PennState
College of Engineering

NucE 497: Reactor Fuel Performance

Lecture 4: Reactor requirements, fuel geometry, and the role of cladding

January 18, 2017

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Mechanical and Nuclear Engineering

Today we will discuss requirements for all reactors, fuel geometry, and the role of cladding

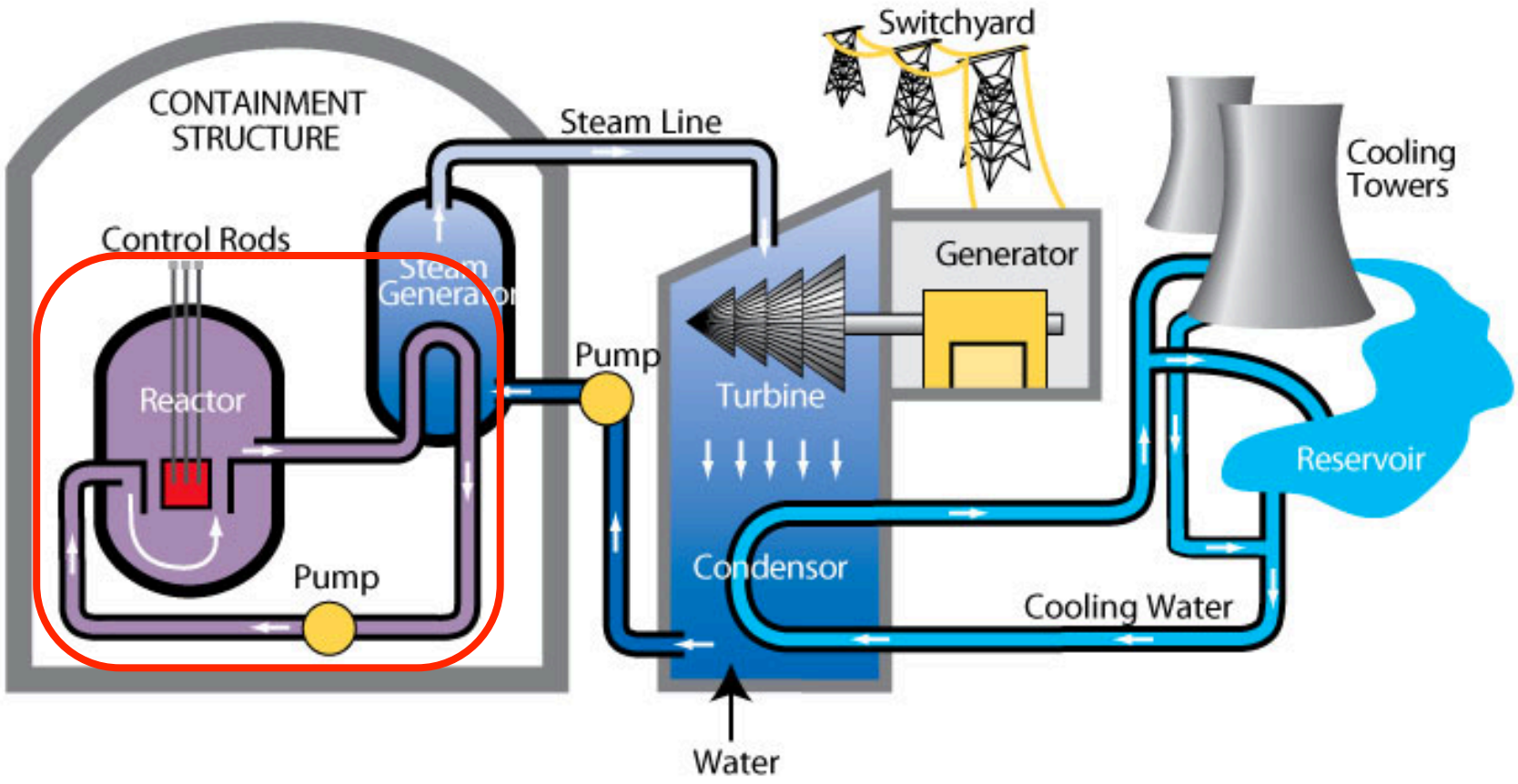
- Module 1: Fuel basics
  - Purpose of the fuel and types of fuel
  - Fission, heat generation, fission products
  - **Reactor requirements, fuel geometry and the role of cladding**
  - Fuel fabrication
- Module 2: Heat transport
- Module 3: Mechanical behavior
- Module 4: Materials issues in the fuel
- Module 5: Materials issues in the cladding
- Module 6: Accidents, used fuel, and fuel cycle

In order for a commercial reactor design to work, there are various required capabilities

- An approach to remove the heat from the fuel
- A method to convert heat to electricity
- The capability to control the reaction
- A moderator (for thermal reactors)
- 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

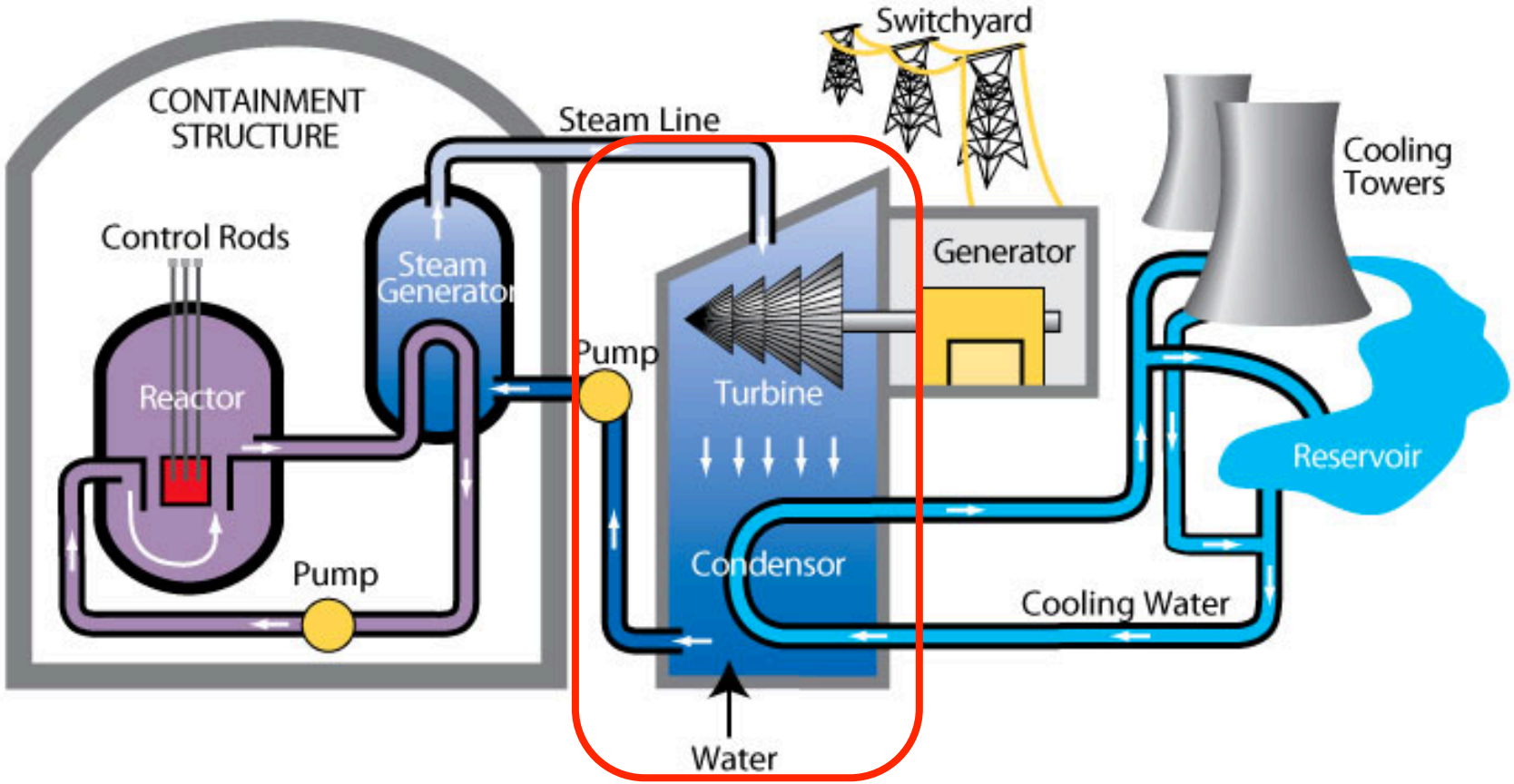
How is heat removed from the fuel in a LWR?

