Development of Chromium Coated Nuclear Fuel Cladding

Martin Sevecek, Anil Gurgen, Arunkumar Seshadri
Koroush Shirvan
Principal Research Scientist
Department of Nuclear Science and Engineering

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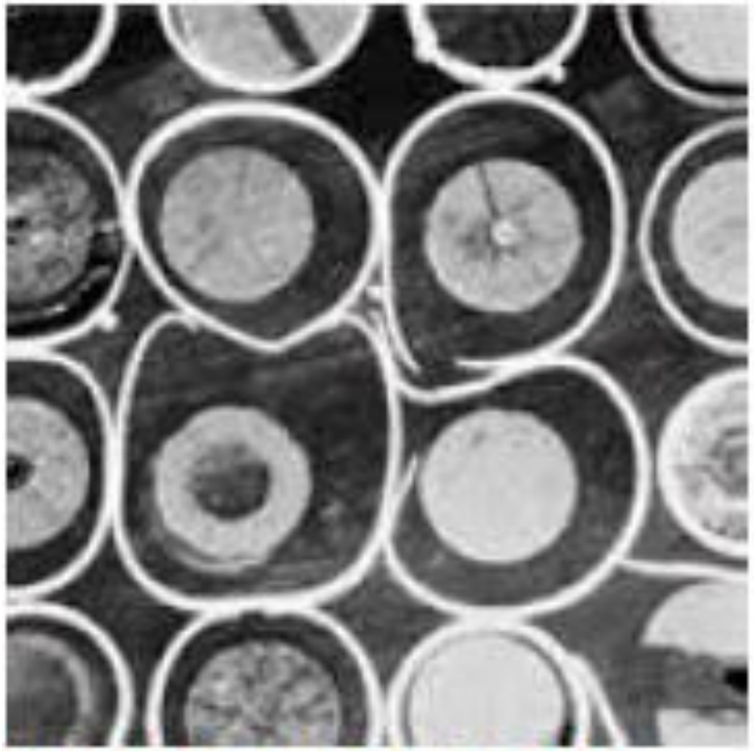

PHEBUS-LOCA (IRSN)

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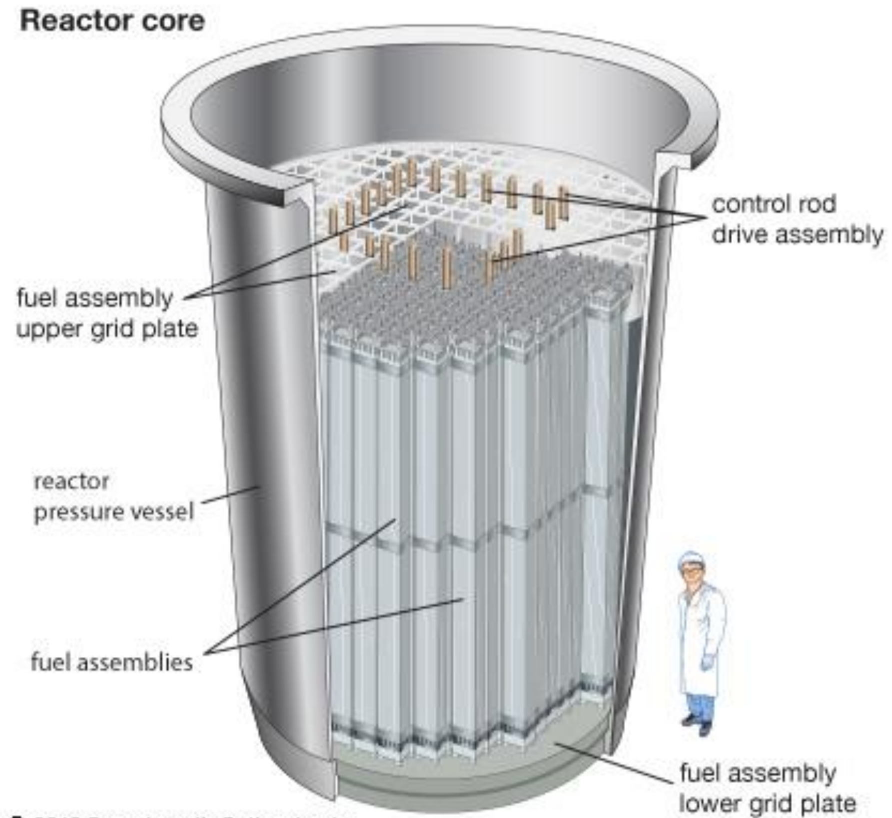
Accident Tolerant Fuel Overview

- The Three Mile Island (TMI) and Fukushima accidents highlighted the weakness of Zirconium based cladding (Generation of Hydrogen).
  - In 2011, after Fukushima, US Congress mandated DOE to develop "melt-proof" nuclear fuel technology.
- According to DOE, the **fuels with enhanced accident tolerance** are those that, in comparison with the standard UO_2 – Zr system, can **tolerate loss of active cooling** in the core for a **considerably longer time period** while **maintaining or improving** the fuel performance during normal operations.
  - Similar programs in UK, France, Germany, Russia, China, Japan, Korea and India are ongoing.
- US Utilities would like to use ATF safety benefits to reduce O&M costs of safety equipment & relax operational limits.

