NUCL 402 Engineering of Nuclear Power Systems

Lecture 15: Fuel Materials

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Fuel Materials

U, UO_2 oxides, UC, Carbides, UNO_3, Nitrides, **Pu, Th**

Life of fuel → irradiation damage

Range of fission products ~ 0.8 μm

Defects – directional

Required Properties:

1. High thermal conductivity
2. Resistance to radiation damage
3. Chemical stability with coolant
4. High melting point and no phase change (density change)
5. Permit economic fabrication
6. Low coefficient of expansion
7. High concentration of fissile atoms and minimum nuetron absorbers

U metal 1 goods, 2,3,4 not good

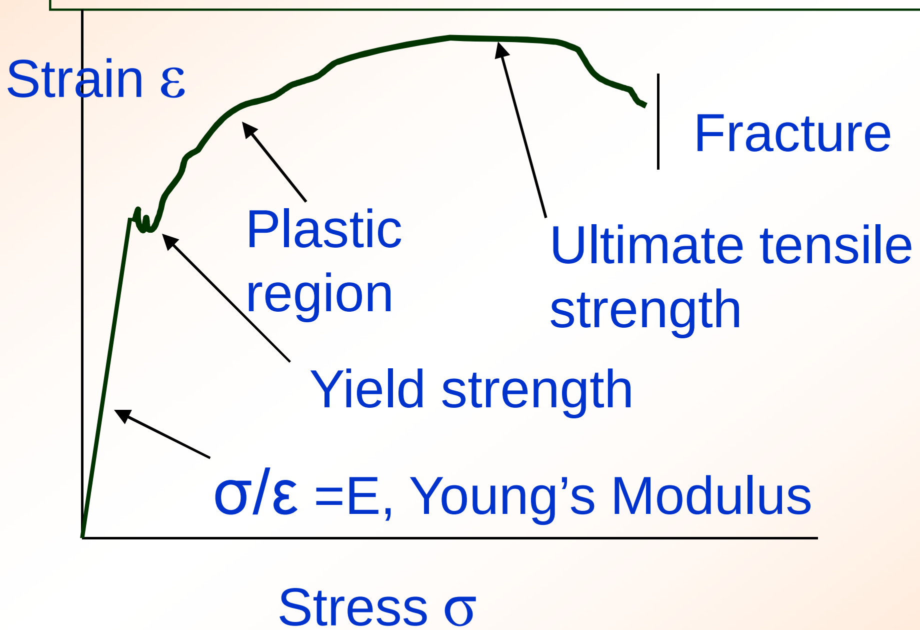
Ceramics of U, Pu, Th 1 not good, 2,3,4,5 good

Uranium Metal

Poor mechanical properties and great susceptibility to radiation damage

Phases- different crystalline structure

	α	β	γ
Stability Range(C)	<665	665 to 770	770 to 1130 (mp)
Crystalline form	orthorhombic	Tetragonal	BCC
Density (gm/cm^3)	19.04	18.11	18.06
	soft & ductile	hard & brittle	very soft

