Nuclear Fuel Performance

NE 533 Spring 2022

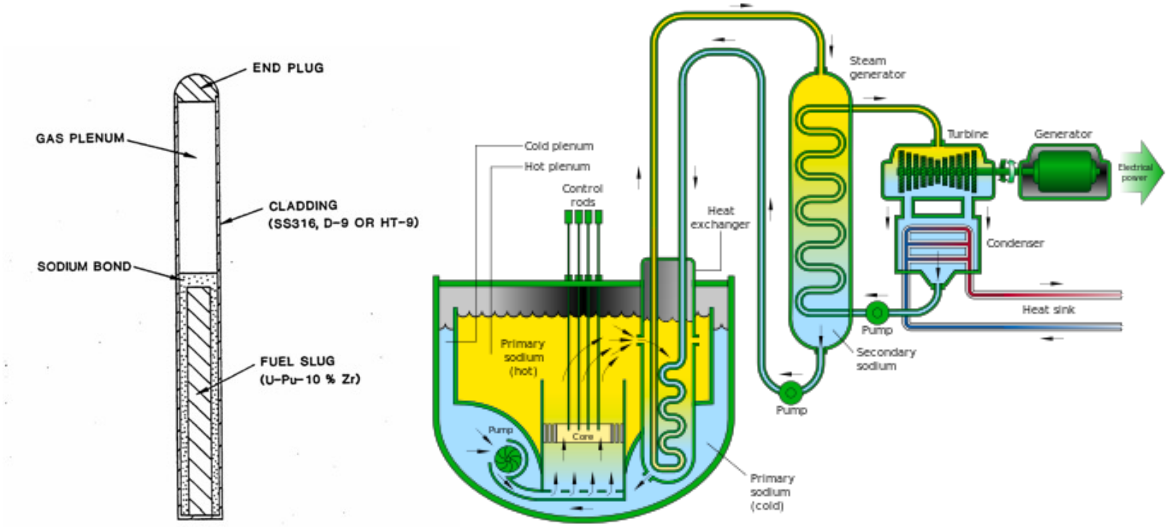
Last Time

- Basics of what fuel performance means
  - Transfer of heat to the coolant
  - Operation without outages
  - Performance during off-normal scenarios
- Intro to Nuclear Fuels
  - Considerations for fuels
  - Why not pure U?
  - Basics of UO2

FUEL TYPES CONTINUED

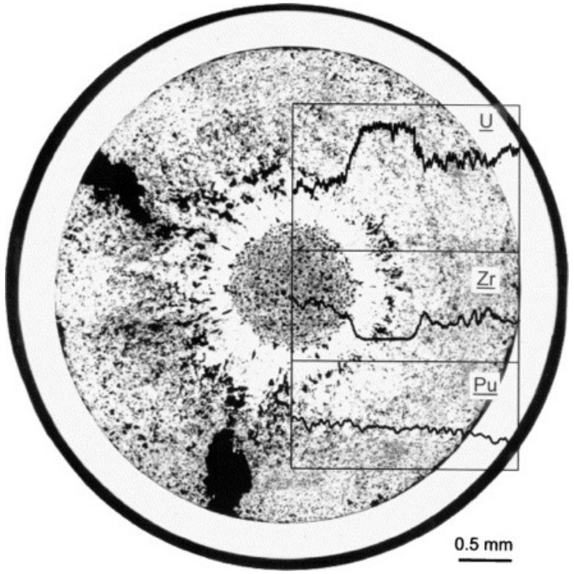
Uranium-Zirconium (UZr)

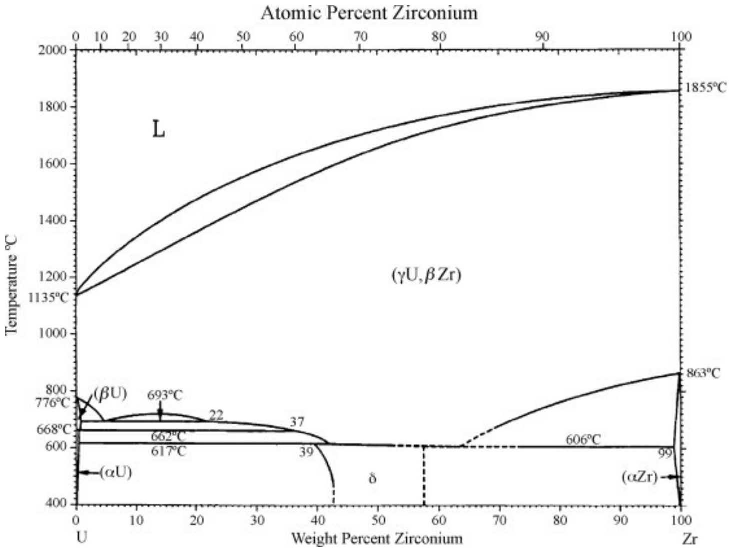
- Utilized in sodium cooled fast reactors (SFRs)
  - EBR I, EBR II
- Varied crystal structure and compositional environment
- Easily alloyed with Pu, minor actinides (MA)
- Can function as a breeder/burner fuel
- Sodium coolant
- Fe-based cladding



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





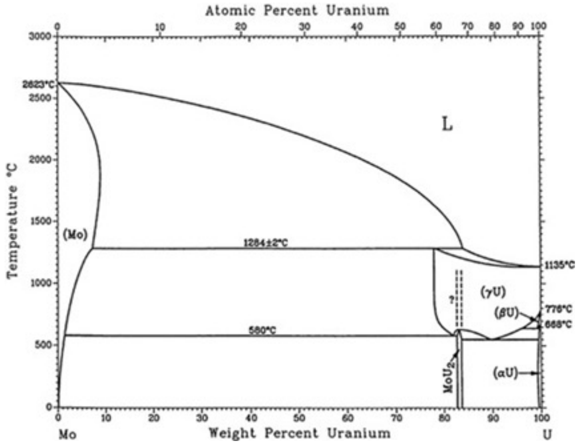
Uranium-Zirconium (UZr)

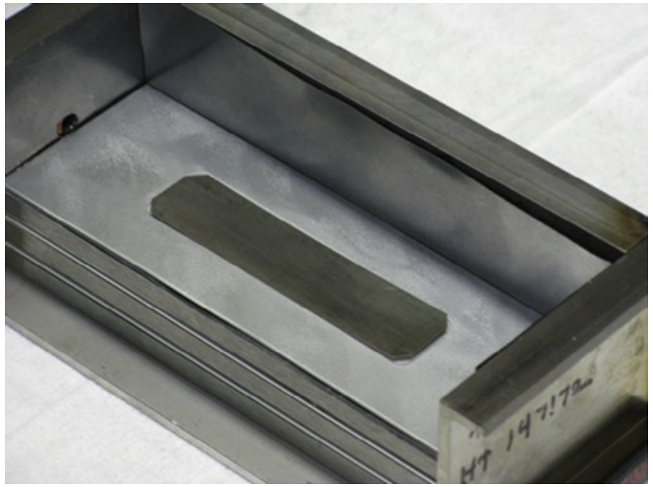
- Good Characteristics
  - High thermal conductivity
  - Stability to high burnups (> 20%)
  - Flexible composition
  - Inherent safety- negative reactivity feedback
  - Good compatibility with Na coolant