Weakness of Zirconium Based Cladding

$$Zr + 2\,H_2O \rightarrow ZrO_2 + 2\,H_2 + \text{Energy}$$



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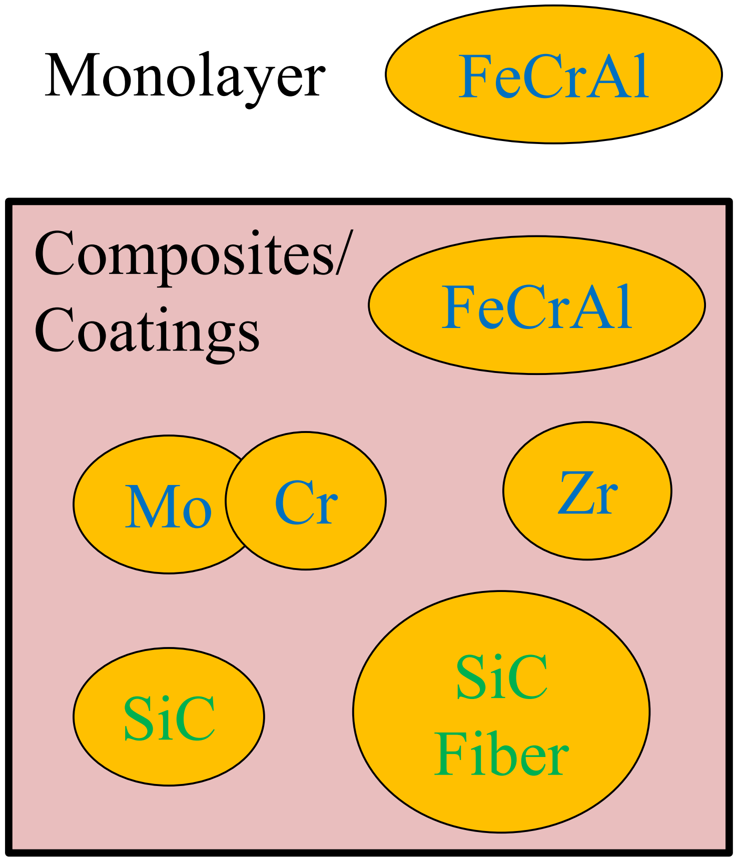
ATF Cladding (Tube) Materials

Claddings



Monolayer

FeCrAl

Composites/ Coatings

FeCrAl

Mo

Cr

Zr

SiC

SiC Fiber

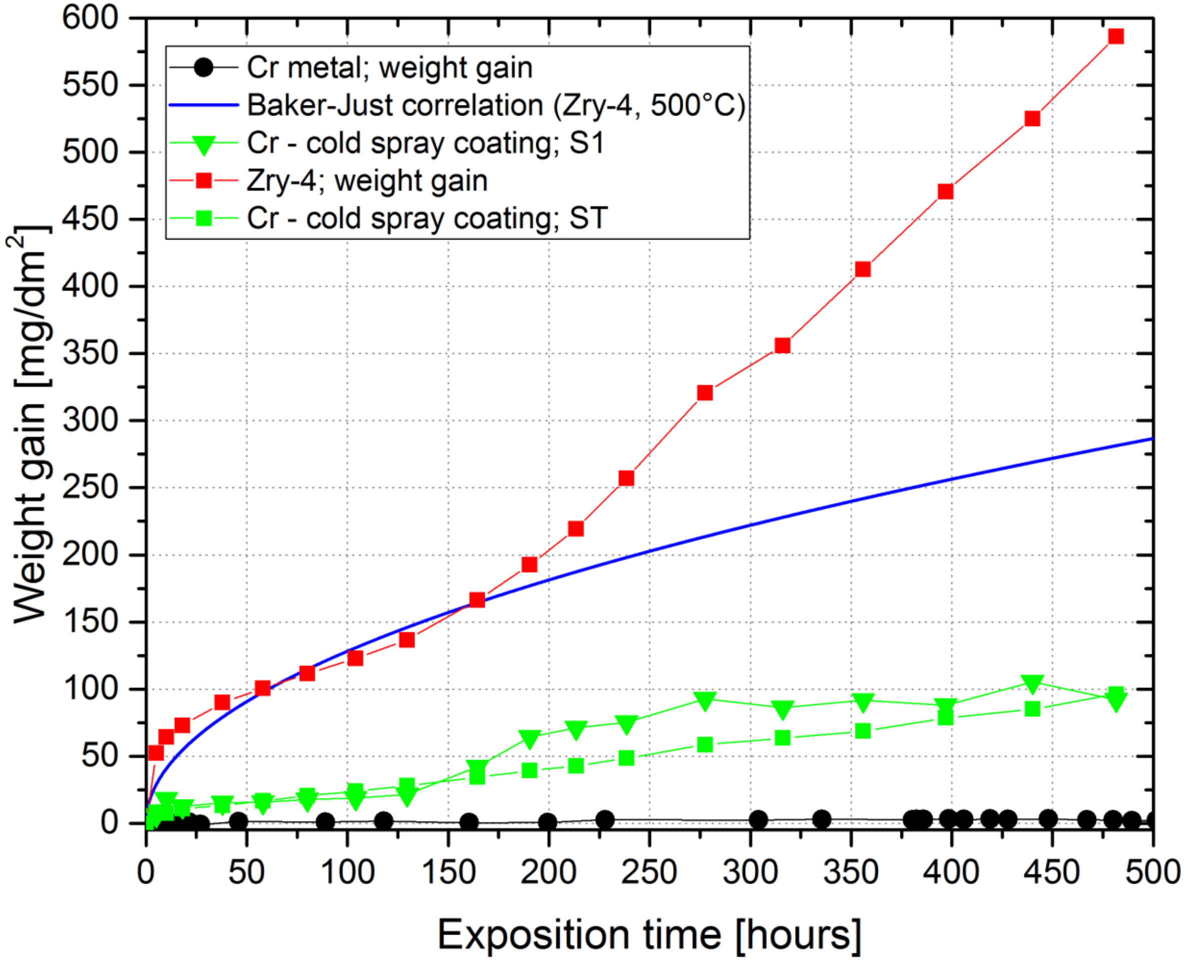
- Maximum Allowable Temperature (Max Temp.)
  - ✓ FeCrAl Cladding limit is the most certain
  - ✓ Mo limit depends on its structural role

