U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Fully Ceramic Microencapsulated Fuel Design and Irradiation Testing

L. L. Snead, K. A. Terrani, Jim Kiggans, Bruce Pint, and Yutai Katoh
Oak Ridge National Laboratory

OECD/NEA Workshop on Accident Tolerant Fuels of LWR's
10-12 December 2012
NEA Headquarters, Issy

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

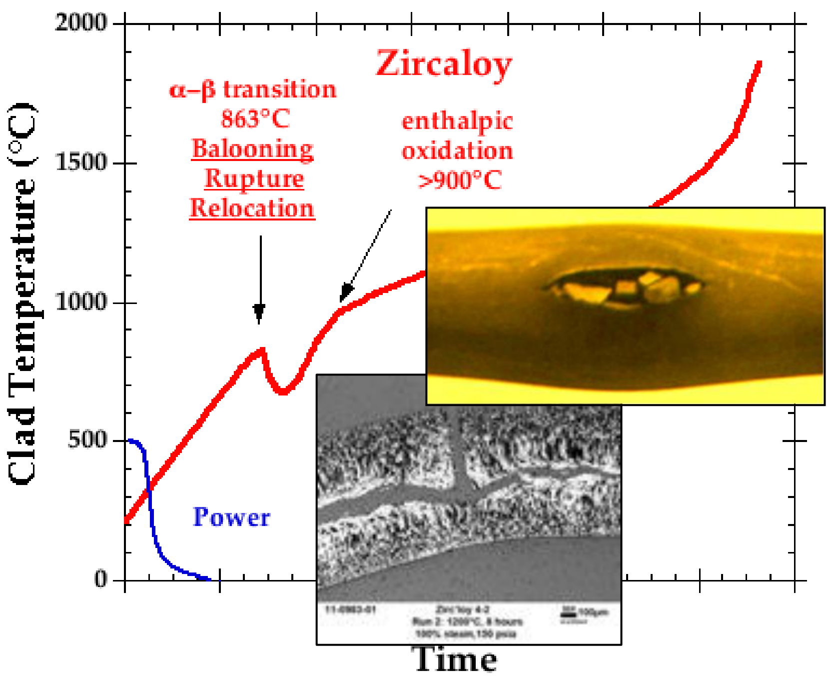
Improved Cladding Properties
- Clad fracture
- Geometric stability
- Thermal shock resistance
- Melting of the cladding

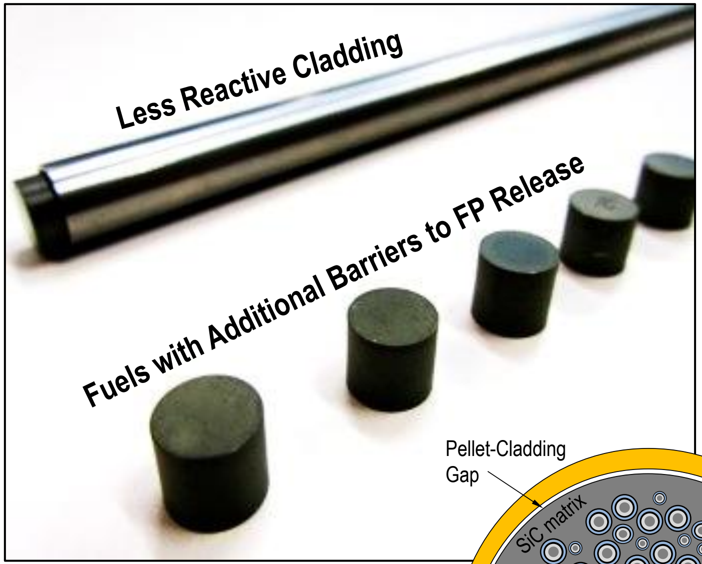
Enhanced Retention of Fission Products
- Gaseous fission products
- Solid/liquid fission products

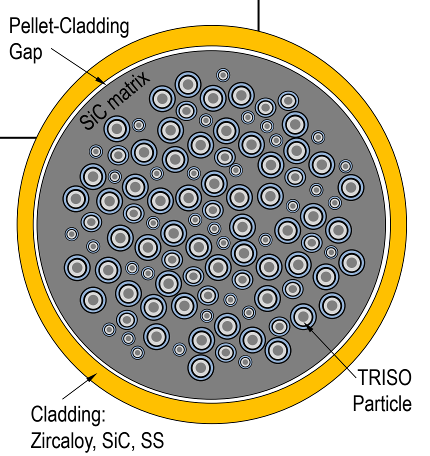
From K. Pasamehmetoglu, AFCI Quarterly Meeting, Salt Lake City. April 4, 2010

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

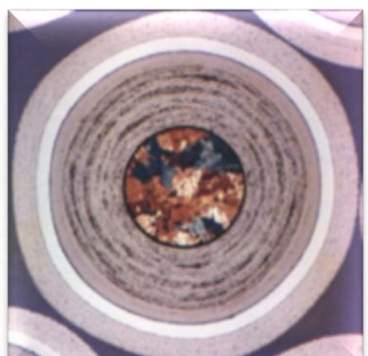
- Ceramic coated particle fuel developed for extreme performance in nuclear rockets (ROVER/NERVA)
- TRISO used for large graphite reactors (HTRs)

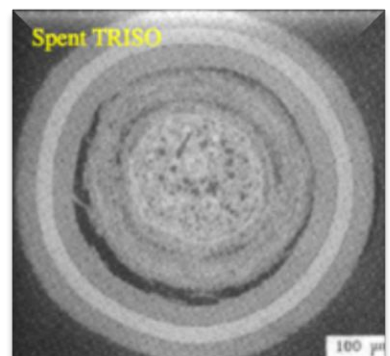
1980s

- TRISO fuel adapted for high temperature operation in modular HTR

2000s

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





New Fuels
Zero Failures @ 19% burn-up

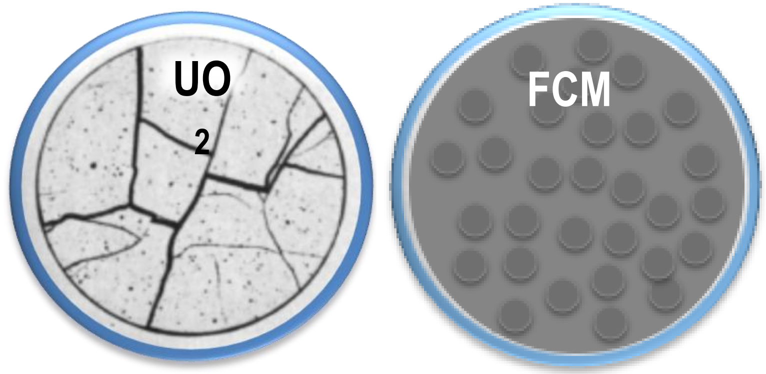
→ Application of TRISO fuel to LWR is arguably a less demanding environment, however the fuel would be re-engineered for the application .