- Light water coolant



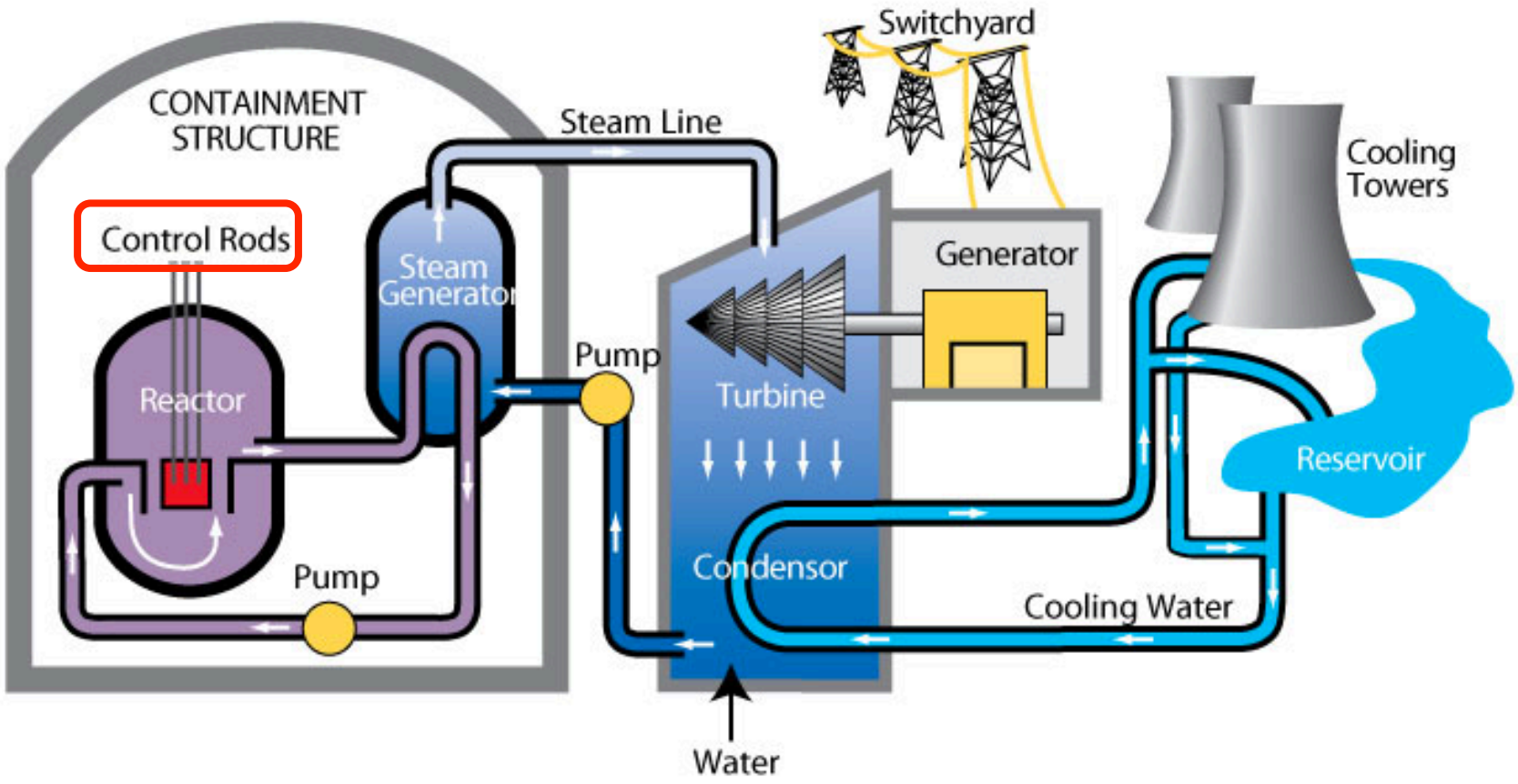
How is heat converted to electricity in a LWR?

- Converting light water to steam and using a steam generator



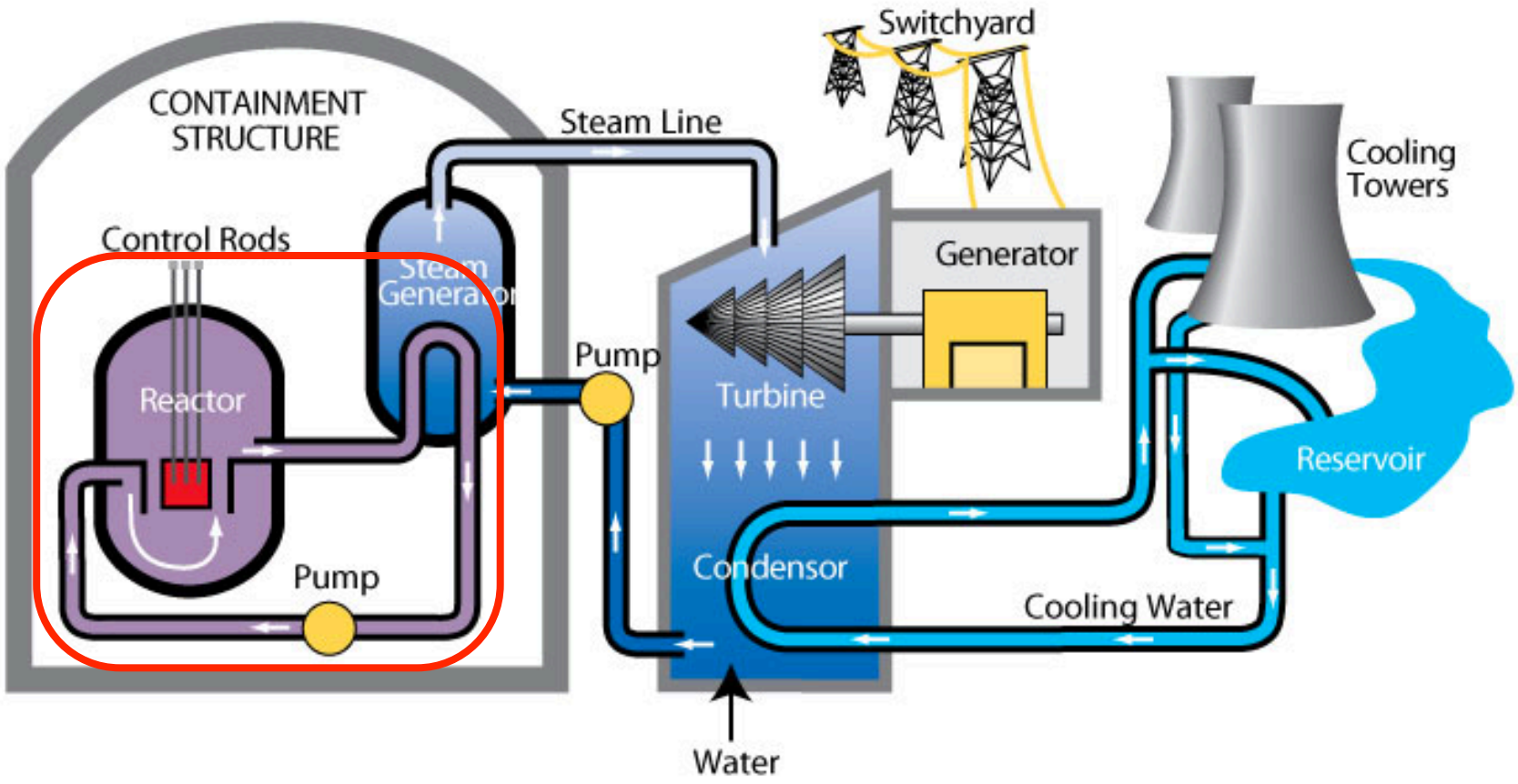
How is the reaction controlled in a LWR?