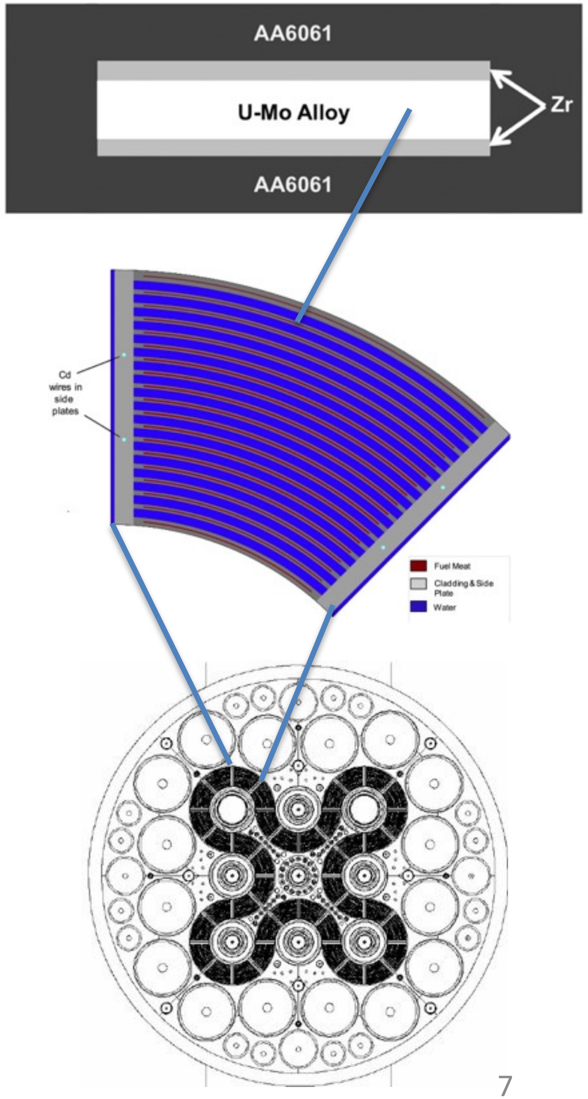
- Bad Characteristics
  - Low melting point
  - Dramatic fuel swelling that must be accounted for
  - Incredibly complex microstructures/unpredictable behavior
  - Fuel-Clad Chemical Interaction
  - Very easily oxidized

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

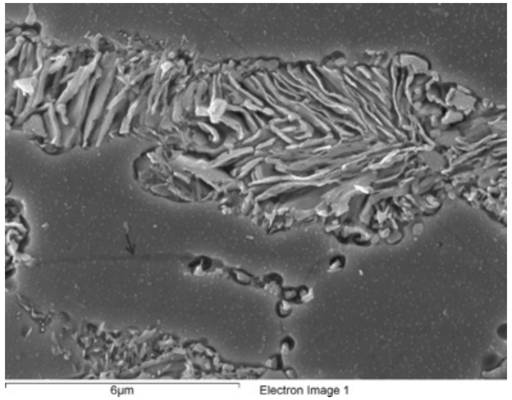


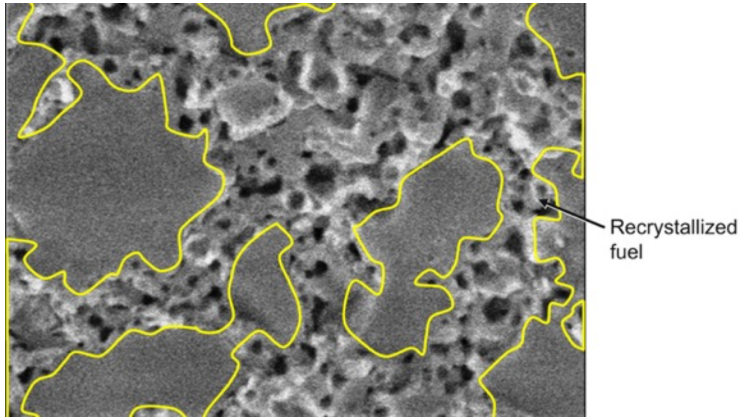


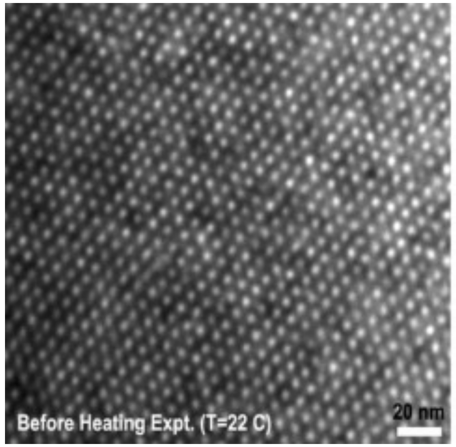


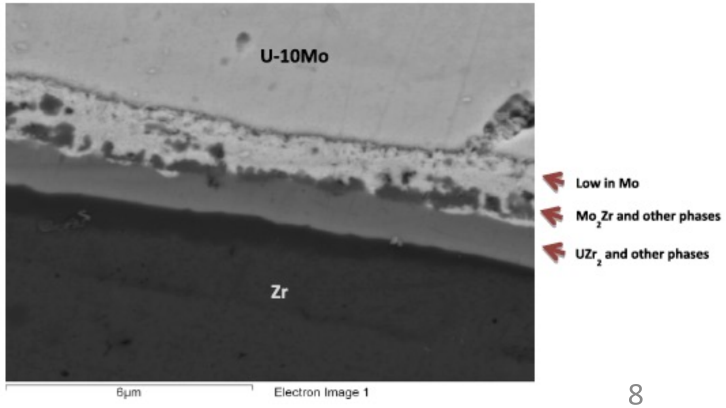
Uranium-Molybdenum (UMo)

