Current status of accident tolerant fuel development in the Republic of Korea

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NEA Headquarters, Paris, 28-29 Oct. 2013

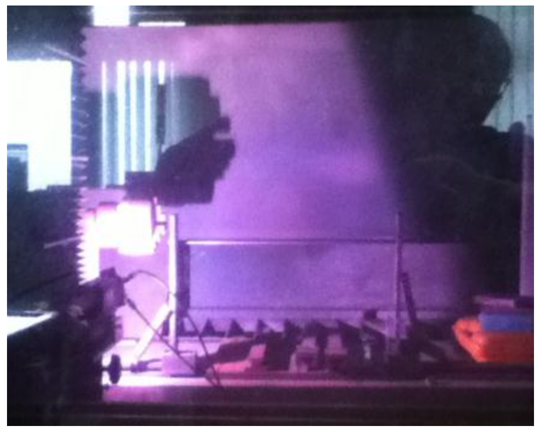
ATF development in Korea

- **New concepts of fuel claddings**
  - Surface modification on the current Zr alloy tubes
  - Metal/ceramic hybrid cladding
  - SiC triplex cladding
  - FeCrAl/Zr duplex cladding
- **Fuel for fission product retention**
  - Micro-cell UO_2 pellet
- **FCM replacement fuel for LWRs** (by Dr. J.H. Chang)

Plasma spray of Cr on Zr tubes

Sand blasting

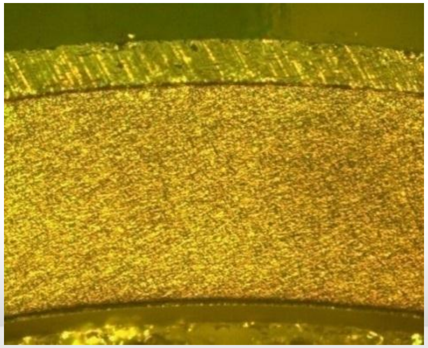
Plasma spray coating

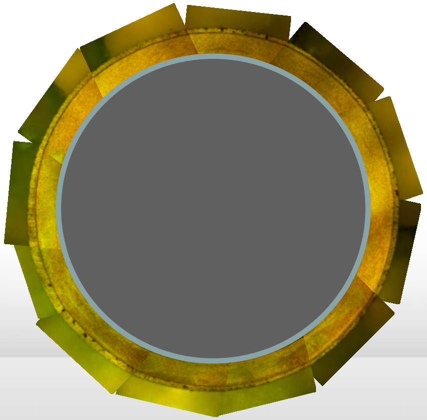


Zr tubes after plasma spray coating

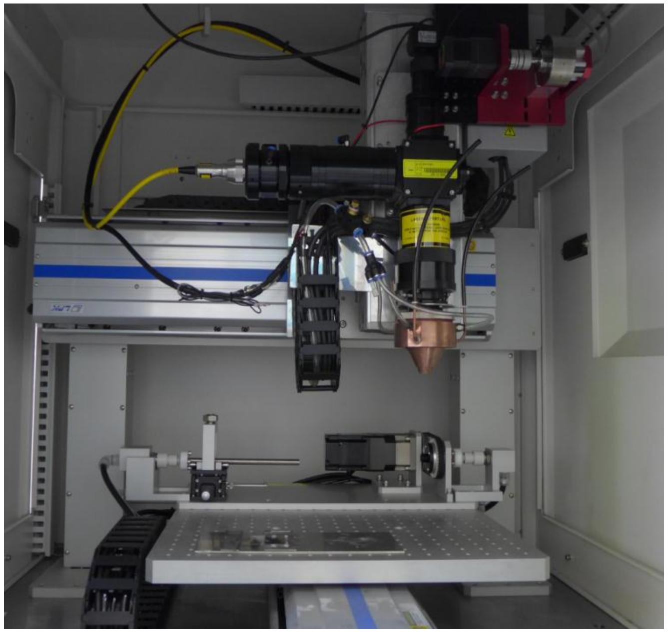
Surface polishing after coating

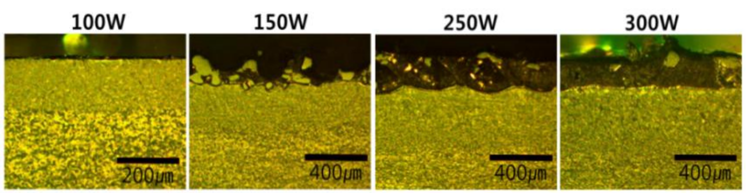
Cross-section of the coated tube



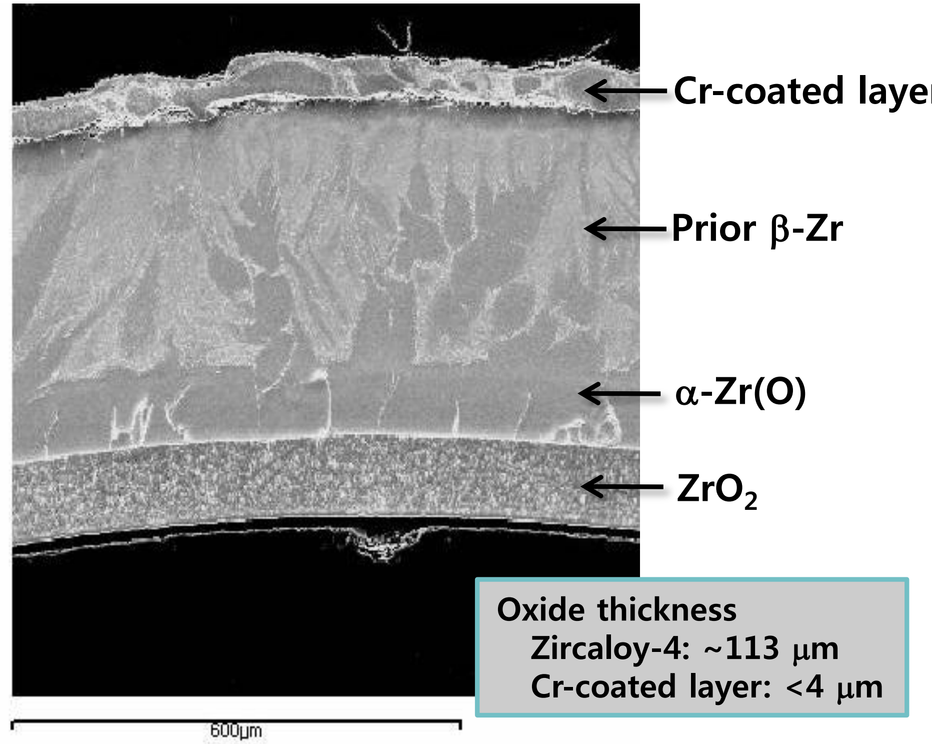


LBS with Cr power on Zr tubes





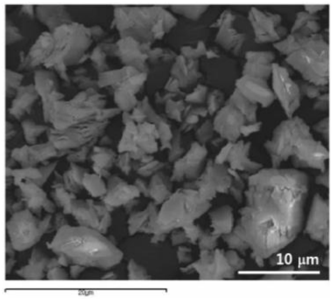
LBS facility and cross sections of Cr-LBSed Zircaloy-4 with different laser powers



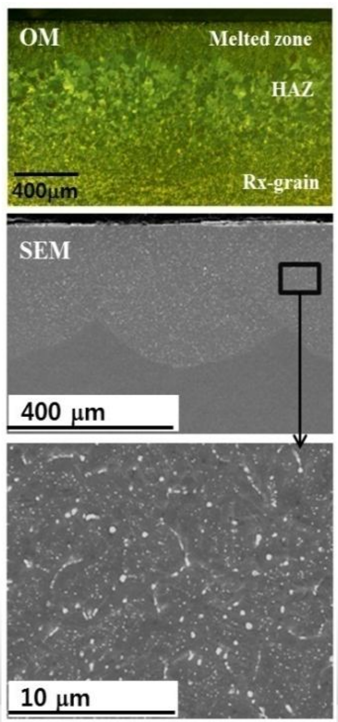
Cross sections of Zicaloy-4 with LBSed Cr layer after HT steam oxidation at 1200°C for 2000s.

