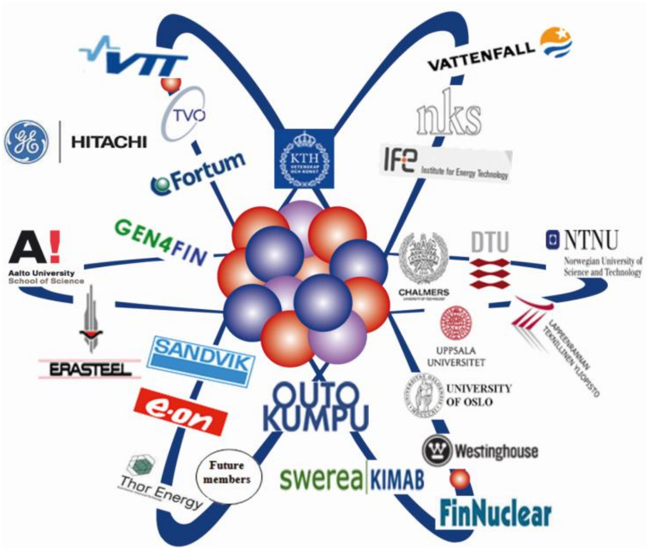
Investigation of coatings for Generation IV reactors



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1. Investigation of coatings for GenIV

- Structural reactor components, as well as fuel are prone to degradation due to corrosion or hydrogen embrittlement
- Problems expected to be enhanced for GenIV type of reactors, operating at higher temperatures
- One possible way to reduce corrosion is to make use of coatings
- However, coatings and plasma treatments could also be useful to reduce corrosion in present-day reactors

Introduction - continued

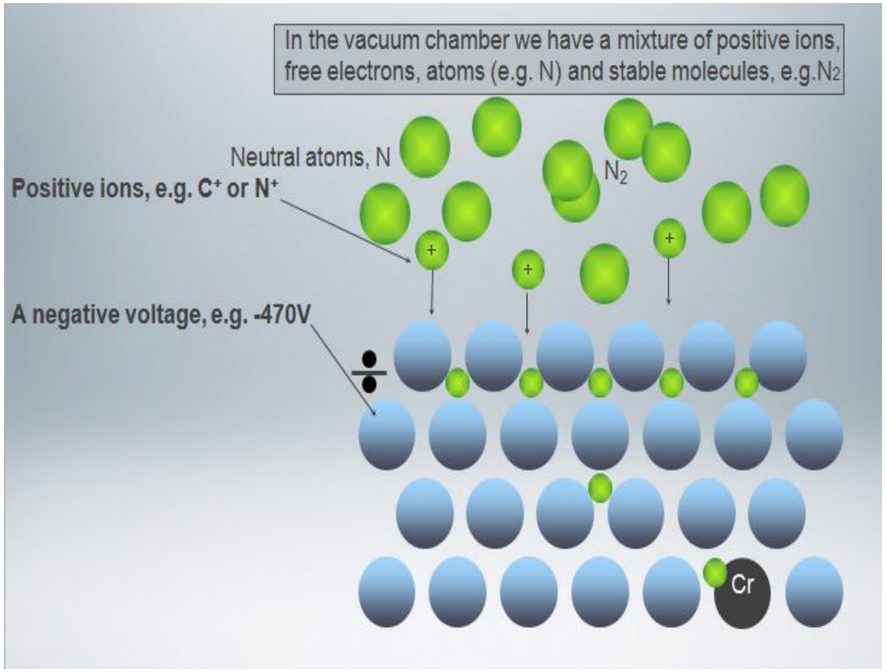
- Coatings are widely used in the industry for many applications
- The spectrum of coatings is very wide, such that there is no need to invent new types of coatings
- However, we need to do a lot of testing under relevant conditions

