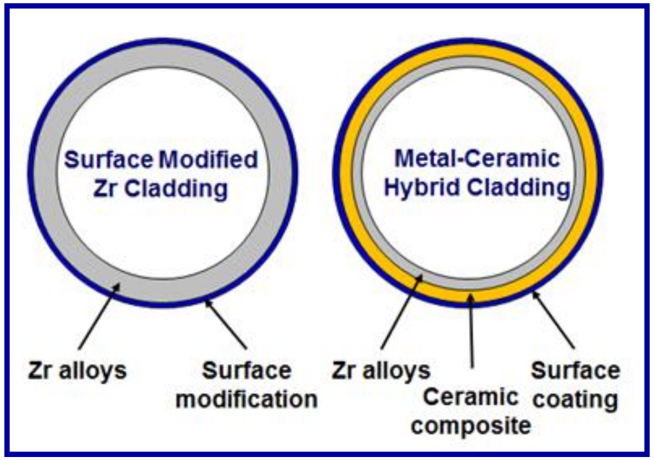
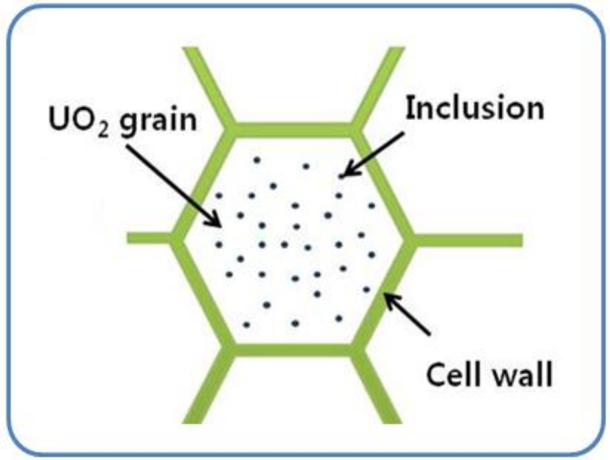
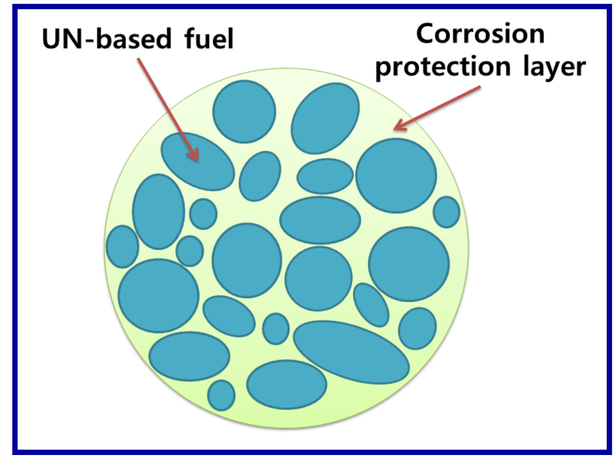
Accident Tolerant Fuel (ATF) Development: KAERI's R&D Status







Start-Up Meeting of the Expert Group on Accident Tolerant Fuels for LWRs, NEA Headquarters, Paris, 28-29 April, 2014

구양현(Koo Yang-Hyun), 양재호(Yang Jae-Ho), 김현길(Kim Hyun-Gil)

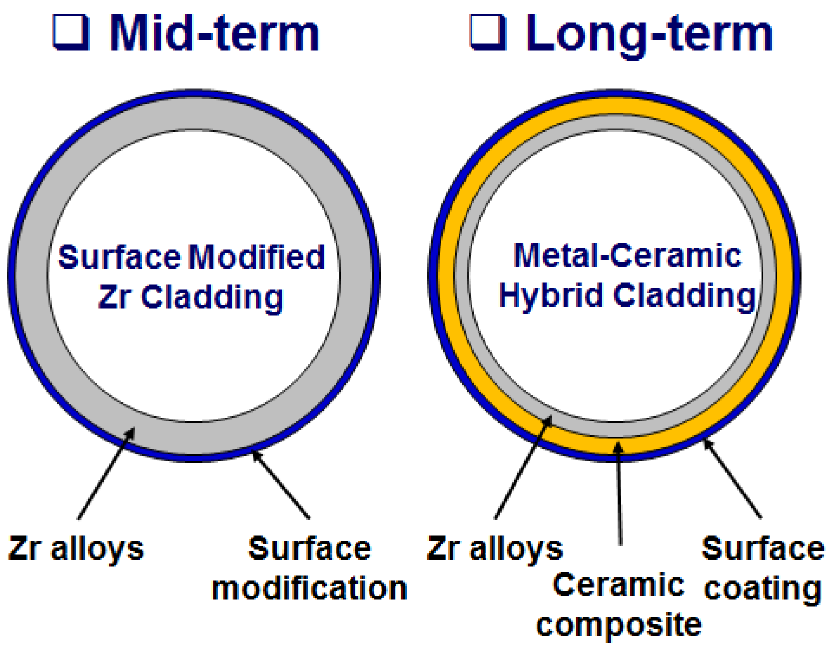
Hydrogen Explosion

- Huge amount of hydrogen is formed: $Zr+2H_2O \rightarrow ZrO_2+2H_2$
- H_2 explodes when its fraction in the steam is higher than ~10%

- Hydrogen explosion: Important in terms of radioactivity release

KAERI's Approach to ATF Cladding

- To reduce H_2 production during accident conditions than current Zr cladding
- KAERI's approach: 1) **Surface modification**, 2) **Metal-ceramic hybrid**



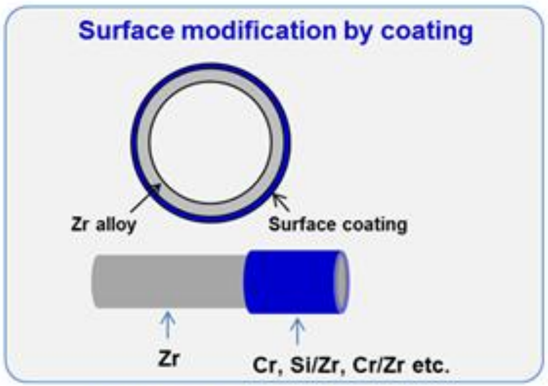
Major Points Considered

- **Oxidation resistance**
- **Thermal conductivity**
- **Thermal expansion coefficient**
- **Phase stability up to high temp.**
- **Adhesion to the matrix**
- **Neutron economy**
- **Irradiation susceptibility**
- **Tube fabricability**

- Material properties, neutron economy, fabricability, irradiation susceptibility