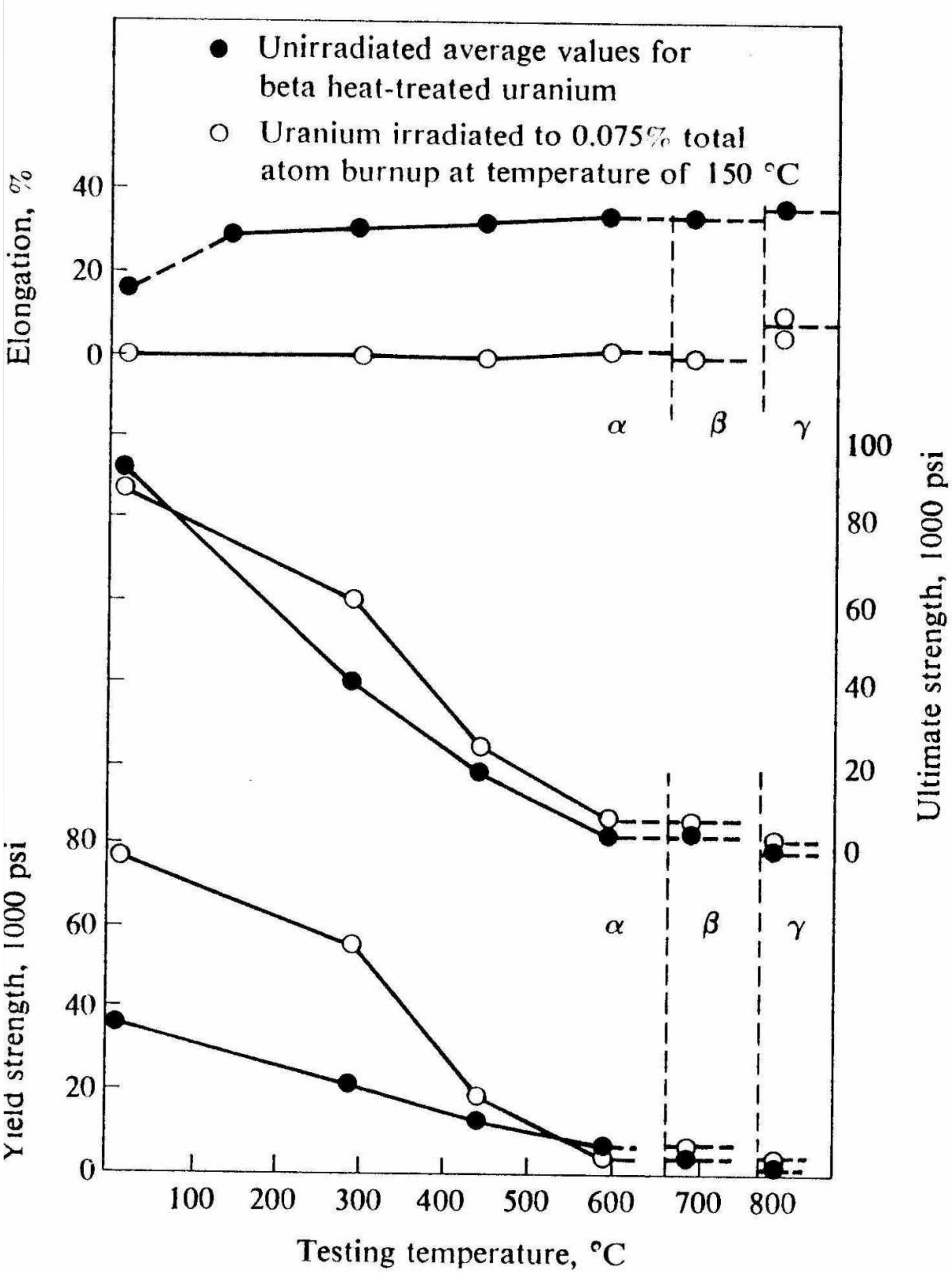


TS 344 to 1380 MPa

YS (0.2%) 172 to 900 MPa

Modulus of Elasticity 1.0 to 1.7×10^{11} MPa

Poissons ratio 0.2 to 0.25



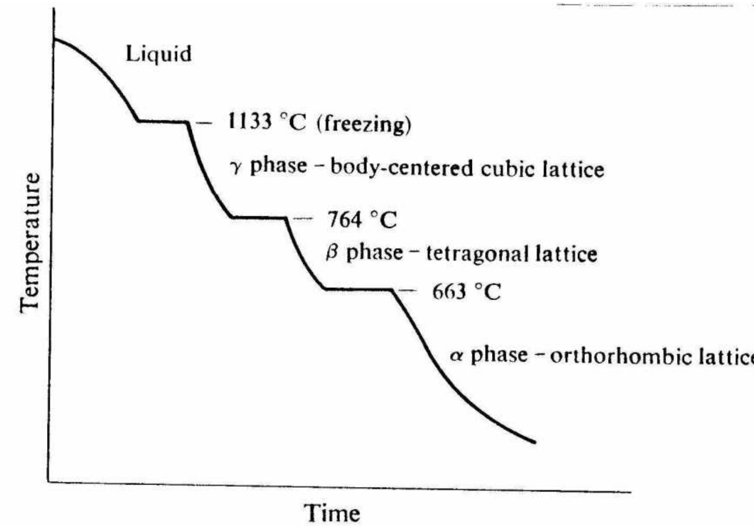


FIG. 11.14 *Cooling curve for unalloyed uranium.*

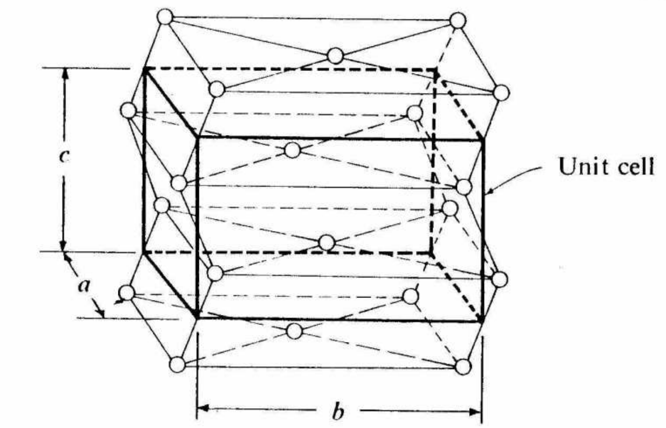


FIG. 11.16 *Structure of orthorhombic alpha phase uranium, its lattice dimensions and coefficient of thermal expansion.*

Lattice Direction		*Lattice Dimension A*	*Coefficient of Thermal Expansion-in/in F (25–325°C)*
a	*100*	*2.852*	*26.5*
b	*010*	*5.865*	*−2.4*
c	*001*	*4.945*	*23.9*

Fabrication: Oxidizes easily, protect from air, casting, rolling, extrusion, forging, machining

