

*NEA/NSC/DOC(2015)14
17-18 September 2015
PSI, Switzerland*

Present status of surface- modified Zr alloy claddings in KAERI

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ATF Cladding Program in KAERI

- **Objective**

- √ Enhanced performances during accidents than current Zr cladding
- √ Increased/Maintained performances under normal condition

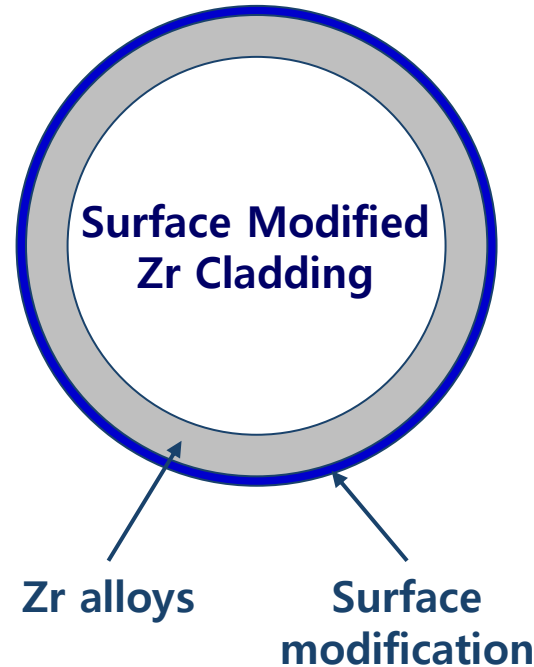
- **Approach**

- √ **Surface modification (1)**
- √ Metal-ceramic hybrid (2)

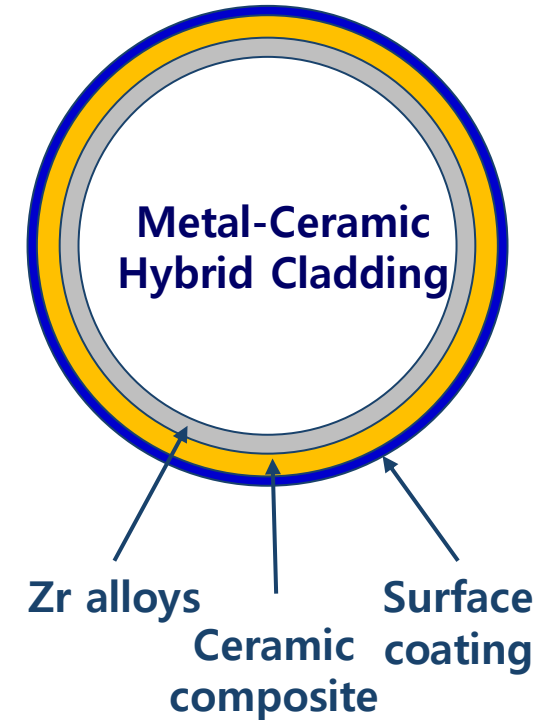
- **Considered issues**

- √ Oxidation/corrosion resistance
- √ Mechanical strength
- √ Thermal conductivity
- √ Thermal expansion coefficient
- √ Phase stability
- √ Adhesion to the matrix
- √ Neutron economy
- √ Irradiation susceptibility
- √ Tube fabricability
- √ Unknowns...