2. Benefits of coatings and plasma treatments
(in nuclear context)

- ✓ Hardening of surfaces of components to avoid thread galling
- ✓ Protection against wear
- ✓ Protection against corrosion
- ✓ Reduction of tritium diffusion
- ✓ Reduction of hydrogen embrittlement
- ✓ Avoid hydrogen release from Zr-claddings (accident situations)
- ✓ Reduction of friction
- ✓ Electric insulation

3. Pulsed plasma surface treatment (PPST)

- Creation of glow discharge plasma
- Surface in contact with plasma is bombarded by high energy particles
- Plasma nitriding (as one possibility):
  - Nitrogen gas is the carrying gas.
  - The ionized positive nitrogen atoms are injected on to the surface of the material, which is polarized negatively (400-500 V)
  - Atoms diffuse into the metal
    - interstitials
    - react with other atoms (example CrN)



Hardening of surfaces of components to avoid thread galling

By hardening components (especially the threaded parts), thread galling can be avoided

4. Requirements of coatings

- ✓ Allow exposure > 600 C
- ✓ Chemical compatibility with coolant
- ✓ Good adhesion to substrate
- ✓ Hard
- ✓ Dense (free of pores and cracks)
- ✓ Application at low temperature

Many coating techniques available

Choice of Halden: by Physical Vapor Deposition (PVD)

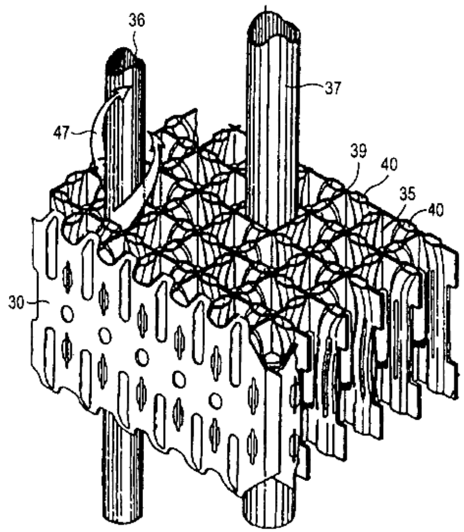
5. Some relevant coatings

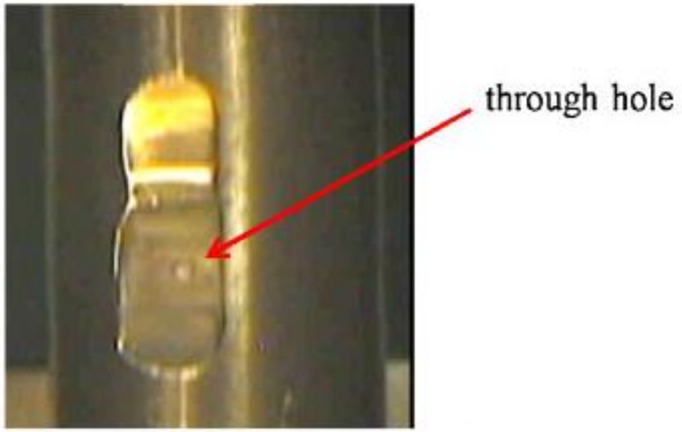
Coating material	Max. service temperature (°C)	Coating colour
DLC, PVD	350	black
TiN , PVD	600	gold-yellow
CrN, PVD	700	silver-grey
TiAlN, PVD	900	violet-grey
AlCrN, PVD	1100	bright grey
ZrO_2, PVD, (ALD)	1000-1500	grey
TiSiN	1100-1500	Metallic gold

- Multilayered coatings
- Nitriding (PPST), followed by coatings

5. Testing of coatings

Fretting at spacer grid locations



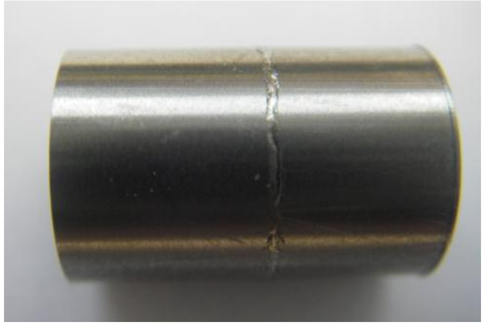


b) Grid-to-rod fretting wear-induced fuel rod perforation at the bottom grid

Accelerated fretting test using sharp pin:

