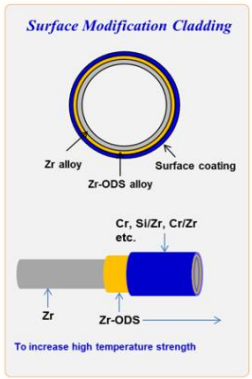
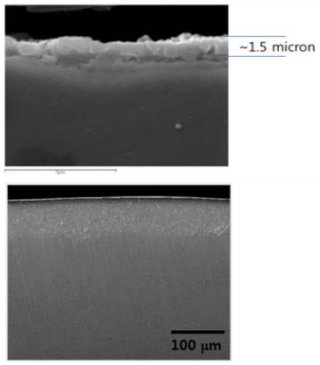
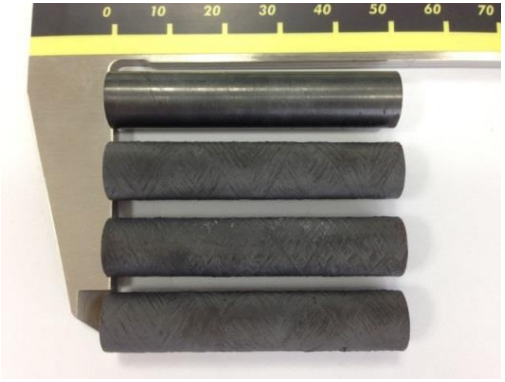
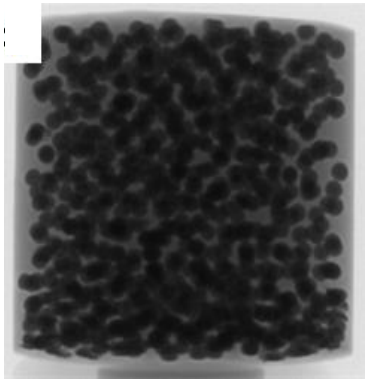
Updates on Accident Tolerant Fuel R&D in Korea









