Nuclear Fuel Performance

NE-591

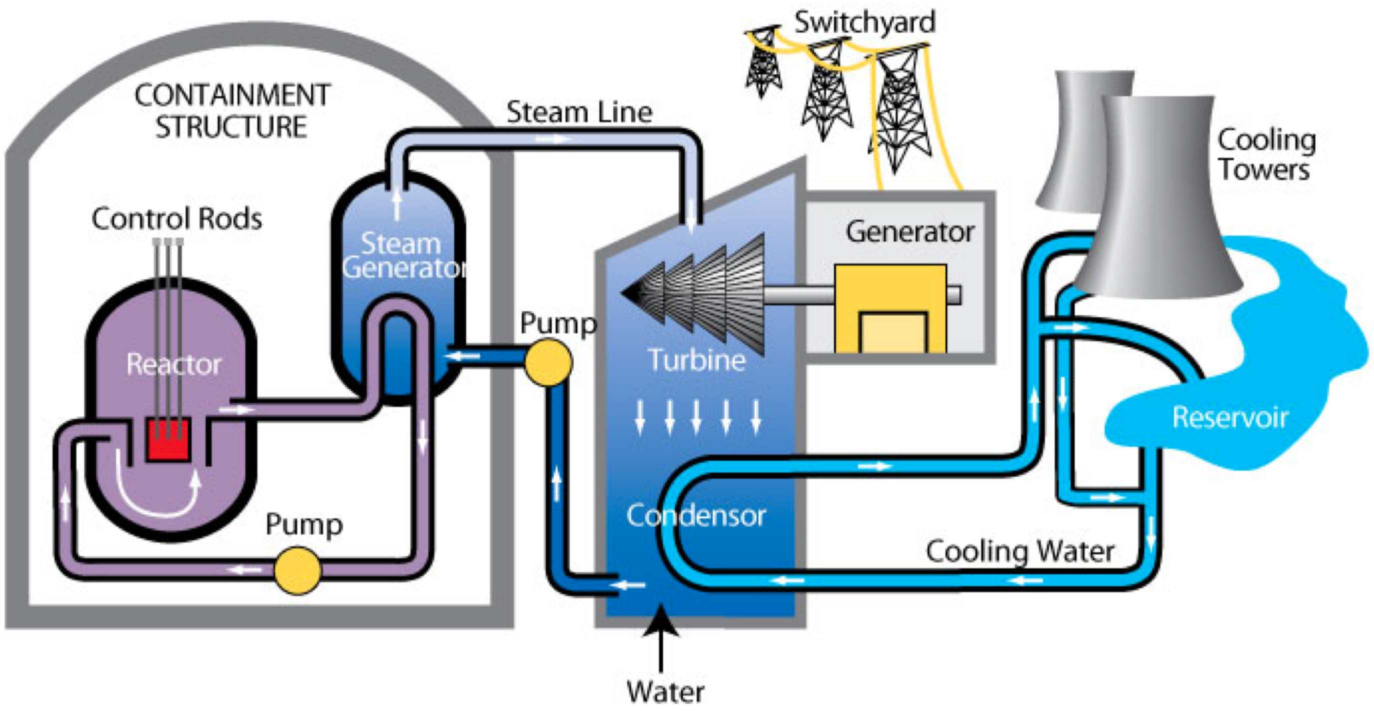
Last Time

- Concluded fuel types
  - 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
- Fuel is not one size fits all; different reactor designs require different fuels