- Cyl. sample mounted/rotated in lathe ; 100g force, 300 turns per minute, duration about 5 minutes

Results of wear tests

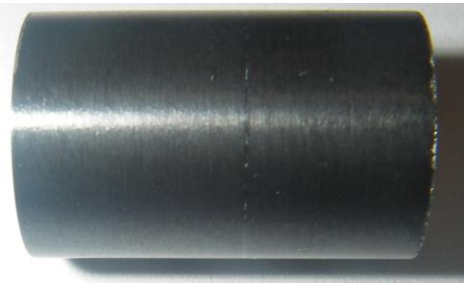


Untreated Zr-4

Track depth; 31 micron

CrN coated

Track depth; not measurable



PPST treated

Track depth; not measurable

TiAlN (PVD): Testing

- Rubbing/wear tests; confirmed hardness, wear resistance
- Exposure to pure water in autoclave at
  350 °C, 160 bar ; no degradation seen

- Exposure to supercritical water at 650 °C and 250 bar for 1000 h:
  Little left of coating

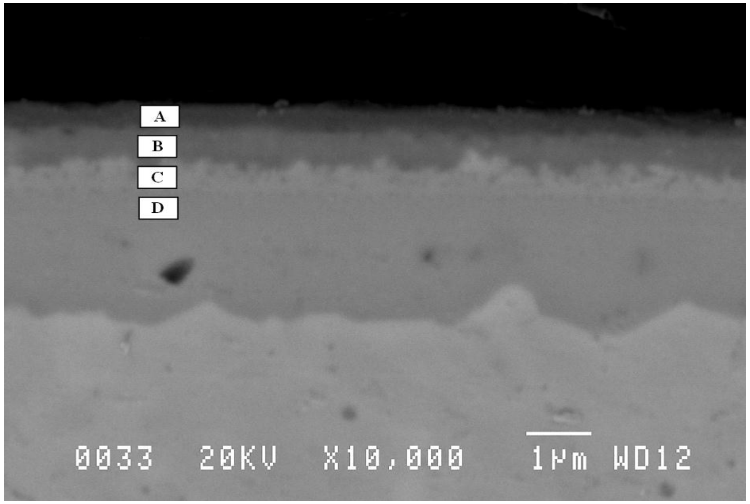
Collaboration with VTT

Conclusion:
TiAlN a good candidate coating for BWR, PWR conditions but not for supercritical water.

CrN (PVD): Testing

- Heating and cooling in an oven in air up to 600 °C:
  coating remains intact (good bonding to substrate)
- Exposure to supercritical water at 650 °C and 250 bar for 1000 h (collaboration with VTT):
  - coating intact
  - different layers observed (see picture)