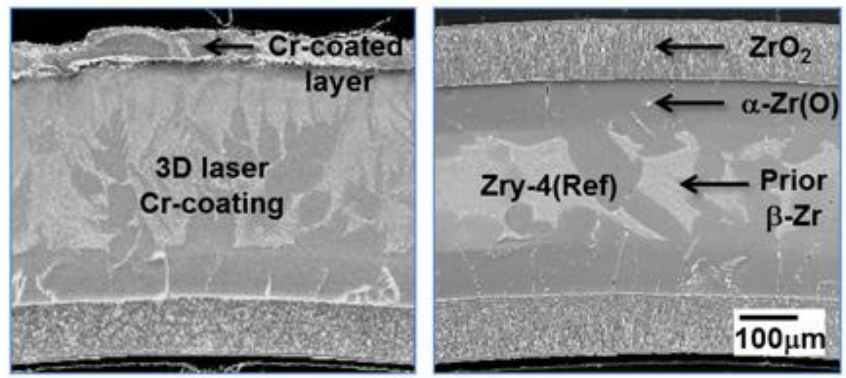
1-1. Zr Surface Modification by Coating

- Surface coating of Zr cladding with Cr powder to enhance corrosion resistance at high temperature



3D laser coating technology

Oxidation behavior at high temperature (1200°C)

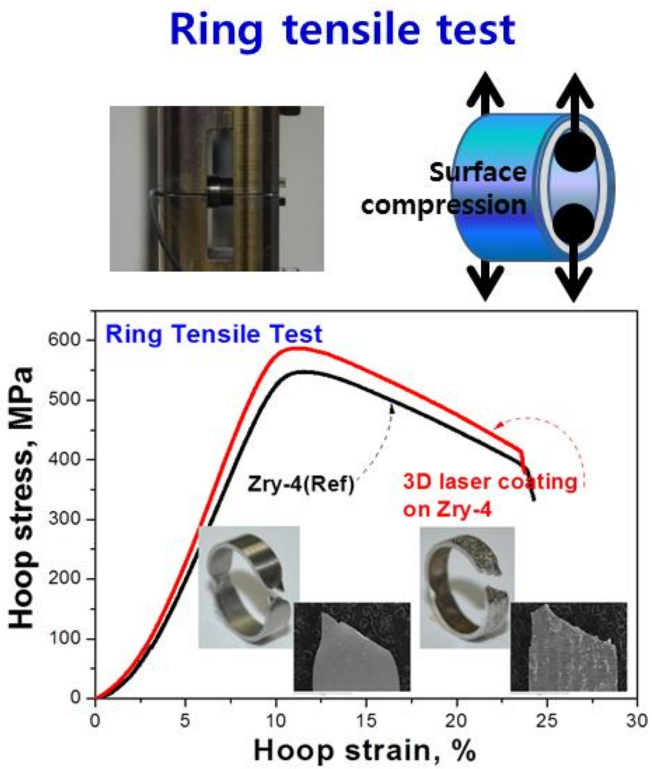


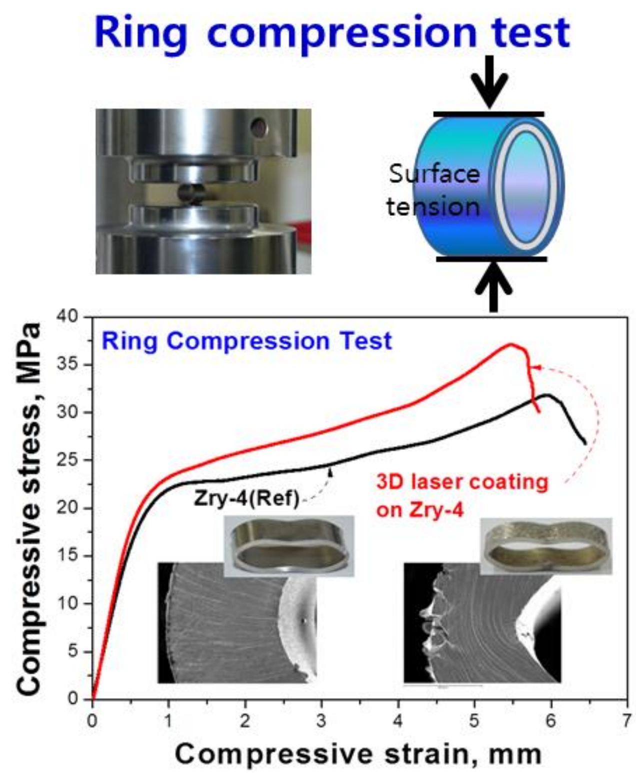
Comparison of oxide thickness (Comparison of hydrogen production)	
Cr-coating	Zry-4
4 micron (1/30 of Zry-4)	~113 micron

- Cr coating: Oxide thickness (**H_2 generation**) is reduced by **1/30** of that in Zry-4 at 1200°C/2000 sec

1-1. Zr Surface Modification by Coating

- **Adhesion of coating** is important to prevent the damage of coated layer during normal/accident conditions

