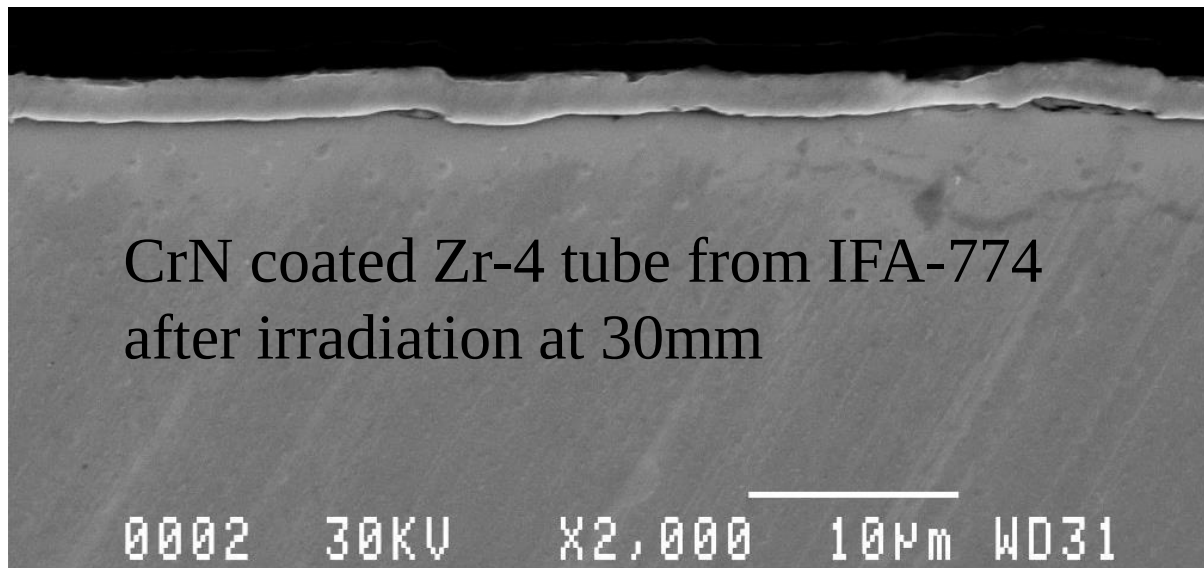
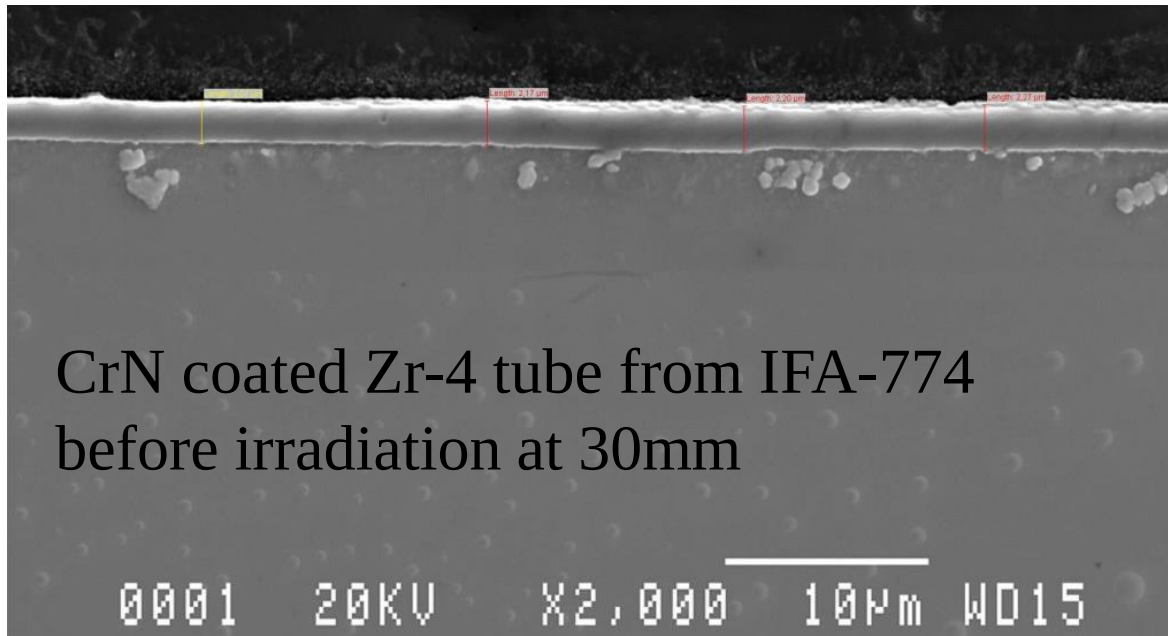