Visual appearance of CrN coated sample after exposure to supercritical water

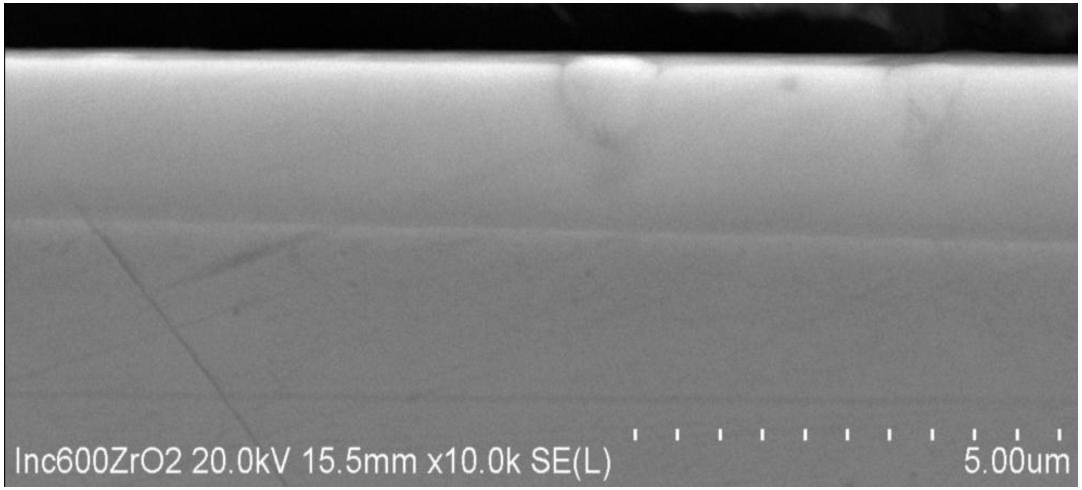


Multi-layered structure after exposure to supercritical water

Conclusion:

Very good coating: Supercritical water, PWR (?), BWR(?)

ZrO_2 (PVD)



Picture (SEM) of the ZrO_2 layer (on Inconel 600); uniform, free of pores and cracks

Large Inconel 600 tube, coated with ZrO_2 (for hydrogen diffusion studies)

Electrically insulating!

Note: Also 1 mm Pt wires have been coated with ZrO_2 (for use in IFA 731)

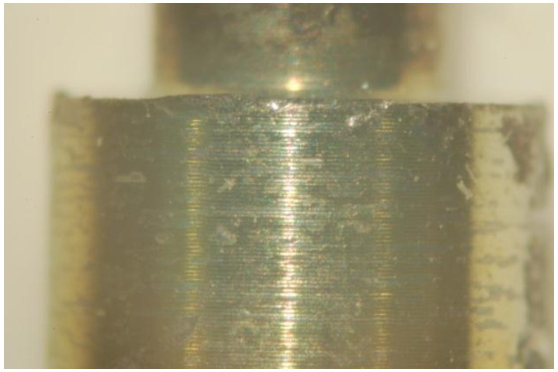
ZrO_2 (PVD): Testing

Exposure to supercritical water (1000 h, 650 C):

- Coating reduced in thickness from 1.8 micron to 0.5 micron

Exposure to liquid Pb (2000 h, 550 C) :