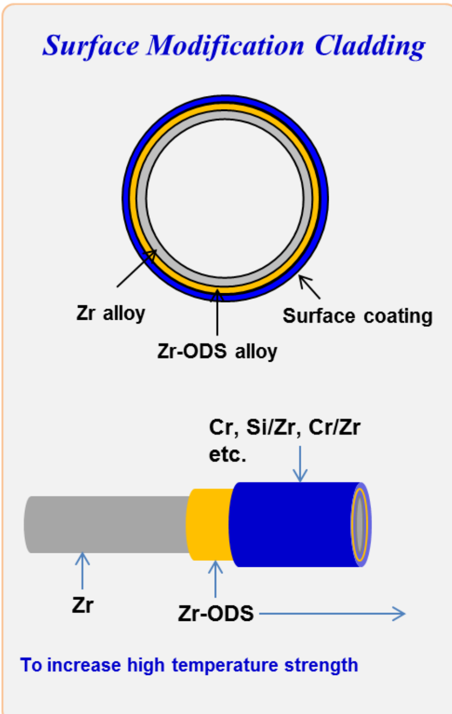


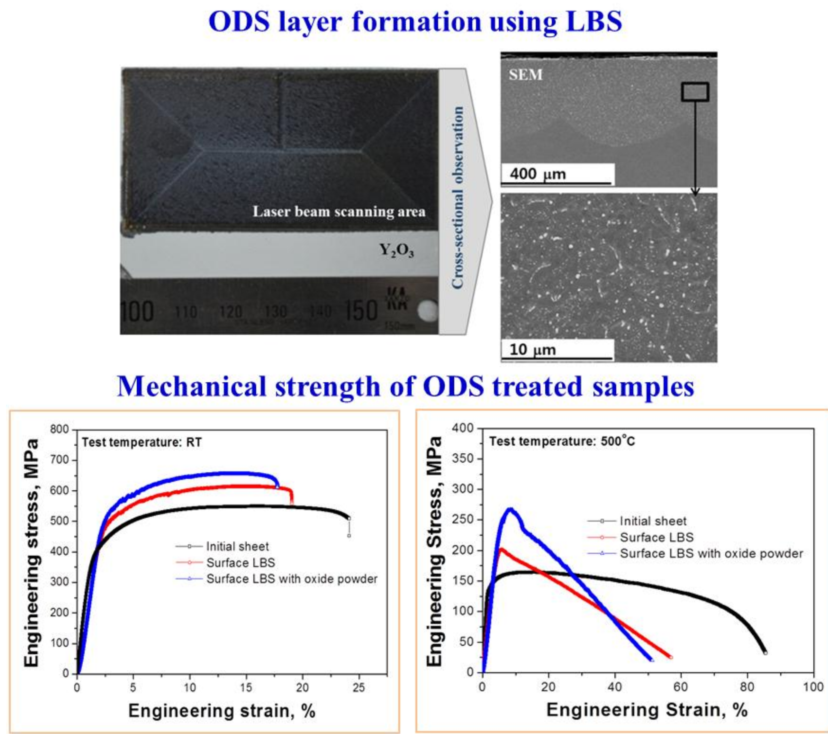


- Ring test shows **good adhesion** of Cr coated layer
  - Cracks were initiated only when strain was higher than 3%

1-2. Zr Surface Modification by ODS Alloying

- ODS alloying to increase mechanical strength: Enhanced deformation resistance → **Reduced ballooning** & **rupture** during accident



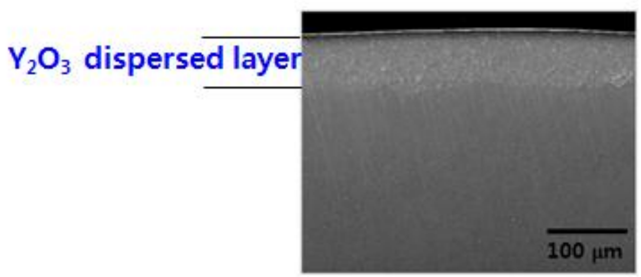


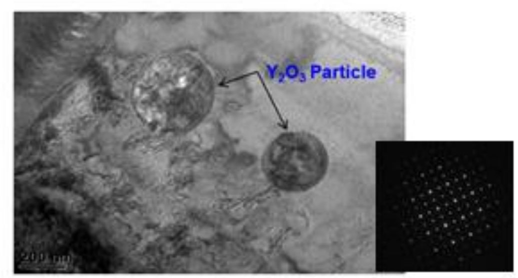
- Y_2O_3 particles alloying: Mechanical strength is increased **2 times** at 500^{o}C

1-2. Zr Surface Modification by ODS Alloying

- Y_2O_3 particles alloying on cladding tube: Test samples are made using **laser beam scanning**. Y_2O_3 particles are uniformly dispersed in cladding surface

Setting for LBS | LBS treatment | After LBS treatment





- The thickness of Y_2O_3 dispersed layer and the density of Y_2O_3 particles: easily controlled by the conditions for **laser beam scanning**

2. Metal-Ceramic Hybrid Cladding

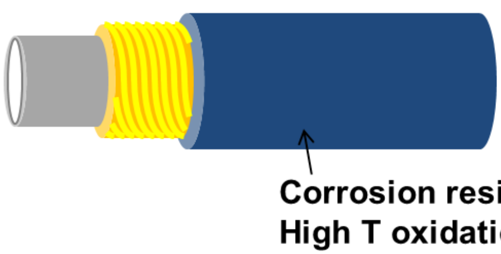
- Combination of advantages of both metal and ceramic
  - Inner layer: **Zr liner** for ductility and fission gas retention
  - Mid layer: **Ceramic composite (SiC_f/SiC)** for high strength and reduced H_2 generation
  - Outer layer: **ZrO_2 coating** to prevent ceramic composite from being dissolved to coolant

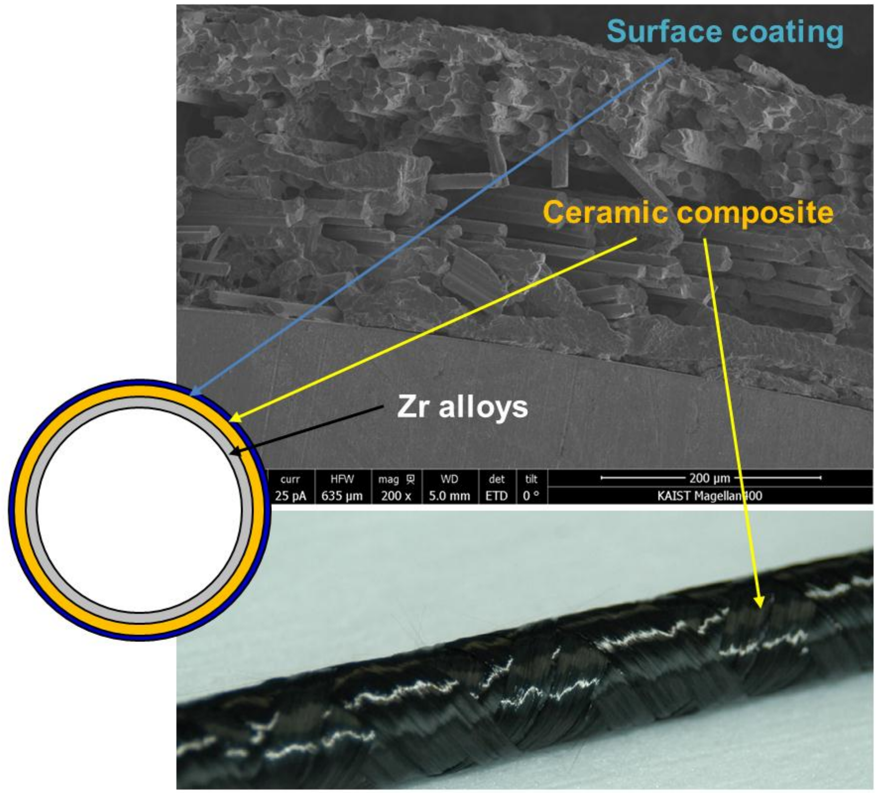
Ceramic Composite (SiCf/SiC)

- Accident Tolerant
  - High temperature strength
  - Low reactivity with water
  - Suppressed hydrogen production
- Strengthening
  - Improved mechanical property

