Fuel Types Continued

NE 533 Spring 2023

Last Time

- Course overview
- My view of fuel performance
  - heat delivery to coolant, length of operation, tolerance to accidents
- Considerations for fuels
- Why not pure U?
- Intro to UO2 and MOX fuels for LWRs

- Reminder to fill out the introduction forum post on moodle

Accident Tolerant Fuel

- USi fuels (U3Si2)
  - A metal-ish compound, with higher thermal conductivity, higher uranium density
  - Complex crystal structure (10 atoms unit cell) with effectively two sub-lattices
  - Amorphizes at low temperatures
  - Poor oxidation resistance
  - Will require improved cladding, liners/coatings or fuel dopants

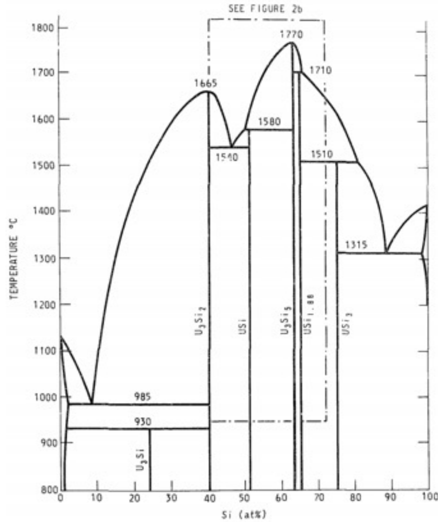
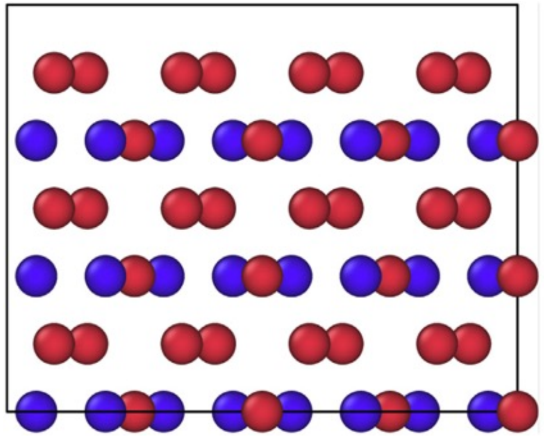
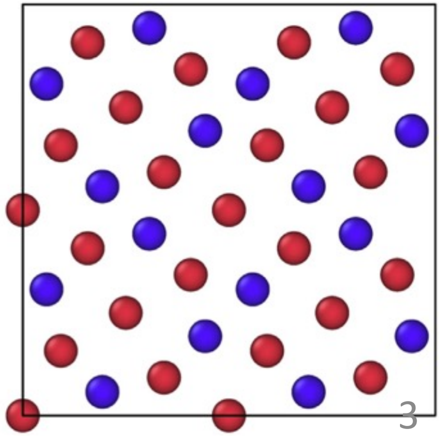


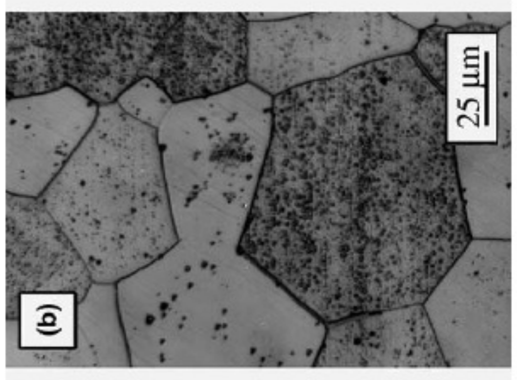
FIGURE 2 URANIUM SILICON EQUILIBRIUM DIAGRAM

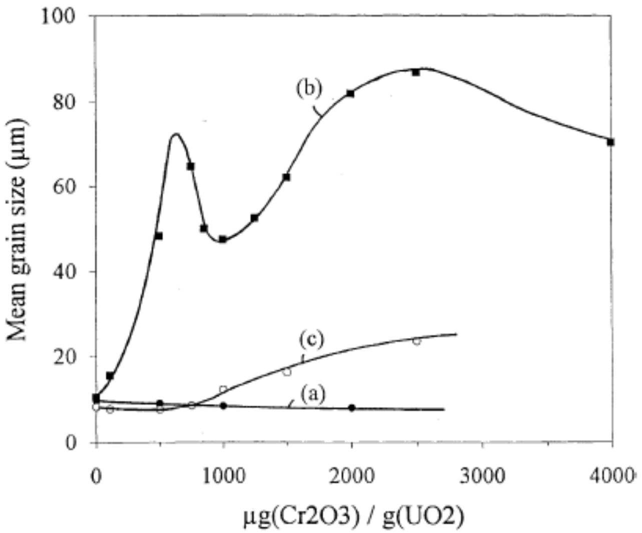




Accident Tolerant Fuel

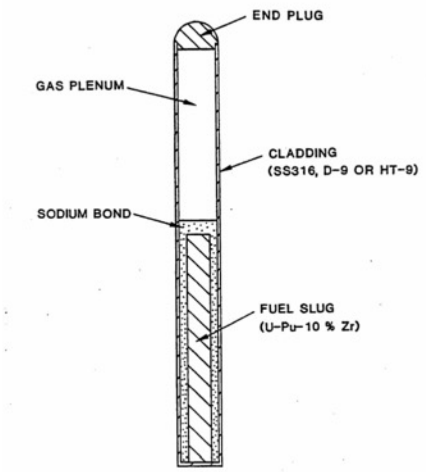
- Cr-doped UO2
  - Larger grain size, theoretically reduced fission gas release
  - Cr changes the O potential present within the fuel, changing defect concentrations and mobilities
- Coatings or alternate claddings – FeCrAl or SiC
  - Improved radiation resistance, corrosion resistance, etc.

