Fuel Types-continued

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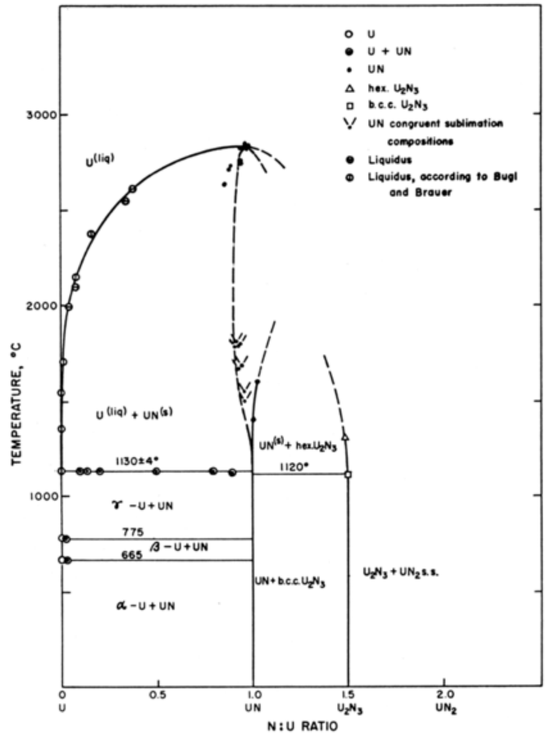
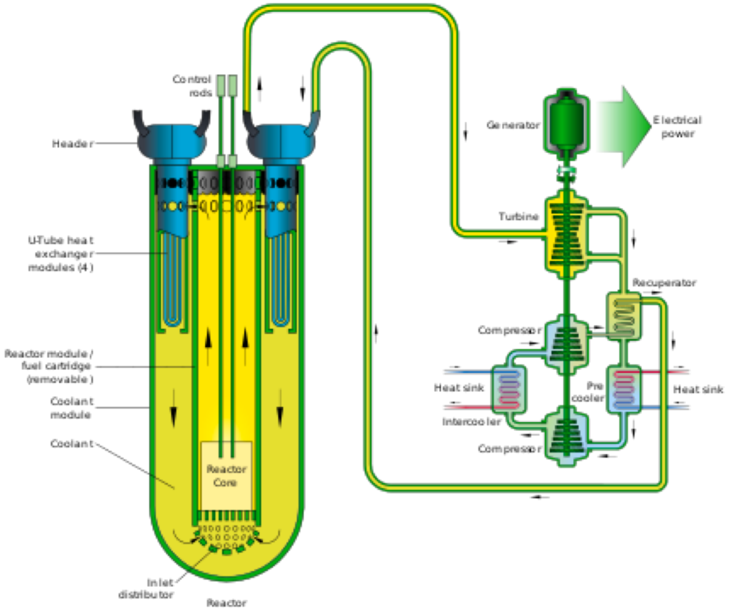
UN – Lead Cooled Reactors

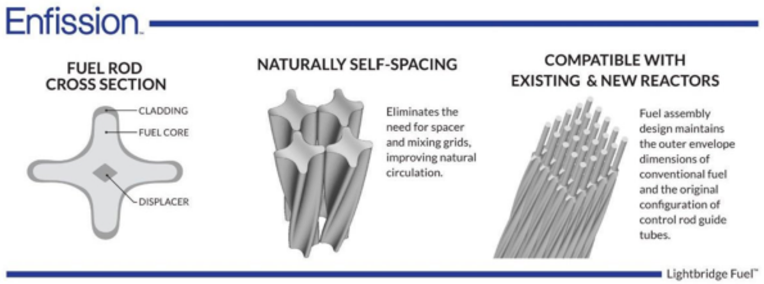
- Can appear as UN, U_2N_3, or UN_2
- Advantages
  - High thermal conductivity
  - High fuel density
  - Thermally stable
  - High melting temperature
- Disadvantages
  - Corrodes in water
  - Reacts with some cladding
  - Difficult to manufacture
  - Requires N-enrichment

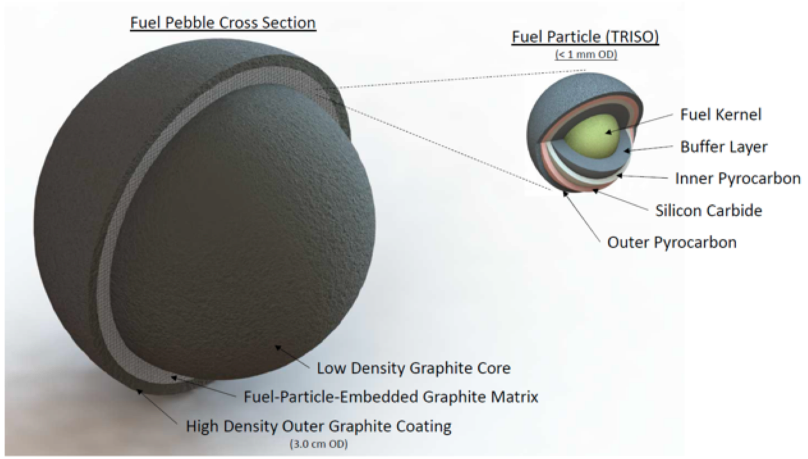




Unique Fuel Designs

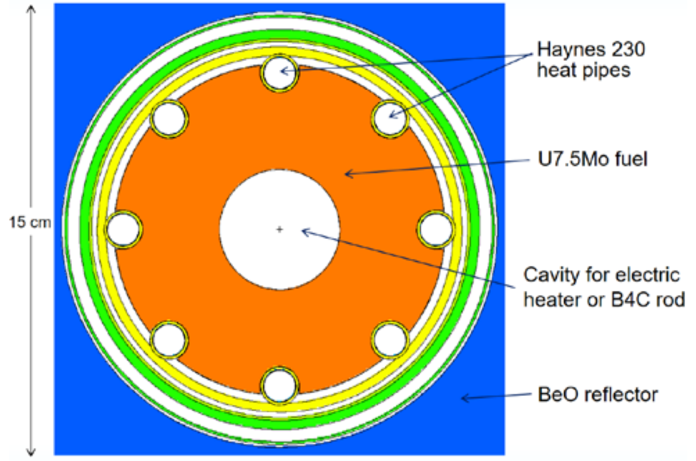
- Lightbridge
  - High Zr content UZr alloy
  - Cruciform geometry fuel rods, combined into fuel elements
- Kairos
  - TRISO particle compacts with low density core
  - Float in molten salt coolant for online refueling