Metal Liner (Zr)

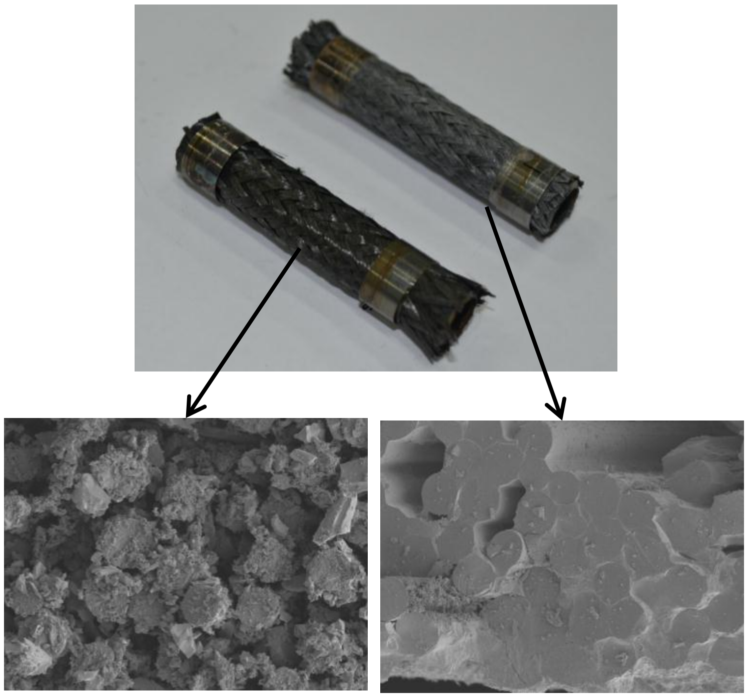
- Proven Performance
  - Ductility
  - Fission gas retention
  - End cap welding



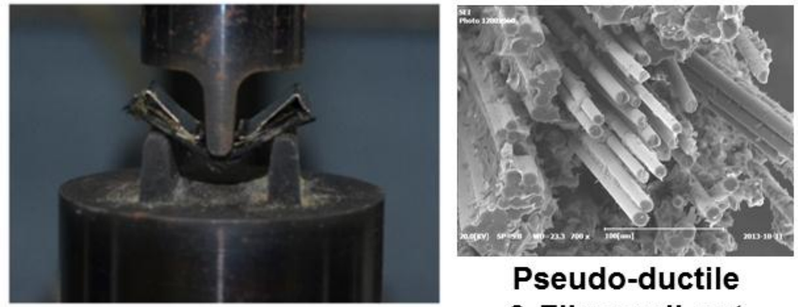


2. Metal-Ceramic Hybrid Cladding

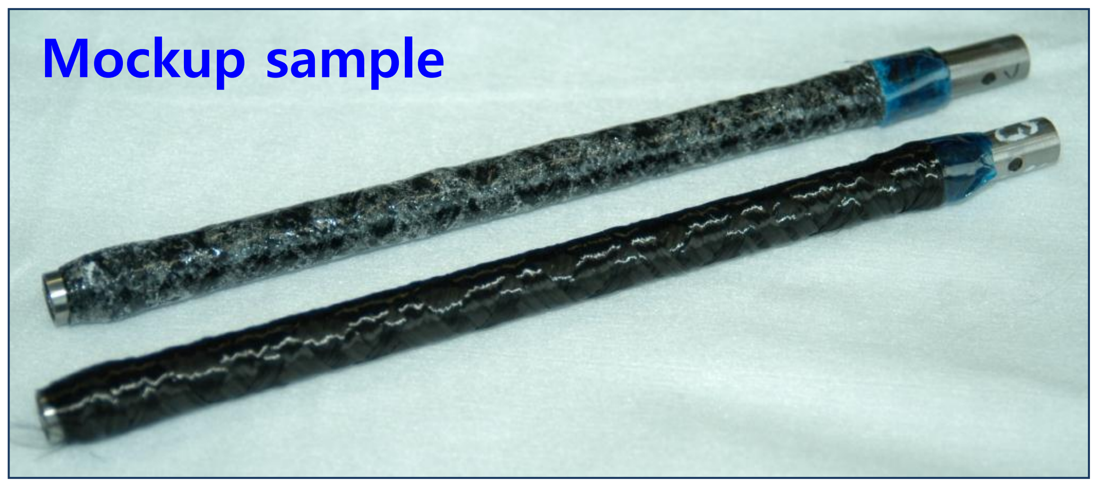
- Important factors in fabricating: Fabric winding, Impregnation, Surface coating, Mechanical strength
- Mockup samples of 20cm in length are made based on parametric studies



Optimization study on impregnation & pyrolysis

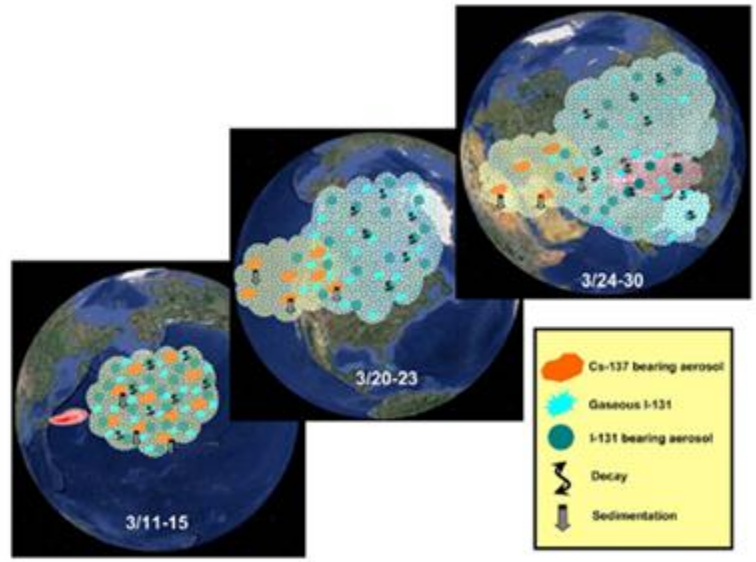


Pseudo-ductile & Fiber pull-out



Radioactivity Release and Transportation

- **Xe** & **Kr**: All the inventory of units 1-3 was released into the atmosphere
- **Cs** & **I**: Less than 10% of the inventory



Shih-Chieh Hsu et al., "Hemispheric dispersion of radioactive plume laced with fission nuclides from the Fukushima nuclear event", Geophysical Research Letters, Vol. 39, L00G22, doi:10.1029/2011GL049986, 2012.