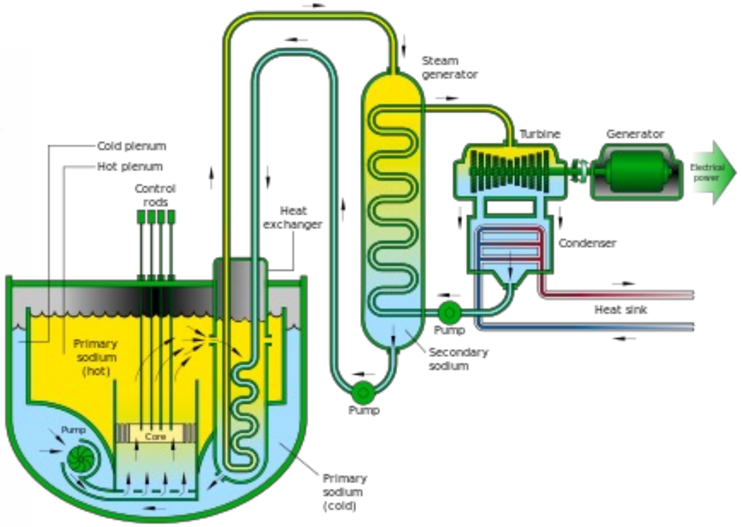




Uranium-Zirconium (UZr)

- Utilized in sodium cooled fast reactors (SFRs)
  - EBR I, EBR II
- Varied crystal structure and compositional environment
- Easily alloyed with Pu, minor actinides (MA)
- Can function as a breeder/burner fuel
- Sodium coolant
- Fe-based cladding





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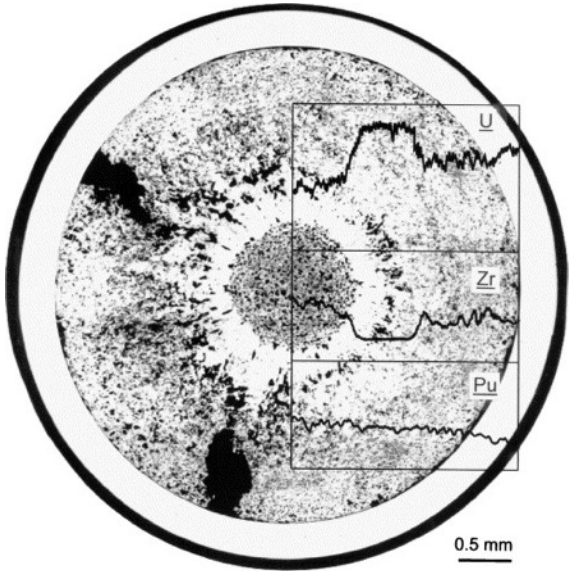
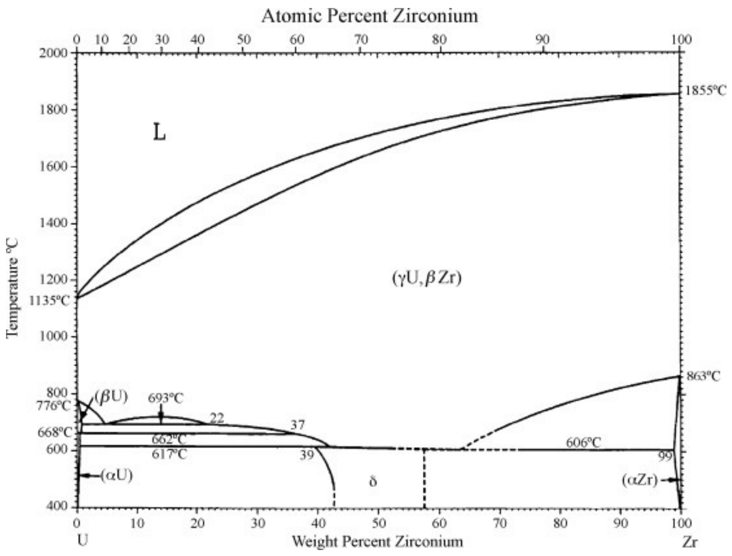
Uranium-Zirconium (UZr)

- Alloy metallic U with Zr to increase the melting point and to stabilize the high temperature body-centered cubic phase
- Interesting phenomena
  - 30-50% swelling
  - Constituent redistribution
  - Alpha tearing
  - FCCI



