Coated Particle Fuel
FCM Replacement Fuel for LWRs

OECD-NEA EGATFL
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I. Introduction

- Lessons from Fukushima Event
  - Fukushima-like Consequence is **UNLIKELY**, if Fuel remains Integral to retain Radioactivity and Hydrogen Generation is avoided
  - Safety is more than ever the Future of Nuclear
    - Accident Risk Cost: 0.45 ~ 0.89 yen/kWh (JAEC, Nov. ‘11)

- US Senate Budget Appropriation
  - (Jul. ‘13) "The Committee is encouraged … *to develop enhanced accident tolerant fuels* … *to cope with beyond design-basis accidents*. … The Committee supports … development on concepts that target *reduced heat and hydrogen production* … and which provide *additional barriers to fission product release*, thus limiting the possibility of offsite contamination in the event of catastrophic accidents."
  - (Jun. ‘14) "The Committee directs … *to continue implementation of the accident tolerant fuels development program, the goal of which is development of meltdown-resistant nuclear fuels* leading to in-reactor testing and utilization in 10 years. …"
Joint I-NERI Project between ORNL/USNC and KAERI

- Objective: Feasibility of FCM Replacement Fuel for LWRs

Project Overview

- Period: 3 years (Nov. 15, ‘11 ~ Nov. 14, ‘14)
- Project Tasks
  - Task 1: Neutronics Exploration (KAERI)
  - Task 2: Core TH Assessment (KAERI)
  - Task 3: Safety Assessment (KAERI)
  - Task 4: Fuel Qualification (ORNL/KAERI)
    - Qualification (ORNL)
    - Performance (KAERI)
  - USNC Analysis Supports All Tasks
I-NERI Project Milestone

**FCM** Replacement Fuel

<table>
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<tr>
<th>2011</th>
<th>FY 2012</th>
<th>FY 2013</th>
<th>FY 2014</th>
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<tr>
<td><strong>FCM Fuel</strong></td>
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<tr>
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<td>Design Selection, Analysis System</td>
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<td>Pre. Scoping (ND/TH/Safety)</td>
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<td><strong>FCM</strong></td>
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<td>Transition/Equilibrium Core</td>
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<td>LP, Scoping Analysis (ND/TH/Safety)</td>
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<td>Transition/Equilibrium Core</td>
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<td><strong>Feasibility</strong></td>
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<td>to SMR Cores</td>
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<td><strong>2nd Phase</strong></td>
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<tr>
<td><strong>PENDED</strong></td>
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* FCM Core: Core initially fully loaded and reloaded with FCM FAs
** Mixed Core: Core initially fully loaded with UO$_2$ FAs and reloaded with FCM FAs
II. FCM Fuel

- Fully Ceramic Microencapsulated (FCM) Fuel
  - Coated Particle Fuel: TRISO (Proven from HTGR)
  - Pellet: TRISOs in High Density SiC Matrix
  - Cladding Options: SS310, SiC, SiC-coated Zr, FeCrAl
Features of FCM Fuel

- **Accident Tolerance**
  - Resistance to Meltdown: TRISO (< 1800°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, …
III. Work Progress

- Reference PWR: OPR-1000
  - 1000MWe Korean Standard PWR
    - Upgraded Design of ABB-CE System 80
  - Core consists of 177 FA’s
    - 16x16 FA Array
III-1. Design Selection of FCM FA

High-Level Screening of Design Candidates

FA-Level Screening

Screening Criteria?

Core-Level Screening
  • Transition Core
  • Equilibrium Core

Screening Criteria?