REACTOR SYSTEMS

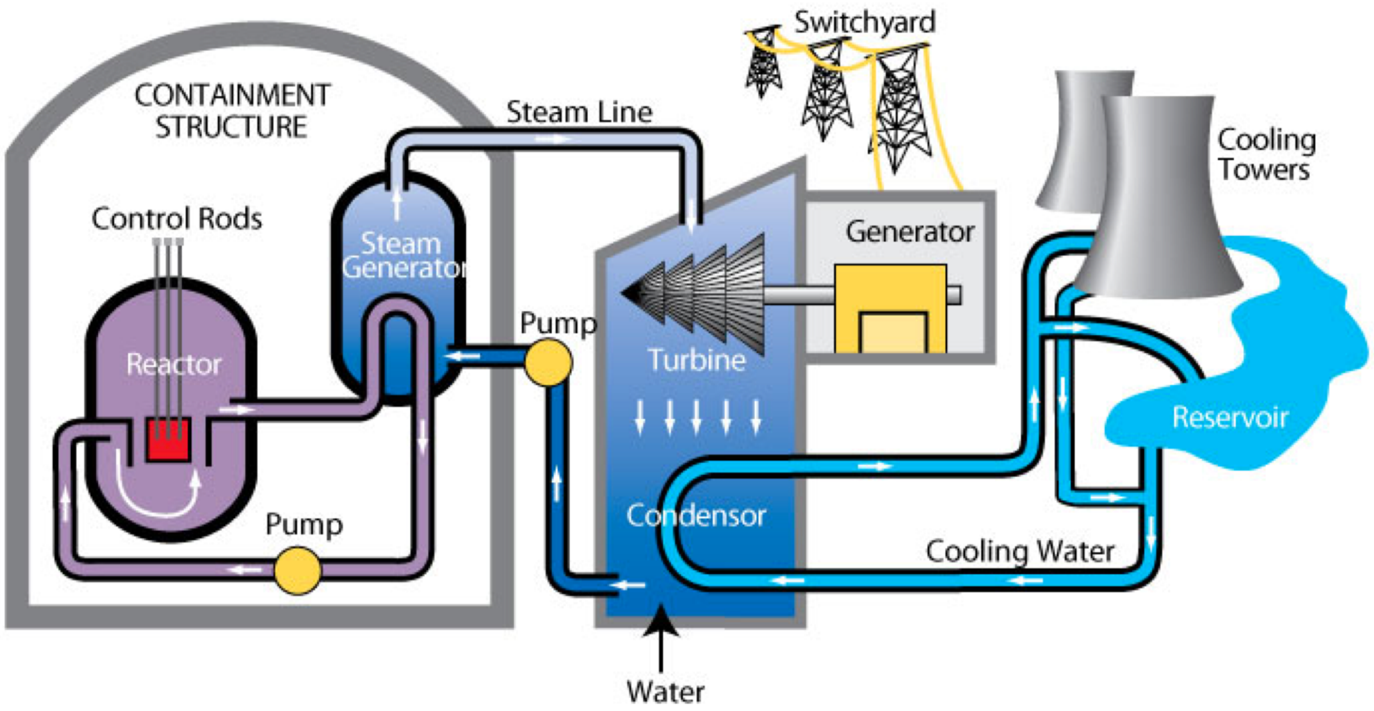
Heat removal systems

- 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



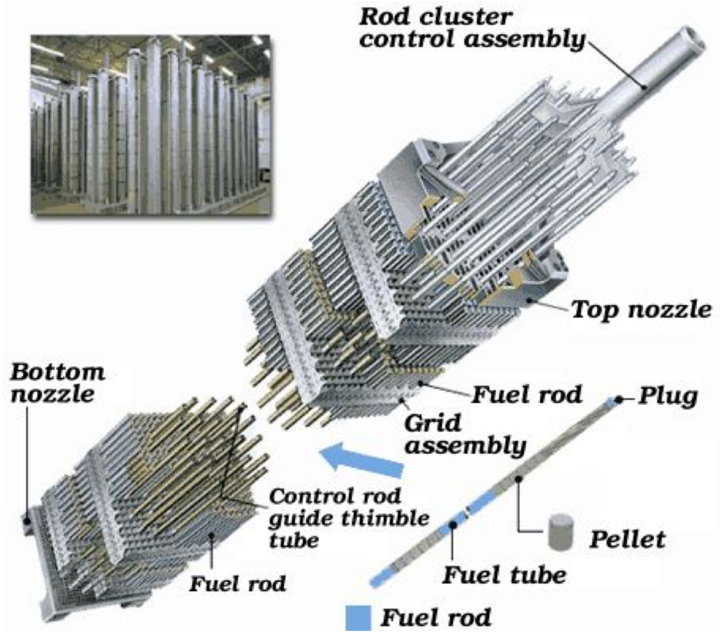
Heat removal systems

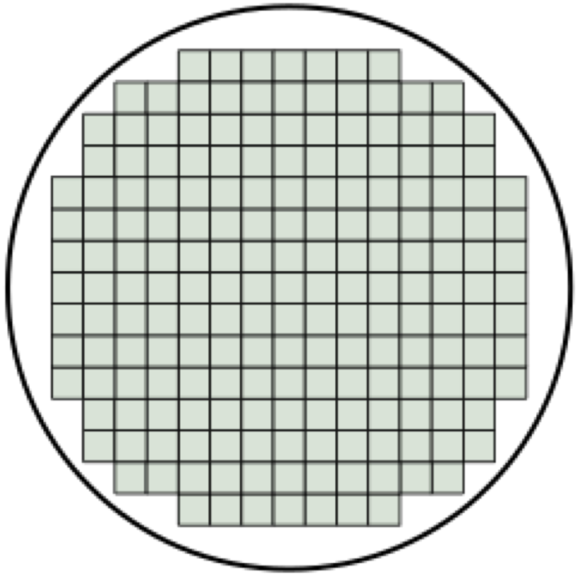
- Primary loop water runs through the core, transporting heat generated by the fuel, to a steam generator in a secondary water loop
- Steam drives a turbine, generating electricity
- A tertiary water loop helps to condense residual steam from the secondary loop via cooling towers and a water reservoir



