Nuclear Fuels

NE 201 Fall 2022

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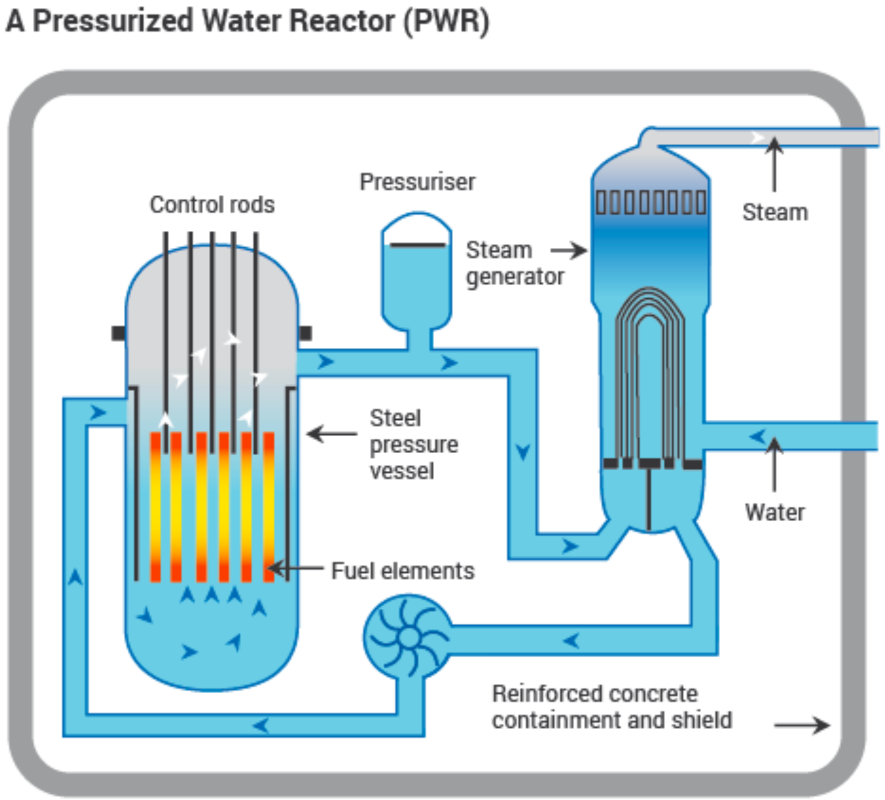
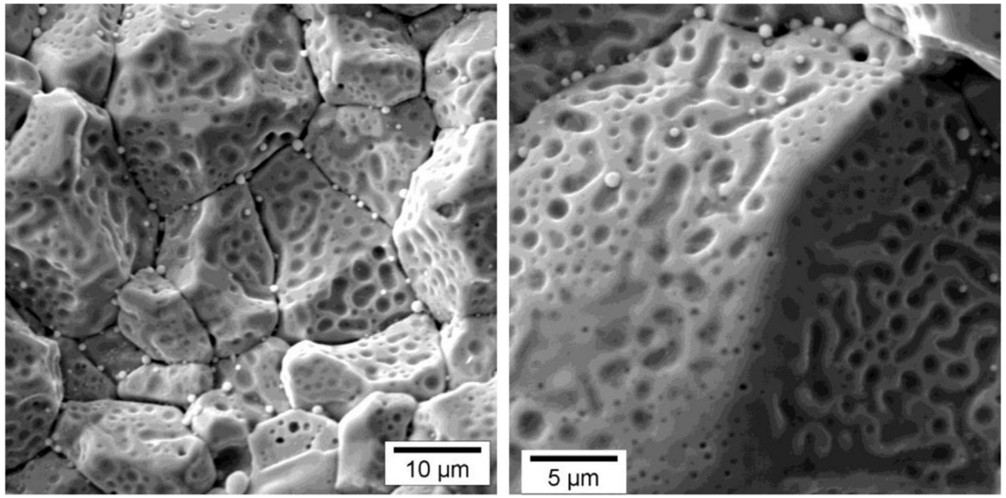
Fuel is the Heat Source

- Although the fuel is a relatively small part of a reactor system, it determines thermal power, which drives electric power generation
- The performance of the fuel is measured by:
  - How much heat is delivered to the coolant
  - The length of time it operates without any problems
  - How well it performs during an accident



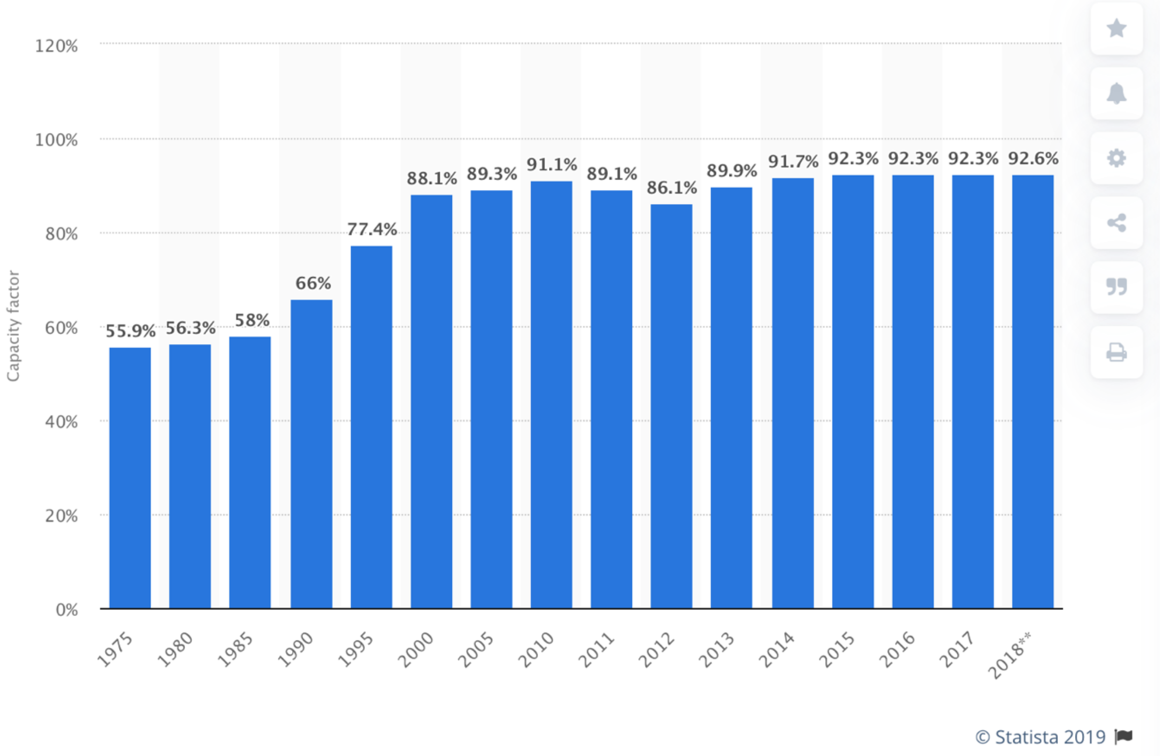
How much heat is delivered to the coolant?

- Heat transport is related to thermal conductivity
- In single crystal, pristine materials, thermal conductivity is reasonably straightforward
- In dynamic, radiation environments, thermal conductivity degrades, fission gas bubbles form, grain boundaries are generated and destroyed
- How does thermal conductivity vary?