Concept	Max Temp.	Comments
FeCrAl Monolayer Clad	~1500 ^{o}C	Melting Point
Zirc with Cr Coating	~1330 ^{o}C	Eutectic Melt Point
Zirc with Mo + Cr Coating	~ 1900 ^{o}C	Depends on Thickness and Inner Layer Oxidation
Zirc with Mo + FeCrAl/Zr	~1900 ^{o}C	Depends on Thickness and Inner Layer Oxidation
SiC with SiCf Composite	> 2000 ^{o}C	Depends on Architecture
SiCf with Cr Coating	~ 1900 ^{o}C	Cr is there for Normal Ops.
Zirc with SiCf with Cr	~1900 ^{o}C	Melt point of Zr and Cr

Chromium History & ATF Requirement

- Why Chromium:
  - Corrosion Resistance
  - Not a strong neutron absorber (compared to Nickle)
  - Good strength and hardness (Protection against wear)
- Existing experience in nuclear reactor core
  - Chrome plating on nuclear control rods
  - As part of structural steel
- ATF Coating Requirements beyond high temperature oxidation resistance
  - Thickness: 20 µm (Wear Limit) to 50 µm (Economic Limit)
  - Scalability: 200,000 m^2 (2 mil ft^2) per year for US market [6,400 km of tubing]
  - Bond: Survive 5 years under 300^{o}C, partial tension, neutron/gamma radiation.
  - Bonus: Allow for internal coating of the fuel rod cladding

500^{o}C Steam Oxidation (2)