Light Water Reactor Core Design

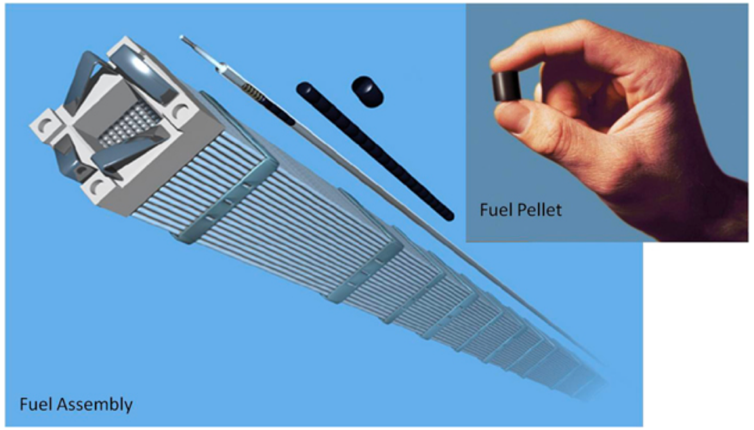
- An LWR core is comprised of fuel assemblies
- Each assembly contains a grid of fuel pins
  - In typical commercial LWR fuel designs, a 17x17 grid
  - Some pins are replaced by control rods
- Water flows from bottom to top



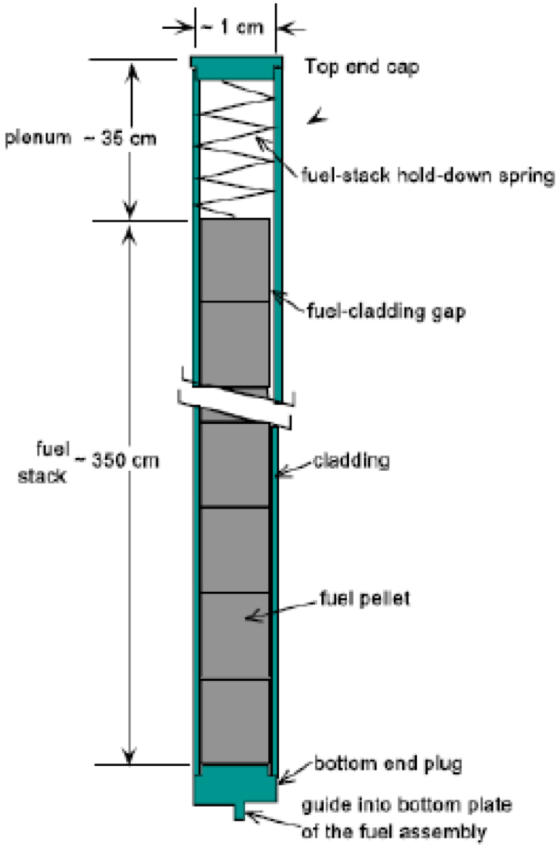


Westinghouse 4-loop PWR

LWR Fuel Pins

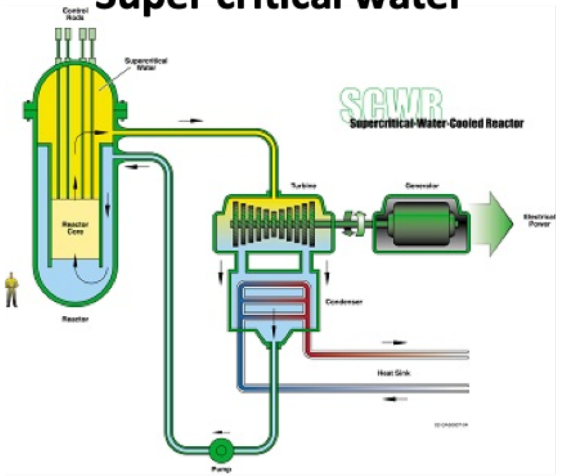


- LWR fuel pins are comprised of a hollow Zircaloy tube
  - This is the cladding
  - Zircaloy is a type of Zr alloy
- Inside the cladding are stacked UO2 pellets
- Each pellet is a cylinder about 1 cm in diameter and 1 cm in height