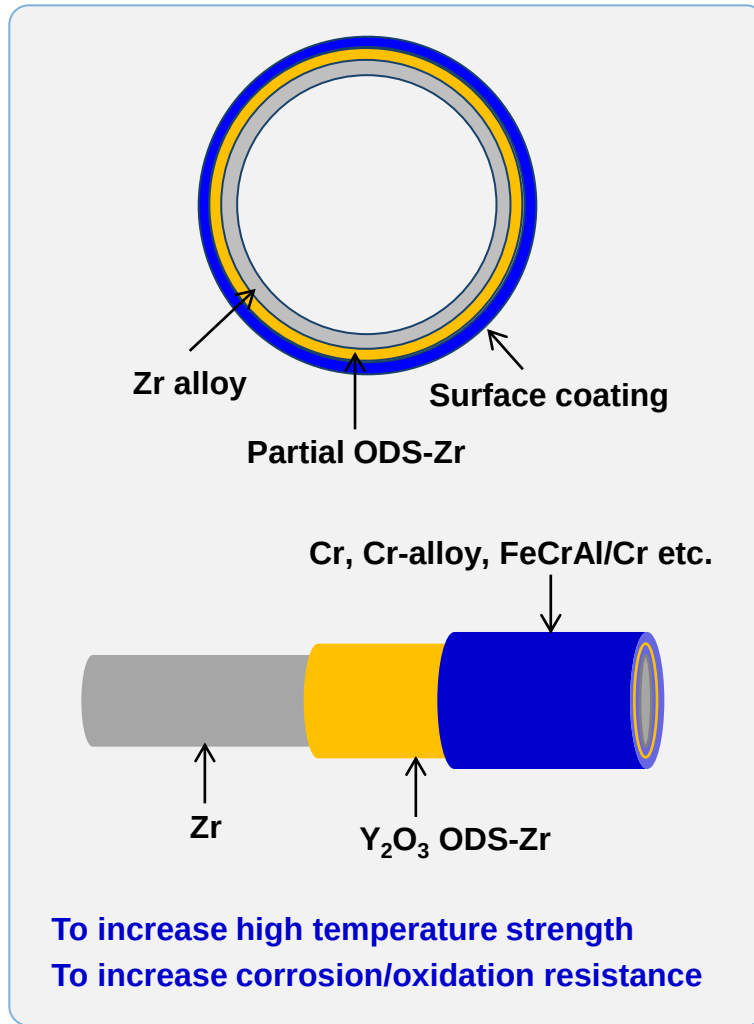
- **Mid-term**



- **Long-term**



Surface Modification Technology



● Objective

✓ Surface coating

- Increase of oxidation/corrosion resistance in both accident and normal condition

✓ Partial ODS-Zr

- Increase of strength at high-temperature without severe decrease of ductility under normal condition

● Approach

✓ Surface coating (~50 micron)

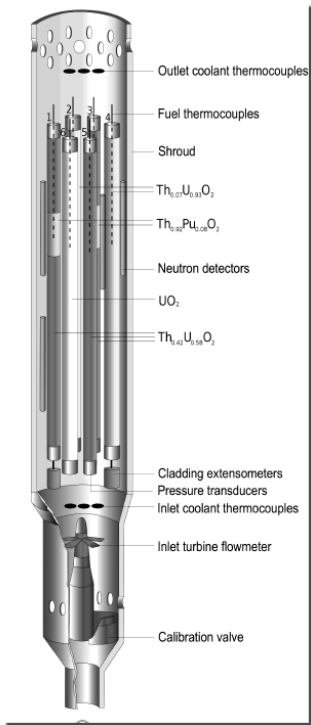
- Coating technology development
 - Cold spray + Laser beam scanning
 - Arc ion plating + Laser beam scanning
 - 3D laser coating

- Coating material development
 - Cr, Cr-alloy, FeCrAl/Cr...

✓ Partial ODS-Zr (~100 micron)

- ODS technology development
 - Laser beam scanning with oxide powder

Irradiation Test Plan



☐ Halden reactor test: Cooperation with “THOR Energy”

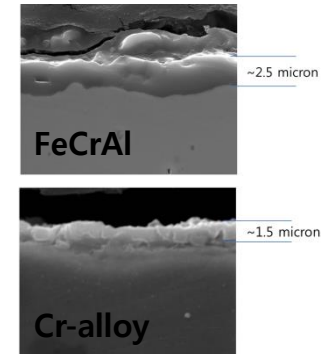
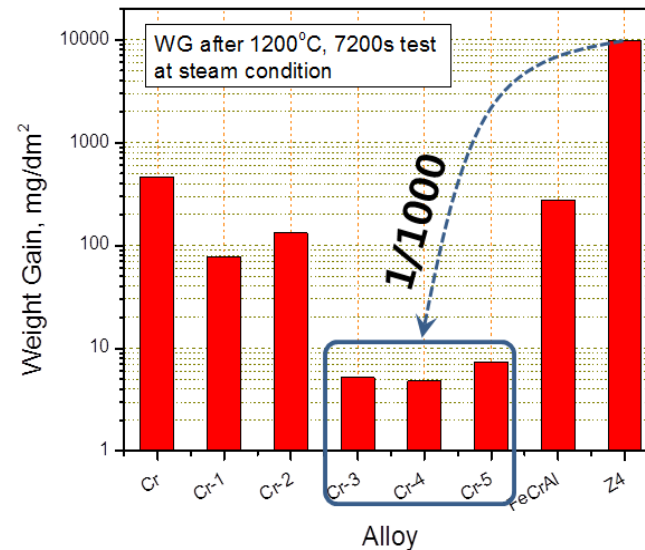
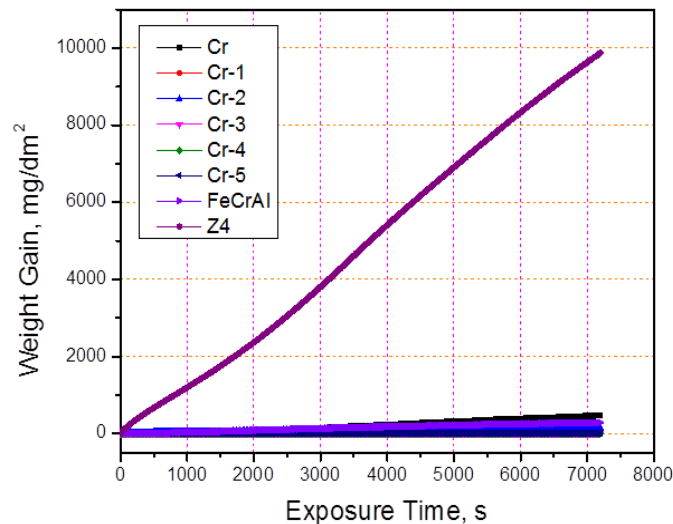
- Two ATF rods with instrumentation
- **Rod 1:** Metallic microcell pellet($\text{UO}_2 + 5\text{vol}\% \text{Cr}$) + **Coated(Cr-based alloy) Zr cladding**
- **Rod 2:** Ceramic microcell pellet($\text{UO}_2 + 0.6\text{wt}\% \text{Si-Ti-O}$) + **Coated(FeCrAl/Cr) Zr cladding**
- Irradiation period: 2015.09 ~ 2017.05
- Estimated burn-up: 25 GWd/MTU