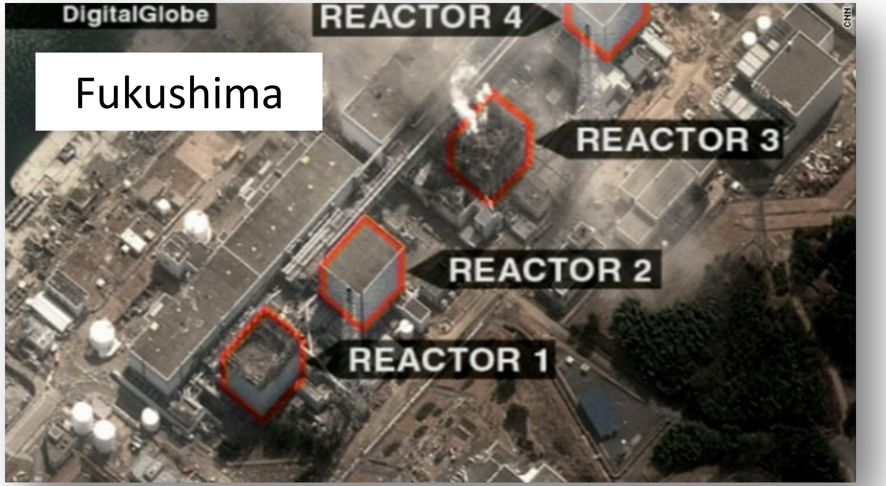
The length of time fuel operates without any problems

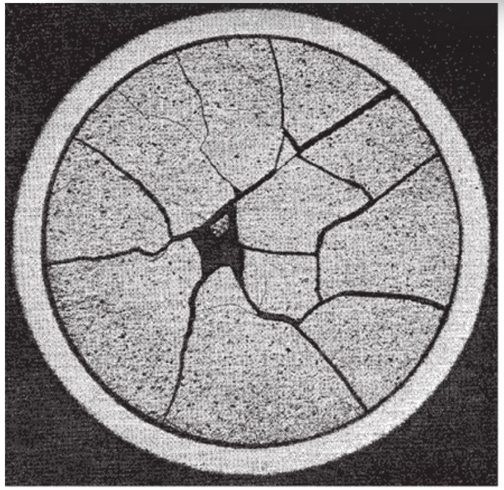
- There are 98 operating nuclear reactors in the US, producing 20% of the electricity
- The net capacity factor is the ratio of an actual electrical energy output to the maximum possible electrical energy output over a period of time
- Nuclear reactor capacity factor is ~92% over the past decade
- The ability to maintain high capacity factor, limit shutdown time, is key in making nuclear power economical
- Fuel is the primary component forcing reactor downtime

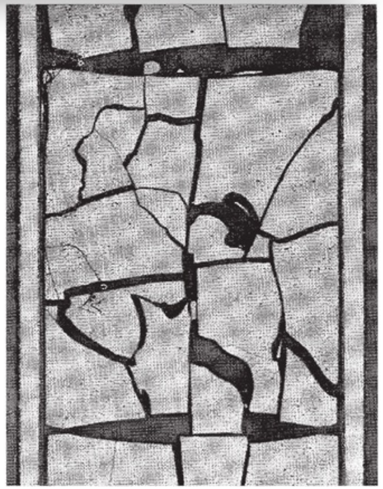


Fuel behavior during accidents

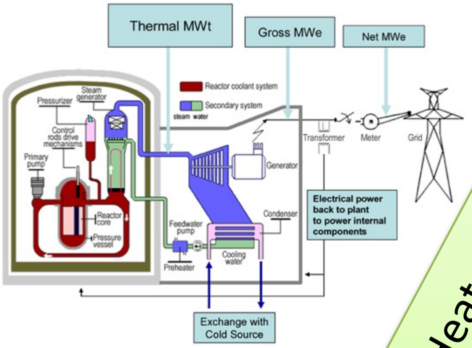
- In addition to normal operating conditions, the behavior of the fuel during accidents is of critical importance
- Predictable, and hopefully stable, behavior is desired during a variety of accident scenarios
- Even low impact accidents are detrimental to public opinion surrounding nuclear energy

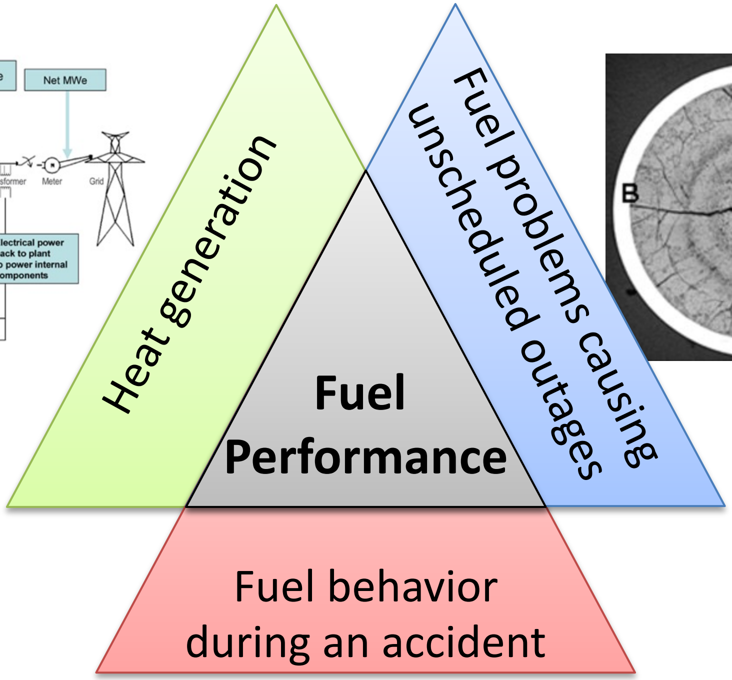


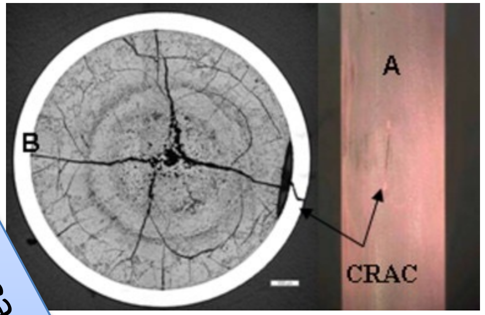


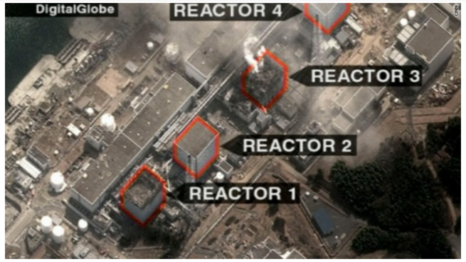


All of these factors together represent what we call "fuel performance"









Fuel Considerations

- Safety:
  - Stable and predictable behavior
  - No melting, no phase changes under transients that lead to deleterious behavior
- Uranium density
- Mechanical integrity
- Cladding interactions
- Swelling and fission gas release
- Operating temperatures

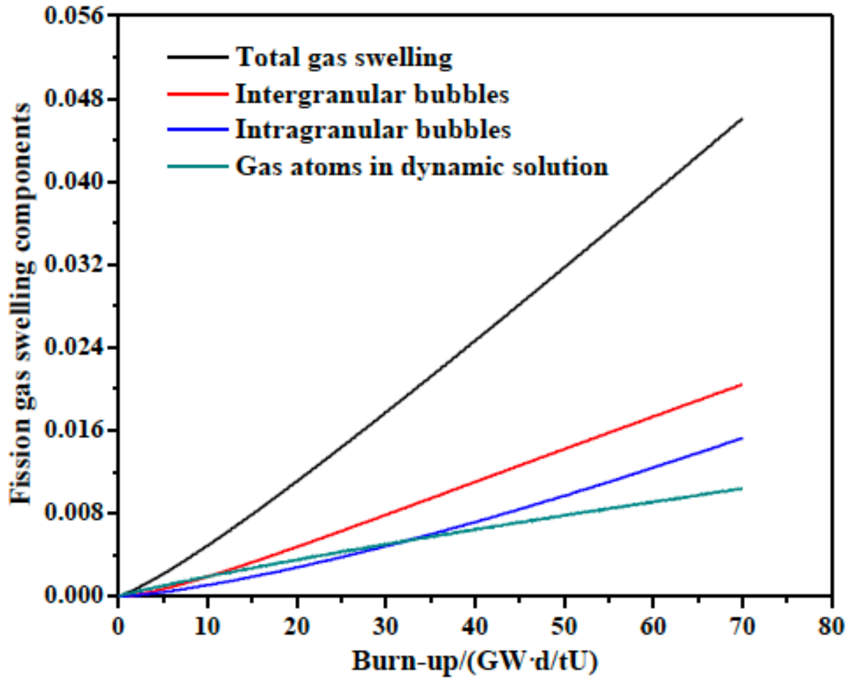
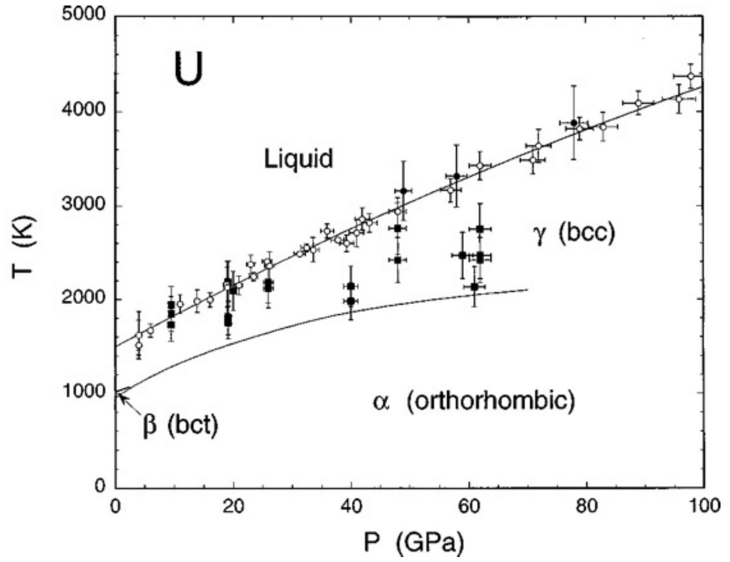
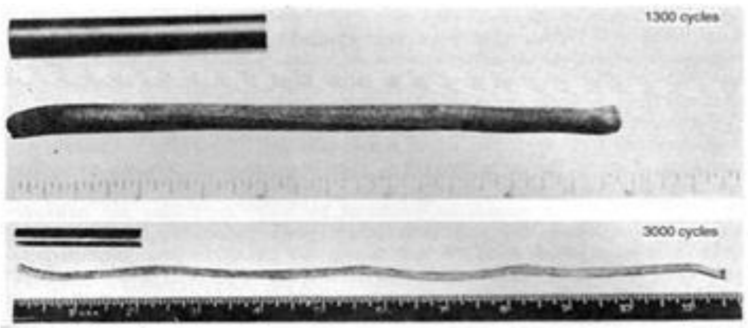