Optimum FA Design Selection

Core Feasibility Assessment

**Key Screening Criteria**
- Nuclear, Thermal-Hydraulic and Mechanical Compatibility with Conventional UO\(_2\) Core
- Enhanced Accident Tolerance

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Criteria</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>FA Array</td>
<td>Compatibility</td>
<td>Mech.</td>
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<tr>
<td>Fissile Inventory</td>
<td>UN, UO(_2), UCO</td>
<td>Nucl.</td>
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<tr>
<td>Enrichment</td>
<td>up to 20 w/o</td>
<td>Non-Prolifer.</td>
</tr>
<tr>
<td>Kernel Diameter</td>
<td>500 ~ 800(\mu)m</td>
<td>Nucl./Mech.</td>
</tr>
<tr>
<td>Buffer Layer</td>
<td>50 ~ 100(\mu)m</td>
<td>Nucl./Mech.</td>
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<tr>
<td>Packing Fraction</td>
<td>up to 45%</td>
<td>Nucl./Mech.</td>
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<tr>
<td>Cycle Length</td>
<td>18 month</td>
<td>Nucl.</td>
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<tr>
<td>Kinetic Parameters</td>
<td>Compatibility</td>
<td>Nucl.</td>
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<tr>
<td>Cladding Material</td>
<td>SS310, SiC, Zr-SiC, FeCrAl</td>
<td>Nucl./Safety</td>
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<tr>
<td>Cladding Thick.</td>
<td>No Buckling</td>
<td>Mech.</td>
</tr>
<tr>
<td>(\Delta P/Lift) Force</td>
<td>&lt; 120% of Ref.</td>
<td>TH</td>
</tr>
<tr>
<td>DNBR</td>
<td>Compatibility</td>
<td>TH</td>
</tr>
<tr>
<td>Fuel Rod Gap</td>
<td>&gt; 2mm</td>
<td>Mech.</td>
</tr>
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</table>
**FA-Level Compatibility**

- **k-infinite vs. Burn-up**
- **Metal-to-Water Ratio**

**FCM Replacement Fuel**
Core-Level Compatibility and Enhanced Safety

Power Peaking Factors (Initial Core)

Power Peaking Factors (Equilibrium Core)

FeCrAl vs. Zircaloy Cladding

Fuel Initial Stored Energy

Oxidation Resistance of Cladding Material

Gain in Safety Margin by FCM FA
Optimized FCM FA Design

- Optimized FCM FA Design was selected from 3-Step Screening
  - 16x16 FA
  - FeCrAl Cladding

- Optimized FCM FA Design is used for Core Feasibility Assessment
  - Core Neutronics
  - Core Thermal-Hydraulics
  - Fuel Performance
  - Core Safety

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<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>16x16-Ref.</th>
<th>16x16-FCA</th>
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<td>Assembly Pitch</td>
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<td>20.78</td>
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<tr>
<td>Cell Pitch</td>
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<td>1.285</td>
<td>1.285</td>
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<td>Fuel Material / Enrichment</td>
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<td>UO$_2$ / &lt; 5%</td>
<td>UN / &lt; 20%</td>
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<td>Fuel Density</td>
<td>g/cc</td>
<td>10.176</td>
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<td>Fuel Kernel Diameter</td>
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<td>Buffer Layer</td>
<td>μm</td>
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<td>50</td>
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<tr>
<td>Inner PyC Coating Layer</td>
<td>μm</td>
<td>-</td>
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<tr>
<td>SiC Coating Layer</td>
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<td>Outer PyC Coating Layer</td>
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<td>20</td>
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<td>TRISO/SiC Matrix</td>
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<td>Clad Material</td>
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<td>Clad Outer Radius</td>
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<td>0.5000</td>
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<td>Rod to Rod Spacing</td>
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<td>0.3350</td>
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<td>Heavy Metal Loading, 1/4</td>
<td>g/cm</td>
<td>279.0</td>
<td>94.5</td>
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III-2. Task 1: Neutronics Exploration

- Core Loading Pattern Search to Equilibrium Core
  - Nuclear Analysis System
    - DeCART-2D (2D Transport Lattice) / MASTER (3D Nodal Diffusion)
  - Among 2 Types of Core Configuration
    - FCM Core
      - Core initially fully loaded and reloaded with FCM FA’s
      - 2-/3-Batch, 18 Months Cycle
    - Mixed Core
      - Core initially fully loaded with UO₂ FA’s and reloaded with FCM FA’s from Cycle 6
      - 3-Batch, 18 Months Cycle
  - Mixed Core Configuration was selected as a Reference Core for Further Assessment