☐ Halden reactor test: Halden Reactor Project (HRP)

- **ATF Claddings** and ATF Pellets were proposed as candidates for test
- **Surface modified Zr claddings (ODS + coating)** are proposed
- Irradiation period: 2016 ~

Coating Material Development for ATFC

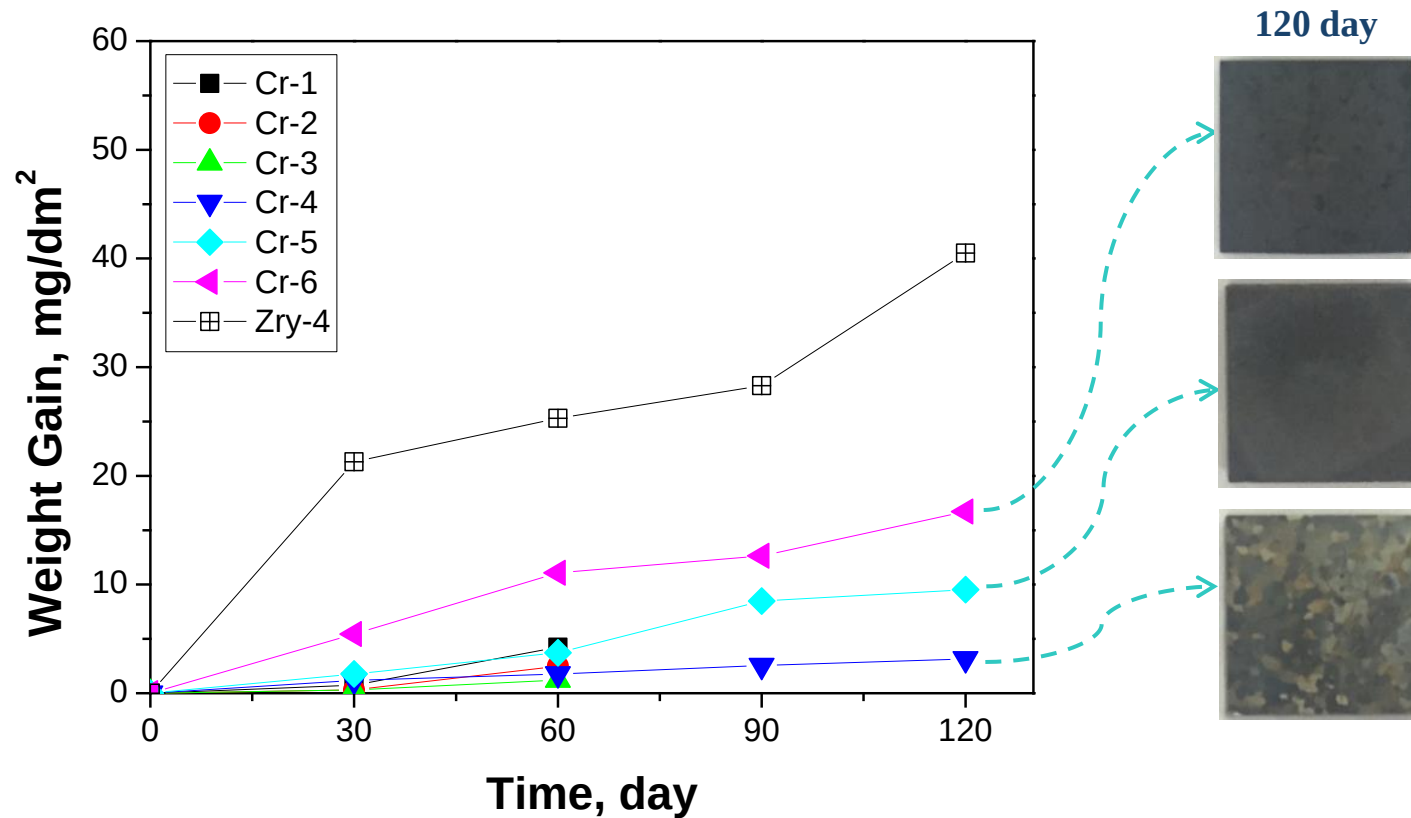
- **Objective of new coating material development**
 - √ more increased oxidation resistance than Cr metal in accident condition
 - √ more increased corrosion resistance than Zr alloy in normal condition
- **Approach**
 - √ model alloy design based on physical/mechanical property, neutron economy, corrosion characteristics, manufacturing process of alloying and coating...
 - √ performance evaluation of model alloy