Unique Fuel Designs

- NASA/LANL
  - UMo fuel for space reactors: KRUSTY
- Stable Salt Reactor (SSR)
  - Dissolved molten salt fuel
  - NaCl-U-Pu-stuff



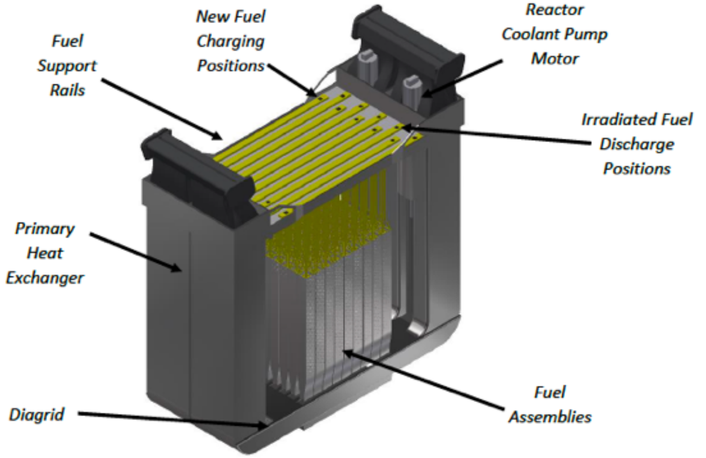


Figure 6: Overview of Stable Salt Reactor Core Module

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/cm³)	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.

Questions/Comments/Summary

- Primary purpose of fuel is heat source
- Uranium is most viable candidate for nuclear fuel materials
- Uranium is combined with O, C, N, transition metals for a variety of fuel types
- UO2: ceramic, commercial reactor fuel, light water reactors
- ATF: U3Si2 and Cr-doped UO2
- UZr: fast reactor fuel
- UMo: research reactor fuel
- UC/UCO: high temperature gas reactors

Fission and heat generation

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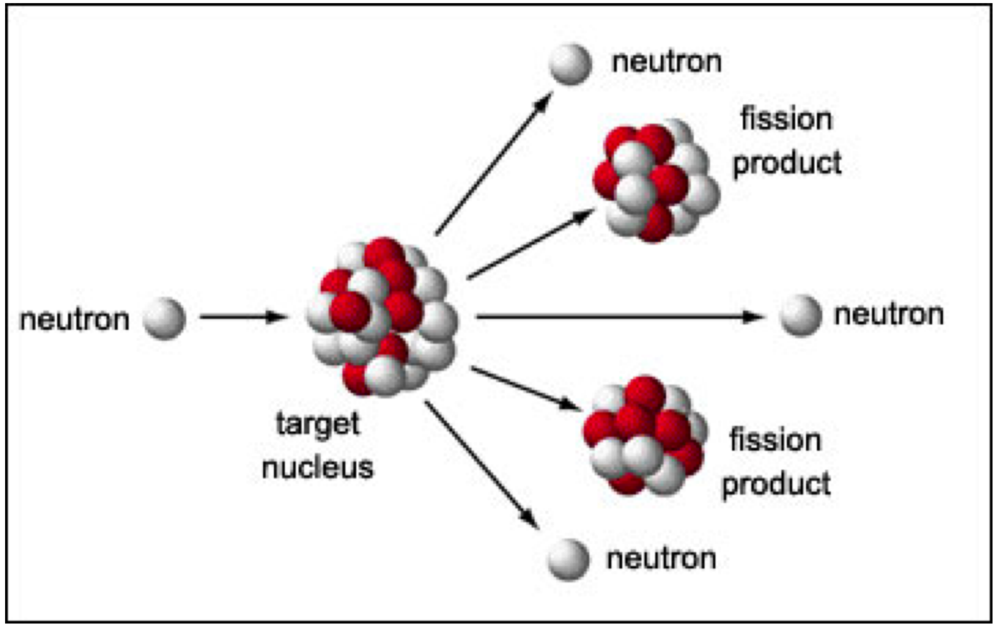
Fission basics

- Impinging neutron of a given energy
  - Neutron energy determines cross section which determines probability of fission event
- Neutron + Target Nucleus -> Two fission products, 2-3 neutrons
- Fission releases around 210 MeV of energy
  - 170 MeV to fission fragments
  - 2 MeV per neutron
  - 7 MeV gamma rays
  - Balance radioactive decay



Energy release with different nuclei

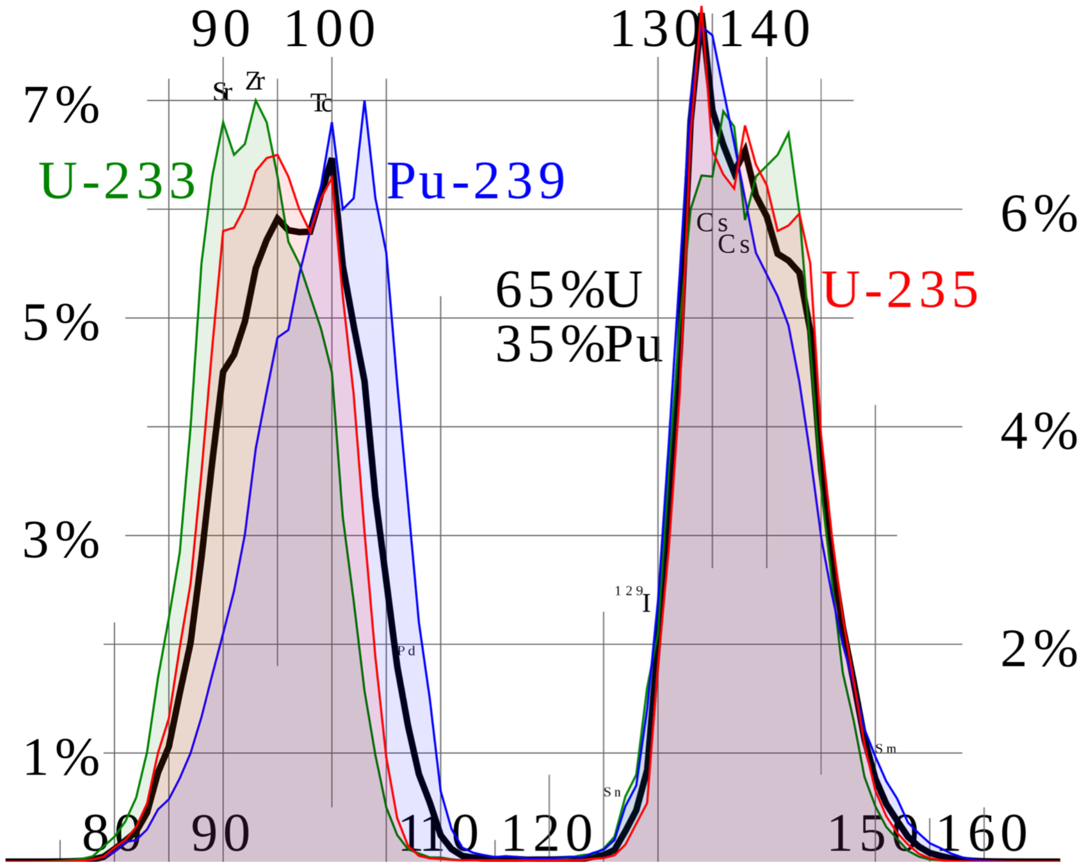
- Energy release is effectively agnostic with regards to the fissioning species
- Comparing U-235 with Pu-239 on the right

