Development of Enhanced Accident tolerat fuel pelletsInnovative High Thermal Conductivity UO_2 Ceramic Composite Fuel Pellets with Silicon Carbide/ CR2O3 Using Spark Plasma Sintering

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U.S. Department of Energy

Motivation

- Lower the temperature gradient in UO_2 pellet with a SiC whiskers or particles so as to eliminate fuel cracking, minimize fission gas release driven by high internal pellet temperatures
- Utilize the Spark Plasma Sintering (SPS) technique to develop a high thermal conductivity UO_2-SiC composite fuel pellet

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Spark Plasma Sintering (SPS)

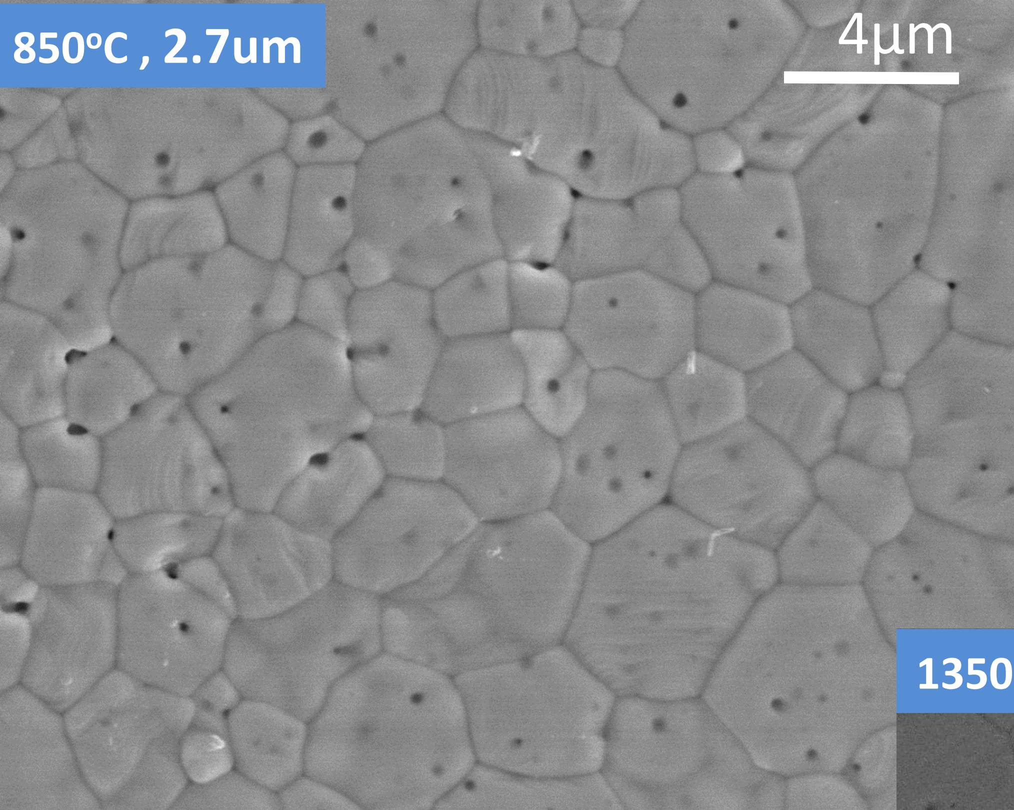
- Conventional UO_2 sintering requires 1700^{o}C with ~10hrs processing time in total

- Spark plasma sintering is a rapid sintering method with
  - Faster heating rates (200^{o}C/min)
  - Lower sintering temperatures (1050 ^{o}C
  - Control of grain growth
  - Reduced processing time
  - Considerable savings in energy

Resulting pellets

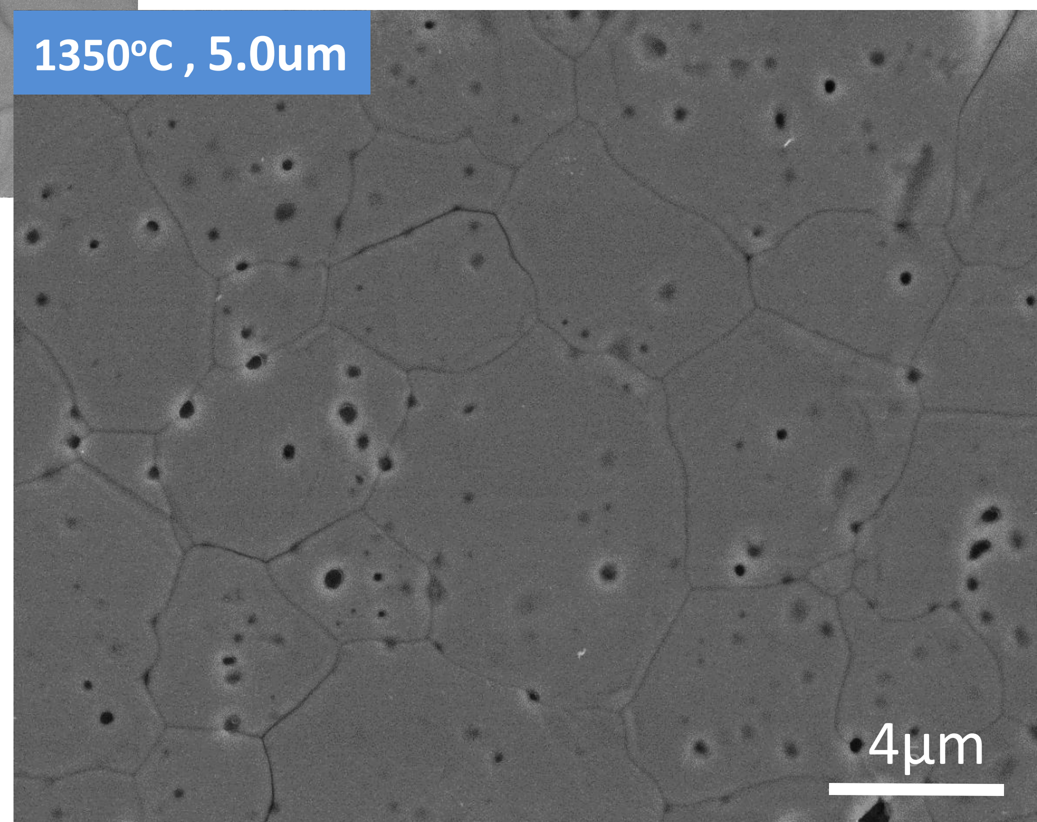
Pellets for characterization

Pellets with dimple and chamfer



Effect of Max. Sintering Temp.

*Heating rate is 200ºC/min.
Hold time is 0.5min.
Thermally etched.

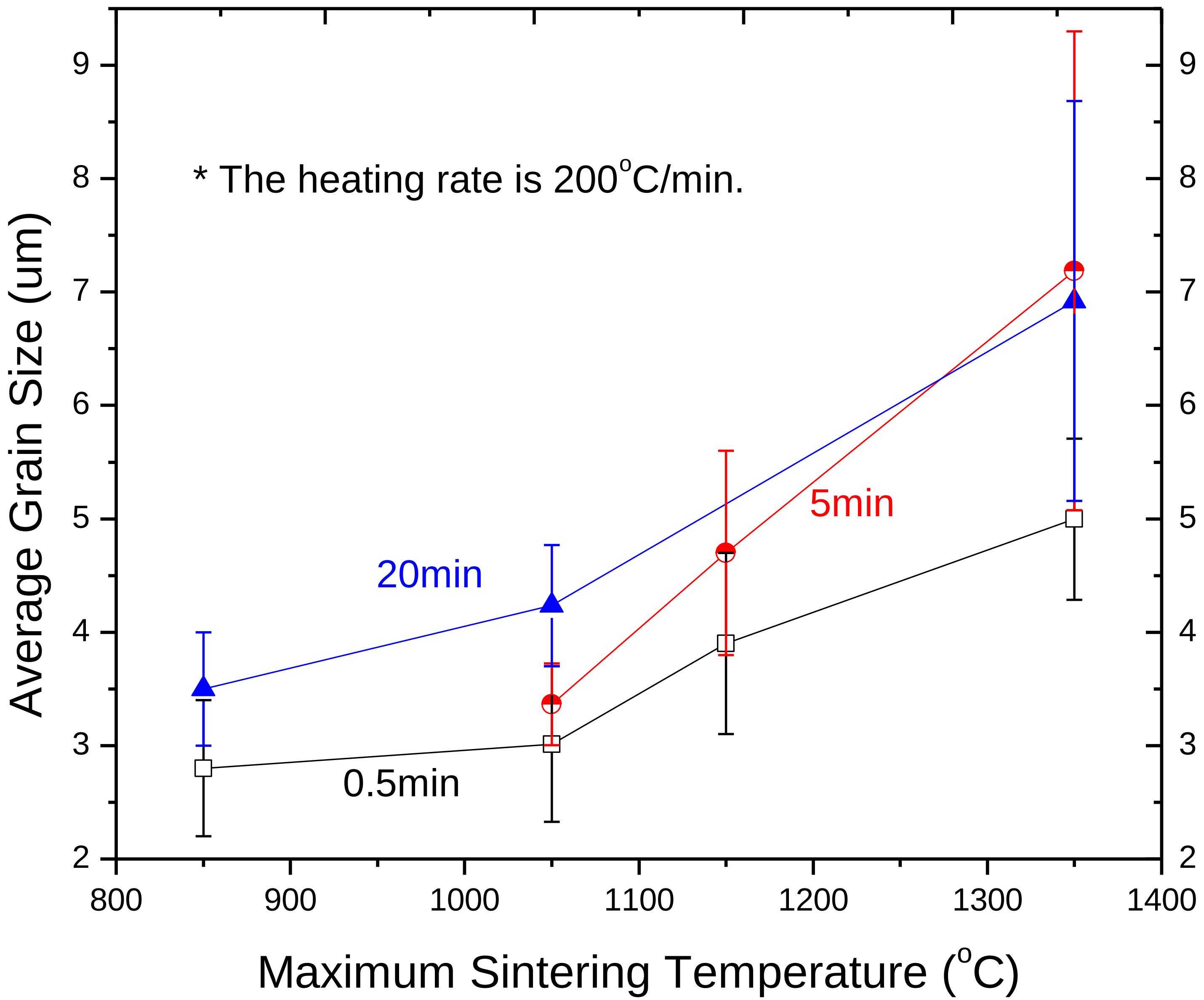


Average Grain Size

Inter-granular porosity

Intra-granular porosity

Grain size vs Max. Sintering Temperature



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Incorporation of Silicon Carbide