Corrosion: reacts with water liberating hydrogen, with sodium little corrosion

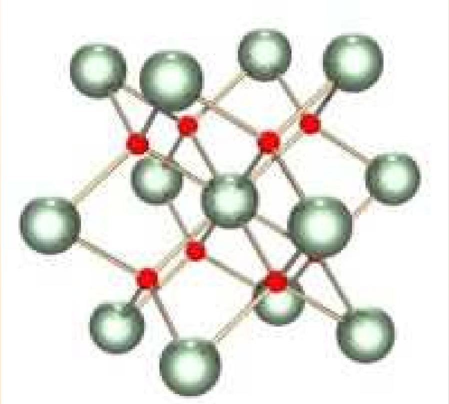
Irradiation effects: dimensional changes-swelling etc

Uranium alloys: Small amount of chromium, molybdenum, niobium, zirconium – stabilizes β or γ phases

Uranium Dioxide UO_2

High temperature stability (mp 2865 C), adequate resistance to radiation , chemical inert, has ability to retain large proportion of fission gas under 1000C –Low *k*

Fracture Strength	~110 MPa
Modulus of Elasticity	$2.x10^{11}$ MPa at 20C
Thermal expansion	$1x10^{-5}$ per C (0 to 1500 C)
FCC crystal structure	