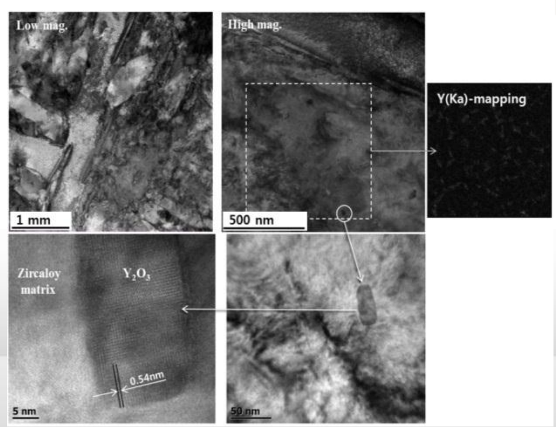
Development of surface ODS technology

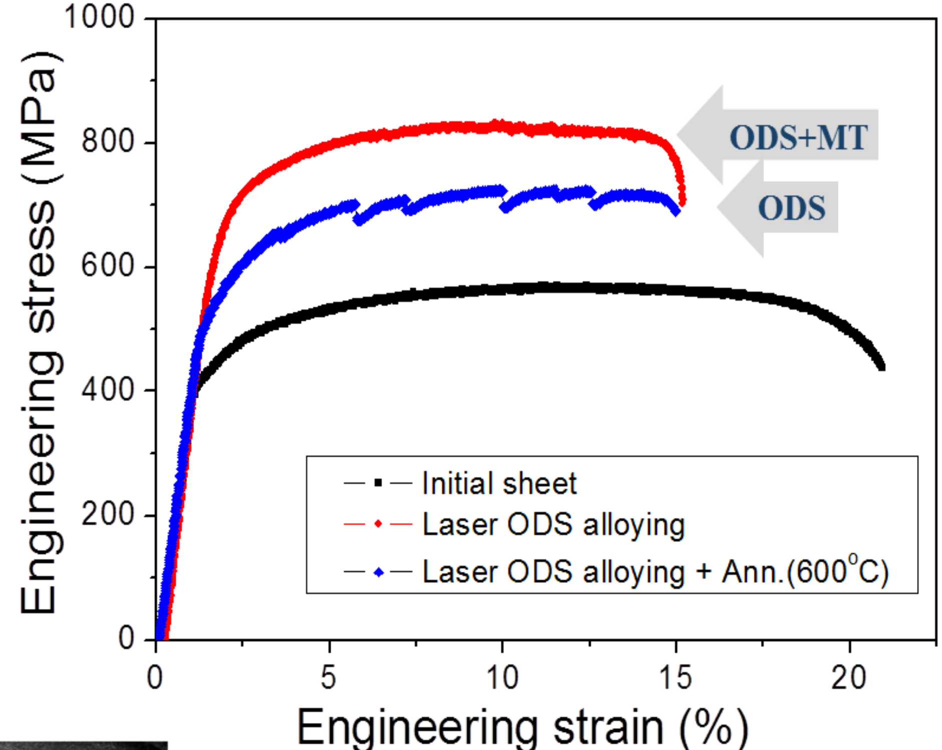
Y_2O_3 powder



LBS with Y_2O_3 powder on Zr surface



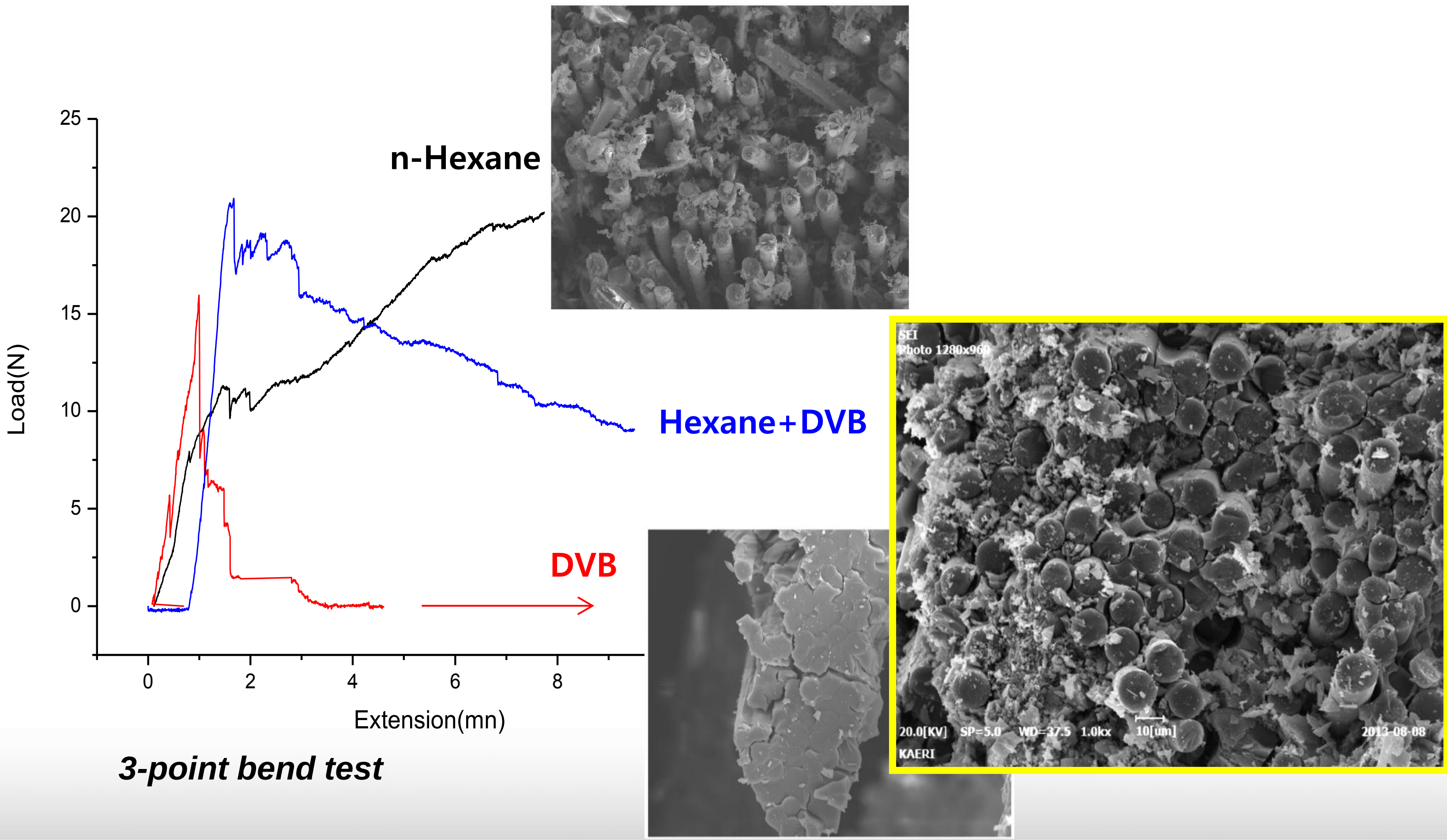




- ODS technology can be applied with the surface coating method to improve the mechanical strength of Zr claddings.

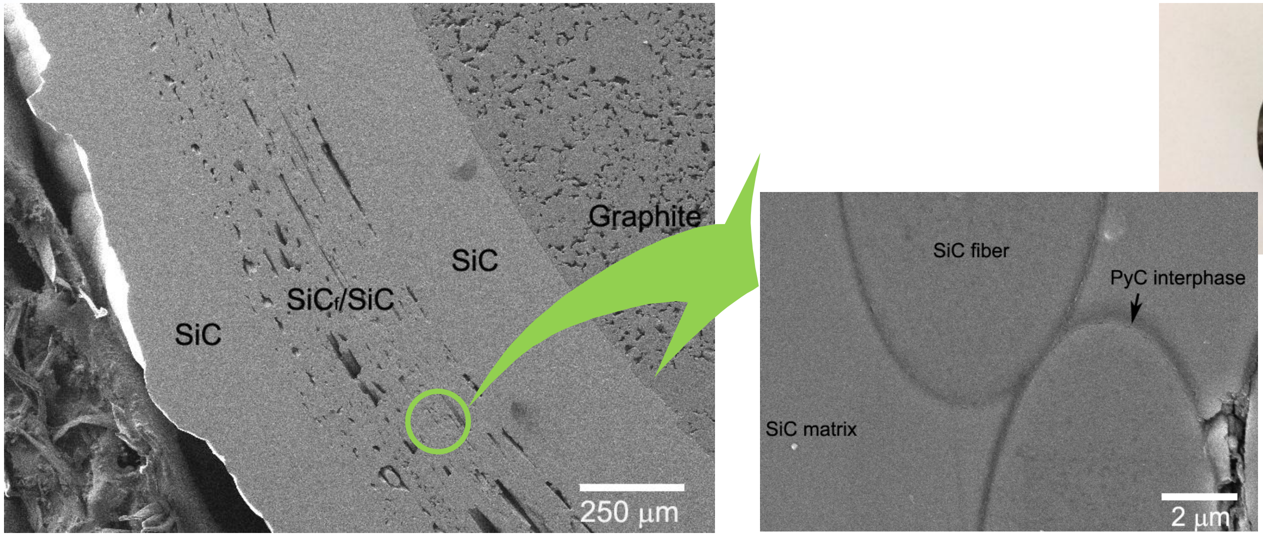
PIP for SiC composite layer of hybrid cladding

- Microstructures and mechanical properties should be considered for the evaluation of impregnation qualities.



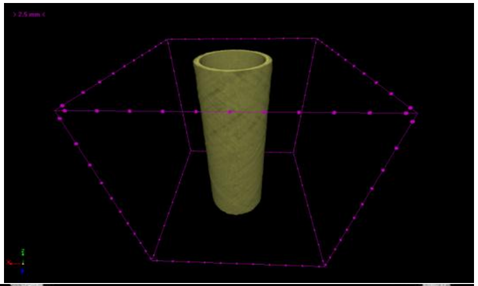
3-point bend test

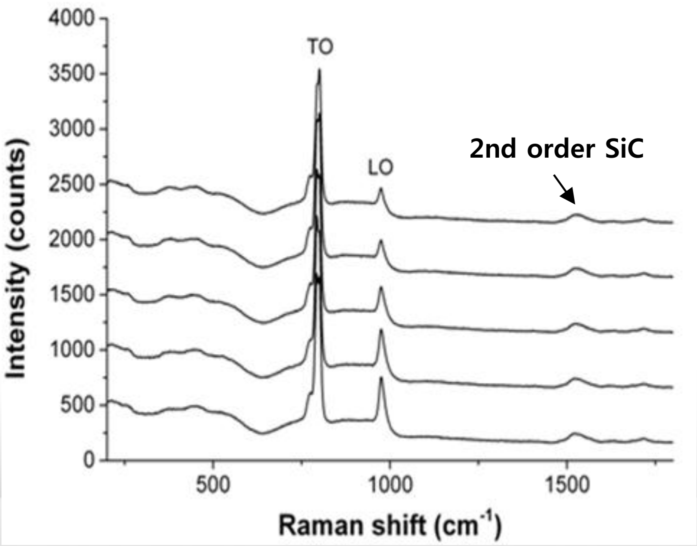
SiC triplex tube: fabrication & characterization



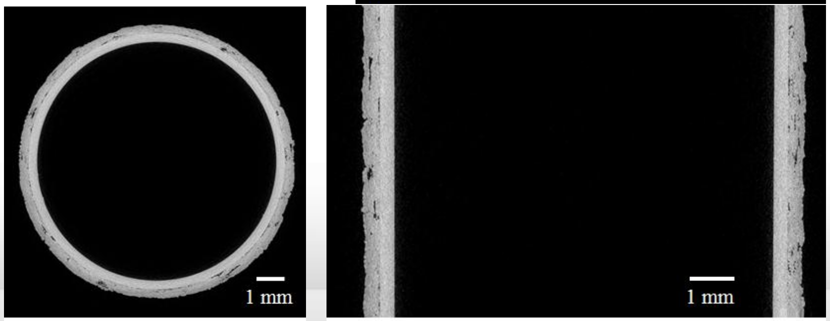
Triplex composite tube
(surface machined)