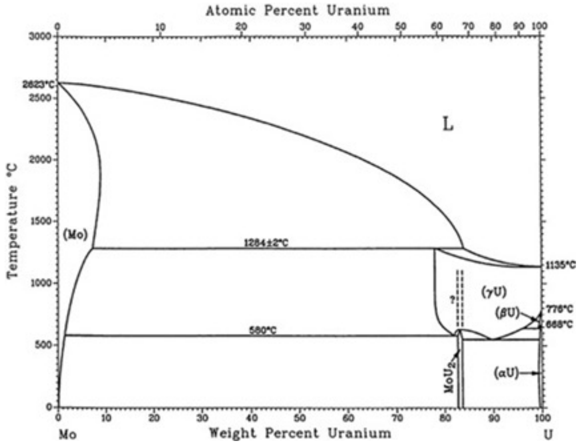


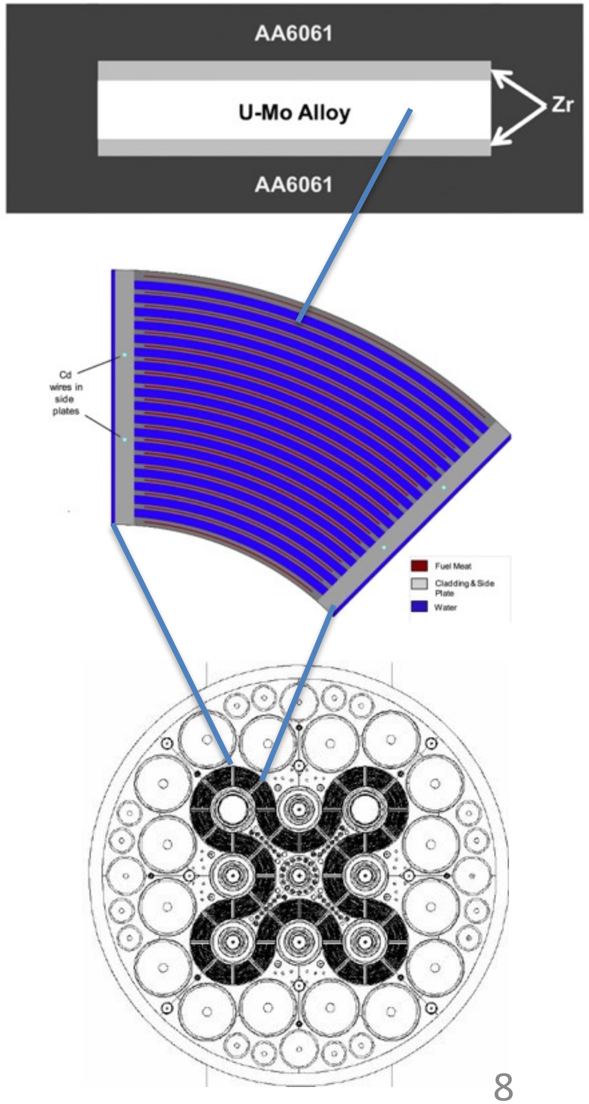
Uranium-Zirconium (UZr)

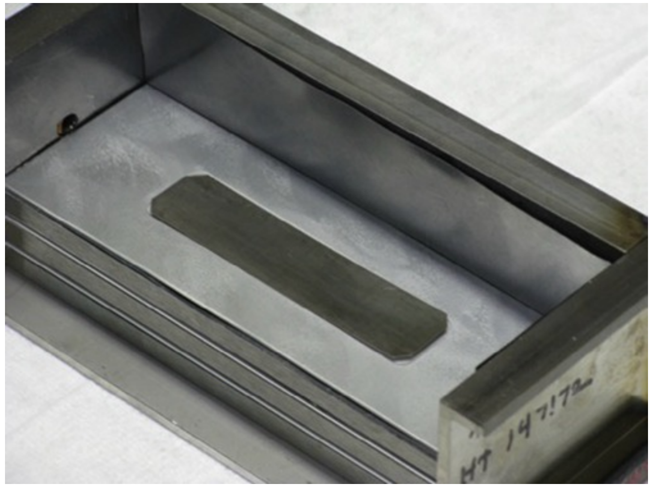
- Good Characteristics
  - High thermal conductivity
  - Stability to high burnups (> 20%)
  - Flexible composition
  - Inherent safety- negative reactivity feedback
  - Good compatibility with Na coolant
- Bad Characteristics
  - Low melting point
  - Dramatic fuel swelling that must be accounted for
  - Incredibly complex microstructures/unpredictable behavior
  - Fuel-Clad Chemical Interaction
  - Very easily oxidized

Uranium-Molybdenum (UMo)

- New fuel being qualified for research reactors
- Fuel foil, with Zr diffusion barrier, Al cladding
- Will be utilized in ATR, NBSR, MITR, MURR