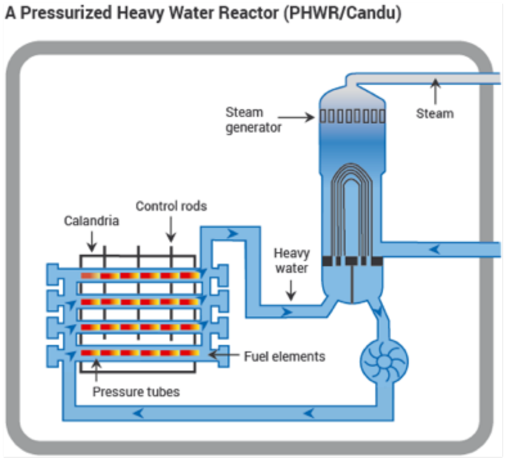


Not only water cooled reactor designs

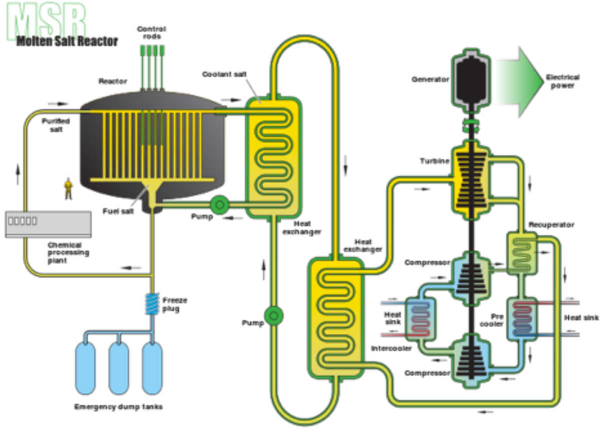
Super critical water



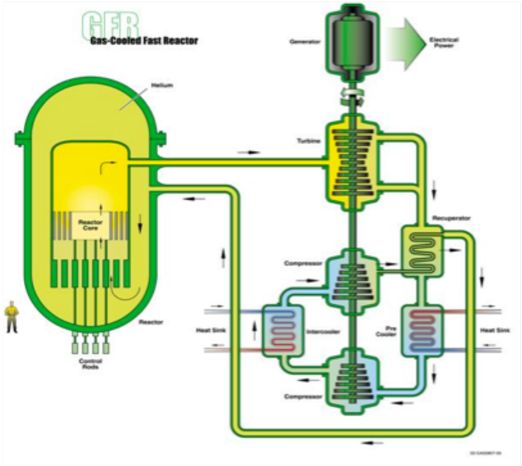
Heavy water



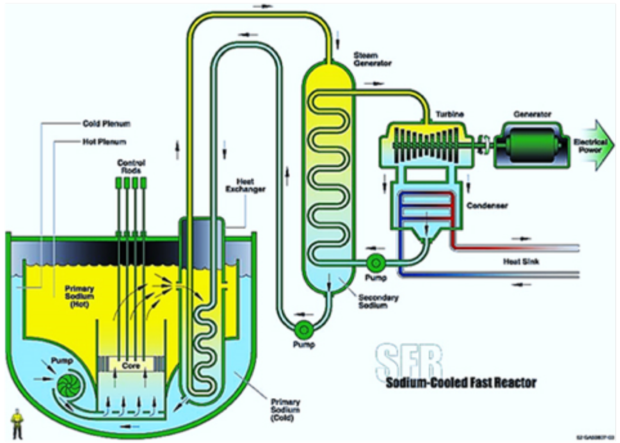
Molten salt



Gas

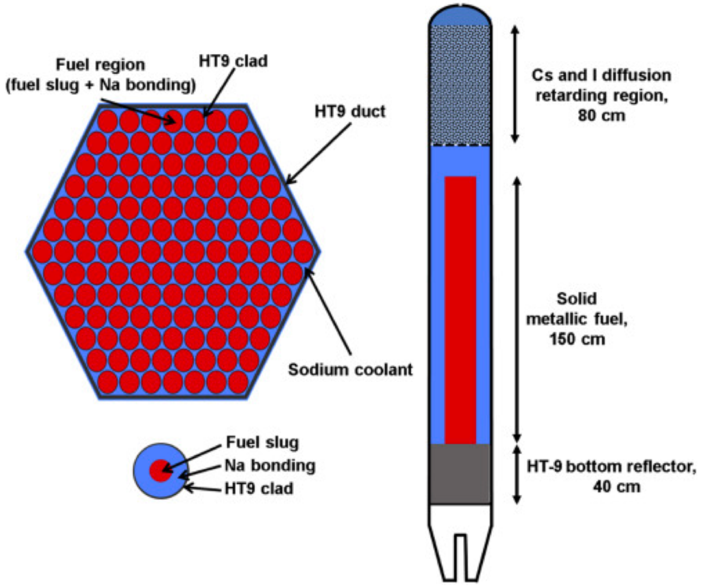


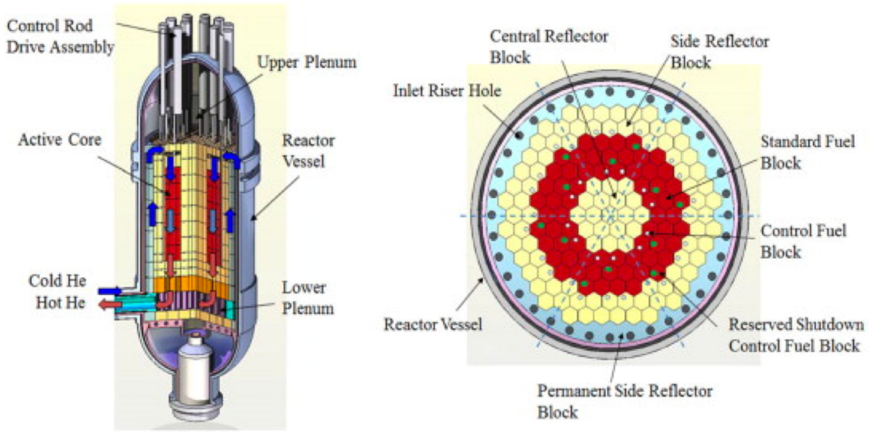
Liquid metal



Not all fuel is pellet-based

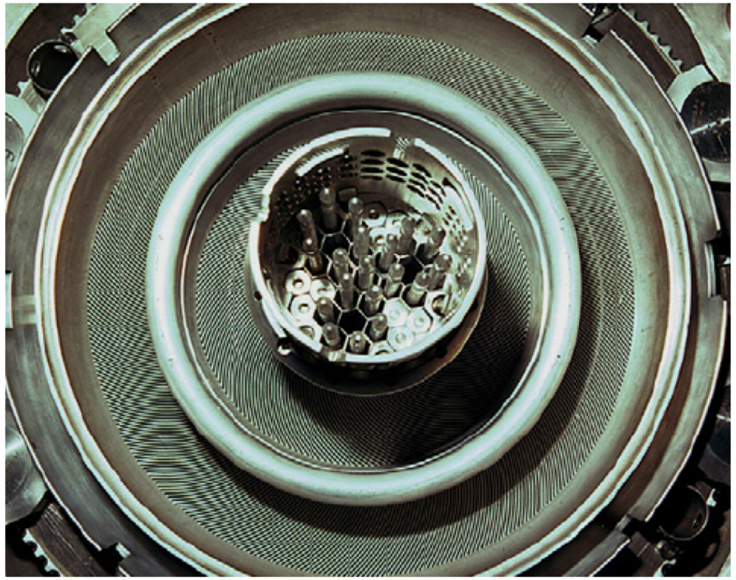
- Metallic fuel is a solid fuel slug
  - Utilized an Fe-based cladding, such as HT-9 or SS
- TRISO particles are formed into spherical compacts, or can be formed into pellet compacts
- UMo and USi have been used in plate fuels
- Assemblies are often hex-shaped and can included reflectors