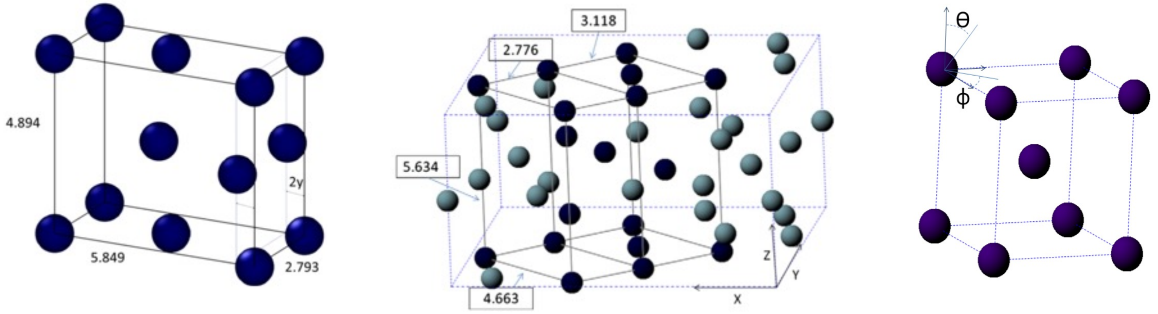
Fig. 4. Variation of swelling rate components of fission gas in UO_2 fuel with the burn-up.

Why not use pure uranium metal?

- Pure uranium has three phases
  - α-phase is orthorhombic
  - β-phase is tetragonal
  - γ-phase is body-centered cubic
  - During thermal cycling, pure uranium dramatically swells
  - Alpha U has both anisotropic thermal expansion and anisotropic irradiation growth





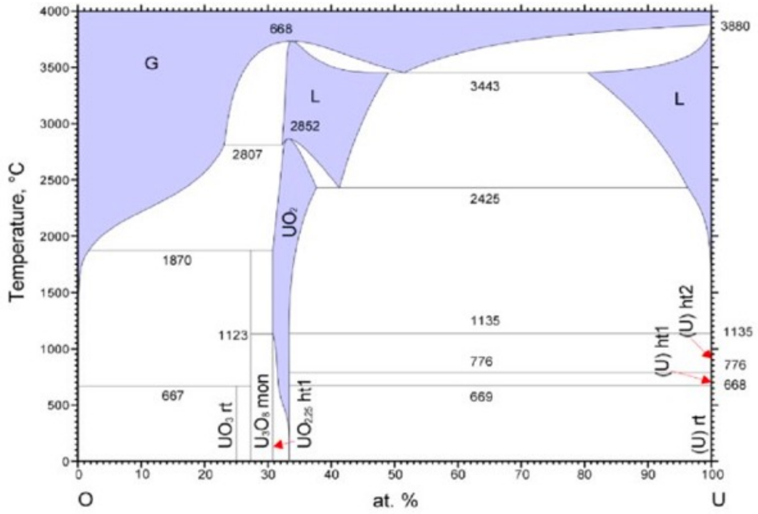


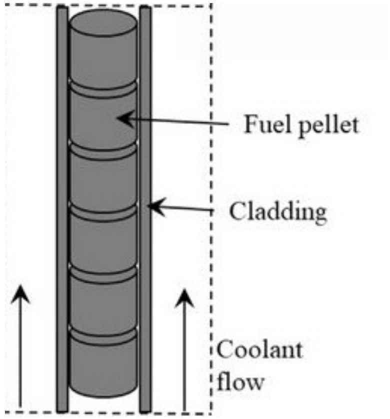
Fuel Types and Associated Reactor Types

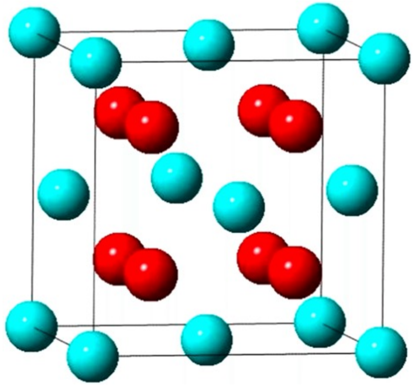
- UO_2 – Light Water Reactors
  - Mixed oxide (MOX)
  - Accident tolerant/Advanced Technology Fuel (ATF)
- UZr – Sodium Cooled Fast Reactors
- UMo – Research Reactors
- UC/UCO – High Temperature Gas Reactors
- UN – Lead Cooled Fast Reactors
- Other

Uranium Dioxide (UO2)

- Reference fuel for nuclear power industry
- Single phase, fluorite structure
- Fabrication via sintering UO2 powder into pellets
- Water coolant
- Pellets are stacked inside Zircaloy cladding tubes

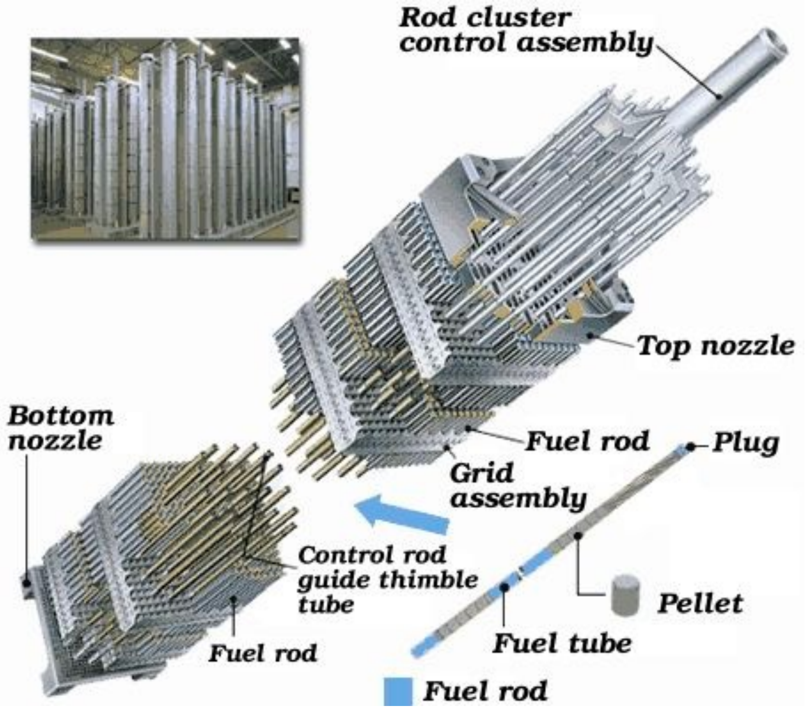






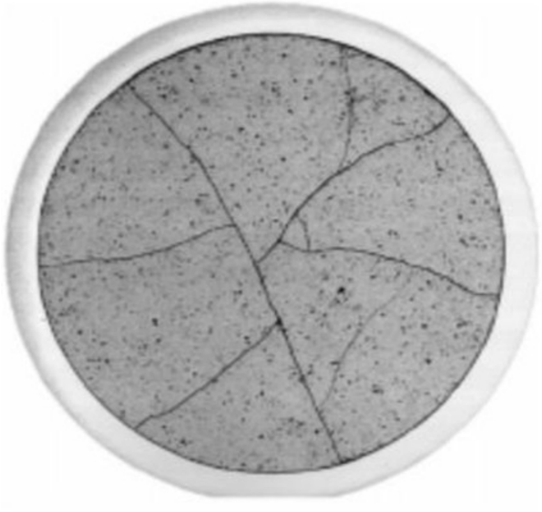
Uranium Dioxide (UO2)