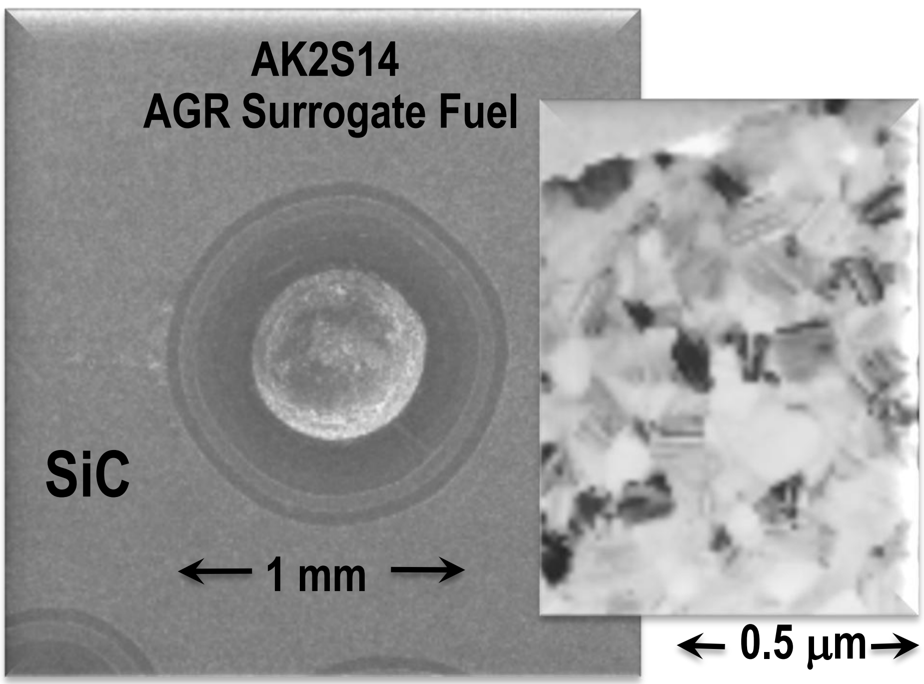
Enabling Technology for LWR Application:
Fully ceramic micro-encapsulated (FCM) fuel

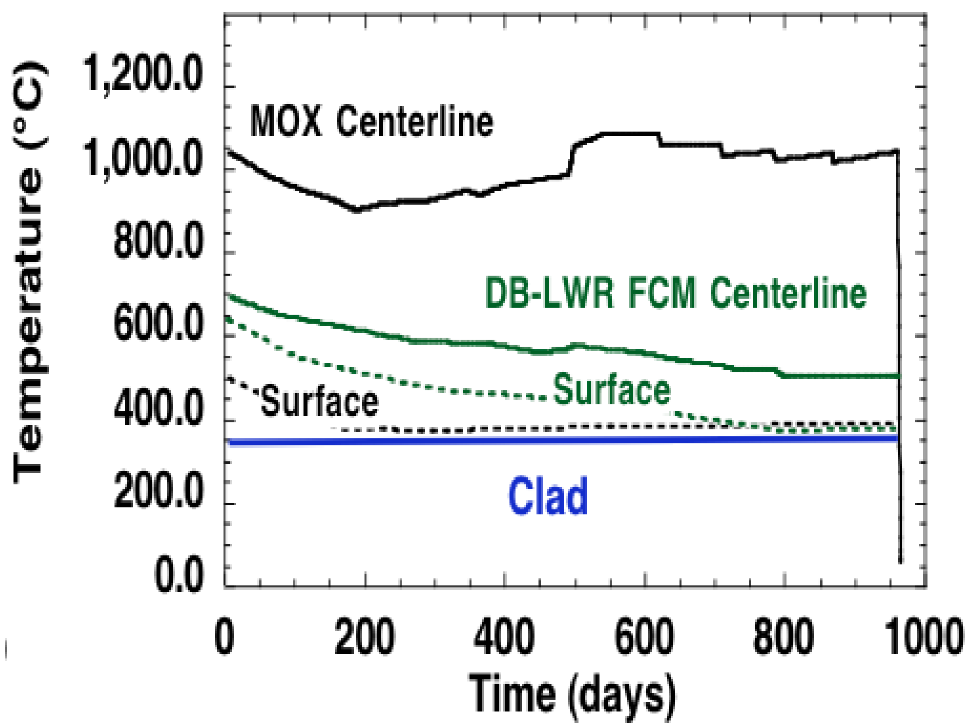
SiC Matrix: High conductivity, radiation stable, should not crack or release Fission Produce (FP) gases