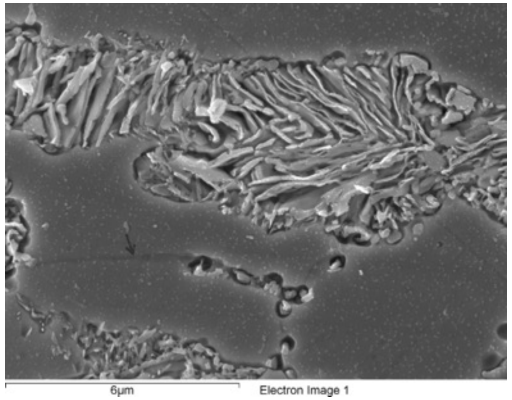


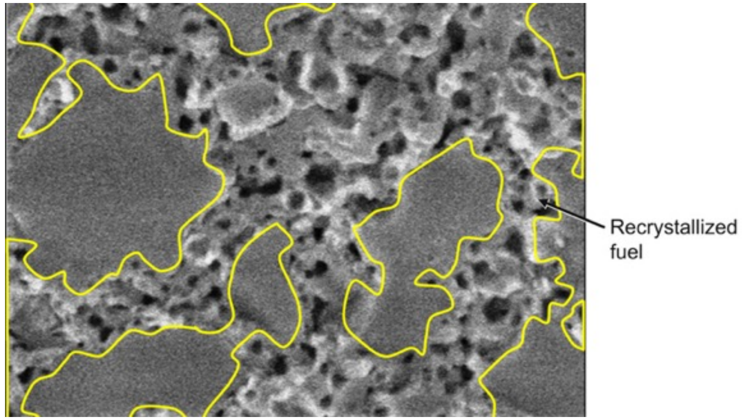


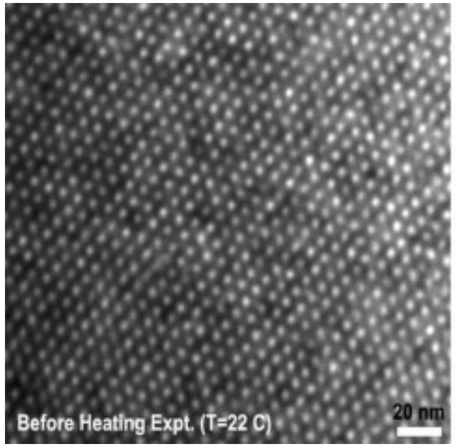


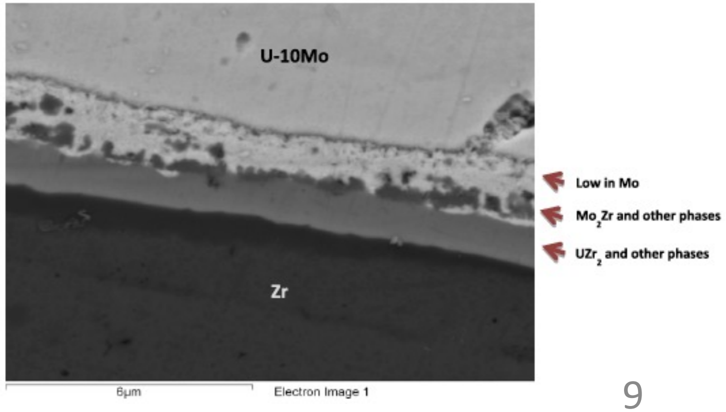
Uranium-Molybdenum (UMo)

- Microstructural phenomena of interest:
  - Decomposition
  - Fission Gas Superlattice
  - Recrystallization
  - Inter-diffusion region
  - Carbides