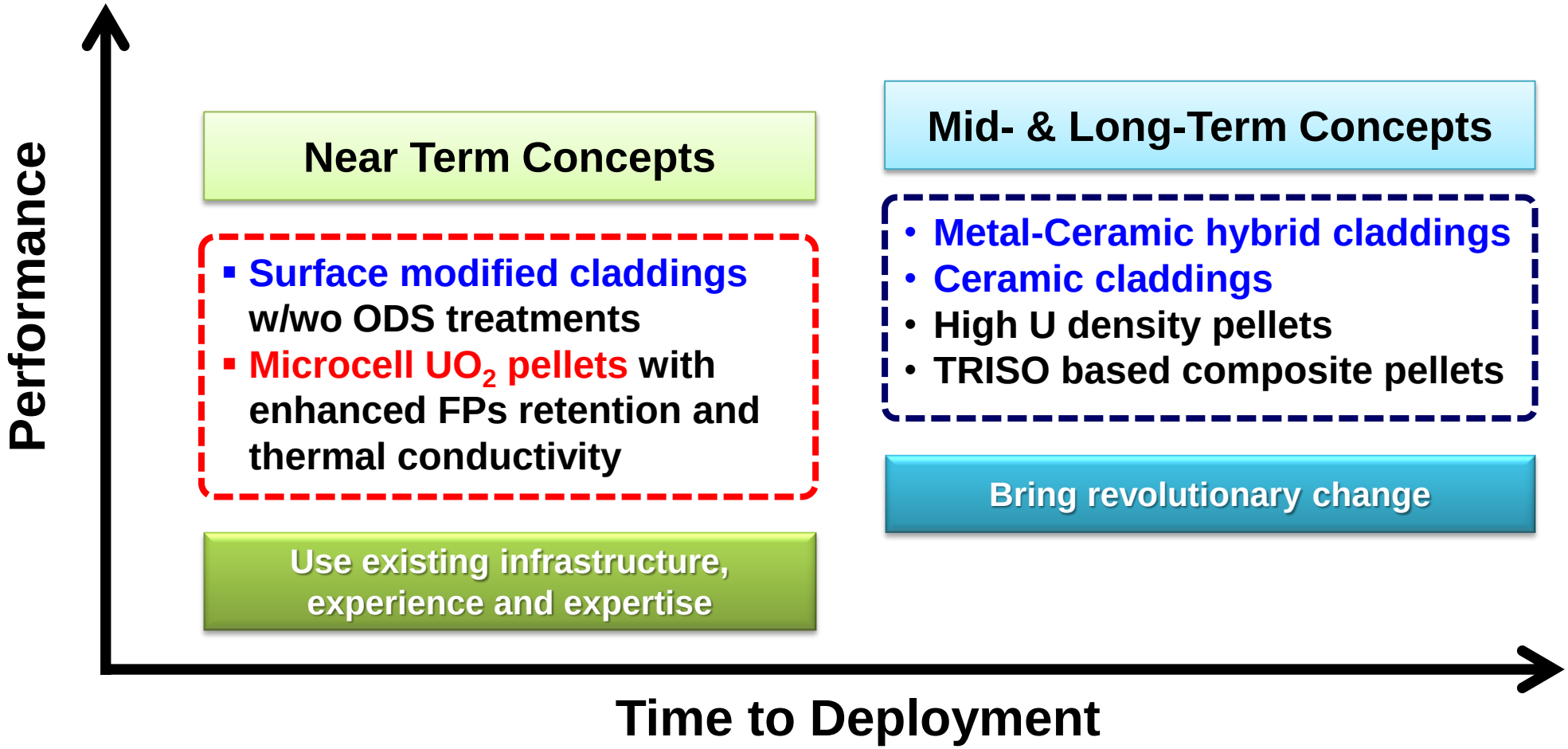
Yang-Hyun KOO, KAERI

6th EGATFL, 15-16 Sept. 2016, Boise, USA

KAERI Korea Atomic Energy Research Institute

R&D activities for ATFs in KOREA

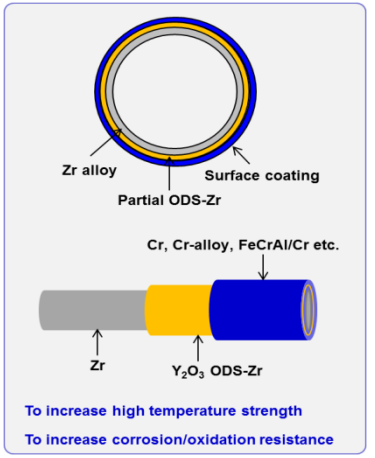
❑ Objective: Develop & select ATF concepts for irradiation test in a commercial reactor by 2021

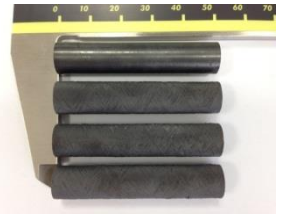


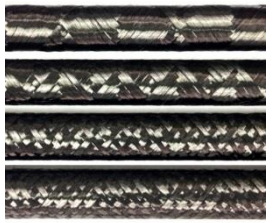
ATF Cladding & Fuel Concepts

❑ Claddings: Enhanced Oxidation Resistance & Strength

- Surface modified Zr-tube (coating/ODS/Zr)
  - ✓ Coating: CrAl, FeCrAl/Cr
  - ✓ ODS: Y_2O_3, Er_2O_3, Gd_2O_3…
- Ceramic Composite
  - ✓ SiC_f/SiC composite
- Metal/Ceramic Hybrid
  - ✓ Metal(coating)/Ceramic-composite(SiC_f/SiC)/Metal(Zr)

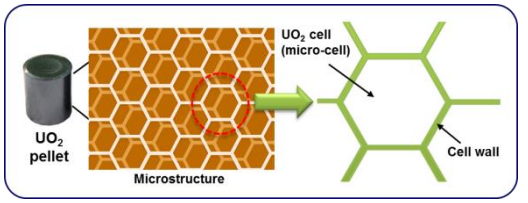


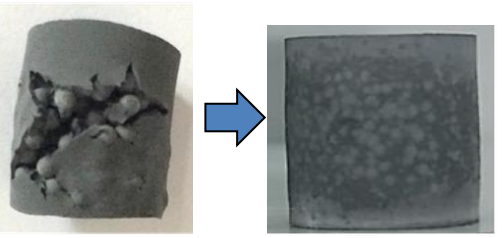




❑ Fuels: Enhanced Thermal conductivity & Fission Products Retention

- Microcell UO_2
  - ✓ Ceramic wall: Si-Ti-O, Cr-Si-O, BeO,…
  - ✓ Metallic wall: Mo, Cr, alloys,…
- High uranium density pellets
  - ✓ UN, U-Si: composite for waterproof
- Coated particle fuel (KEPCO NF KEPCO NUCLEAR FUEL COMPANY, LTD.)
  - ✓ SiC-TRISO : Pressure-less sintering





