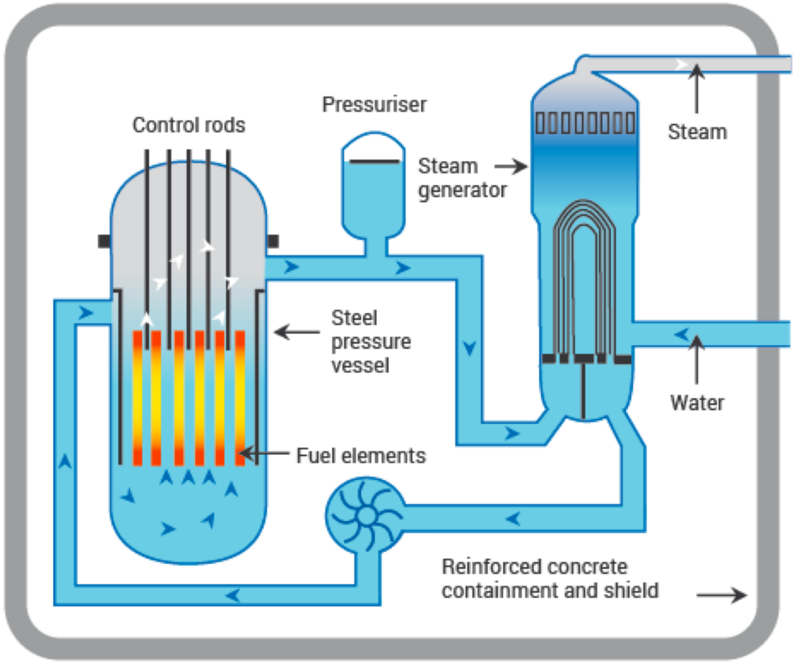
Fuel Types

NE 591

Fuel is the Heat Source

- Fuel functions as a heat source, generating heat that is transferred to a coolant, which transfers heat through external loops, heat exchangers, etc., to run a generator

A Pressurized Water Reactor (PWR)



Fuel is limited to select elements

- A **fissionable nuclide** is capable of undergoing fission (even with a low probability) after capturing a high energy neutron
- A **fissile nuclide** is capable of sustaining a nuclear fission chain reaction with neutrons of any energy
- A **fertile material** is a material that, although not itself fissionable, can be converted into a fissile nuclide by neutron absorption and subsequent nuclei conversions.

- The Ronen **fissile rule** states that for a heavy element with $90 \leq Z \leq 100$, its isotopes with neutrons $(A-Z) = 2 \times Z - N$, where $N = 43 \pm 2$ are fissile (with some exceptions)

Potential fuel candidates

- The heavy elements with $90 \leq Z \leq 100$
  - Thorium (Th), Protactinium (Pa), Uranium (U), Neptunium (Np), Plutonium (Pu), Americium (Am), Curium (Cm), Berkelium (Bk), Californium (Cf), Einsteinium (Es) and Fermium (Fm)
- Lets apply the fissile rule to U ($2 \times Z - N$)
  - $(A\text{-}Z) = 2Z - (43 \pm 2)$
  - $(A\text{-}Z) = 2 \times 92 - [41, 42, 43, 44, 45] = [143, 142, 141, 140, 139]$ neutrons
  - So, U-231 through U-235 should be fissile

There are only four fissile nuclides that are practical for nuclear fuel

- U-235
  - Naturally occurs in uranium in small amounts (0.7%). Can be enriched
- Pu-239
  - Bred from U-238 by neutron capture

$$^{238}\mathrm{U} + n \xrightarrow{\gamma} {}^{239}\mathrm{U} \xrightarrow{\beta} {}^{239}\mathrm{Np} \xrightarrow{\beta} {}^{239}\mathrm{Pu}$$

- Pu-241
  - Bred from Pu-240 (which comes from Pu-239) by neutron capture

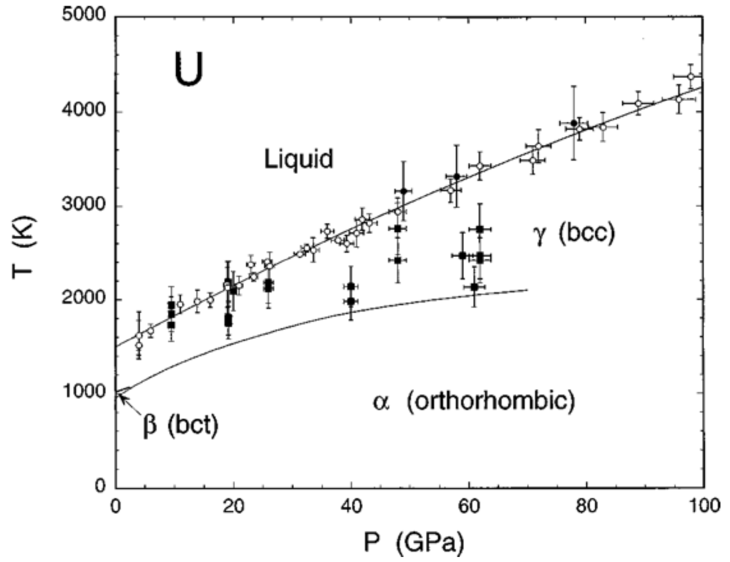
$$^{239}Pu + n \rightarrow {}^{240}Pu + n \rightarrow {}^{241}Pu$$