SiC Properties

- High thermal conductivity
- Excellent chemical stability
- Good irradiation stability
- Low neutron cross section
- High melting point

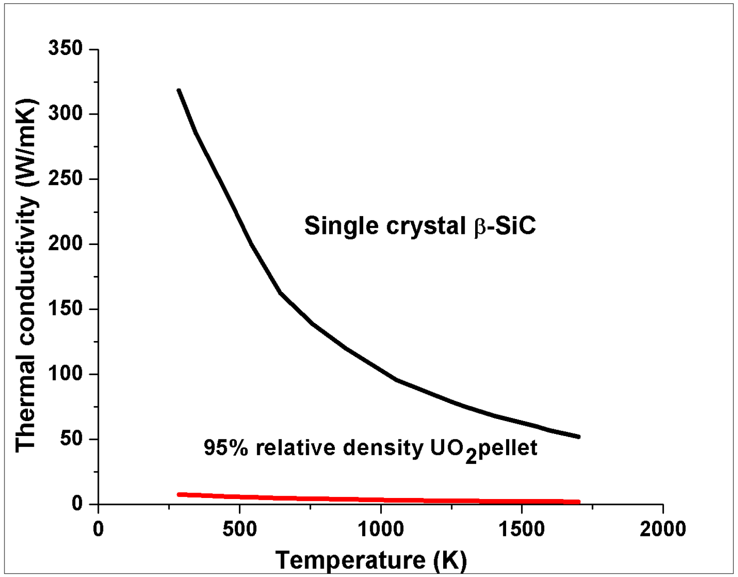
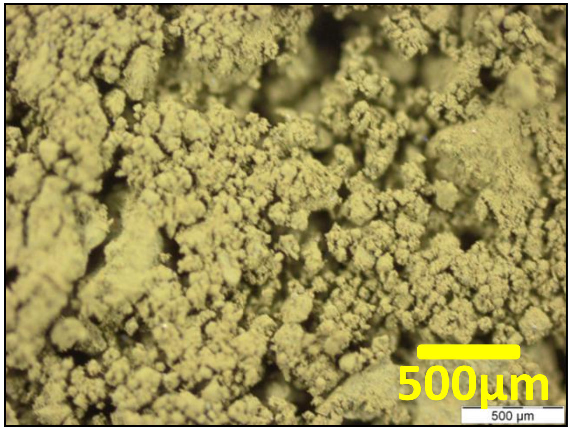


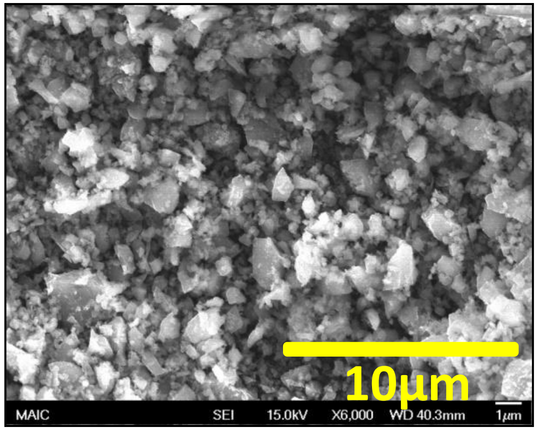
Fig. Thermal conductivity of UO_2 and SiC [1-2]

UO_2 powder



Particle size : **2.4µm**

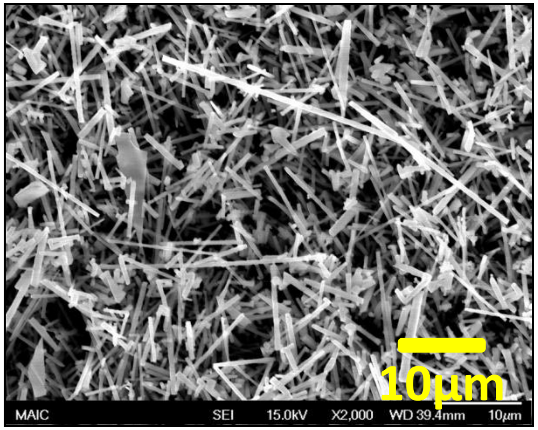
Powder type β-SiC (SiCp)



Mean diameter : **1µm**

OR

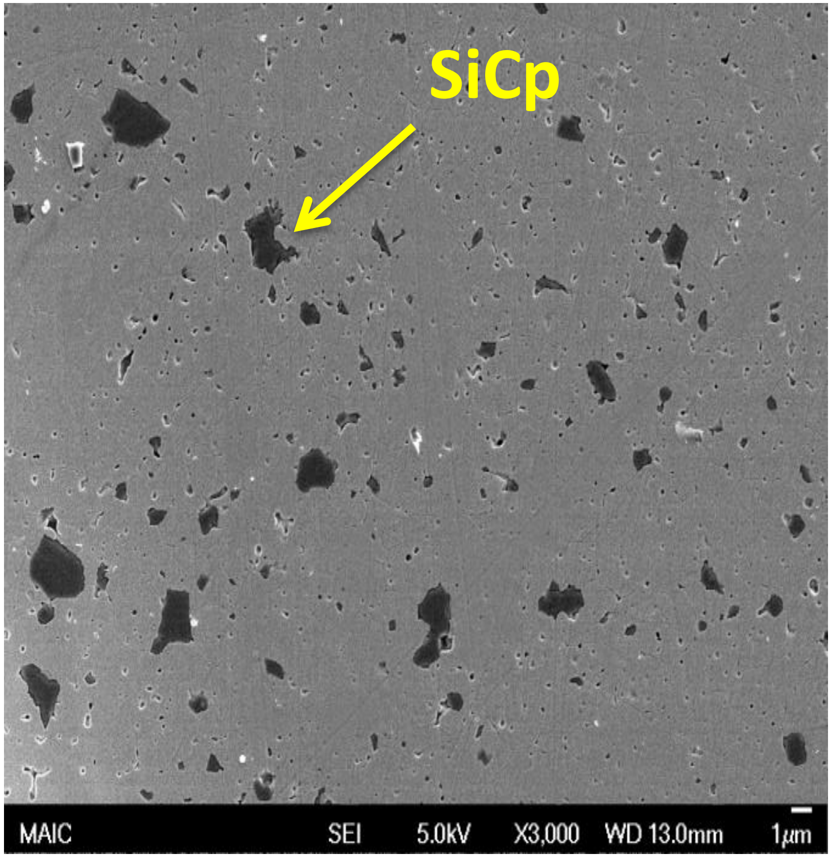
Whisker type β-SiC (SiCw)

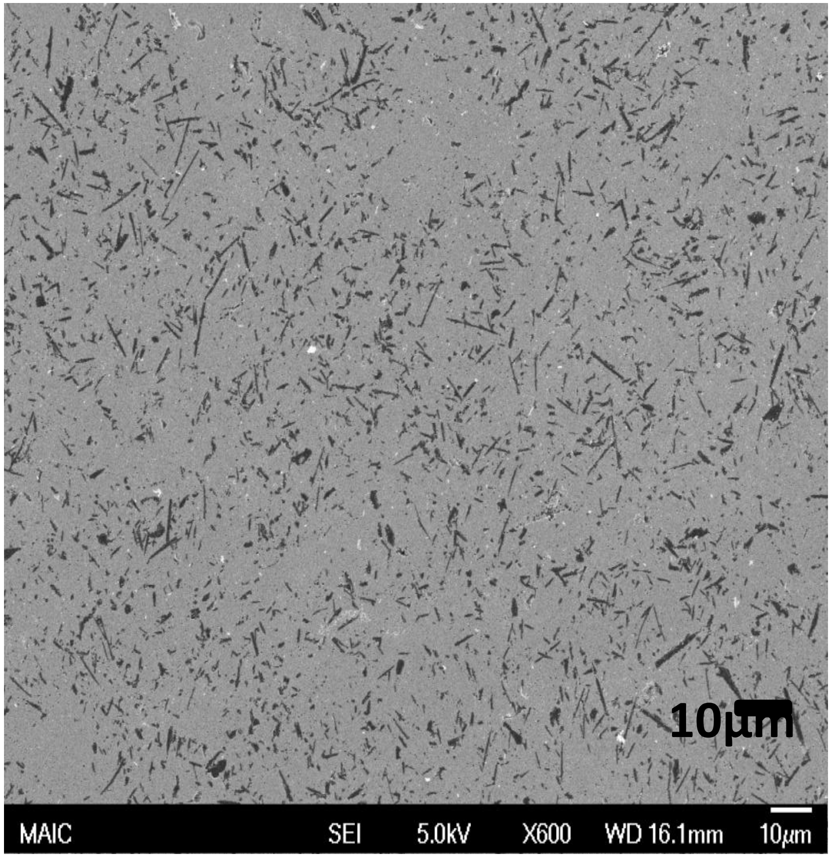


Mean diameter : **0.65µm**
Mean length : **10µm**

[1]J. K. Fink, Journal of Nuclear Materials 279, 1 (2000)
[2]J. Li, L. Porter, S. Yip, Journal of Nuclear Materials 255, 139 (1998)