- The control rods



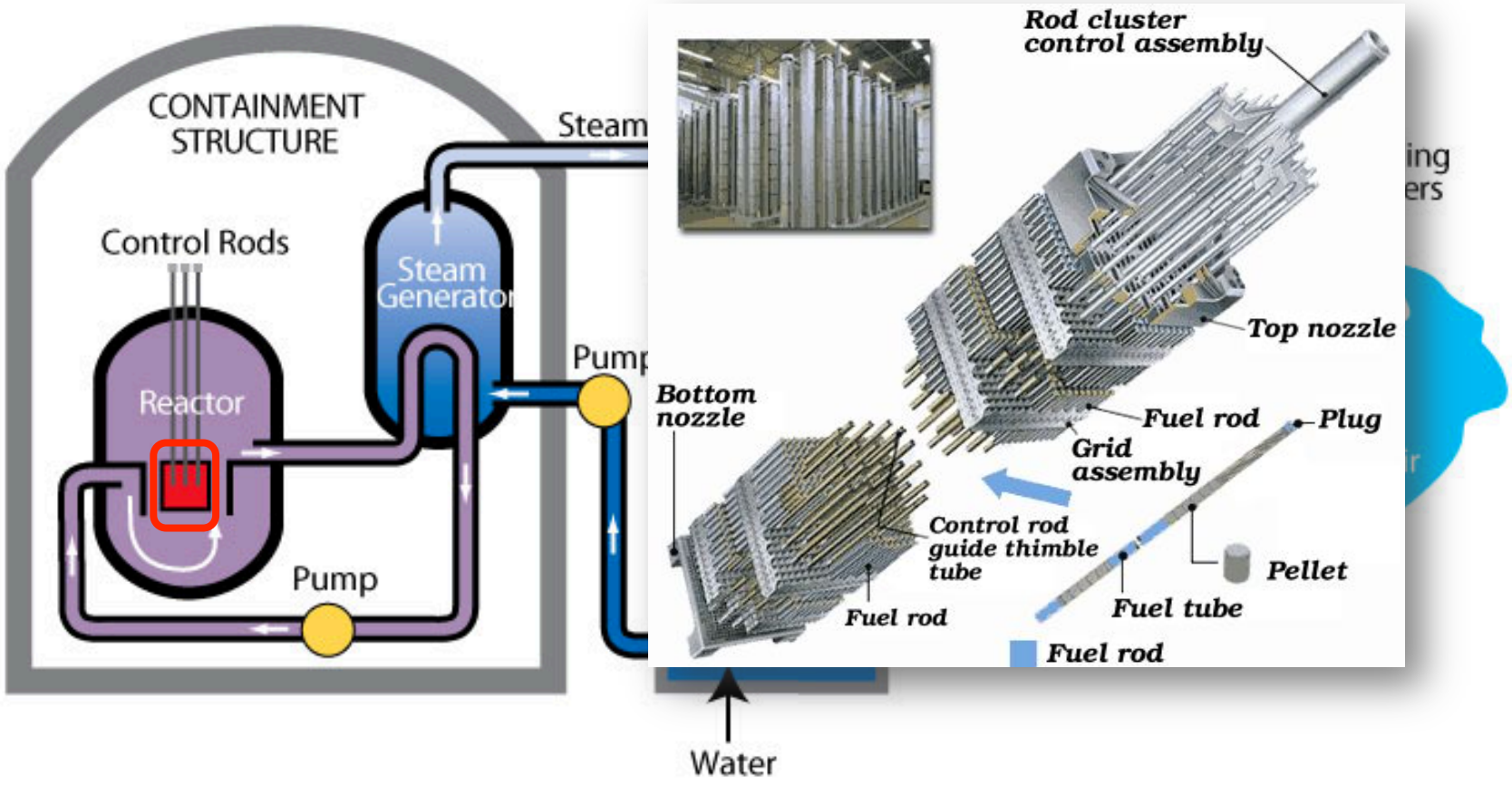
What moderator is used in a LWR?

- Light water coolant



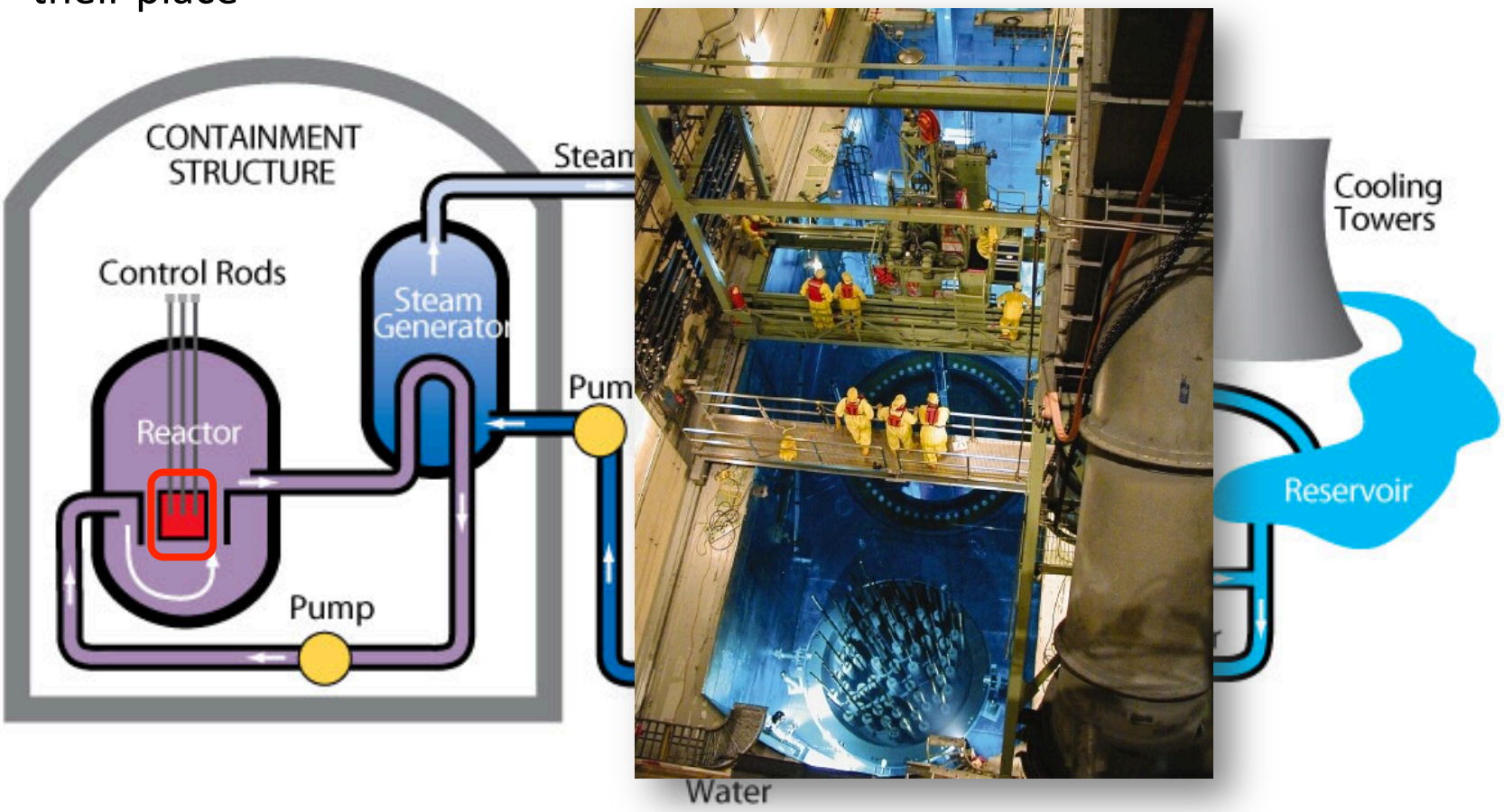
How is the fuel cycled in a LWR?