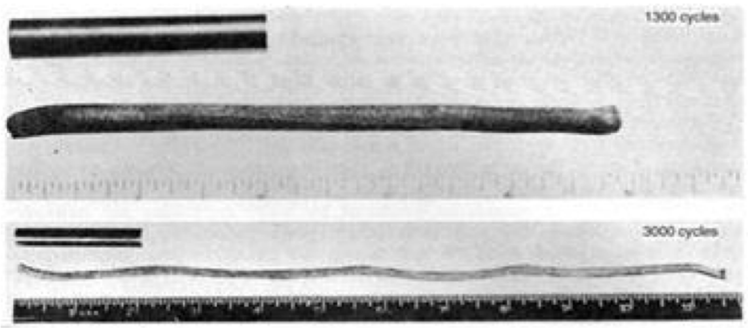
- U-233
  - Bred from Th-232 by neutron capture

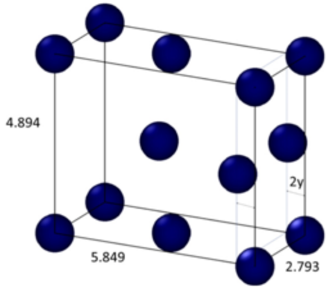
$$^{232}\mathrm{Th} + n \xrightarrow{\gamma} {}^{233}\mathrm{Th} \xrightarrow{\beta} {}^{233}\mathrm{Pa} \xrightarrow{\beta} {}^{233}\mathrm{U}$$

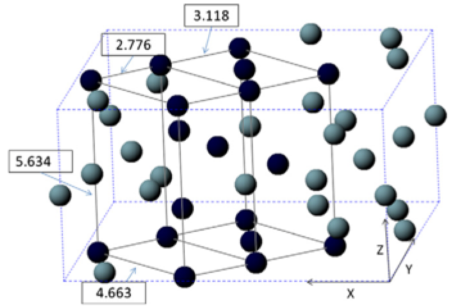
Why not use pure uranium metal?

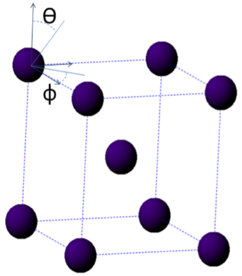
- Pure uranium has three phases
  - α-phase is orthorhombic
  - β-phase is tetragonal
  - γ-phase is body-centered cubic
  - During thermal cycling, pure uranium dramatically swells
  - Alpha U has both anisotropic thermal expansion and anisotropic irradiation growth











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

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

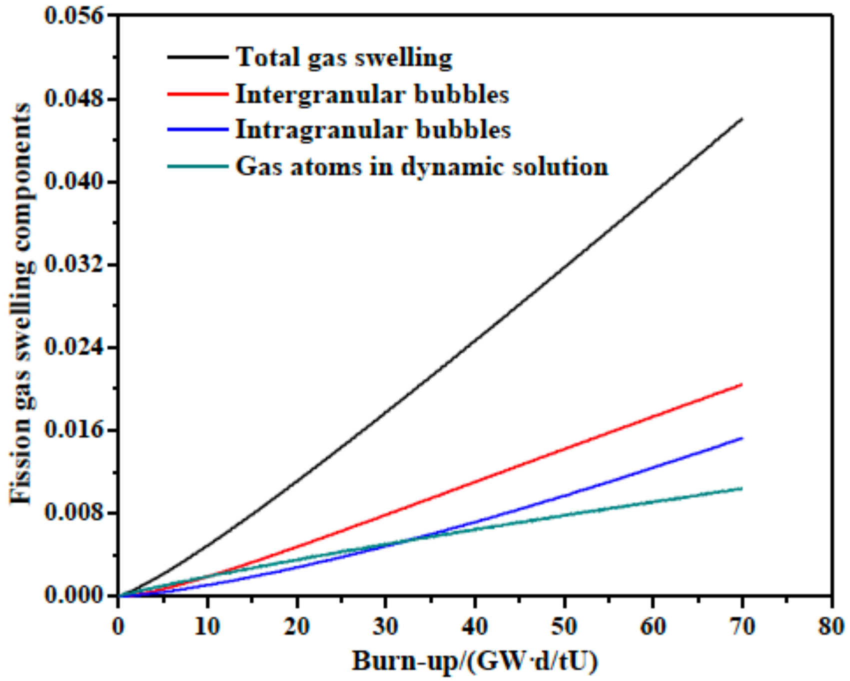
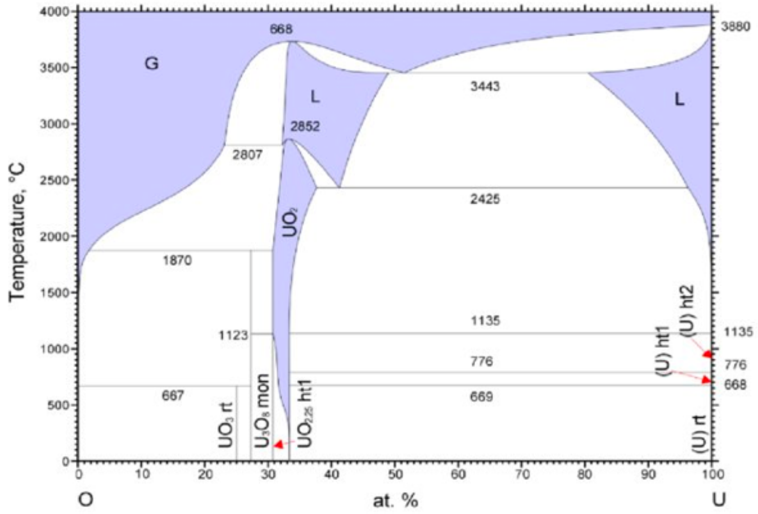
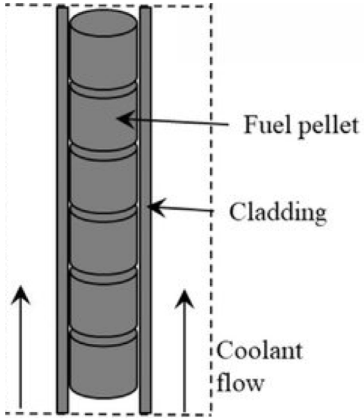