Performance Evaluation of Test Samples

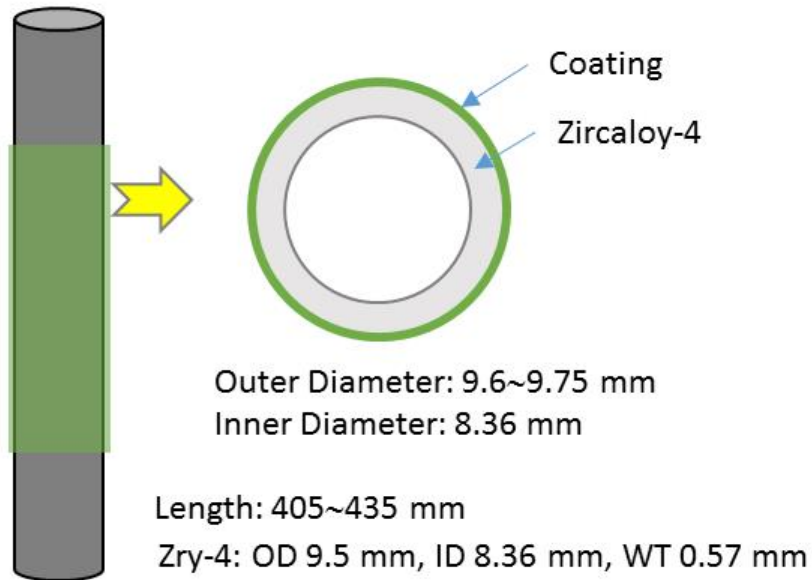
❖ Corrosion test of coating materials

➤ Test conditions: PWR simulated-loop, 360°C, 18.9MPa



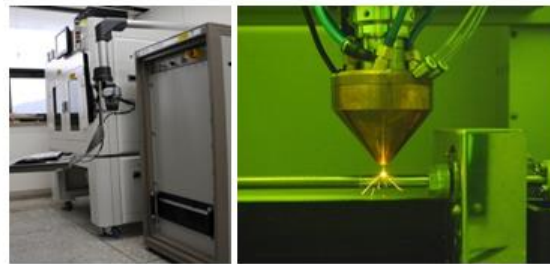
Sample Fabrication for Irradiation Test

Test sample design



Test sample fabrication

3D laser coating



Arc ion plating



Coating A FeCrAl/Cr coated Zry-4 cladding



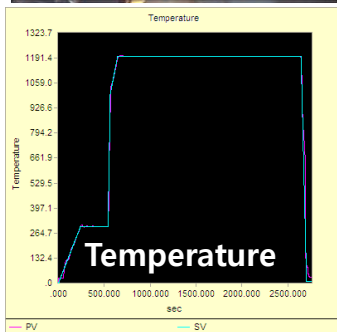
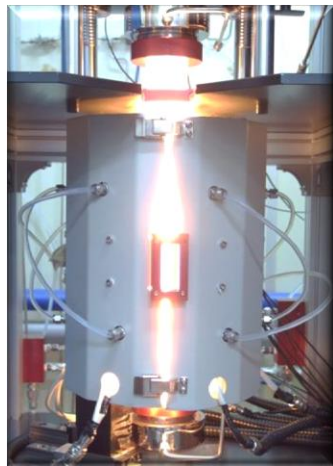
Coating B Cr-alloy coated Zry-4 cladding



