Fully ceramic micro-encapsulated fuel design and irradiation testing

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Fully ceramic microencapsulated fuel design and irradiation testing light water reactor fuels consisting of a silicon carbide matrix and specifically engineered TRistructural ISOtropic (TRISO) particles are currently under development and analysis as part of the DOE Fuel Cycle R&D Programme. This concept is specifically referred to as the fully ceramic microencapsulated (FCM) fuel form. As part of this effort SiC matrix processing (compaction) optimisation, uranium nitride (UN) kernel fabrication, and irradiation studies are underway. This report described the development programme and the irradiation campaign, and post-irradiation examination campaign was carried out to determine the stability of the SiC matrix and surrogate fuel form. A series of surrogate FCM fuel pellets with TRISO fuel particles (zirconia substituted for the fissile containing kernel) were fabricated and irradiated at ORNL’s High Flux Isotope Reactor to examine SiC matrix irradiation behaviour. The pellets were clad in PWR 17×17 zircaloy-4 and irradiated at 425°C. By selecting the zircaloy cladding this experiment also provides insight into any potential fuel-clad interaction. Four capsules, each containing 5 pellets, were irradiated up to ~8 dpa (SiC matrix, or about 8x1 025 n/m² E>0.1 MeV) at fluence intervals of ~2 dpa. TRISO volume loadings up to 41% were studied. Of note is no apparent cracking, deformation, discoloration, or pellet clad interaction (standard microscopy inspection of both surfaces) was observed. Thermal conductivity, which has been optimised pre-irradiation and is a significant design attribute of this fuel, will be reported on post-irradiation and compared with existing algorithms for irradiation-induced degradation. Similarly, swelling of the compact will be compared with the existing database for CVD SiC and SiC composite-based materials. Also of note was the lack of interaction between the fuel matrix and zircaloy holder suggesting the potential for nil fuel clad interaction in the final fuel form.
Fully Ceramic Microencapsulated Fuel Design and Irradiation Testing

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OECD/NEA Workshop on Accident Tolerant Fuels of LWR’s
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Possible Routes To Enhanced Accident Tolerant Fuel

Improved Reaction Kinetics with Steam
- Heat of oxidation
- Oxidation rate

Slower Hydrogen Generation Rate
- Hydrogen bubble
- Hydrogen explosion
- Hydrogen embrittlement of the clad

Improved Fuel Properties
- Lower operating temperatures
- Clad internal oxidation
- Fuel relocation / dispersion
- Fuel melting

High temperature during loss of active cooling

Improved Cladding Properties
- Clad fracture
- Geometric stability
- Thermal shock resistance
- Melting of the cladding

Enhanced Retention of Fission Products
- Gaseous fission products
- Solid/liquid fission products

From K. Pasamehmetoglu, AFCI Quarterly Meeting, Salt Lake City. April 4, 2010
Enhancing Safety Margin with Advanced Fuels

Reactor safety margin can be improved through new fuel forms with much reduced exothermic reaction, suppressed hydrogen production, and greater time to fission product release.

ORNL under the DOE-NE Advanced Fuel Campaign is studying and developing a number of new clad/fuel combinations:

- Cladding: Advanced Steel, SiC Clad, Refractory Alloys
- Fuel: TRISO-SiC (FCM), BISO-SiC, TRISO-Metal Matrix
Microencapsulated Fuel History

1960s
- Ceramic coated particle fuel developed for extreme performance in nuclear rockets (ROVER/NERVA)
- TRISO used for large graphite reactors (HTRs)

1980s
- TRISO fuel adapted for high temperature operation in modular HTR

2000s
- Technology re-established for multiple international program
  - PBMR
  - NGNP
  - HTR-PM
- Record performance

→ Application of TRISO fuel to LWR is arguably a less demanding environment, however the fuel would be re-engineered for the application.
**Enabling Technology for LWR Application:**

**Fully ceramic micro-encapsulated (FCM) fuel**

SiC Matrix: High conductivity, radiation stable, should not crack or release Fission Produce (FP) gases

- Graphite replaced with radiation stable, high conductivity SiC
- SiC matrix provides secondary FP barrier
- Benign reaction with water under operating/LOCA conditions.
- Low centerline temperature in LWRs should eliminate Fission Product migration issues, mitigate LOCA concerns.
- UN kernel replaces UO2 to enhance Heavy Metal Loading

![SiC Matrix Image](image)

![Graphite Replacement](image)

![FCM Reaction](image)

![LOCA Conditions](image)

![UN Kernel](image)

![Comparison Graph](image)
Fully Ceramic Matrix Fuel Development

**Q2/2010**
FCM Introduction (surrogate)

**Q1/2011**
Optimized Matrix

**2Q/2011-Ongoing**
U-FCM Production

**3Q/2011**
Surrogate Irradiation

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

**2Q/2012-Ongoing**
Model, Demonstrate, Produce UN
Fractured (intentionally) FCM pellet with 45 vol% TRISO loading (very high loading!)

Backscattered electron image of TRISO particles embedded in NITE SiC
Selecting SiC for Irradiation Application

There are myriad SiC forming methods. However, irradiation stability requires unique microstructure.
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
Swelling and Integrity of Fuel Matrix

- Swelling of SiC Matrix saturates at a few percent (compared with >10% swelling for UO2).
- Samples upon removal from reactor appear unchanged.
Calculated and Measured Thermal Conductivity
Virgin and As-Irradiated

HFIR Irradiated Surrogate Fuel
- Saturation Conductivity Reached
- Somewhat lower than calculated based on CVD SiC Data.
CVD SiC Oxidation in Steam

- Overall parilinear oxidation kinetics: simultaneous parabolic oxidation + linear oxide scale volatilization

- At large times protective scale thickness reaches a constant value and material recession is dominated by oxide scale volatilization

\[
\frac{dx}{dt} = \frac{k_{\text{parabolic}}}{2x} - k_{\text{linear}}
\]

\[
k_{\text{linear}} \propto P^{3/2} v^{1/2}
\]

Steam Accident Test Station

Temperature
Low → 1700°C

Pressure
ATM → 30bar

TGA
To 1550°C
In H2/Steam

Opila et al., 1997, 1999, 2004; Robinson & Smialek, 1999
CVD SiC Oxidation in Steam by Linear Scale Volatilization

- Results to date suggest that material recession is dominated by linear scale volatilization and \( P^{3/2}v^{1/2} \) dependence points towards \( \text{Si(OH)}_4 \) gas as the volatile species

![Graph](image-url)
• Under severe accident conditions breach of cladding leads to FP release only after SiC Matrix recession and breach of SiC TRISO shell. At 1200°C recession rate ~ 10 μm/day.
The FCM fuel is primary focus fuel form in the FCRD-AFC program targeting fission product retention.

demonstrated benefit: high thermal conductivity
irradiation resistance (low swelling, negligible FCI) of surrogate fuel
simulated accident resistance (steam tests, limited systems analysis)

challenges: we are in the early stages of systems analysis (operational and accident scenarios)
economics (having a perfect fuel is of little value if it is unaffordable)
high burn-up performance of UN kernel and LWR-engineered FCM is unknown

Development is continuing.
- Analysis (Operational and Accident Scenarios)
- Fuel Manufacture (LWR-Optimized TRISO, Compacting Studies, UN Kernel Development)
- QA and Irradiation Campaign for Prototypical Zircaloy/UN Rodlet (2014 ATR Irradiation)
- Simulated Accident Testing (LOCA and Beyond Design Basis Testing)