X-ray mCT volume image



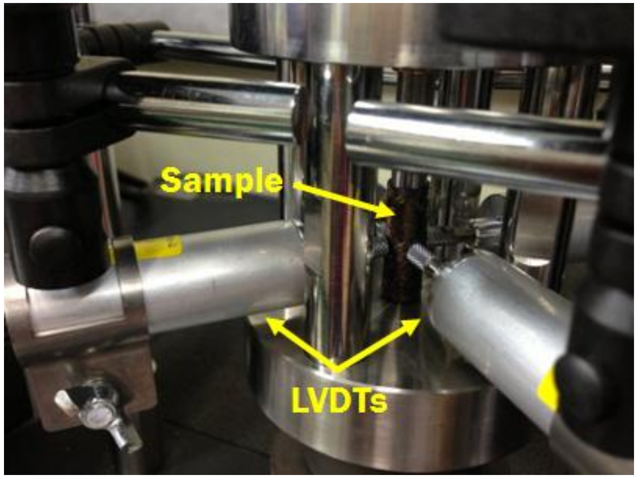


Raman micro spectroscopy on CVD SiC

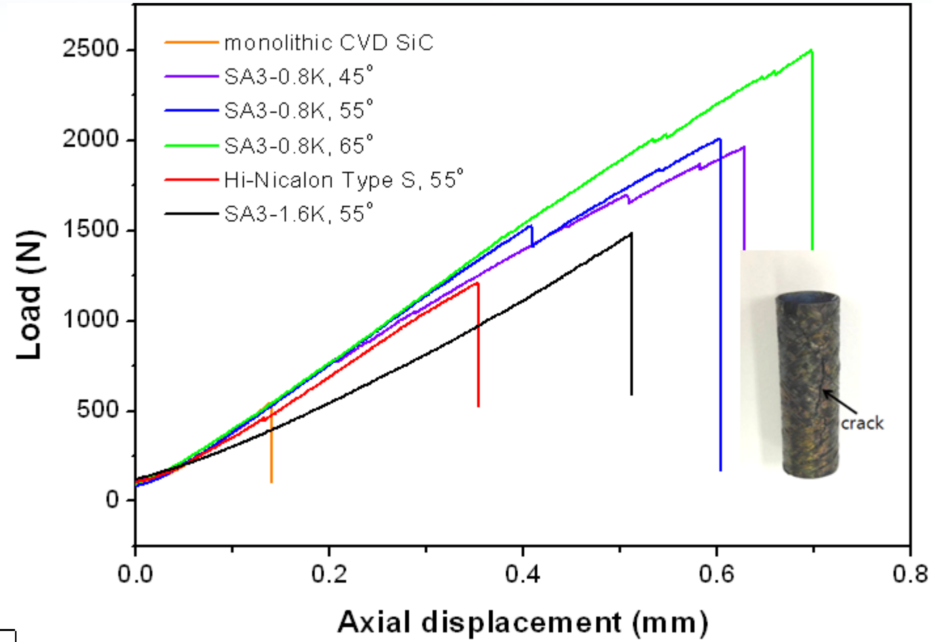


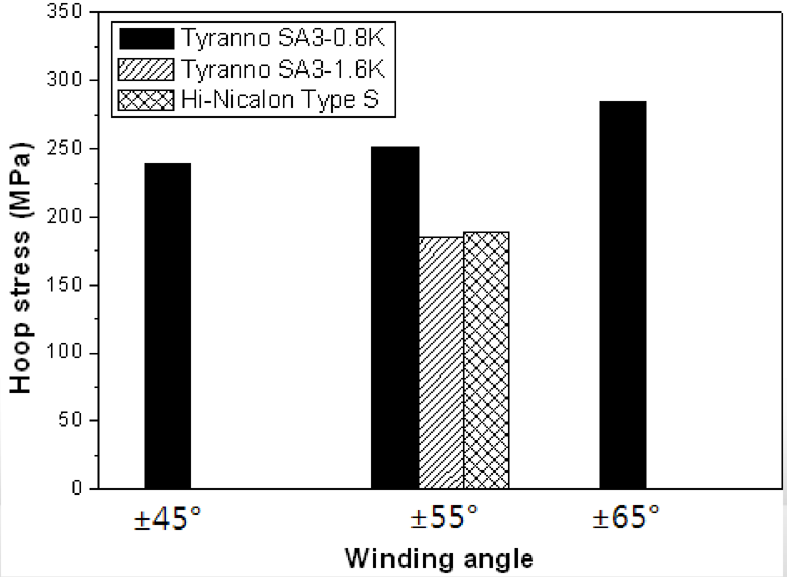
X-ray mCT sliced images

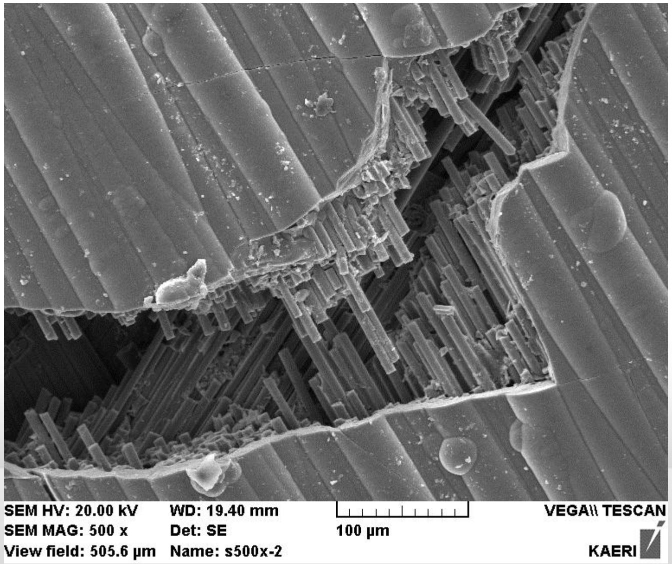
Hoop strength of SiC composite tube



Hoop test apparatus for triplex tube





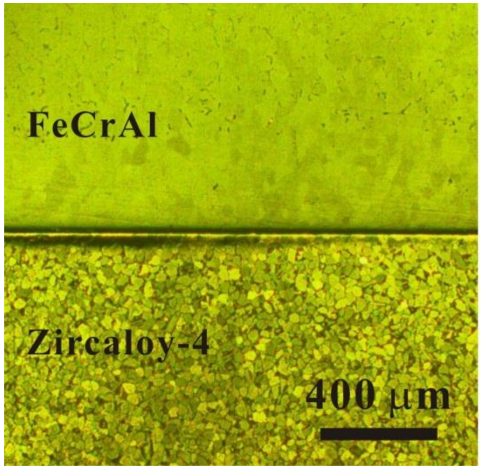


Development of FeCrAl/Zr duplex cladding

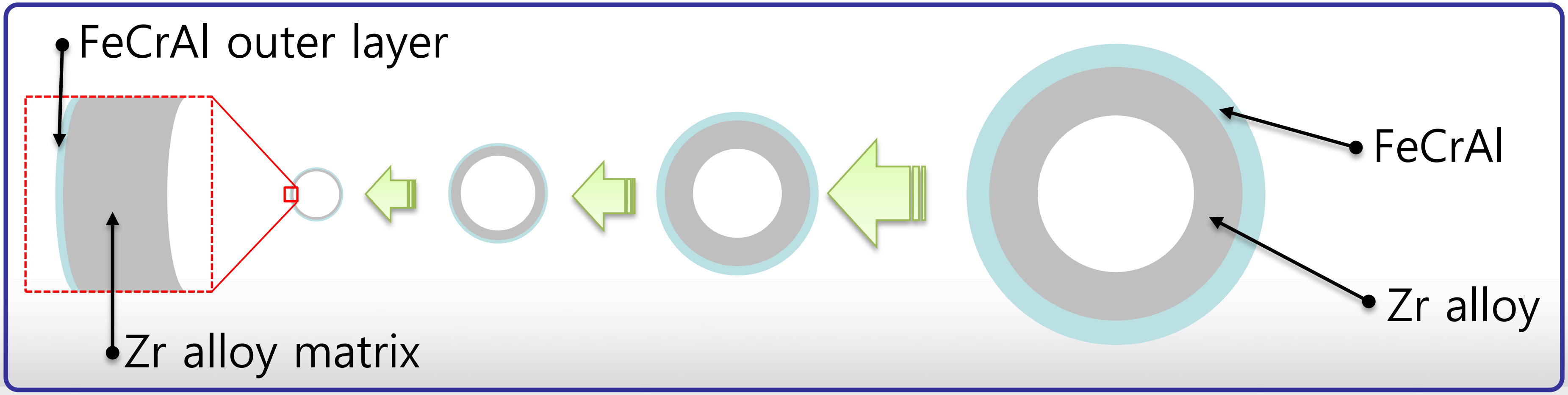
FeCrAl alloys

Advantage
- Excellent formability
- High strength at high temperature
- Excellent HT oxidation resistance

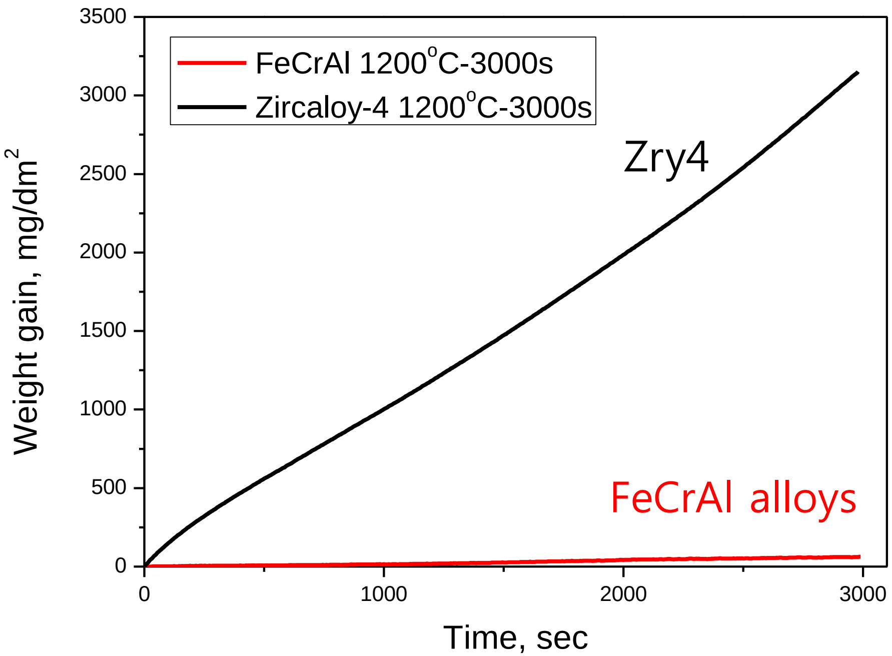
Drawback
- Relatively low melting temperature
- High neutron capture cross-section