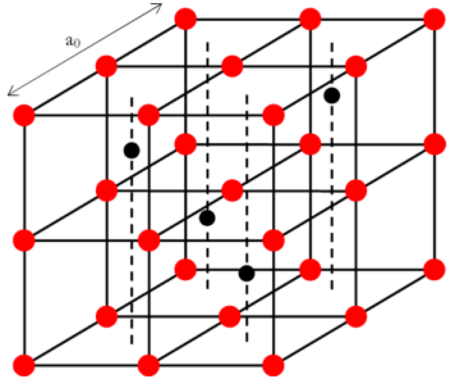
Fig. 4. Variation of swelling rate components of fission gas in UO_2 fuel with the burn-up.

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

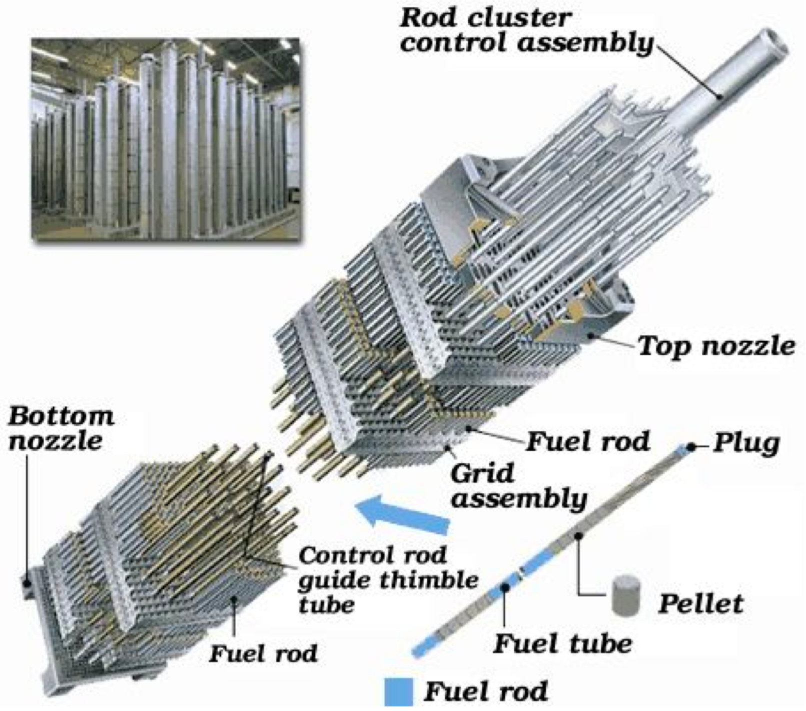






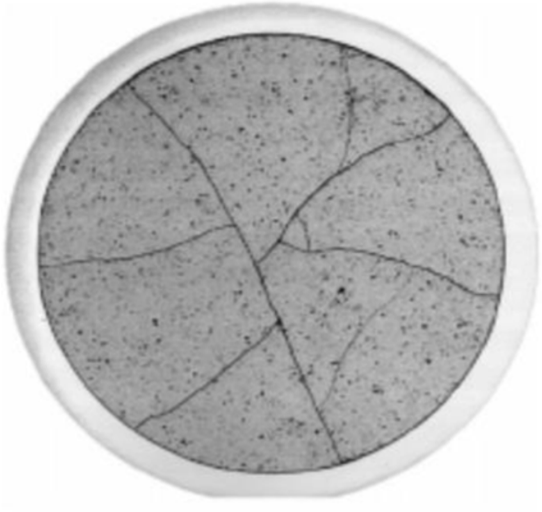
Uranium Dioxide (UO2)

- Good!
  - 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!
  - 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



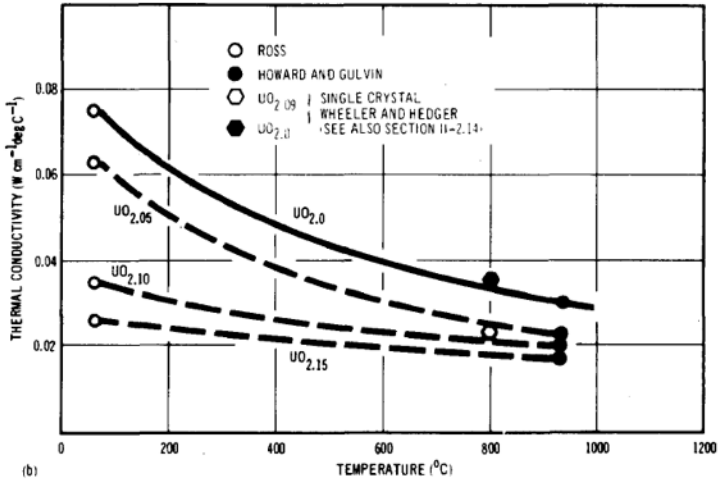
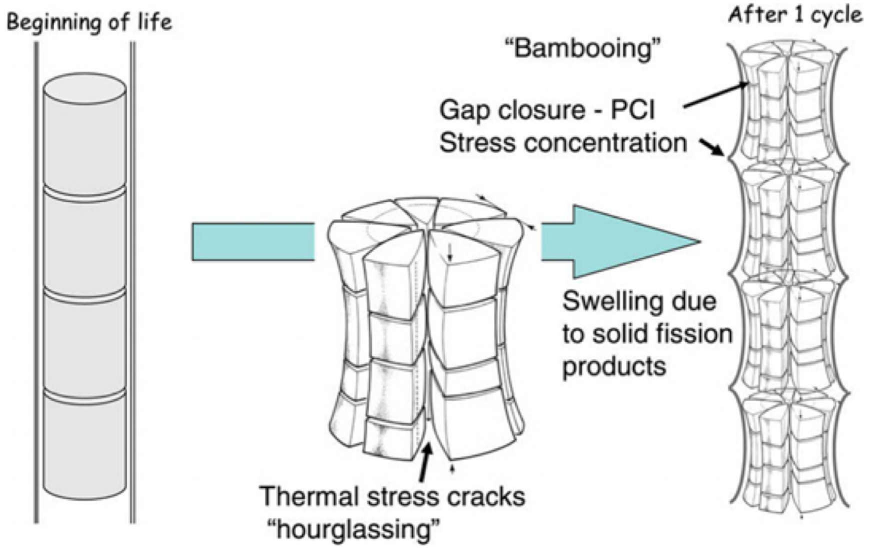
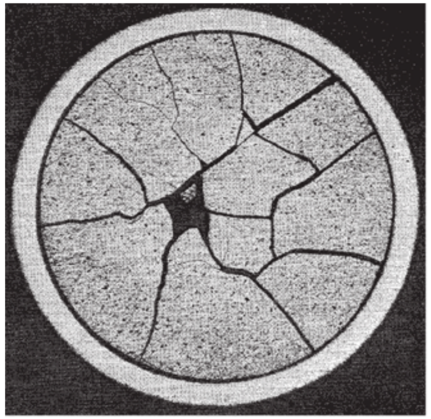