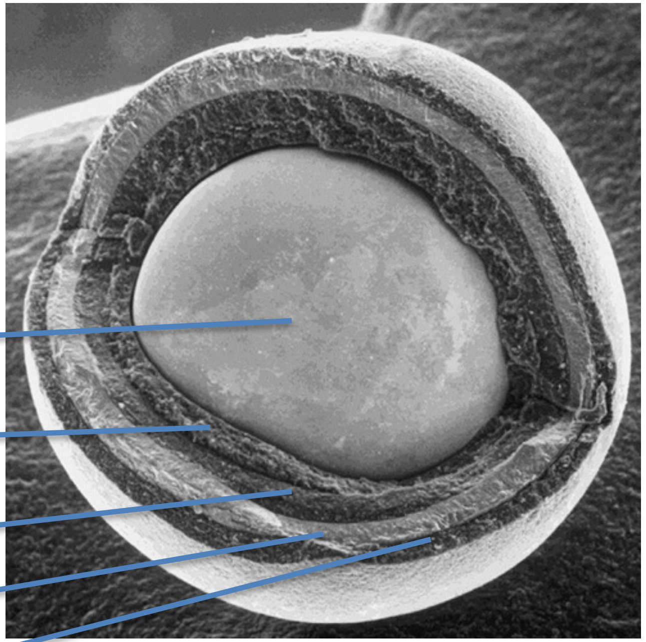






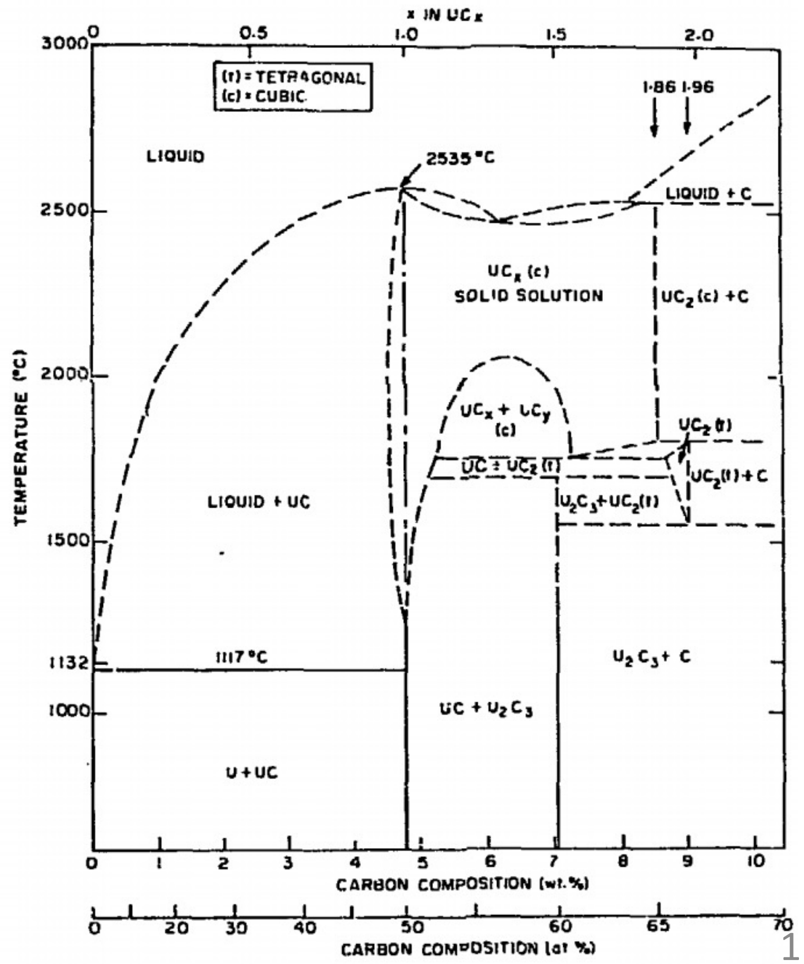
UC/UCO TRISO Fuels

- TRISO: TRistructural ISOtropic particle fuel
- Layered fuel in mm-sized particles
- Layers:
  - Fuel Kernel
  - Buffer
  - Inner Pyrolitic Carbon (IPyC)
  - SiC
  - Outer Pyrolitic Carbon (OPyC)



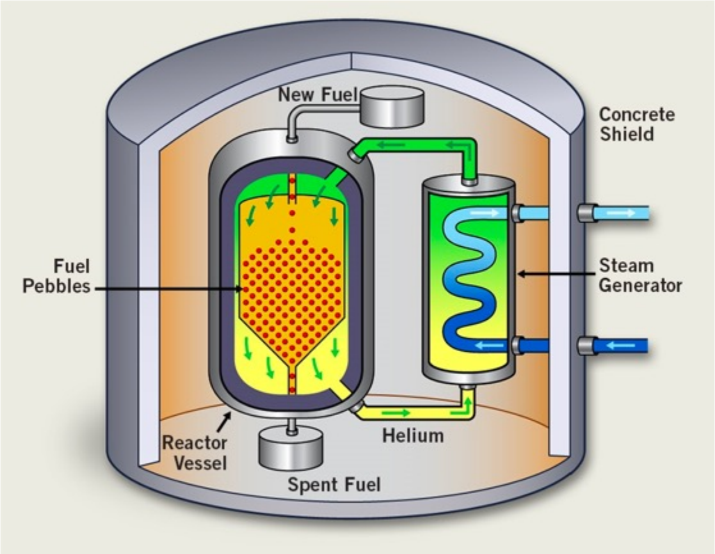
UC/UCO TRISO Fuels

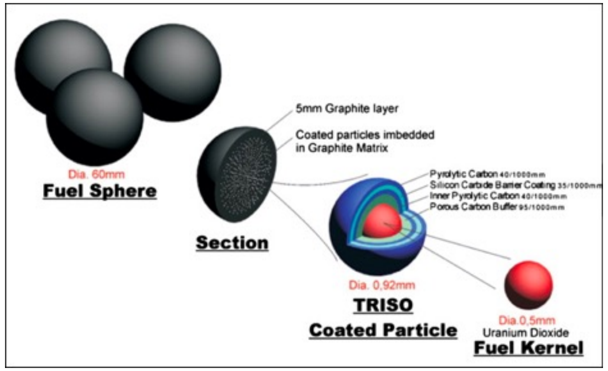
- Can appear as UC, U_2C_3, or UC_2
- Advantages
  - High thermal conductivity
  - High fuel density
  - Thermally stable
  - High melting temperature
- Disadvantages
  - Rapidly corrodes in water
  - Reacts with some cladding