- Fuel rods are loaded in assemblies, and the assemblies are moved around the core during refueling



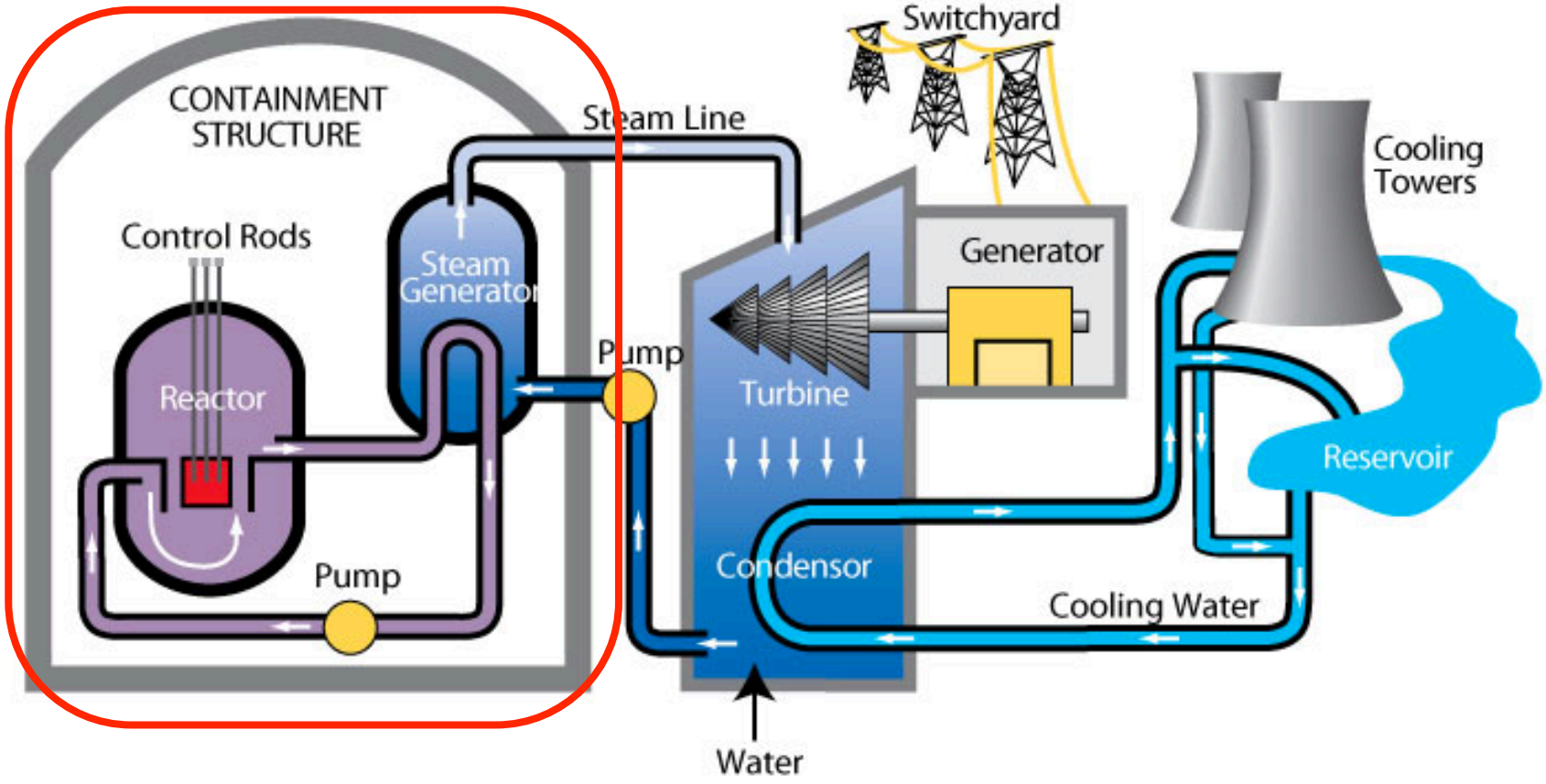
How is refueling done in an LWR?

- Used fuel assemblies are removed from the core and fresh ones are put in their place

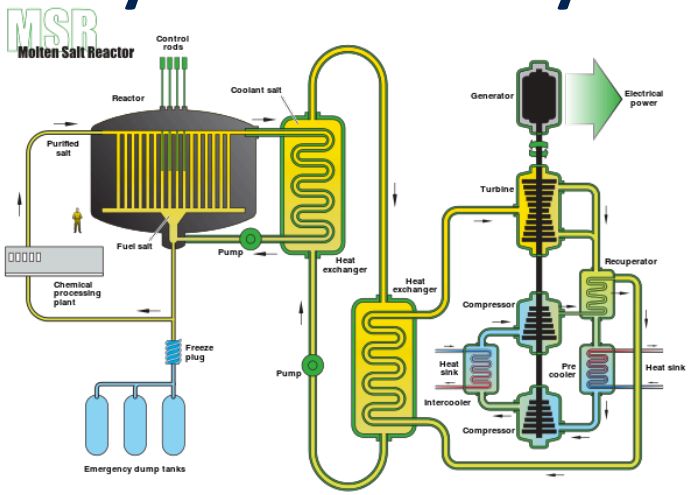


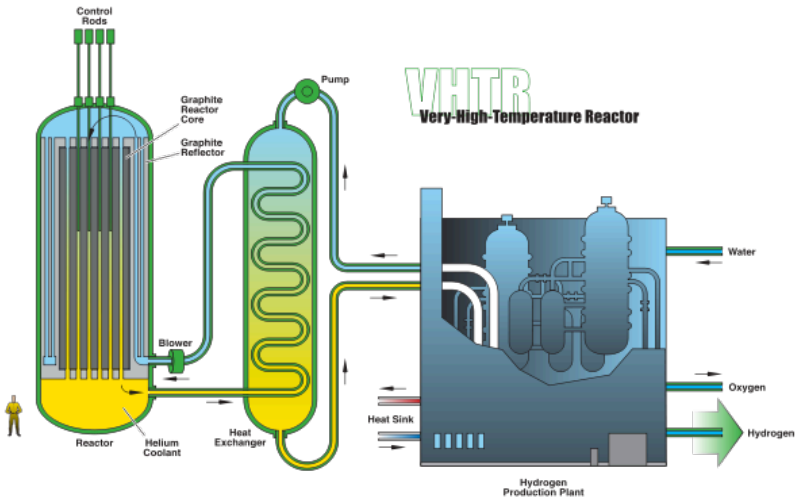
What containment is used in an LWR?