- 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

UO_2 $\Delta V/V$ = 10%
SiC $\Delta V/V$ = 2%

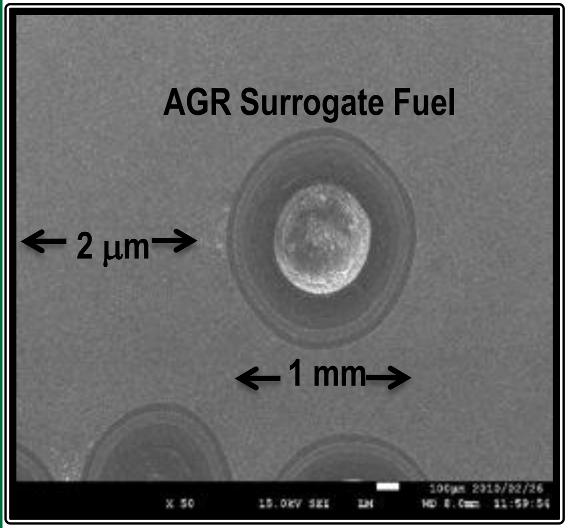




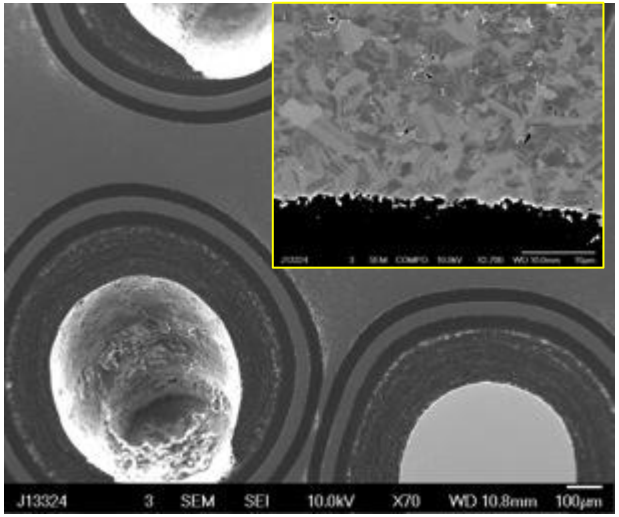


Fully Ceramic Matrix Fuel Development

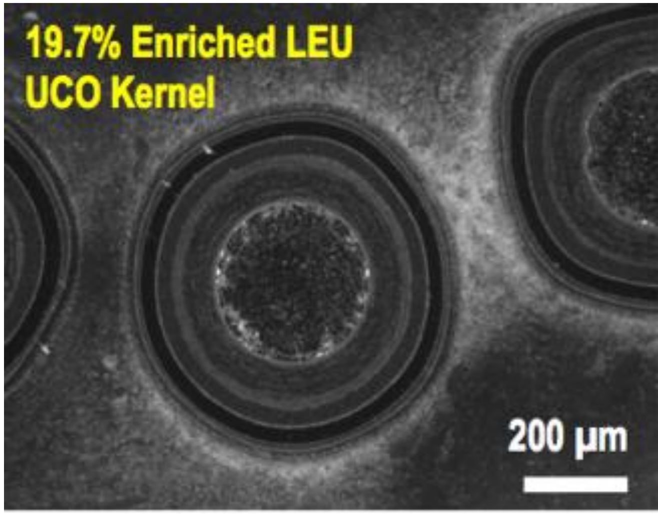
Q2/2010
FCM Introduction (surrogate)



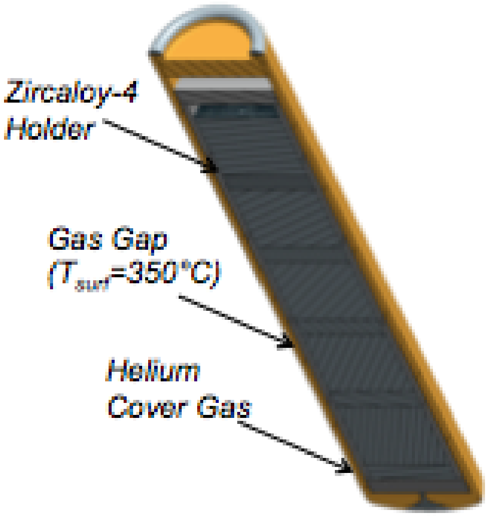
Q1/2011
Optimized Matrix



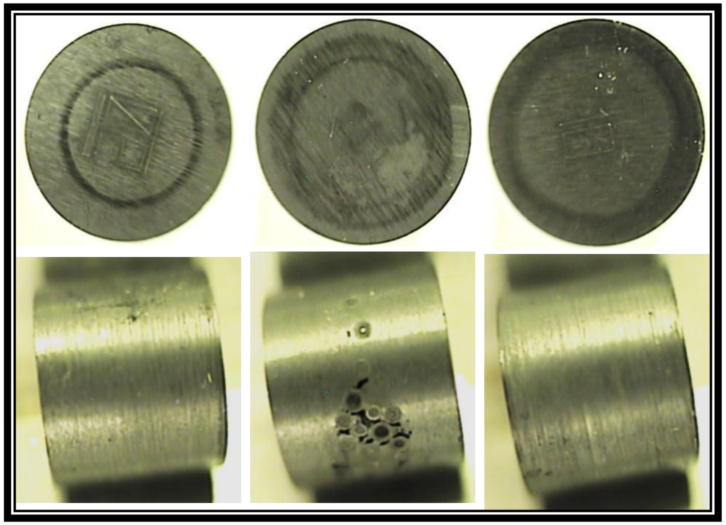
2Q/2011-Ongoing
U-FCM Production



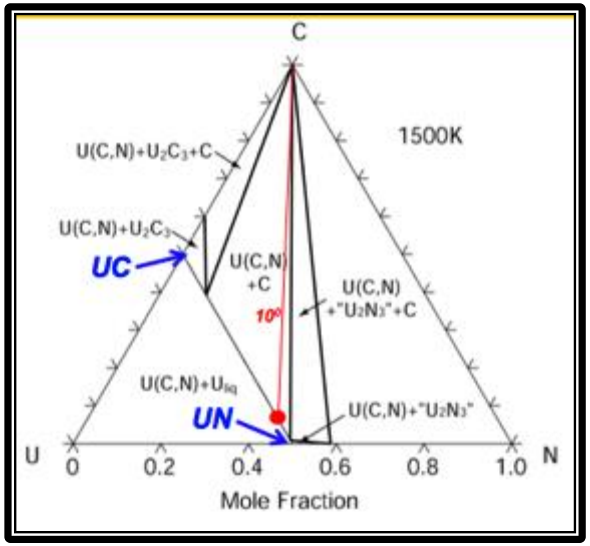
3Q/2011
Surrogate Irradiation



1Q/2012-Ongoing
PIE of Surrogate FCM

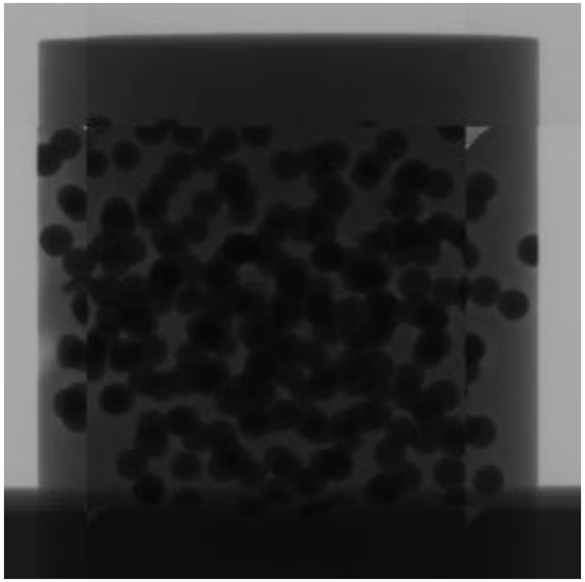


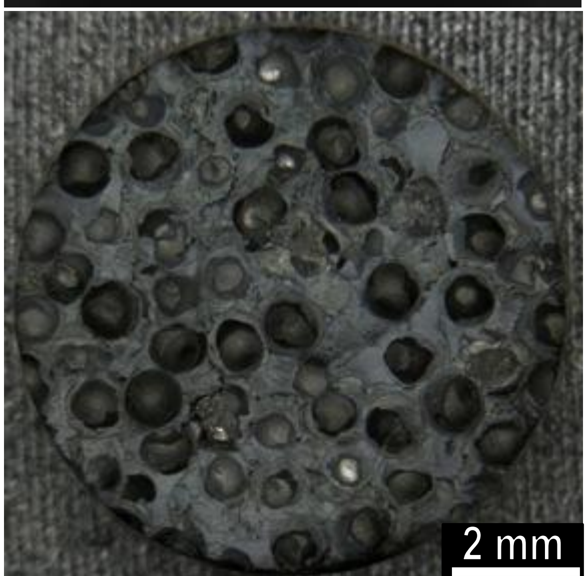
2Q/2012-Ongoing
Model, Demonstrate, Produce UN