- Once **Xe, Kr, Cs, and I** are released, they can be **easily transported** around the world together with wind

KAERI's Approach to ATF Pellet

- **Mid-term: Micro-cell UO_2 pellets**

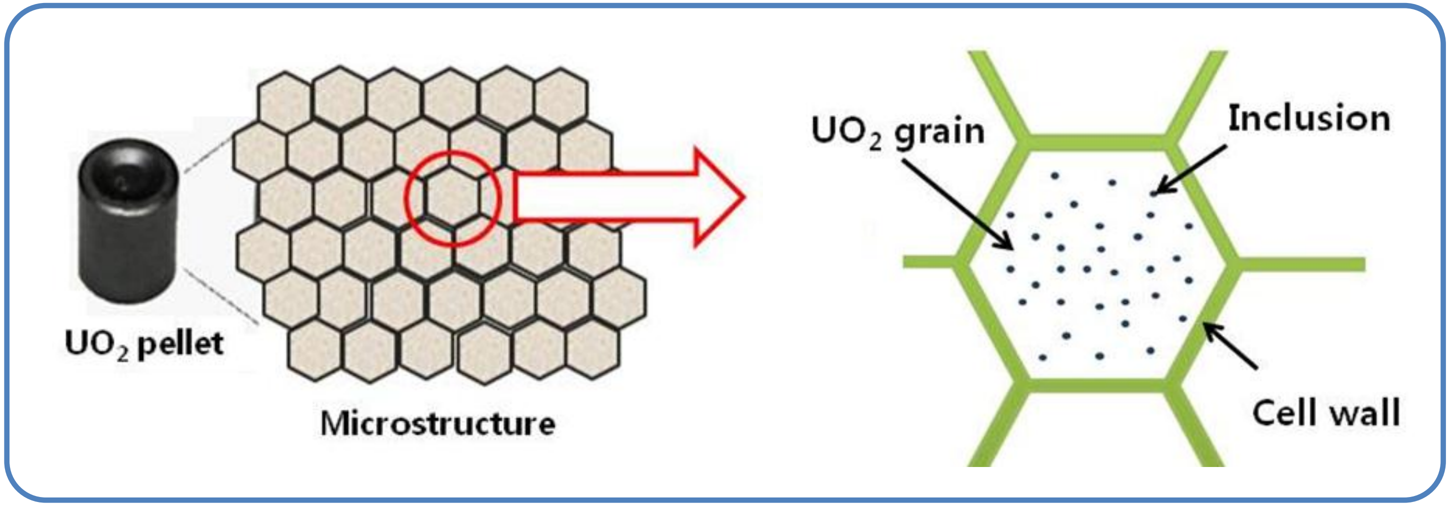
  - To **enhance retention capability** of volatile fission products (Cs, I) → Reduced radioactivity release to the environment
  - To **use existing infrastructure**, experience and expertise to the maximum extent possible → Implemented in the near future

- **Long-term: Uranium nitride (UN) composite pellets**

  - To develop innovative fuel pellets with **uranium nitride composite**
  - To **increase thermal conductivity & uranium density** → Reduced fuel temperature (safety) and increased discharge burnup (economy)

1. Micro-cell UO_2 Pellet

- To **enhance the retention capability** of volatile fission products (Cs, I) during accident and normal conditions

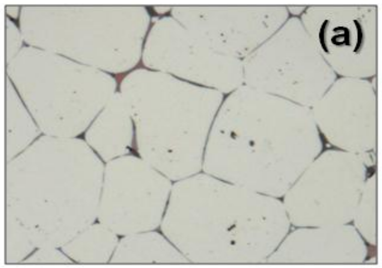


- To provide many **chemical traps** and/or **physical barriers** within UO_2 pellet that prevents volatile fission products from being released to pellet outside
- Cell wall material: Ceramic / metallic micro-cell pellet

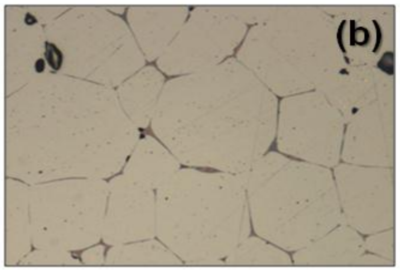
1-1. Ceramic Micro-cell UO_2 pellet

- **Si containing mixed oxide** for cell-wall: Si reacts with Cs and form meta-stable phase. Micro-cell concept was implemented successfully

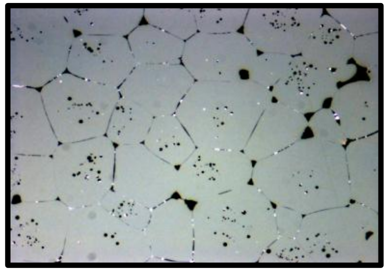
❑ Pellet fabrication



Si-Ti-O (**CM-1**)
- Wall volume : ~3%
- Grain size: ~80μm
- Density : 10.6g/cm^3

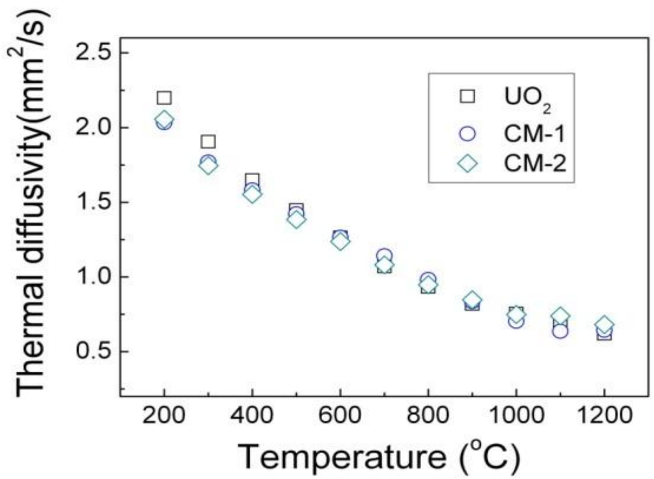


Si-Ti-Al-O (**CM-2**)
- Wall volume: ~3%
- Grain size: ~85μm
- Density : ~10.6g/cm^3