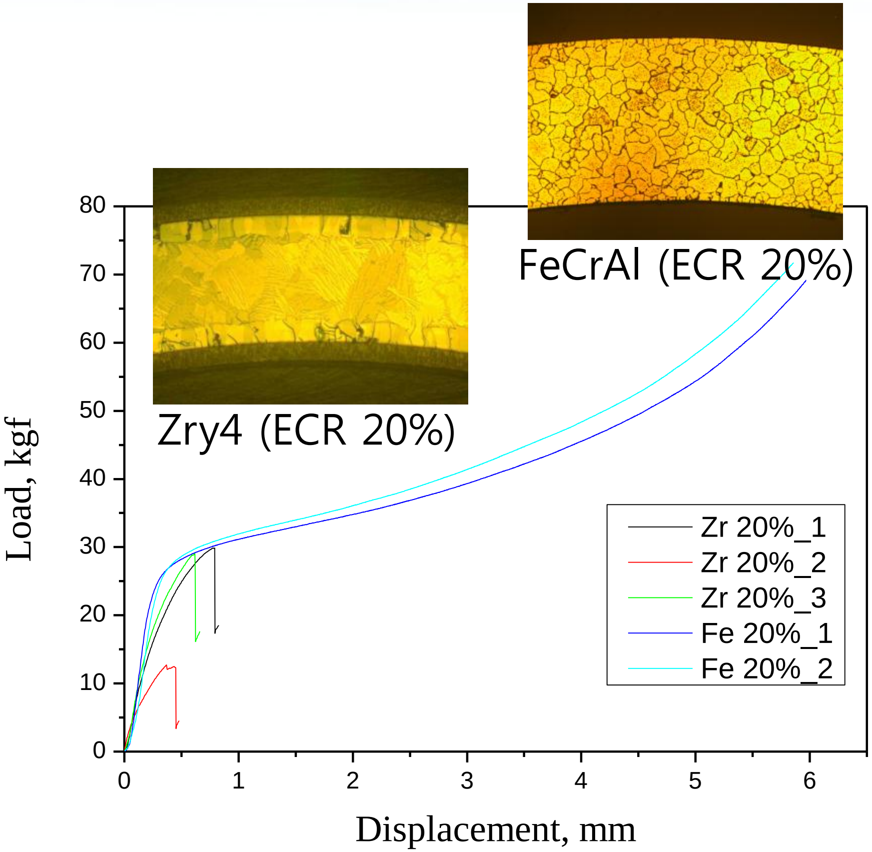
Final tube ← TREX
(Joining FeCrAl to Zr TREX)



FeCrAl alloys under LOCA conditions

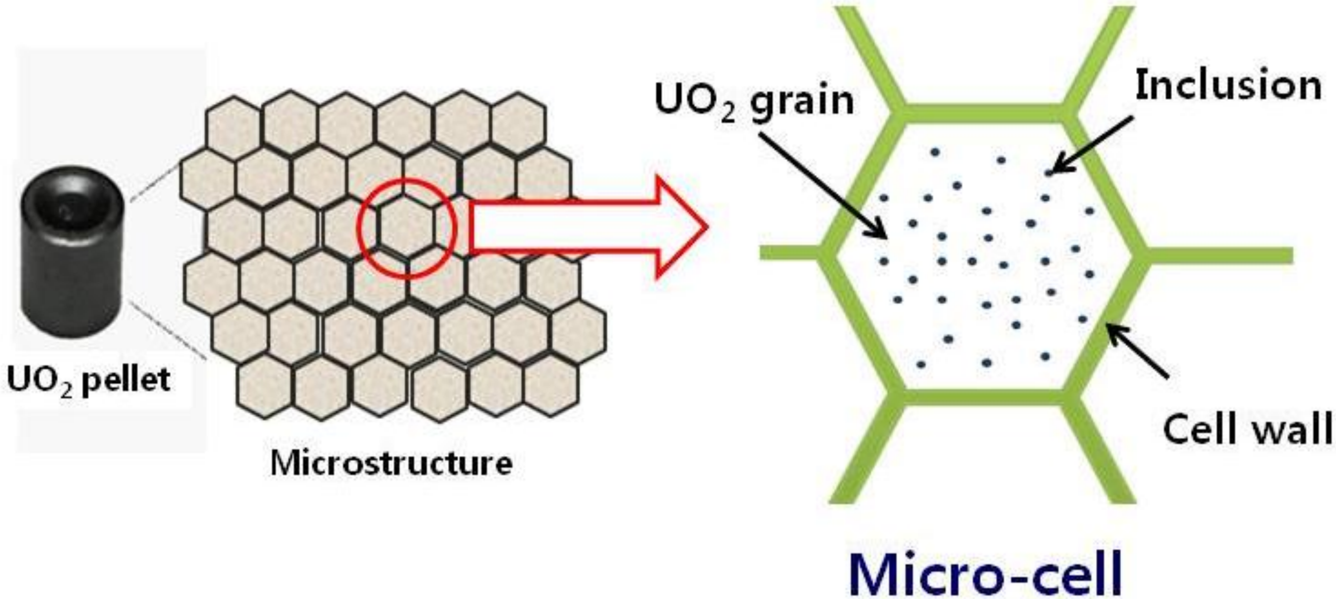


Oxidation behavior in high temperature steam



Post quench ductility after the oxidation to CP-ECR 20%

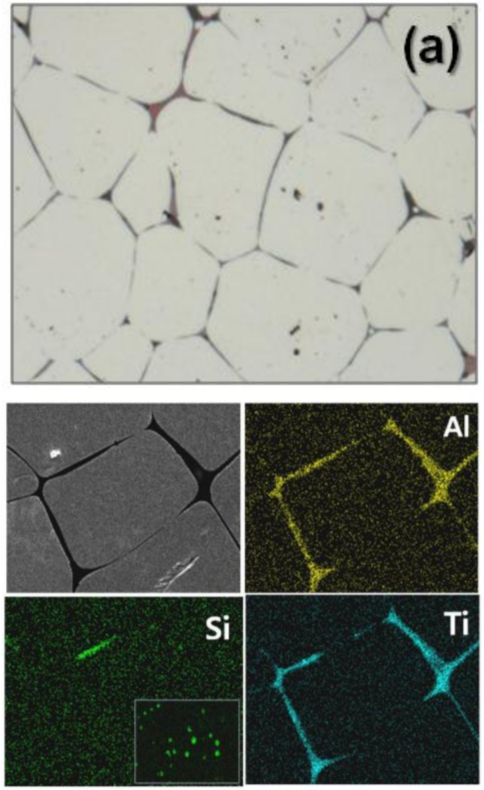
Micro-cell UO_2 pellets



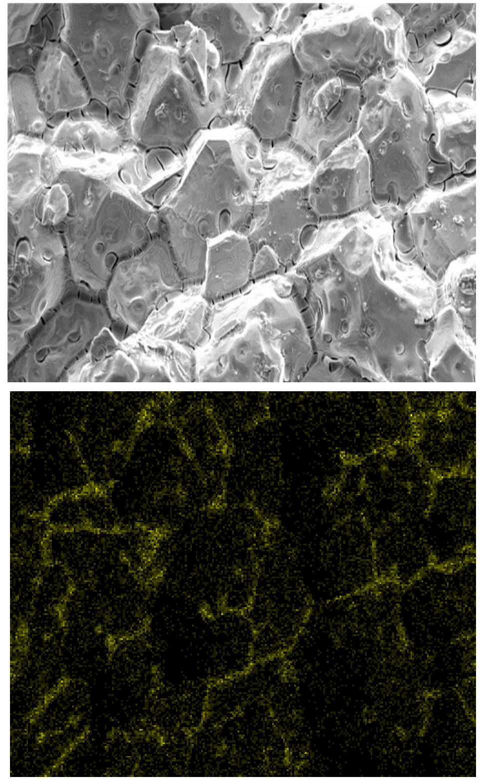
- Enhance the fission products (Cs, I) retention capability of pellet by
  - providing multiple chemical traps in the pellets
  - reducing diffusivities of FPs.
- UO_2 grains are enveloped in thin cell-wall.
  - Cell-wall: a chemical trap or physical barrier for FPs movement
  - Small inclusions: excess oxygen consumer

Ceramic micro-cell UO_2 pellets

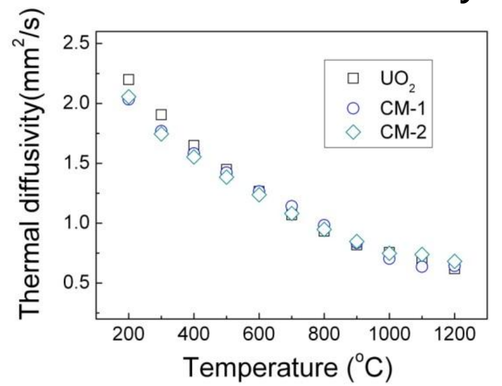
Microstructure



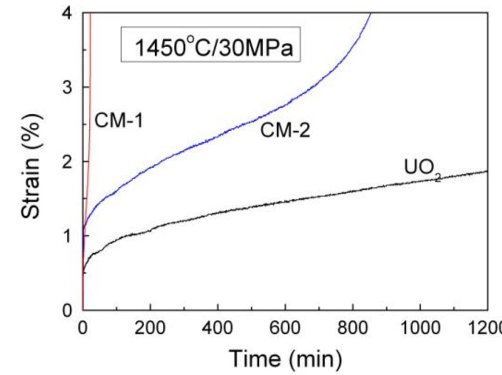
Cs capture test



Thermal diffusivity



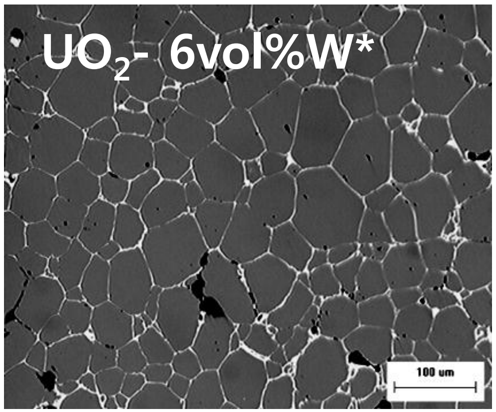
Creep deformation

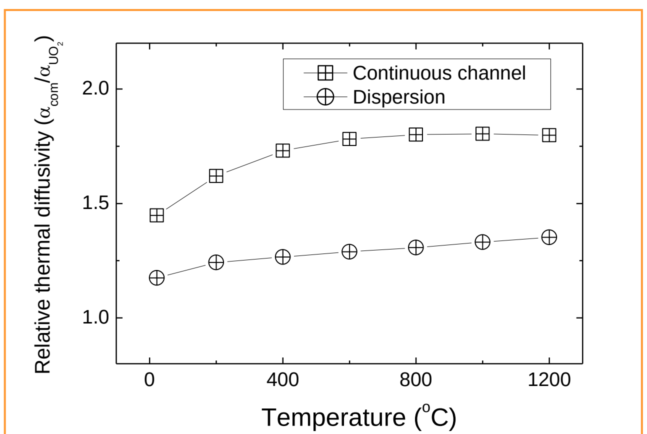


- Micro-cell concept was successfully implemented.
- Cs preferentially reacts with the grain boundary phase.
- Ceramic micro-cell pellets deform easily than UO_2 pellets.