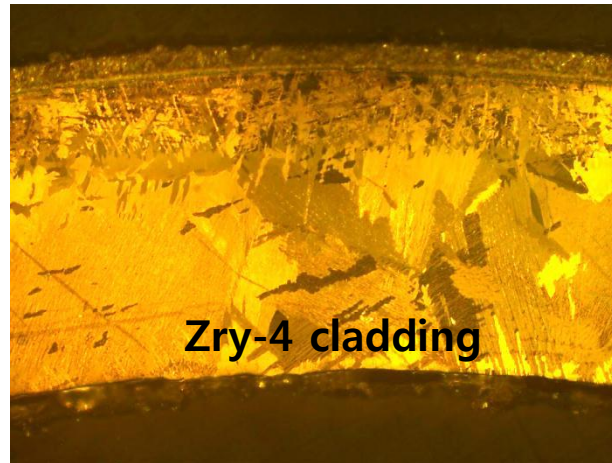
Performance Evaluation of Test Samples

❖ Oxidation test of coated cladding tubes

- Test conditions: 1200°C for 2000s, steam
no internal pressure

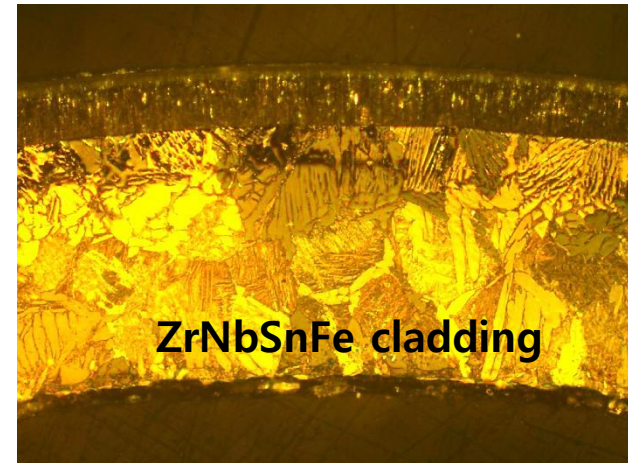


Coated cladding



Zry-4 cladding

Ref. cladding



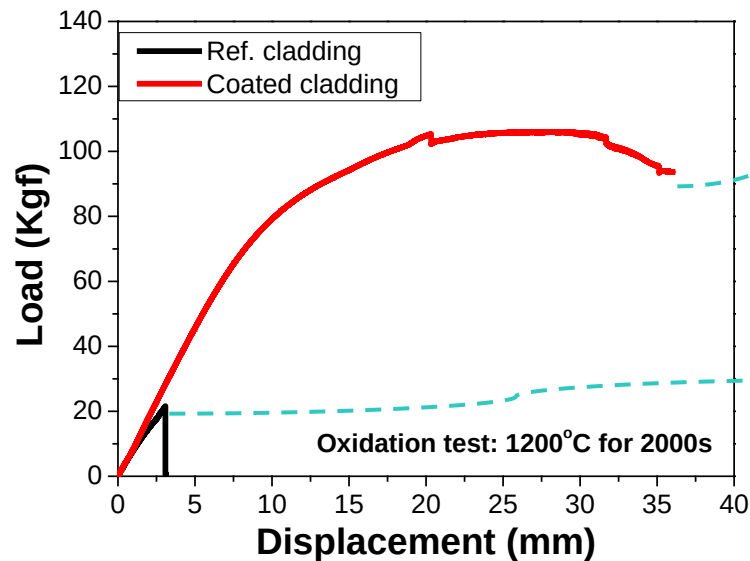
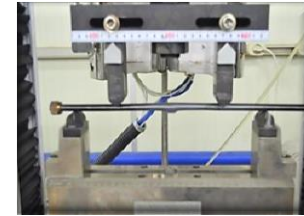
ZrNbSnFe cladding

Oxidation resistance of coated cladding is superior to that of Ref. cladding.