Source	Energy, MeV/f	
	^{235}U	^{239}Pu
Energy released instantaneously		
Kinetic energy of fission fragments	169.1	175.8
Kinetic energy of prompt neutrons	4.8	5.9
Energy of prompt γ-rays	7	7.8
Energy of γ-rays from nγ capture	8.8	11.5
Energy from decay of fission products		
Energy of β^--particles	6.5	5.3
Energy of delayed γ-rays	6.3	5.2
Energy of anti-neutrinos[1]	8.8	7.1
Total available energy	202.5	211.5

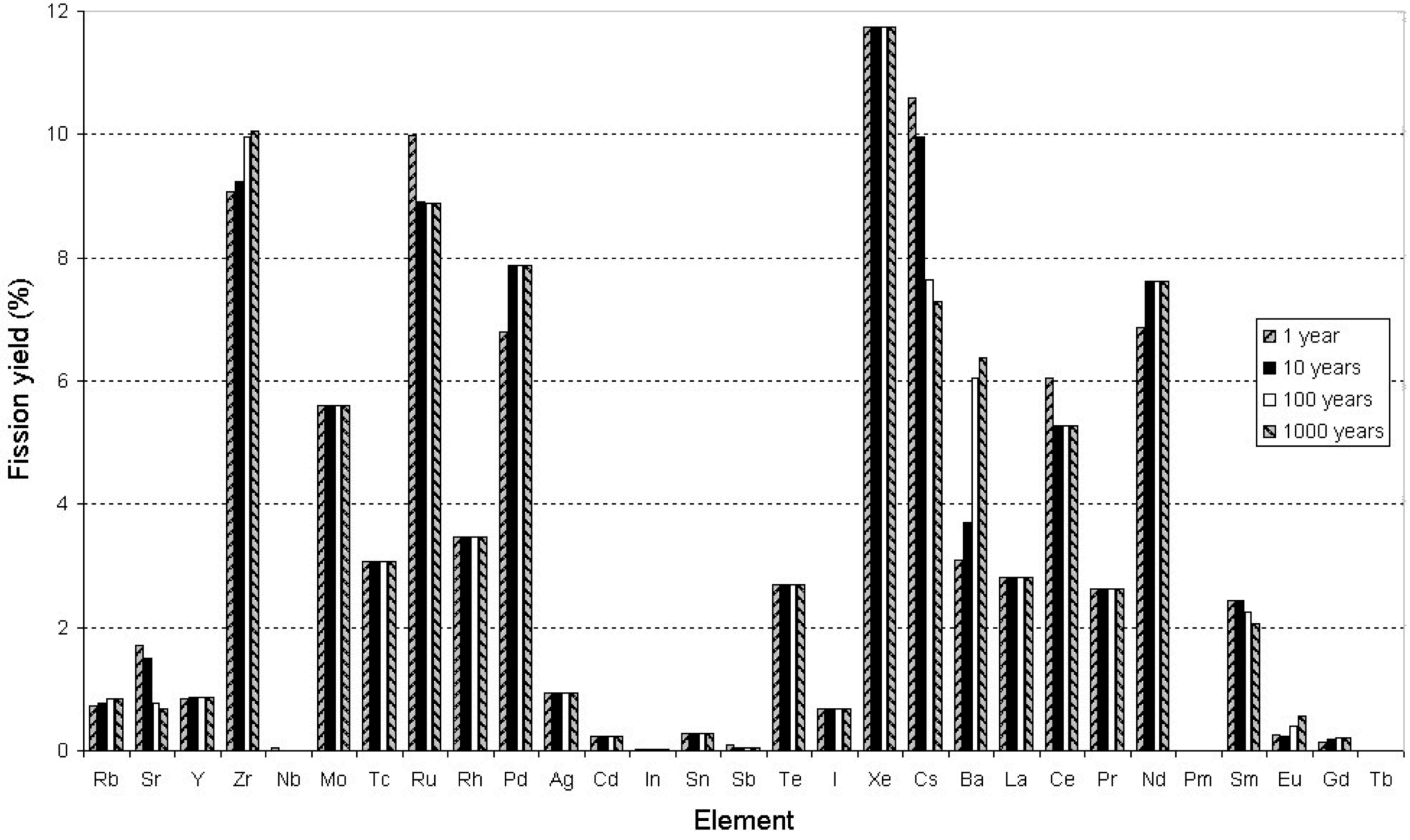
Note 1: Anti-neutrino energy is not absorbed in the reactor and does not contribute to the total available yield.