Fig. 9. Effect of hyperstoichiometry on conductivity.

Uranium Dioxide (UO2)

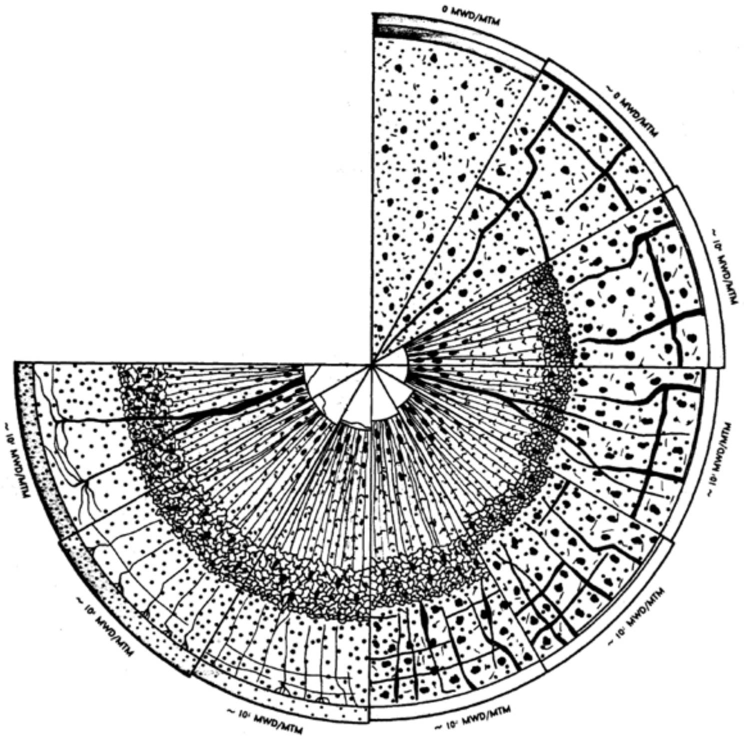
- Critical Phenomena
  - Thermal conductivity (and degradation)
  - Fission gas release, leading to pressure increase inside the cladding
  - Fuel fragmentation and relocation under transients
  - Bambooing creating stress concentrations
- All 98 operational reactors in US utilize UO2





Mixed Oxides (MOX)

- Can be combined with PuO2 for a mixed oxide (MOX) fuel for use in fast reactors
- Allows to burn excess weapons grad plutonium
- About 30 reactors in Europe currently utilize a partial MOX core
- Similar behavior to UO2, but different neutronics, fission gas release, thermal conductivity, etc.
- Less common is inclusion of minor actinides in MOX to burn waste



Accident Tolerant Fuel/Advanced Technology Fuel

- Kept the acronym, changed the concept
- 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