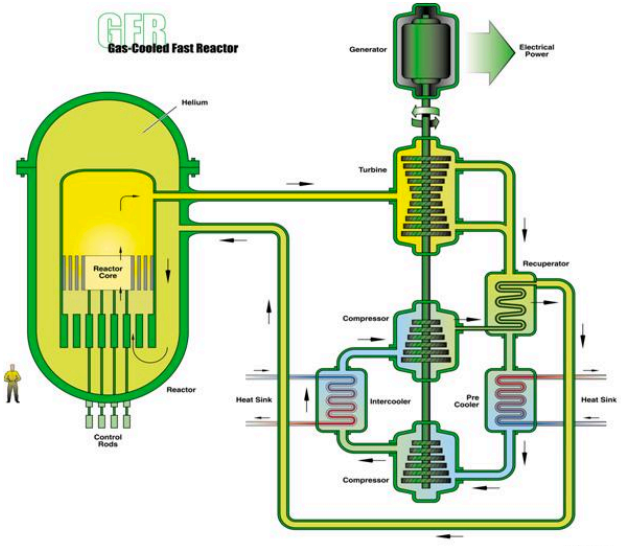
- Both the reactor pressure vessel and the containment structure are there to keep bad things from happening

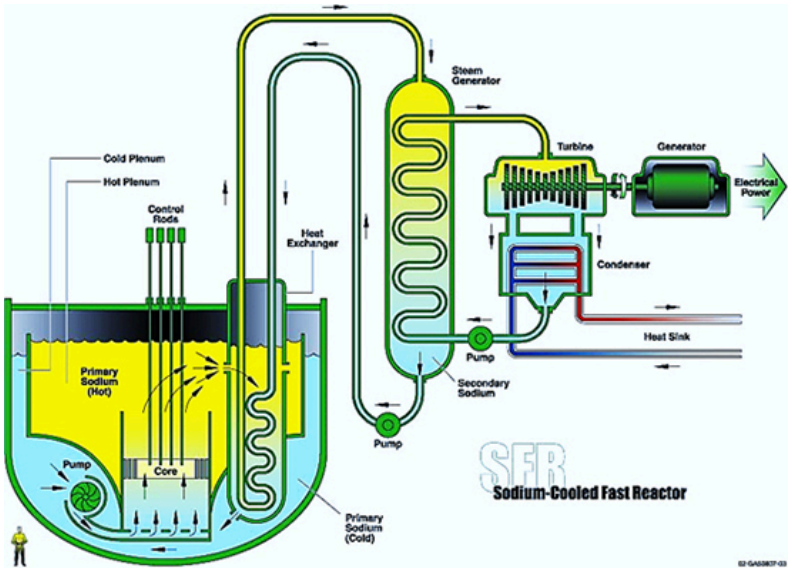


Though most reactors in the world are LWRs, there are many different ways to build a reactor