Fission product yield

- Regardless of fissioning isotope, fission product yields are effectively the same, in this double hump distribution
- One broad peak centered around A=95, the other around A=135
- Examples:
  - Mo (Z=42, A=96)
  - Cs (Z=55, A=133)



Fission Product Yields



Calculating heat generation rate for a given fuel

- We know about 200 MeV of energy is available due to a fission (210 MeV minus neutrinos)
- We know the fission cross section of the target nuclide (tabulated)
- We can calculate the fission atom density
- The heat generation rate, Q is given by:
  - $Q = E_f \times N_f \times \sigma_f \times \phi$
  - Where E_f is the fission energy, N_f is the fission atom density, σ_f is the fission cross section, and ϕ is the neutron flux
  - Units: J/fission x atoms/cm^3 x (fission/neutron)*(cm^2/atom) x (neutron/cm^2-s) = J/cm^3-s

Calculating heat generation rate for a given fuel

- Cross sections:
  - ENDF database: Nuclear Data Sheets 148 (2018) 1–142
  - Thermal neutron (E=0.025 eV) U235 fission cross section: 586.8 barns
    - 1 barn = 10^{-24} cm^2
- Fission atom density
  - Atom density of U-235 = UO_2 density x 1/molar mass x Avogadros number x atom fraction x enrichment

Calculating heat generation rate for a given fuel

- Given a density of UO2 (10.97 g/cm^3)
- Enrichment of 3%
- Molar mass of 3% enriched UO2
  - 235*0.03 + 238*0.97 + 2*16 = 269.9 g/mol
- Atom density of U-235 = 10.97 x 1/269.9 x 6.022E23 x 1/1 x 0.03
  - 2.45E20 atoms/cm^3
- Given a flux of 5E13 neutrons/cm^2/s
- $Q = E_f \times N_f \times \sigma_f \times \phi$
  - 200E6 eV x 1.602E-19 J/eV x 2.45E20 atoms/cc x 587E-24 cm^2 x 5E13 n/cm^2/s
- Q = 230 J/s/cm^3 = 230 W/cm^3

Some notes

- Fast neutron cross section ~100x less than thermal neutron cross section
- Fuels for fast neutron spectrum typically have high enrichments, 19.7% U-235
- Historical research reactor fuels, such as UMo and U3Si2, have had an enrichment of 90+%
- Neutron flux will vary depending on the reactor
  - HFIR has a peak neutron flux of 3E15 n/cm^2/s
  - PULSTAR has a peak neutron flux of 1E13 n/cm^2/s
- Significant variability in heat generation depending on fuel type and reactor conditions

Reactor Systems

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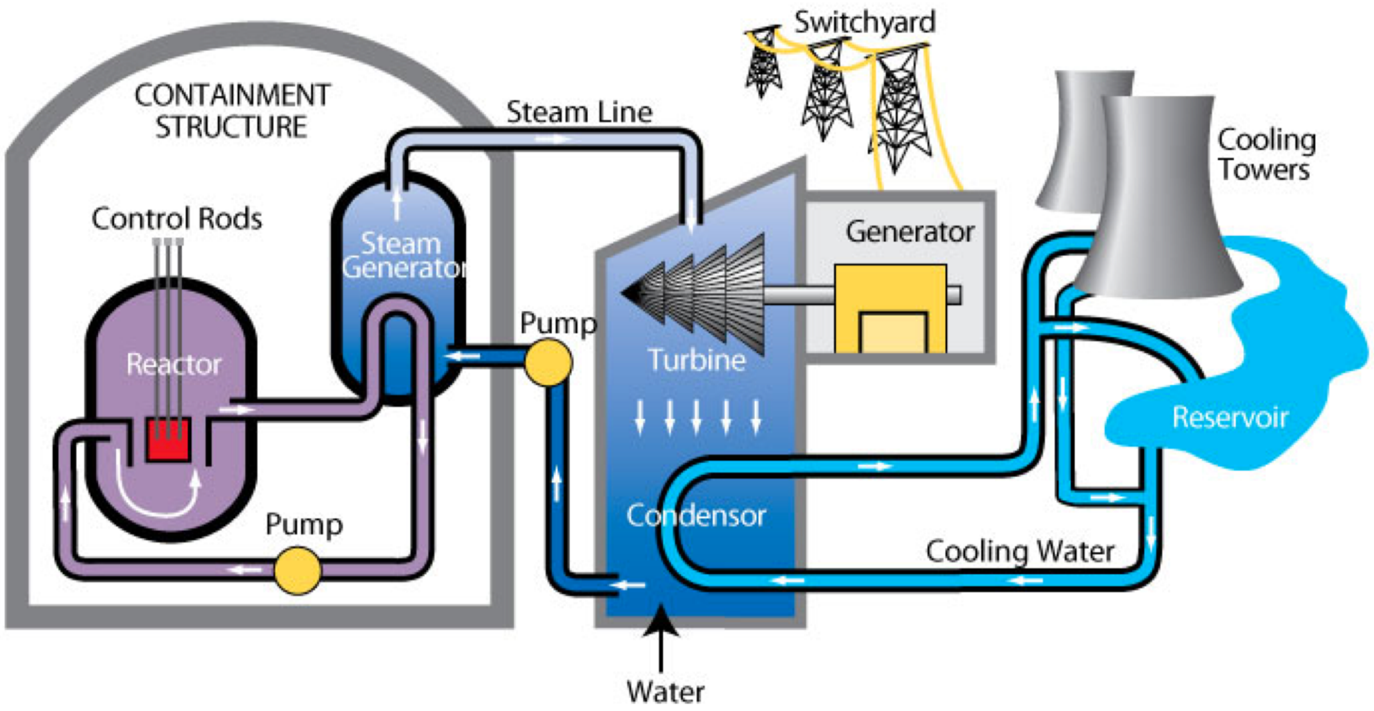
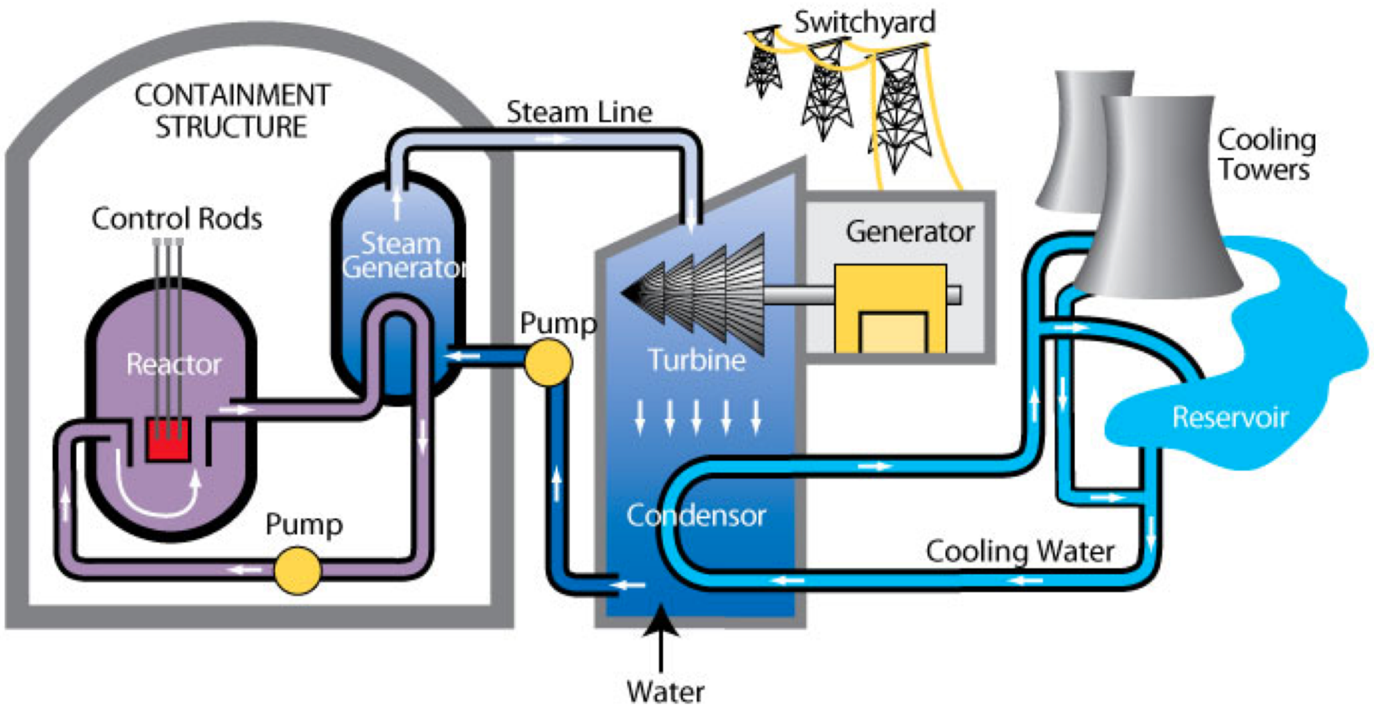
Heat removal systems