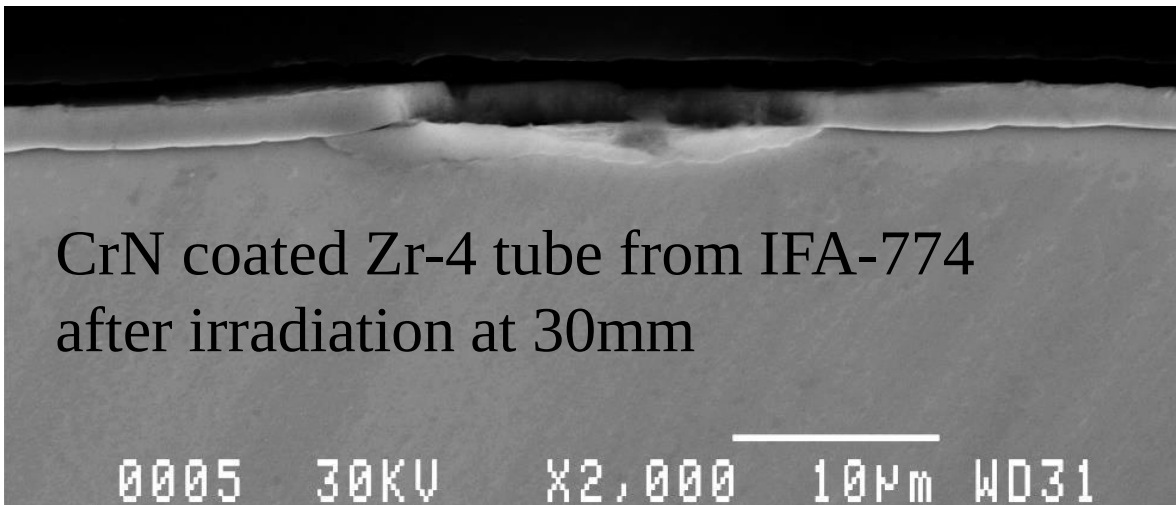
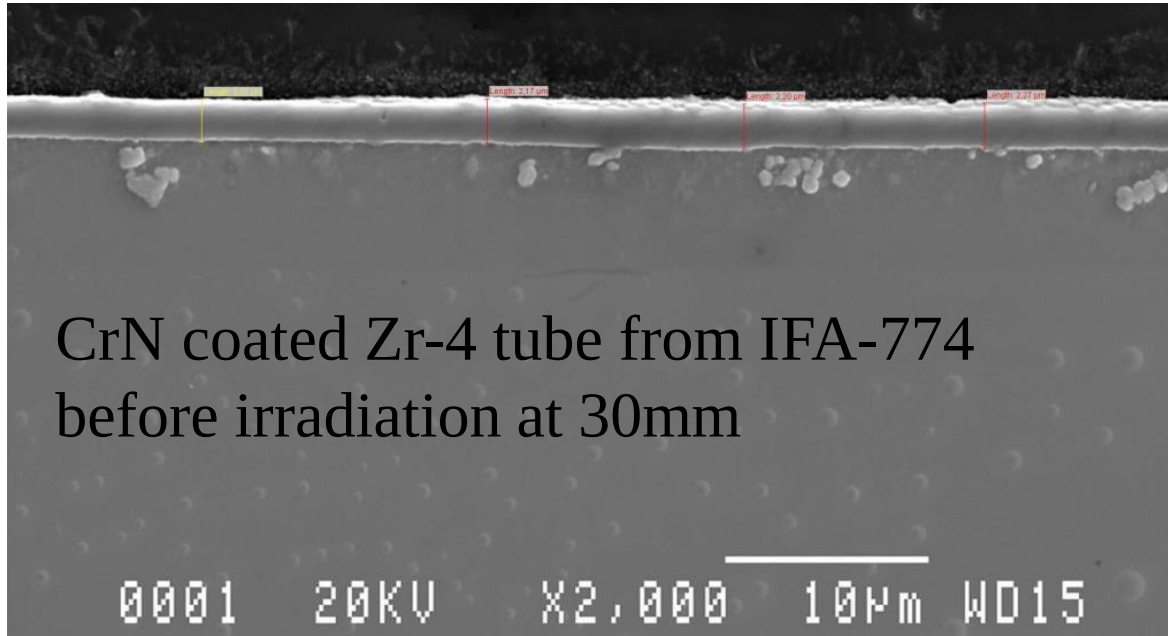