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



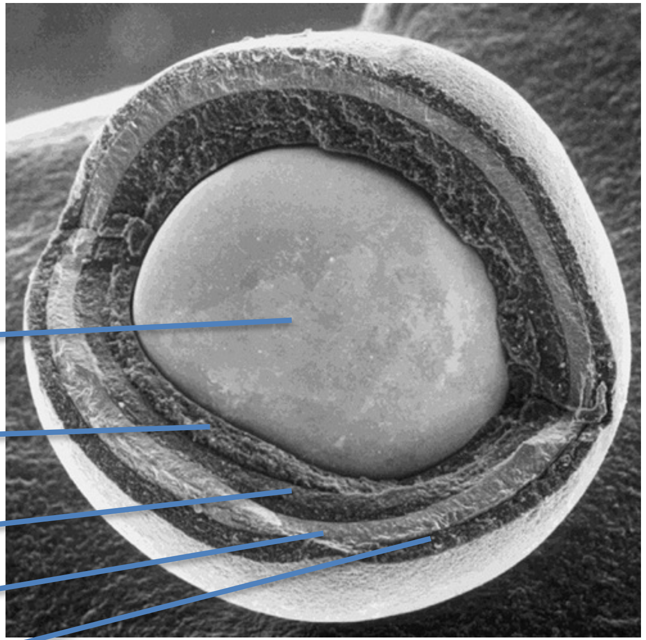






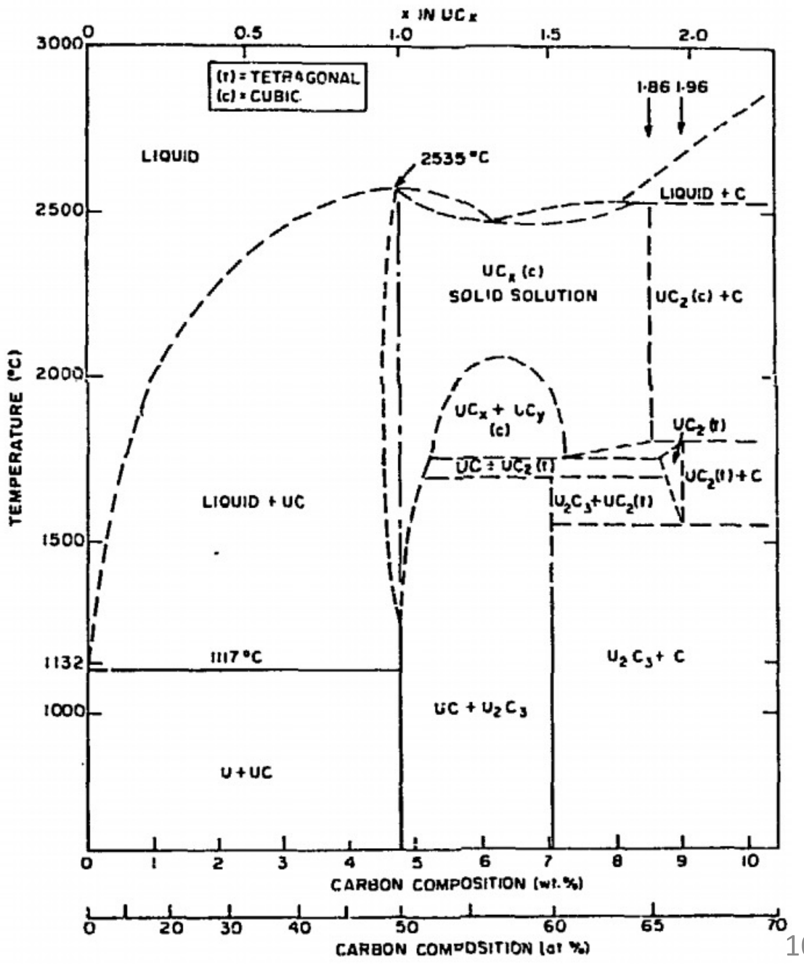
UC/UCO TRISO Fuels

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



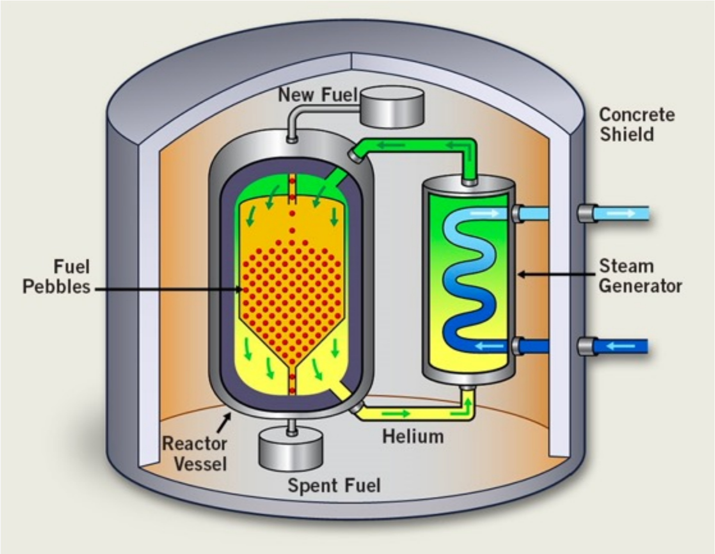
UC/UCO TRISO Fuels

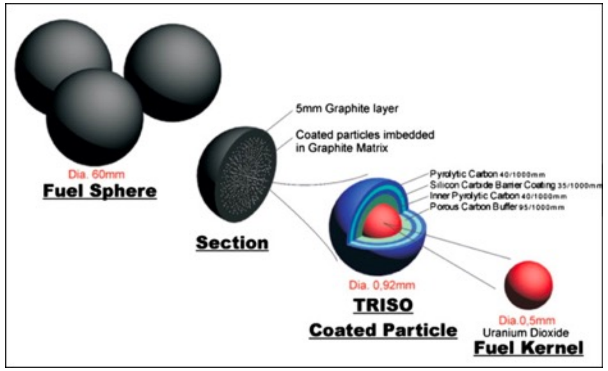
- Can appear as UC, U_2C_3, or UC_2
- Advantages
  - High thermal conductivity
  - High fuel density
  - Thermally stable
  - High melting temperature
- Disadvantages
  - Rapidly corrodes in water
  - Reacts with some cladding



UC/UCO TRISO Fuels

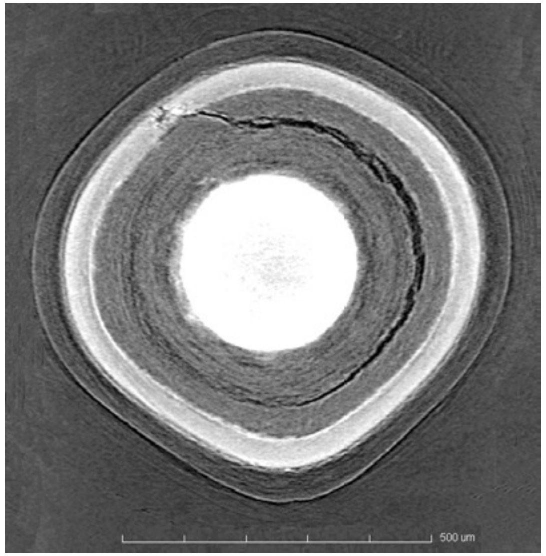
- High temperature gas reactors (HTGR) or molten salt reactors (MSRs)
- Pebble bed and prismatic types
- Particles are agglomerated with graphite into a larger pebble, or into a cylindrical block
- Current designs utilize UCO, which is a heterogeneous mixture of UO2 and UC fuel
- Helium cooled gas or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

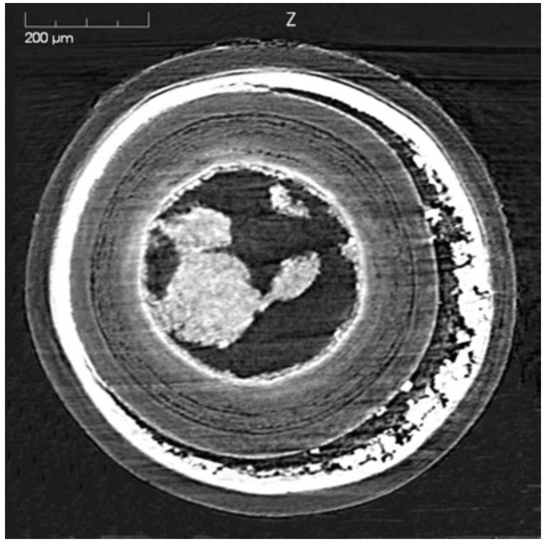




UC/UCO TRISO Fuels

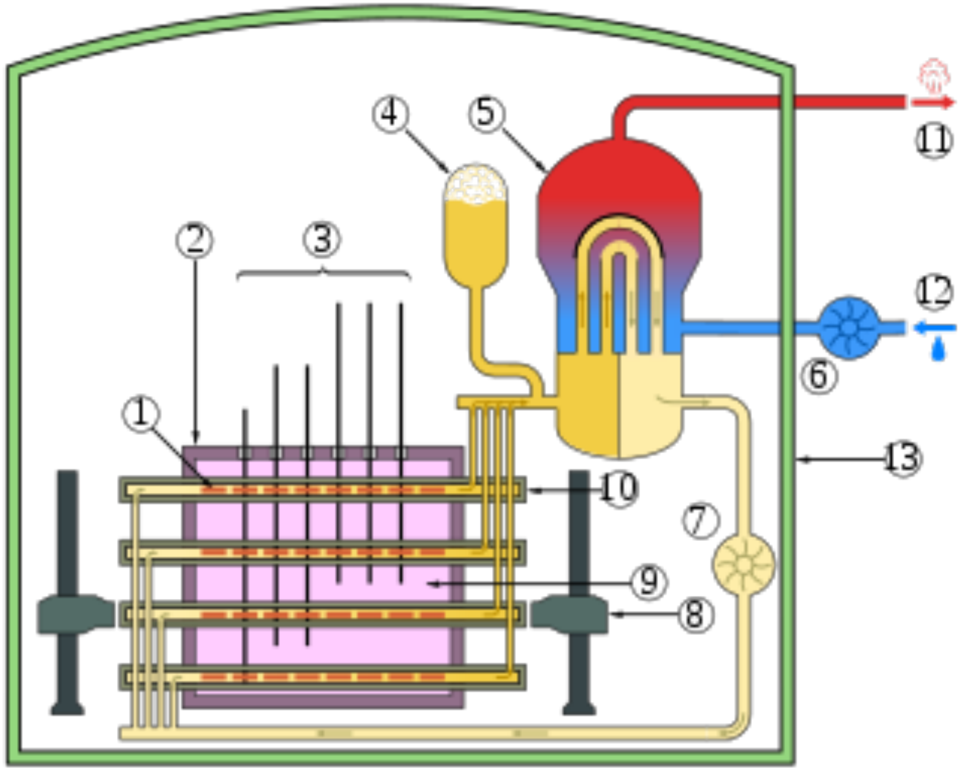
- Each individual pebble acts as its own containment, and allows fuels to go to much higher burnups and higher temperatures than UO2
- Highly reliant on accurate fabrication processes that create high integrity, uniform layers and spherical particles
- Integrity of the SiC is key for fission product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