Metal micro-cell UO_2 pellets

- Manufacturing feasibility and improved thermal diffusivity were demonstrated.



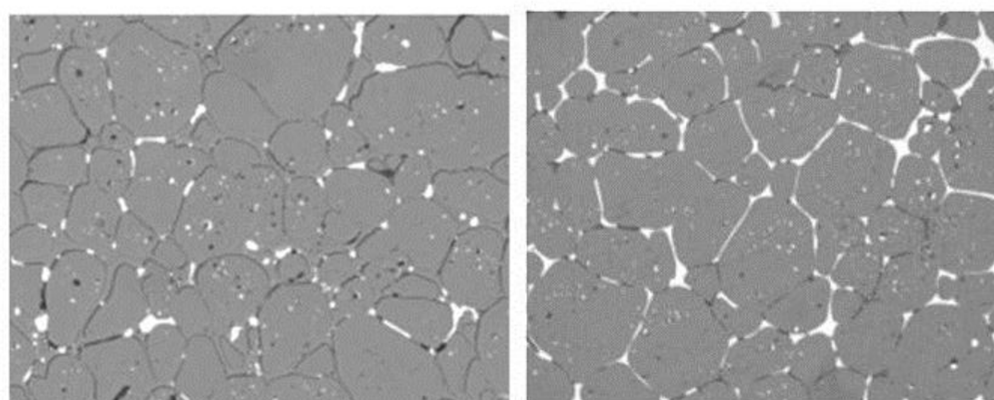


*Yang et al., JNM 353(2006)

- Advantages: cold pellet
  - Increased FPs retention**: Low diffusivity, Physical barrier
  - Reduced stored energy: Enhanced safety margins
  - Reduced thermal expansion: Reduced stress on cladding
- Selected candidates
  - UO_2 – Cr alloy
  - Metal cell wall volume: ~ 5 vol%

**IAEA TECDOC-970

- UO_2+3wt% Cr_2O_3



Summary (cladding & fuel)

- Accident tolerant fuel claddings are being developed with new concepts including the surface coating, metal/ceramic hybrid, SiC triplex and FeCrAl/Zr duplex claddings to suppress the hydrogen emission under severe accident conditions.
- Micro-cell UO_2 pellet are being developed to enhance the fission products (Cs, I) retention capability of pellet by providing multiple chemical traps in the pellets and reducing diffusivities of FPs.

FCM Replacement Fuel for LWRs

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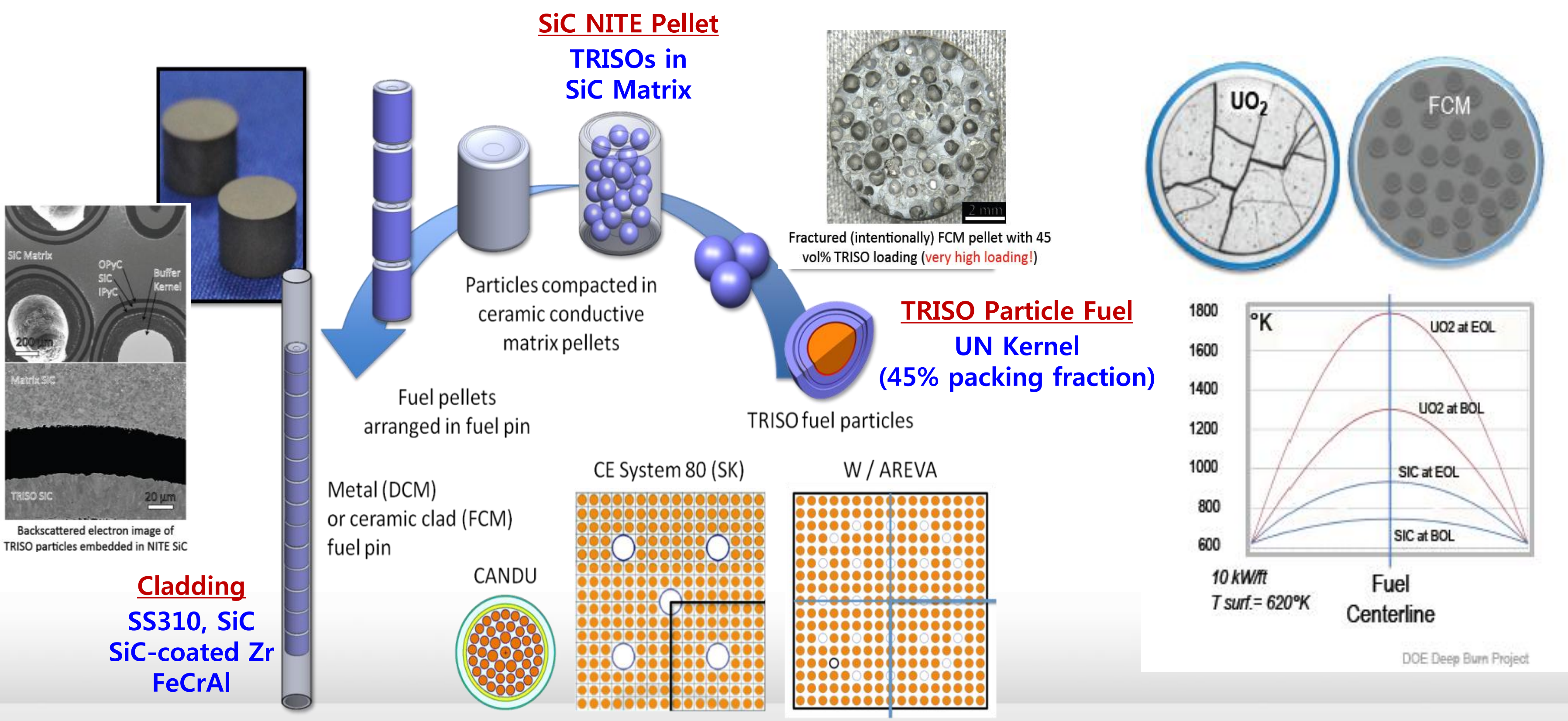
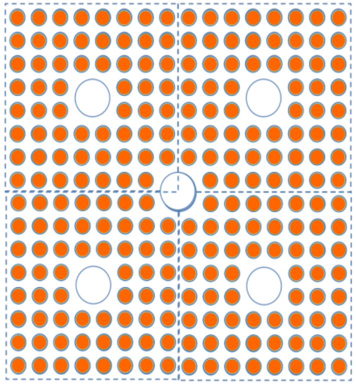
Concept

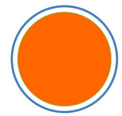
- **Fully Ceramic Microencapsulated (FCM) Fuel**
  - Coated Particle Fuel: TRISO (Proven from HTGR experiences)
  - Pellet: TRISO-SiC Matrix
  - Cladding Options: SS310, SiC, SiC-coated Zr, FeCrAl



Candidate FCM Fuel Assemblies

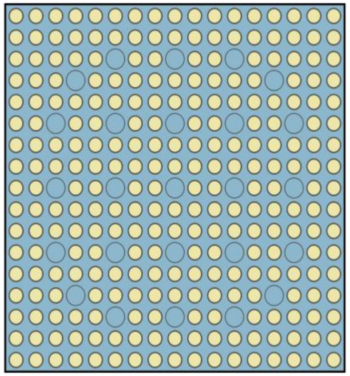
OPR 16x16 UO_2 FA

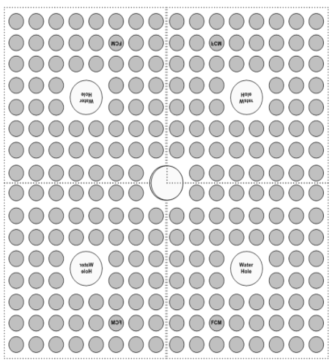




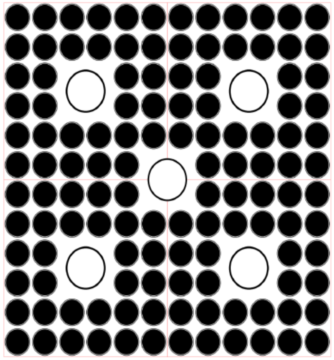
UO_2 fuel pin

WH 17x17 UO_2 FA

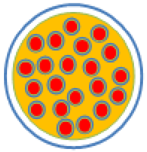




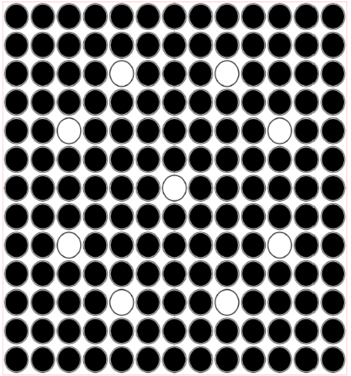
OPR 16x16 FCM FA



OPR 12x12 FCM FA



FCM fuel pins



WH 13x13 FCM FA

To increase the Fissile Inventory of FCM Fuel, Fat Pellet Design is introduced having higher Enrichment and Packing Fraction of UN TRISOs in SiC Matrix

Features of FCM Fuel

- **Accident Tolerance**
  - Resistance to Meltdown: TRISO (< 1600°C), SiC Matrix (< 2700°C)
  - Resistance to Fission Product Release: TRISO & SiC Matrix Barriers
  - Resistance to Hydrogen Generation: Low Reaction Rate Cladding
  - Resistance to Fuel Thermo-Mechanical Degradation
    - Highly Conductive Fuel: Low Fuel Centerline Temp (~ 800°C)
    - Mechanical Integrity of Cladding during LOCA: Low Internal Press.