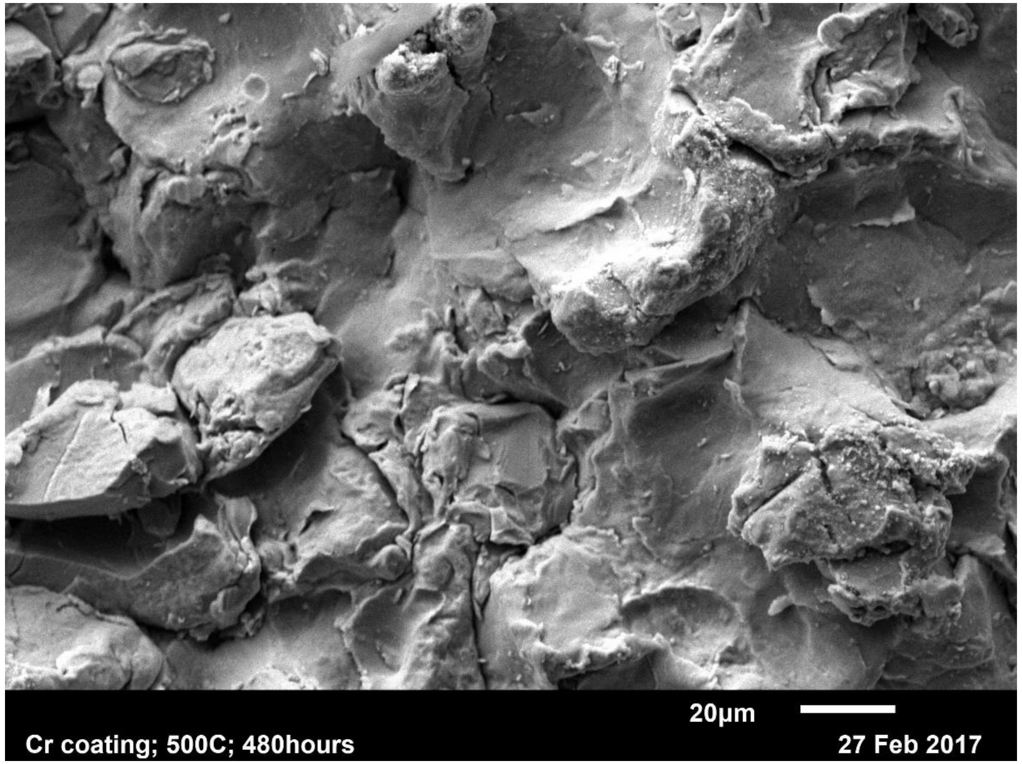
After 18 hours

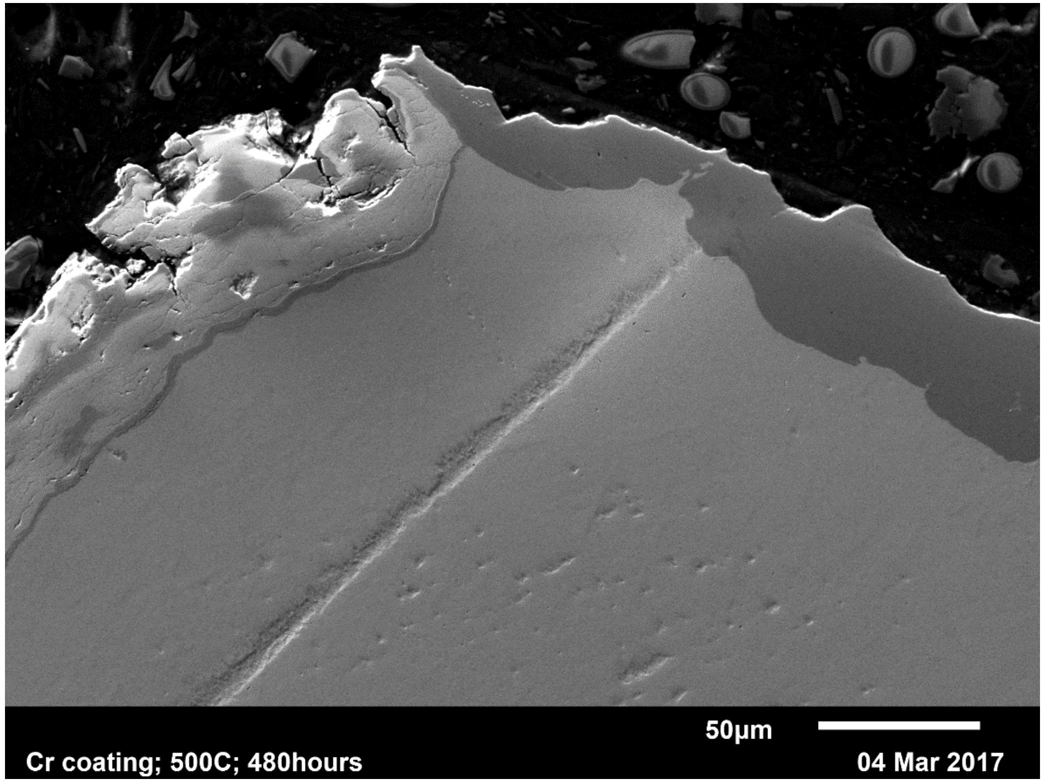
Cr

Zr

500ºC Steam Oxidation (2)

- Cr coating shows complete much lower corrosion rate compared to Zircaloy.