UC/UCO TRISO Fuels

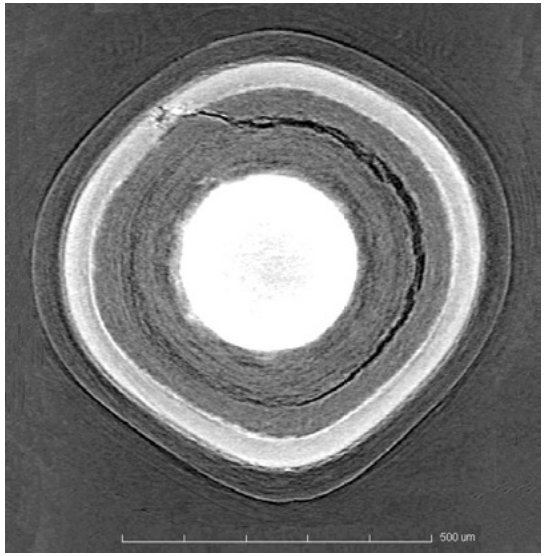
- High temperature gas reactors (HTGR) or molten salt reactors (MSRs)
- Pebble bed and prismatic types
- Particles are agglomerated with graphite into a larger pebble, or into a cylindrical block
- Current designs utilize UCO, which is a heterogeneous mixture of UO2 and UC fuel
- Helium cooled gas or molten salt cooled

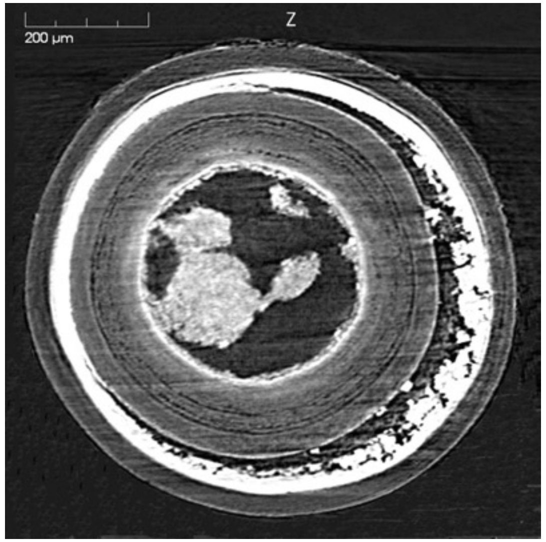




UC/UCO TRISO Fuels

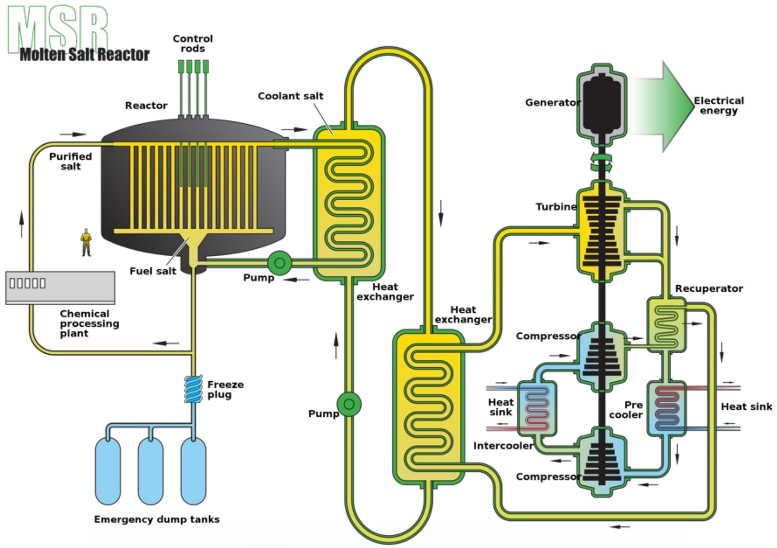
- Each individual pebble acts as its own containment, and allows fuels to go to much higher burnups and higher temperatures than UO2
- Highly reliant on accurate fabrication processes that create high integrity, uniform layers and spherical particles
- Integrity of the SiC is key for fission product retention