- Last time, worked though the heat generation rate in the fuel
- 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



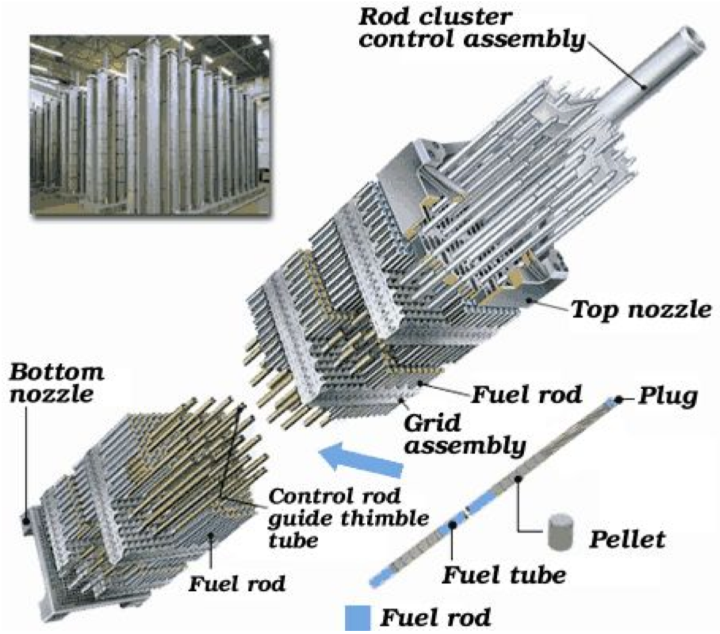
Heat removal systems

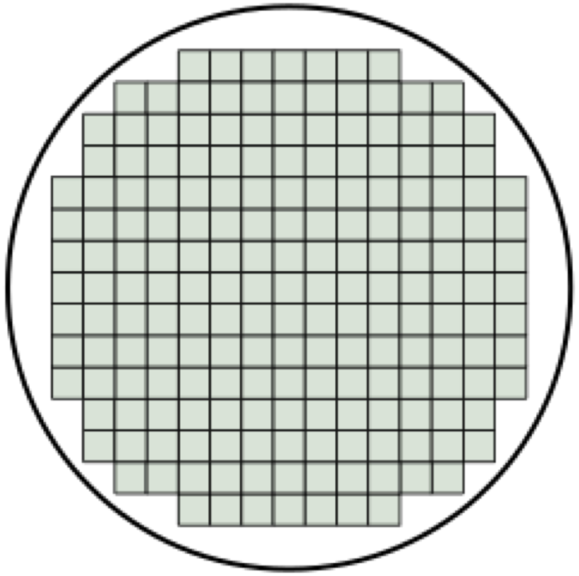
- Primary loop water runs through the core, transporting heat generated by the fuel, to a steam generator in a secondary water loop
- Steam drives a turbine, generating electricity
- A tertiary water loop helps to condense residual steam from the secondary loop via cooling towers and a water reservoir



Light Water Reactor Core Design

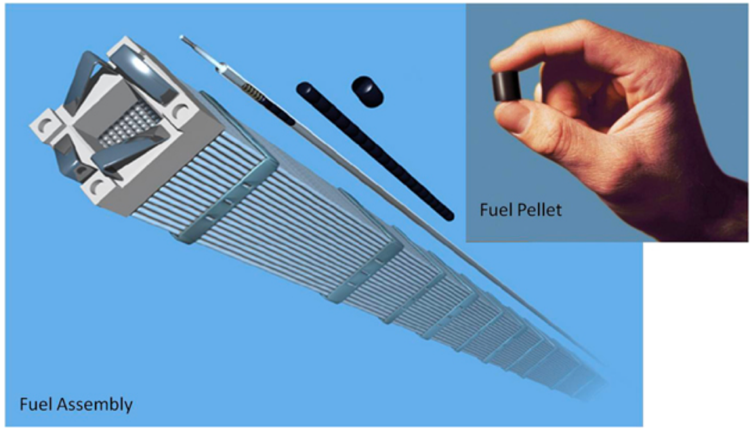
- An LWR core is comprised of fuel assemblies
- Each assembly contains a grid of fuel pins
  - In typical commercial LWR fuel designs, a 17x17 grid
  - Some pins are replaced by control rods
- Water flows from bottom to top