Collaboration with KTH, Sweden

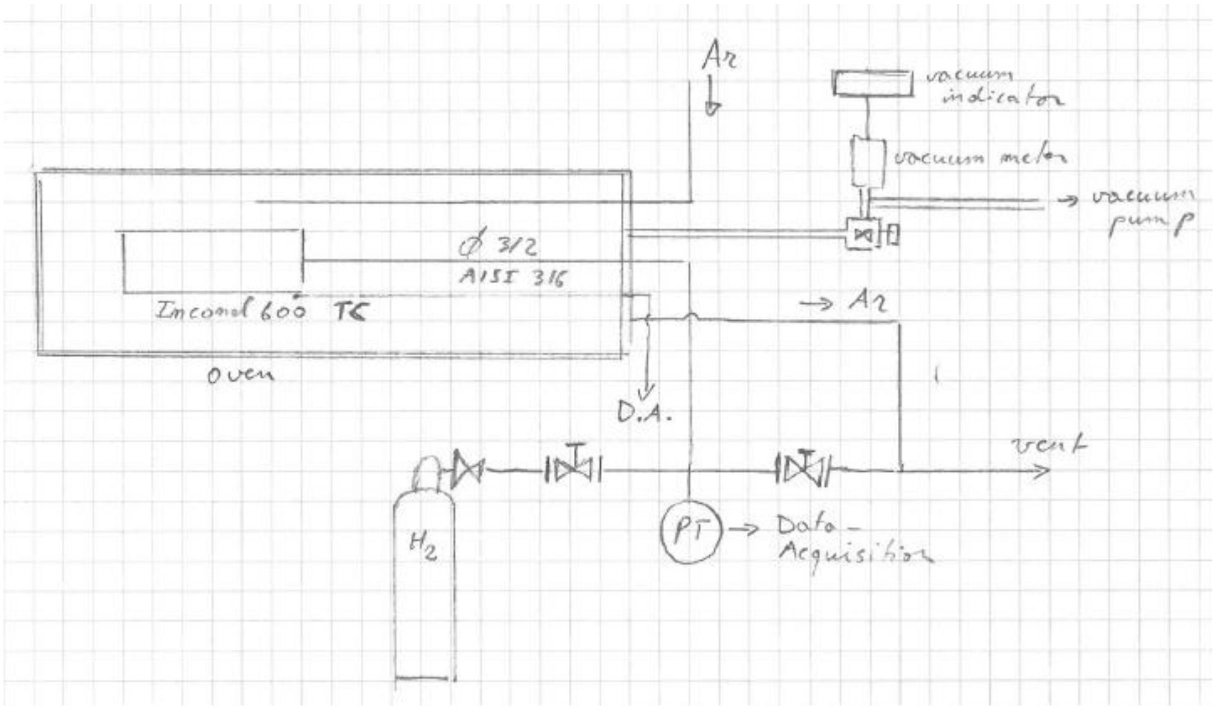


Coating largely survived

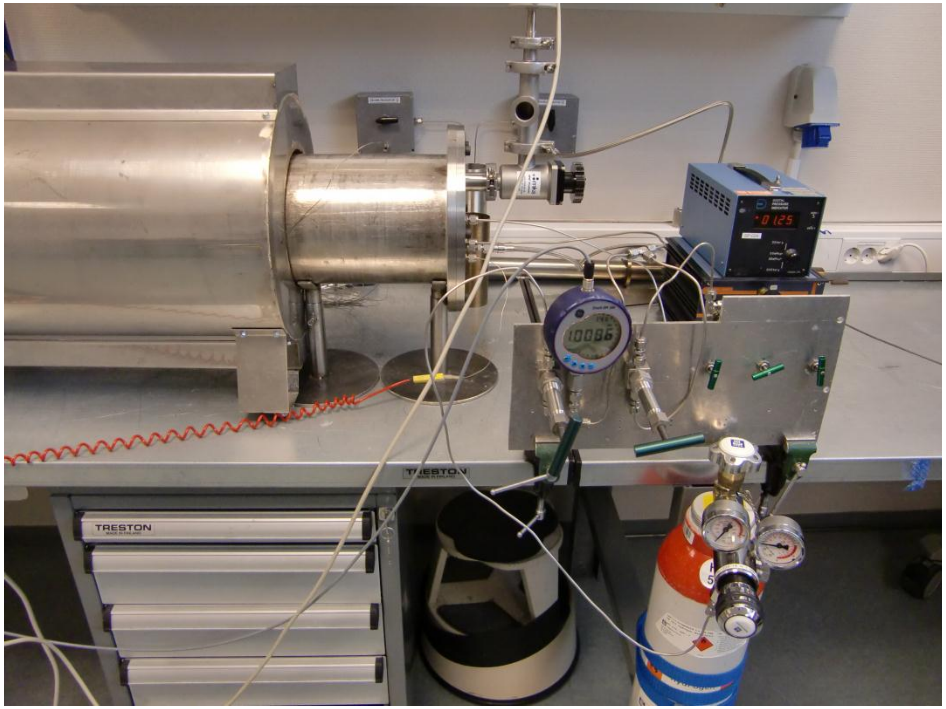
Could be improved by better surface finish before coating