UO_2-SiC Pellets Showing Good Dispersion of SiC particles and Whiskers





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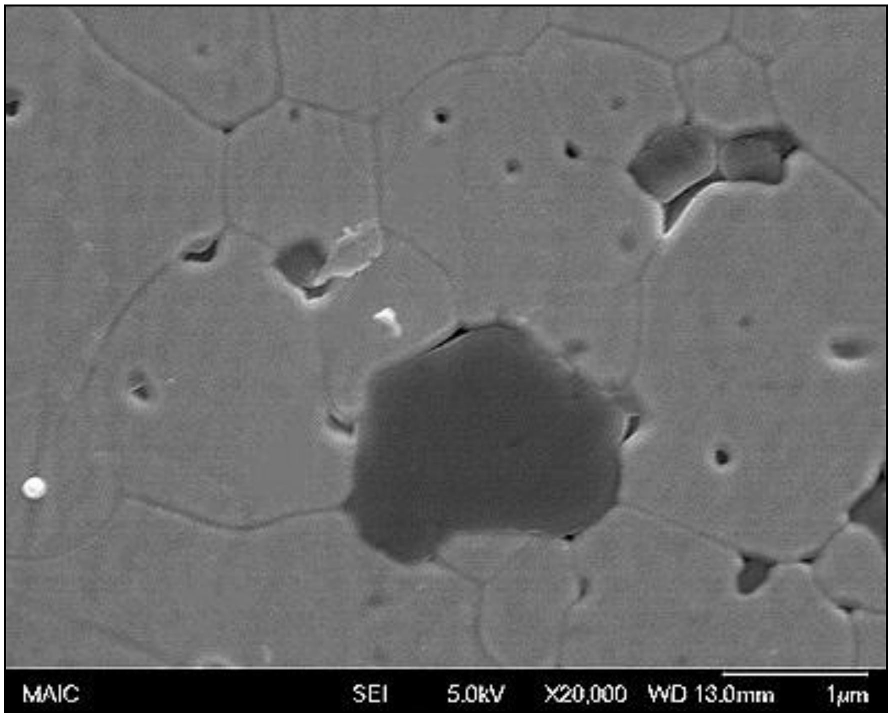
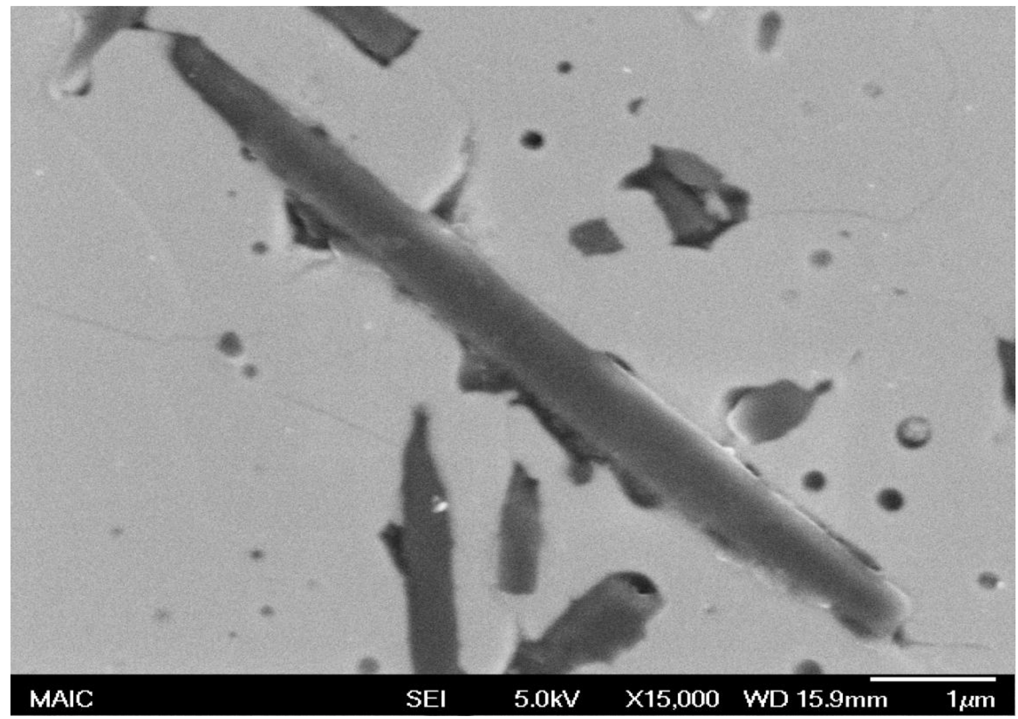
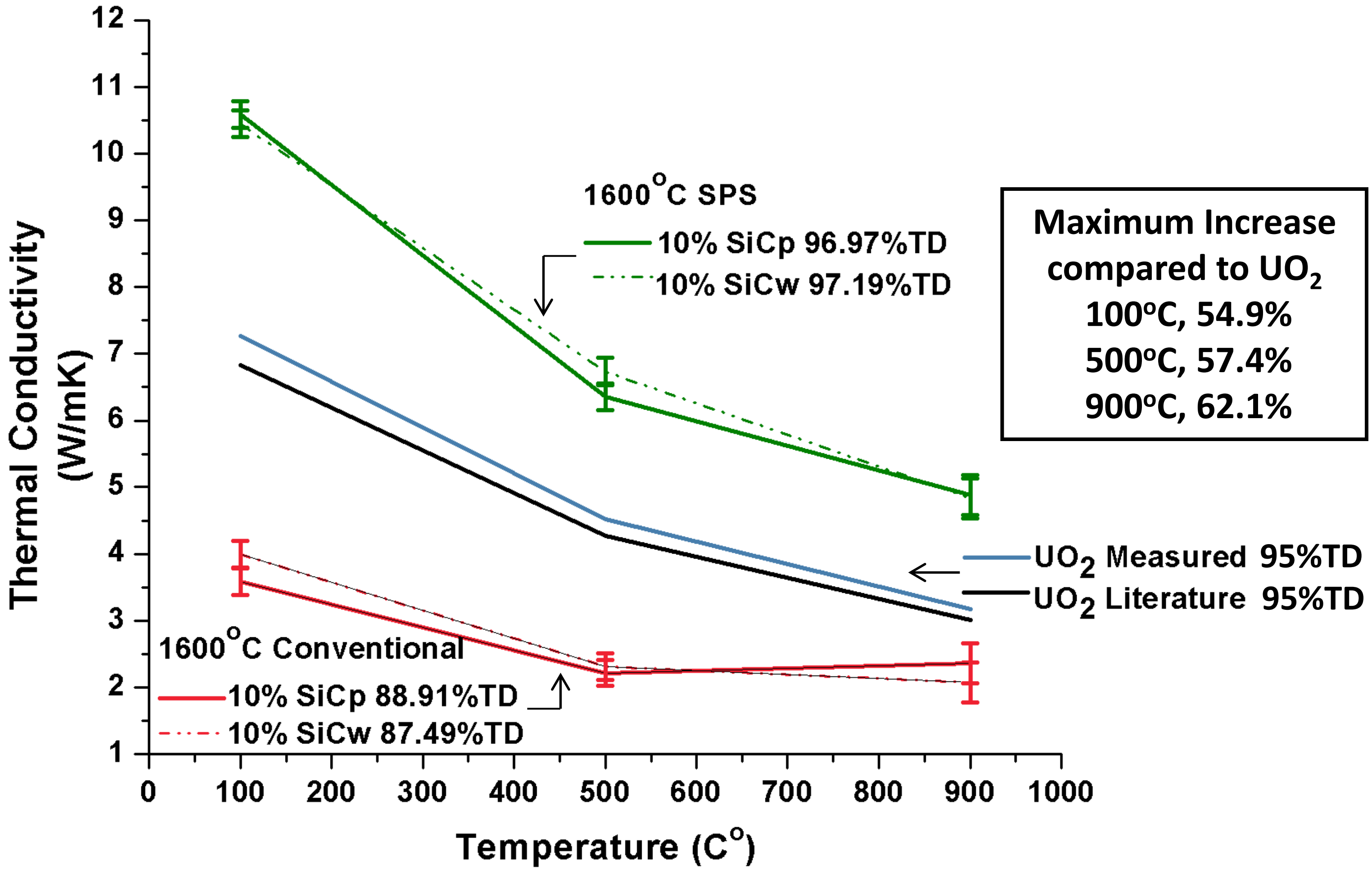
UO_2-SiC Microstructure Showing Good Bonding Between SiC and UO2 Matrix



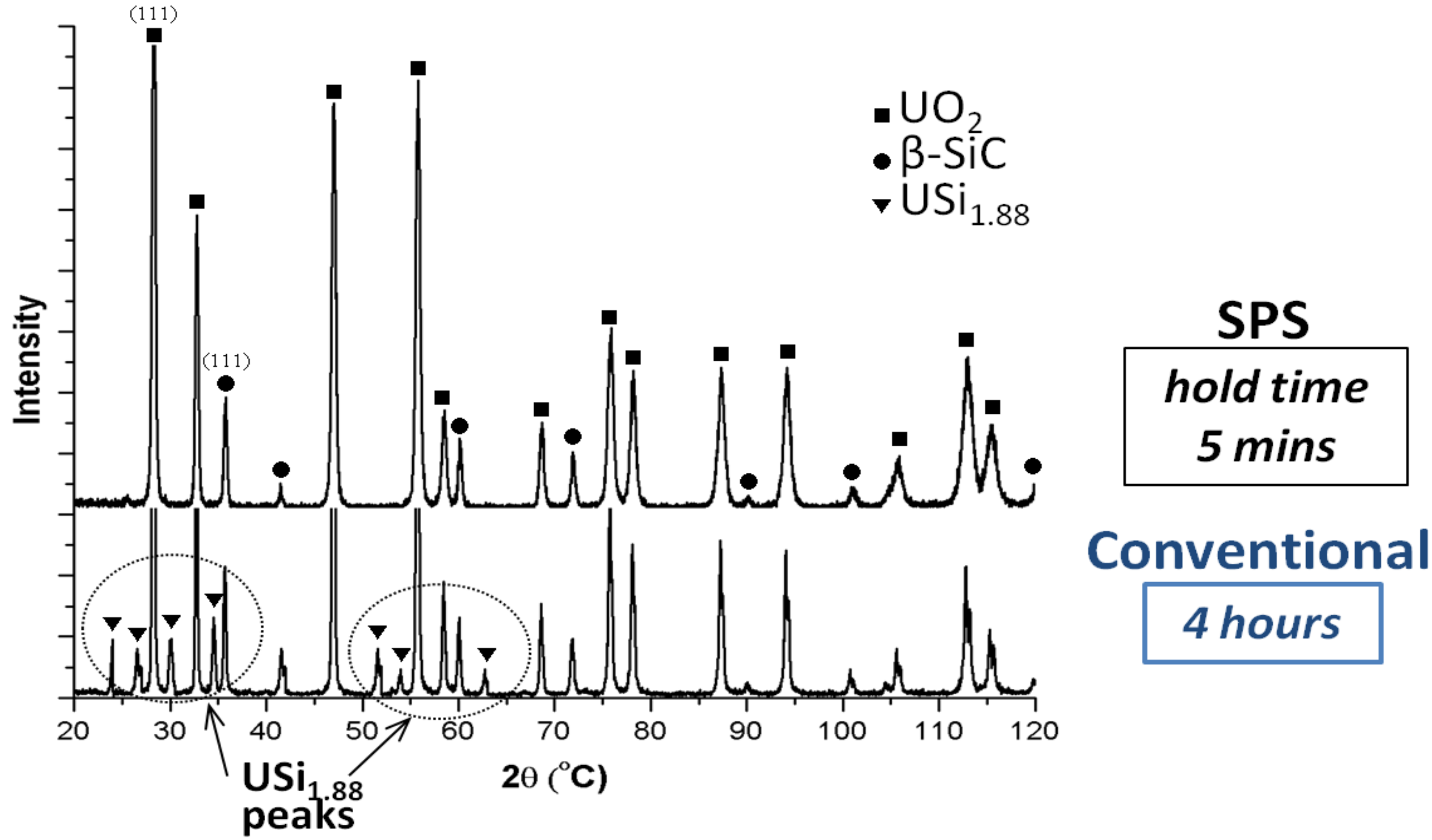


Thermal Conductivity



- UO_2-SiC pellets sintered by SPS technique showed enhanced thermal conductivity up to 62.1%

