NE 591: Advanced Reactor Materials

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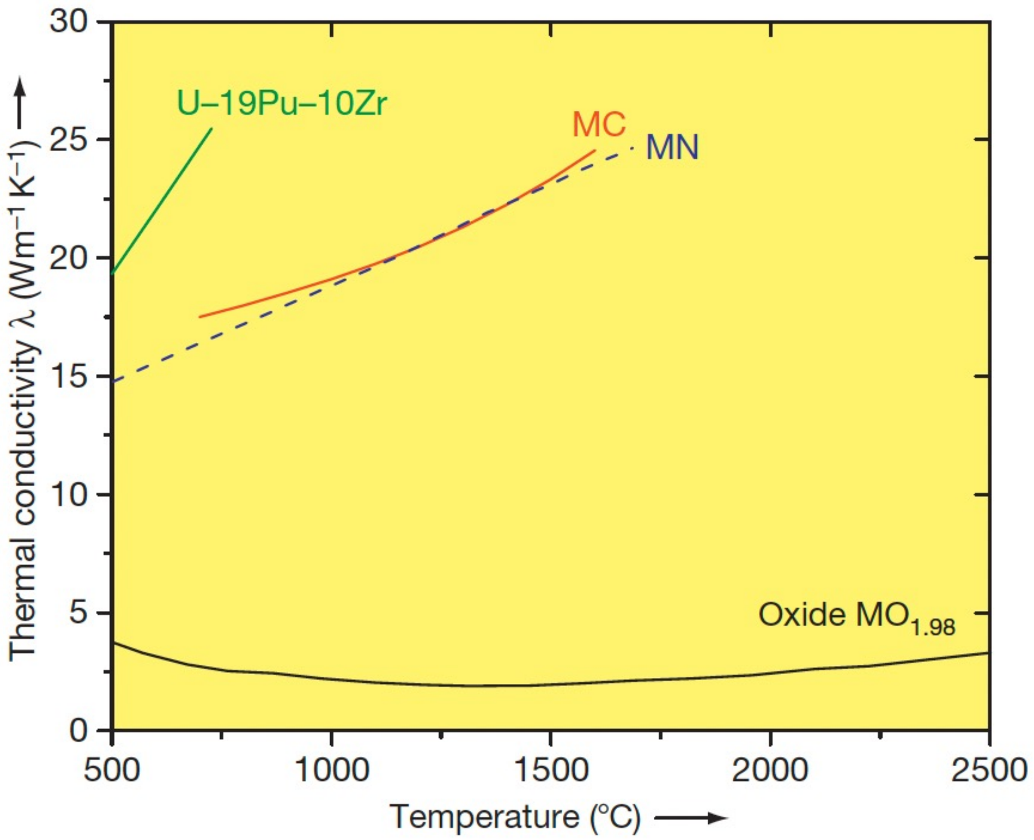
Last Time

- DFT overview

CARBIDES AND NITRIDES

Why Carbides?

- Possible fuel compositions with higher fissile atom density are nonoxide ceramics, for example, uranium–plutonium-mixed carbide or nitride
- These fuels have higher thermal conductivity, high fissile heavy-atom density, and a high melting point compared to metallic fuel
- The higher thermal conductivity of carbide fuel and high melting point makes carbide fuel suitable for operation at high power



Why Carbides?

- The more efficient heat transfer also allows for the possibility of large diameter fuel pins, with more fissile material per pin, and more power generation
- High-specific-power operation permits fewer pins, compared to oxide, and a more compact core, which can reduce plant costs
- A large amount of development work on carbide and nitride fuels was performed from 1960 to 1970, and more than 5000 advanced fuel pins have been fabricated and irradiated
- The practical difficulty of fabrication of carbide fuel hampered carbide development
- The high-purity inert cover gas required for fuel fabrication was expensive and maintenance of C/M ratio was difficult