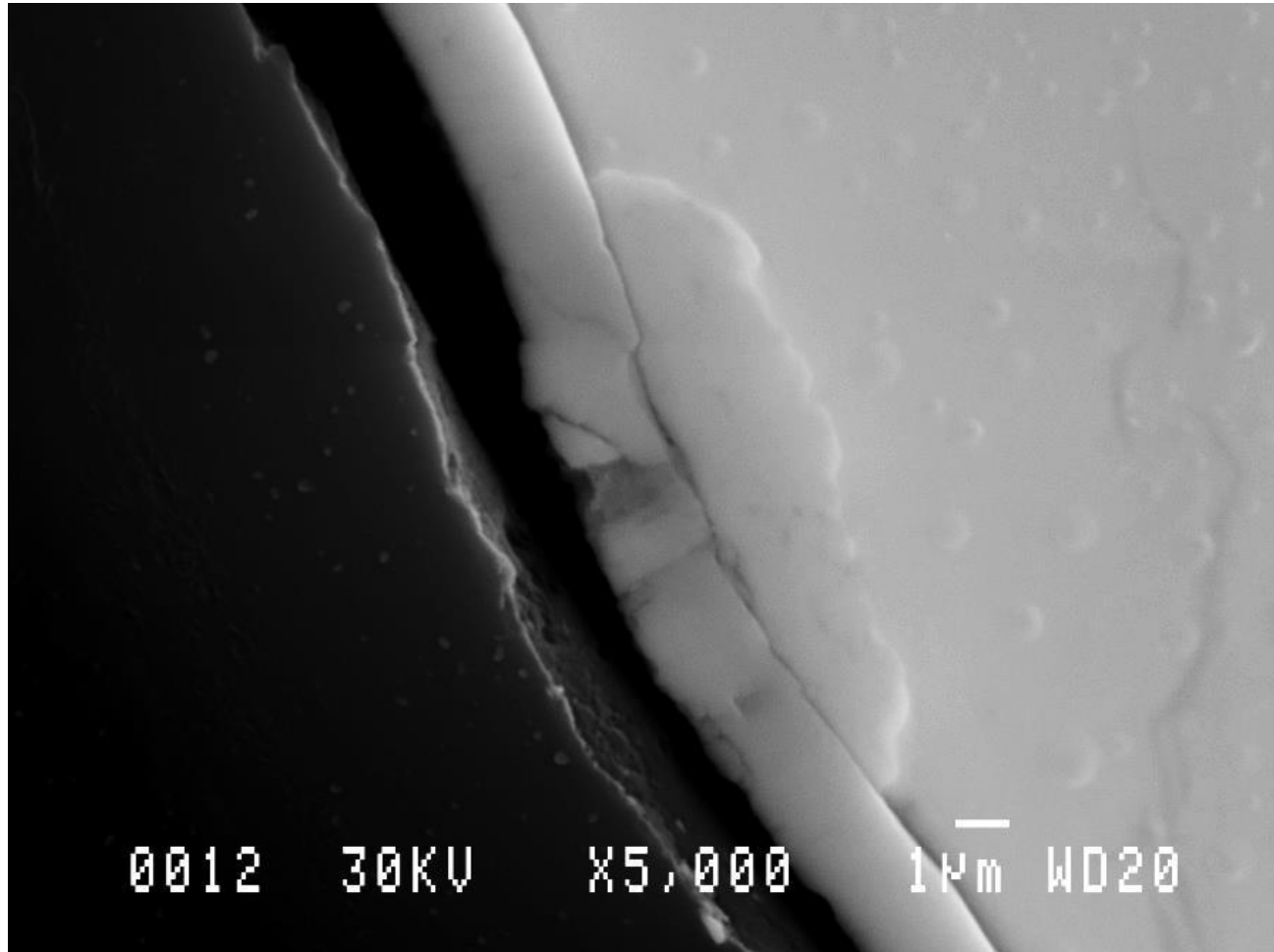
Visual inspection of CrN coated Zr-4 tube from IFA-774 – 0 degree