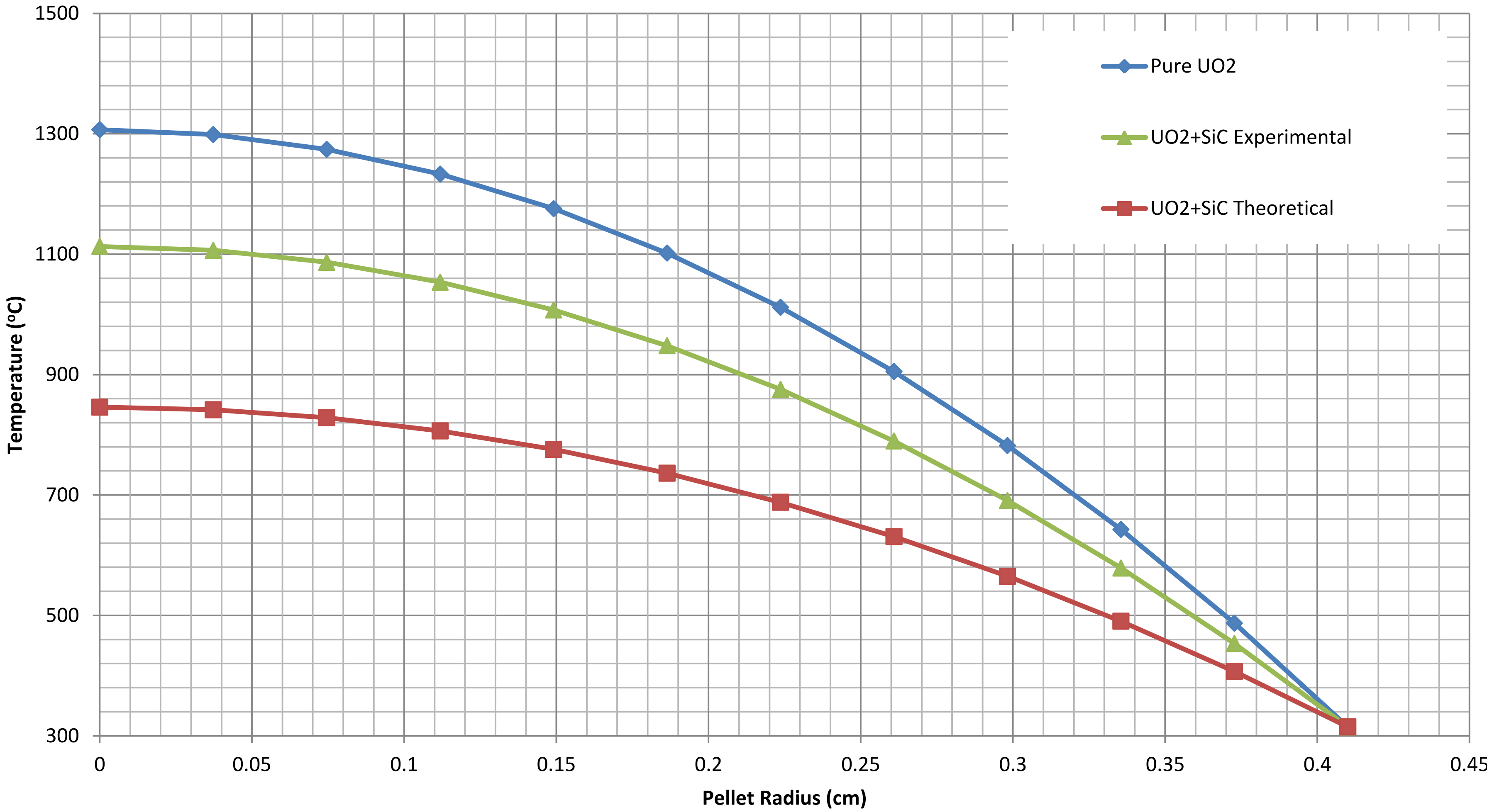
Chemical Reaction of UO_2-70vol%SiC pellets



- **Reduced formation of chemical products in the SPS pellet**

Chemical Reactions	Intermetallic phases ($USi_{1.88}$) →	Phonon scattering cites	Lower thermal conductivity
	Gas phases (CO or CO_2) →	Poor interfacial contact	

Pellet Temperature as a Function of Pellet Radius at O GWD/MTU Burnup – 10 Kw/ft (32.8Kw/m)



Conclusions

- **The feasibility of successfully achieving the proposed improved pellet performance is considered excellent**
- **The UF Team has chosen a unique processing approach and materials that have been shown to provide benefits**
- **The ability to construct a uniform material with repeatability will be confirmed by the proposed testing**
- **The accident condition performance will be better quantified by mechanical and thermal tests**
- **In reactor performance will be confirmed by ATR testing**

Utilization of FRAPCON 3.4 to Determine Enhanced Fuel Performance

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Enhanced LWR Fuel Performance with increased thermal conductivity due to additives:

- Diamond Powder (5 and 10 vol%)

- Silicon Carbide Whiskers/Powder (5 and 10 vol%)

Enhanced LWR Fuel Performance with increased thermal conductivity of fuel and the gap using:

- UO_2 doped with SiC and a Liquid Bond Gap

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Enhanced Thermal Properties

At End of Life (EOL), decrease in:

- Average Fuel Temperature
- Centerline Temperature
- Axial Fuel Swelling
- Plenum Pressure
- Fission Gas Release

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Fuel Thermal Conductivity Equation in FRAPCON 3.4

$$k_s = \frac{1}{A + BT + f(Bu) + \ (1 - 0.9\exp(-0.4Bu))g(Bu)h(T)} + \frac{E}{T^2}\exp(\frac{-F}{T})$$

T = Temperature (K)
Bu = Burnup (GWD MTU^{-1})
f(Bu) = 0.00187·Bu
g(Bu) = 0.038·$Bu^{0.28}$
h(T) = $[1+396e^{-Q/T}]^{-1}$
Q = 6380 K
A = 0.0452 m-K/W
B = 2.46E-4 m-K/W/K
C = 5.47E-9 W/m-K^3
D = 2.29E14 W/m-K^3
E = 3.5E9 W-K/m
F = 16361 K

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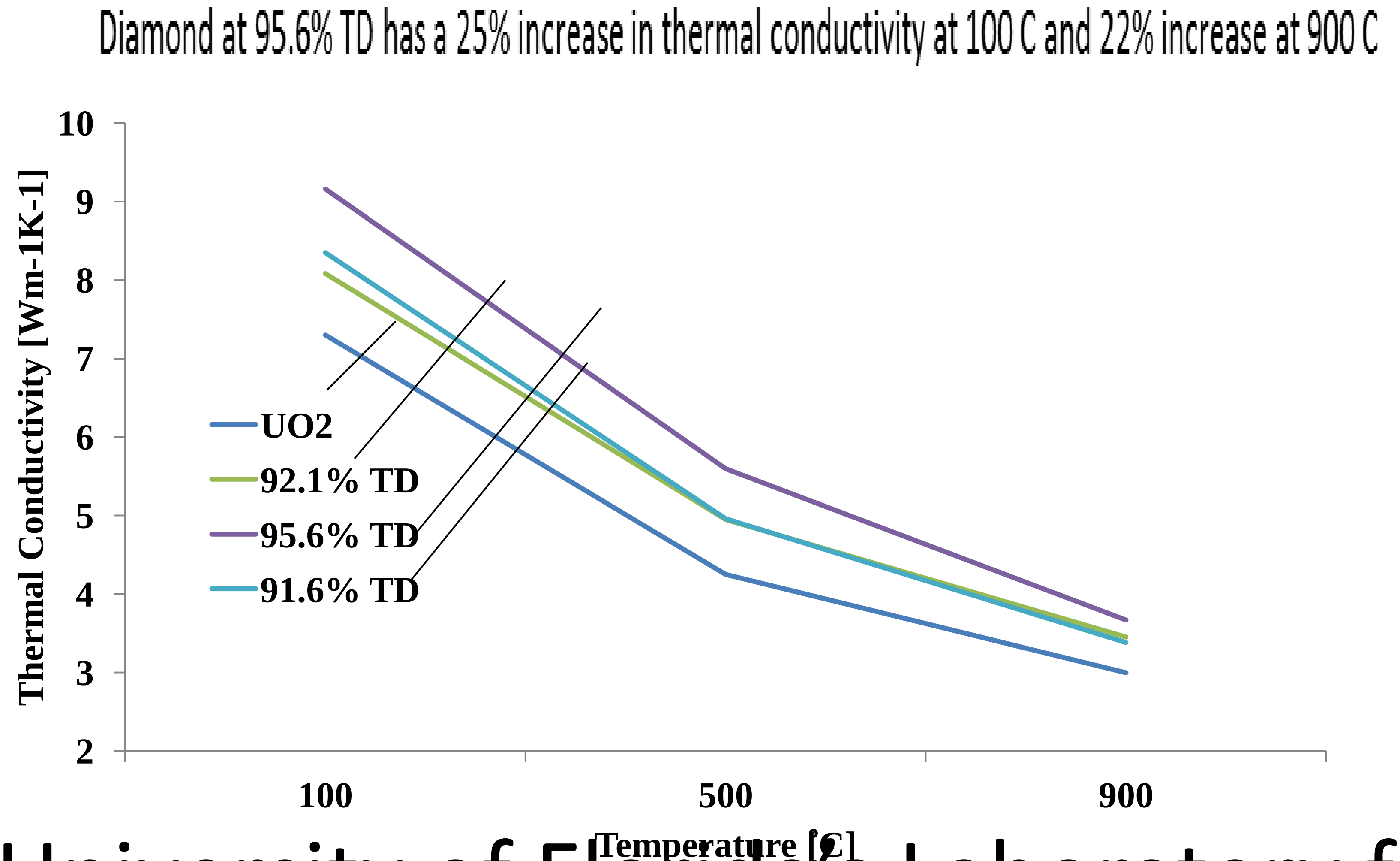
Thermal Conductivity with Diamond Dopant