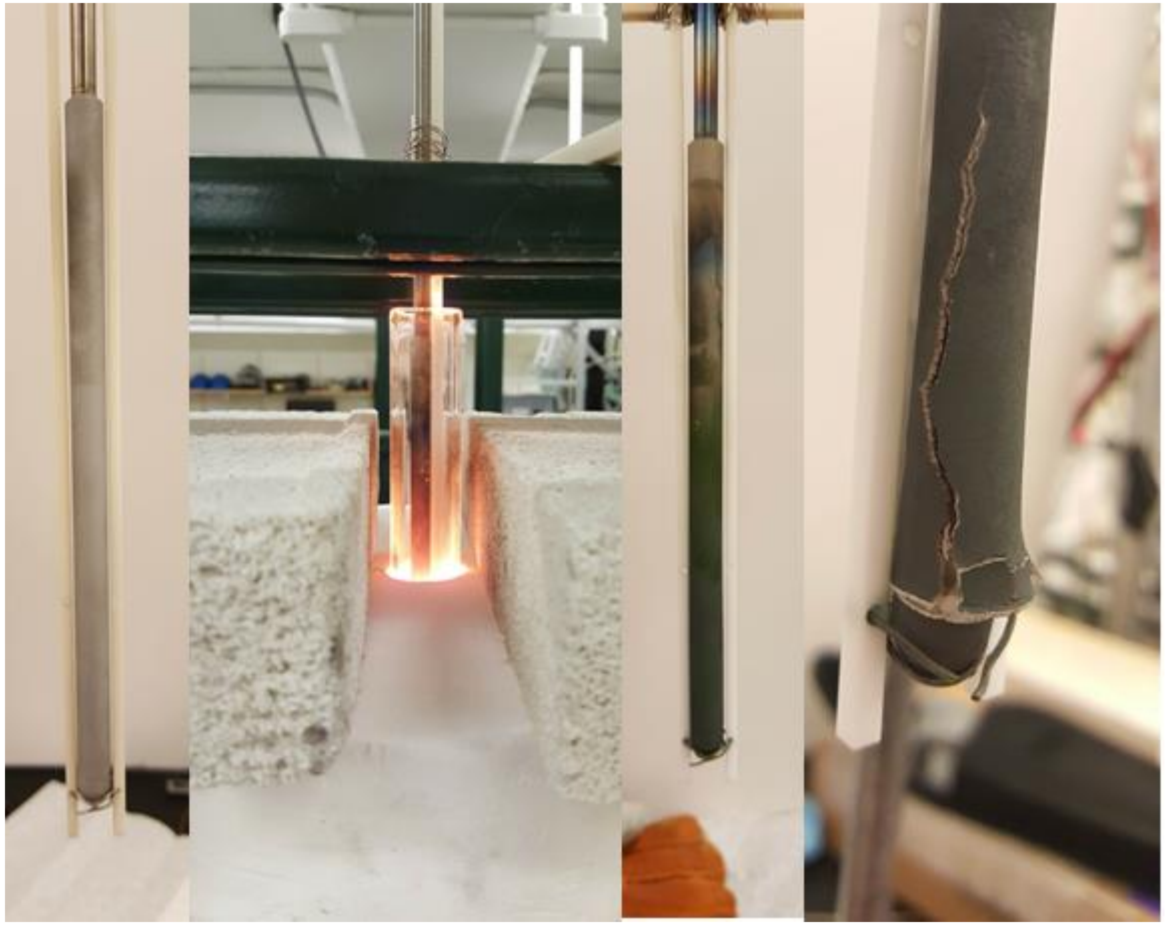




Pressure Tube Autoclave Testing

12 MPa @ 300 C water : 2 weeks no internal pressure & 2 weeks 25 MPa internal pressure

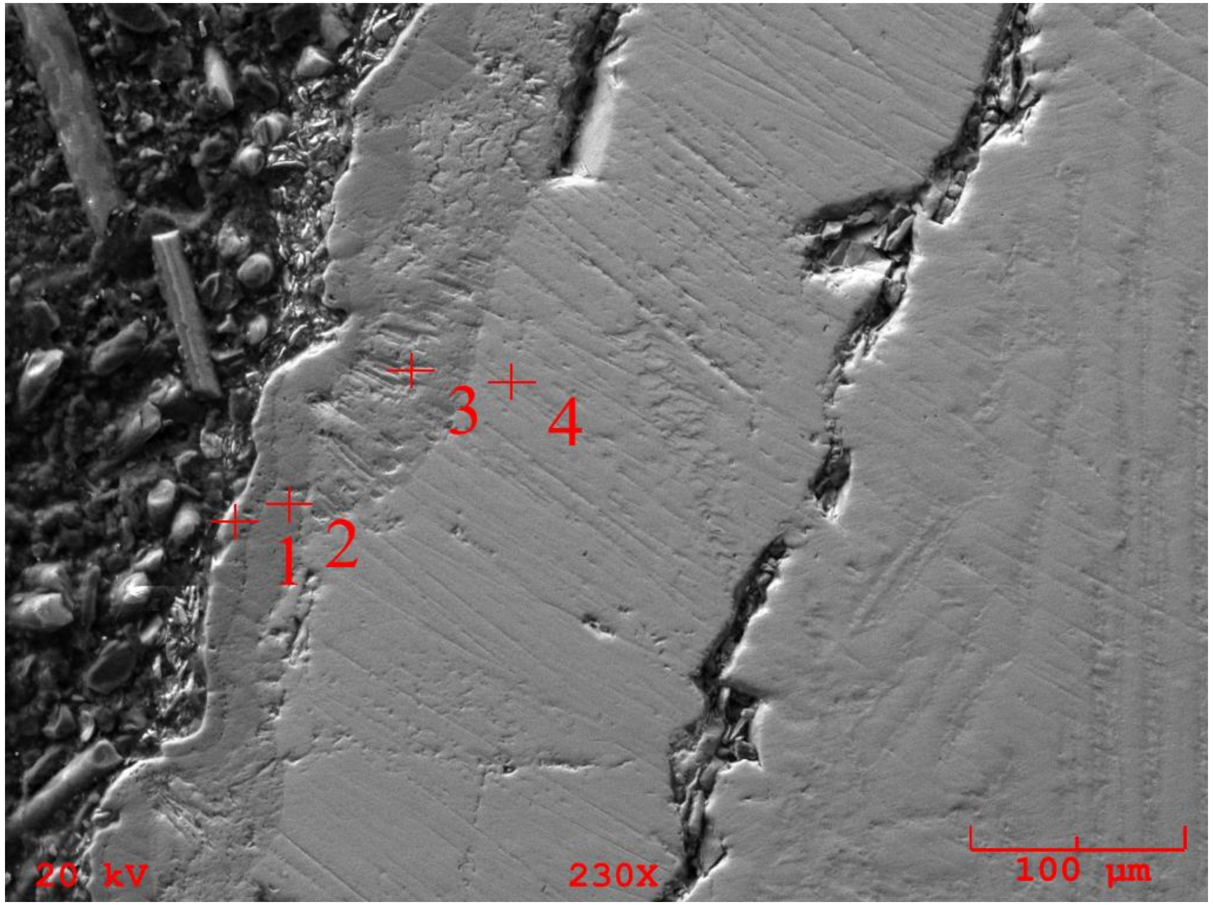
High Temperature Steam Oxidation (1)



Before During After 90 Min

- The sample was air quenched 2 times prior to break
  - Phase transformation of Zircaloy combine with its anisotropy.