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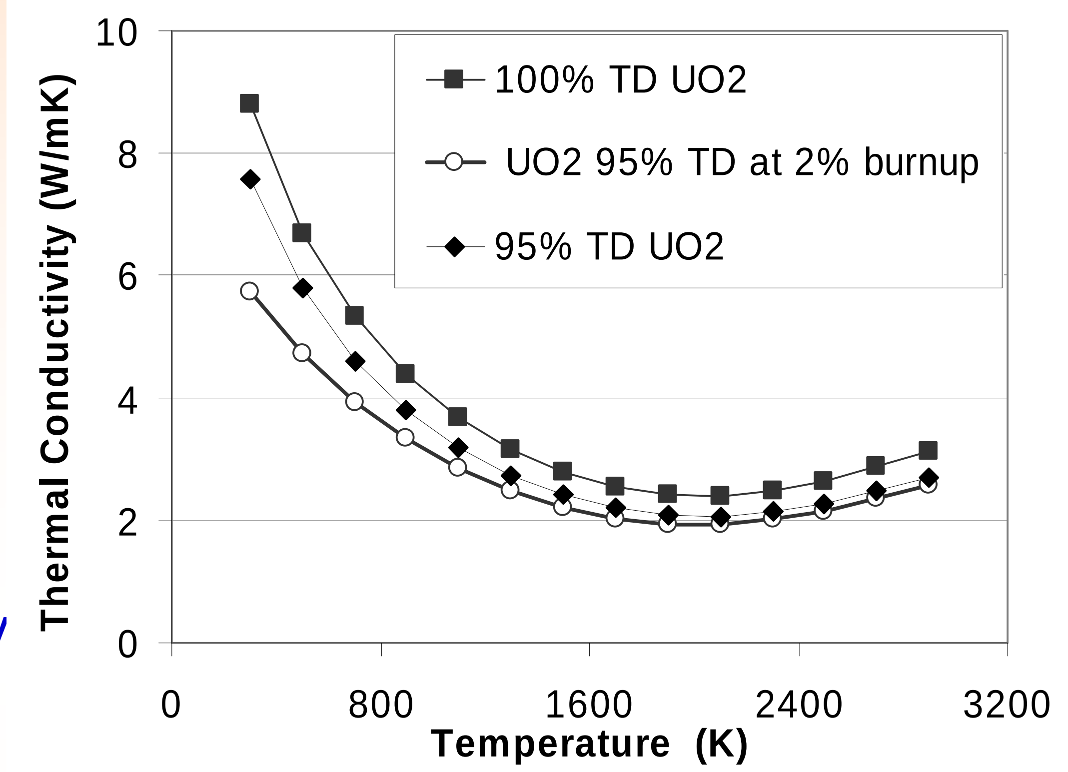
Uranium Dioxide UO_2

Thermal conductivity of UO_2, 95% TD fresh fuel, 95%TD at 2% burnup and 100% TD fresh fuel.



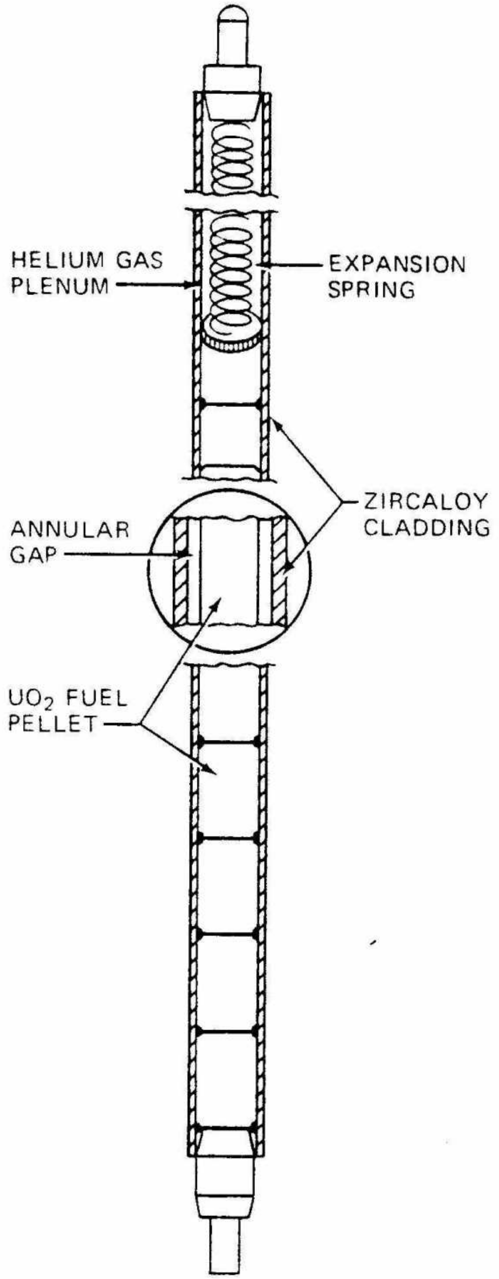
Fabrication:

UO_2 powder –cold press to make pallets followed by Sintering at reduced atm. at 1700 C to increase density

Density = 10.96 g/cm^3

Structural changes:

Fission gas (Xe, Kr, I) release for >1000C



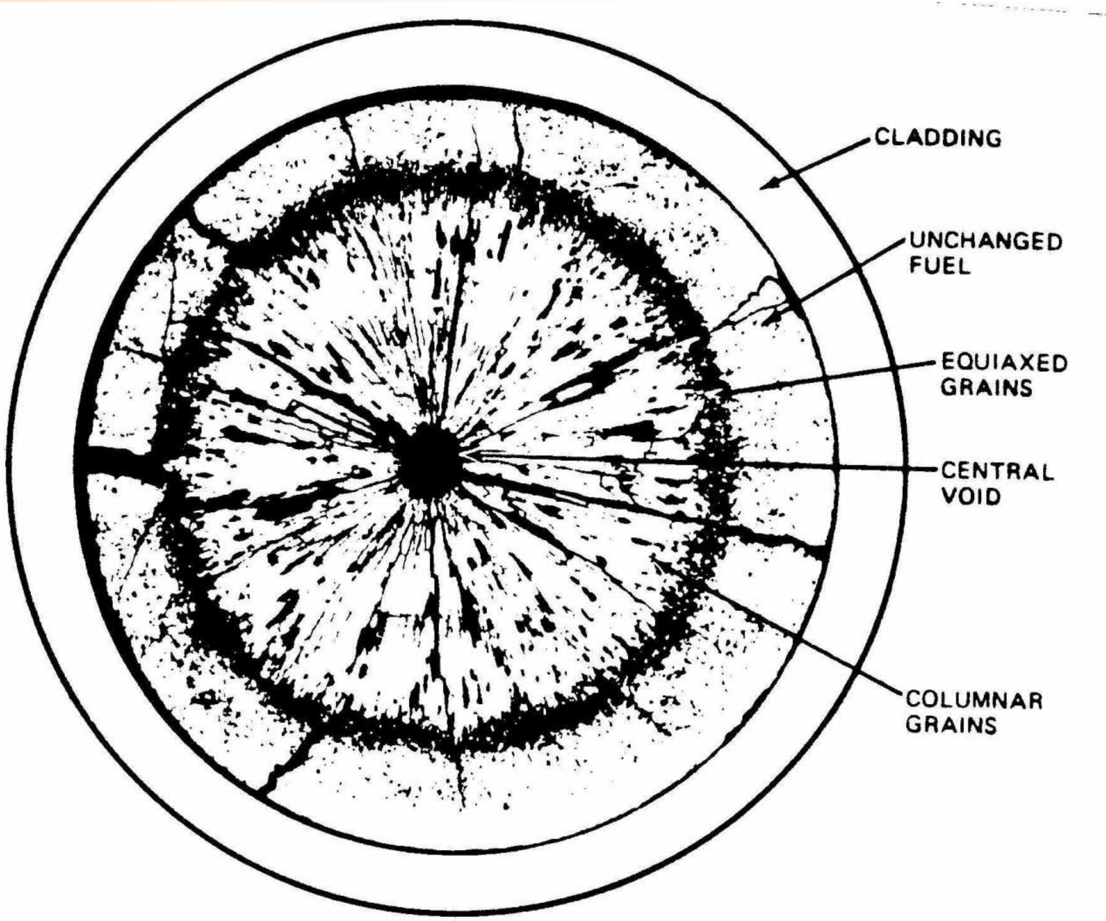


Fig. 8.8. Cross section of an oxide fuel pellet showing restructuring following extended neutron irradiation (M. D. Freshley, BNWL). (Structural changes are much less in normal operation of commercial water-cooled reactors.)

