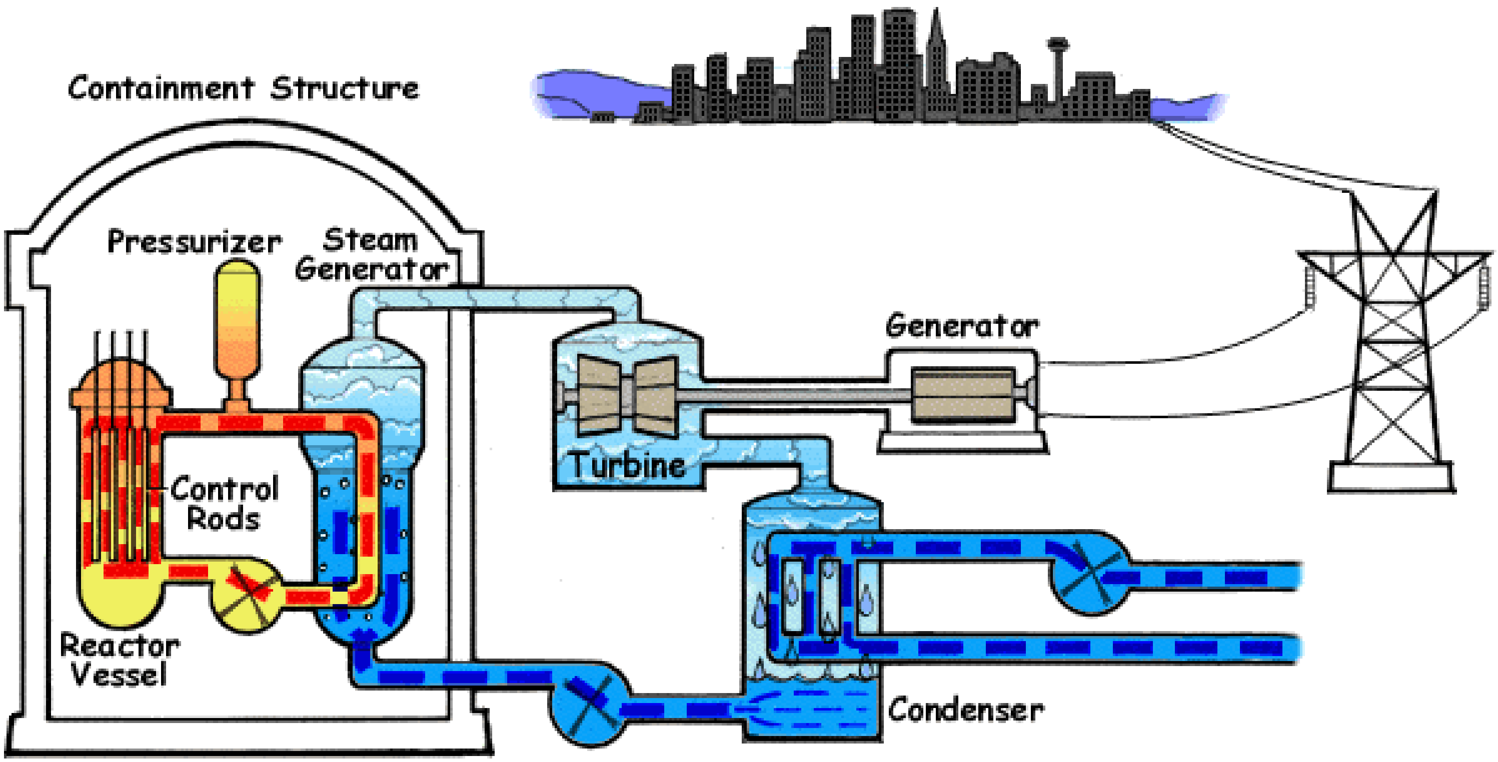
Chapter 4

Power Reactor Core

PWR

- About 70-75% of US commercial reactors
- Two separate coolant loops
  - Primary: Reactor cooling to steam generators (single phase)
  - Secondary: Steam generators to Turbines to Condenser (phase change)
- About 150-200 fuel assemblies
  - 1000 to 1200 MWe
  - Roughly 21 cm x 21 cm