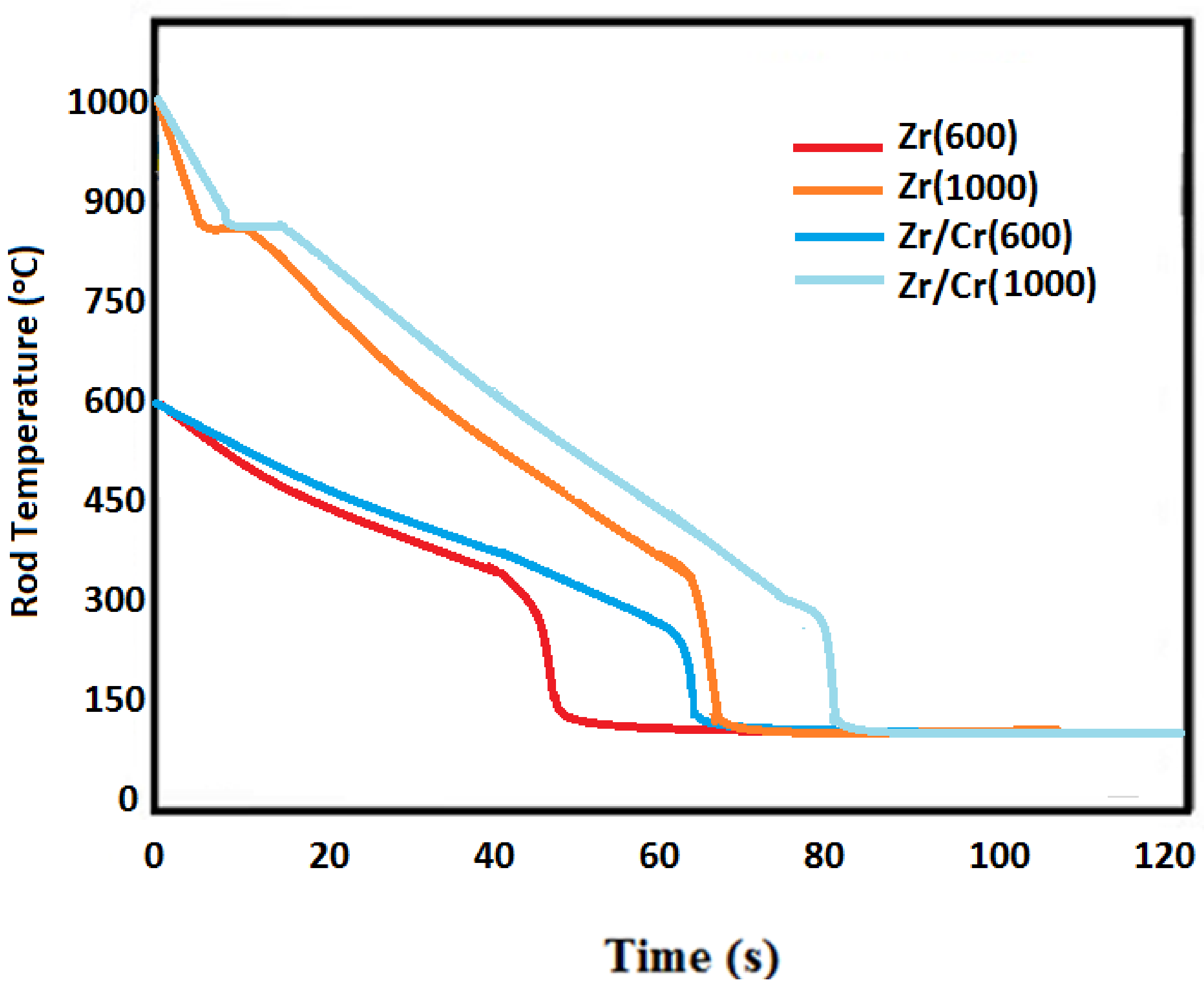
High Temperature Steam Oxidation (2)



- Cr coating still survived after 90 min of 1200°C oxidation
- Even though Zirc was oxidized from the underneath, no delamination of Cr was observed.

Element	1 (%)	2 (%)	3 (%)	4 (%)
O	70.2	37.9	57.8	23.9
Cr	29.7	60.1	0.1	0.6
Zr	0.1	2.0	42.1	75.4