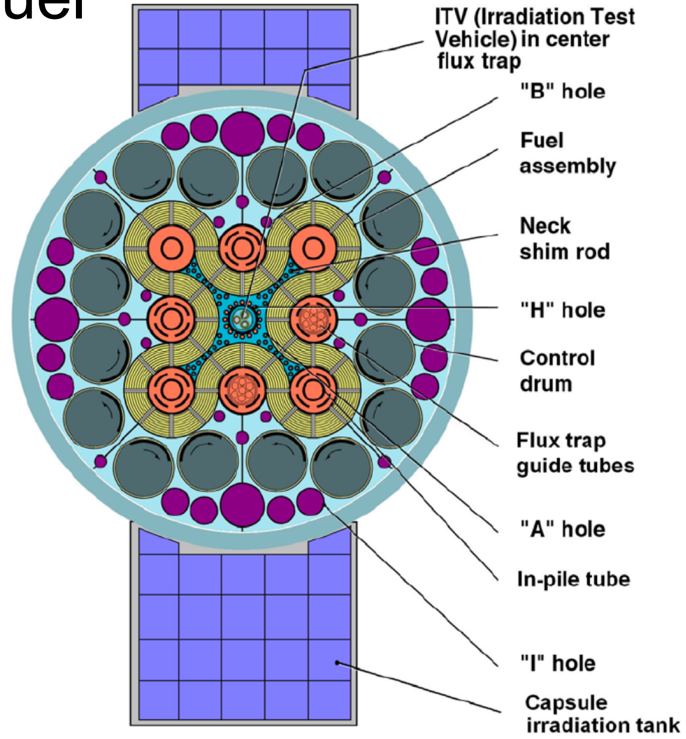


ATR and HFIR Core design

- HFIR combines curved plates in concentric regions



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

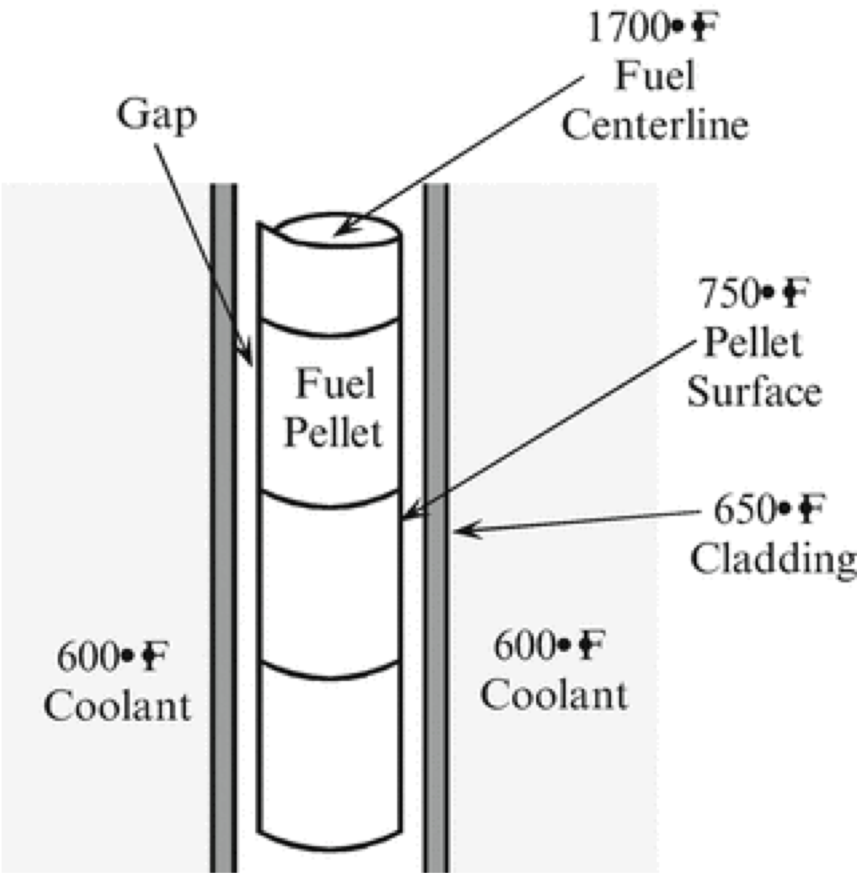


Most fuel designs employ some type of cladding

- 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

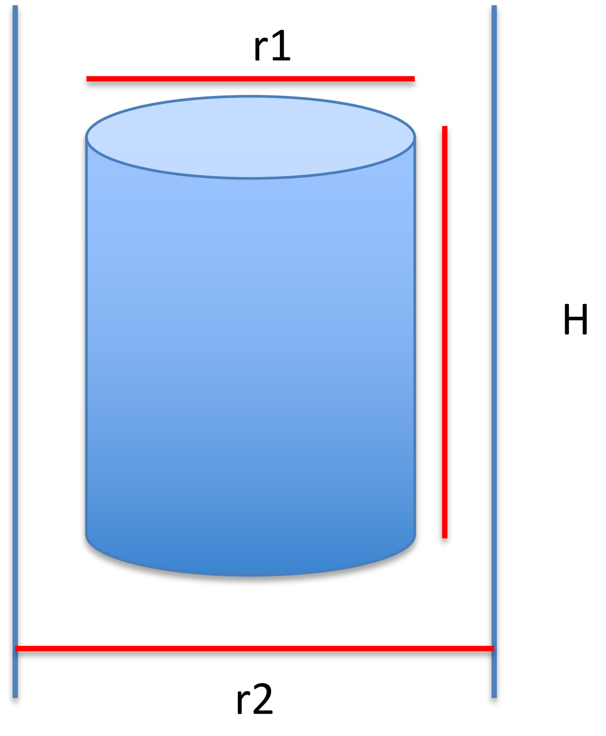
Fuel/Cladding Gap