Equilibrium Core reached in 6 Cycles of Reloads

Cycle Length (EFPD) vs Core Cycle Number
- Mixed Core - 3 Batch
- FCM Core - 3 Batch
- FCM Core - 2 Batch
**Core Physics Parameters**

- **Core Loading Pattern – Equilibrium Core**
  - Mixed, 3-Batch

<table>
<thead>
<tr>
<th>FA Type</th>
<th># of FAs</th>
<th>Batch Total</th>
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<tbody>
<tr>
<td>T1/T2/T3</td>
<td>20/20/9</td>
<td>49</td>
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<tr>
<td>O1/O2/O3</td>
<td>20/20/24</td>
<td>64</td>
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<tr>
<td>F1/F2/F3</td>
<td>20/20/24</td>
<td>64</td>
</tr>
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</table>

- **Generation of Core Physics Parameters**
  - Power Distributions, Shutdown Margin, Kinetic Parameters, …
  - All Parameters meet Interim Design Acceptance Criteria

**Peaking Factors for Mixed Core, 3-Batch**

- **16x16-FeCrAl-3B**

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FCM Replacement Fuel
III-3. Task 2: Core TH Assessment

- Core TH Margin Assessment for a Mixed Core Configuration
  - Core TH Design Analysis System
    - MATRA (Pin-by-Pin Full Core Subchannel TH (Parallel Processing))
    - Subchannel Cross Flow Loss Coefficient Model for a Mixed Core
  - Core TH Assessment Model from Mixed to Equilibrium Cycles
    - Pin-by-Pin Quarter Core Model
    - Core Physics Parameters obtained from Core Neutronics Exploration

Loading pattern (Blue: UO$_2$ FA (PLUS-7), Red: FCM FA)
Core DNBR Margins from Mixed to Equilibrium Cycles

- MDNBR Margins available from Mixed to Equilibrium Cycles
- Comparable Margins in FCM Core with those of a Reference UO$_2$ Core at Equilibrium Cycle

MDNBR of FCM and UO$_2$ FAs in Mixed Transition Cycles 1 & 2

Comparison of MDNBR with Reference UO$_2$ Core in Equilibrium Cycle
III-4. Task 3: Safety Assessment

Safety Margin Assessment for a Mixed Core Configuration
- Accident Analysis System
  - MARS (System TH)
  - Thermal Conductivity Model of Irradiated FCM Pellet
- Safety Margin Assessment from Mixed to Equilibrium Cycles
  - Limiting Design Basis Accidents
    - Complete Loss of Flow Accident (LOFA)
    - CEA Ejection Accident (REA)
    - Large Break Loss of Coolant (LBLOCA)
  - Beyond Design Basis Accidents
    - LBLOCA without Safety Injection (SI)
    - Station Blackout (SBO)
  - Core Physics Parameters obtained from Core Neutronics Exploration
Mixed Transition Cycles (Reload Cycle 1 and 2)
- Safety Margins available for both FCM and UO₂ Fuels

LOFA (1ˢᵗ Cycle, Mixed Core)
- DNBR Criterion = 1.3

LBLOCA (2ⁿᵈ Cycle, Mixed Core)
- Cladding Temperature
  - PCT Criterion of FeCrAl = 1530 K
  - PCT Criterion of Zircaloy = 1470 K

REA (2ⁿᵈ Cycle, Mixed Core)
- Fuel Enthalpy Criterion = 230 cal/gm
Equilibrium Cycle (Full FCM Core)

- Increased Safety Margins in FCM Core when compared with those of a Reference \(\text{UO}_2\) Core

**Design Basis Accidents**

- LOFA, Equilibrium Core
  - DNBR Criterion = 1.3

- LBLOCA, Equilibrium Core
  - PCT Criterion of FeCrAl = 1530 K
  - PCT Criterion of Zircaloy = 1470 K

- REA, Equilibrium Core
  - Fuel Enthalpy Criterion = 230 cal/gm
Equilibrium Cycle (Full FCM Core)

- FCM Core allows Longer Grace Times for Operator Action when compared with those of a Reference UO$_2$ Core
  - SBO: 127 min Longer
  - LBLOCA w/o SI: 26 min Longer

![Graph showing time vs. fuel temperature for Station Blackout and LBLOCA w/o SI scenarios.]