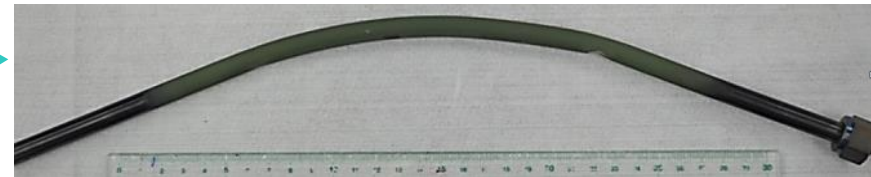
Performance Evaluation of Test Samples

❖ 4-point bend test after oxidation test

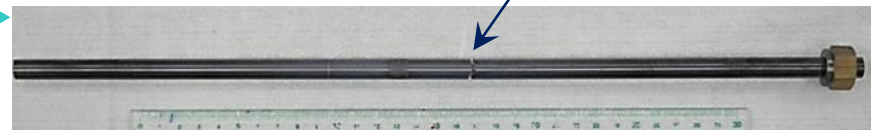
➤ Test conditions: 0.15mm/min



Coated cladding



Ref. cladding

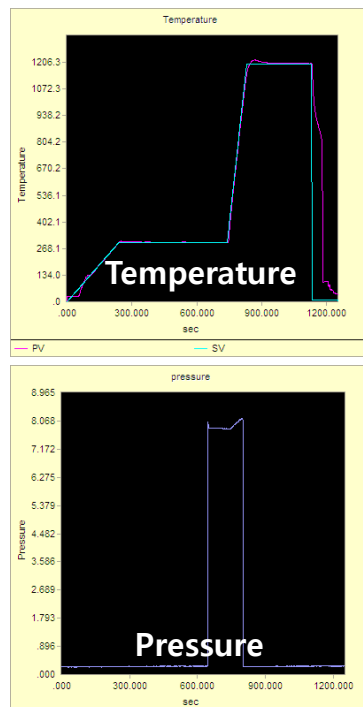


Bending strength of coated cladding is superior to that of Ref. cladding

Performance Evaluation of Test Samples

❖ LOCA-simulation test

- Test conditions: 1200°C for 300s, steam
hoop stress of $61 \pm 2\text{MPa}$



Coated cladding

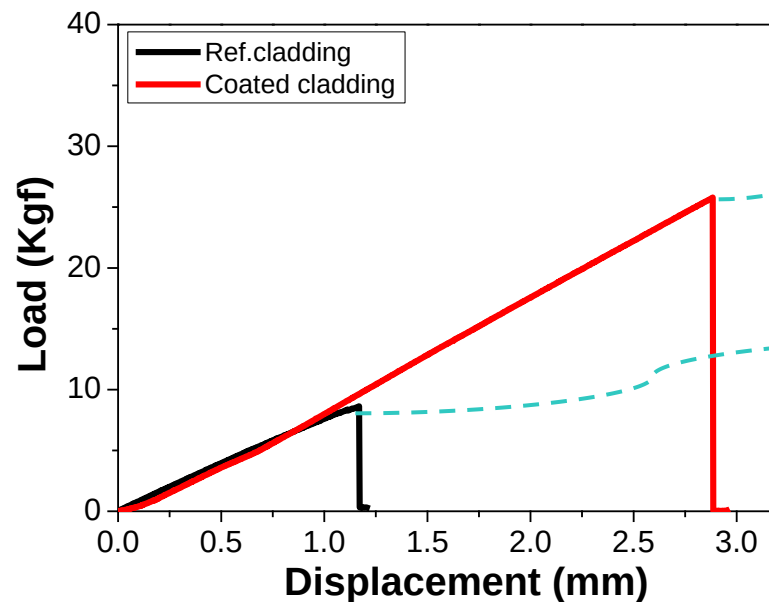
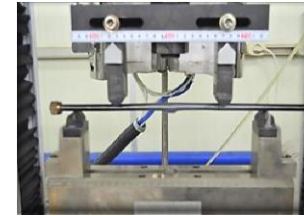
Ref. cladding

Ballooning and rupture behaviors are shown in both claddings

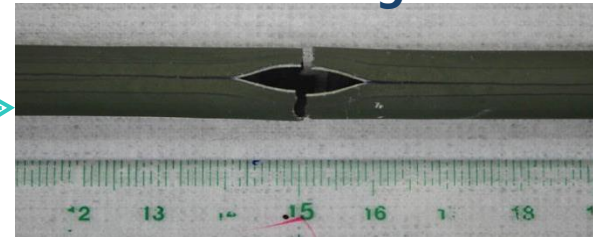
Performance Evaluation of Test Samples

❖ 4-point bend test after oxidation test

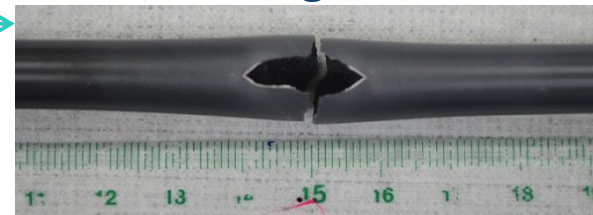
➤ Test conditions: 0.15mm/min



Coated cladding



Ref. cladding



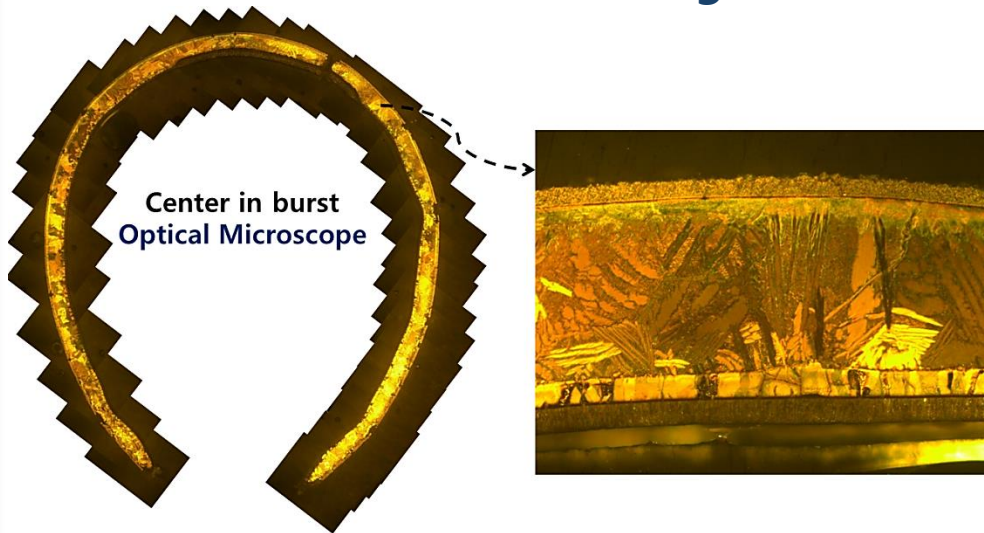
Bending strength of coated cladding is superior to that of Ref. cladding

Performance Evaluation of Test Samples

❖ Microstructural observation

- Test conditions: 1200°C for 300s, steam
hoop stress of 61 ± 2 MPa

Coated cladding



Ref. cladding



Oxidation resistance of coated cladding is superior to that of Ref. cladding at outer surface.