Visual inspection of CrN coated Zr-4 tube from IFA-774 – 180 degree



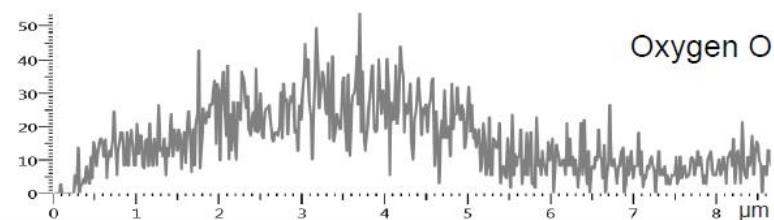
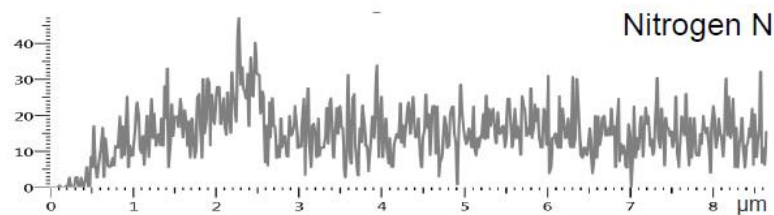
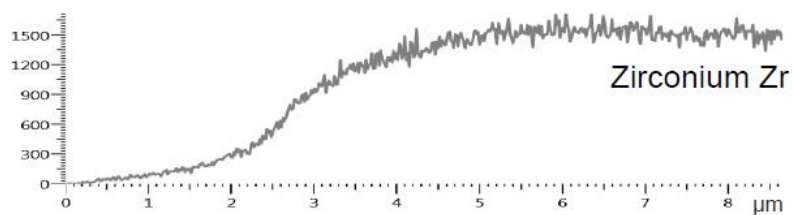
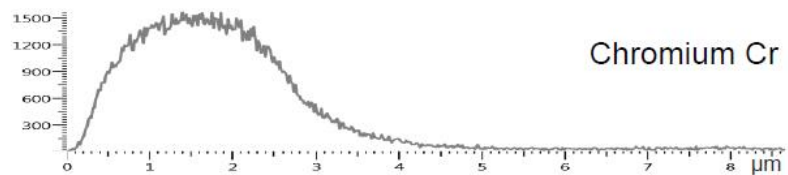
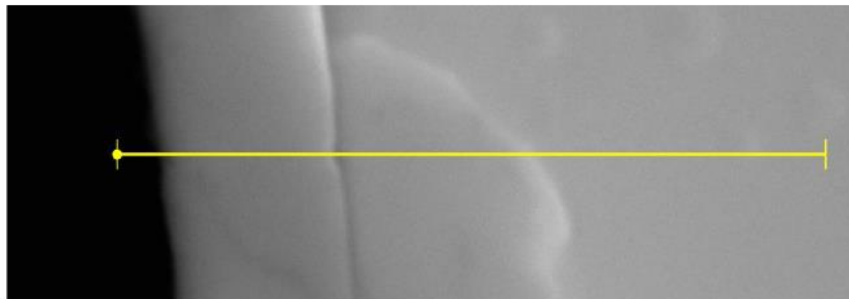




CrN coated Zr-4 tube from IFA-774 - After irradiation at 30mm Oxide under coating