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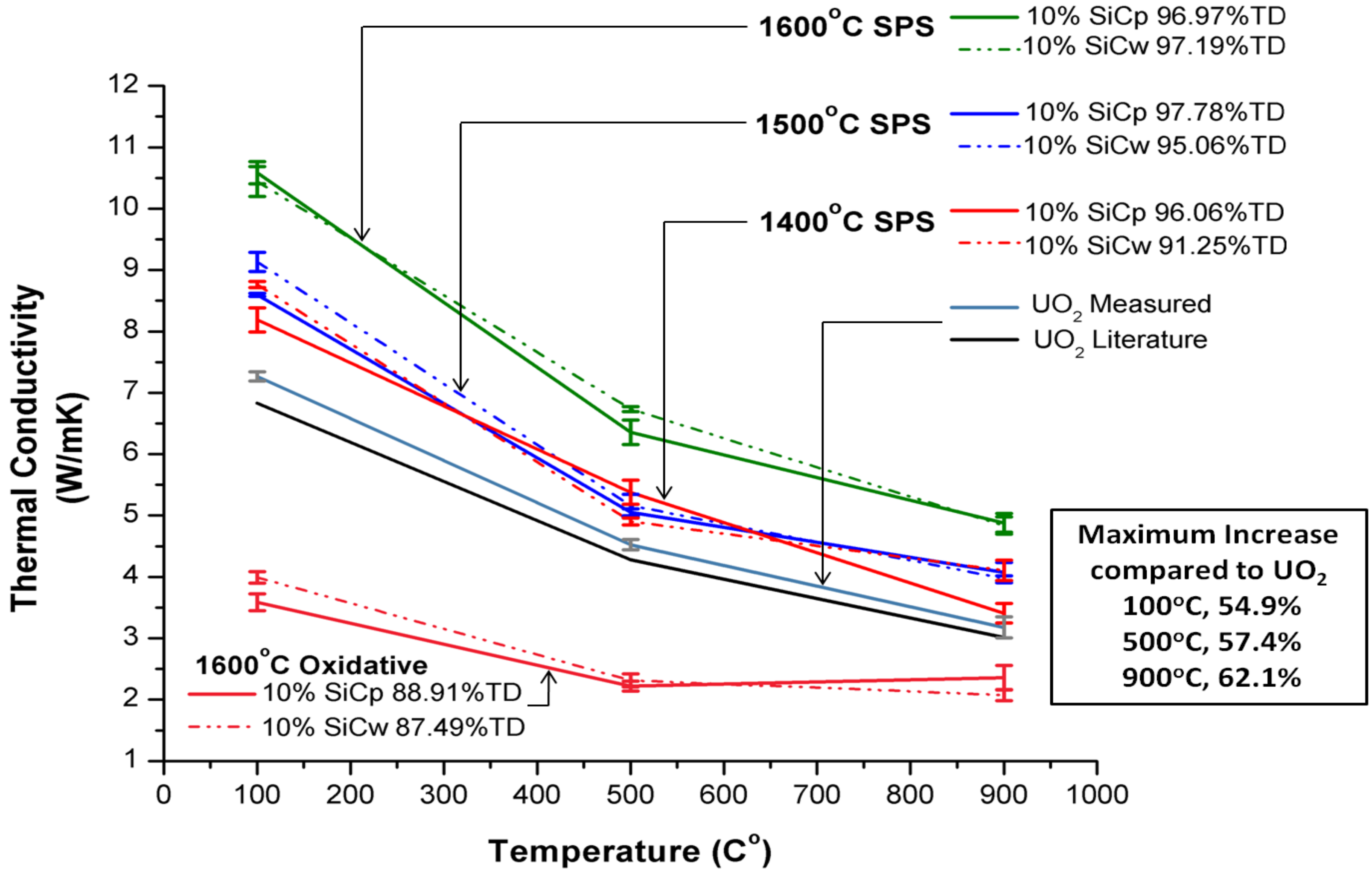
Thermal Conductivity with Silicon Carbide Dopant



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Revised Fuel Thermal Conductivity Equation

$$k_s = \frac{1}{A + BT + f(Bu) + \ (1 - 0.9\exp(-0.4Bu))g(Bu)h(T)} + \frac{E}{T^2}\exp(\frac{-F}{T})$$

T = Temperature (K)
Bu = Burnup (GWD MTU^{-1})
f(Bu) = 0.00187·Bu
g(Bu) = 0.038·$Bu^{0.28}$
h(T) = $[1+396e^{-Q/T}]^{-1}$
Q = 6380 K
A = 0.038646 m-K/W for diamond dopant 0.03367 for SiC dopant
B = 2.10E-4 m-K/W/K for diamond dopant 1.47E-4 for SiC dopant
C = 5.47E-9 W/m-K^3
D = 2.29E14 W/m-K^3
E = 3.5E9 W-K/m
F = 16361 K

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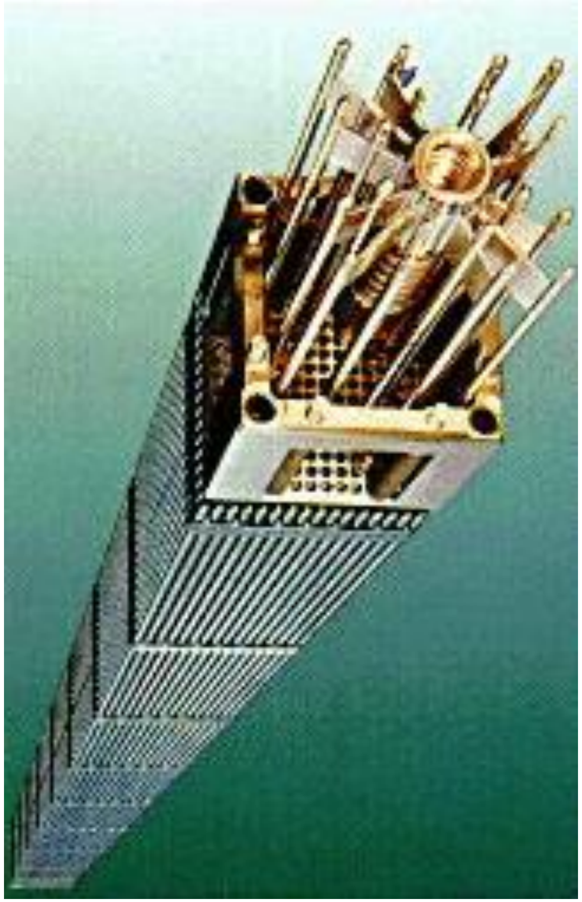
FRAPCON 3.4 Assessment Case

Westinghouse 15 x 15

- U.S. DOE Sponsored
- High Burnup of 5 Test Rods
- Goal Peak Burnups > 70 GWd/MTU
- PWR Conditions
- 4 of 5 rods were selected for comparison with Frapcon predictions



Frapcon-3. Integral Assessment. Lanning et al. PNNL. NUREG/CR-6534. Vol 3. 1997.

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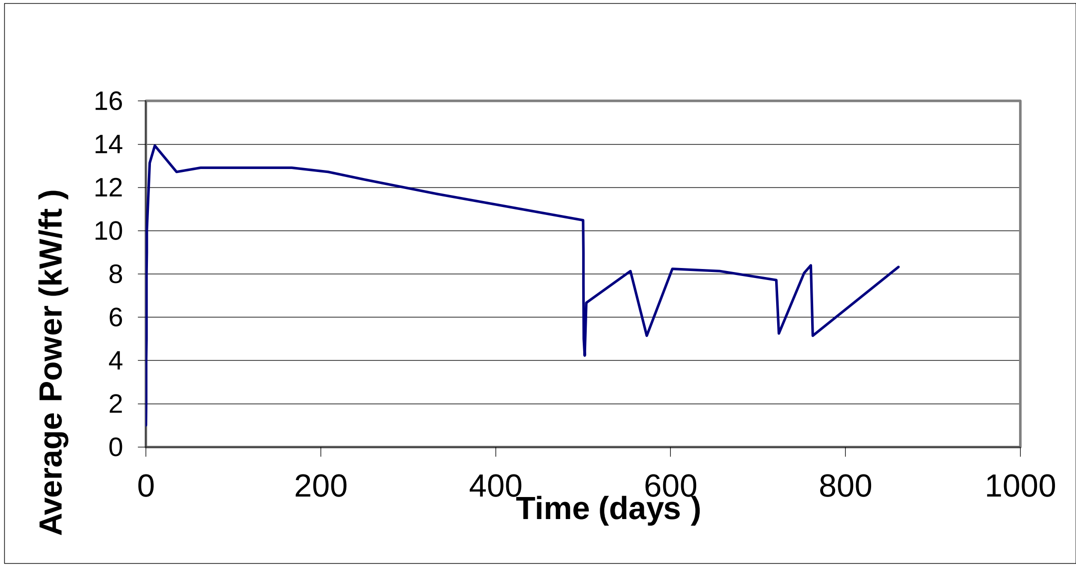
BR-3 Reactor Conditions

- Coolant Inlet Temp 255 °C
- System Pressure 2250 psi
- Power History (See Chart)



Irradiation History

- 1974 – 1980
- 5 test rods in one assembly for three cycle
- Rod-Average Burnup 61 GWd/MTU
- Max Burnup ~70 GWd/MTU

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Frapcon-3: Integral Assessment. Lanning et al. PNNL. NUREG/CR-6534. Vol 3. 1997.