Cladding Water-Side Heat Transfer

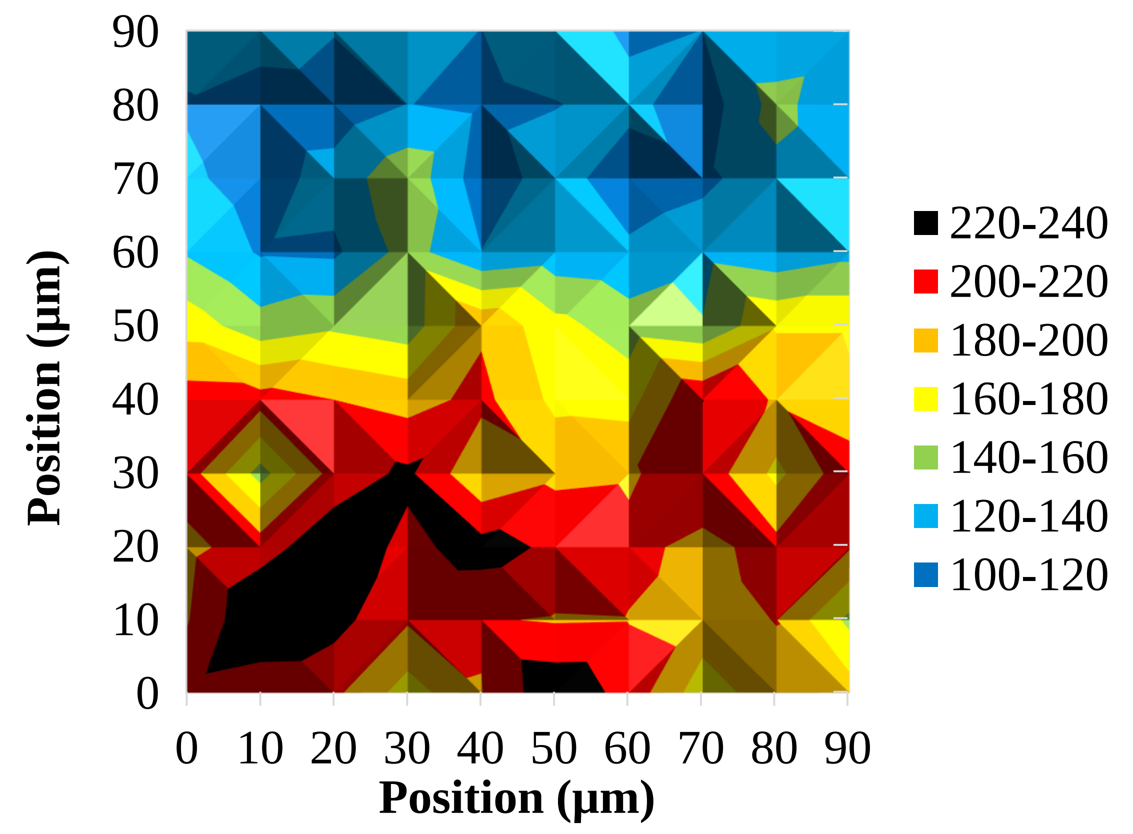


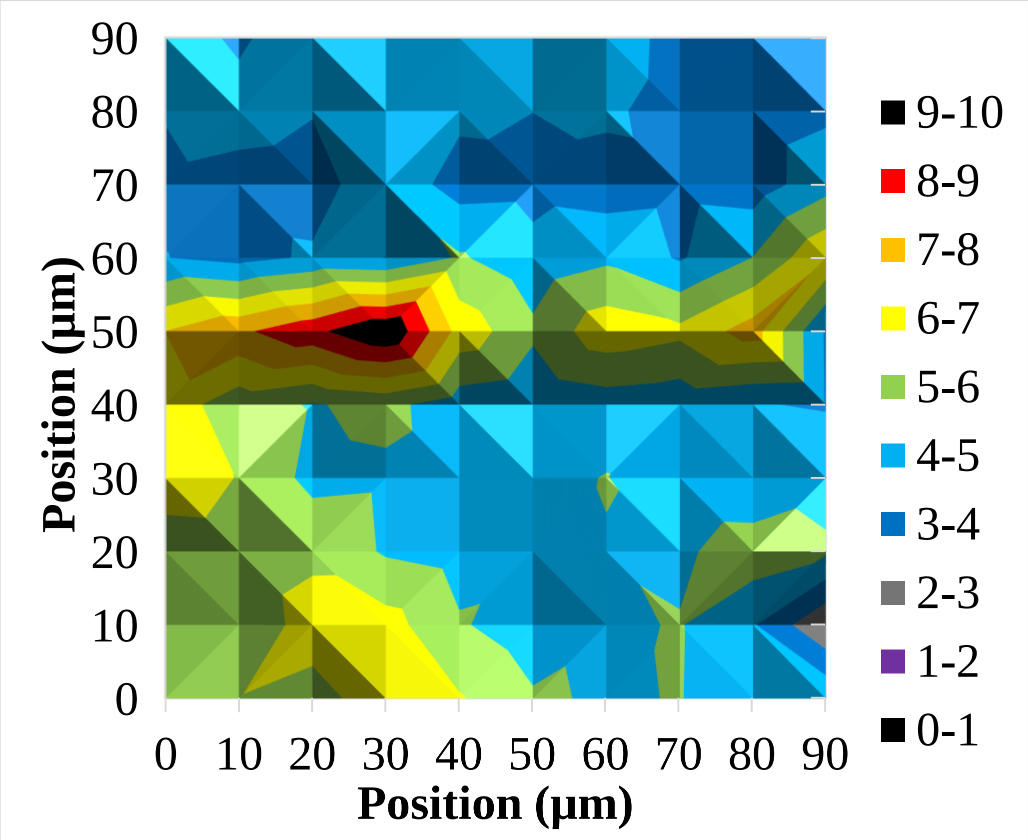
MATERIAL	CONTACT ANGLE
AS MACHINED	
Zirc	83.54
Chrome coated Zirc	95.65
Pure Chrome	91.23
OXIDIZED (After recovery)	
Zirc	48.18
Chrome coated Zirc	32.12
Pure Chrome	35.16

While Cr is not as wetting as Zirc, Cr-oxide is more wetting.

Coating Strength

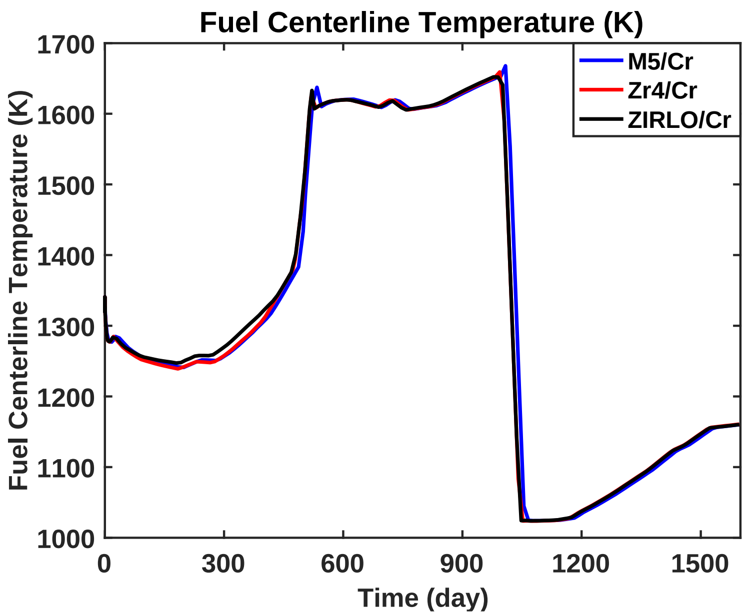
- Nano-Indentation across coating (top Zirc/Bot Cr) displayed the expected outcome of higher hardness at the interface.
  - ➢ Ongoing 4-pt bend cyclic load tests will give us more insight