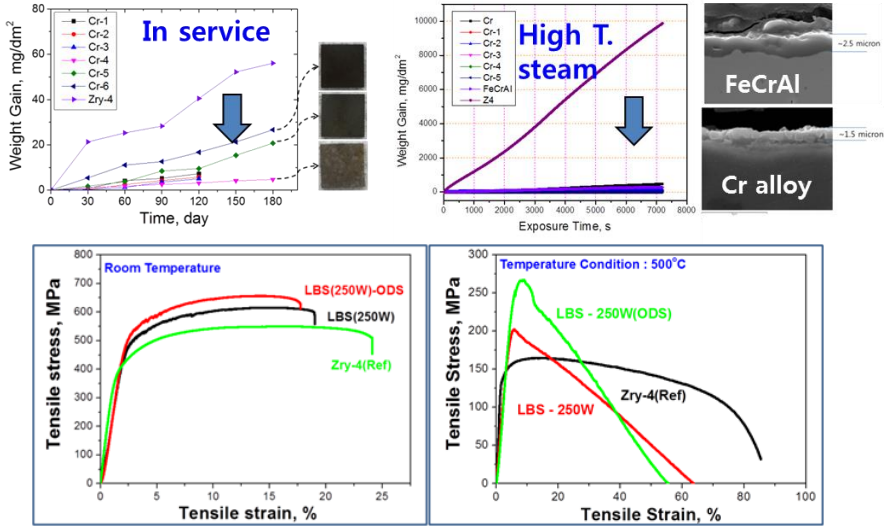
1. Surface Modified Cladding-Highlights

❑ Alloy & structure design

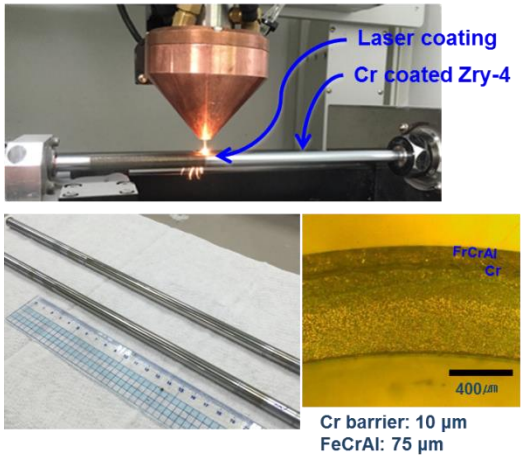
- **Cr-Al alloy** : Superior oxidation resistance & no pitting corrosion
- **FeCrAl/Cr multi-layer** : thin Cr-barrier to prevent Fe-Zr eutectic reaction
- **Partial ODS** (Y_2O_3, Gd_2O_3, Er_2O_3): Increase deformation resistance, Economic & flexible reactivity control

❑ Fabrication processes

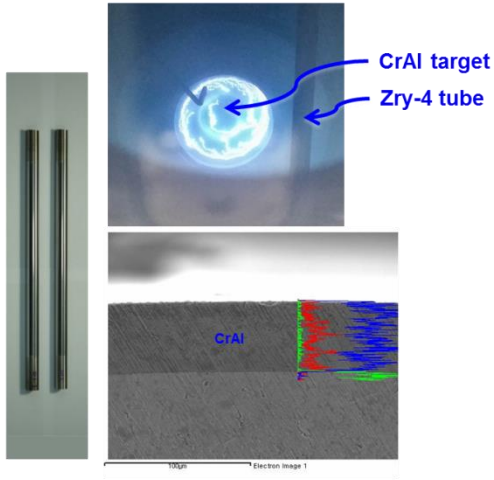
- 3D laser coating : coating & ODS treating
- Arc ion plating : thin layer and alloy coating



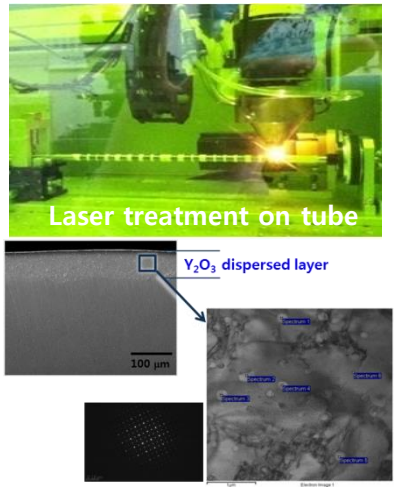
FeCrAl/Cr/Zry-4



CrAl/Zry-4



ODS(Y_2O_3)/Zry-4

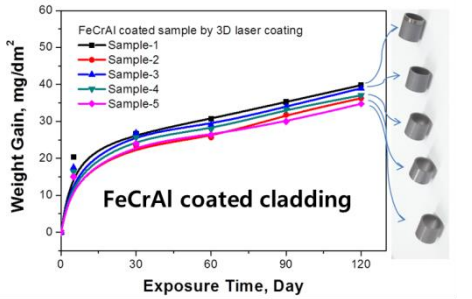


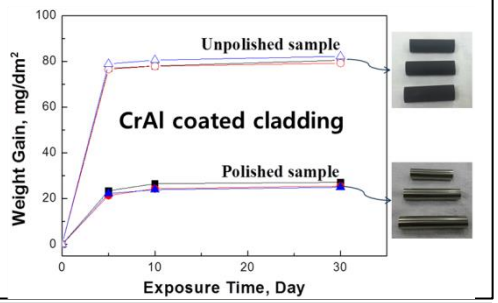
1. Surface Modified Cladding-Highlights

❑ Performance evaluation

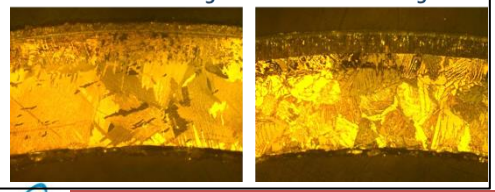
- Oxidation tests in PWR simulation loop & high T. steam (1200°C)
- Integral LOCA tests
- 4-point bending tests after the oxidation and integral LOCA tests