Image: http://www.nirond.be/engels/7.7_ontmanteling_eng.html

Test Rod Number 111-I-5

Fuel Rod	
Overall length (in.)	44.714
Diameter (in.)	0.4220
Fuel stack height (in.)	38.40
Nominal plenum length (in.)	4.0145
Number of pellets per rod	64
Fuel gaps (mils)	7.5
Fill gas	He
Fill gas pressure (psi)	214.4
Cladding	
Material	Zircaloy-4
Diameter outside (in.)	0.4220
Diameter inside (in.)	0.3734
Clad wall thickness (in.)	0.0244
Fuel	
Material	UO_2
Enrichment (% - U_{235})	5.2
Pellet sintered density (% TD)	94.77
Pellet diameter (in.)	0.3659
Pellet length	0.600
Pellet geometry	Dished ends
Dish radius (in.)	0.6600
Dish depth (in.)	0.0135

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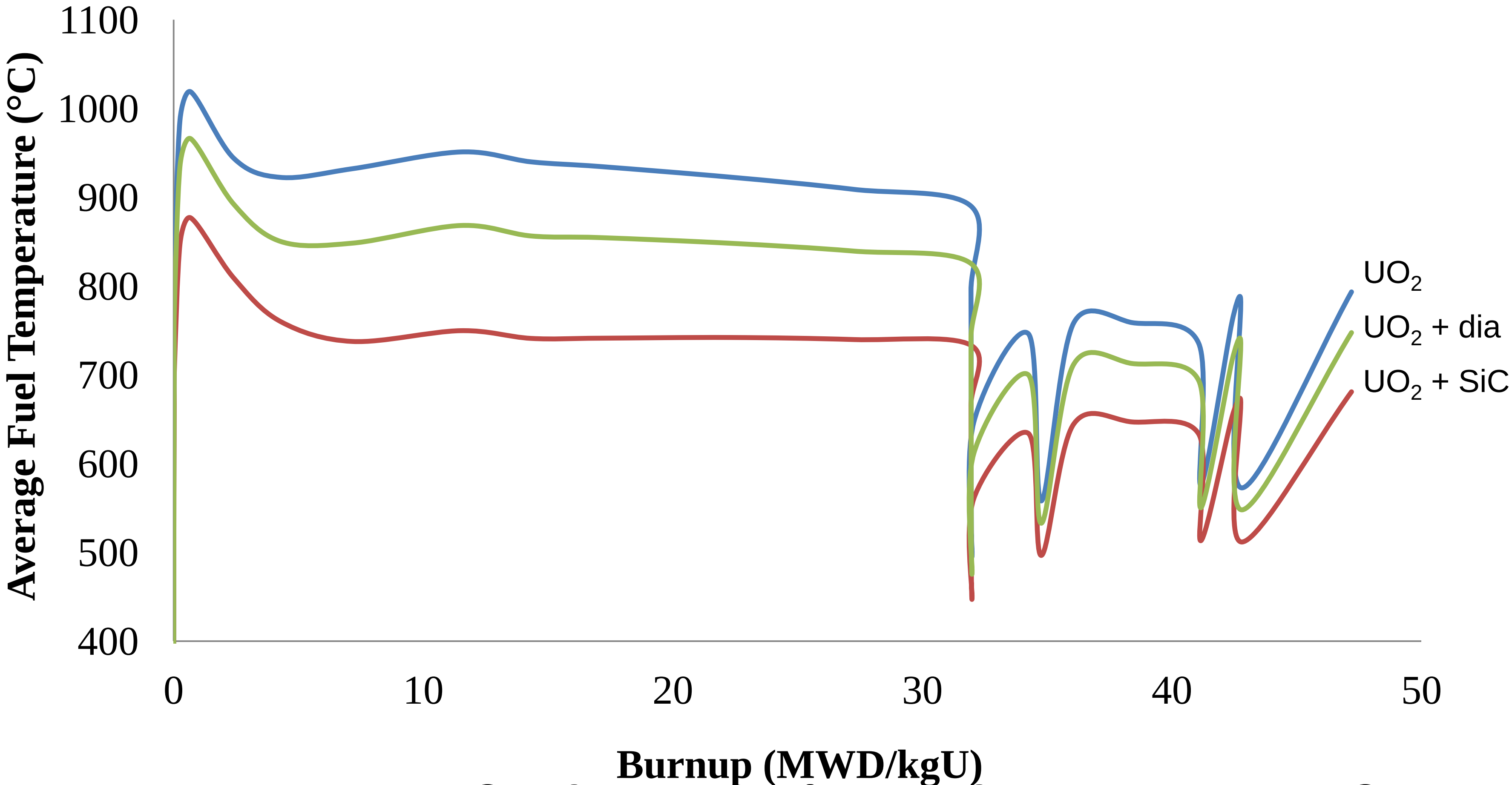
Frapcon-3: Integral Assessment. Lanning et al. PNNL. NUREG/CR-6534. Vol 3. 1997.

Average Fuel Temperature



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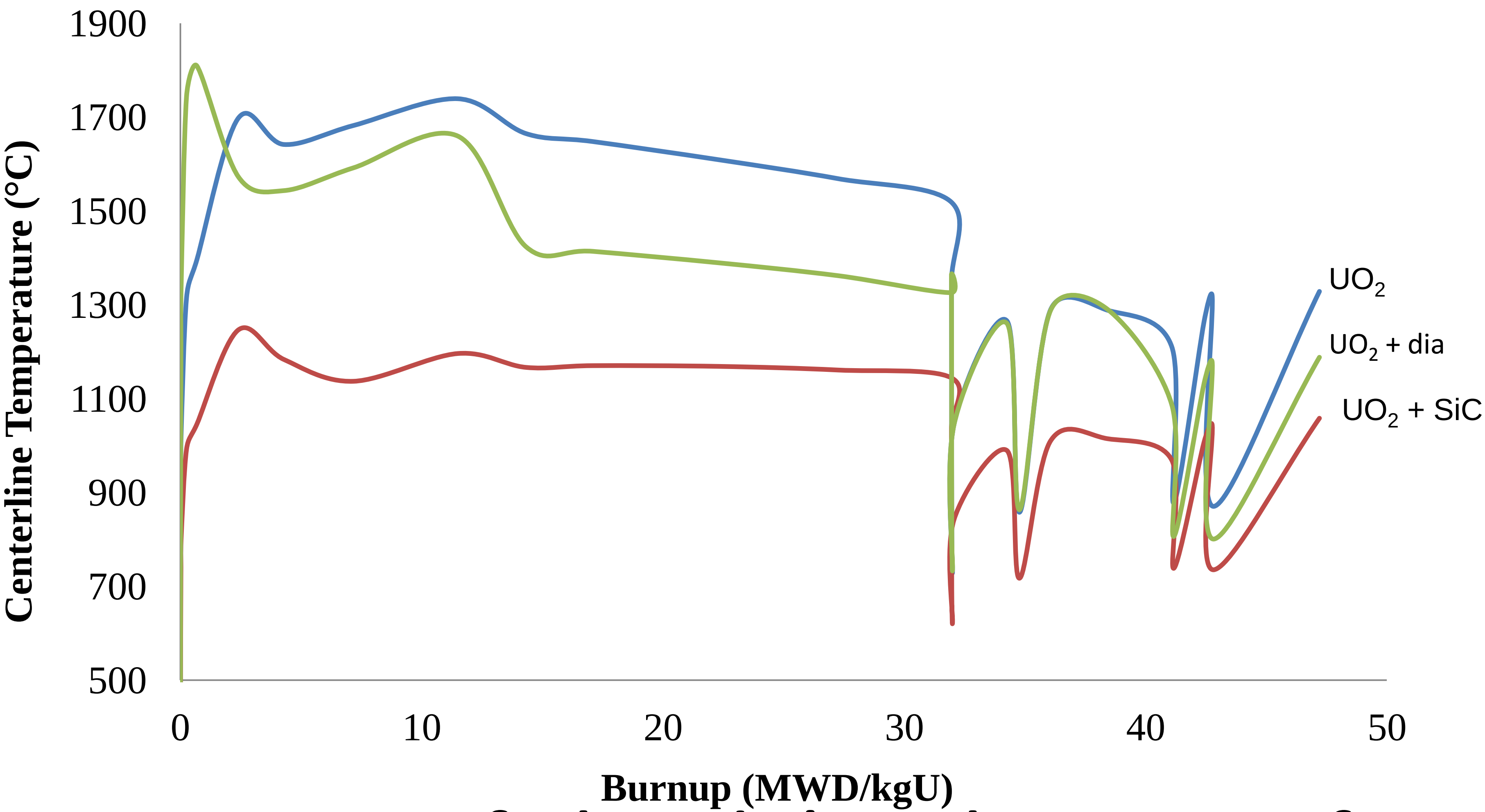
Fuel Centerline Temperature



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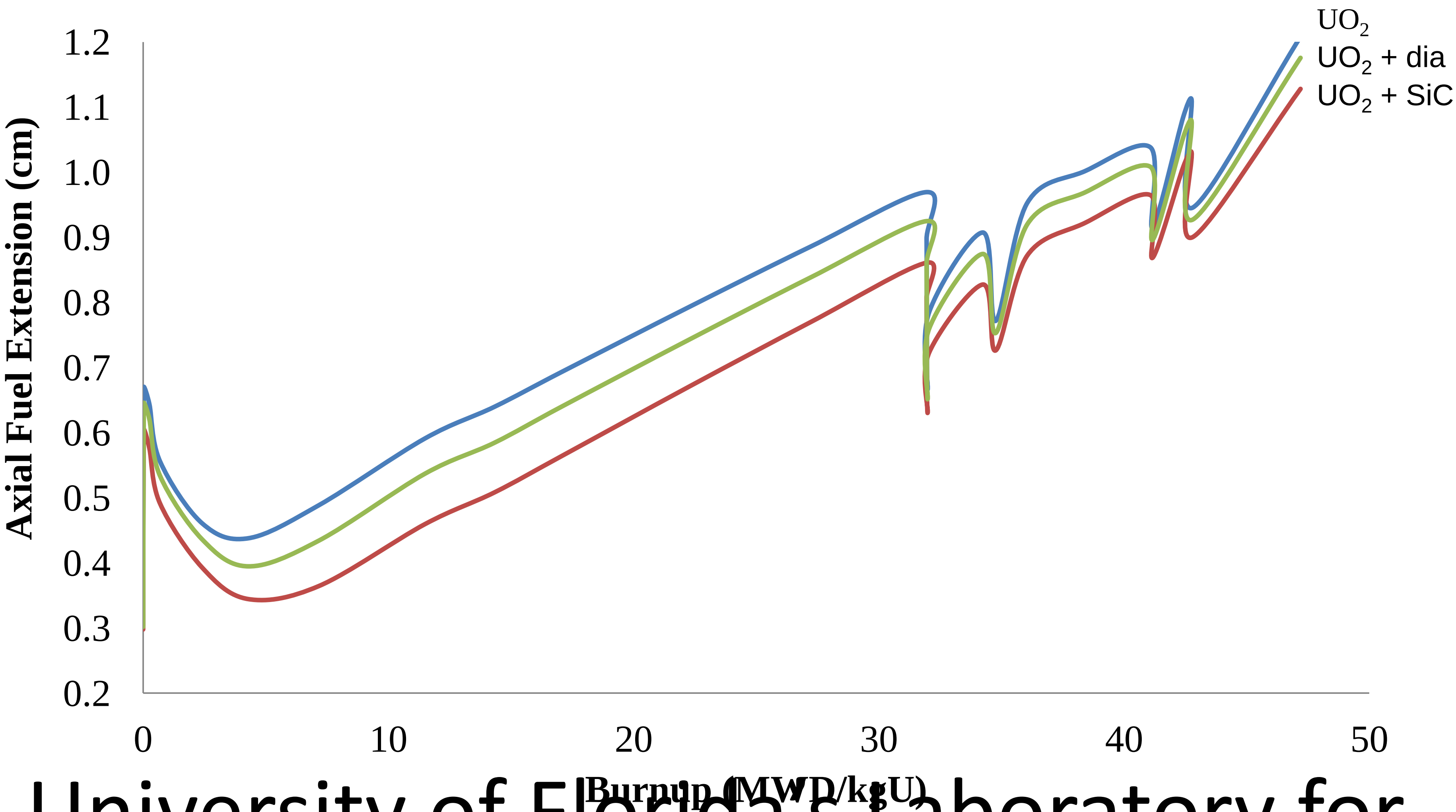
Axial Fuel Swelling