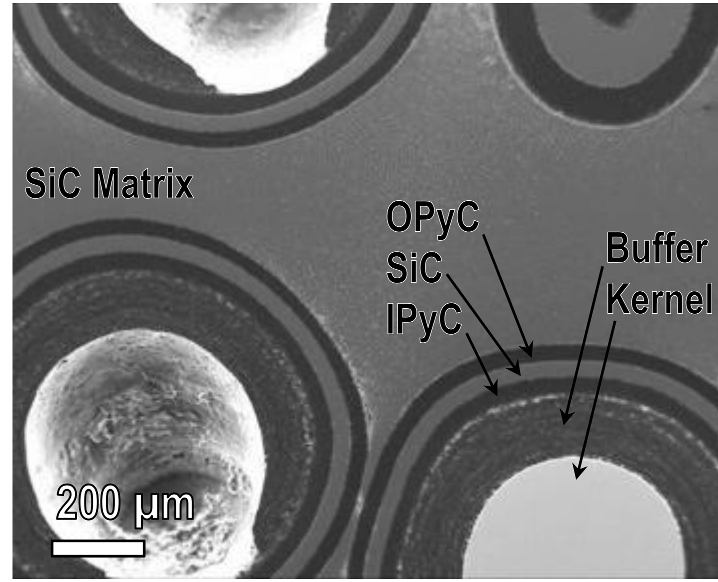
FCM Fuel Fabrication

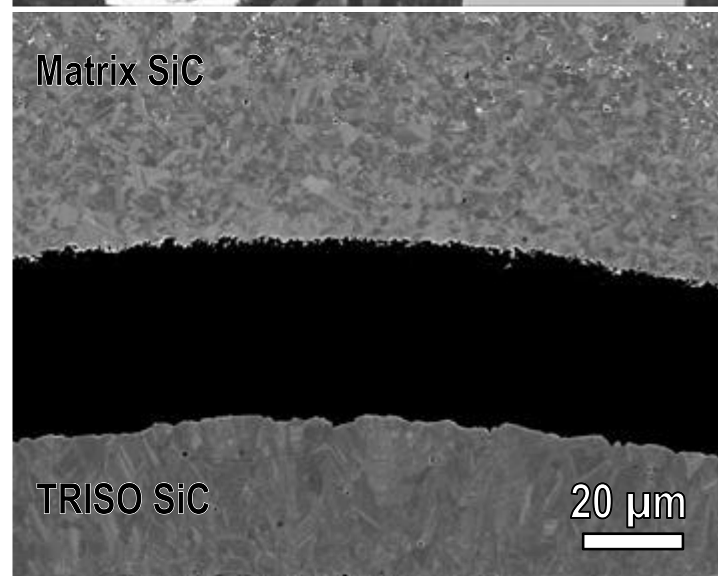
X-Ray of FCM Pellet





Fractured (intentionally) FCM pellet with 45 vol% TRISO loading (very high loading!)



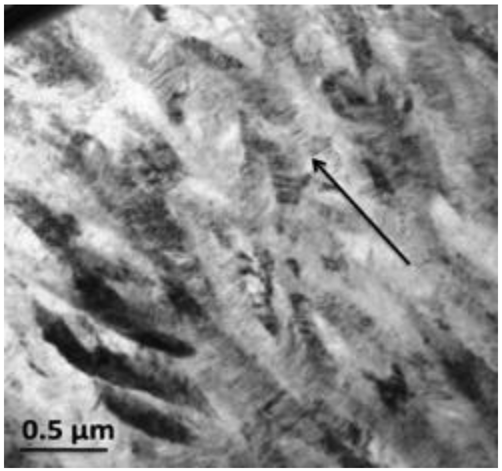


Backscattered electron image of TRISO particles embedded in NITE SiC

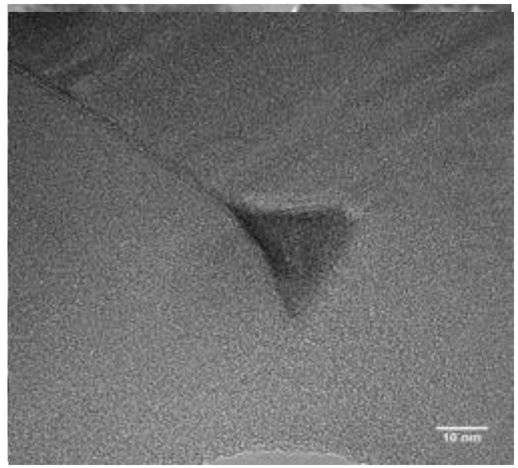
Selecting SiC for Irradiation Application

There are myriad SiC forming methods. However, irradiation stability requires unique microstructure.