PWR simulation loop test

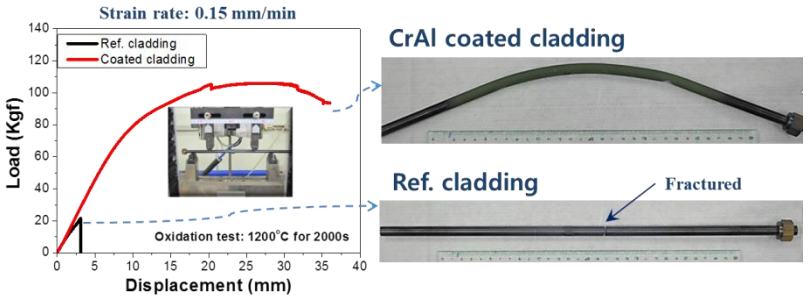




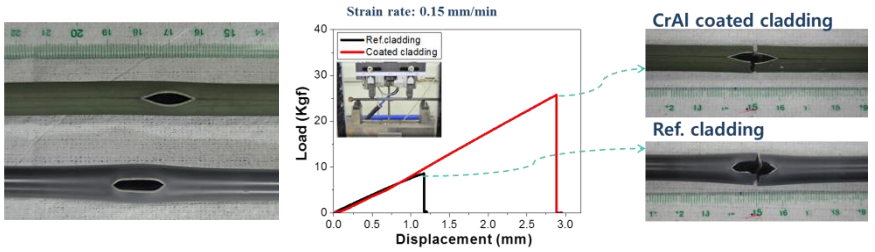
High T. steam test



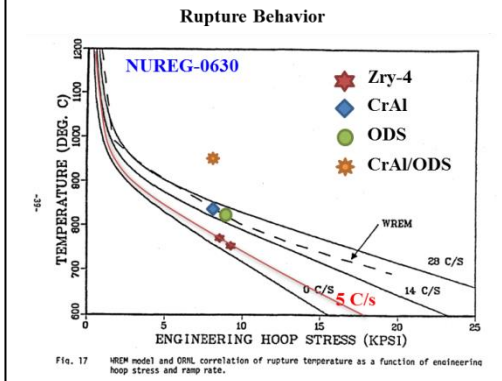
• 4-point bending after high T. steam oxidation