Hydrogen diffusion tests at high temperature

Aim: Investigate the effectiveness of coatings in reducing hydrogen diffusion

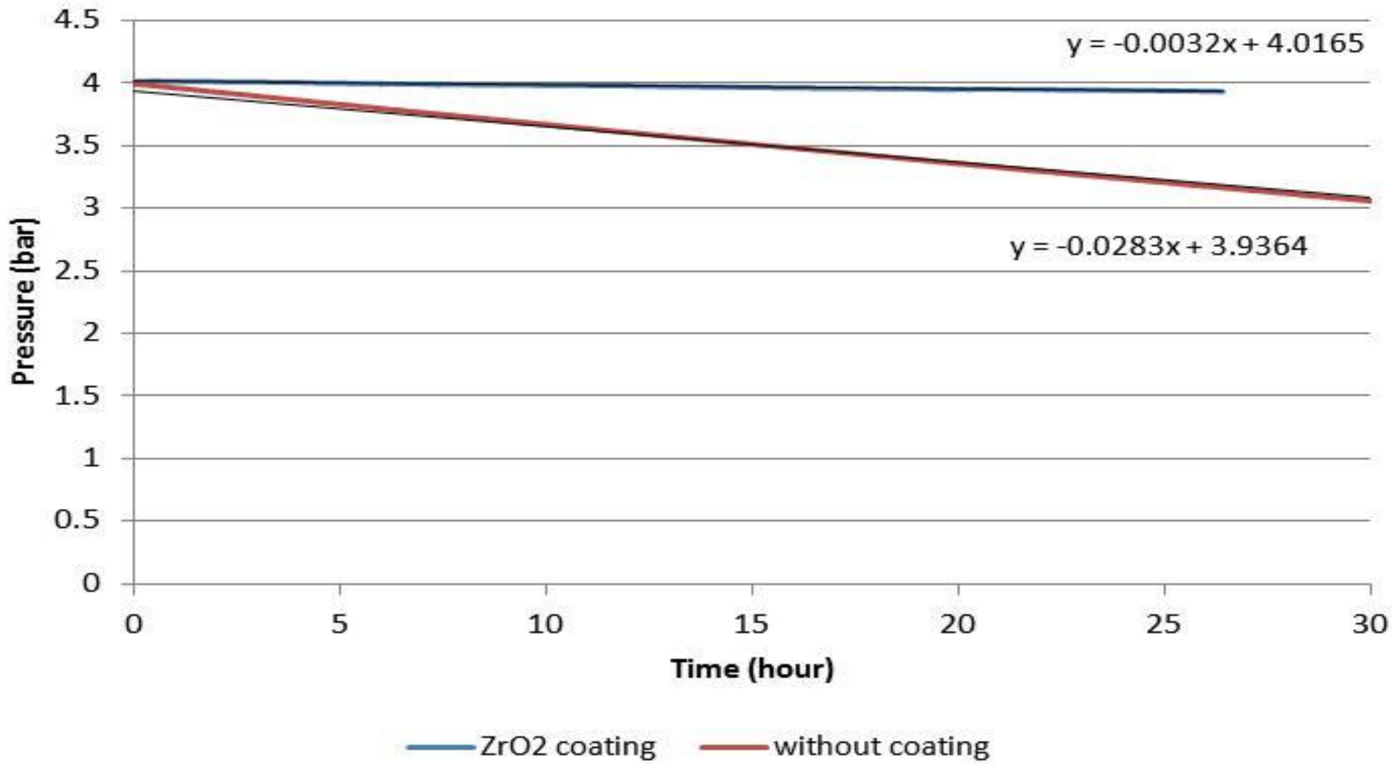


Principle:
Measure pressure drop in a tube



Picture of set-up for hydrogen diffusion measurements

Picture of ZrO_2 coated tube



ZrO_2 coating reduces the hydrogen diffusion through Inconel 600 by a factor 9

Liquid Pb/Bi corrosion

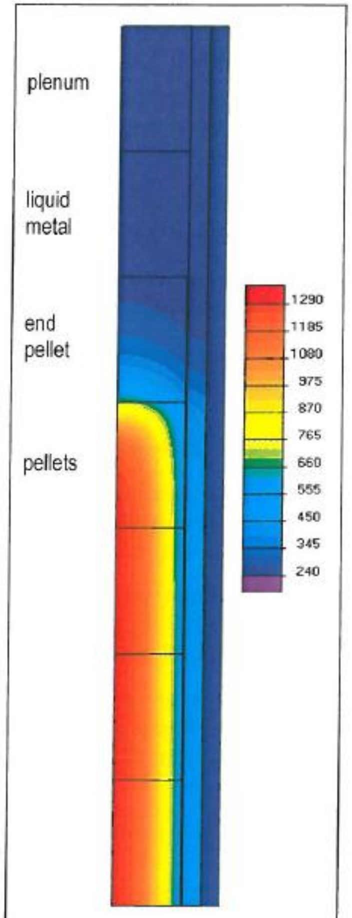


Fig. 9 – temperature distribution

Fuel thermal conductivity degradation test at the HRP

In order to study this in a better way the gap between Pellets and cladding is filled with liquid Pb/Bi

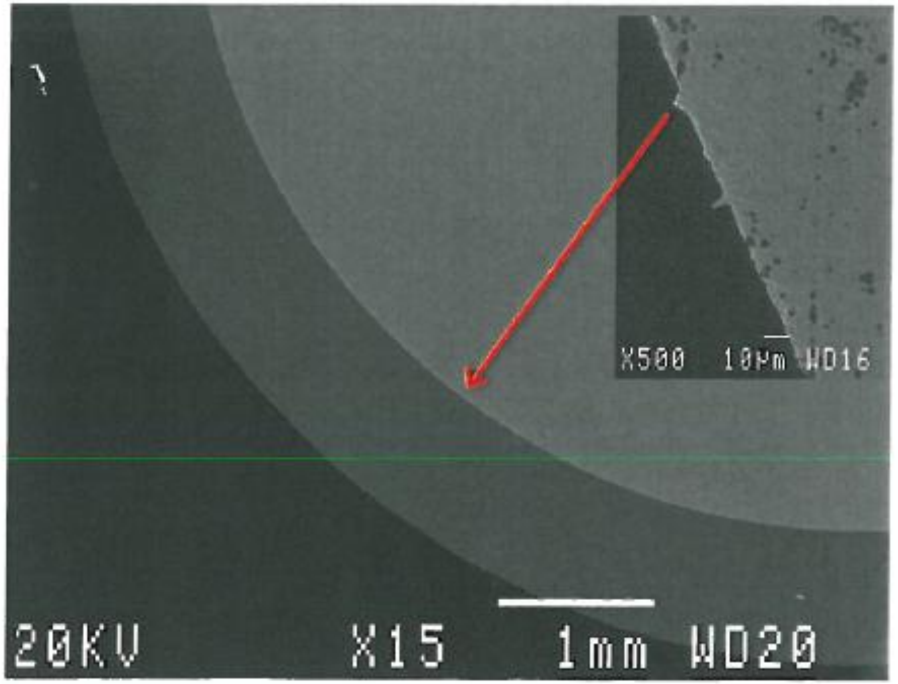
Need for a material with

1) Low thermal expansion
2) Low corrosion

Chosen material: AISI 410 (ferritic)

Chemical Composition		**Min. %**	**Max. %**
	Carbon	0.09	0.15
	Silicon	0	1.00
	Manganese	0	1.00
	*Nickel	0	1.00
	Chromium	11.50	13.50
	Phosphorous	0	0.04
*Nickel addition optional.	Sulphur	0	0.03

Long term (1000 h) corrosion test at high temperature (400 h at 740 C, 600 h at 550 C)



Almost no corrosion seen!

A Zr-4 ring was present
In the same capsule.

Zr works as corrosion inhibitor;
Formation of ZrN layer

See also; G. Ilincev, Nuclear Eng. And Design, 217 (2002) 167-177

"Self healing protective layer"

Conclusions

- Coatings, applied by PVD (commercial), as well as plasma surface treatments have many interesting applications for Gen-IV reactors but can also find applications in present-day reactors (preventing fuel rod cladding failures).

- Most promising coatings
  - Water environment : CrN, maybe TiAlN (PWR and BWR)
  - Liquid lead : ZrO2, Ta coating (PVD)

- AISI 410, in combination with Zr (inhibitor) is corrosion resistant in Pb/Bi up to 740 °C


Thank you for your attention !