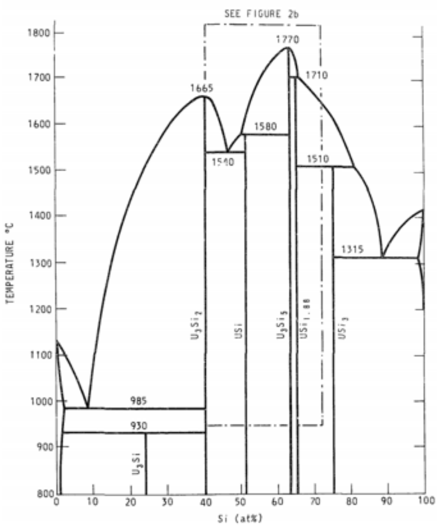
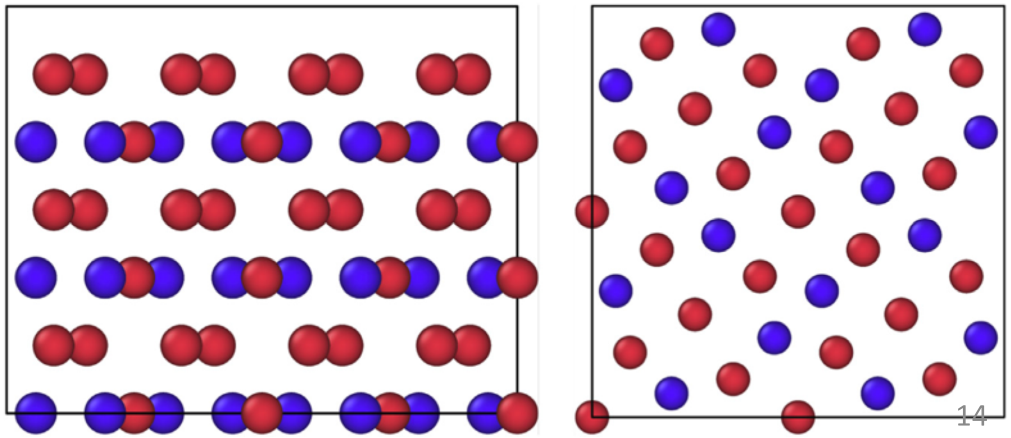
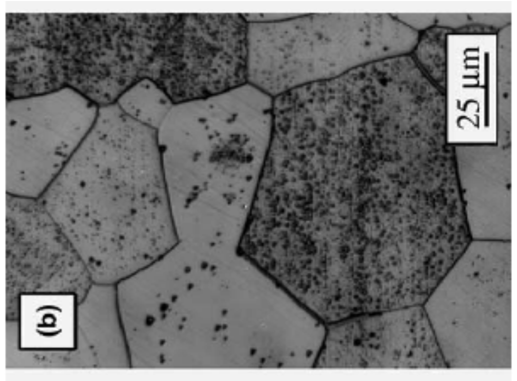


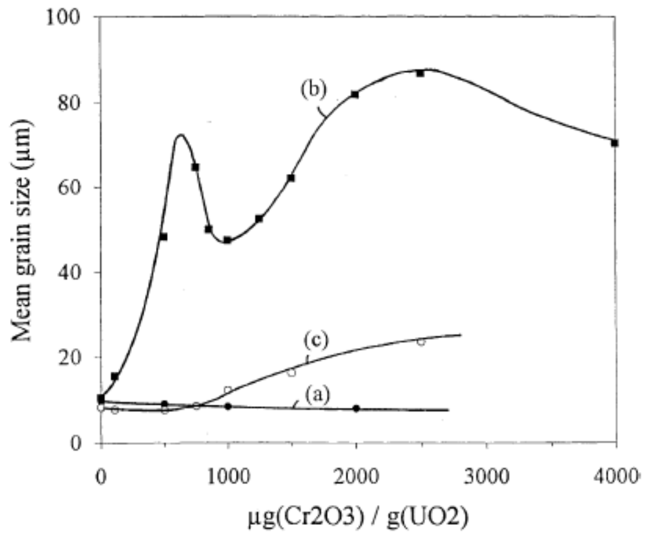
FIGURE 2 URANIUM SILICON EQUILIBRIUM DIAGRAM



Accident Tolerant Fuel/Advanced Technology Fuel

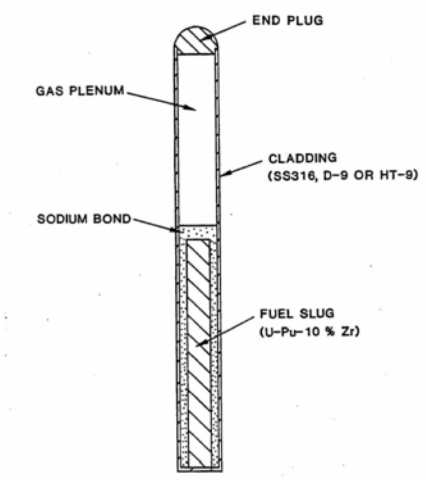
- Cr-doped UO2
  - Larger grain size, theoretically reduced fission gas release
  - Cr changes the O potential present within the fuel, changing defect concentrations and mobilities
- Coatings or alternate claddings – FeCrAl or SiC
  - Improved radiation resistance, corrosion resistance, etc.

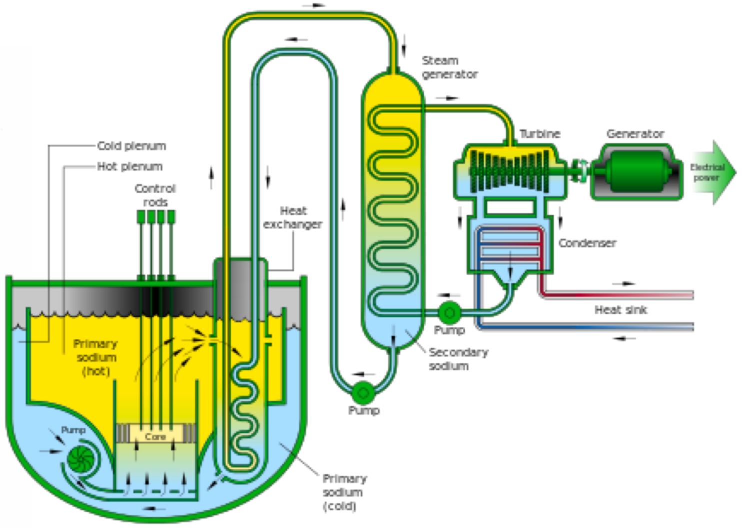




Uranium-Zirconium (UZr)