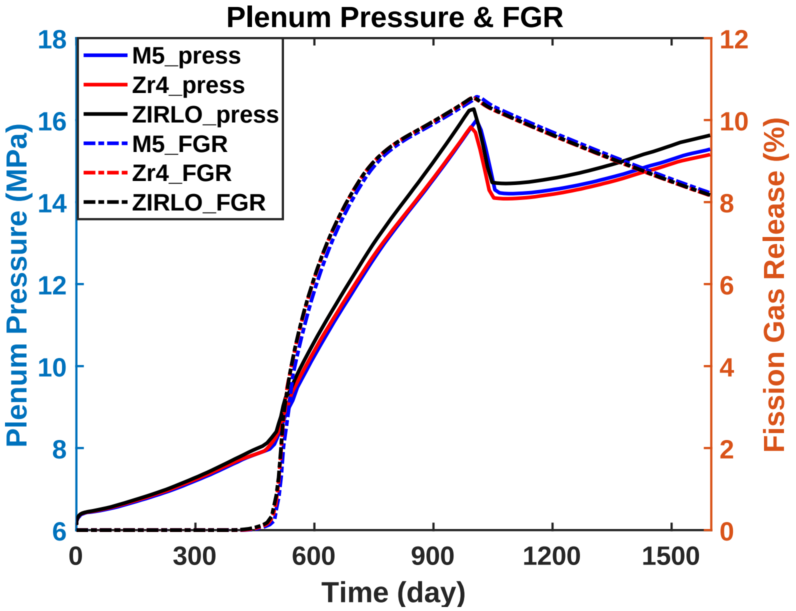


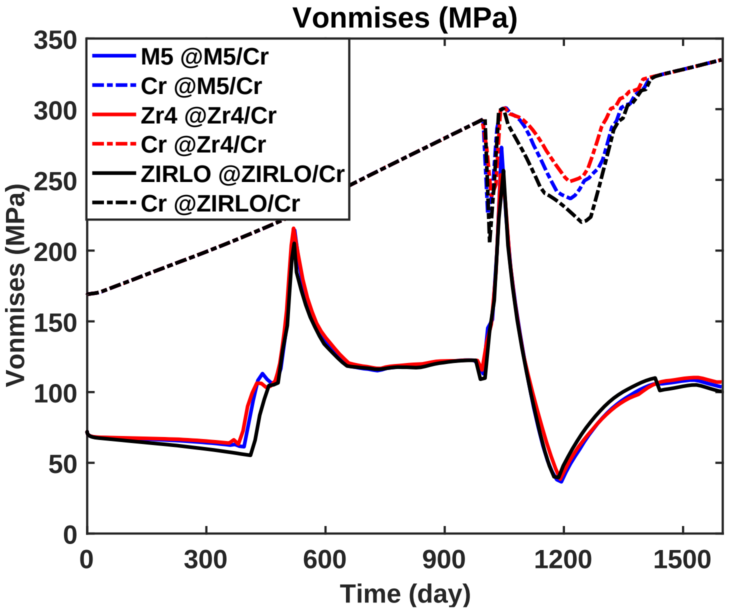


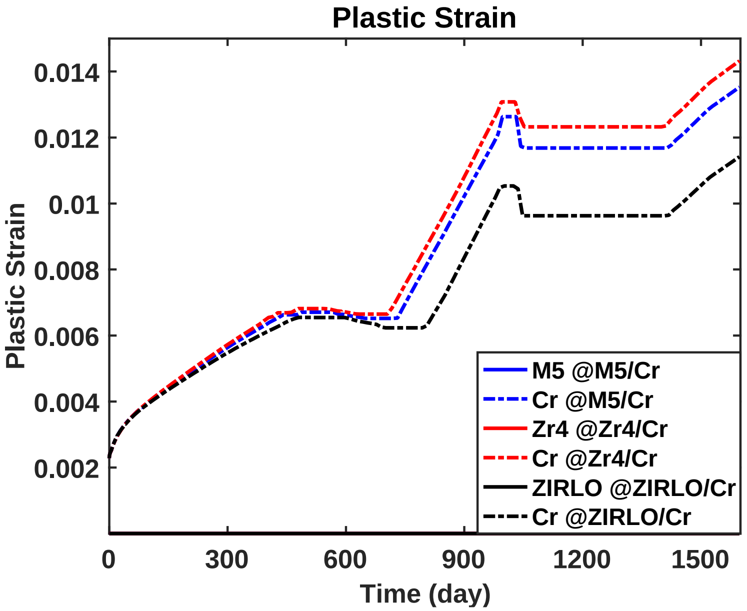
Reactor Performance

- Very little impact on fuel temperature and fuel rod internal pressure.
- The coating will go under higher stresses compared to base Zircaloy material
  - Plasticity is expected (1-2%) in the coating

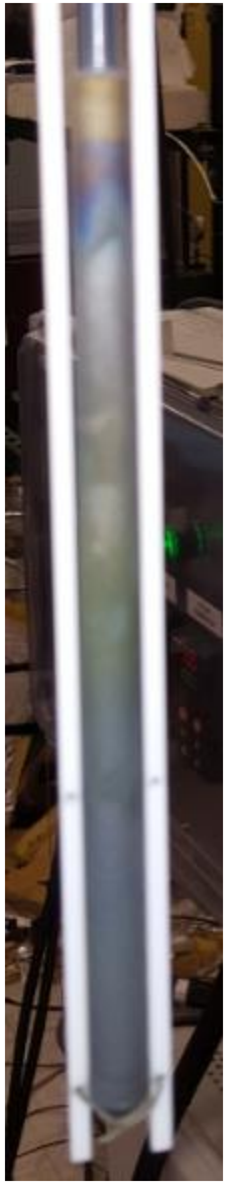








Concluding Remarks



- ATF technology could provide a large incentive in terms of safety
  - Cr coating via Cold-Spray is a promising concept
- Advanced materials and manufacturing R&D are keys for ATF success
  - Example: ODS and Nanostructured Metals
- Close collaboration of all organization involved in coating fabrication and nuclear R&D is critical for Accident Tolerant Nuclear Fuel Deployment.
  - Lets Join Forces to Tackle the ATF Challenge Problem!