- Good Characteristics
  - Very high melting point, about 2800 C
  - Maintains a stable fluorite phase up to melting
  - Very compatible with Zircaloy clad (no interaction zones forming/no FCCI)
  - Relative stability in water
  - Reasonably radiation resistant
    - no amorphization
    - Can incorporate a large number of fission products as substitutional defects



Uranium Dioxide (UO2)

- Bad Characteristics
  - Brittle (thermal stress fractures, fragmentation)
  - Poor thermal conductivity
  - Properties very sensitive to stoichiometry
  - Limited linear heating rates
  - Non-negligible thermal expansion/swelling
  - Higher stored thermal energy than other fuel materials



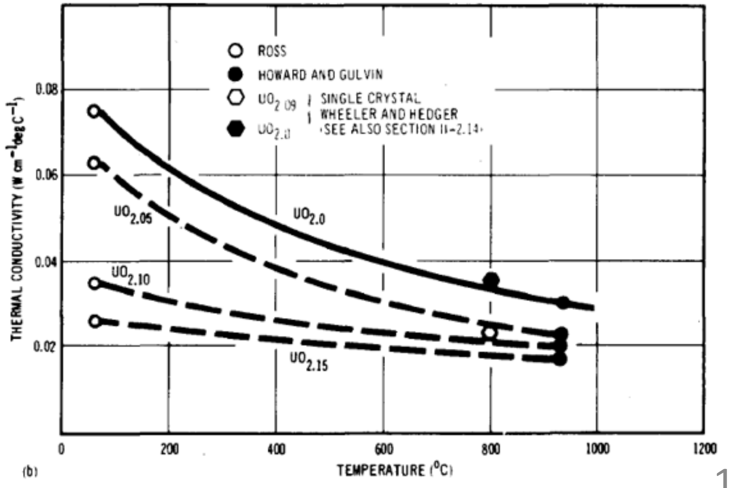
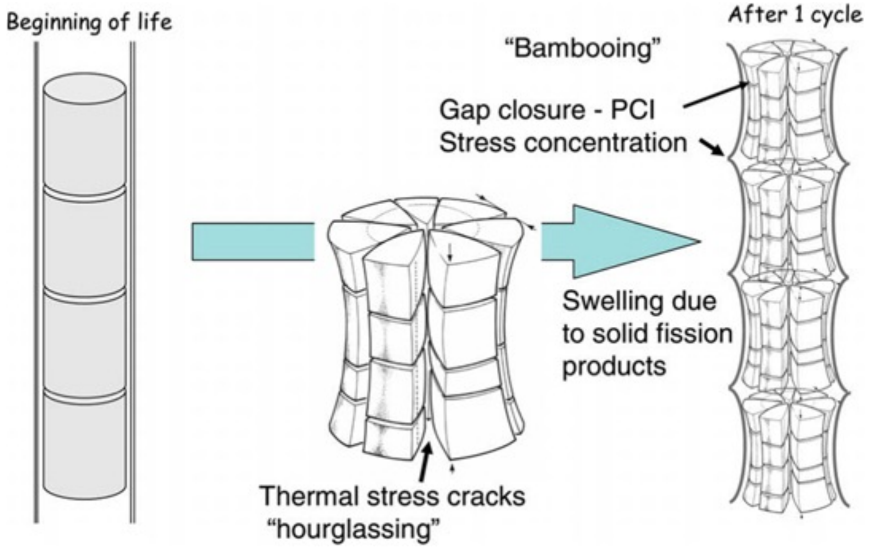
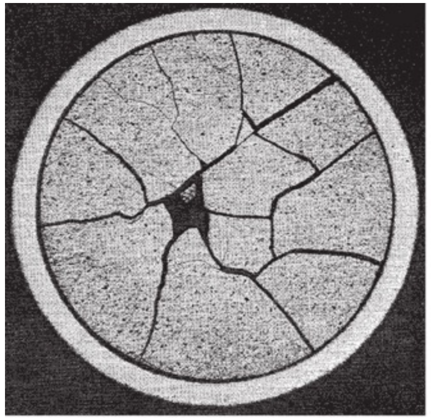


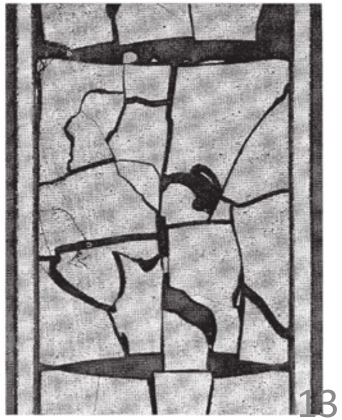
Fig. 9. Effect of hyperstoichiometry on conductivity.

Uranium Dioxide (UO2)

- Critical Phenomena
  - Thermal conductivity (and degradation)
  - Fission gas release, leading to pressure increase inside the cladding
  - Fuel fragmentation and relocation under transients
  - Bambooing creating stress concentrations
- All 98 operational reactors in US utilize UO2

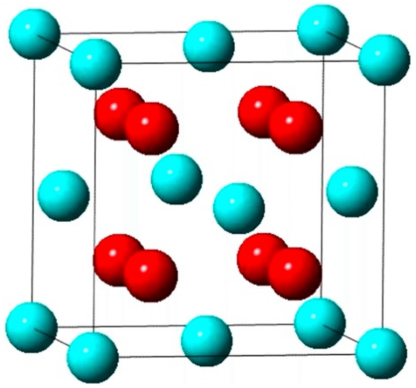


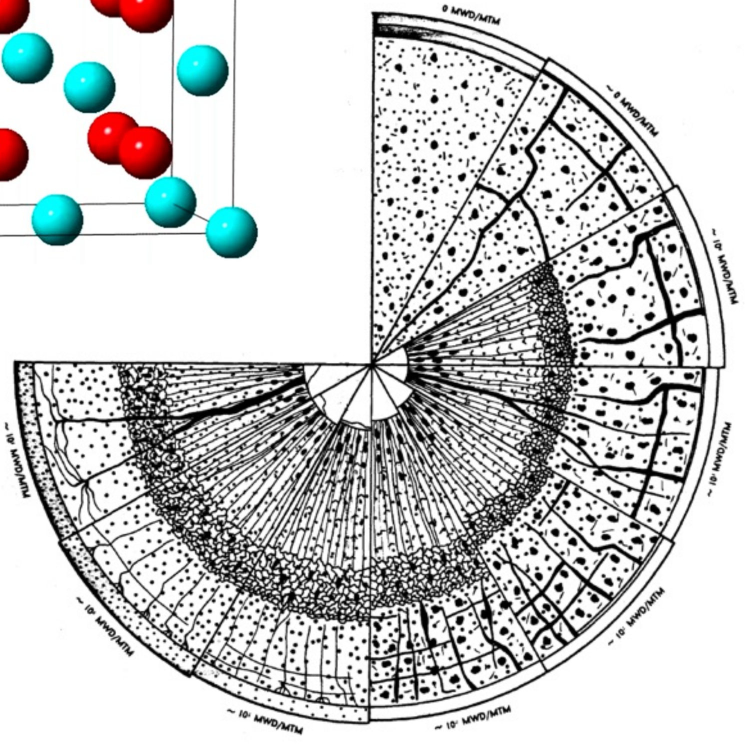




Mixed Oxides (MOX)

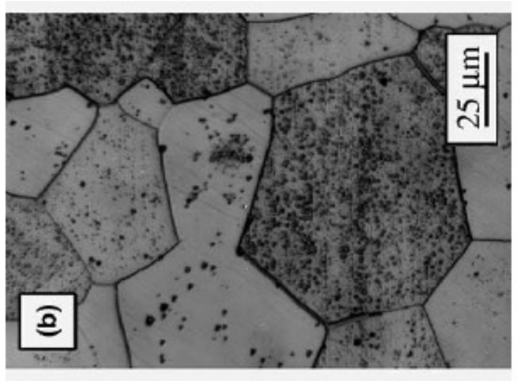
- Can be combined with PuO_2 for a mixed oxide (MOX) fuel for use in fast reactors
- Allows to burn excess weapons grade plutonium
- About 30 reactors in Europe currently utilize a partial MOX core
- Similar behavior to UO_2, but different neutronics, fission gas release, thermal conductivity, etc.
- Less common is inclusion of minor actinides in MOX to burn waste