- **Additional Features**
  - Benefit in Spent Fuel Management and Disposal
    - Deep-Burn of Recycled Spent Fuel
    - Dry Disposal and Long-Term Containment of Radioactivity
  - Proliferation Resistance
    - Difficulty in Pu Extraction and Low Quality W-Pu in Spent Fuel
  - Flexible Applications to Other Reactor Types like HTGR, CANDU, …

Neutronics Exploration

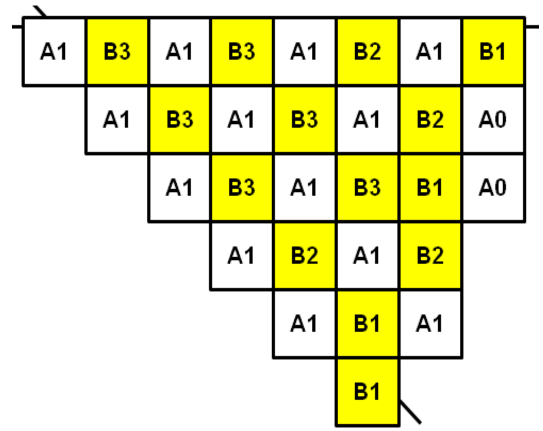
- **Work Scopes**
  - Loading Pattern Search for the FCM FA-only Transition Cores
  - Generation of FCM Transition Core Physics Parameters
  - Development of DPA (Displacement per Atom) Model

- **Screening Criteria for Loading Pattern Search**
  - FCM FA Designs: 5 Candidates
  - Fuel Management and Cycle Length: 2 Batch 18 Month (> 450 EFPD)
  - Fuel Enrichment: < 20%
  - Peaking Factors: Fq < 2.31, Fr < 1.65, Fz < 1.4
  - Axial Offset < ±10%
  - Core Kinetic Parameters: HFP MTC < 0., HZP MTC < +9 pcm/^{o}C
  - Fast Neutron Fluence (> 0.18MeV): $15.x10^{21}$ #/cm^2

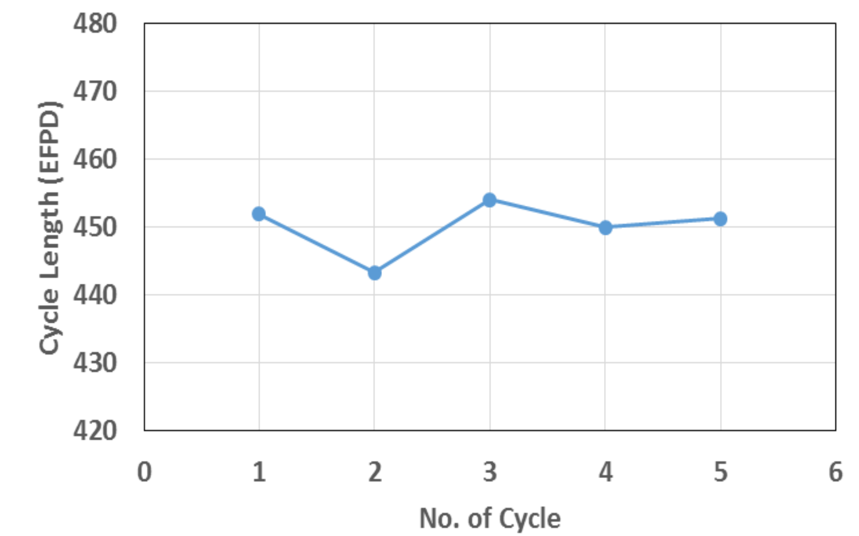
Equilibrium Core

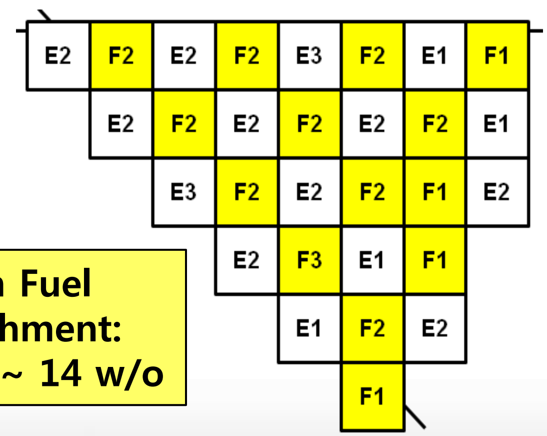
- Loading Pattern Search for 5 Types of FA Candidates

LP No.	Fuel Rod Array	Cladding Material	BP Type	TRISO Packing Fraction
1	16x16	SS	Admixed	45%
2	12x12	SS	BISO	42%
3	16x16	SiC	BISO	42%
4	12x12	SiC	Admixed	45%
5	16x16	SiC-coated Zr	BISO	45%



Cycle 1



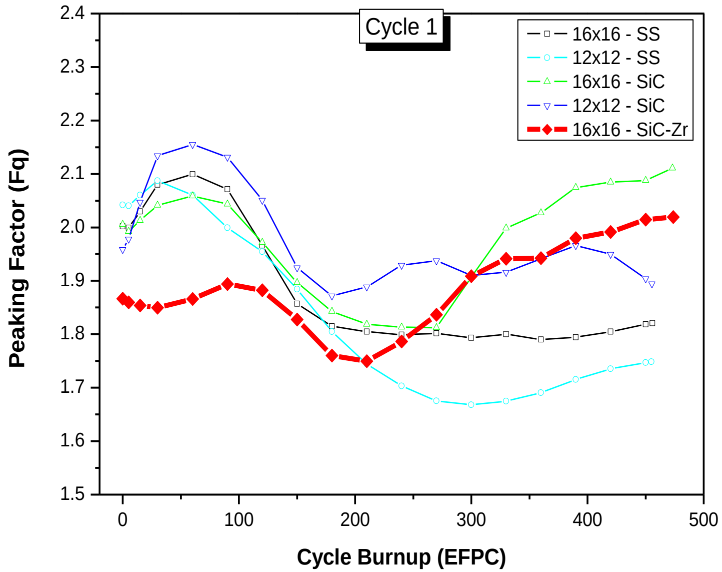


Fresh Fuel Enrichment: 12.8 ~ 14 w/o

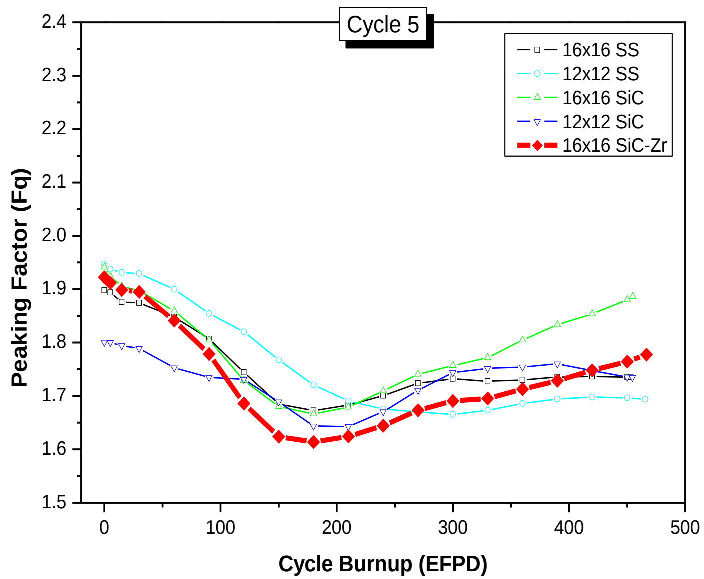
Cycle 5

Transition Core

- Generation of FCM Transition Core Physics Parameters for Core TH, Safety and Fuel Performance Analysis
  - Critical Boron Concentration, Peaking Factors, Power Distribution, Reactivity Feedbacks, Fast Neutron Fluence, etc…
  - Recommended FCM FA Design: 16x16 SiC-coated Zr Cladding



Cycle 1

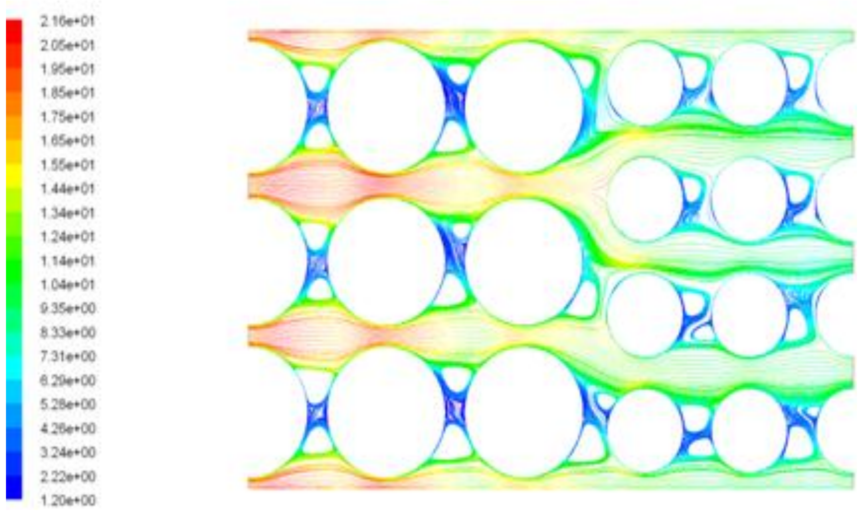


Cycle 5

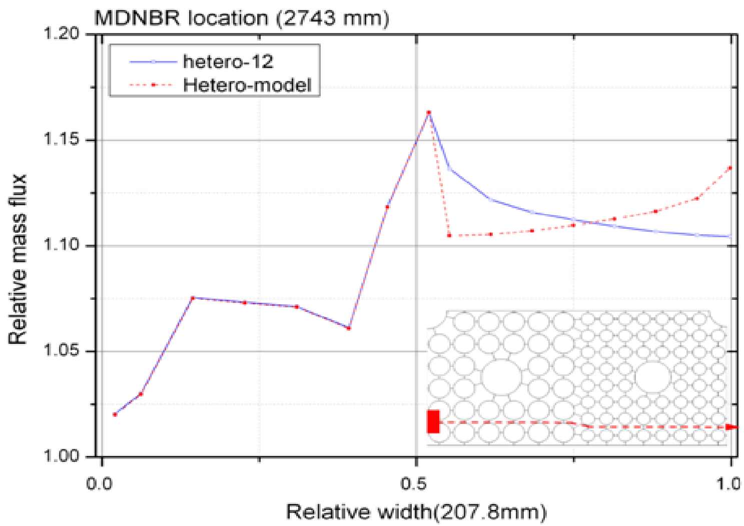
Power Peaking in Transition Cores

Core TH Assessment

- **Work Scopes**
  - Subchannel TH Model for Mixed Transition Core (FCM and UO_2 FAs)
  - 2-Step Full Core to Subchannel TH Analysis Method
  - Core/Subchannel TH Scoping Analysis for FCM Transition Cores
- **Subchannel TH Model for Mixed Transition Core (FCM and UO_2 FAs)**
  - Cross Flow Loss Coefficient Model: Idel'chik with Zukasukas P/D