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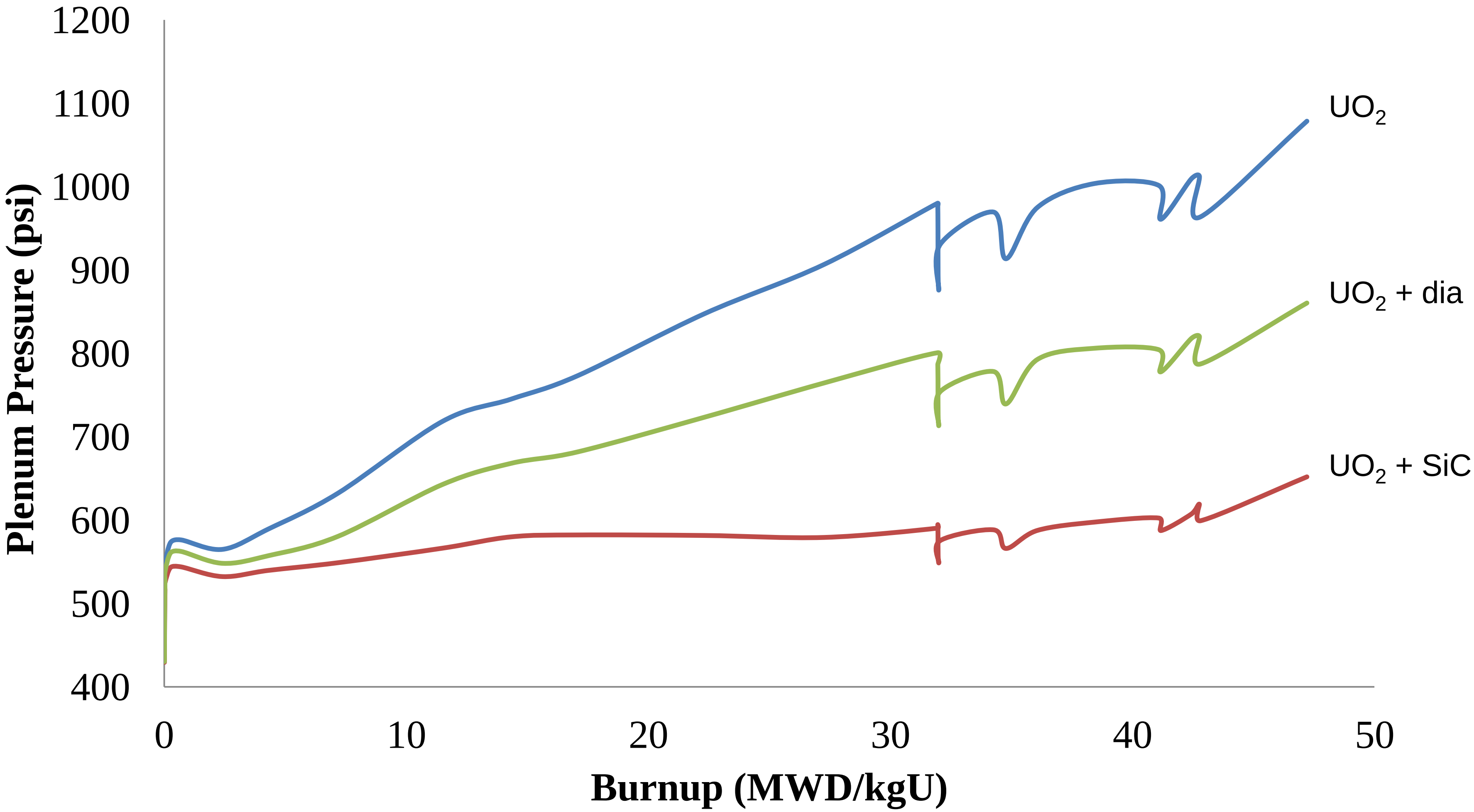
Plenum Pressure



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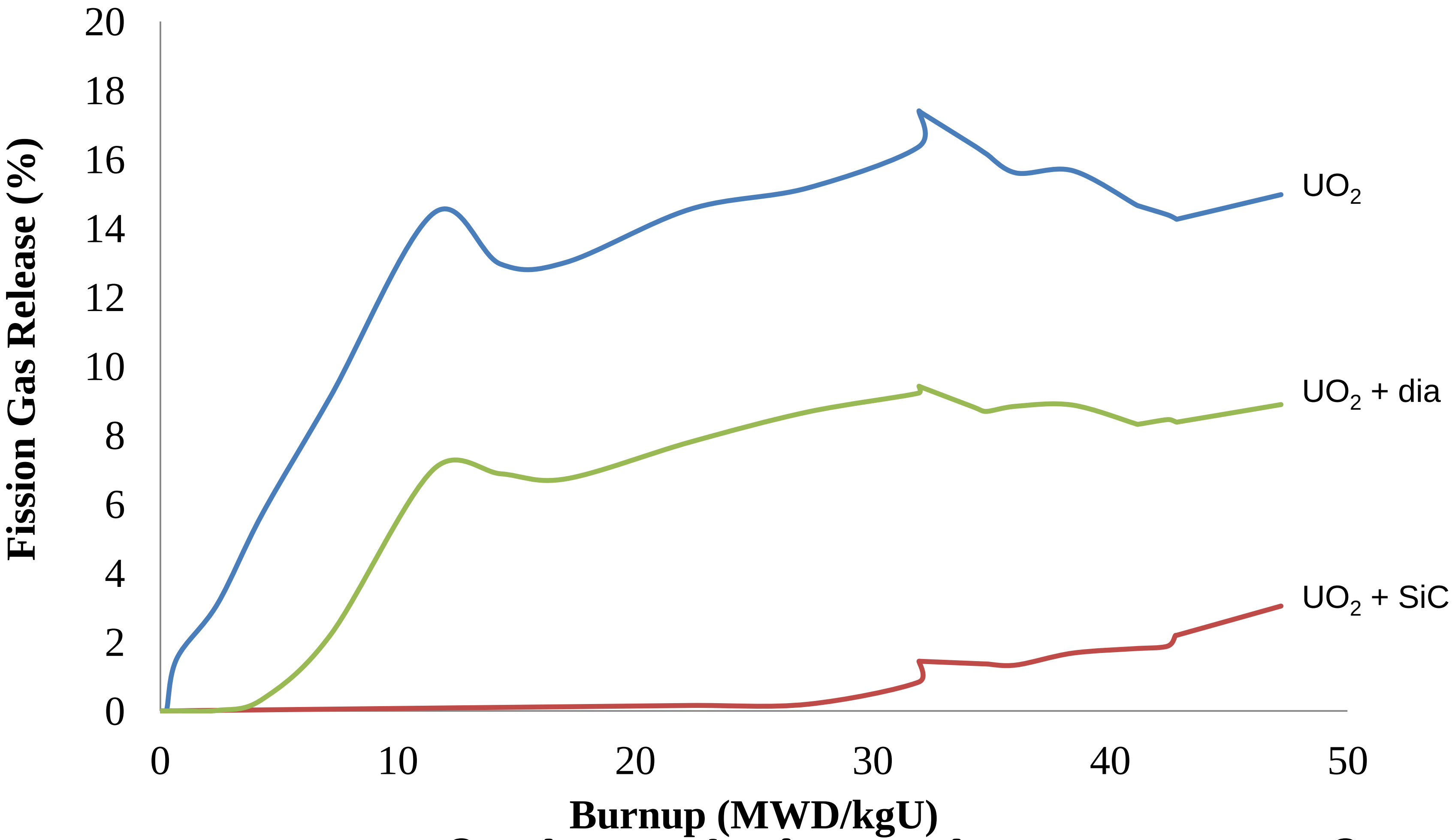
Fission Gas Release



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Liquid Gap

- Using SiC as fuel pellet
- ~100 times the thermal conductivity of Helium Gas Gap
- Lead-Tin-Bismuth
- Beginning of Life temperature difference for a liquid bond gap

