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

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OECD/NEA Meeting on Increased Accident Tolerance of Fuels for LWRs
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

Cross-section of the coated tube

Surface polishing after coating
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.

Cr-coated layer
Prior β-Zr
α-Zr(O)
ZrO₂

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

Oxide thickness
Zircaloy-4: ~113 μm
Cr-coated layer: <4 μm
Development of surface ODS technology

- 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

Raman micro spectroscopy on CVD SiC

X-ray mCT volume image

Triplex composite tube (surface machined)
Hoop strength of SiC composite tube

Hoop test apparatus for triplex tube

Graph showing load vs. axial displacement for different materials and winding angles.

Bar graph showing hoop stress (MPa) for different winding angles.

Scanning electron microscope image of a composite material.
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 outer layer

Zr alloy matrix
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
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.

- 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%

- UO$_2$ + 3wt% Cr$_2$O$_3$

*Yang et al., JNM 353(2006)

**IAEA TECDOC-970
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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OECD/NEA Meeting on Increased Accident Tolerance of Fuels for LWRs
**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

![Schematic of FCM Fuel](image)

- **SiC NITE Pellet**
  - TRISOs in SiC Matrix
- **TRISO Particle Fuel**
  - UN Kernel (45% packing fraction)

![Graph](image)

- **Cladding Options**:
  - SS310
  - SiC
  - SiC-coated Zr
  - FeCrAl
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/°C
  - Fast Neutron Fluence (> 0.18MeV): 15.x10^{21}#/cm^2
Equilibrium Core

- Loading Pattern Search for 5 Types of FA Candidates

<table>
<thead>
<tr>
<th>LP No.</th>
<th>Fuel Rod Array</th>
<th>Cladding Material</th>
<th>BP Type</th>
<th>TRISO Packing Fraction</th>
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<tbody>
<tr>
<td>1</td>
<td>16x16</td>
<td>SS</td>
<td>Admixed</td>
<td>45%</td>
</tr>
<tr>
<td>2</td>
<td>12x12</td>
<td>SS</td>
<td>BISO</td>
<td>42%</td>
</tr>
<tr>
<td>3</td>
<td>16x16</td>
<td>SiC</td>
<td>BISO</td>
<td>42%</td>
</tr>
<tr>
<td>4</td>
<td>12x12</td>
<td>SiC</td>
<td>Admixed</td>
<td>45%</td>
</tr>
<tr>
<td>5</td>
<td>16x16</td>
<td>SiC-coated Zr</td>
<td>BISO</td>
<td>45%</td>
</tr>
</tbody>
</table>

Fresh Fuel Enrichment: 12.8 ~ 14 w/o
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
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

- Pin Fr
- FA Fr
- Axial Power shape

- Cal. FA Enthalpy rise
- Hot FA identified
- Estimate MDNBR
- Pin by Pin Fr of limiting FA
- APS

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)**

<table>
<thead>
<tr>
<th></th>
<th>16x16 (OPR) homogeneous</th>
<th>CHK</th>
<th>16x16 (FCM) homogeneous</th>
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<tbody>
<tr>
<td>DNBR</td>
<td>2.79</td>
<td>2.92 / 3.02</td>
<td>3.13</td>
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<tr>
<td>DP (bar)</td>
<td>1.33</td>
<td>1.45</td>
<td>1.57</td>
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</table>
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

![Graph showing Fuel Thermal Conductivity as a Function of Temperature and Fuel Burnup](image-url)
Accident Analysis

- Preliminary Scoping Analysis
  - Screening of FA Designs
    - Minimize Initial Stored Energy at Full Power
  - DBA/BDBA Scoping Analysis
    - Enhanced Accident Tolerance than OPR UO$_2$ Core

<table>
<thead>
<tr>
<th>Accident</th>
<th>Safety Parameter</th>
<th>Reference UO$_2$ Core</th>
<th>FCM Core</th>
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<tbody>
<tr>
<td>LOFA</td>
<td>mDNBR</td>
<td>2.82</td>
<td>2.9</td>
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<tr>
<td>LBLOCA</td>
<td>Peak Clad. Temp.</td>
<td>1102 K</td>
<td>1020.4 K</td>
</tr>
<tr>
<td>REA</td>
<td>Peak Fuel Temp.</td>
<td>1784 K</td>
<td>1482 K</td>
</tr>
<tr>
<td>LBLOCA w/o SI</td>
<td>Grace Time</td>
<td>549 sec.</td>
<td>1577 sec.</td>
</tr>
<tr>
<td>SBO</td>
<td>Grace Time</td>
<td>105 min.</td>
<td>217 min.</td>
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</tbody>
</table>
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
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

SiC Layer Integrity

- 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