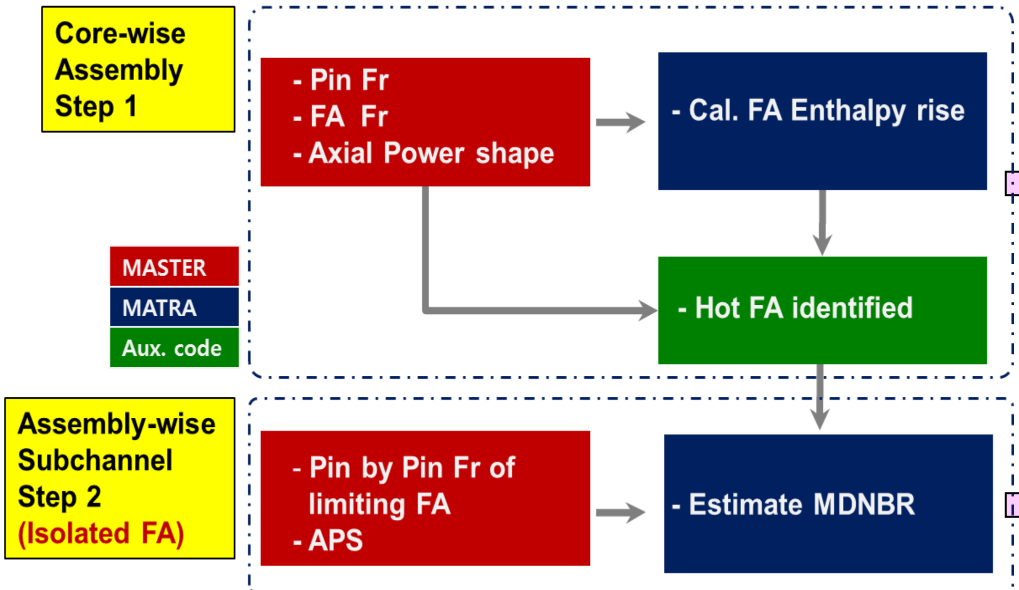
Mixed Core Flow Pattern (FCM 12x12 and UO_2 FAs)



Cross Flow by MATRA Subchannel Model

TH Method

- 2-Step Full Core to Subchannel TH Analysis Method
  - Step 1: Core-wise FA Analysis and Selection of Hot Channel
  - Step 2: Assembly-wise Subchannel and Thermal Margin Analysis



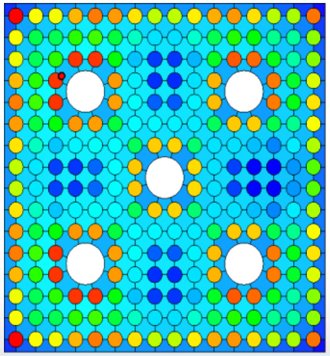
2-Step Full Core to Subchannel Method

Exit flow

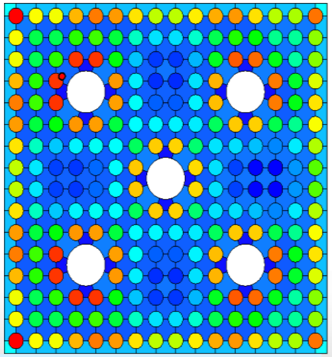
	H	J	K	L	M	N	P	R
8	1.004	0.994	0.999	0.995	0.998	0.984	0.992	1.005
9	0.995	1.000	1.003	1.002	0.995	0.996	0.993	1.015
10	1.002	0.996	0.994	0.997	0.995	0.986	0.994	1.025
11	0.997	1.001	0.992	0.996	0.989	0.990	1.003	
12	0.999	0.998	1.004	0.993	1.003	0.995	1.021	
13	0.984	0.993	0.987	0.989	0.992	1.030		
14	0.996	0.995	0.997	1.008	1.023			
15	1.007	1.015	1.024					

Enthalpy rise

	H	J	K	L	M	N	P	R
8	0.989	1.009	0.998	1.009	1.002	1.029	1.017	0.985
9	1.008	0.996	1.007	0.995	1.012	1.009	1.018	0.964
10	0.997	1.010	1.009	1.011	1.004	1.027	1.013	0.947
11	1.009	0.996	1.012	1.005	1.022	1.012	0.993	
12	1.001	1.011	1.000	1.021	1.001	1.003	0.956	
13	1.027	1.010	1.027	1.013	1.004	0.971		
14	1.013	1.017	1.012	0.993	0.956			
15	0.982	0.964	0.949					



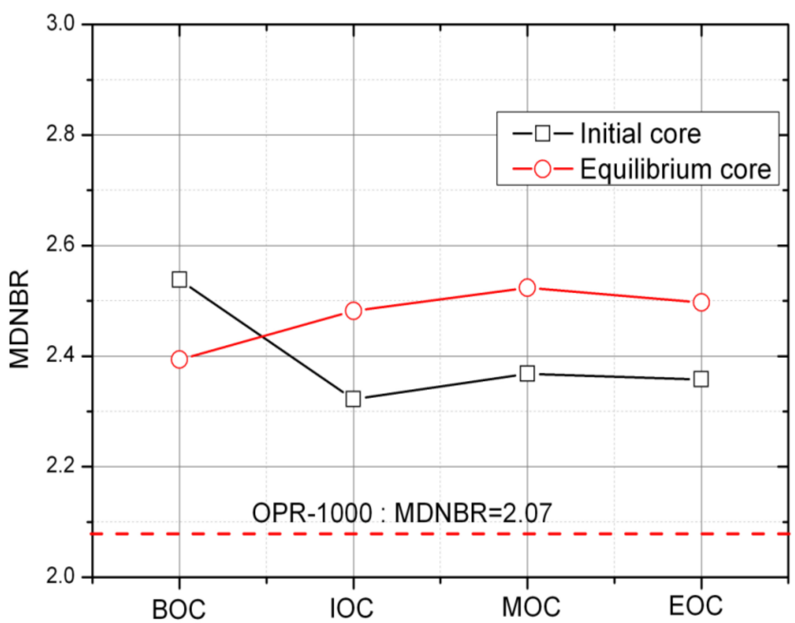
Enthalpy Distribution



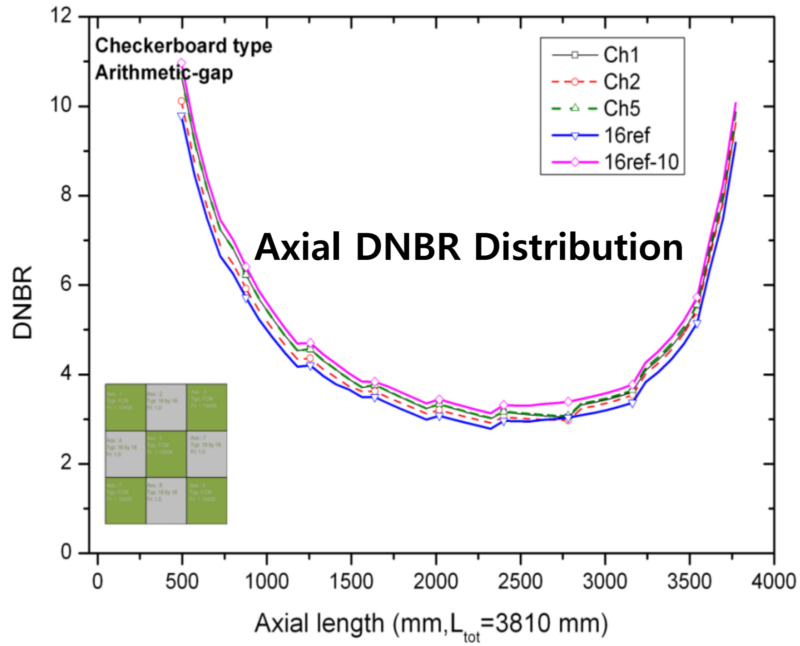
Flow Distribution

Mixed Core Result

- Core/Subchannel TH Scoping Analysis for Transition Cores
  - **FCM Transition Core**
    - More DNB Margin than OPR
  - **Mixed Transition Core Compatibility**



Minimum DNBR vs. Fuel Cycle for FCM Transition Core

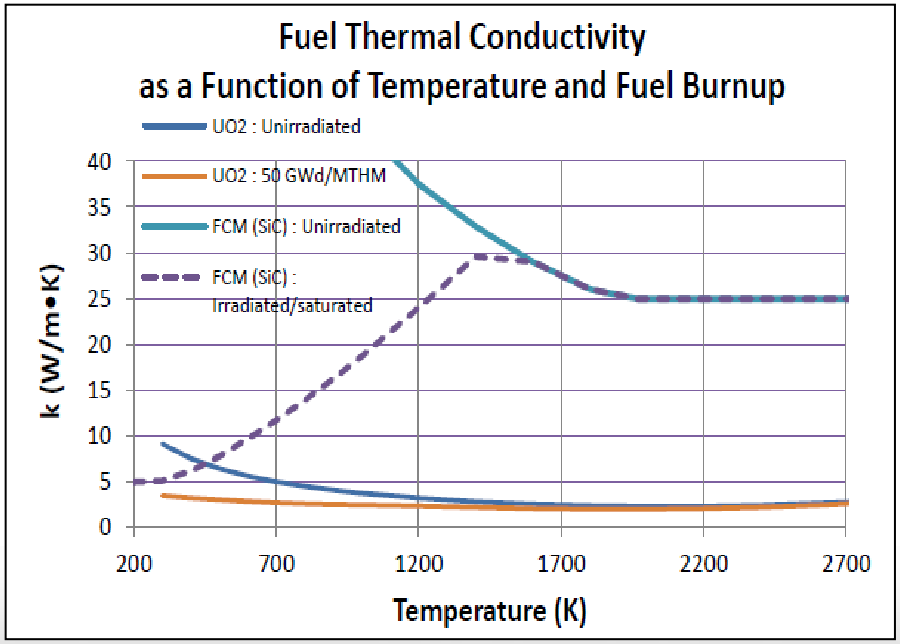


Mixed Transition Core Compatibility (9-Channel Model)