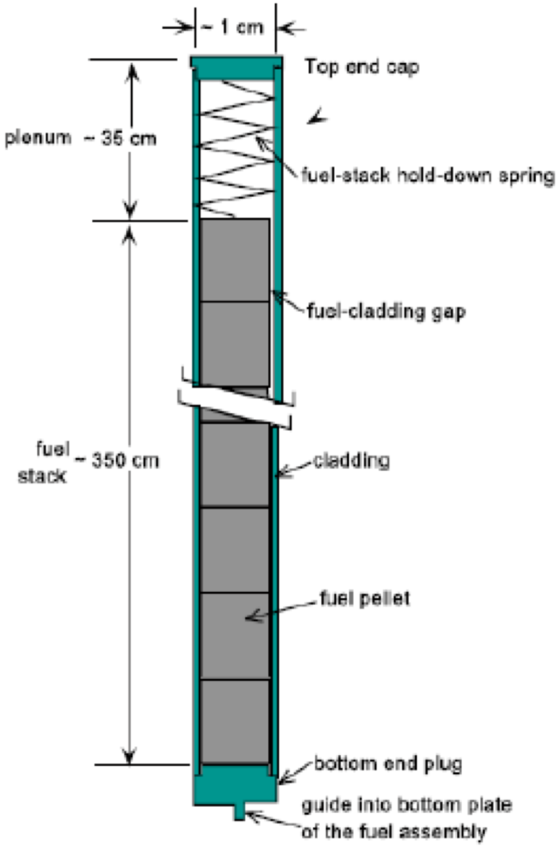


Westinghouse 4-loop PWR

LWR Fuel Pins

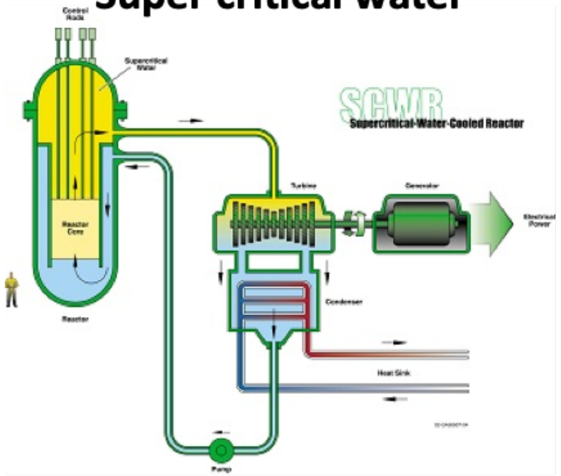


- LWR fuel pins are comprised of a hollow Zircaloy tube
  - This is the cladding
  - Zircaloy is a type of Zr alloy
- Inside the cladding are stacked UO2 pellets
- Each pellet is a cylinder about 1 cm in diameter and 1 cm in height