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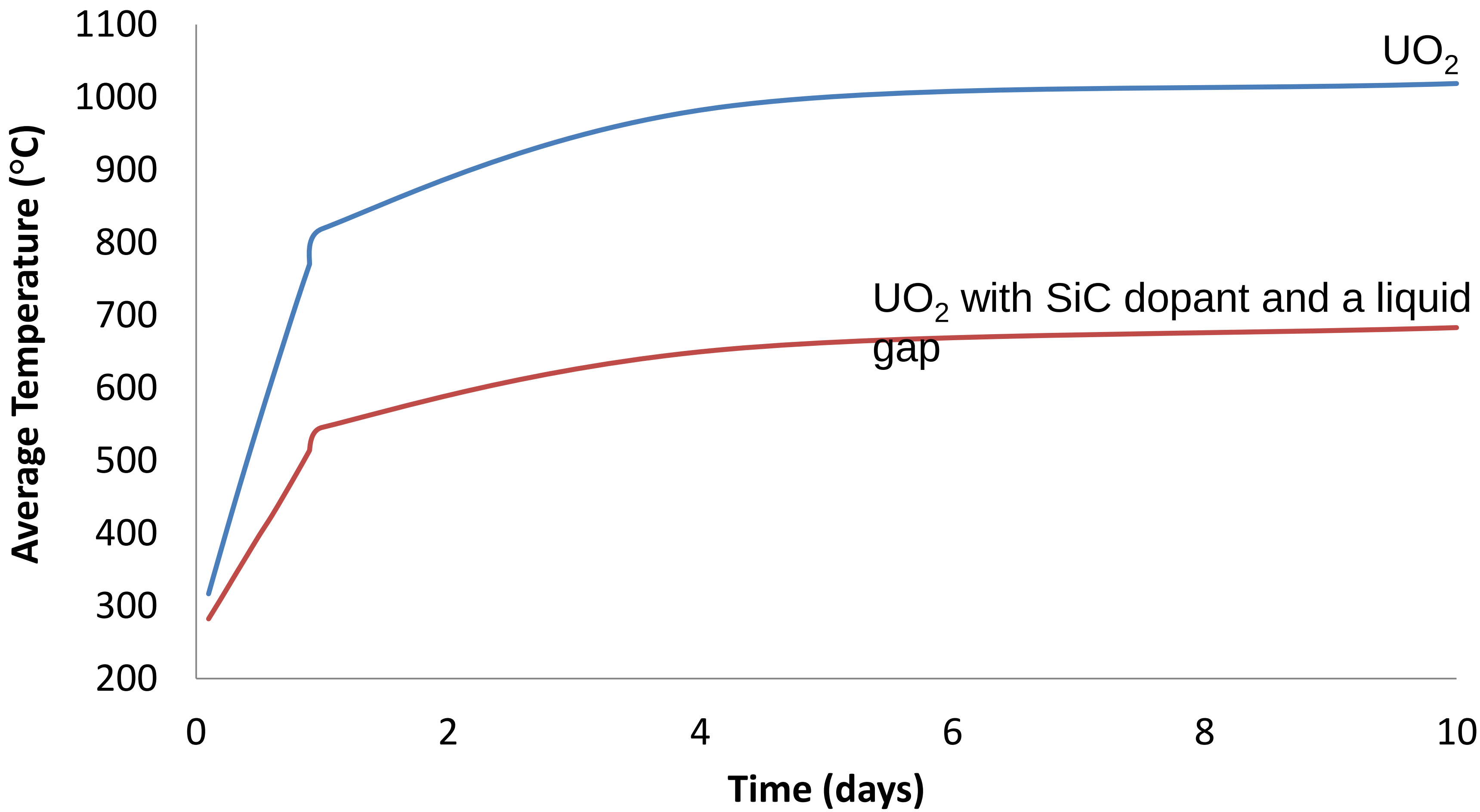
BOL Average Temperature Difference



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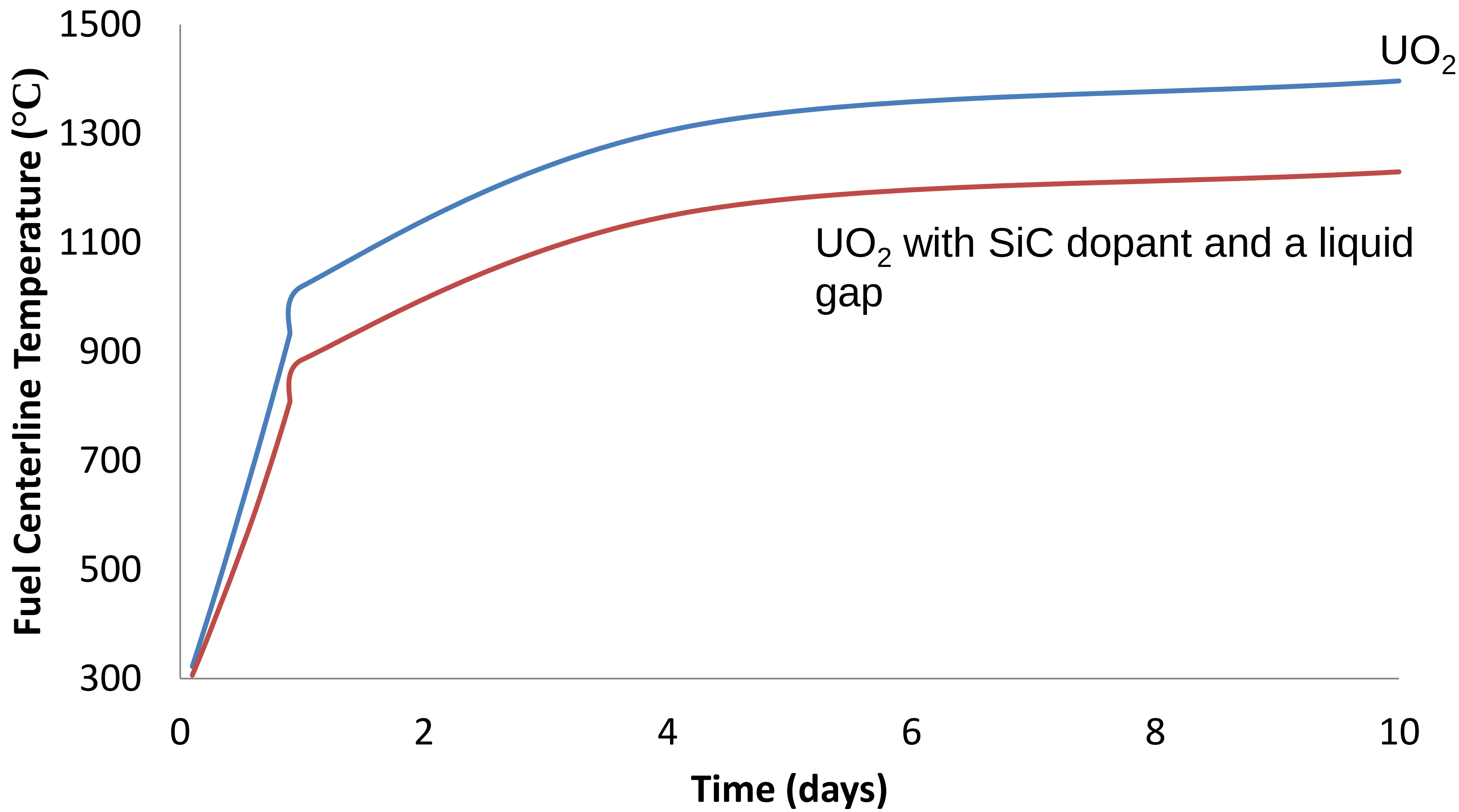
BOL Centerline Temperature Difference



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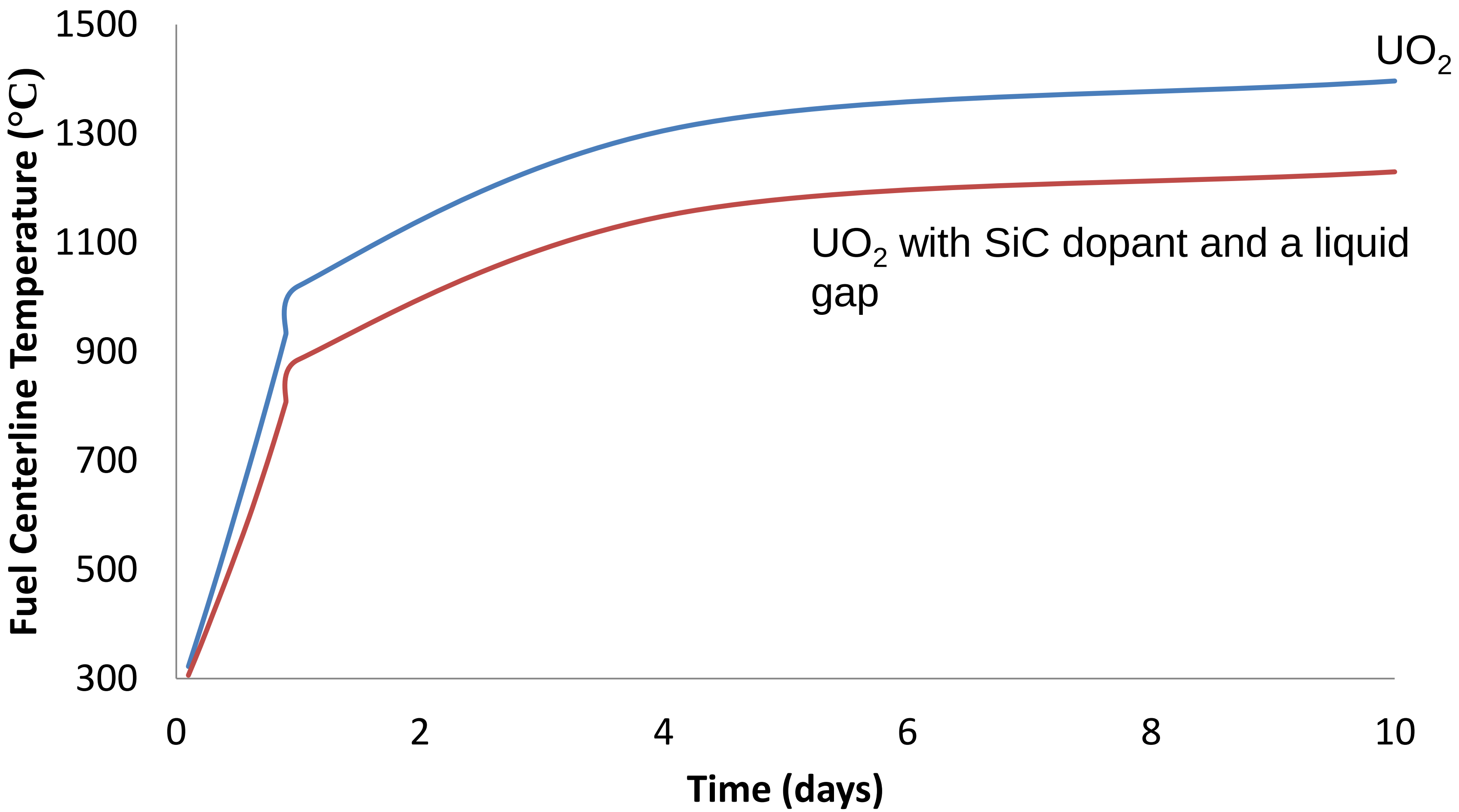
BOL Centerline Temperature Difference



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