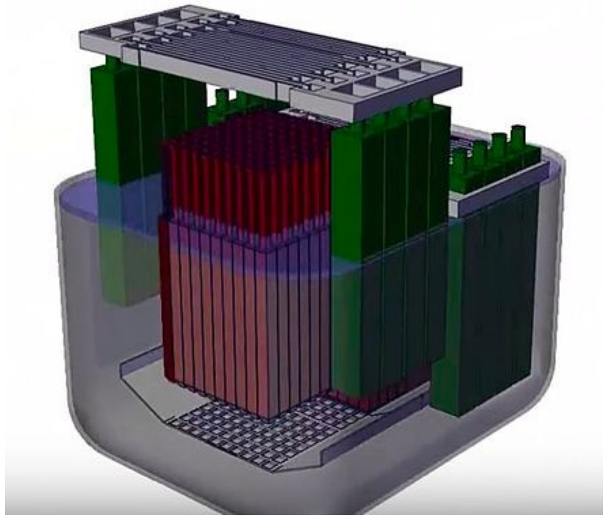




Molten Salt Reactors

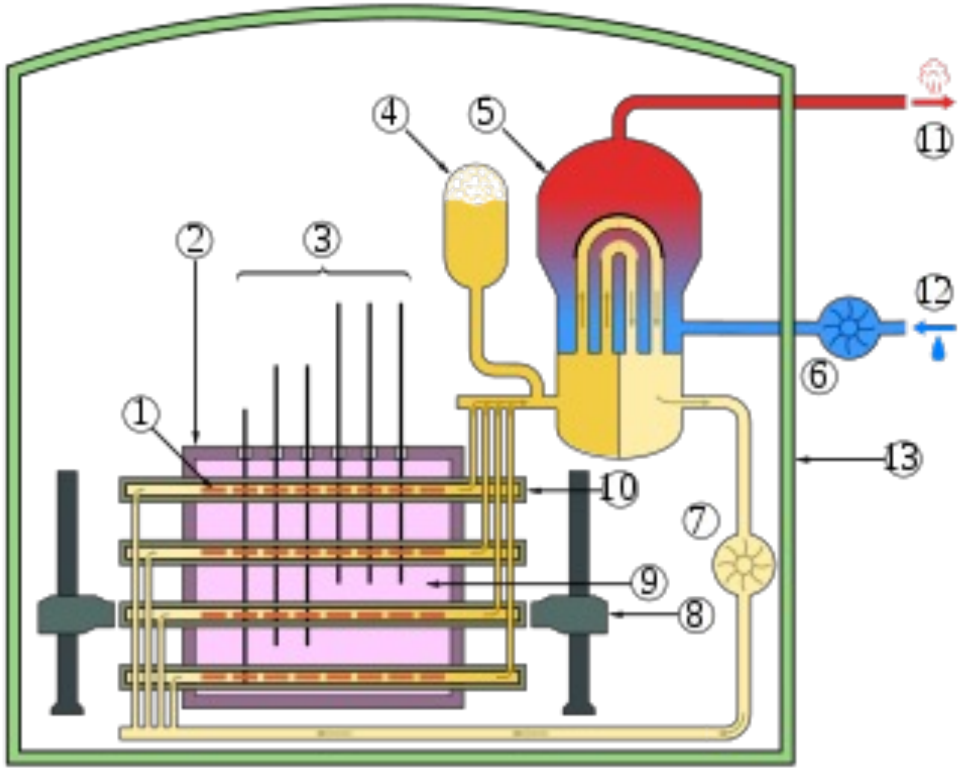
- Molten Salt Reactor
  - Utilizes flowing fuel salt (i.e., UF4-ZrF4-KF) with a secondary molten salt coolant loop (FLiBe)
  - MSRE at ORNL, some modern designs
- Stable Salt Reactor
  - Utilizes fuel that is dissolved in molten salts (NaCl-(U/Pu)Cl3), contained in rods
  - Molten salt coolant (NaF-ZrF, FLiBe, FLiNaK, etc.)
- Can mix other actinides into the fuel in order to burn waste
- Designed to be inherently safe
- Molten salt corrosion is a big problem, as well as the lack of information on thermophysical properties of complex salt