- 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%

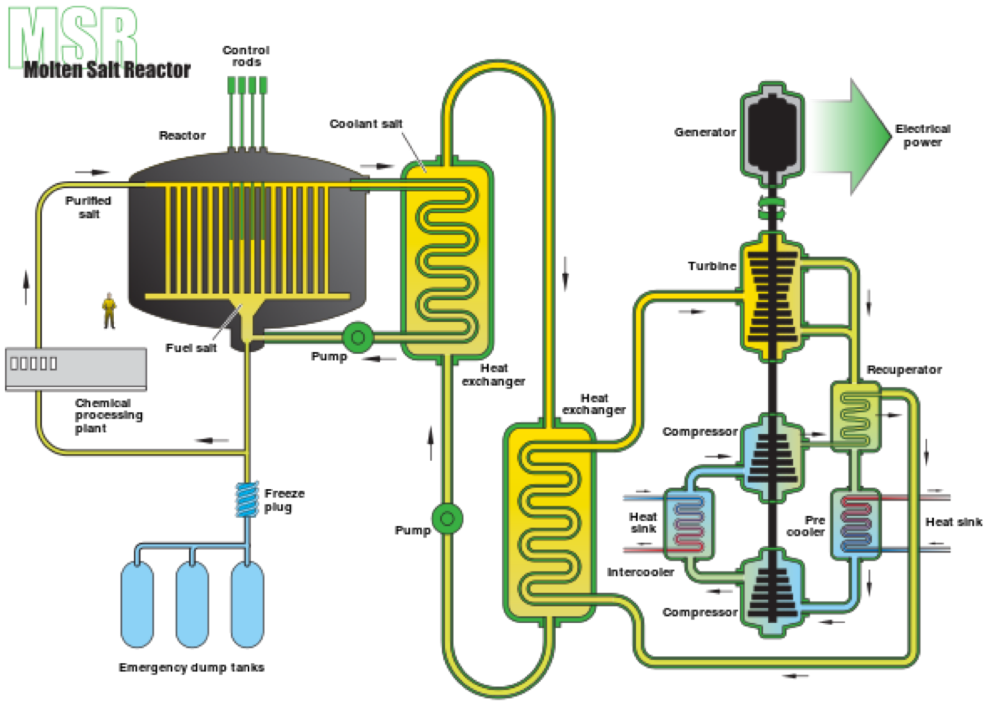


Cladding material selection

- 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

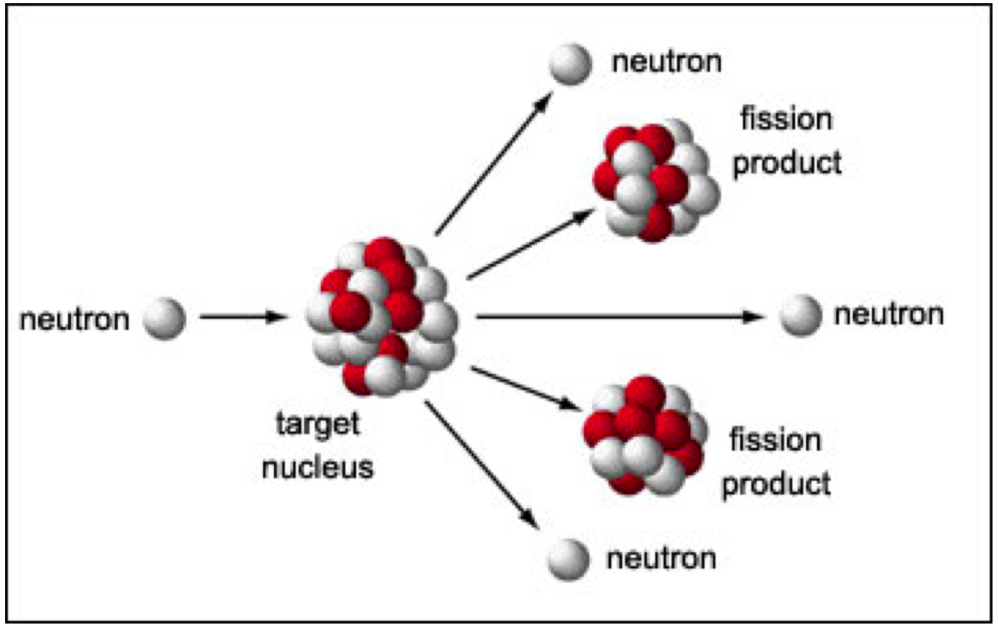
- Some MSRs plan to utilize liquid molten salts as the fuel, flowing continuously through the core
- Secondary loop comprised of coolant salt, such as FLiBe
- Example was the MSRE from ORNL, which utilized LiF-BeF2-ZrF4-UF4 as the fuel