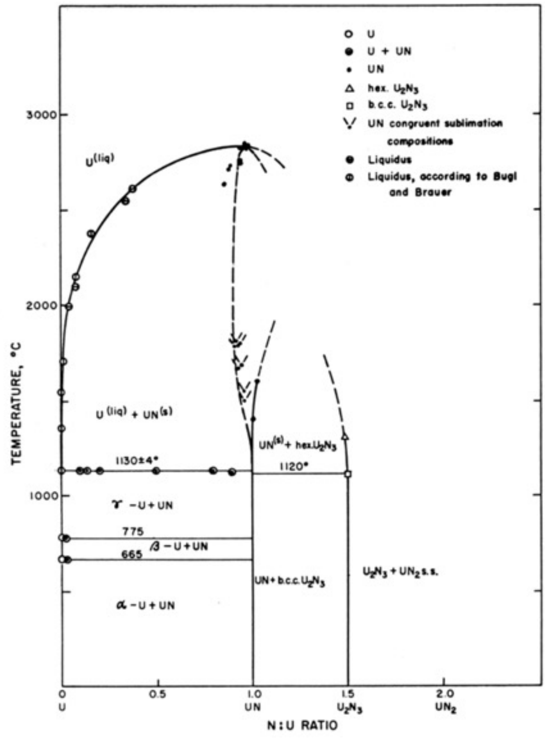
CANDU Reactors

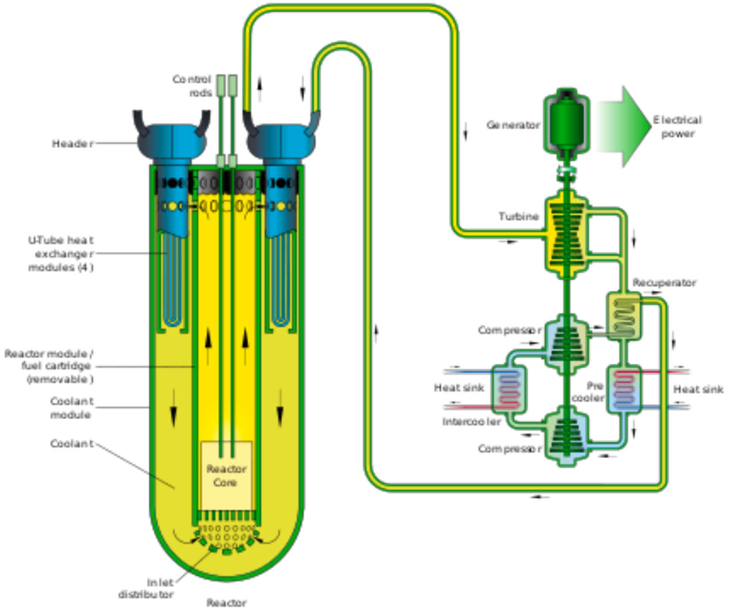
- Canada Deuterium Uranium: pressurized heavy water reactor
- Natural uranium, as UO2, as the fuel source
- Heavy water is the coolant, has a lower absorption of neutrons
- Fuel pins are horizontal, as opposed to vertical
- CANDU can be refueled online
- Removes costs associated with enrichment



UN – Lead Cooled Reactors

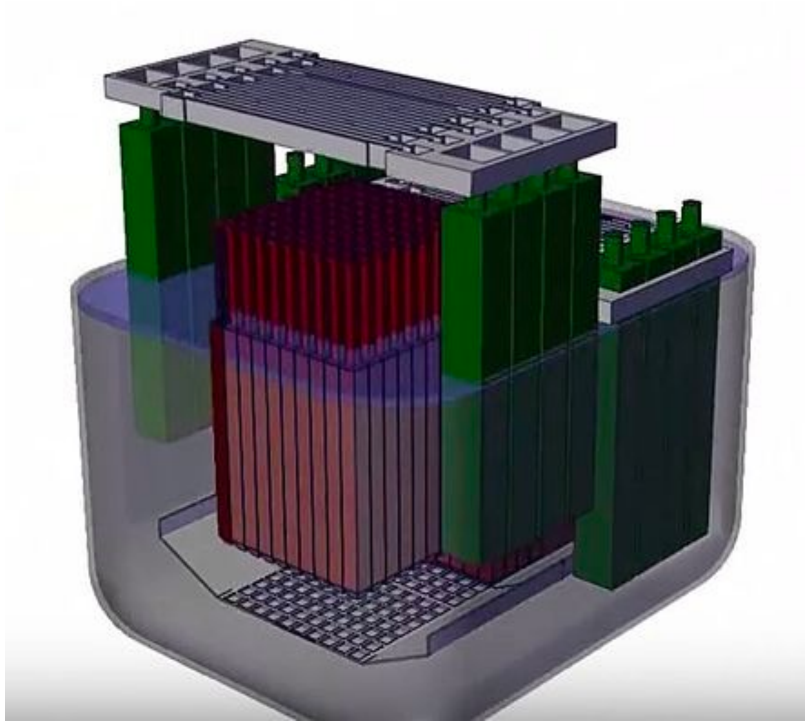
- Can appear as UN, U_2N_3, or UN_2
- Advantages
  - High thermal conductivity
  - High fuel density
  - Thermally stable
  - High melting temperature
- Disadvantages
  - Corrodes in water
  - Reacts with some cladding
  - Difficult to manufacture
  - Requires N-enrichment





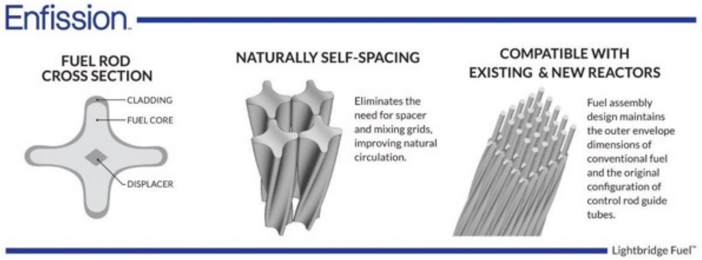
Stable Salt Reactor

- Utilizes fuel that is dissolved in molten salts
  - NaCl-(U/Pu)Cl3
  - Liquid fuel is contained in rods/assemblies
  - 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