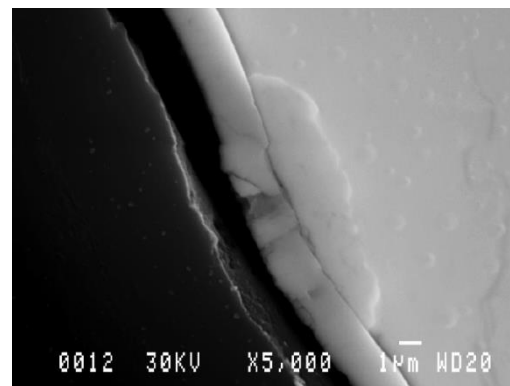
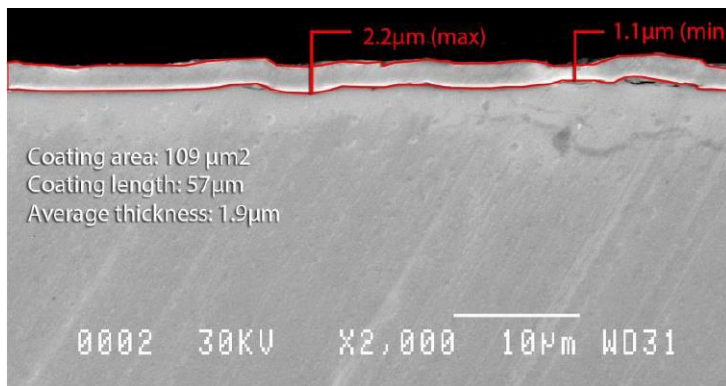
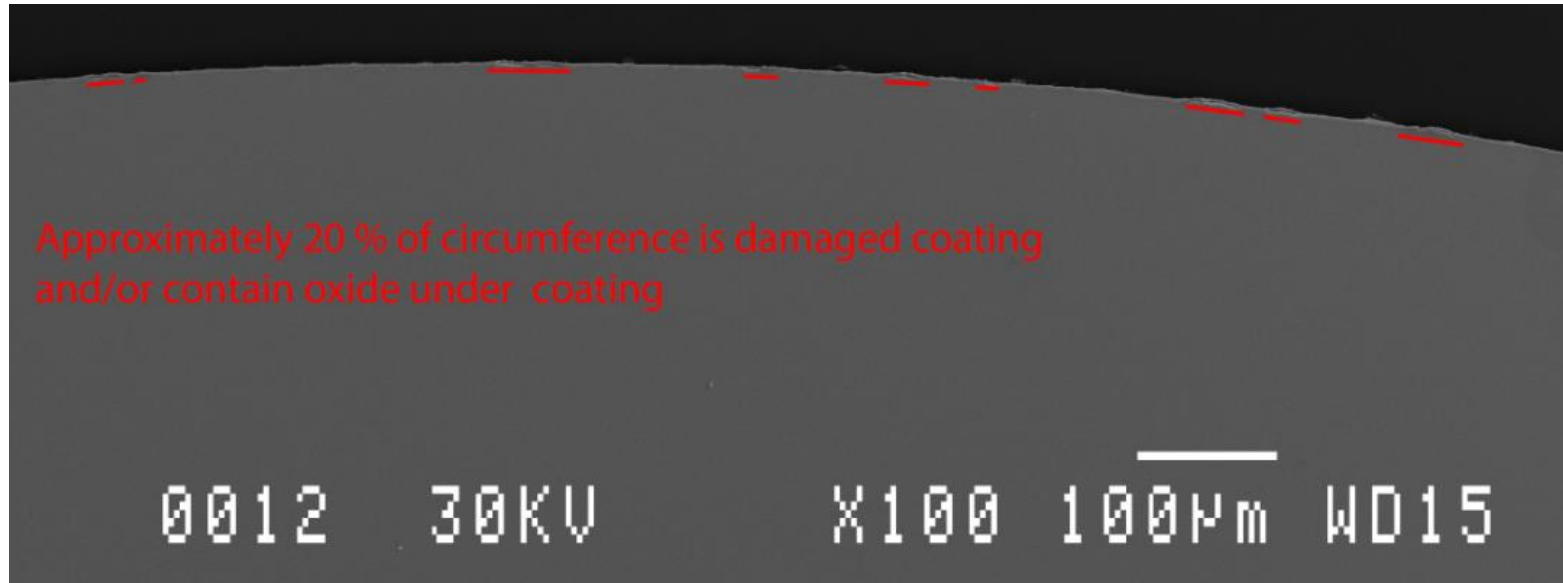