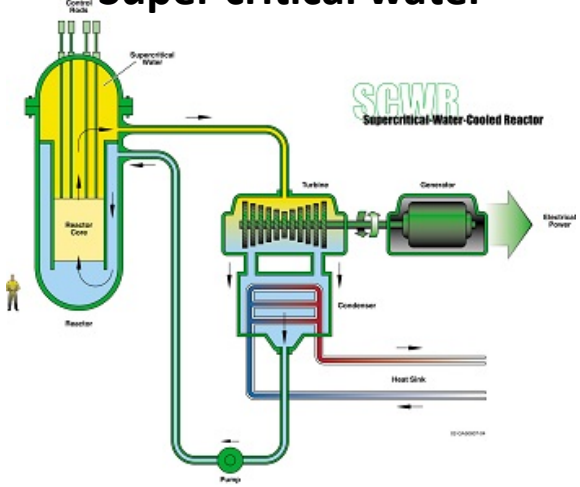




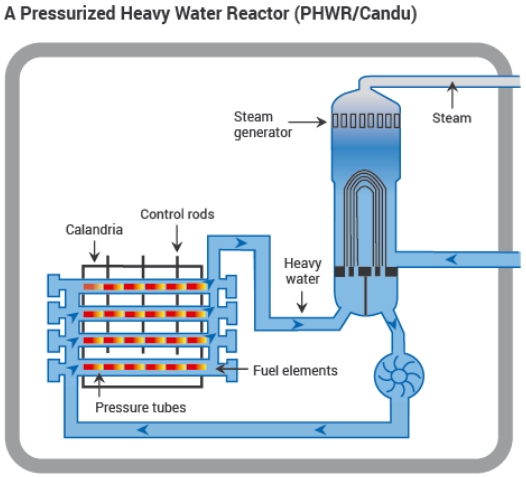


There are many ways besides light water to remove heat from the fuel

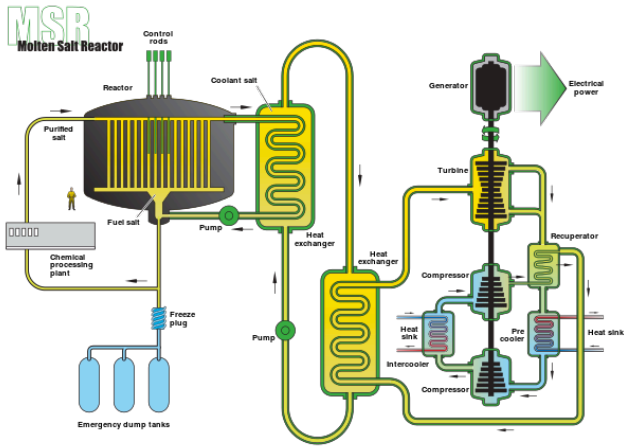
Super critical water



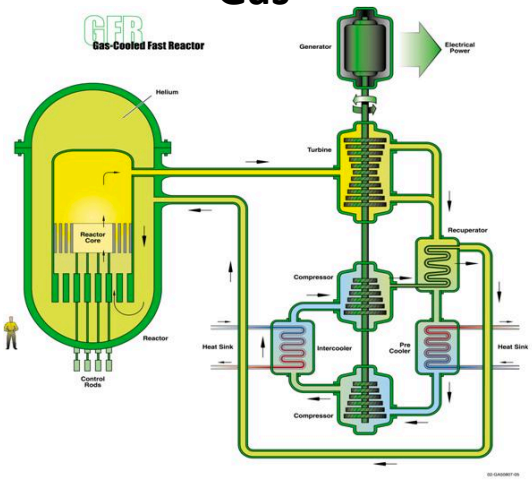
Heavy water



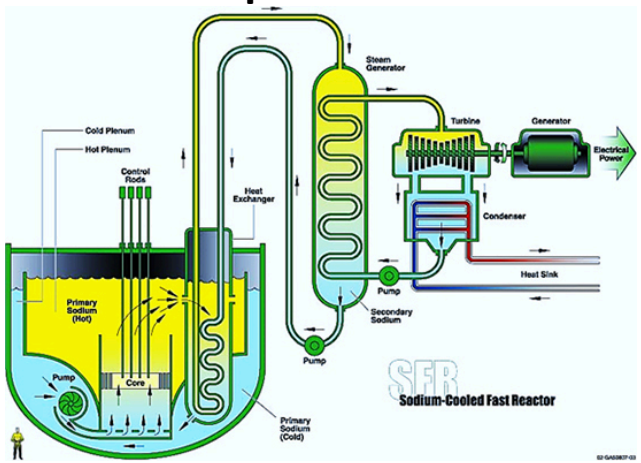
Molten salt



Gas

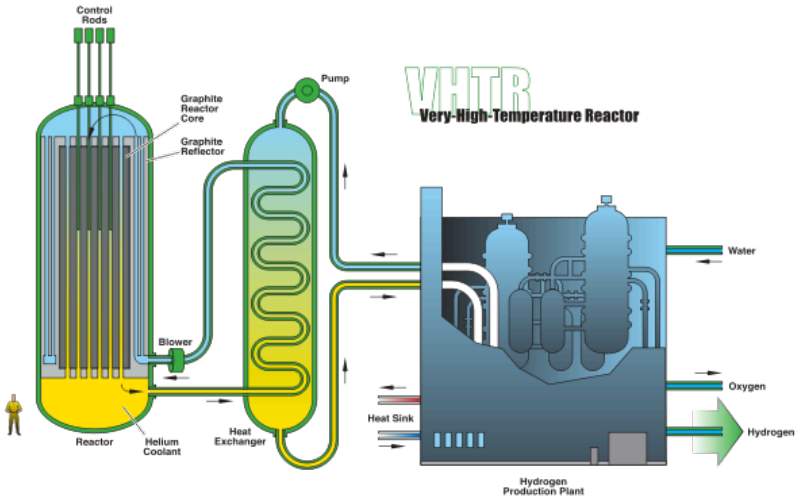


Liquid metal



There are more ways to use the heat than generating electricity from steam

We could use the heat to generate hydrogen



- The heat could also be used for industrial purposes
  - Oil refining
  - Waste water treatment
  - Oil shale production
  - Thermal-chemical processes

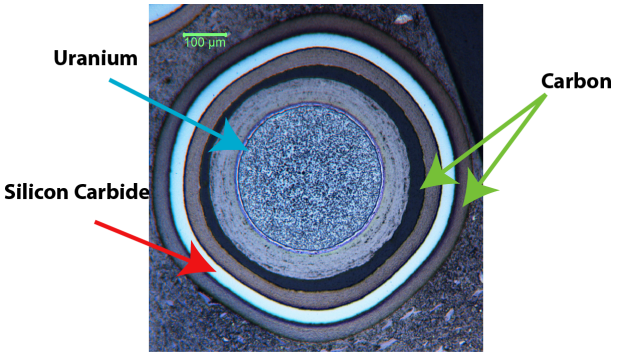
As far as I am aware, all reactor designs control the reaction with control rods

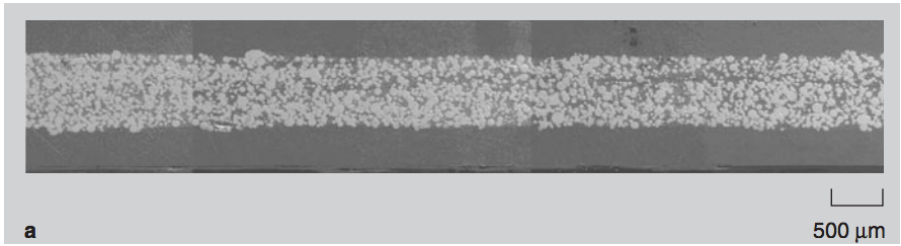
- Additives to the reactor coolant are also used to control reactivity, but they cannot provide enough control to replace control rods.
- Do you have any ideas?

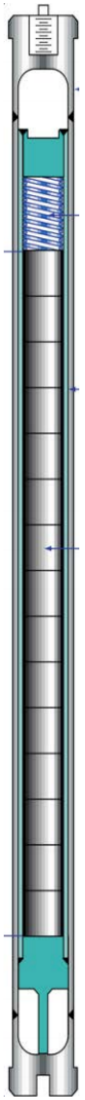
There are five materials typically used as moderators

- Light water (hydrogen)
- Heavy water (deuterium)
- Graphite (carbon)
- Beryllium metal (beryllium)
- Lithium fluoride salt (Lithium-7)
- They take the form of liquid, blocks, or even balls

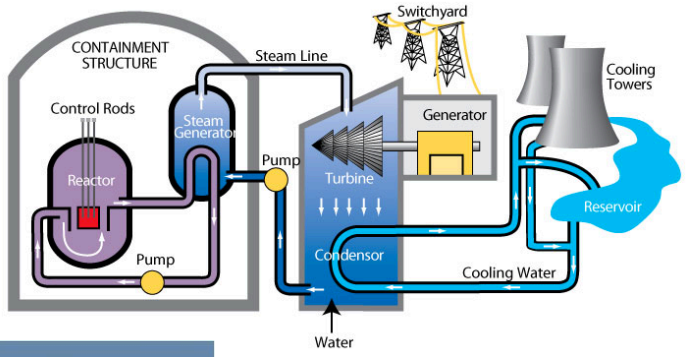
The structure of the fuel facilitates trapping fission products, rotating the fuel, and refueling







We are most familiar with fuel pellets, stacked in together within a cladding to form a fuel rod