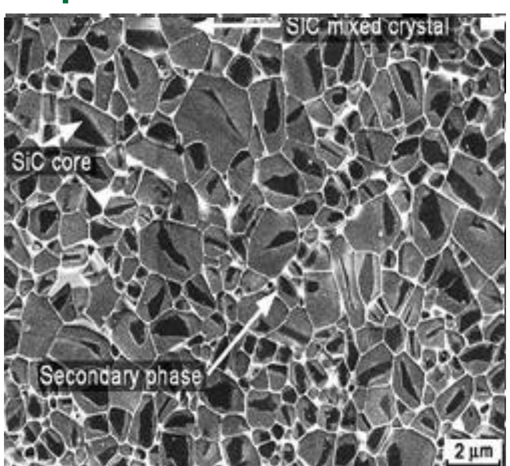
CVI / CVD SiC



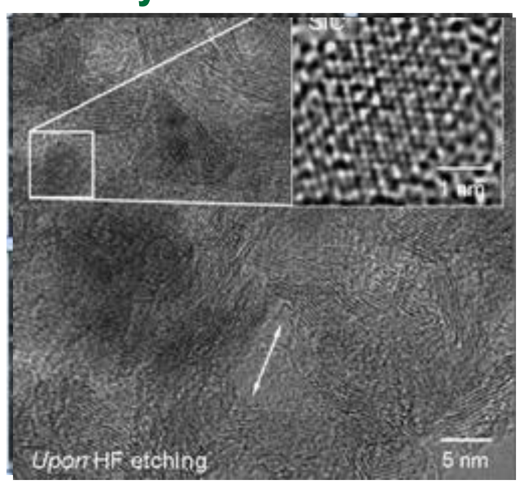
"NITE" Nano Powder SiC

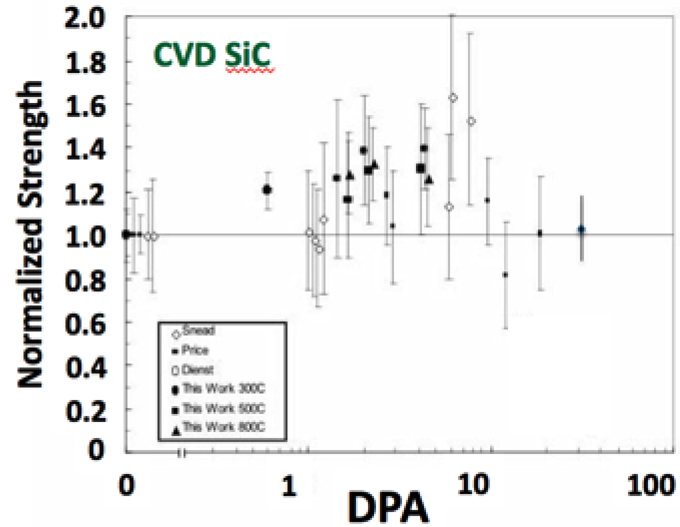


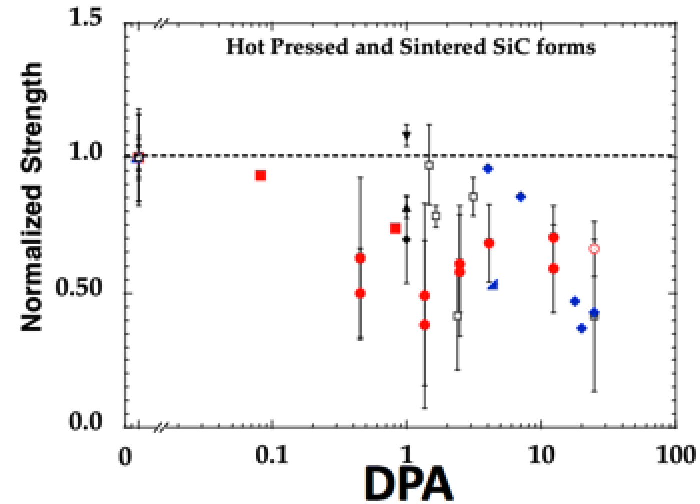
Liquid Phase Sintered SiC



Polymer Based SiC