Uranium Carbide (UC)

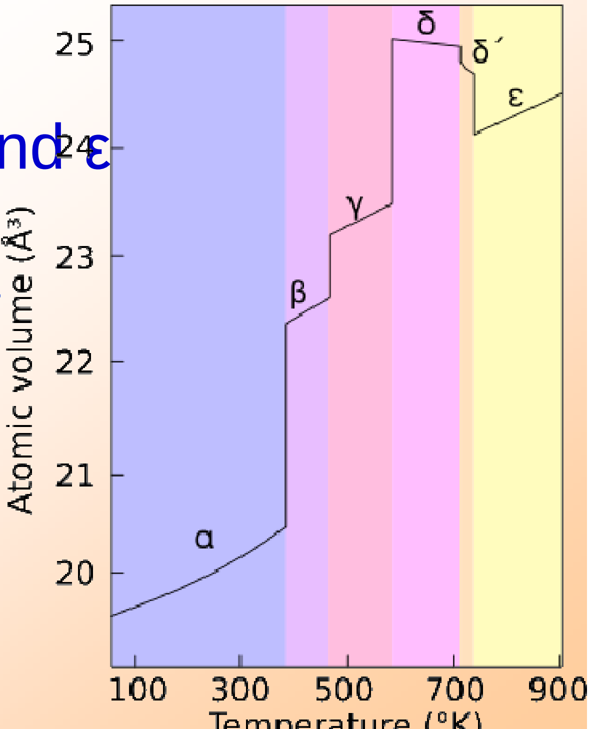
Produced by heating UO2 with graphite powder 1600C to 1900 C in vacuum → ground to powder

Melting point	2380C	Fracture Strength	62 MPa
Density	13.6 g/cm^3	E	2.1x1011 Pa
k	33 W/mK	Thermal expansion	1x10^{-5} per C (20 to 1000C)
FCC crystal structure			

Plutonium Fuel Material

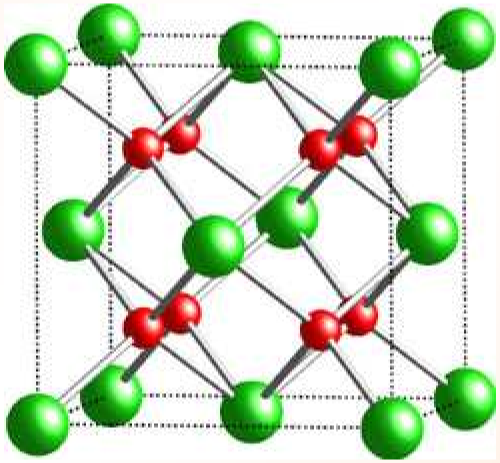
Pu Metal has six allotropic forms: α, β, γ,δ, δ’ and ε

Thermal conductivity	(300 K) 6.74 W·m^{-1}·K^{-1}
Thermal expansion	(25 ℃) 46.7 µm·m^{-1}·K^{-1}
Young's modulus	96 GPa
Shear modulus	43 GPa
Poisson ratio	0.21



Plutonium(IV) oxide

PuO_2 is used in mixed oxide (MOX) fuels



Density	11.5 g/cm^3,
Melting point	2400 ℃ (2673.15 K)
Crystal structure	FCC
	yellow-brown, solid

Thorium

Thorium metal is a silvery white metal. Oxidizes to grey and eventually black thorium dioxide (ThO_2), also called thoria, has the highest melting point of any oxide (3300℃)

Thermal conductivity	(300 K) 54.0 $W \cdot m^{-1} \cdot K^{-1}$
Thermal expansion	(25 ℃) 11.0 $\mu m \cdot m^{-1} \cdot K^{-1}$
Young's modulus	79 GPa
Shear modulus	31 GPa
Bulk modulus	54 GPa
Poisson ratio	0.27

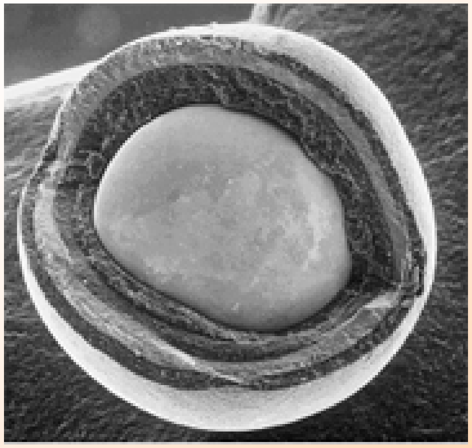
Density (20C)	11.7 $g \cdot cm^{-3}$
Melting point	1842 ℃
FCC structure	