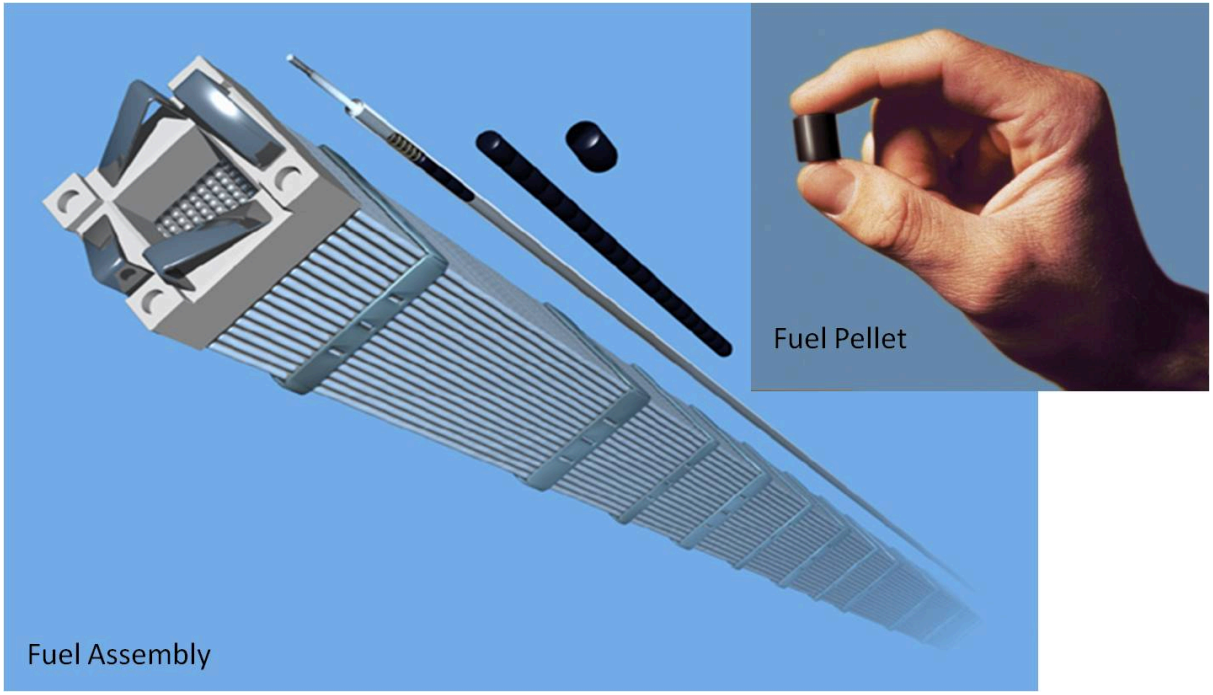
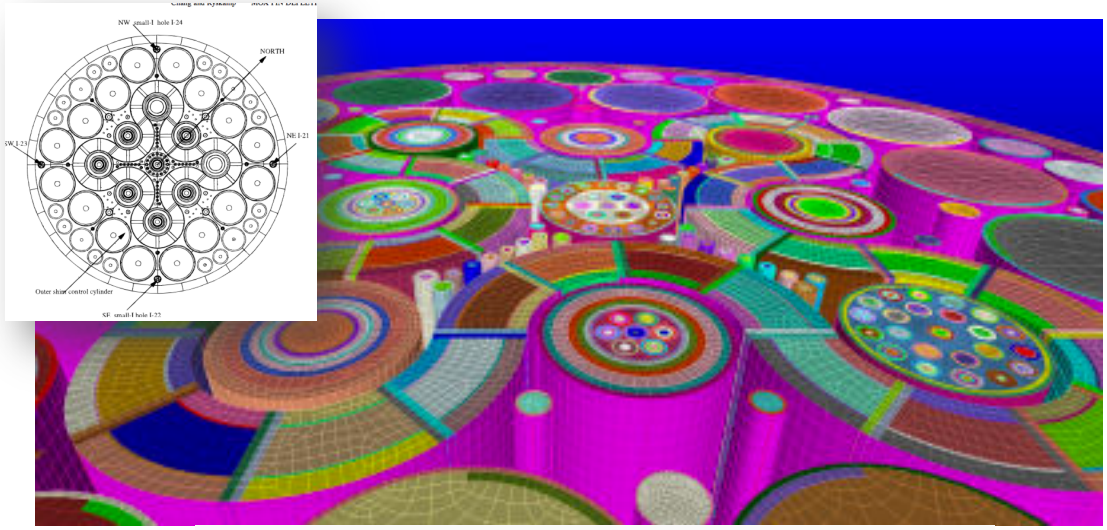
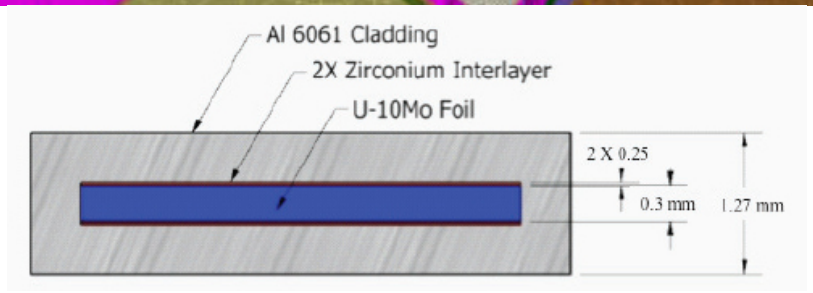
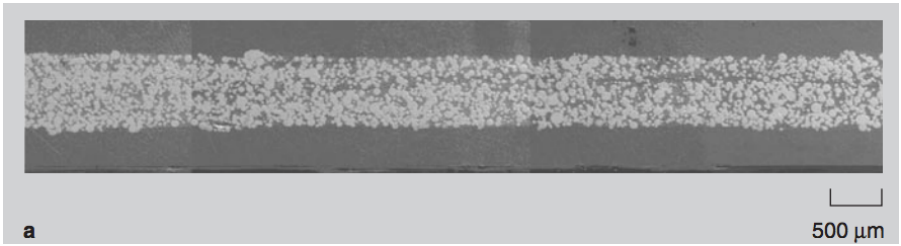


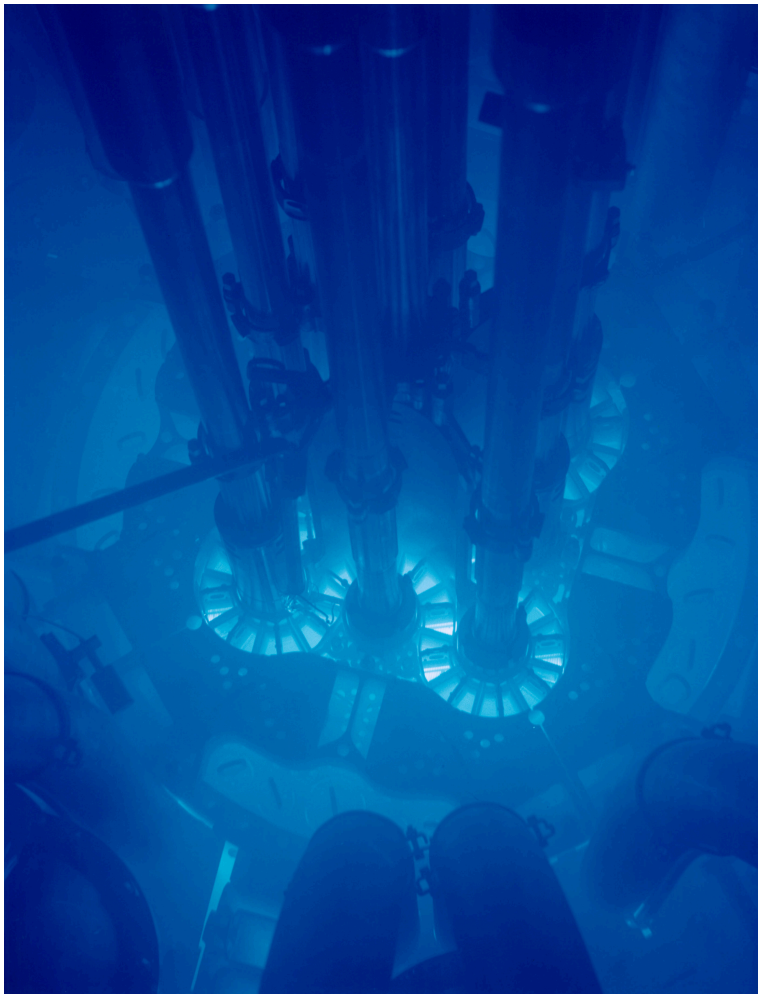
Plate fuel sandwiched in cladding is often used in test reactors