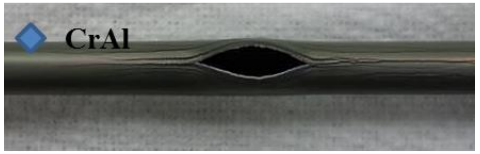


• 4-point bending after LOCA-simulation



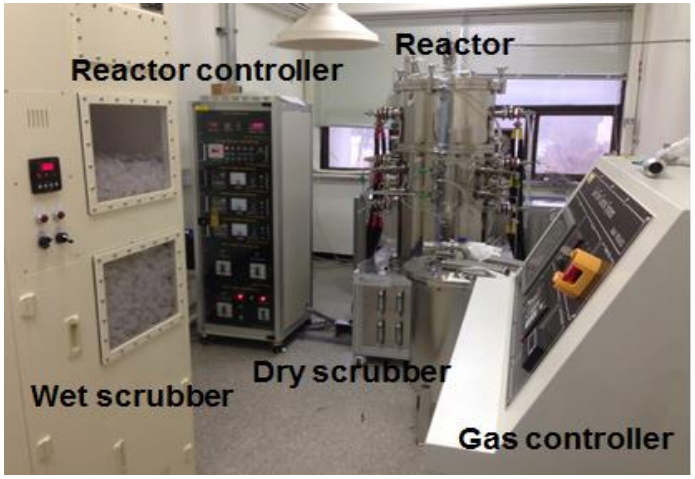
Integral LOCA

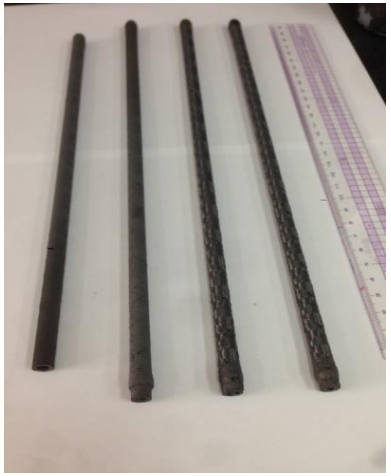




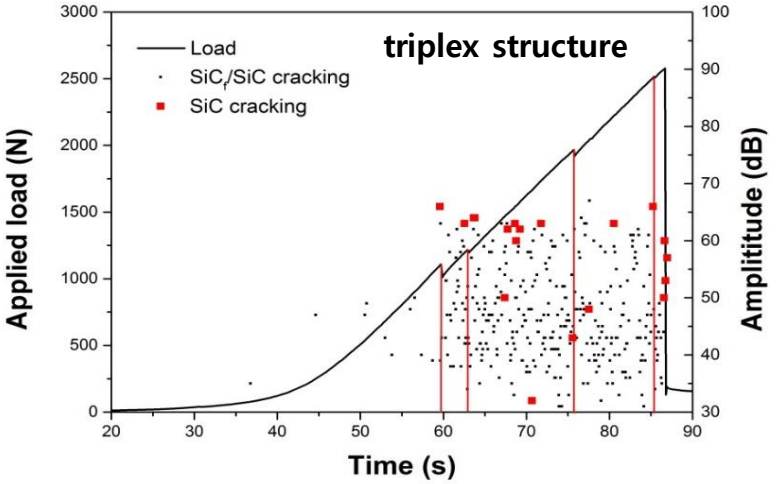
2. Ceramic Composite Cladding-Highlights

- Installation of CVI reactor for ~30 cm long SiC composite tubes

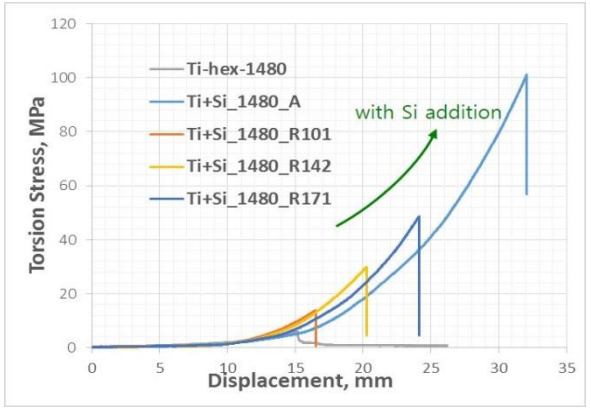


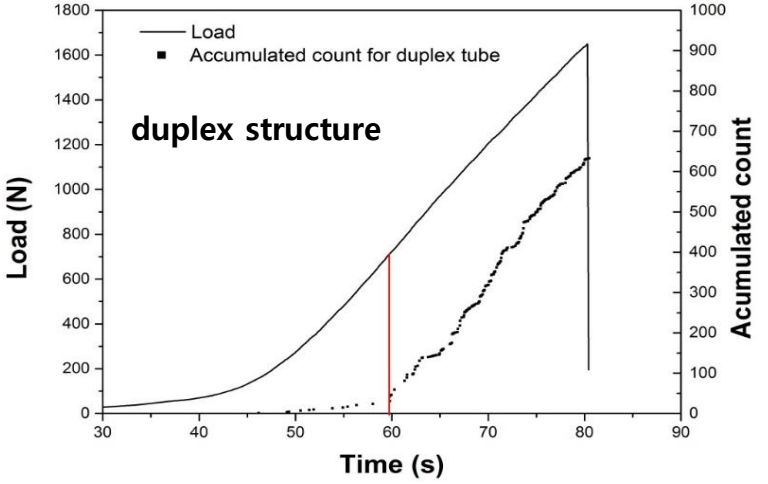


- Analysis of crack formation by acoustic emission for different structural designs



- Development of joining process





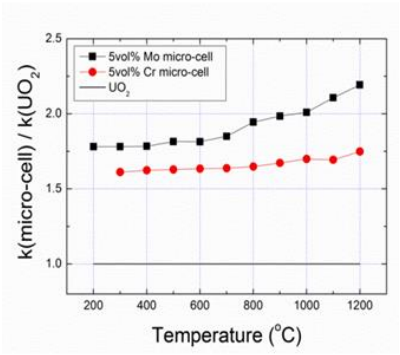
3. Micro-cell UO_2 Pellets-Highlights

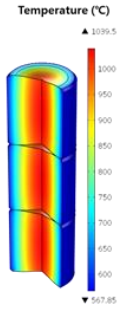
❑ Material selection, Structure Design & Fabrication Processes

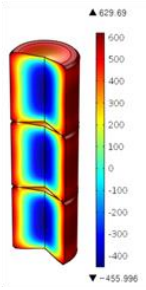
- **Material candidates:** Mo, Cr, BeO, Si-Ti-O, Cr-Si-O,…
- **Structure:** Cell size 100~350μm, wall thickness 1~8 μm
- **Fabrication:** Conventional pressure-less sintering