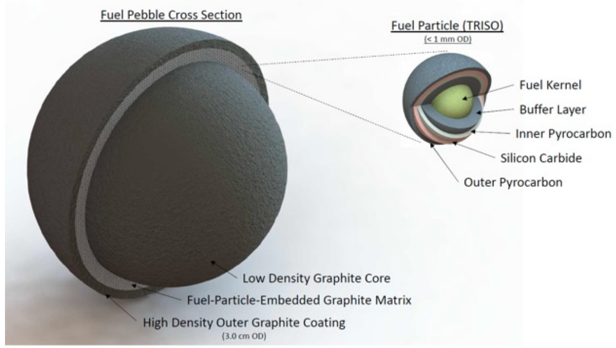


Unique Fuel Designs

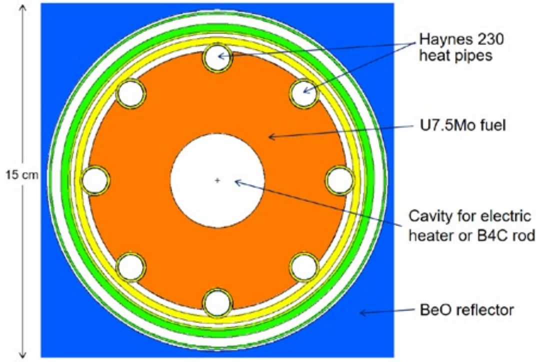
- Lightbridge
  - High Zr content UZr alloy
  - Cruciform geometry fuel rods, combined into fuel elements



- 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
- 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.

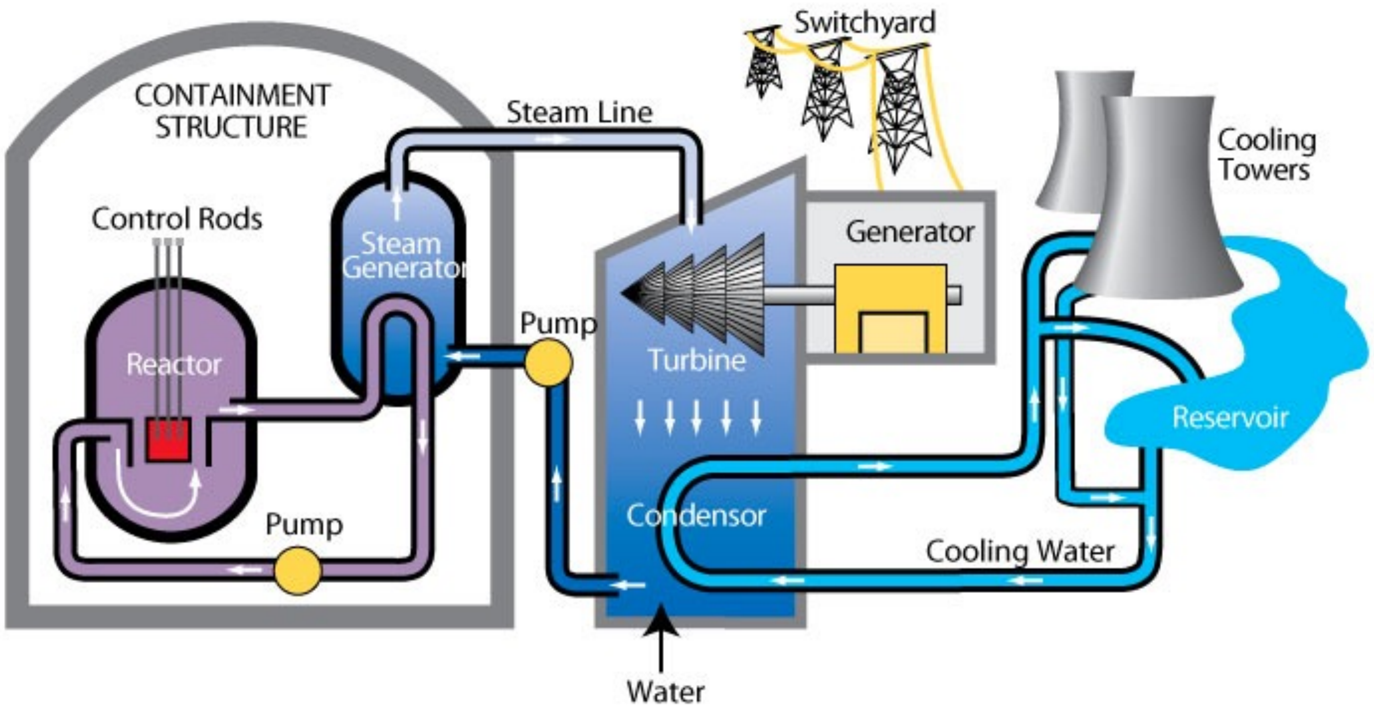
Summary

- 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

REACTOR SYSTEMS

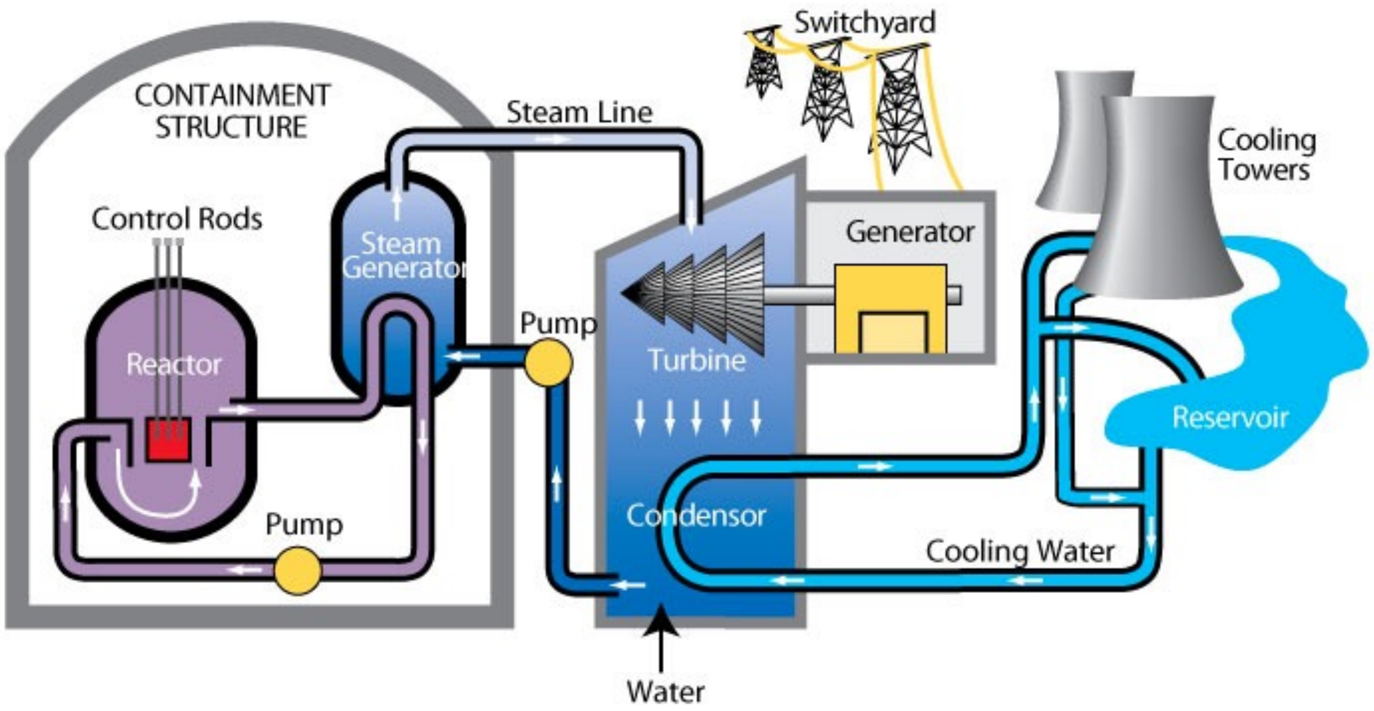
Heat removal systems

- Now we touch on how heat is removed from the fuel
- Primary mechanism to remove heat directly from fuel is a coolant
- Various coolant types, most common is water