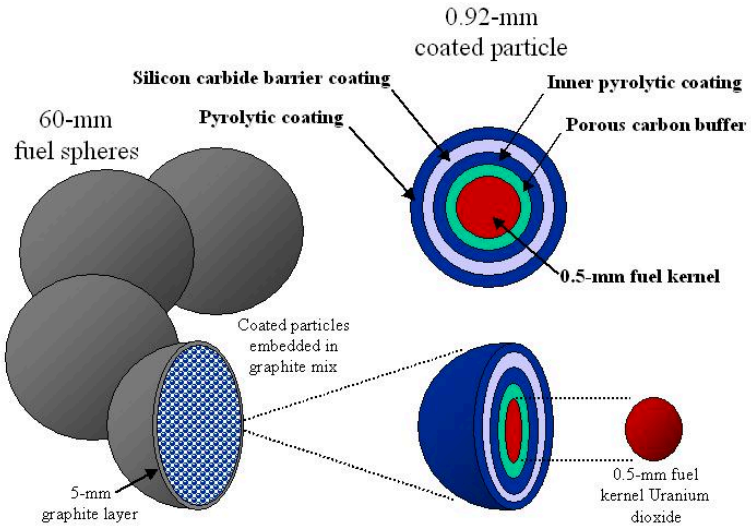


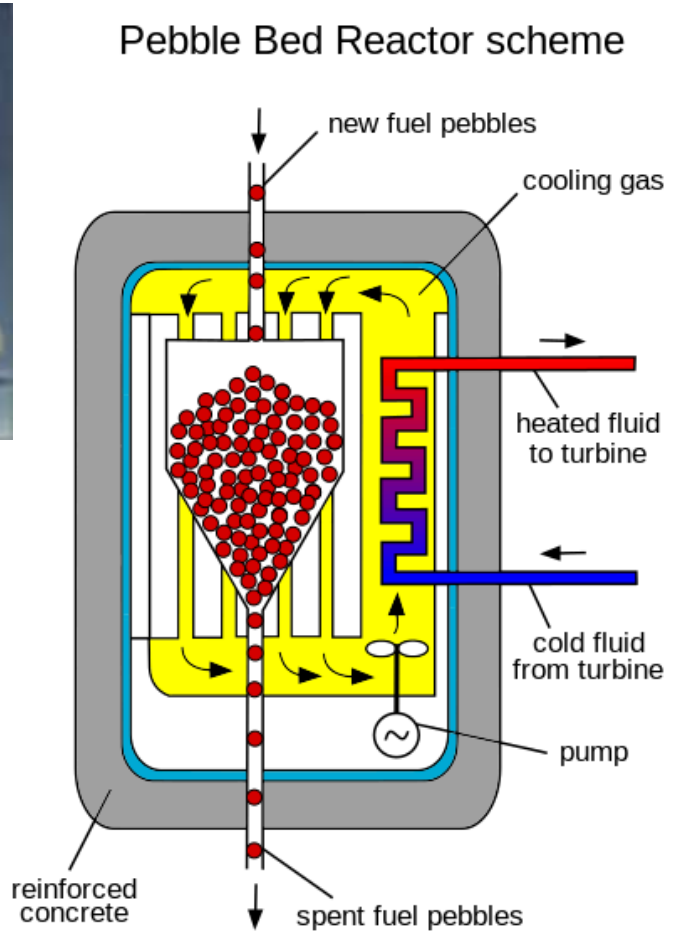


INL's Advanced Test Reactor



TRISO fuel particles are a promising fuel geometry that could be used in pebble bed Gen IV VHTRs





Quiz question: Nearly all reactor fuel employs some other material as a cladding that surrounds the fuel. Which is NOT a reason for the use of cladding?

- Provides a barrier between the fuel and the coolant
- Contains fission products
- Provides thermal barrier between the fuel and the coolant
- Prevents fuel fragments from impeding coolant flow

Attempts: 33 out of 33

+0.60

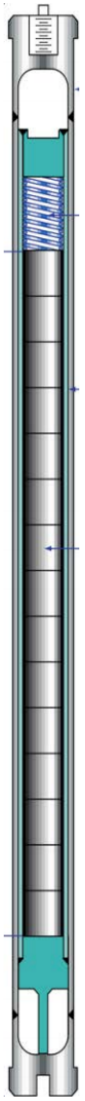
Discrimination Index

Nearly all reactor fuel employs some other material as a cladding that surrounds the fuel. Which is NOT a reason for the use of cladding?

Provides a barrier between the fuel and the coolant		0 %
Contains fission products	1 respondents	3 %
Provides thermal barrier between the fuel and the coolant	30 respondents	91 % ✓
Prevents fuel fragments from impeding coolant flow	2 respondents	6 %

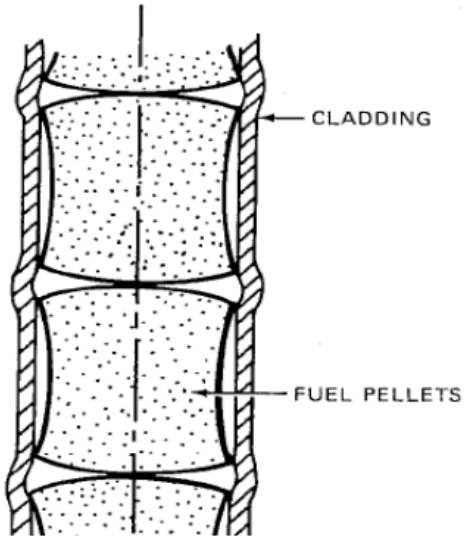
Most fuel geometries have some sort of cladding around the fuel

- The primary focus of the cladding is to separate the fuel from the coolant.
  - It 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



There is a gap between the fuel and the cladding in most fuel rods to avoid pellet/cladding interaction

- Fuel swells during reactor operation and the cladding creeps down around the fuel.
- To avoid 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

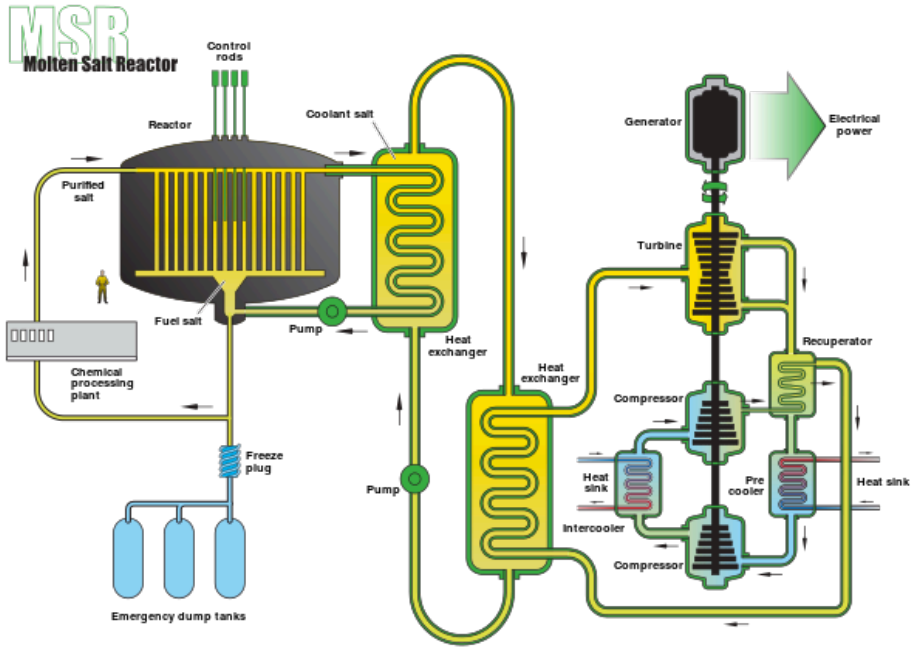


Olander, p. 584 (1978)

LWR cladding is made from zirconium alloys, but other reactor designs use other materials

- 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
  - FeCrAl steels

Molten salt reactors dissolve U-235 in molten salt for the fuel and use molten salt for the coolant



- Advantages
  - "Walk away safe" – We aren't aware of major negative consequences during typical accident scenarios. Simpler than typical LWRs
  - Liquid fuel avoids most fission product issues and can burn actinides
- Disadvantages
  - Though a molten salt test reactor was run for several years, we still don't know enough to be sure there aren't major issues.

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
  - The capability to control the reaction
  - A moderator (for thermal reactors)
  - 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