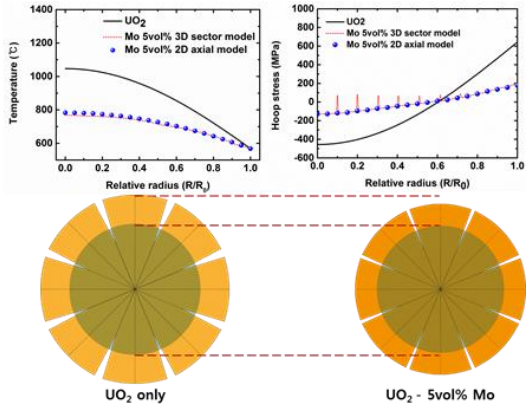
❑ Property tests & Performance modeling

- Thermo-physical properties
- Modeling & simulation: Hoop stress calculation to simulate pellet fracture
- Oxidation tests in autoclave & high T. steam (500~1100°C)
- Pellet integrity tests under LOCA simulated thermal shock and high temperature(~2600°C)

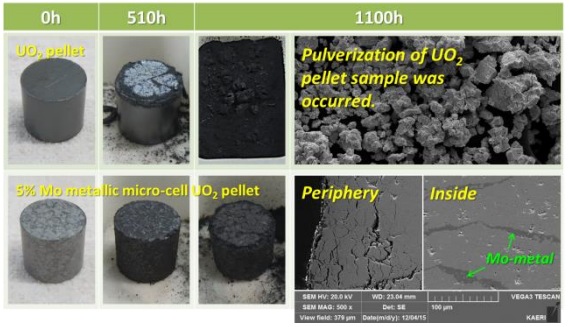




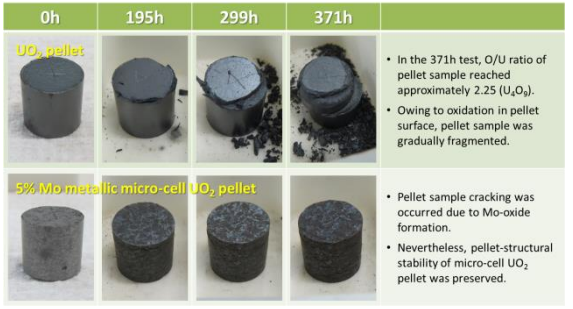




Steam oxidation tests for UO_2-5vol%Mo

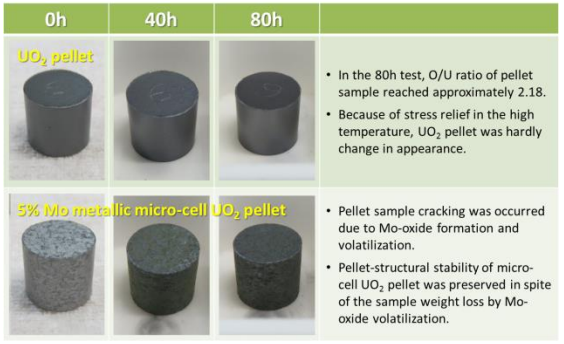


at 500°C



- In the 371h test, O/U ratio of pellet sample reached approximately 2.25 (U_4O_9).
- Owing to oxidation in pellet surface, pellet sample was gradually fragmented.
- Pellet sample cracking was occurred due to Mo-oxide formation.
- Nevertheless, pellet-structural stability of micro-cell UO_2 pellet was preserved.

at 800°C



- In the 80h test, O/U ratio of pellet sample reached approximately 2.18.
- Because of stress relief in the high temperature, UO_2 pellet was hardly change in appearance.
- Pellet sample cracking was occurred due to Mo-oxide formation and volatilization.
- Pellet-structural stability of micro-cell UO_2 pellet was preserved in spite of the sample weight loss by Mo-oxide volatilization.