Si-Cr-O
- Grain size: ~65μm
- Density : 10.7g/cm^3

❑ Thermal diffusivity

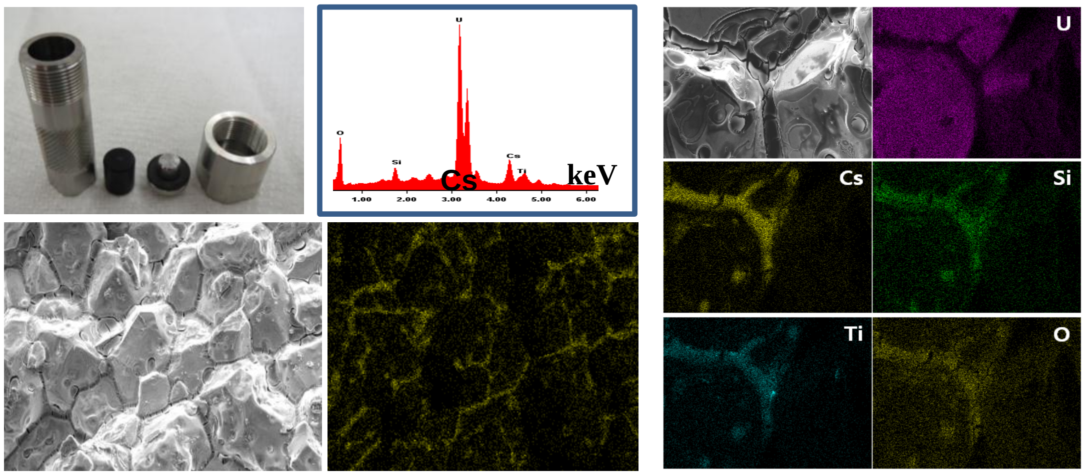


- **Thermal diffusivity**: Ceramic micro-cell pellets have almost the same value as that of pure UO_2

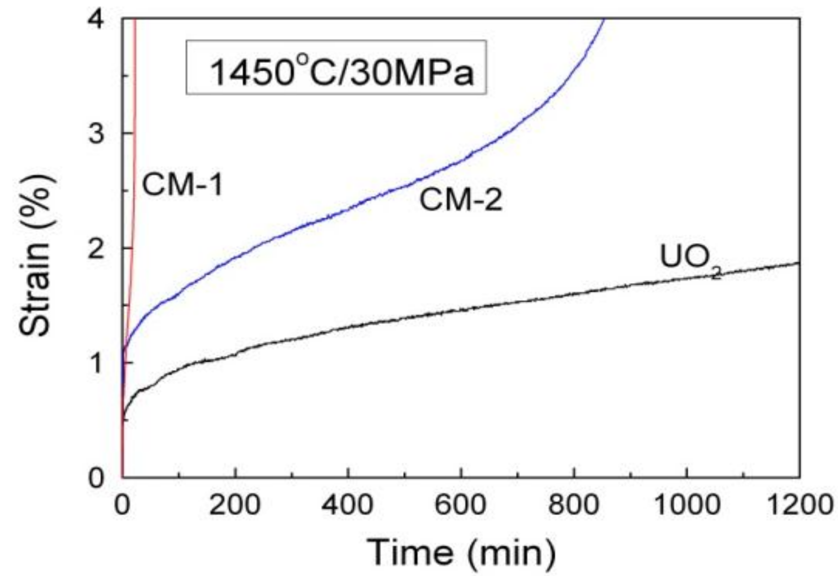
1-1. Ceramic Micro-cell UO_2 pellet

- **Cs capture test:** Cs element mapping by EDS shows high Cs concentration (yellow spots) along cell walls → Cs reacts preferentially with cell wall material

Cs capture



Creep deformation

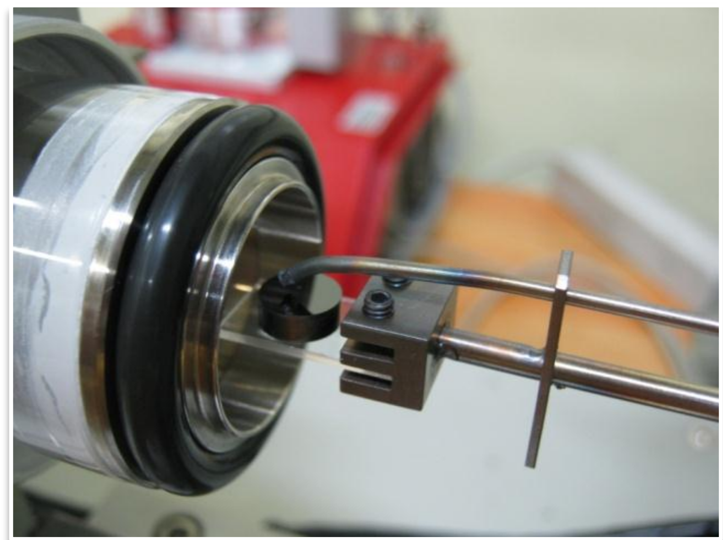


- **Creep deformation test**: Ceramic cell pellets deform more easily than pure UO_2 due to soft cell-wall

1-1. Ceramic Micro-cell UO_2 pellet

- To test the behavior of ceramic micro-cell pellet under accident condition and normal operation, test equipment is being installed:
  - **Thermal stability test under LOCA simulating heating conditions**