HEAT GENERATION

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

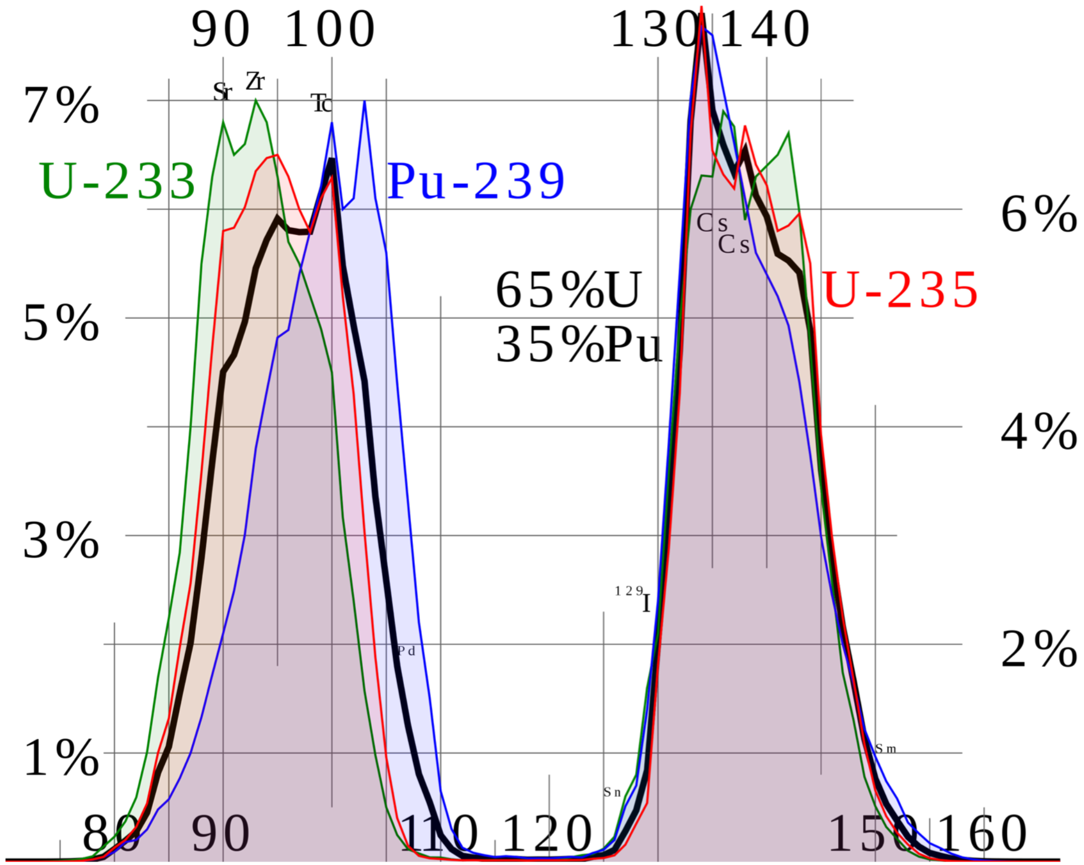
- Energy release is effectively agnostic with regards to the fissioning species
- Comparing U-235 with Pu-239 on the right
  - Pu releases about 9 MeV more usable energy per fission
  - Less than a 5% difference
- Partition of energy is largely identical as well