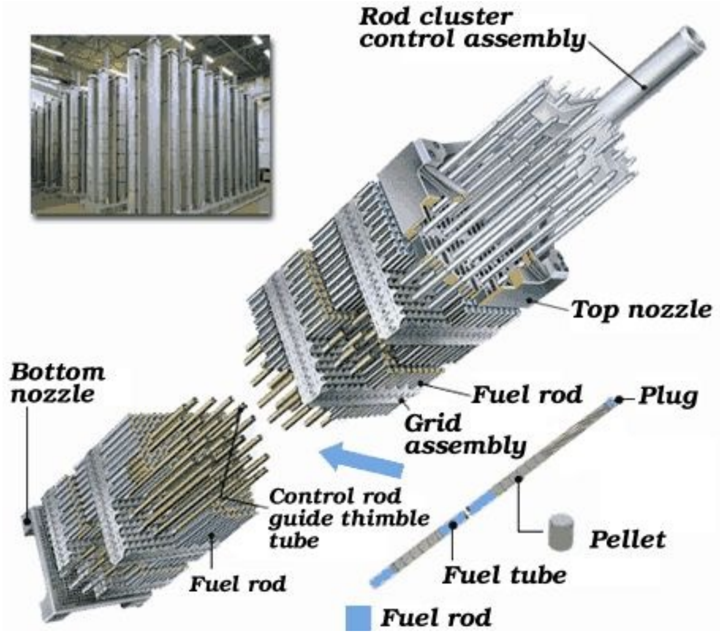
Heat removal systems

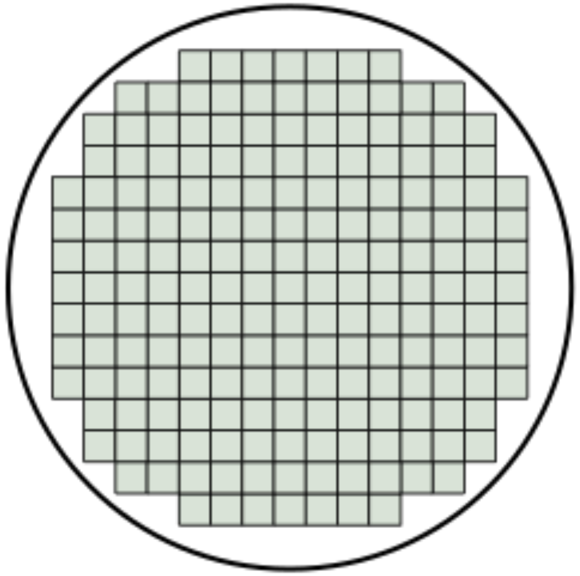
- Primary loop water runs through the core, transporting heat generated by the fuel, to a steam generator in a secondary water loop
- Steam drives a turbine, generating electricity
- A tertiary water loop helps to condense residual steam from the secondary loop via cooling towers and a water reservoir



Light Water Reactor Core Design

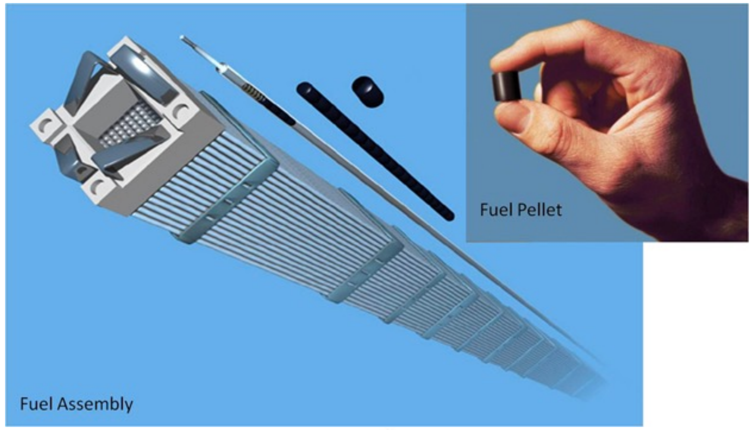
- An LWR core is comprised of fuel assemblies
- Each assembly contains a grid of fuel pins
  - In typical commercial LWR fuel designs, a 17x17 grid
  - Some pins are replaced by control rods
- Water flows from bottom to top

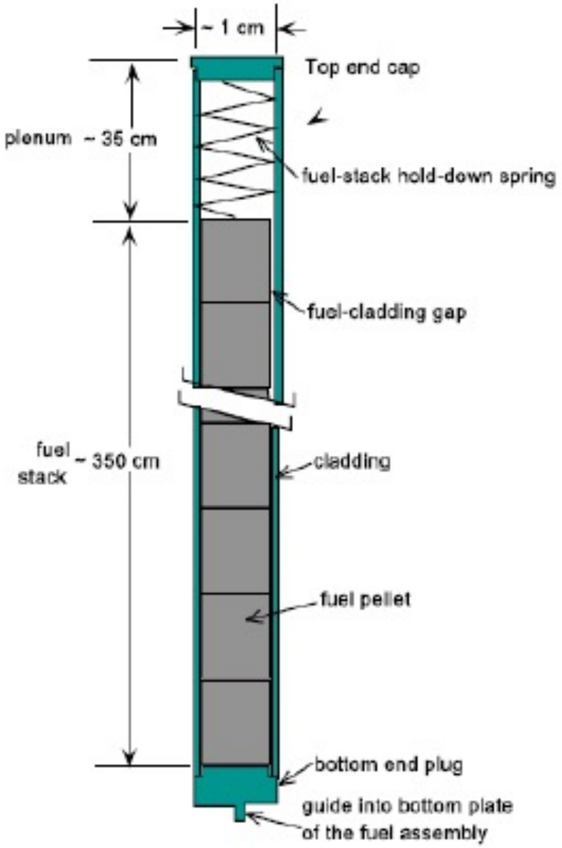




Westinghouse 4-loop PWR

LWR Fuel Pins

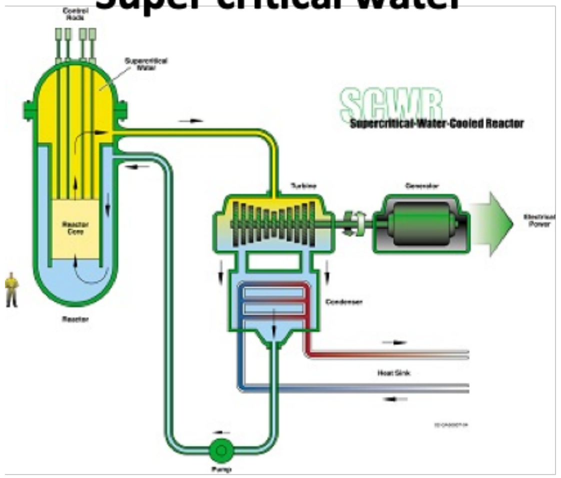




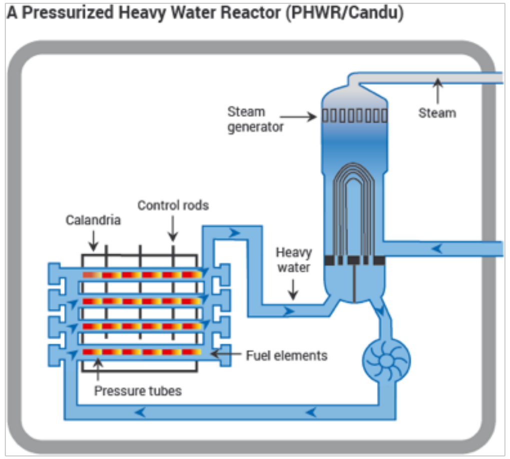
- LWR fuel pins are comprised of a hollow Zircaloy tube
  - This is the cladding
  - Zircaloy is a type of Zr alloy
- Inside the cladding are stacked UO2 pellets
- Each pellet is a cylinder about 1 cm in diameter and 1 cm in height