at 1100°C

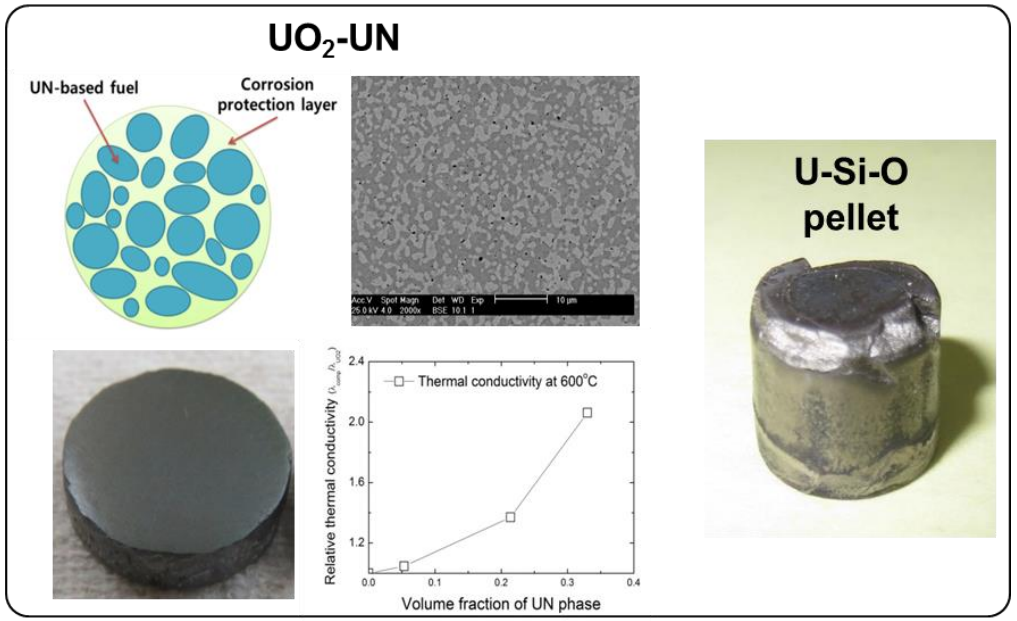
4. High U-density & Coated Fuel

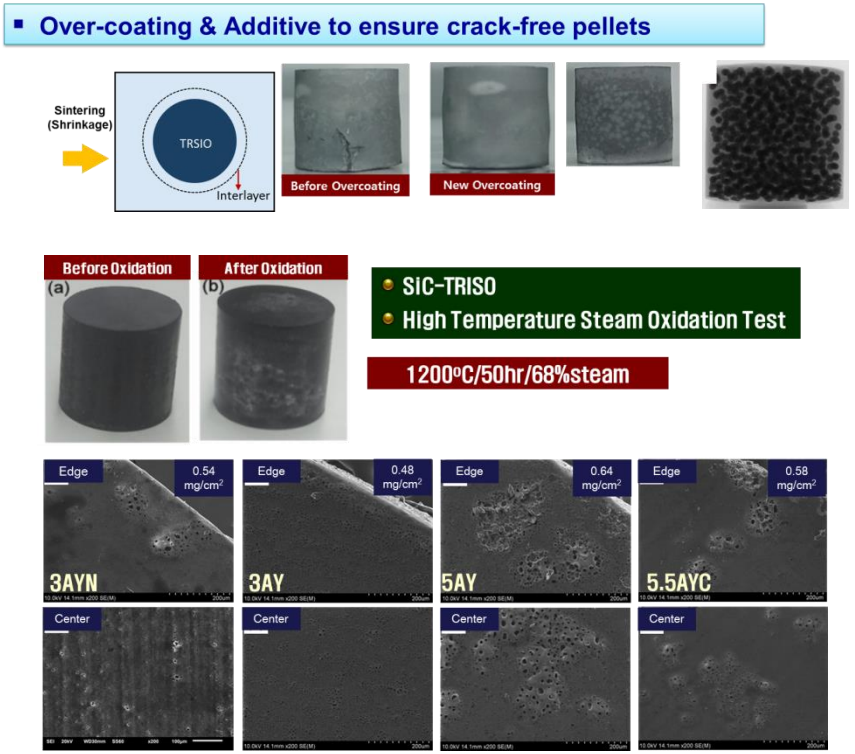
❑ High U-density pellets

- **UO_2-UN pellets**: UO_2 matrix delay oxidation(further improvement required)
- **U-Si-O pellets:** Simple mixing & conventional pressure-less sintering is being explored sintering

❑ SiC-TRISO pellets

- Pressure-less sintering process: Over-coating & Additive to ensure crack-free pellets
- High temperature steam oxidation test for additives doped-SiC matrix (1200°C)
- Reaction between additives and TRISO

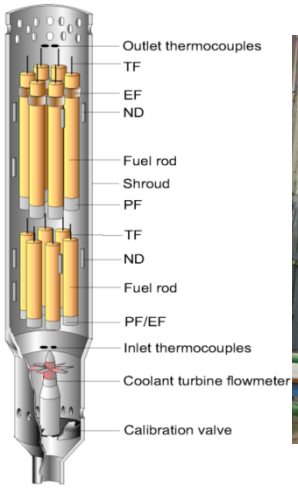


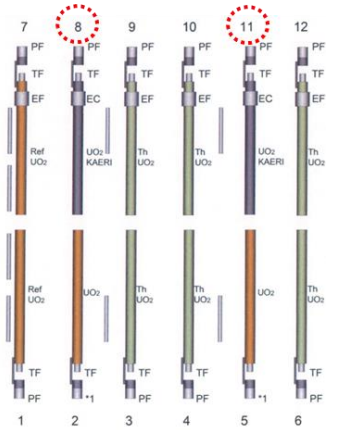


Irradiation Test-Highlight

❑ Two ATF Pins in Halden reactor

- IFA-790 (with Thor Energy)
- **Pin #8**: **Ceramic** micro-cell pellet (**0.6wt%Si-Ti-O**)
  + **CrAlFe/Cr** coated Zircaloy cladding
- **Pin #11**: **Metallic** micro-cell pellet (**5vol%Cr**)
  + **CrAl** coated Zircaloy cladding
- Linear power: ~30 kW/m
- Irradiation period: ′15.12~ ′17.12. (25 GWd/MTU)
- Burnup reached: 7.5 GWd/MTU