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

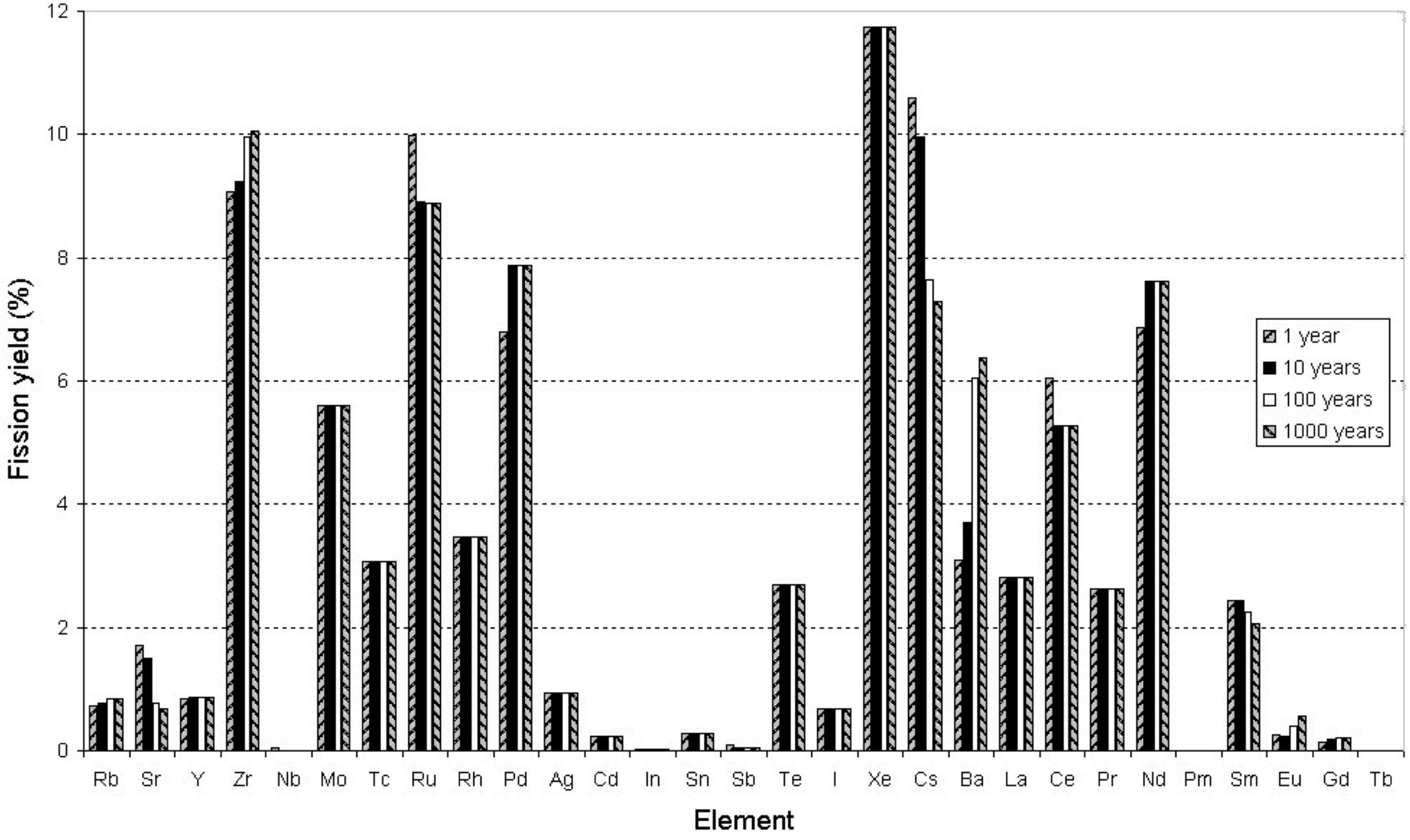
Note 1: Anti-neutrino energy is not absorbed in the reactor and does not contribute to the total available yield.

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 = W/cm^3

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 = UO2 density x 1/molar mass x Avogadro's number x atom fraction x enrichment

Calculating heat generation rate for a given fuel

- Given a density of UO_2 (10.97 g/cm^3)
- Enrichment of 3%
- Molar mass of 3% enriched UO_2
  - 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
  - 7.34E20 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 7.34E20 atoms/cc x 587E-24 cm^2 x 5E13 n/cm^2/s
- Q = 690 J/s/cm^3 = 690 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

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