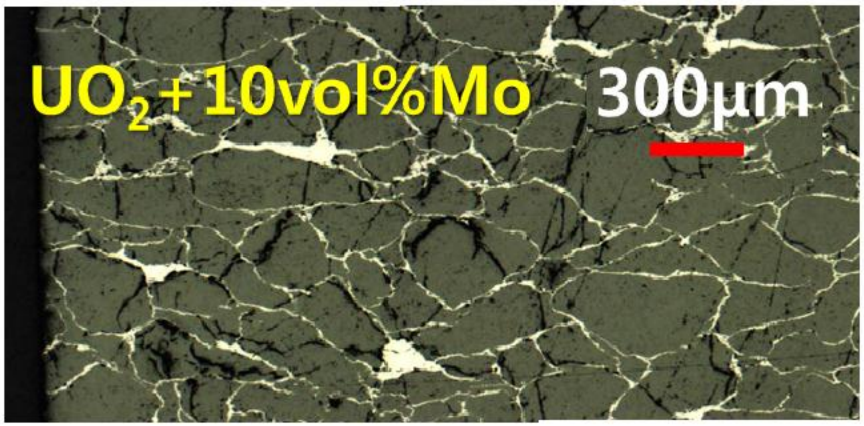
1-1. Ceramic Micro-cell UO_2 pellet

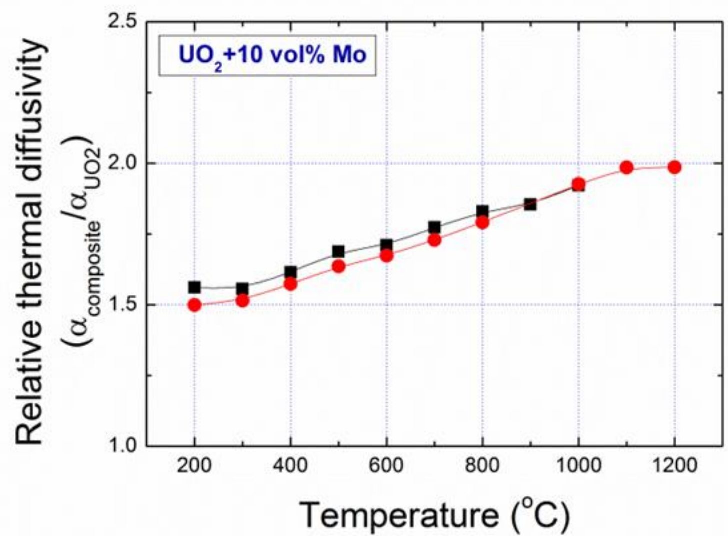
- To test the behavior of ceramic micro-cell pellet under accident condition and normal operation, test equipment is being installed:
  - **High temperature steam oxidation test (1700ºC, 3 bar of H_2O)**
  - **Water corrosion test in autoclave** under normal operating condition

1-2. Metallic Micro-cell UO_2 pellet

- **Mo and Cr**: Selected as metallic cell-wall material
- Microstructure shows that metallic cell wall was formed along grain boundaries

Element	$T_{melting}$ (℃)	k (W/mK)	σ_a (barn)
Mo	2623	139	2.48



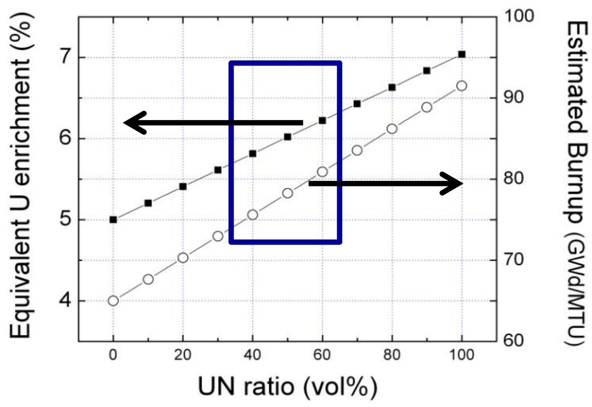


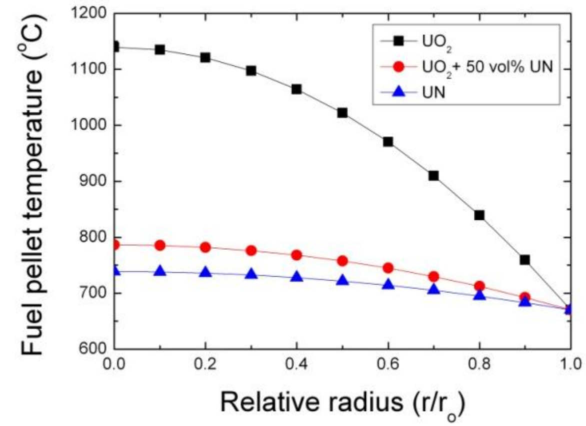
- Main advantage: Enhanced thermal conductivity & retention capability
- Thermal diffusivity: increased **1.5~2 times** compared to UO_2

2. Uranium Nitride Composite

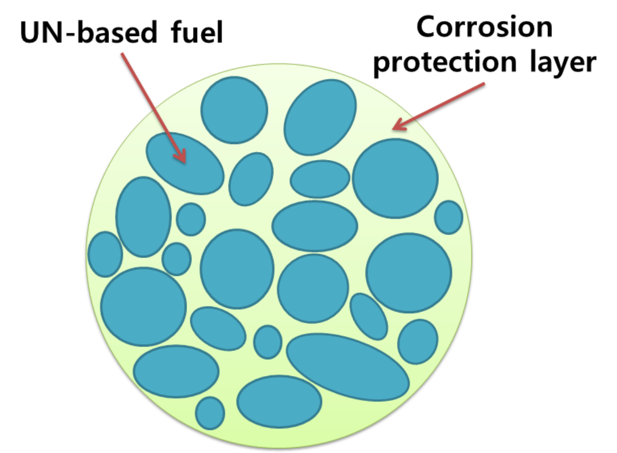
- UN's advantage: High uranium density & high thermal conductivity

	UO_2	UN
Theoretical density (g/cm³)	**10.96**	**14.32**
Uranium density (U-g/cm³)	**9.7**	**13.5**
Melting point (ºC)	**2,865**	**2,597**



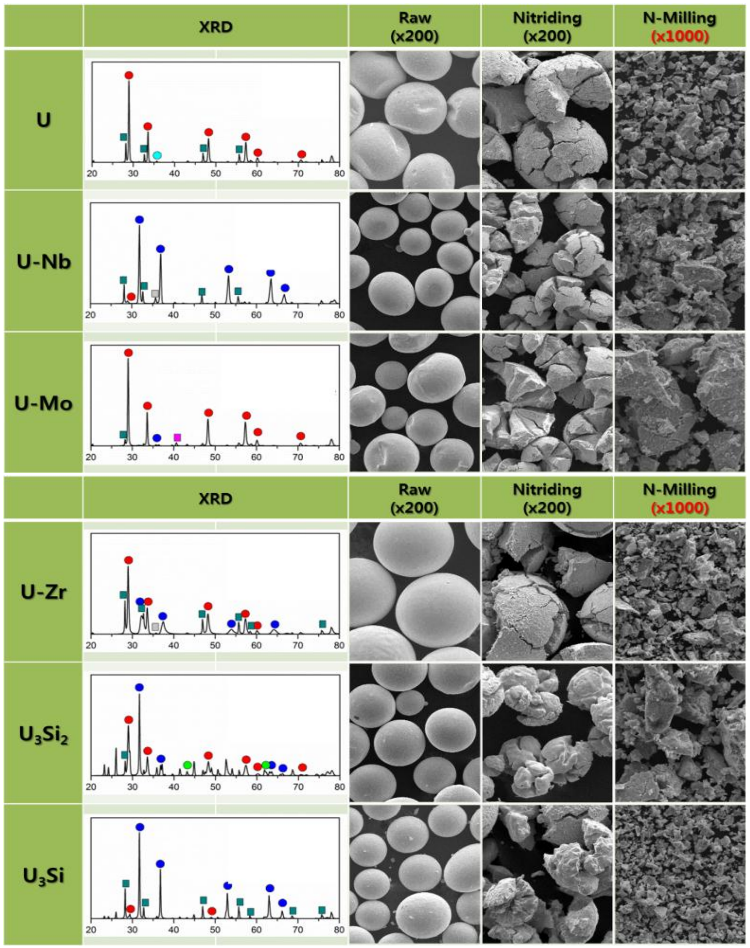


- UN's disadvantage: **Violent reaction with water**
- To enhance corrosion resistance: 1) modifying atomic structure of UN with minor alloying elements, 2) providing multiple protective layers