Tristructural-isotropic (TRISO) fuel

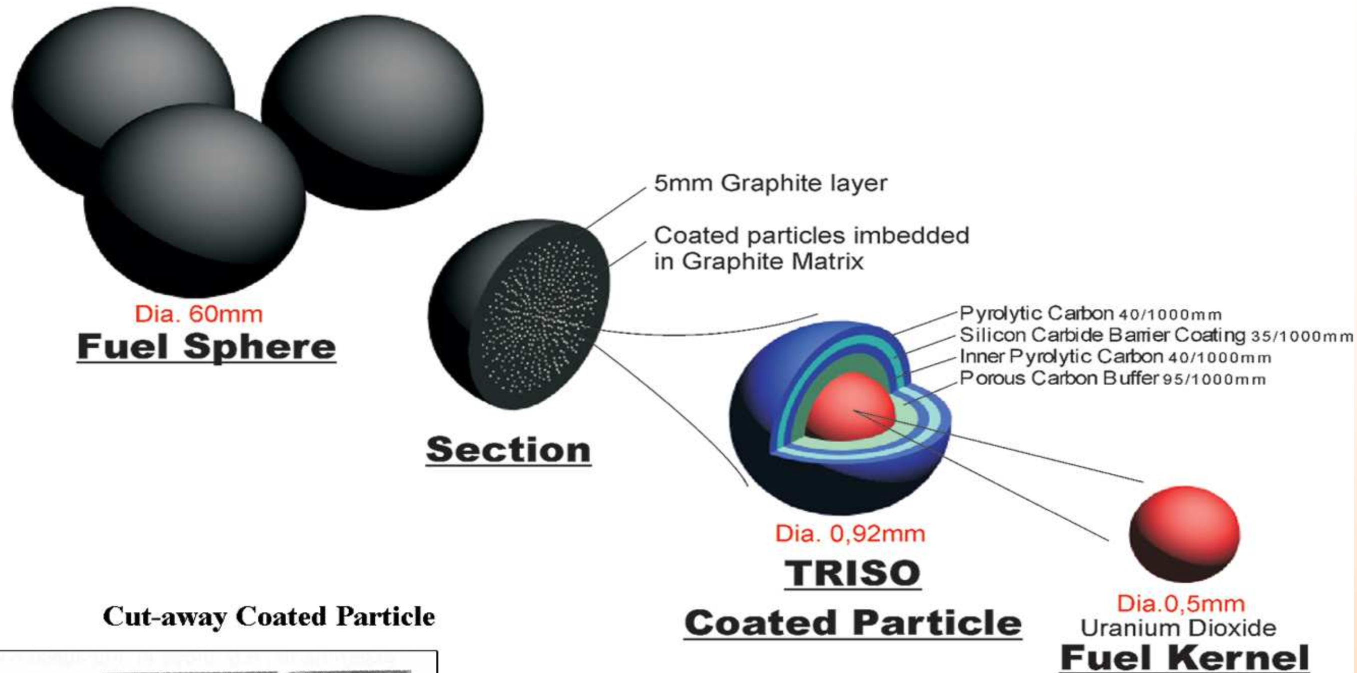
It consists of a fuel kernel composed of UO_X (sometimes UC or UCO) in the center, coated with four layers of three isotropic materials.

The four layers are a porous buffer layer made of carbon, followed by a dense inner layer of pyrolytic carbon (PyC), followed by a ceramic layer of SiC to retain fission products at elevated temperatures and to give the TRISO particle more structural integrity, followed by a dense outer layer of PyC. TRISO fuel particles are designed not to crack due to the stresses from processes (such as differential thermal expansion or fission gas pressure) at temperatures beyond 1600°C, and therefore can contain the fuel in the worst of accident scenarios in a properly designed reactor.

PBMR GT-MHR, , HTGR, VHTR



FUEL ELEMENT DESIGN FOR PBMR



HTR Pebble Cross-section **Cut-away Coated Particle**