Performance Evaluation of Test Samples

❖ Corrosion test of coated cladding tubes

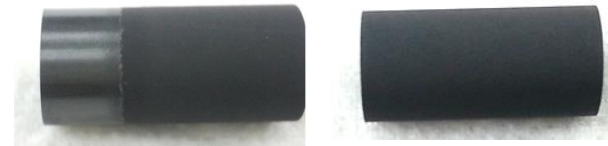
➤ Test conditions: static autoclave, 360°C, pure water, 18.9MPa

Coating A: FeCrAl/Cr



60 day

Coating B: Cr-based alloy



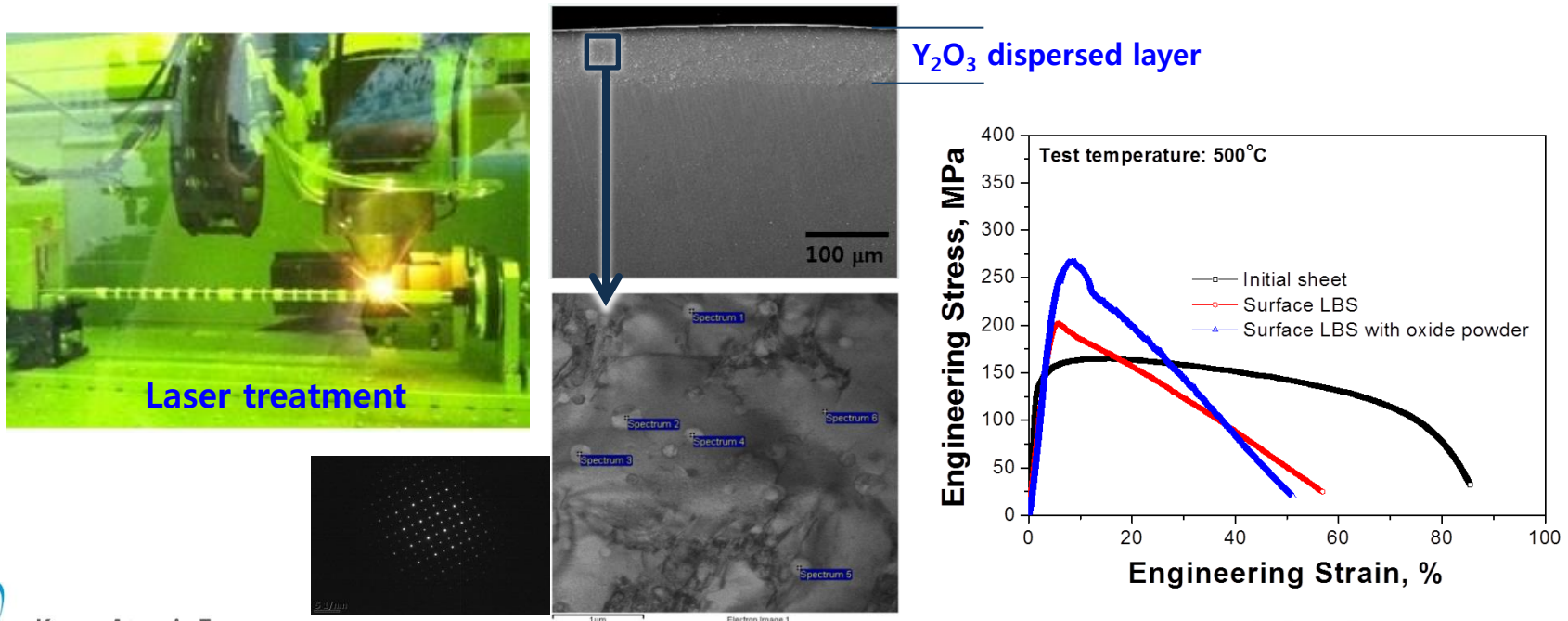
60 day

From the static autoclave test result, the flaking and other damages were not observed in the tested samples, although the period of corrosion test was not fully enough.