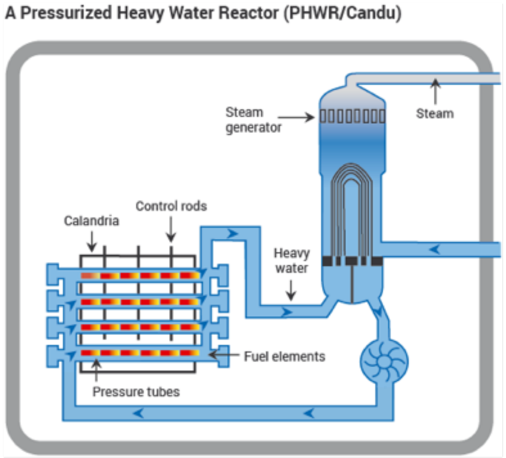


Not only water cooled reactor designs

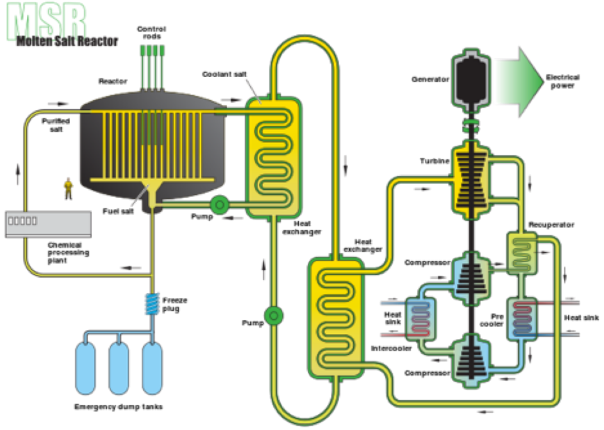
Super critical water



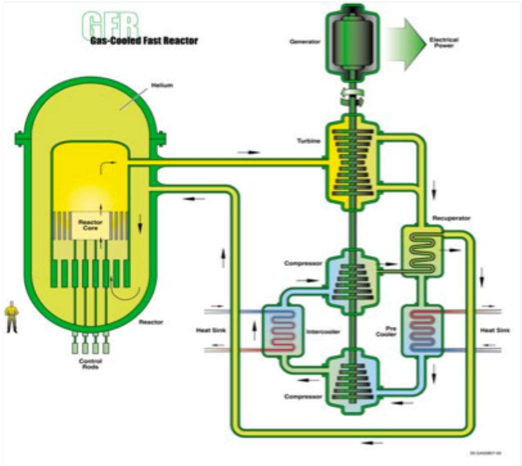
Heavy water



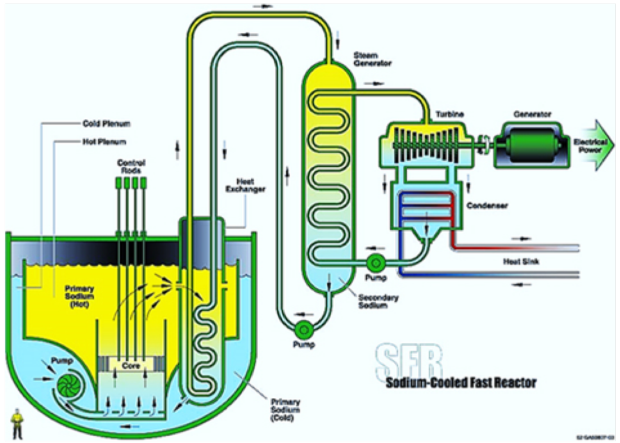
Molten salt



Gas

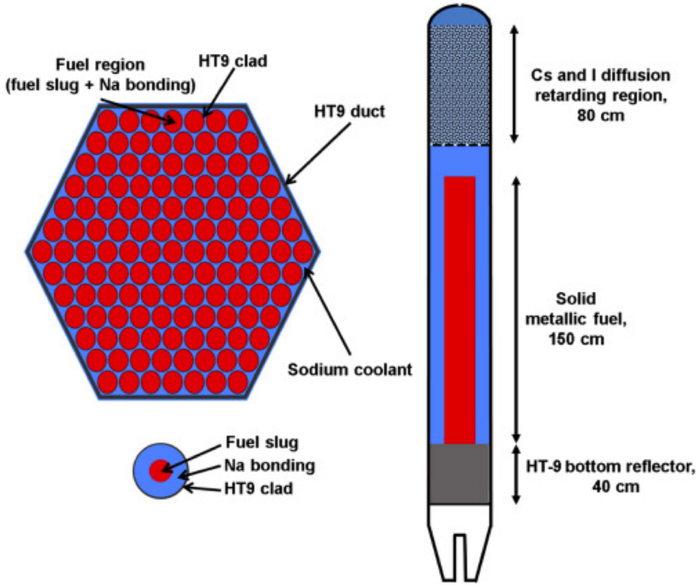


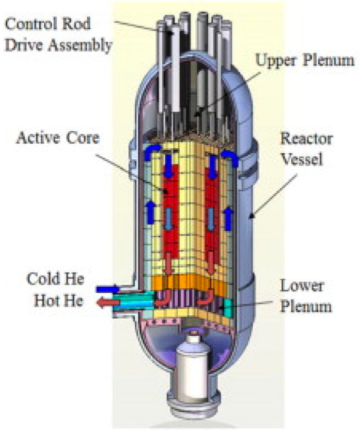
Liquid metal

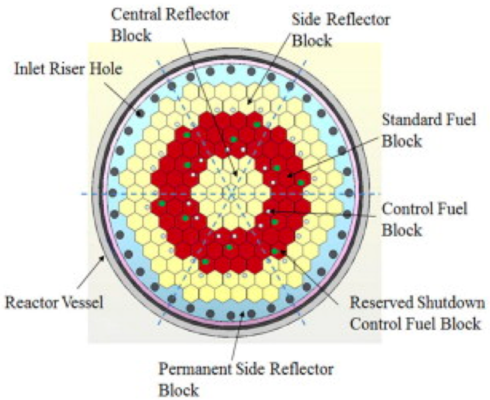


Not all fuel is pellet-based

- 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

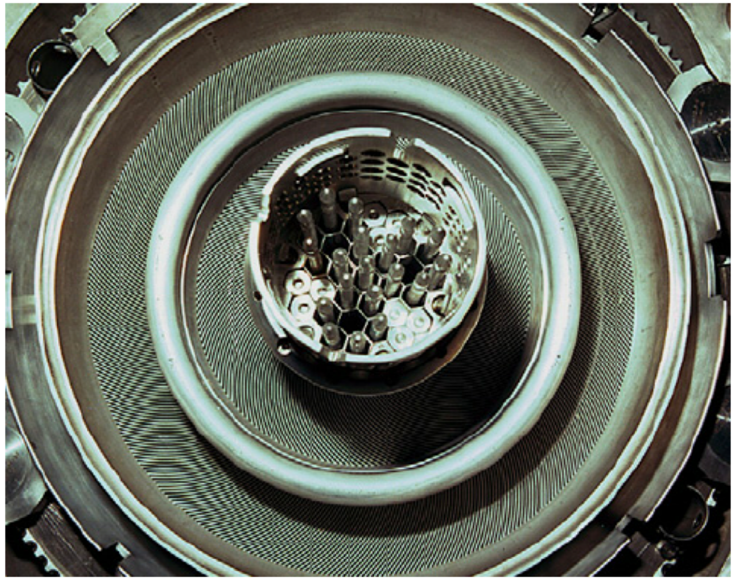




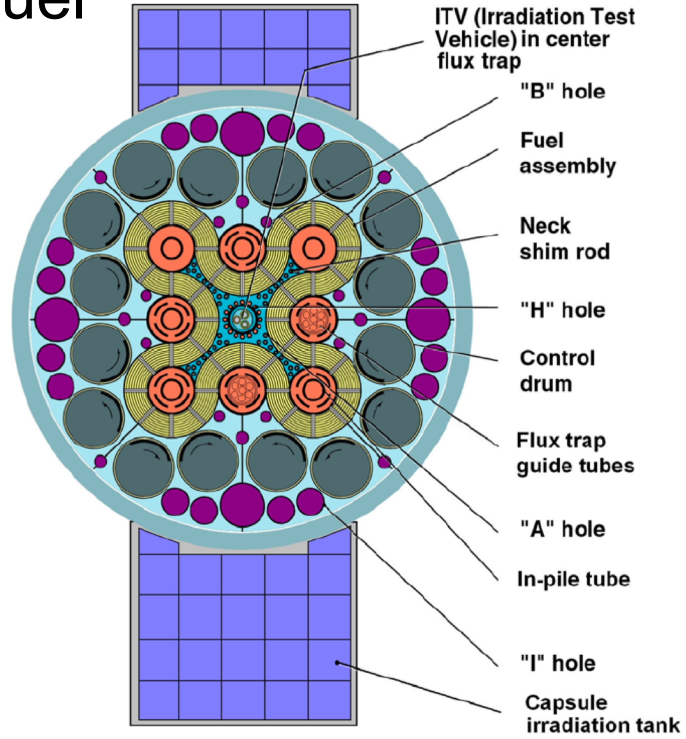


ATR and HFIR Core design

- HFIR combines curved plates in concentric regions



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

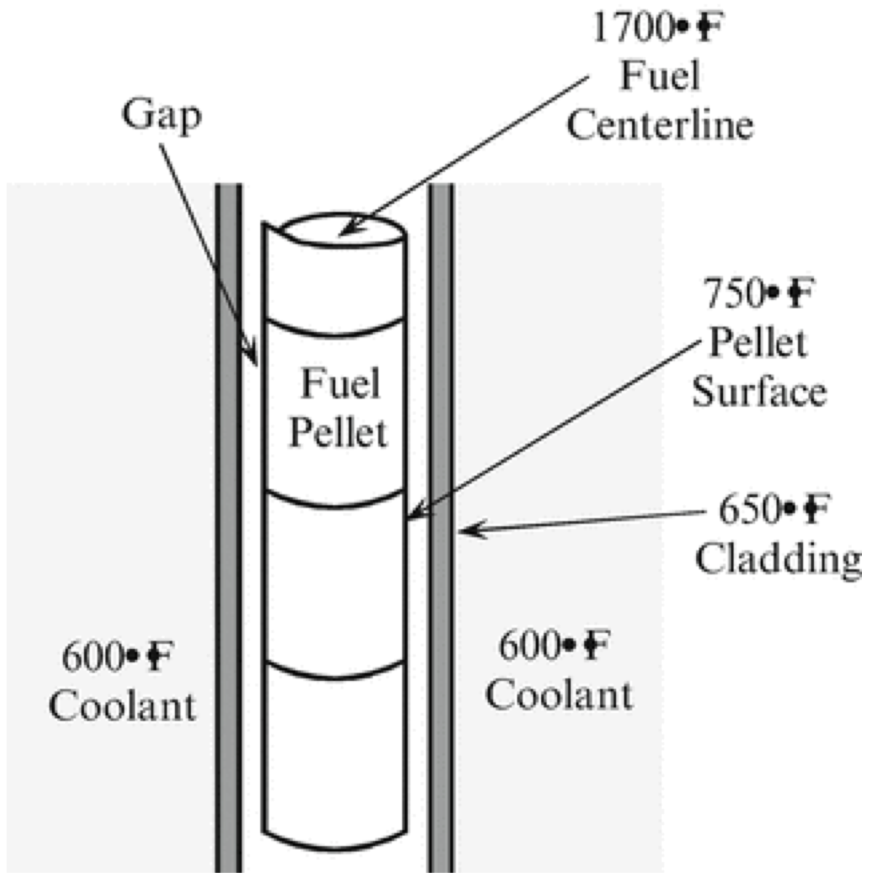


Most fuel designs employ some type of cladding

- The primary focus of the cladding is to separate the fuel from the coolant
  - Fuel contains dangerous 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