Line scan





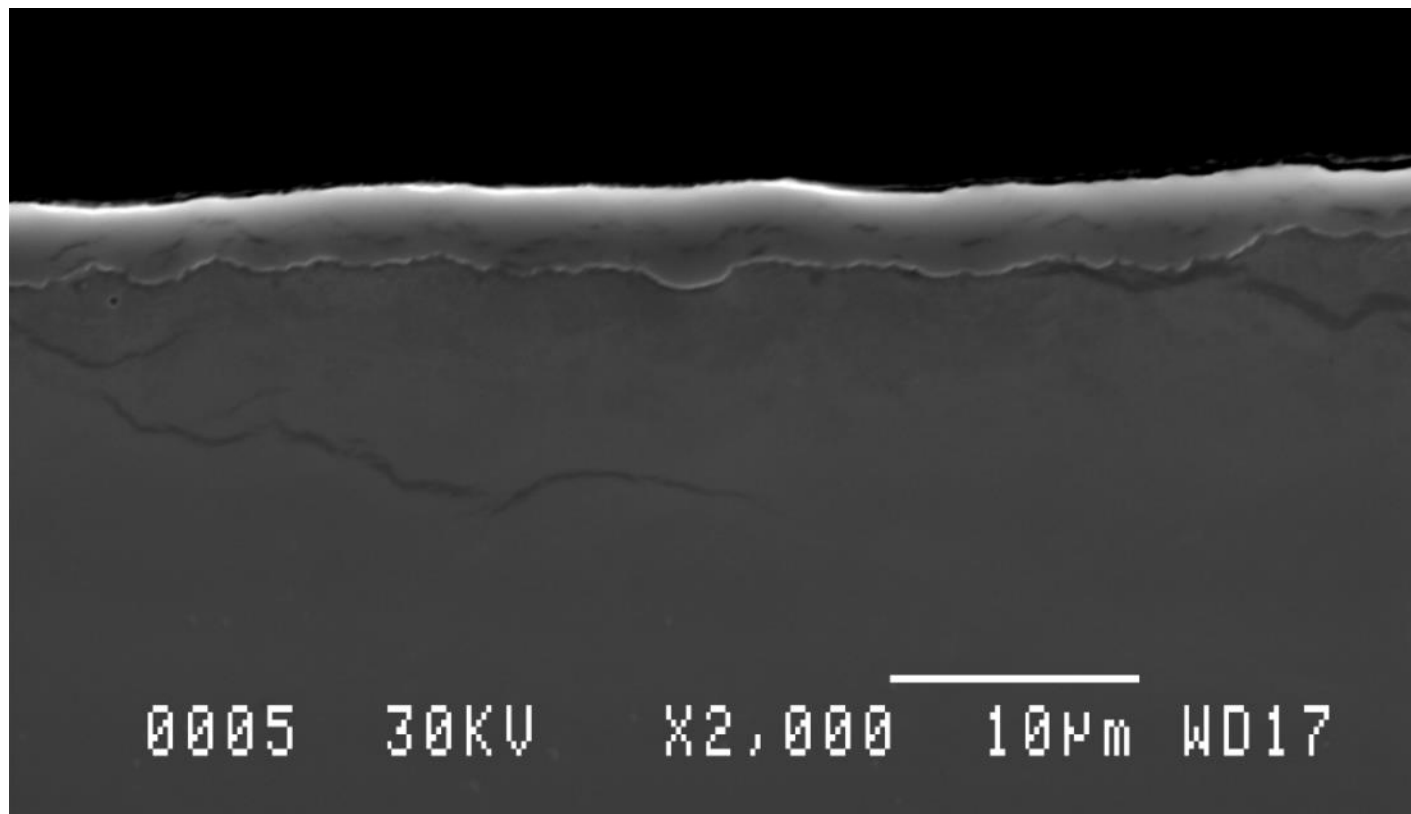
SEM analysis performed on the CrN coated cladding