Carbide Reactor

- The Indian FBR program, however, started with the introduction of plutonium-rich mixed uranium–plutonium carbide as the driver fuel for 40MWth loop-type fast breeder test reactor (FBTR)
- The reactor became critical in the year 1985 and it is the only reactor operative on a full core of carbide fuel
- Carbide fuel cannot be used in LWR because of its incompatibility with the coolant
- However, it can be safely used with liquid metal (Na or lead) or gas cooled (CO_2 or He) in Gen-IV type of high-temperature reactor
- Carbide fuel has a breeding ratio of at least 1.30, a doubling time of 15 years or less, and the burnup limit of more than 15 at.%

US Interest in Carbide Fuels

- Following the oil crisis in 1974, a national advanced liquid-metal-cooled fast breeder reactor (LMFBR) fuels development program was initiated that built upon early years of carbide fuel development
- Both carbide and nitride fuels offer a middle ground for LMFBR performance because of their higher thermal conductivity, fissile-atom density, and chemical compatibility with liquid sodium, and much higher melting point than metallic fuels

Properties	*$(U_{0.8}Pu_{0.2})O_2$*	*$(U_{0.8}Pu_{0.2})C$*	*$(U_{0.8}Pu_{0.2})N$*	*U–19Pu–10Zr*
Theoretical density ($g\,cm^{-3}$)	11.04	13.58	14.32	15.73
Melting point (°K)	3083	2750	3070	1400
Thermal conductivity ($W\,m^{-1}\,°K$)				
1000 K	2.6	18.8	15.8	40
2000 K	2.4	21.2	20.1	
Crystal structure	Fluorite	NaCl	NaCl	Multiphase
Breeding ratio	1.1	1.2–1.3	1.2–1.3	1.4–1.5
Swelling	Moderate	High	High (?)	High
Handling	In air	Inert atmosphere	Inert atmosphere	Inert atmosphere
Compatibility				
Clad	Average	Carburization	Good	Eutectics
Coolant	Average	Good	Good	Good
Dissolution and reprocessing amenability	Demonstrated on industrial scale for aqueous and pilot scale for pyro-processes	Dissolution not simple. Process not yet demonstrated on industrial scale	Dissolution easy but risk of C^{14} in waste management	Pyro-reprocessing demonstrated on pilot plant scale
Fabrication/irradiation experience	Large	Limited	Very little	Limited
	Good			

Carbide Pin Designs

- There are two concepts available for the carbide fuel pin depending upon the type of bond between the fuel pellet and the cladding material: He-bonded and Na-bonded carbide fuels
- The average operating fuel temperature of the He-bonded pin is high because of low thermal conductivity of the He bond compared to the Na bond
- This design requires a larger fuel–clad gap and 85% smear density to accommodate the swelling of the fuel
- The fission gas release in a He-bonded pin will be higher compared to that from a sodium-bonded pin, due to the higher temperatures
- Na-bonded carbide fuel pins also require a reduced smear density compared to oxide fuels to account for fuel swelling
- The purity of the Na bond is very important, requiring strict tolerances on O content

Carbide Fuel Details

- A hyperstoichiometric (C/M>1, carbon to metal ratio) fuel composition is chosen so that it contains some amount of sesquicarbide M2C3 phase (M=U+Pu), which accounts for the decrease in (C/M) ratio with burnup
- A sufficiently low C/M ratio may result in the formation of actinide metal phases, which may form low-melting eutectic with the cladding and limit the life of the fuel pin
- FCMI can potentially exist, depending upon the operating temperature of the fuel
- O and N impurities play important roles, as they act as 'carbon equivalent', which affect the carbon potential of the fuel

	$(Pu_{0.7}U_{0.3})C$	$(Pu_{0.2}U_{0.8})C$
Plutonium (wt%)	66 ± 1	21.3 ± 1
Pu/(U + Pu)	0.70	0.225
Oxygen (ppm)	≤ 6000	360
Oxygen + nitrogen (ppm)	≤ 7500	~ 400
M_2C_3 (wt%)	5–20	12.5 ± 1.4
Density (% TD)	90 ± 1	80 ± 1
Grain size	$\sim$10–12 μm	12 μm