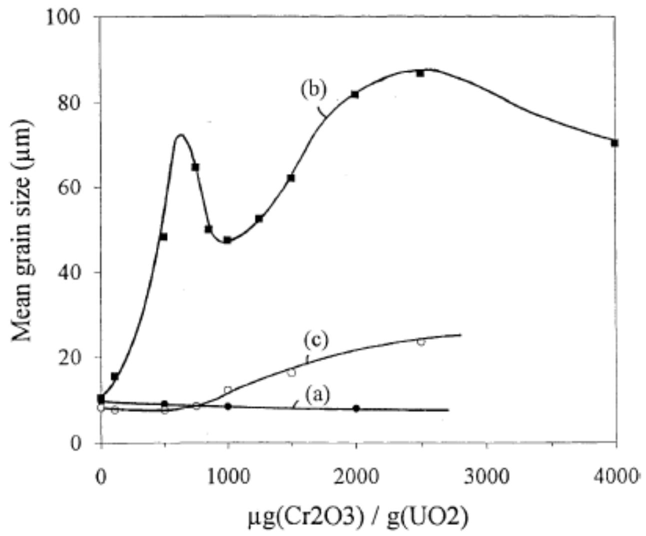




Accident Tolerant Fuel

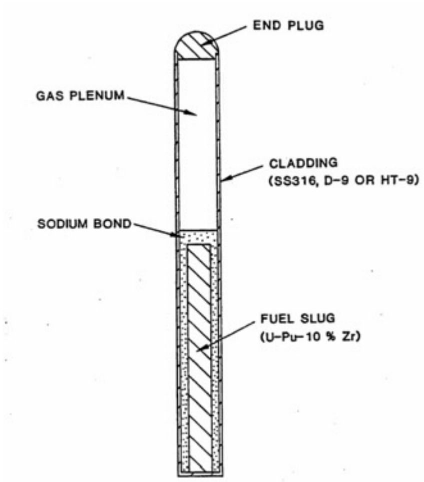
- Cr-doped UO2
  - Larger grain size, theoretically reduced fission gas release
  - Cr changes the O potential present within the fuel, changing defect concentrations and mobilities
- Coatings or alternate claddings – FeCrAl or SiC
  - Improved radiation resistance, corrosion resistance, etc.

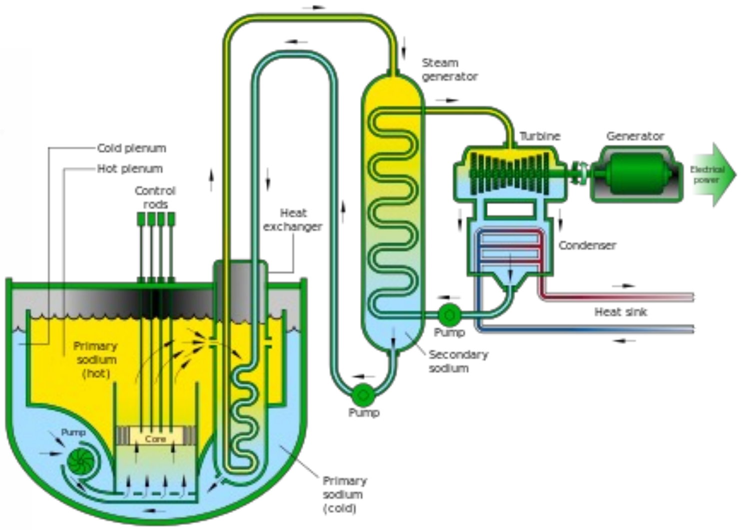




Uranium-Zirconium (UZr)

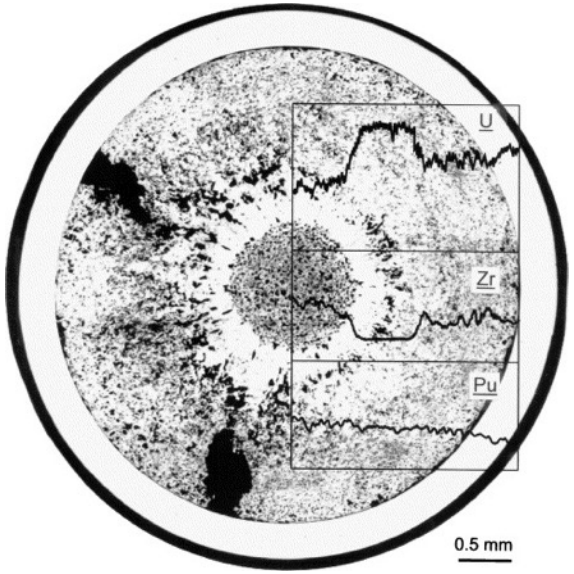
- Utilized in sodium cooled fast reactors (SFRs)
  - EBR I, EBR II
- Varied crystal structure and compositional environment
- Easily alloyed with Pu, minor actinides (MA)
- Can function as a breeder/burner fuel
- Sodium coolant
- Fe-based cladding

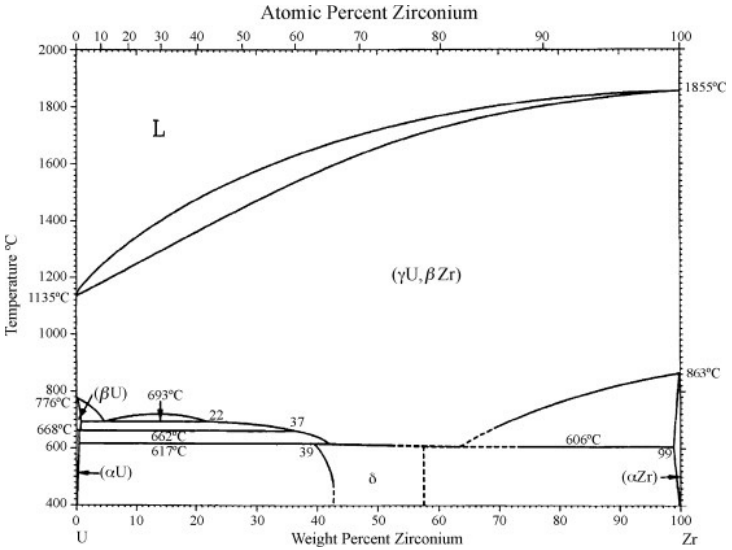




Uranium-Zirconium (UZr)

- 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





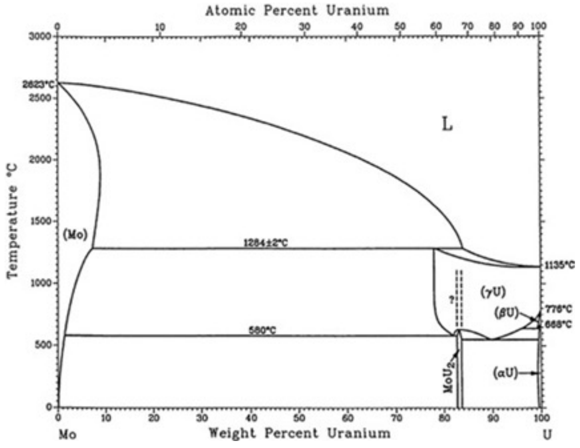
Uranium-Zirconium (UZr)

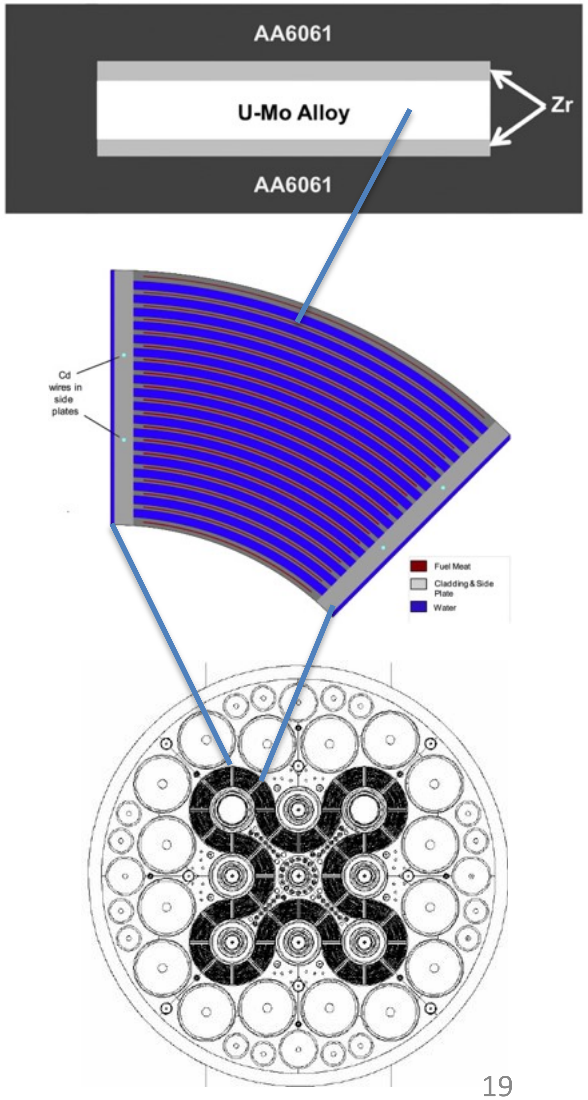
- Good Characteristics
  - High thermal conductivity
  - Stability to high burnups (> 20%)
  - Flexible composition
  - Inherent safety- negative reactivity feedback
  - Good compatibility with Na coolant