SEM analysis of TiAlN coated rod

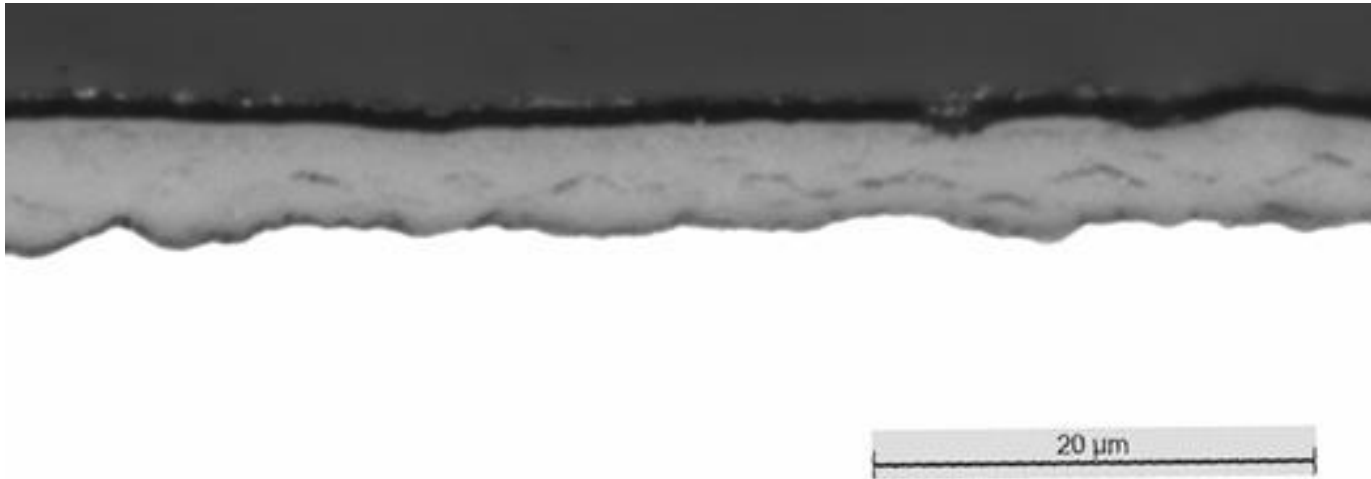
Coating disappeared.