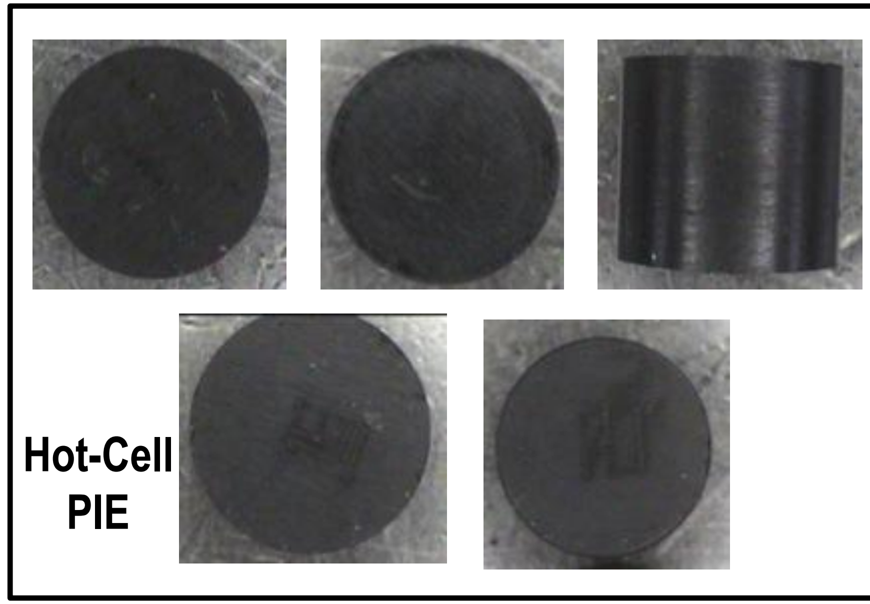


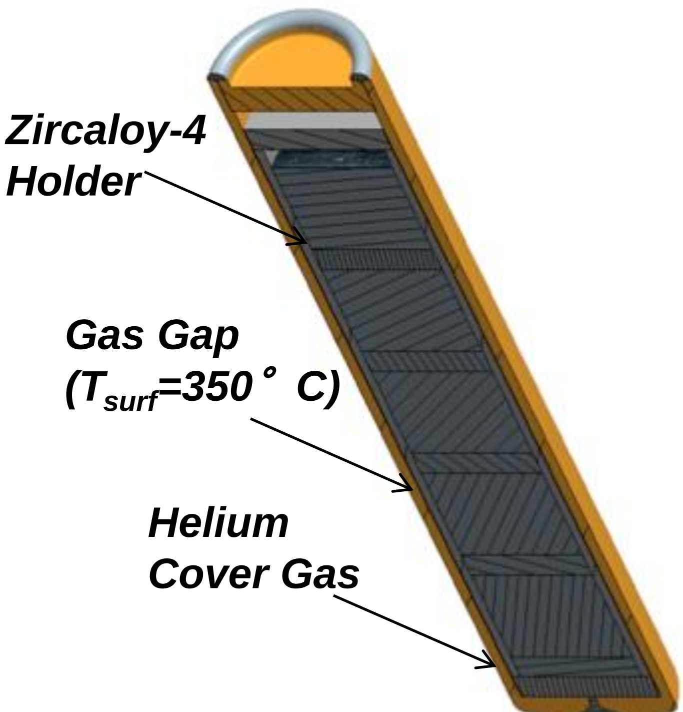




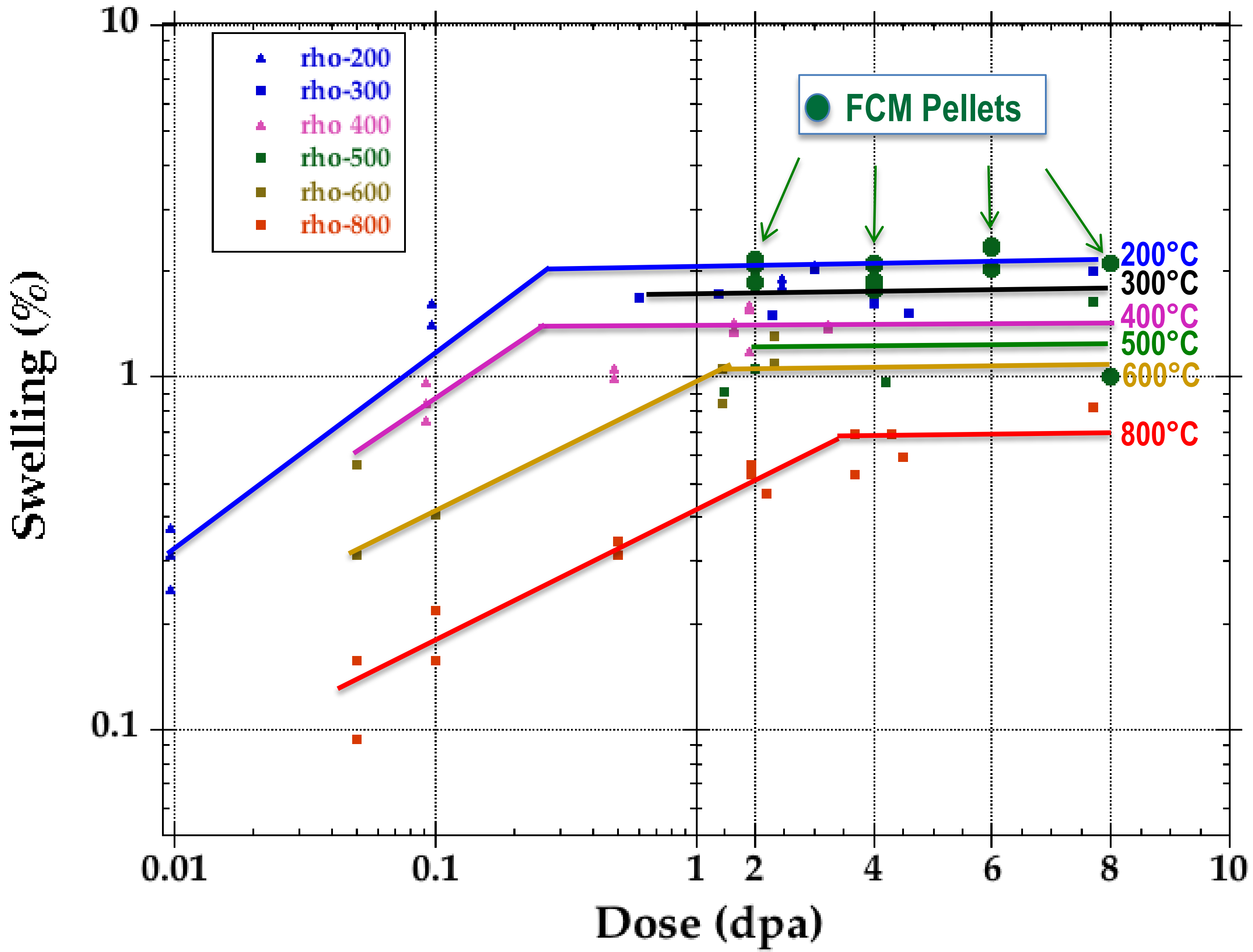
FCM HFIR Irradiation

- 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 ºC



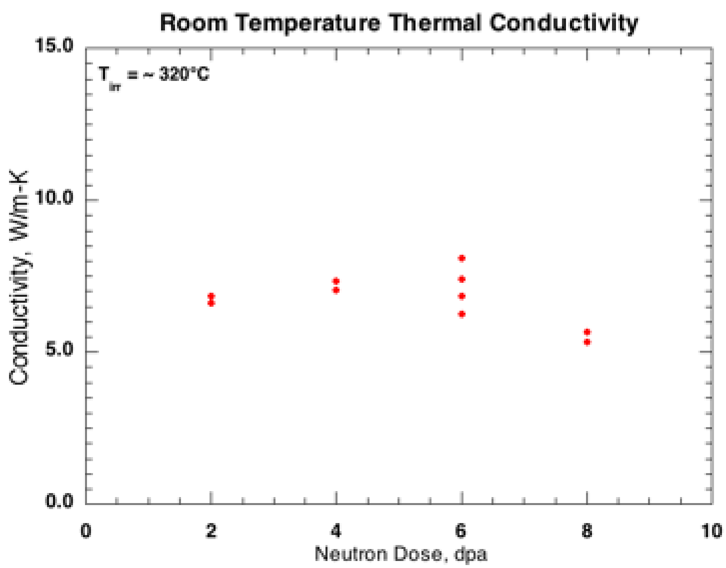


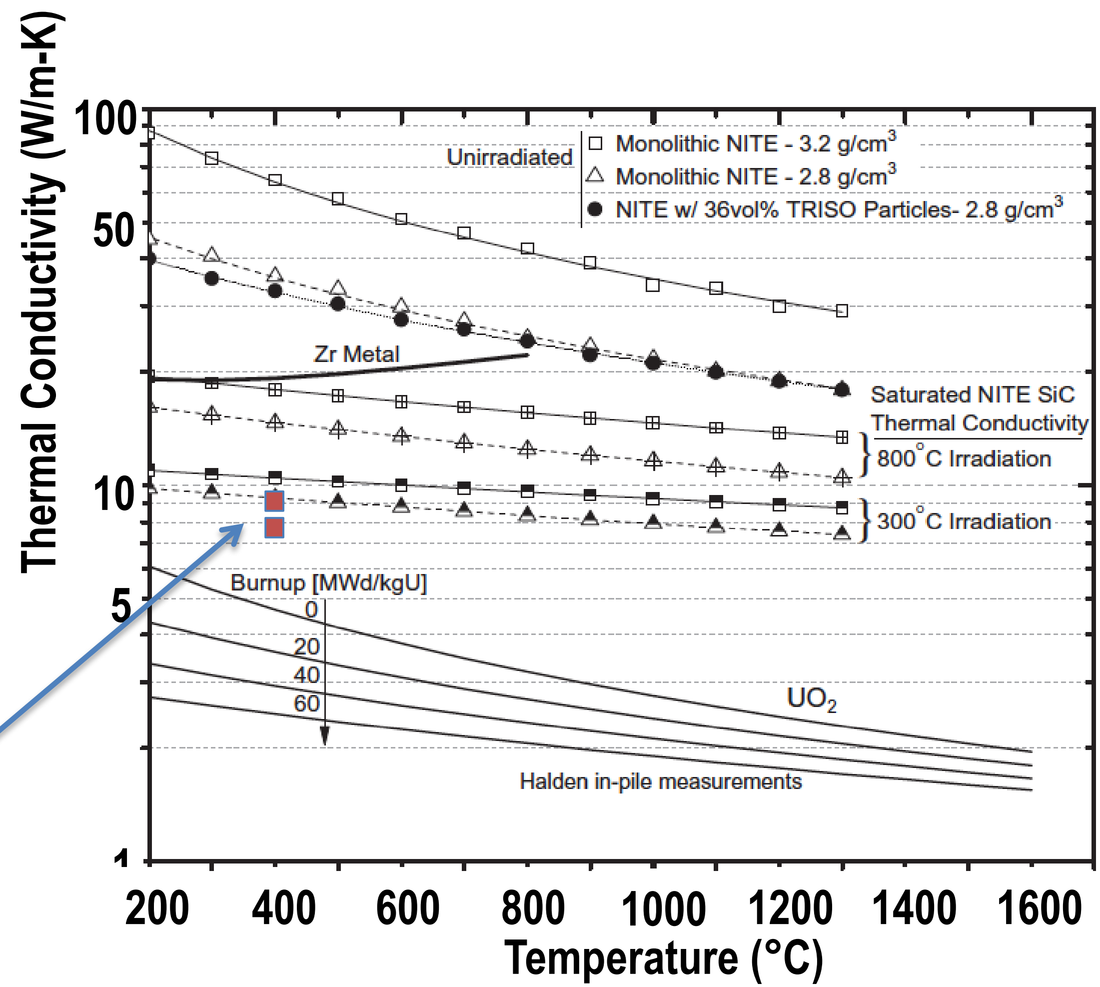