ODS Technology Development for ATFC

- **Objective of partial ODS-Zr development**
 - √ more increased mechanical strength than Zr-alloy at high-temperature
 - reduce of severe ballooning/rupture deformation during accident
- **Approach**
 - √ consideration of strength mechanism of Zr-alloy at high-temperature
 - √ consideration of performance, easy application, and efficiency

❖ Laser Beam Scanning with Y_2O_3 Powder



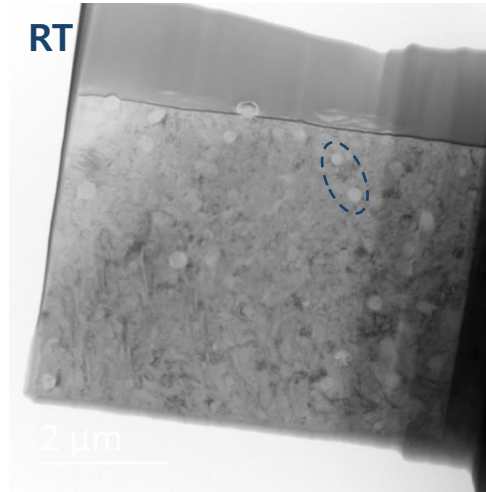
Performance Evaluation of Test Samples

❖ Observation of oxide particles with increasing temperatures

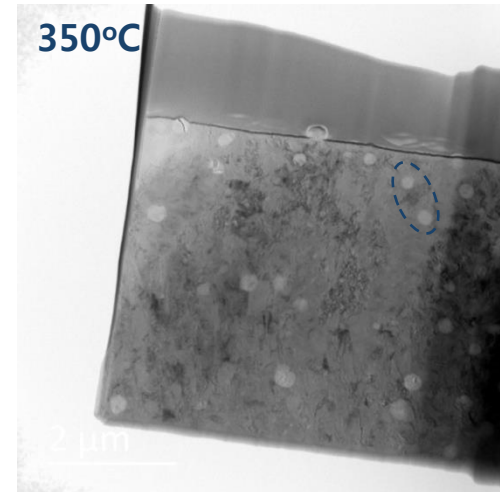
HVEM



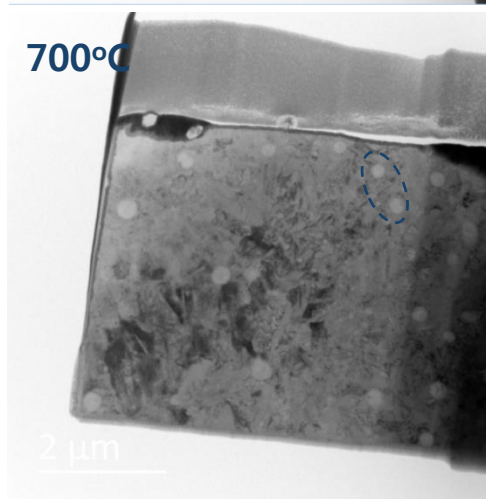
RT



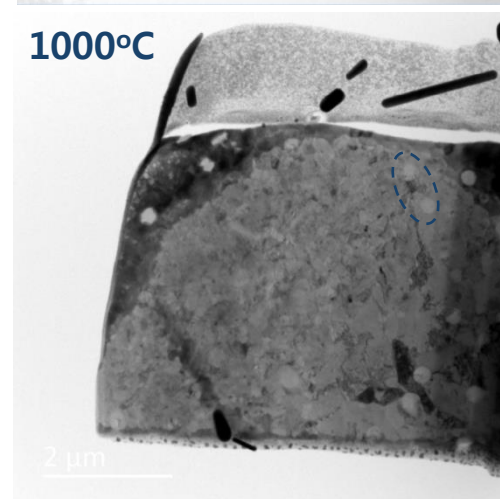
350°C



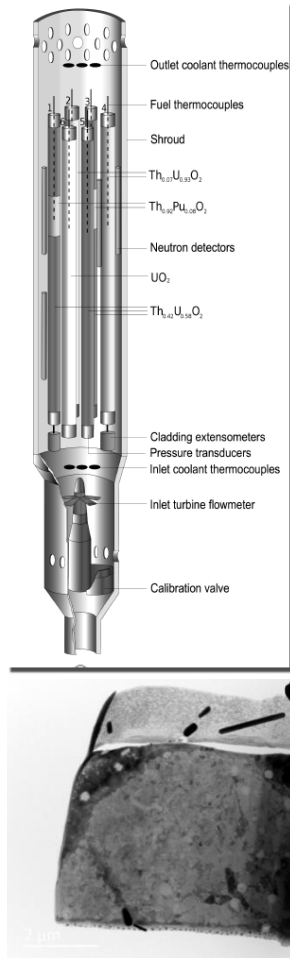
700°C



1000°C



Summary



- **For the research reactor test, the two types of coated samples were fabricated.**
 - √ New Cr based alloys are developed and coated on the Zry-4 cladding.
 - √ Oxidation resistance of coated cladding is superior to that of Ref. cladding.
 - √ Adhesion property of coated claddings is very reasonable during the accident conditions and normal operating corrosion.
- **Stability of oxide particles is identified to accomplish the surface-modified concept (partial ODS + coating).**
 - √ The Y_2O_3 particles are maintained without a reaction to Zr matrix up to 1000°C.

감사합니다.

Thank you for your attention.