Not only water-cooled reactor designs

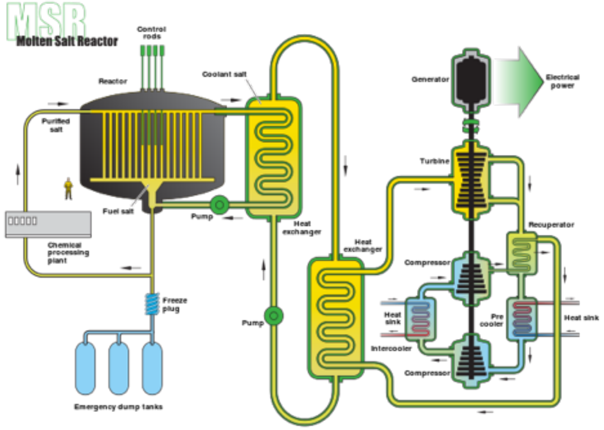
Super critical water



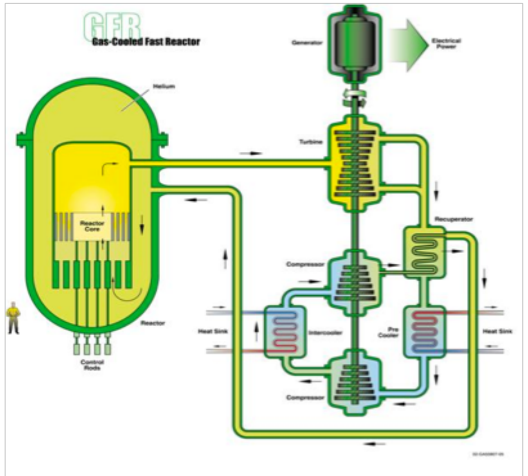
Heavy water



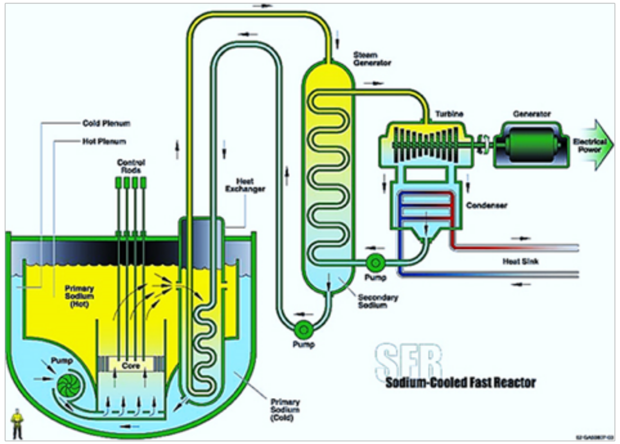
Molten salt



Gas

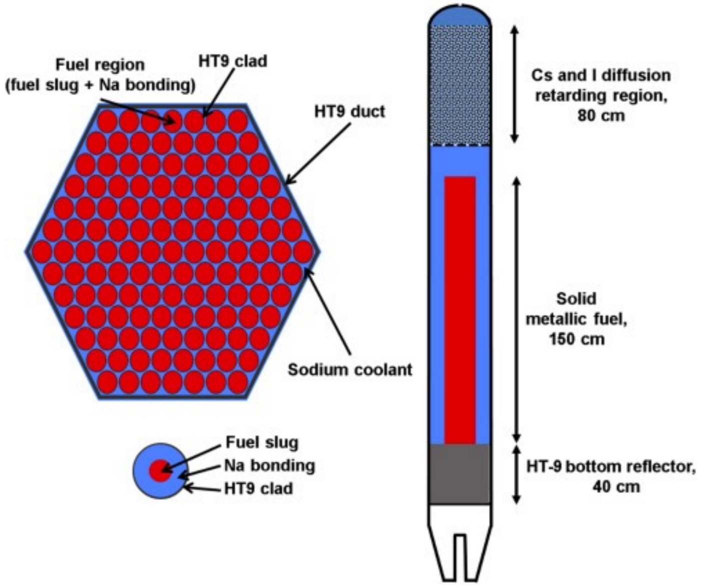


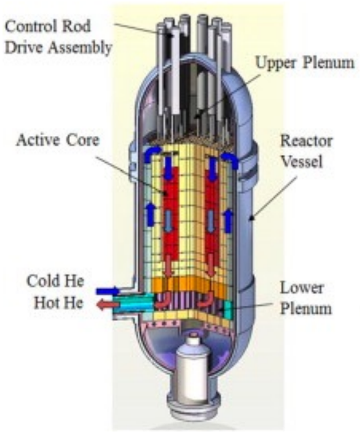
Liquid metal

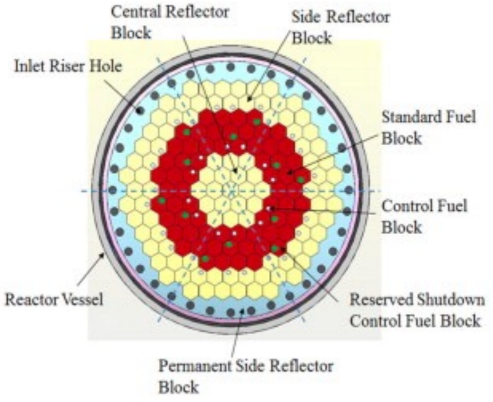


Not all fuel is pellet-based

- Metallic fuel is a solid fuel slug
  - Utilized an Fe-based cladding, such as HT-9 or SS
- TRISO particles are formed into spherical compacts, or can be formed into pellet compacts
- UMo and USi have been used in plate fuels
- Assemblies are often hex-shaped and can included reflectors