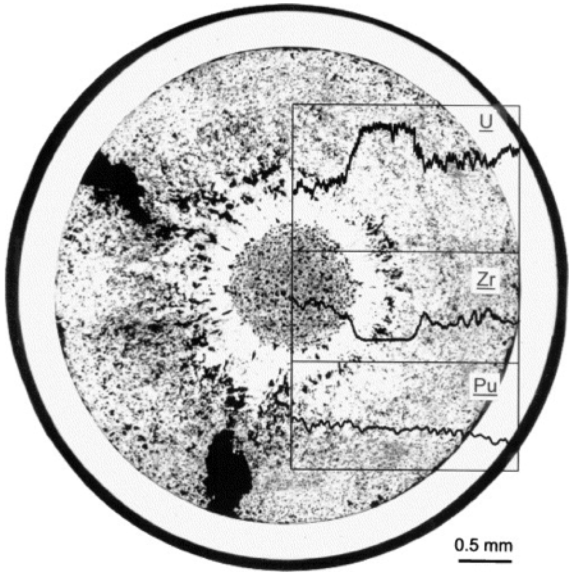
- Utilized in sodium cooled fast reactors (SFRs)
  - EBR I, EBR II
- Varied crystal structure and compositional environment
- Easily alloyed with Pu, minor actinides (MA)
- Can function as a breeder/burner fuel
- Sodium coolant
- Fe-based cladding

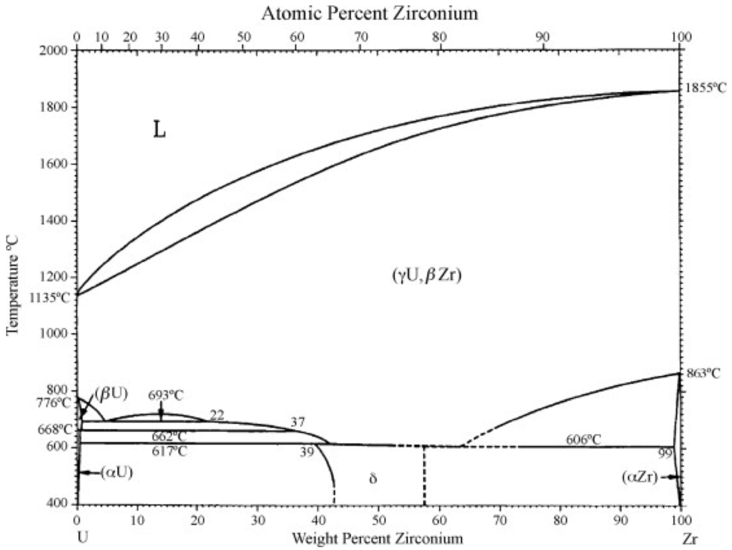




Uranium-Zirconium (UZr)

- 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



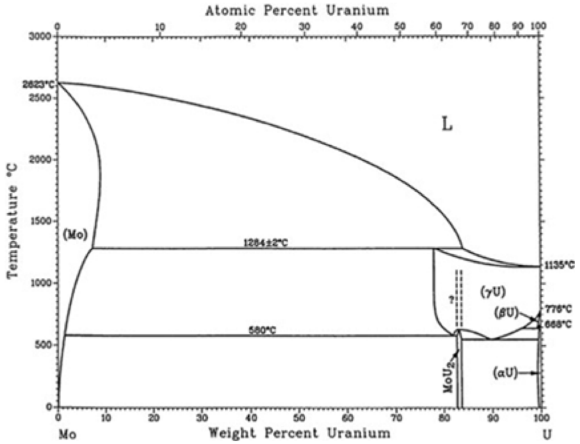


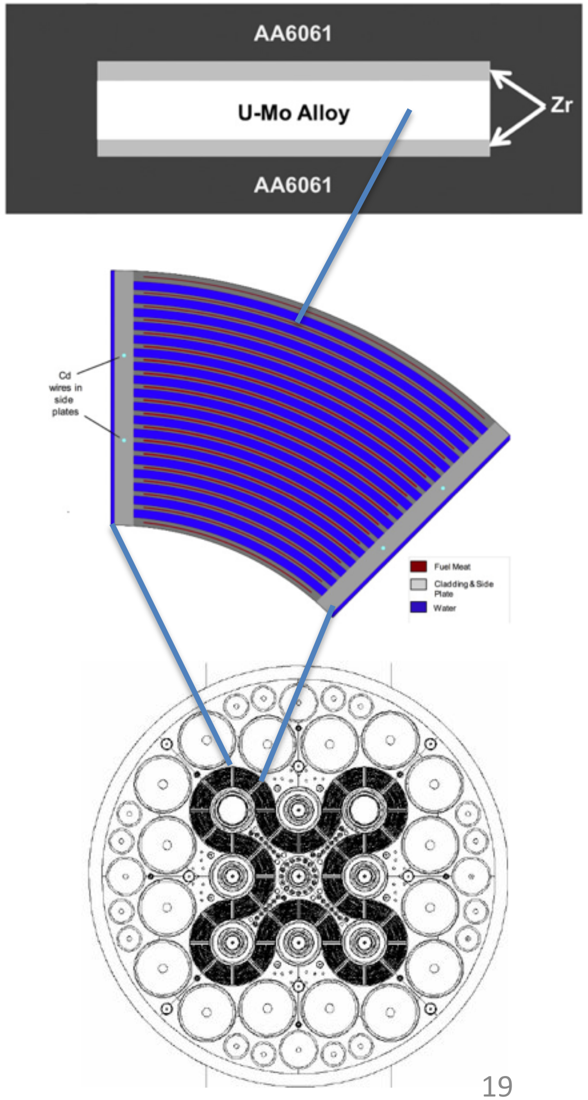
Uranium-Zirconium (UZr)