Swelling and Integrity of Fuel Matrix



- 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

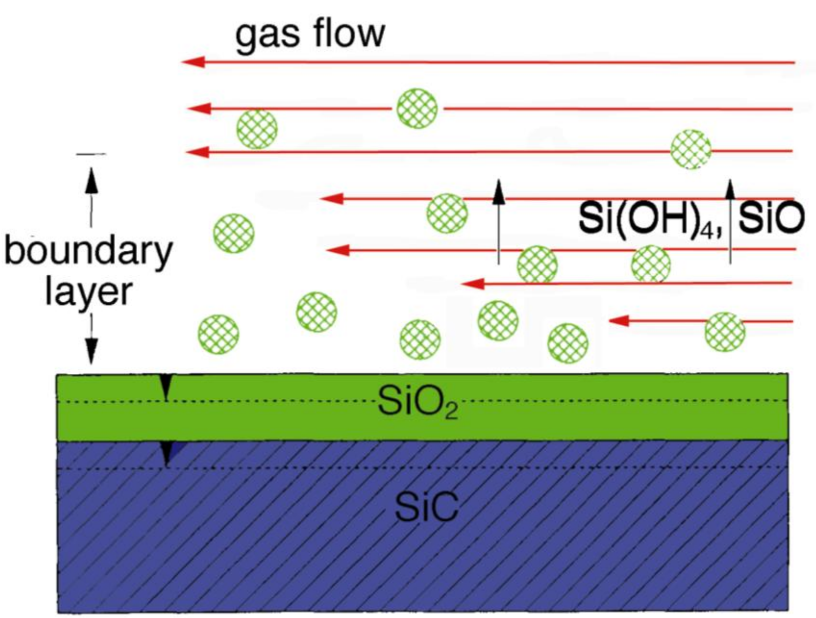
- Overall paralinear oxidation kinetics: simultaneous parabolic oxidation + linear oxide scale volatilization