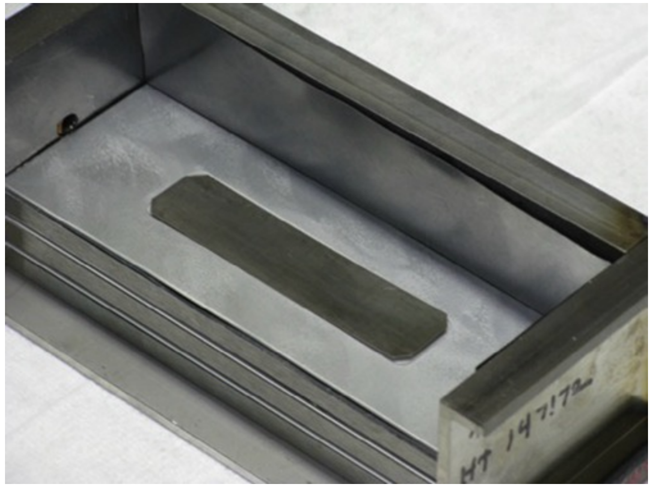
- Bad Characteristics
  - Low melting point
  - Dramatic fuel swelling that must be accounted for
  - Incredibly complex microstructures/unpredictable behavior
  - Fuel-Clad Chemical Interaction
  - Very easily oxidized

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

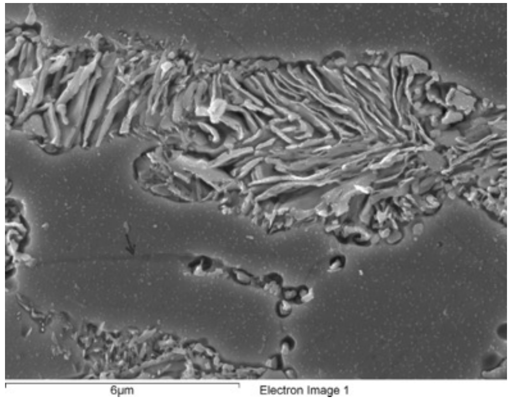


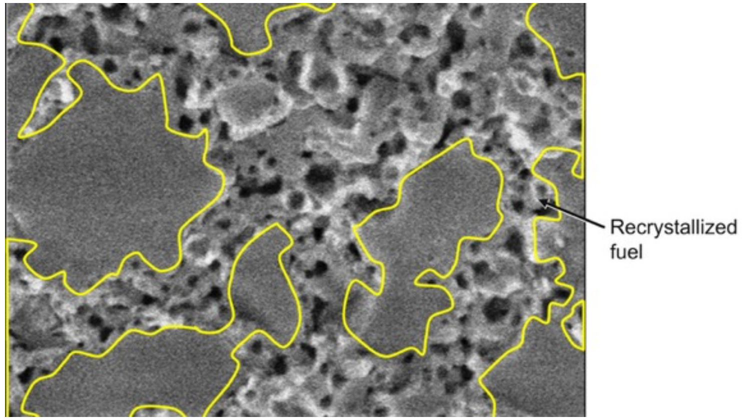


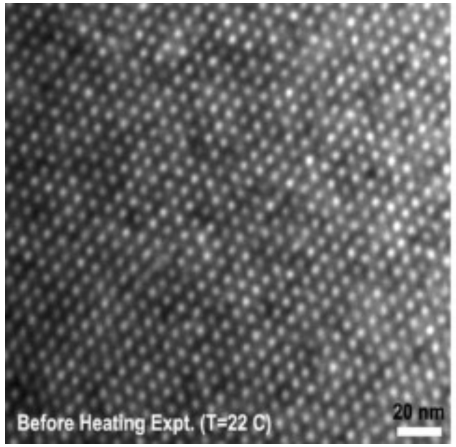


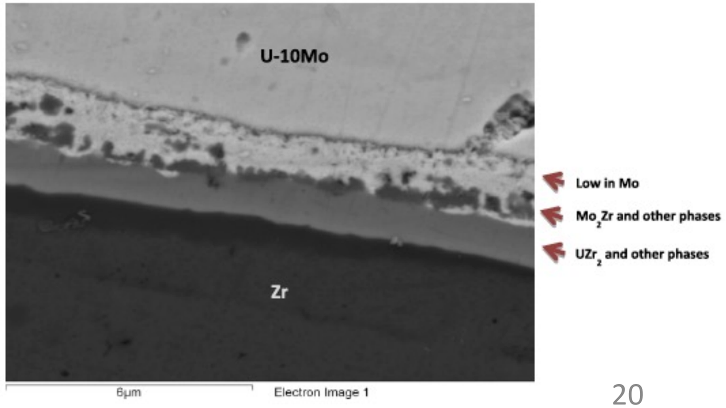
Uranium-Molybdenum (UMo)