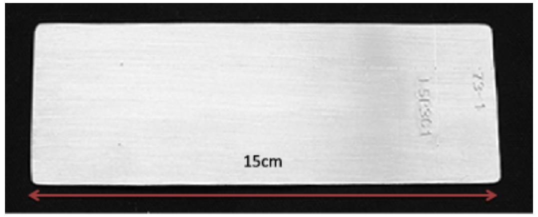
- Good!
  - High thermal conductivity
  - Stability to high burnups (> 20%)
  - Flexible composition
  - Inherent safety- negative reactivity feedback
  - Good compatibility with Na coolant
- Bad!
  - Low melting point
  - Dramatic fuel swelling that must be accounted for
  - Incredibly complex microstructures/unpredictable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

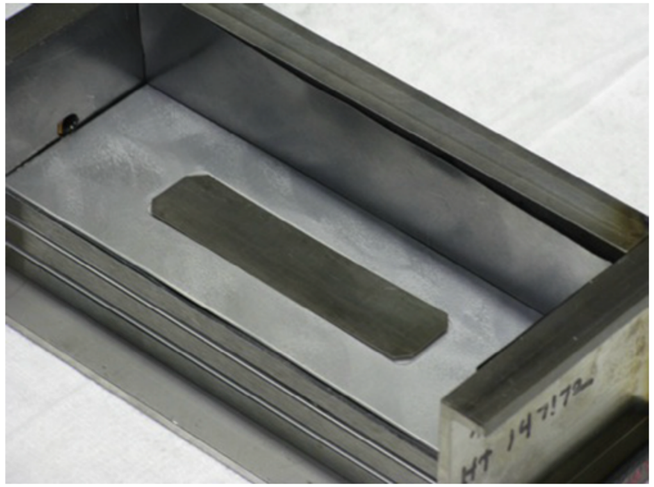
Uranium-Molybdenum (UMo)

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



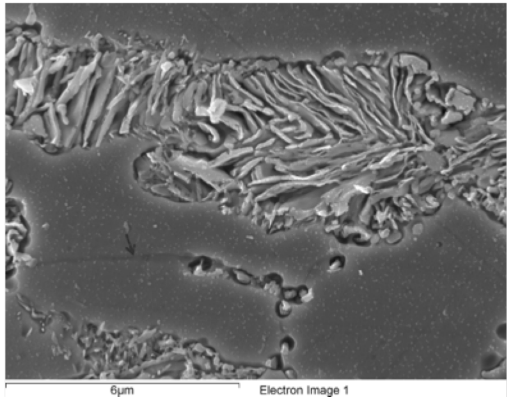


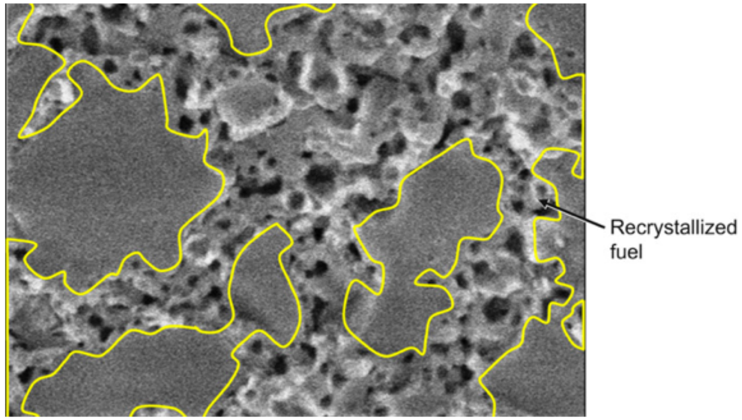


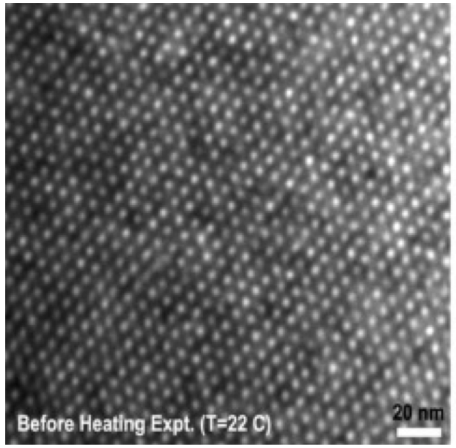


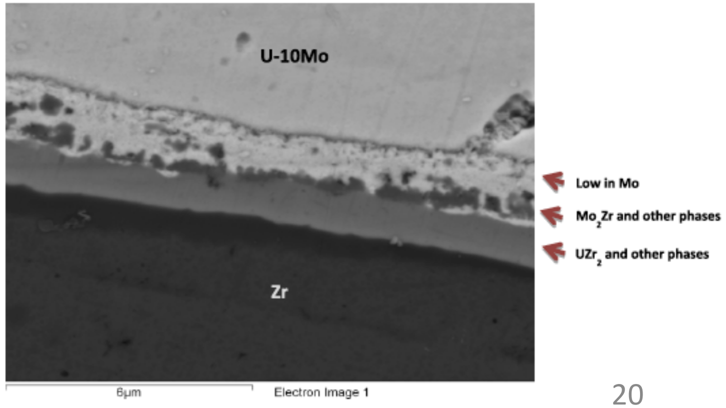
Uranium-Molybdenum (UMo)