- FCM Fuel Melting = 3003 K
- UO$_2$ Corium Melting = 2300 K
III-5. Task 4: Fuel Qualification

- Fuel Qualification (ORNL)
  - FCM Fuel Fabrication
    - UN Fuel Kernel Fabrication: ~ 96% dense UN$_{0.99}$C$_{0.01}$, ~ 800μm Dia.
    - R&D of Coating Processes for UN Kernels
    - FCM Pellet Fabrication
      - Overcoating TRISO with NITE SiC
  - FCM Fuel Irradiation
    - Surrogate FCM Fuel irradiation in HFIR
    - Possible Irradiation of UN FCM in ATR: Plan

- Fuel Performance at OPR-1000 Operating Conditions
  - Coated Particle Performance Analysis
    - COPA: TRISO Performance Analysis System
  - FA Performance Analysis
    - Fuel Rod Buckling and Fuel Assembly Vibration
Fully Ceramic Matrix Fuel Development

- **Q2/2010**
  - FCM Introduction (surrogate)
  - AGR Surrogate Fuel
    - 2 μm
    - 1 mm

- **Q1/2011**
  - Optimized Matrix

- **2Q/2011-Ongoing**
  - U-FCM Production
  - 19.7% Enriched LEU UCO Kernel
    - 200 μm

- **3Q/2011**
  - Surrogate Irradiation

- **1Q/2012-Ongoing**
  - PIE of Surrogate FCM

- **2Q/2012-Ongoing**
  - Model, Demonstrate, Produce UN
FCM HFIR Irradiation

- 20 FCM pellets with variable loading of surrogate particles irradiated in 4 capsules (to 130% LWR lifetime)
- TRISO loading fractions: 0 - 41 vol%
- FCM pellets are in 17x17 PWR rod geometry and are clad in Zircaloy-4
- Pellet temperature: 425 °C

No visual change in appearance
No reaction with Zircaloy
Coated Fuel Particle Performance over Fuel Lifetime

- Fast Neutron Fluence (> 0.18MeV): up to $10.7 \times 10^{21} n/cm^2$
- Internal Fission Gas Pressure
  - Negligible at PWR Conditions (< 850°C)
  - Little Cs-Release under 910°C
- SiC Layer Integrity
  - No Failure up to $10.7 \times 10^{21} n/cm^2$
  - At Higher Fluence, SiC Layer Integrity may be challenged by Swelling of iPyc Layer, however, it may survive if iPyc fails
  - Irradiation Tests @ PWR Conditions are required to remove Uncertainties involved in iPyc Deformation Model
IV. Summary and Conclusions

- Accident Tolerant FCM Replacement Fuel Design for OPR-1000 has been proposed and demonstrated Feasible
  - Optimum FCM FA Design: 16x16 FA with FeCrAl Cladding
  - Nuclear, Thermal-Hydraulic and Mechanical Compatibility
  - Enhanced Accident Tolerance
  - Fuel Fabrication and Qualification through Irradiation Tests (ORNL)

- Further Works required for Deployment
  - Characterization and Qualification of FCM Fuel through extensive Irradiation and Experiment Program: Performance and Safety
  - Scale-up of Fuel Fabrication Technologies to Engineering Scale
  - Collaboration with Nuclear Industries
  - Extended Application of FCM Fuel to SMRs, CANDUs, HTGRs, …
... thank you for your kind attention