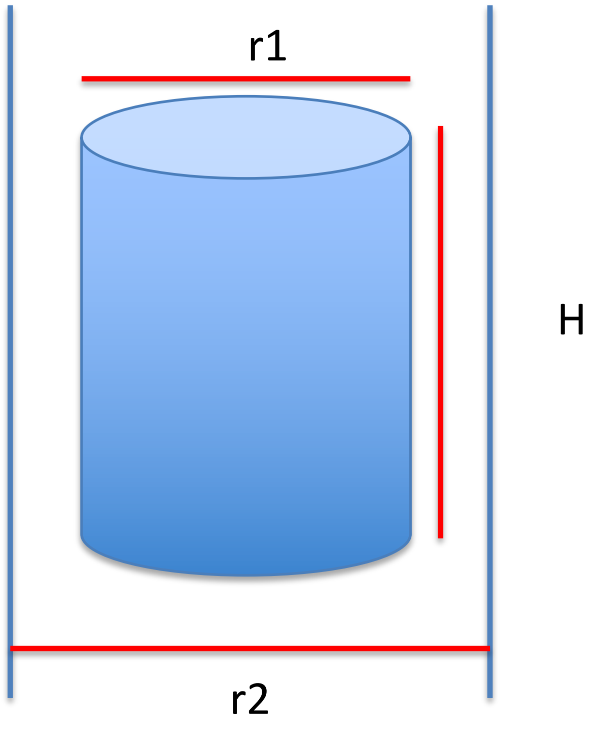
Fuel/Cladding Gap

- 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 mass-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%

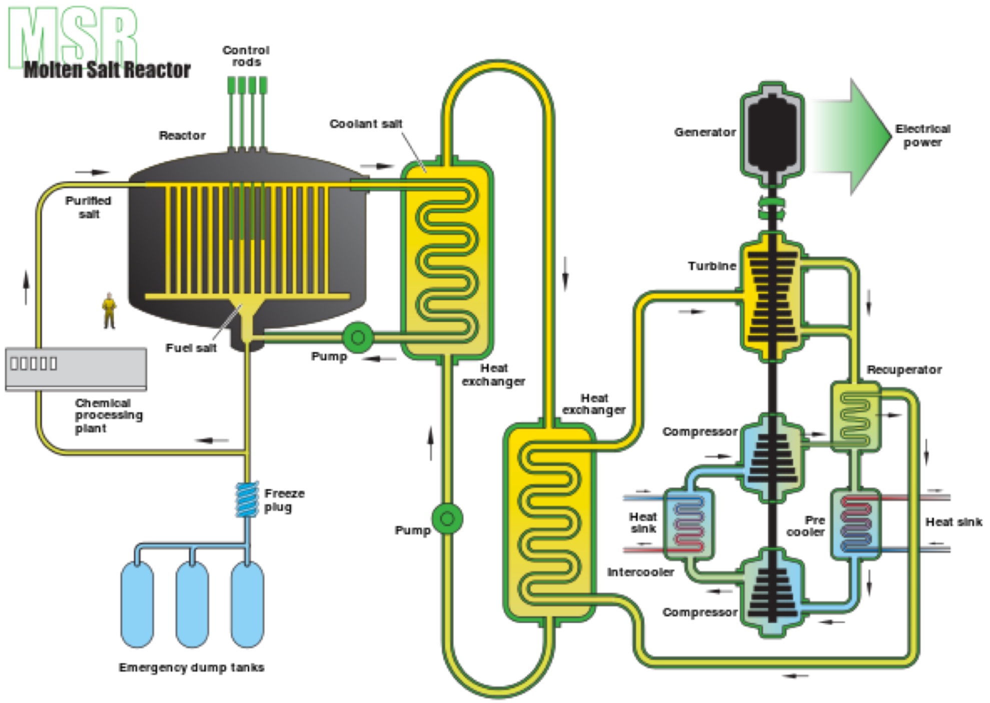


Cladding material selection

- 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 UCl3 as the fuel, flowing continuously through the core
- Secondary loop comprised of coolant salt, such as LiCl-KCl



Summary

- All reactors have basic requirements they must meet
  - An approach to remove the heat from the fuel
  - A method to convert heat to electricity
  - An approach to prevent radioactive products from leaving the fuel
  - A method to cycle the fuel
  - A method to remove used fuel and add new fuel
  - Containment in case something goes very wrong
- LWRs have a certain way of meeting these requirements, but there are other options
- Various fuel geometries have been used
- Cladding is often required between the fuel and the coolant