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



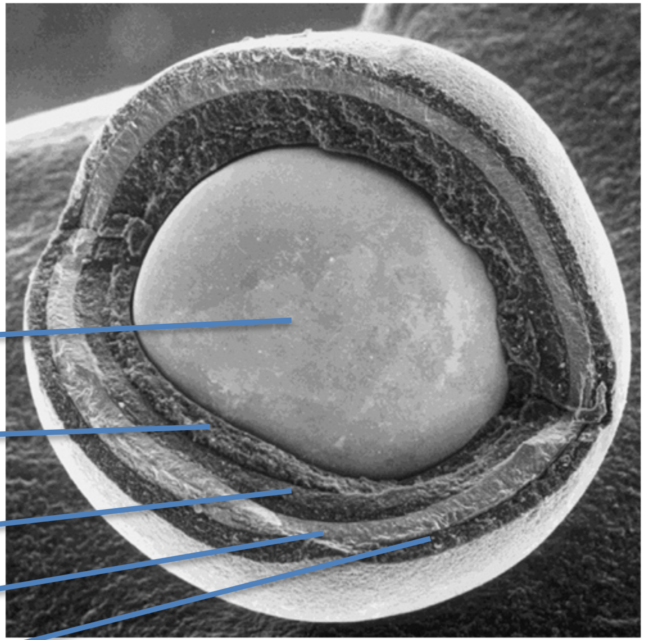






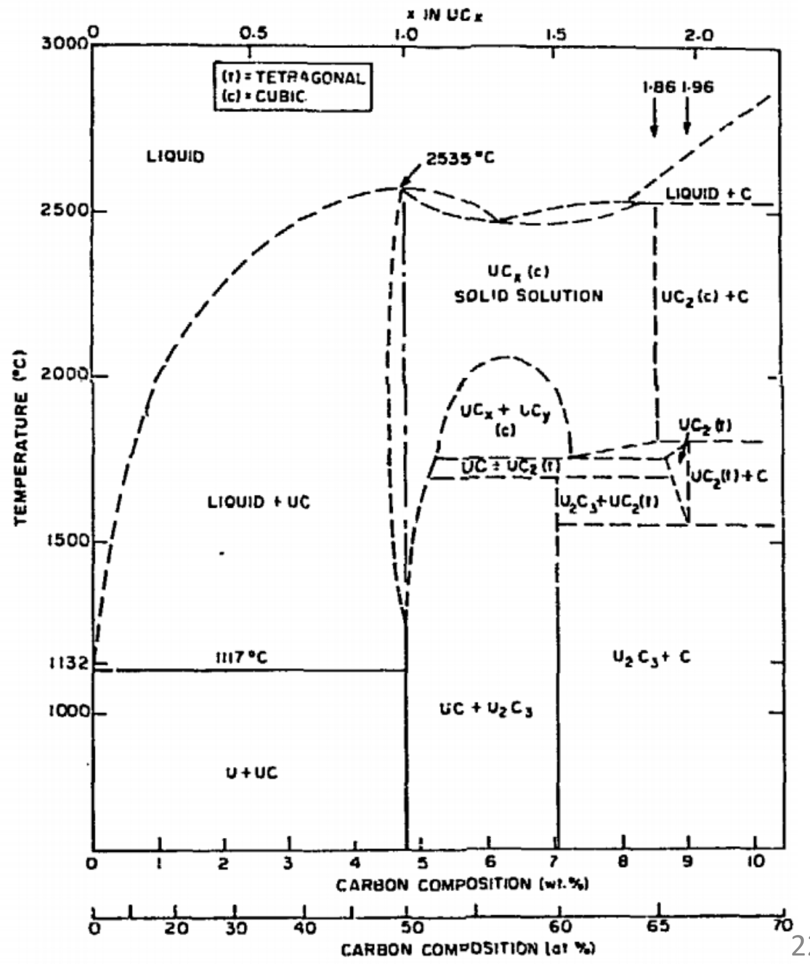
UC/UCO TRISO Fuels

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



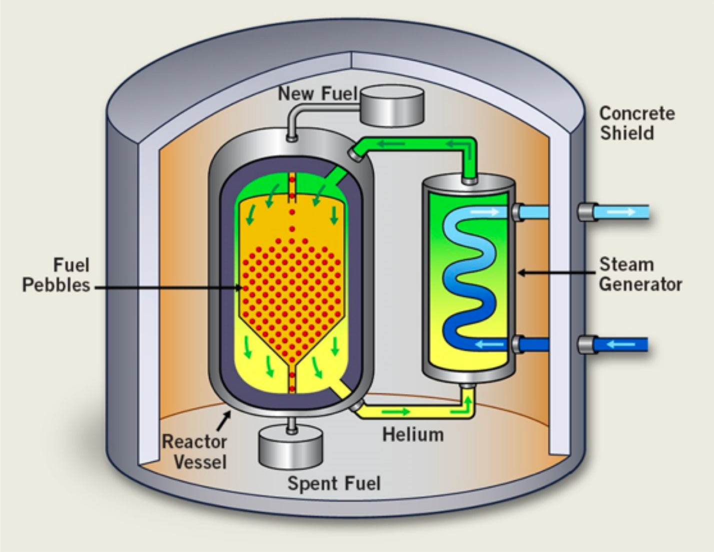
UC/UCO TRISO Fuels

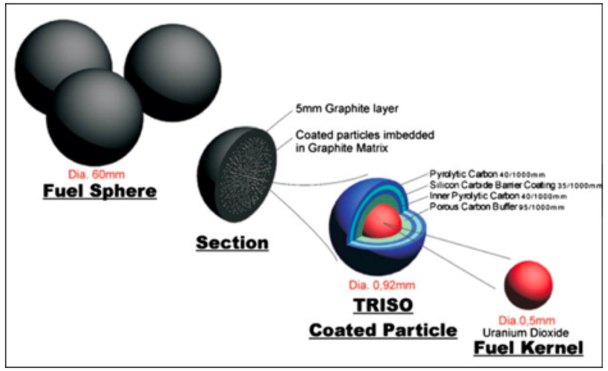
- Can appear as UC, U_2C_3, or UC_2
- Advantages
  - High thermal conductivity
  - High fuel density
  - Thermally stable
  - High melting temperature
- Disadvantages
  - Rapidly corrodes in water
  - Reacts with some cladding



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