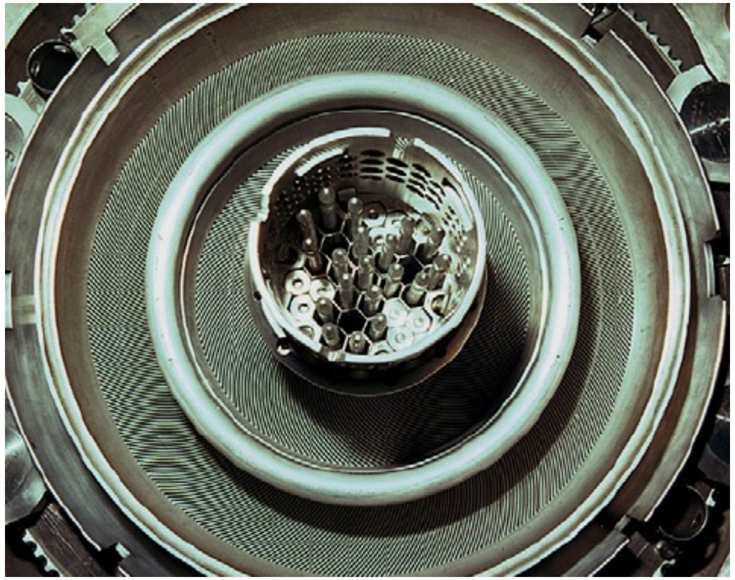




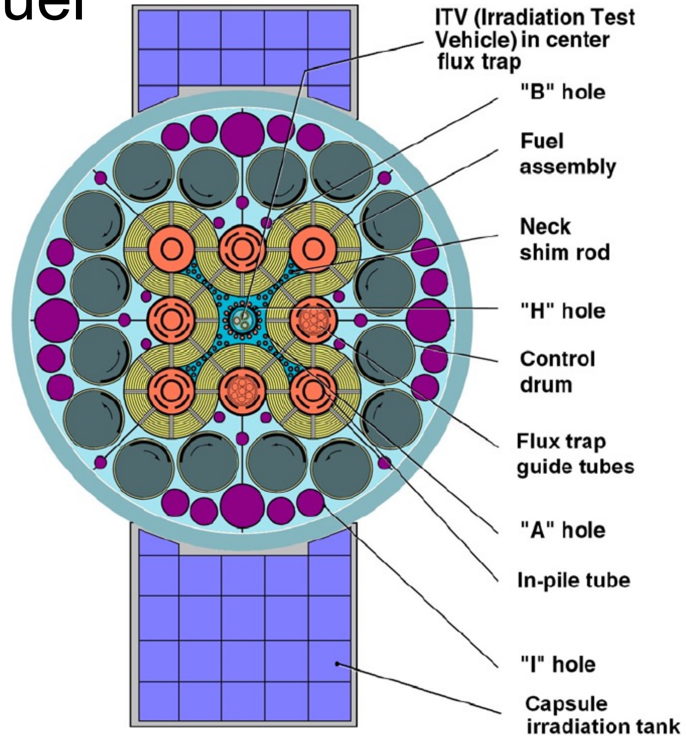


ATR and HFIR Core design

- HFIR combines curved plates in concentric regions



- The ATR core is a unique curved design with plate type fuel

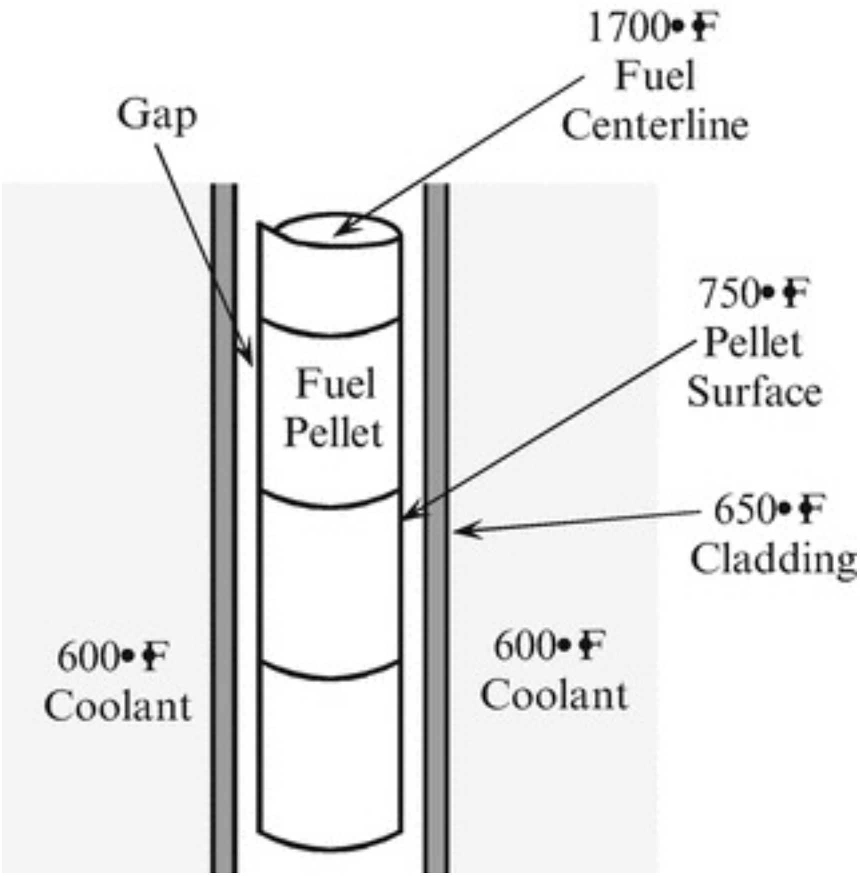


Most fuel designs employ some type of cladding

- The primary focus of the cladding is to separate the fuel from the coolant
  - Fuel contains radioactive fission products
  - Avoids corrosion of the fuel by the coolant
  - Keeps the fuel together, not blocking coolant flow
- The cladding should be thin and have a high thermal conductivity, so it doesn't trap any of the heat produced by the fuel
- Cladding should also be neutron transparent

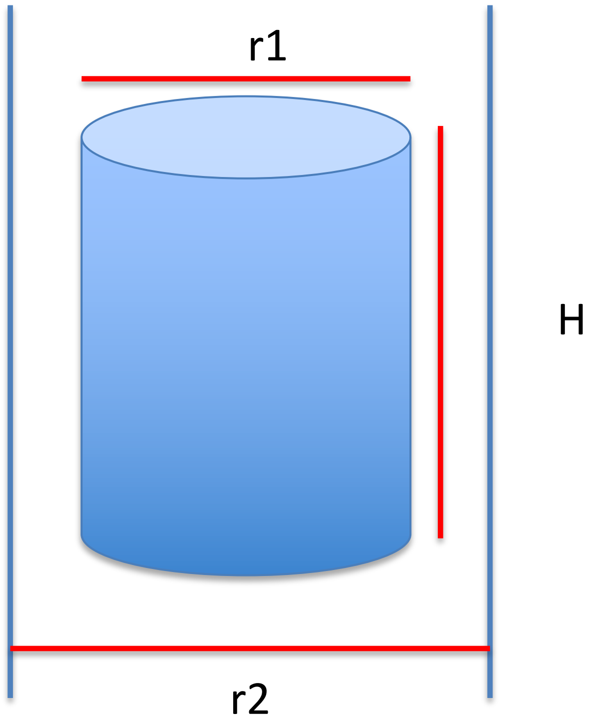
Fuel/Cladding Gap

- Fuel swells during reactor operation and the cladding creeps down around the fuel
- To avoid/limit both chemical and mechanical interaction, the pellet radius is smaller that the inner radius of the cladding
- In LWRs, the gap is filled with gas, significantly impacting the heat transport
- In metal fuels, the gap is filled with liquid sodium, so there is little impact on the heat transport



Smear Density

- Smear density is the ratio of fuel volume to total internal volume of the fuel element
- Cylinder volume = $\pi r^2 h$
- Smear density = $\pi r_1^2 h / \pi r_2^2 h$
- Smear density = r_1^2 / r_2^2
- Typical smear densities:
  - Oxides ~ 90+%
  - Metallic ~ 75%



Cladding material selection

- Cladding must be compatible with the coolant, reasonably compatible with the fuel, have good thermal conductivity and reasonable radiation resistance
- Zirconium is used because of its
  - Low neutron cross section
  - Corrosion resistance in 300 C water
  - Resistance to void swelling
  - Adequate mechanical properties
  - Good thermal conductivity
  - Affordable cost
  - Available in large quantities
- Other cladding materials in use include
  - Stainless steel
  - Silicon Carbide
  - Ferritic-Martensitic steels like Fe-Cr and Fe-Cr-Al
  - Oxide dispersion strengthened (ODS) ferritic steels

Molten Salt Reactors w/o cladding

- Some MSRs plan to utilize liquid molten salts as the fuel, flowing continuously through the core
- Secondary loop comprised of coolant salt, such as FLiBe
- Example was the MSRE from ORNL, which utilized LiF-BeF2-ZrF4-UF4 as the fuel
- Cladding is the flow piping