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



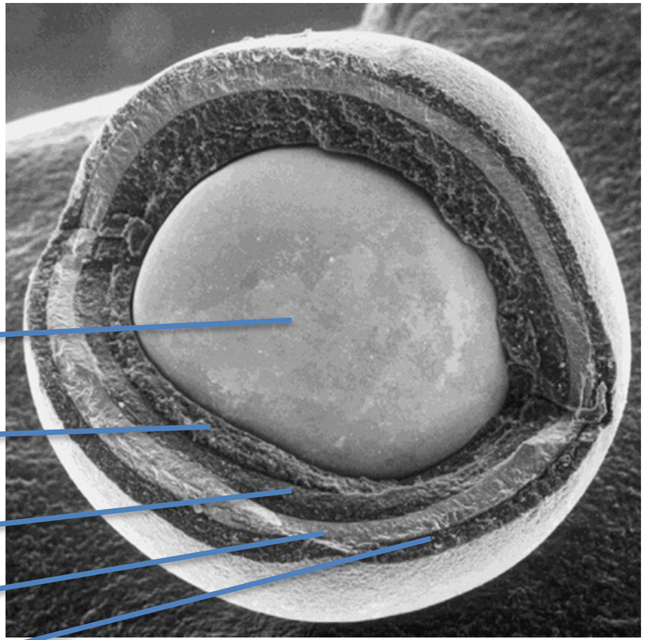






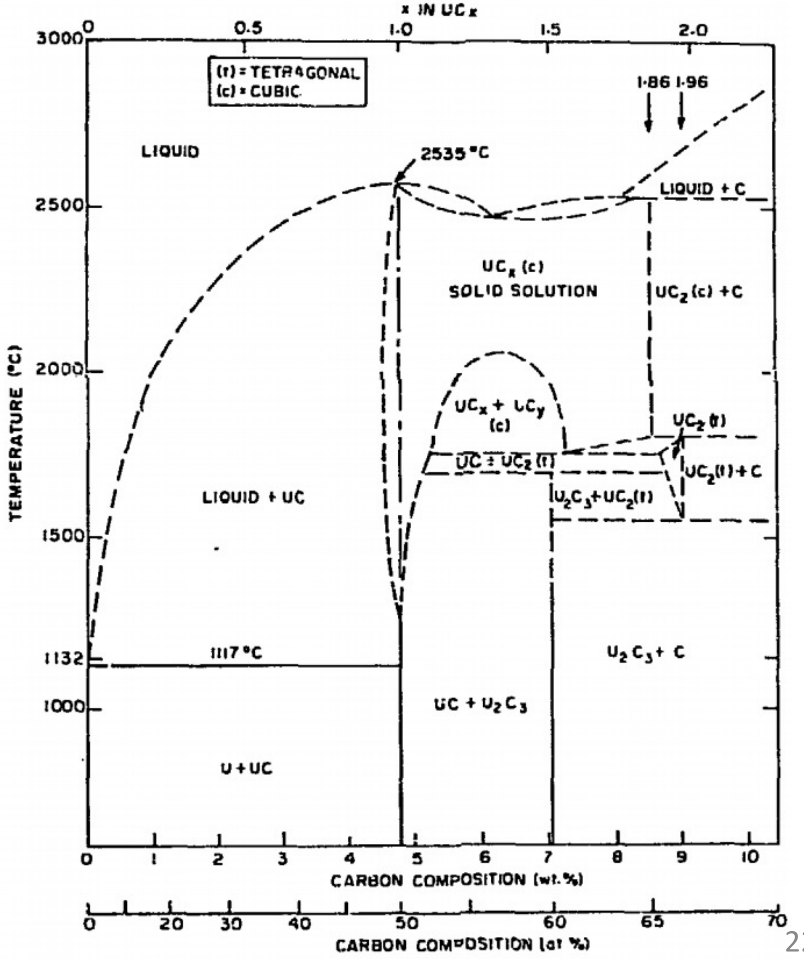
UC/UCO TRISO Fuels

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



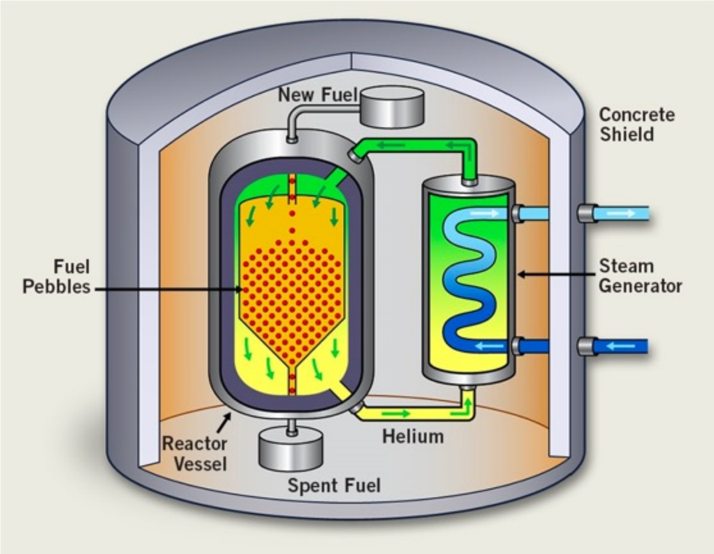
UC/UCO TRISO Fuels

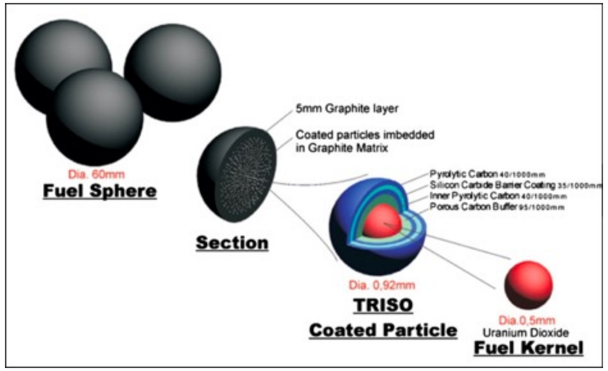
- Can appear as UC, U_2C_3, or UC_2
- Advantages
  - High thermal conductivity
  - High fuel density
  - Thermally stable
  - High melting temperature
- Disadvantages
  - Rapidly corrodes in water
  - Reacts with some cladding



UC/UCO TRISO Fuels

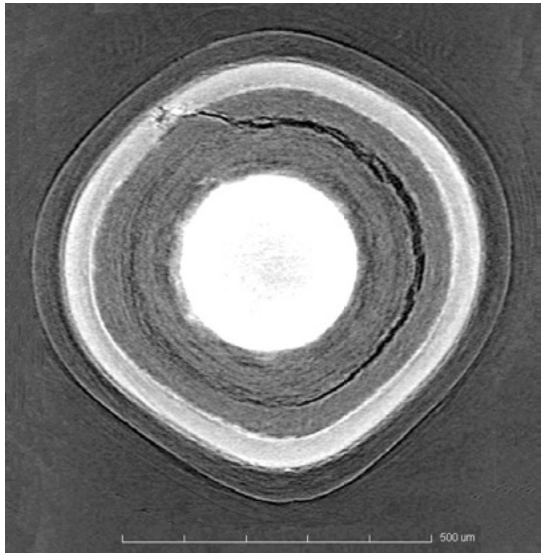
- High temperature gas reactors (HTGR) or molten salt reactors (MSRs)
- Pebble bed and prismatic types
- Particles are agglomerated with graphite into a larger pebble, or into a cylindrical block
- Current designs utilize UCO, which is a heterogeneous mixture of UO2 and UC fuel
- Helium cooled gas or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

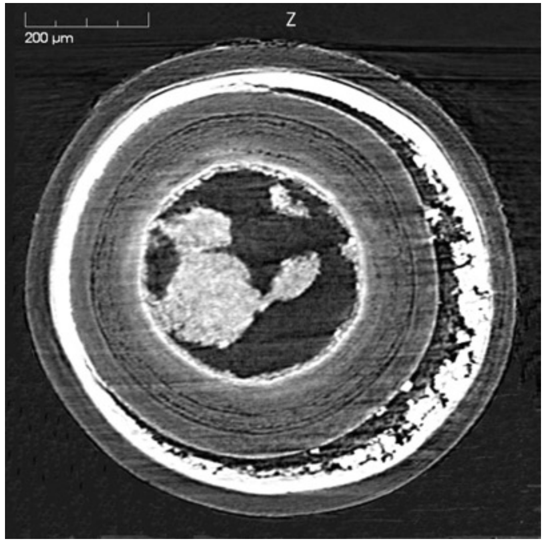




UC/UCO TRISO Fuels

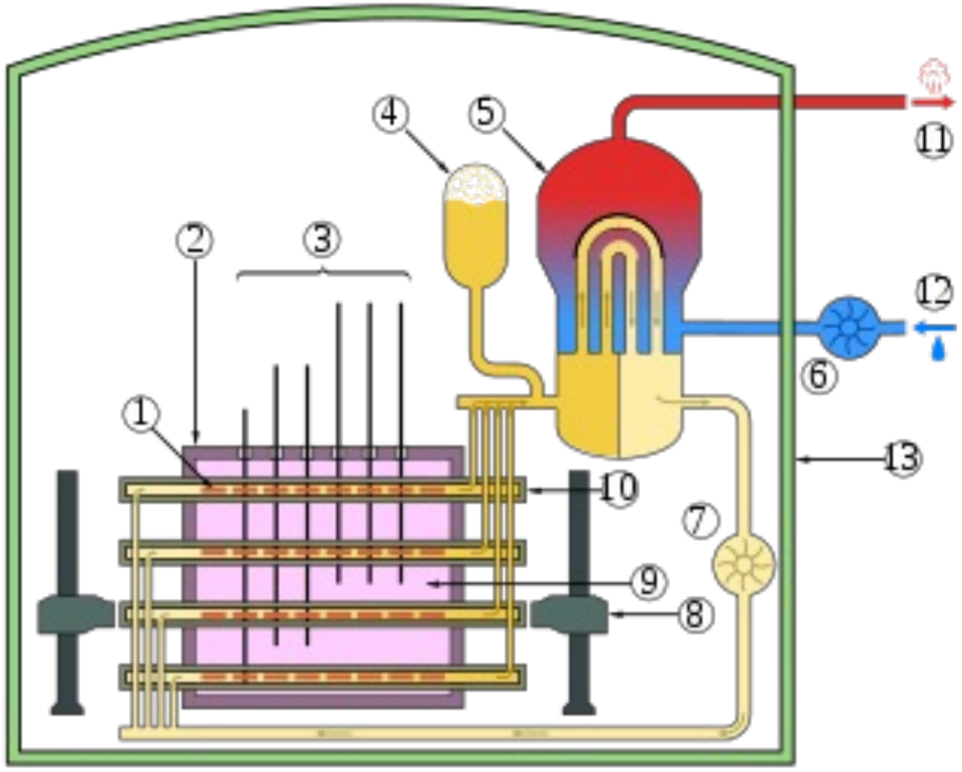
- Each individual pebble acts as its own containment, and allows fuels to go to much higher burnups and higher temperatures than UO2
- Highly reliant on accurate fabrication processes that create high integrity, uniform layers and spherical particles
- Integrity of the SiC is key for fission product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