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

oxide thickness

$$\frac{dx}{dt} = \frac{k_{parabolic}}{2x} - k_{linear}$$

$$k_{linear} \propto P^{3/2} v^{1/2}$$



Opila et al., 1997, 1999, 2004; Robinson & Smialek, 1999

Steam Accident Test Station

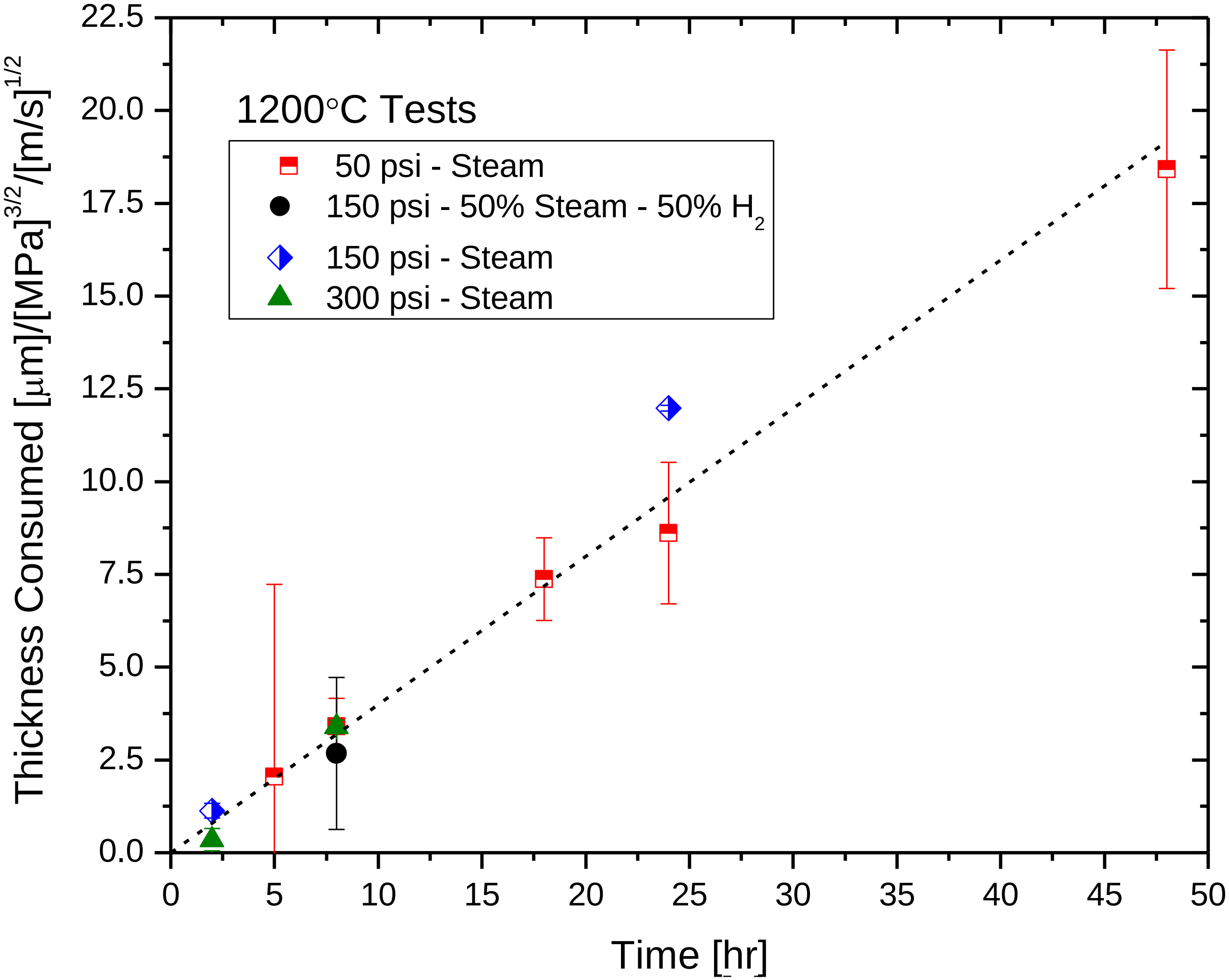
Temperature
Low→1700°C

Pressure
ATM→30bar

TGA
To 1550°C
In H2/Steam

CVD SiC Oxidation in Steam by Linear Scale Volatilization

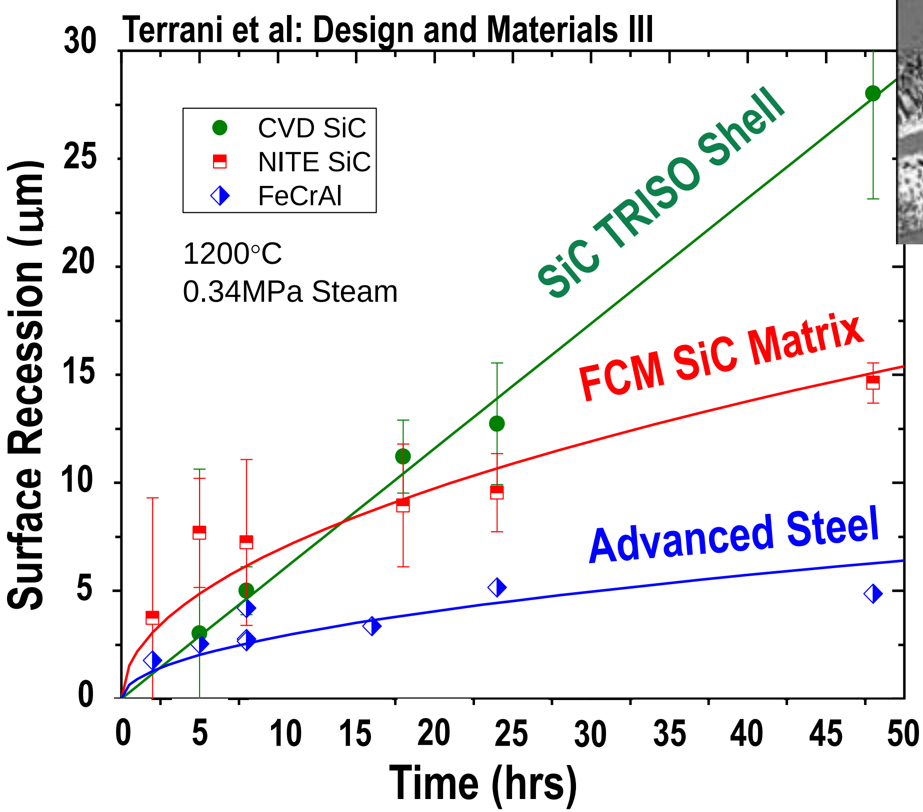
- Results to date suggest that material recession is dominated by linear scale volatilization and $P^{3/2}v^{1/2}$ dependence points towards $Si(OH)_4$ gas as the volatile species

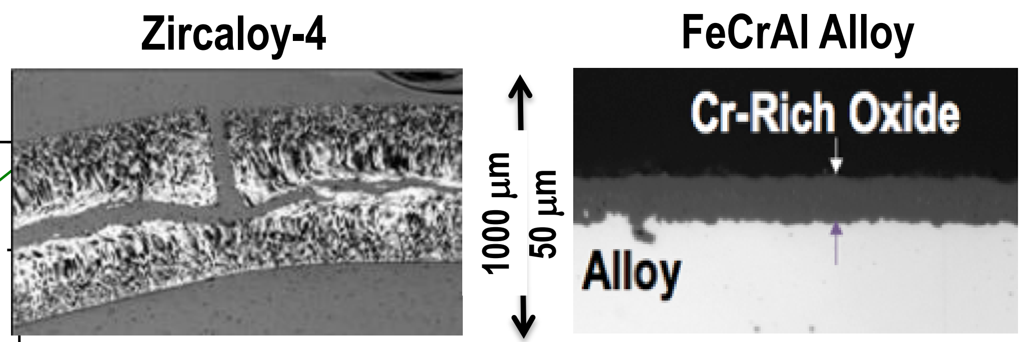


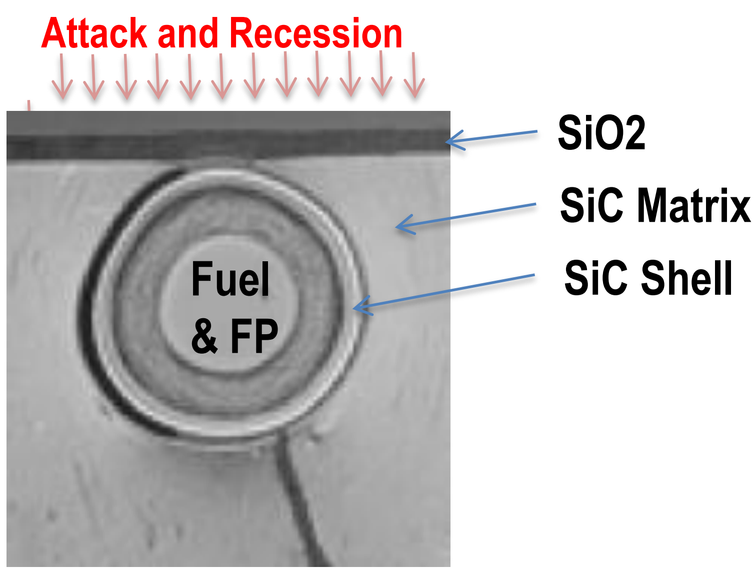
U.S. DEPARTMENT OF ENERGY

Nuclear Energy

1200°C Steam Attack







- 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)