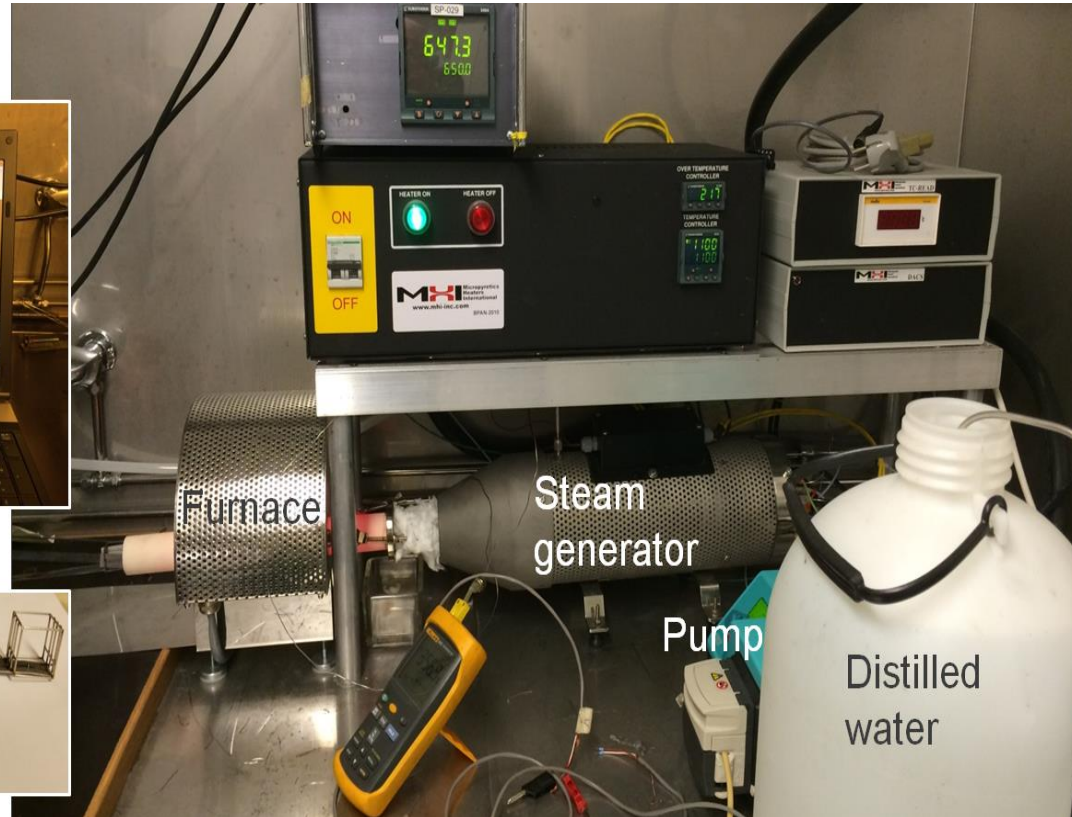
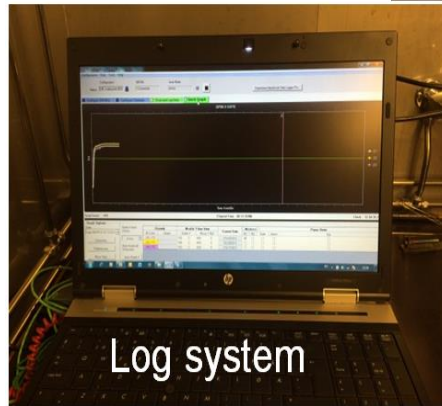
Optical investigation AlCrN coated rod

Coating disappeared.





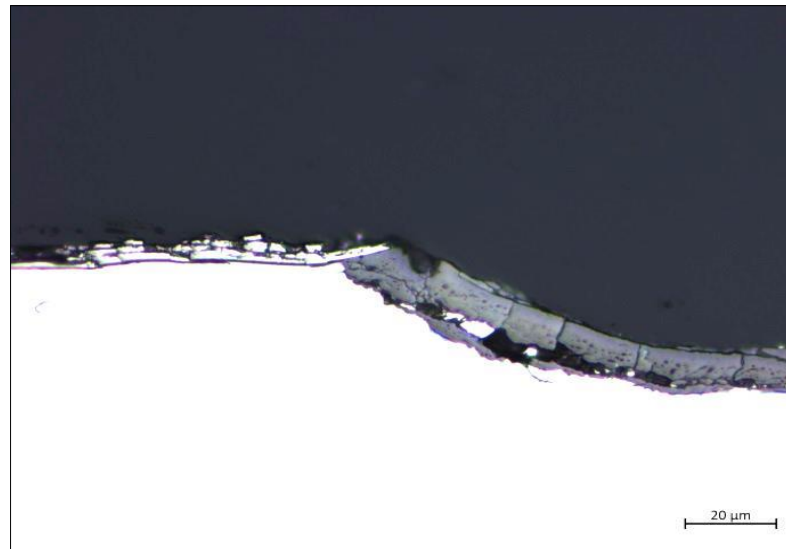
Testing in steam (+ air) up to 1000 °C



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)

Segment	CEA	KAERI	IFE	ORNL	EPRI	REF
	Rod 1	Rod 2	Rod 3	Rod 4	Rod 5	Rod 6
Top*	~5 μm Cr	~80 μm Cr	CrN	FeCrAl-1	Mo-LCAC FeCrAl	Zry-4
Top-mid	~15 μm Cr	ODS	FeCrAl-2		Mo-LCAC Zry	Zry-4
Bot-mid	~5 μm Cr	~80 μm Cr	CrN		Mo-ODS FeCrAl	Zry-4
Bottom*	~15 μm Cr	ODS	FeCrAl-2		Mo-ODS Zry	Zry-4

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