Fuel centerline temperature

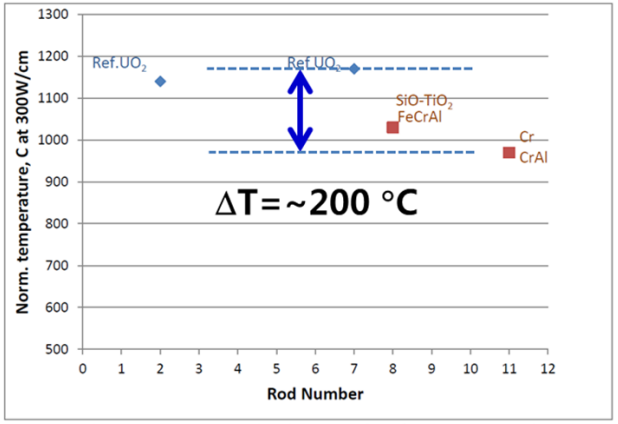


Fig.2 - Fuel temperatures (normalised at 300 W/cm) for the KAERI rods and two rods used as reference. As one can notice, the KAERI fuel rods exhibit lower temperature.

Rod internal pressure

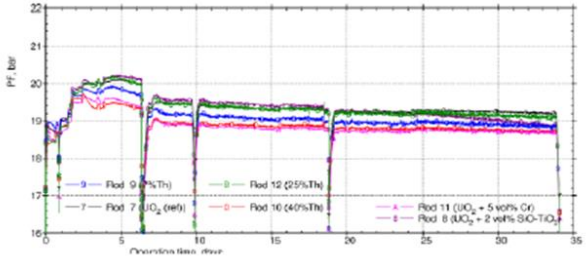


Fig. 5 – Rod pressure vs time in the upper cluster rods. The slight decrease vs. time can be attributed to (very moderate) fuel densification

Rod elongation

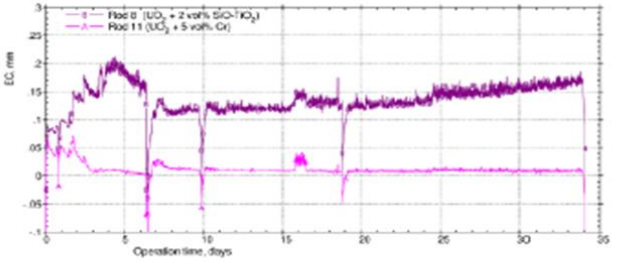


Fig. 6 – Cladding elongation behaviour in the two KAERI rods. Very moderate or no PCMI is apparent from these data

Further Irradiation Test Plan

- **OECD/NEA Halden Reactor Project for ATF cladding and pellet: 2017**
  - 4 kinds of ATF cladding samples were delivered (2016)
    - ✓ CrAl coating on Zircaloy-4 w/wo ODS layer
    - ✓ FeCrAl/Cr coating on Zircaloy-4 w/wo ODS layer
  - Microcell UO_2 pellets having optimized cell composition

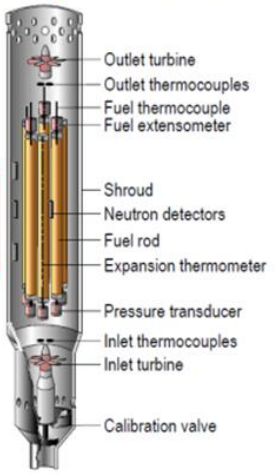
ATF cladding test - test matrix under discussion

add EC?

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

Long-term irradiation of additive / ATF fuels

- A long-term fuel irradiation experiment is planned to study the thermo-mechanical and FGR behaviour of enhanced performance fuels
- Candidate fuels proposed by HRP participants:
  - Additive fuel aimed at retaining fission gas products in the pellets during transients/accidents and/or imparting higher thermal conductivity (KAERI)
  - UN fuel with USi (SSM/KTH)
  - Fuel as disks (high BU accumulation rate) for future PIE (cooperation with EPRI – NFIR) e.g v.small/v.large GS, USi, UN, AlSi-UO2
- Discussion and decision by HPG during **2015/2016** with irradiation starting **2017**



- **Cooperation with MIT**
  - Mechanical test and Irradiation tests in MITR: Interface behaviors of surface modified Zr coupons and tubes provided by KAERI
  - Samples were provided & expected to be loaded at **December 2016**.