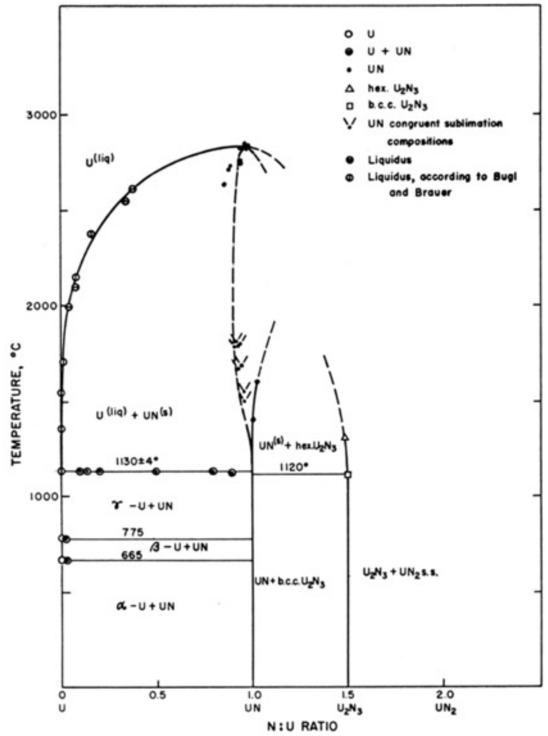
CANDU Reactors

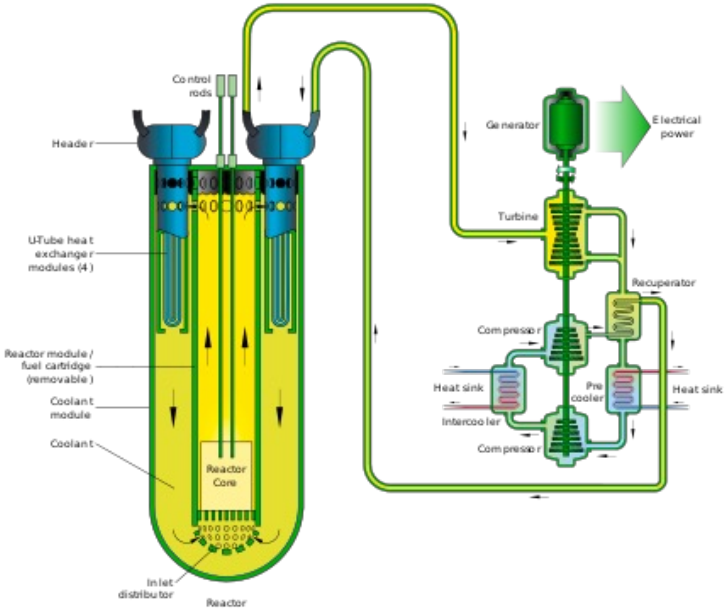
- Canada Deuterium Uranium: pressurized heavy water reactor
- Natural uranium, as UO2, as the fuel source
- Heavy water is the coolant, has a lower absorption of neutrons
- Fuel pins are horizontal, as opposed to vertical
- CANDU can be refueled online
- Removes costs associated with enrichment



UN – Lead Cooled Reactors

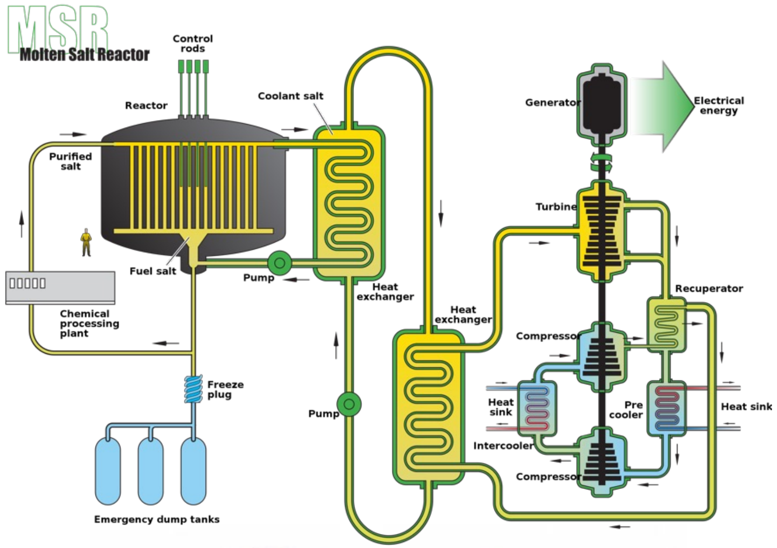
- Can appear as UN, U_2N_3, or UN_2
- Advantages
  - High thermal conductivity
  - High fuel density
  - Thermally stable
  - High melting temperature
- Disadvantages
  - Corrodes in water
  - Reacts with some cladding
  - Difficult to manufacture
  - Requires N-enrichment

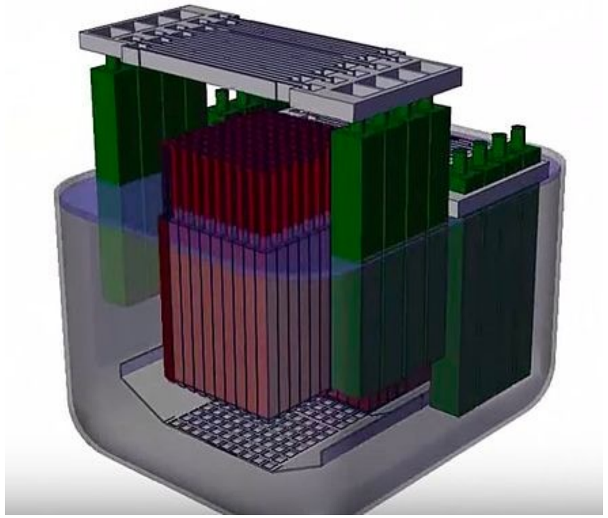




Molten Salt Reactors

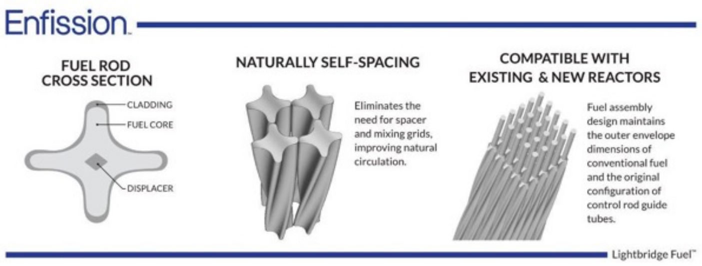
- Molten Salt Reactor
  - Utilizes flowing fuel salt (i.e., UF4-ZrF4-KF) with a secondary molten salt coolant loop (FLiBe)
  - MSRE at ORNL, some modern designs
- Stable Salt Reactor
  - Utilizes fuel that is dissolved in molten salts (NaCl-(U/Pu)Cl3), contained in rods
  - Molten salt coolant (NaF-ZrF, 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



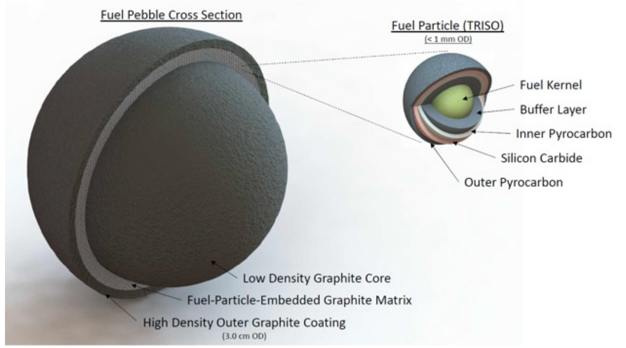


Unique Fuel Designs

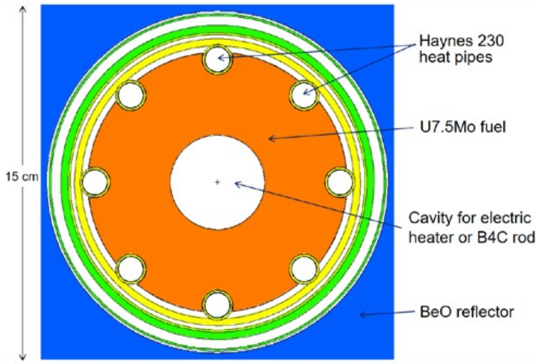
- Lightbridge
  - High Zr content UZr alloy
  - Cruciform geometry fuel rods, combined into fuel elements



- 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	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)	1132	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
- Uranium is combined with O, C, N, transition metals for a variety of fuel types
- UO2: ceramic, commercial reactor fuel, light water reactors
- 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.

QUESTIONS?