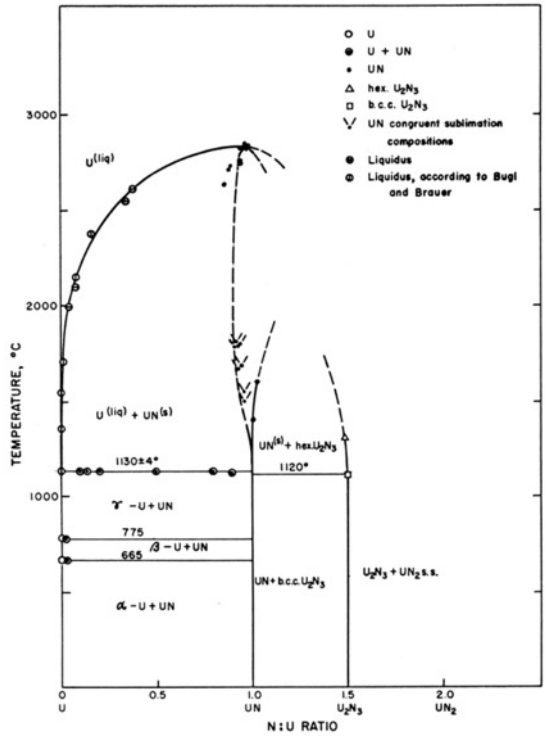
CANDU Reactors

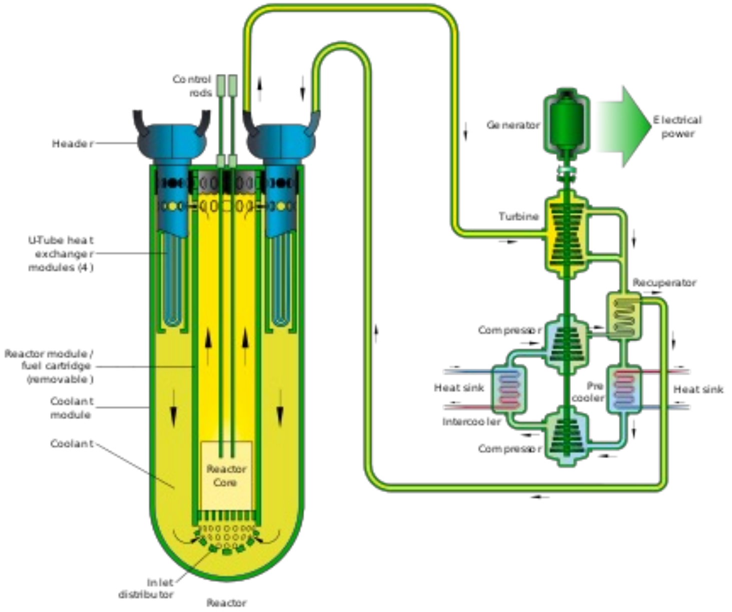
- Canada Deuterium Uranium: pressurized heavy water reactor
- Natural uranium, as UO2, as the fuel source
- Heavy water is the coolant, has a lower absorption of neutrons
- Fuel pins are horizontal, as opposed to vertical
- CANDU can be refueled online
- Removes costs associated with enrichment



UN – Lead Cooled Reactors

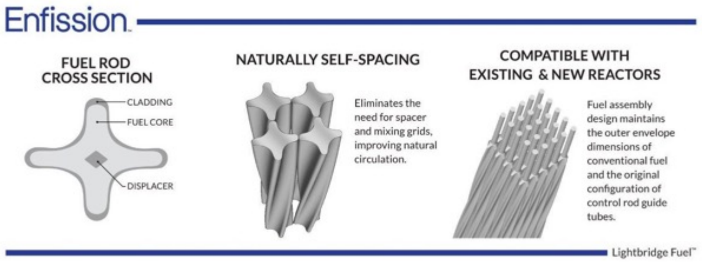
- Can appear as UN, U_2N_3, or UN_2
- Advantages
  - High thermal conductivity
  - High fuel density
  - Thermally stable
  - High melting temperature
- Disadvantages
  - Corrodes in water
  - Reacts with some cladding
  - Difficult to manufacture
  - Requires N-enrichment
- Pb or Pb-Bi coolant
- Operates in the fast spectrum

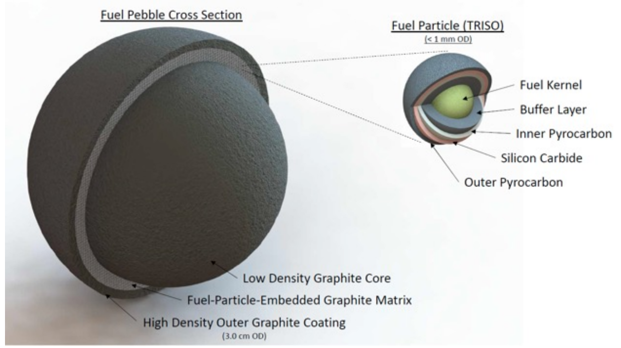


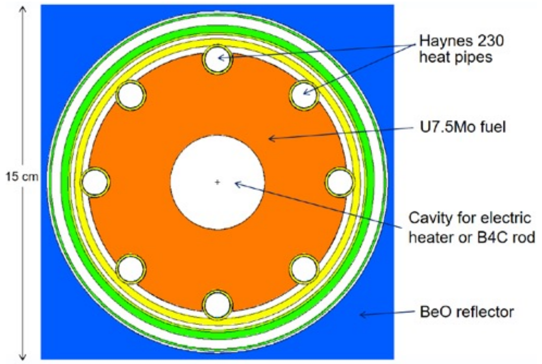


Unique Fuel Designs

- Lightbridge
  - High Zr content UZr alloy
  - Cruciform geometry fuel rods, combined into fuel elements
- Kairos
  - TRISO particle compacts with low density core
  - Float in molten salt coolant for online refueling
- NASA/LANL
  - UMo fuel for space reactors: KRUSTY







Fuel Summary Table

Property	UZr	UO_2	UC	UN	U_3Si_2
Corrosion resistance in water	Very poor	Excellent	Very poor	Poor	Very Poor
Compatibility with clad materials	Reacts with normal clad	Excellent	Variable	Variable	Variable
Thermal stability	Phase change at 665 and 770 °C	Good	Good	Good	Good
Uranium (metal) density (g/cm^3)	19.04	9.65	12.97	13.52	11.31
Melting point (°C)	1205	2865	2850	2860	1665
Thermal conductivity (W/m-K)	38 at 430 °C	3 at 1000°C	25 at 500°C	20 at 750°C	23 at 773°C

Fuel Types Summary

- There exist a number of nuclear fuels in different stages of utilization and development
- Each reactor design or application has individual needs, and no one fuel is one size fits all
- Need to balance safety, performance (normal, off-normal, extended), manufacturability, processing, waste, etc.

Summary

- Uranium is combined with O, C, N, transition metals for a variety of fuel types
- UO_2: ceramic, commercial reactor fuel, light water reactors
- ATF: U_3Si_2 and Cr-doped UO_2
- UZr: fast reactor fuel
- UMo: research reactor fuel
- UC/UCO: high temperature gas reactors

QUESTIONS?