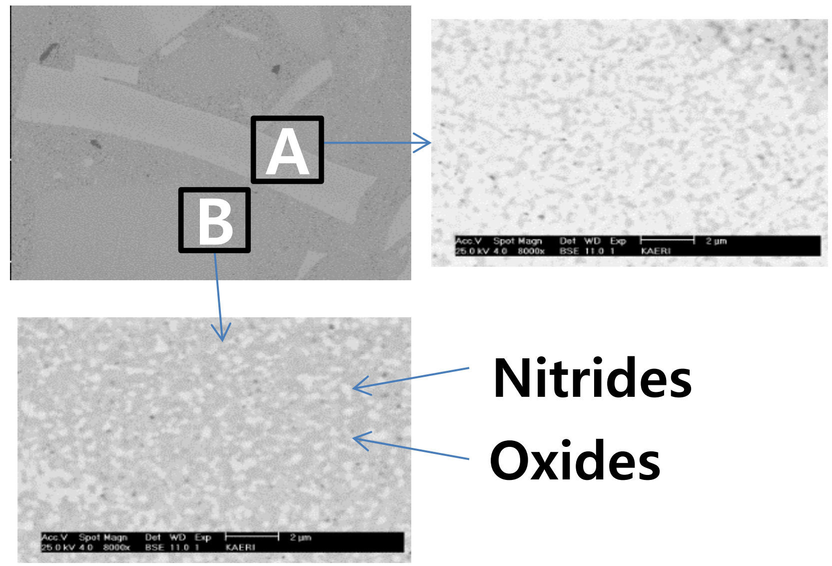


2. Uranium Nitride Composite

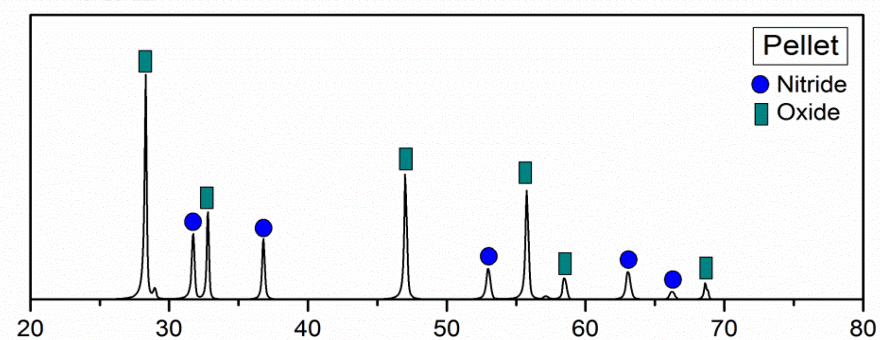
- **Nitride alloy powders**



- **Sintered composite pellet**
  - **Microstructure**

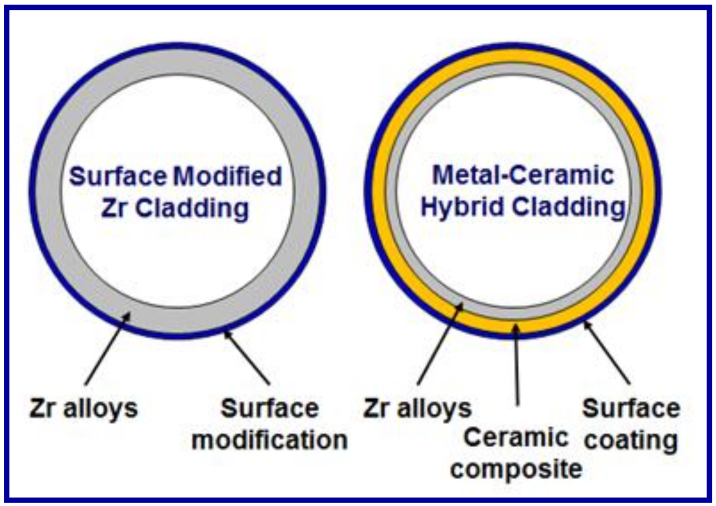


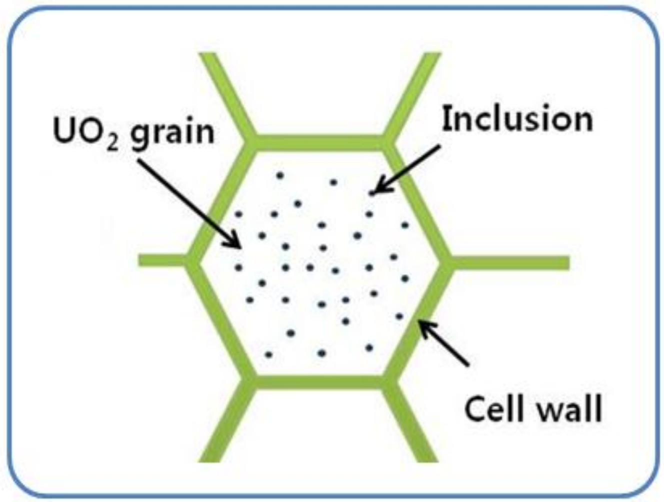
  - **XRD**

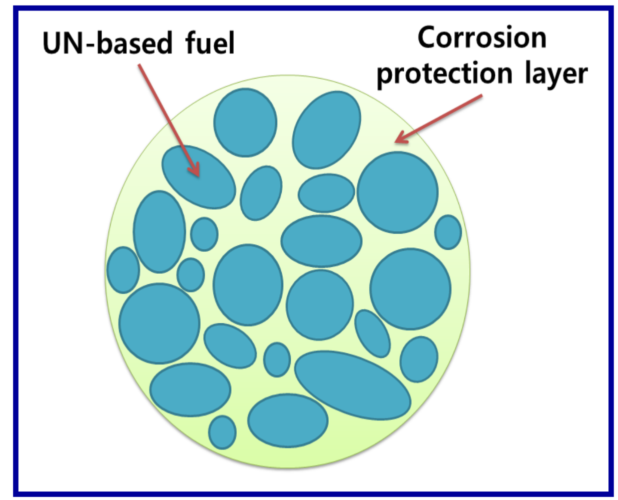


3. Summary

- Cladding material: **Surface modified clad** & **Metal-ceramic hybrid clad**
- Pellet material: **Micro-cell pellet** & **UN composite pellet**







Thank you for your attention.