	16x16 (OPR) homogeneous	CHK	16x16 (FCM) homogeneous
DNBR	2.79	2.92 / 3.02	3.13
DP (bar)	1.33	1.45	1.57

Safety Assessment

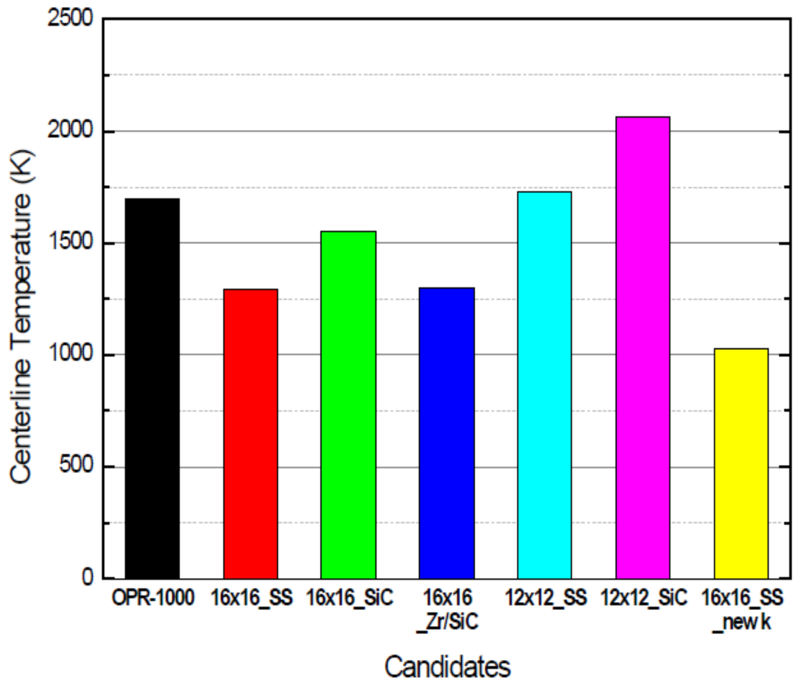
- **Work Scopes**
  - FCM Fuel Modeling
  - Preliminary Scoping Analysis
  - Scoping Analysis of Design and Beyond-Design Basis Accidents (DBA/BDBA) for FCM Transition Cores
- **FCM Fuel Modeling**
  - Thermal Conductivity Model of SiC NITE Pellet
    - MARS Code Modification to take into account the Effect of Irradiation Temperature



Accident Analysis

- Preliminary Scoping Analysis

  - **Screening of FA Designs**
    - **Minimize Initial Stored Energy at Full Power**



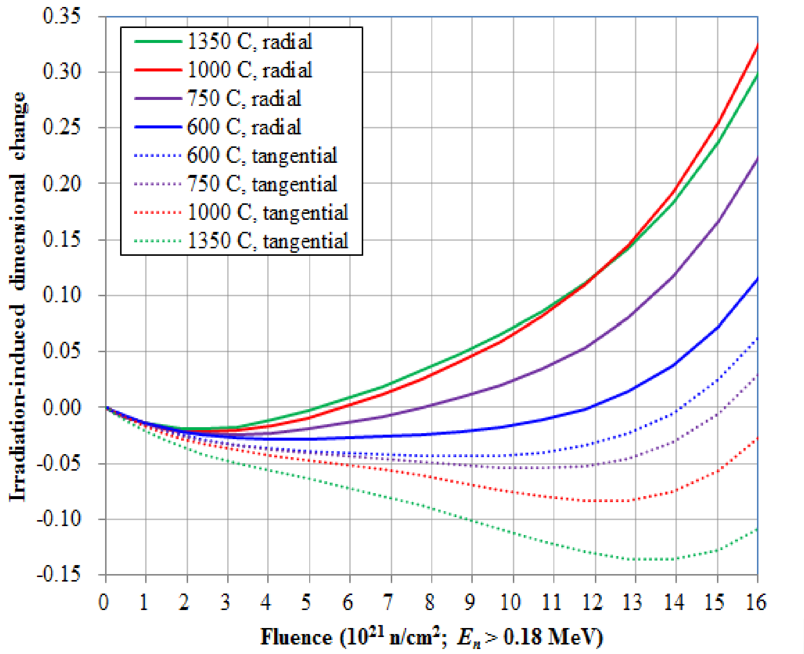
Fuel Centerline Temperatures for FA Candidates

  - **DBA/BDBA Scoping Analysis**
    - **Enhanced Accident Tolerance than OPR UO_2 Core**

Accident	Safety Parameter	Reference UO_2 Core	FCM Core
LOFA	mDNBR	2.82	2.9
LBLOCA	Peak Clad. Temp.	1102 K	1020.4 K
REA	Peak Fuel Temp.	1784 K	1482 K
LBLOCA w/o SI	Grace Time	549 sec.	1577 sec.
SBO	Grace Time	105 min.	217 min.

Fuel Performance

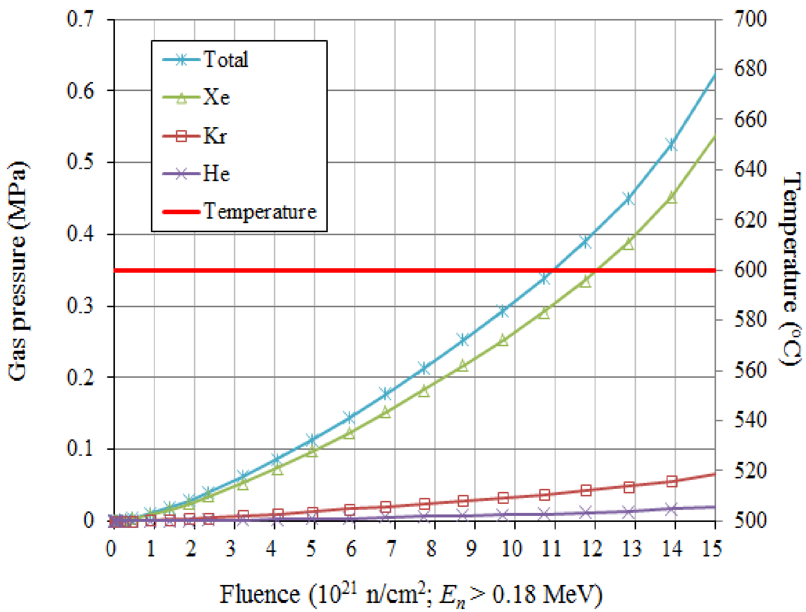
- **Work Scopes**
  - Coated Particle Fuel Modeling
  - Coated Particle Fuel Performance Analysis
  - Mechanical Integrity of FCM FA in Mixed Transition Core
- **Coated Particle Fuel Modeling**
  - PyC Irradiation-Induced Dimensional Change Model
    - CEGA-based Model
  - Coating Layers Failure Model
    - CEGA-based Weibull Model



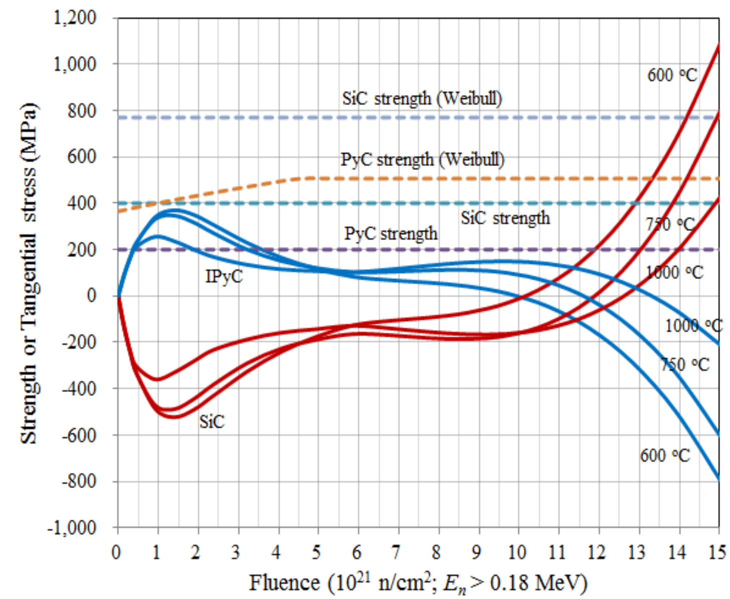
PyC IIDC Model

TRISO in LWR

- Coated Particle Fuel Performance Analysis
  - SiC Layer Internal Pressure
    - Negligible at PWR Condition
  - SiC Layer Integrity
    - No Failure as PyC fails



SiC Layer Internal Pressure by Fission Products



Stresses at PyC and SiC Layers

- Mechanical Integrity of FCM FA in Mixed Transition Core
  - Flow Induced Vibration by Cross Flow (0.6m/s): Margin Available

Summary (FCM)

- **Neutronics Exploration**
  - Loading Pattern Search for Transition Cores fully loaded with FCM FA's and Generation of Core Physics Parameters
  - Development of DPA (Displacement per Atom) Model
- **Core TH Assessment**
  - Subchannel TH Model for Mixed Transition Core (FCM and UO_2 FAs) and 2-Step Full Core to Subchannel TH Analysis Method
  - Core/Subchannel TH Scoping Analysis for Transition Cores fully loaded with FCM FA's
- **Safety Assessment**
  - FCM Fuel Modeling and Preliminary Scoping Analysis
  - Scoping Analysis of Design and Beyond-Design Basis Accidents (DBA/BDBA) for Transition Cores fully loaded with FCM FA's