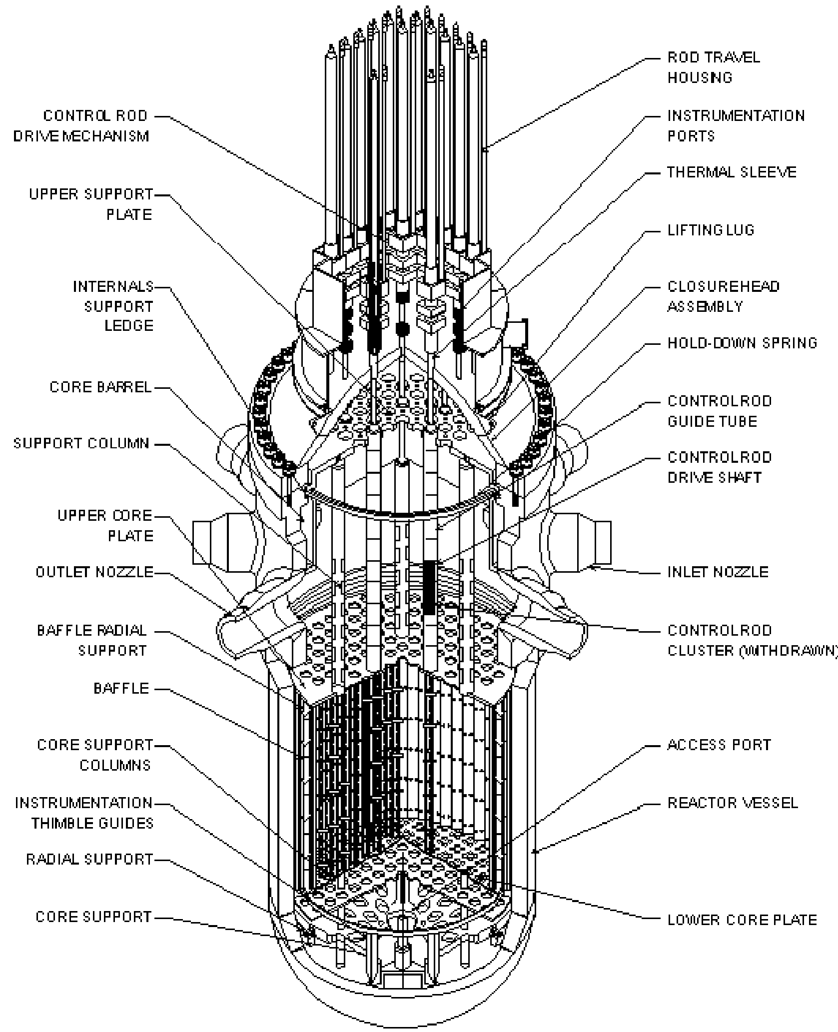
PWR



Public domain image from wikipedia.

PWR

- Light water coolant and moderator: no physical separation
  - Inlet: 275 C
  - Outlet: 315 C
  - Pressure: 15 MPa
  - 32-33% efficient



Public domain image from wikipedia.

PWR: Fuel Assembly

- UO_2 fuel: ceramic form
- Enrichment 3-4.5% (max of 5% in US)
- Zircaloy cladding
- 14 x 14 to 17 x 17 fuel rods
- 4 meters long

Public domain image from wikipedia.

PWR: Control Mechanism

- Boron in moderator (coolant): Boric acid mixed in the water, B-10 has a high thermal x.s.
  - Concentration is adjusted to keep reactor critical
- Control rod banks
- Roles
  - Control excess reactivity
  - Enable startup
  - Counter act
    - the fission product poisons
    - negative temperature feedback
    - fuel depletion

PWR: Important Component

- Pressurizer: Maintains pressure inside primary coolant loop
  - If coolant temperature increases, water density will decrease, thus taking more space. The water expands in the pressurizer and raises the water level, compressing the steam at the top and increasing the loop pressure.
    - Cold water is sprayed on top of the steam, thus condensing it and reducing pressure. If pressure keeps increasing, release valves open.
  - If coolant temperature decreases, water density increases, thus taking less space. The water level of the pressurizer drops .
    - Heaters kick in to boil some of the water and increases qty of steam, thus increasing the pressure in the loop.

PWR: Emergency Core Cooling

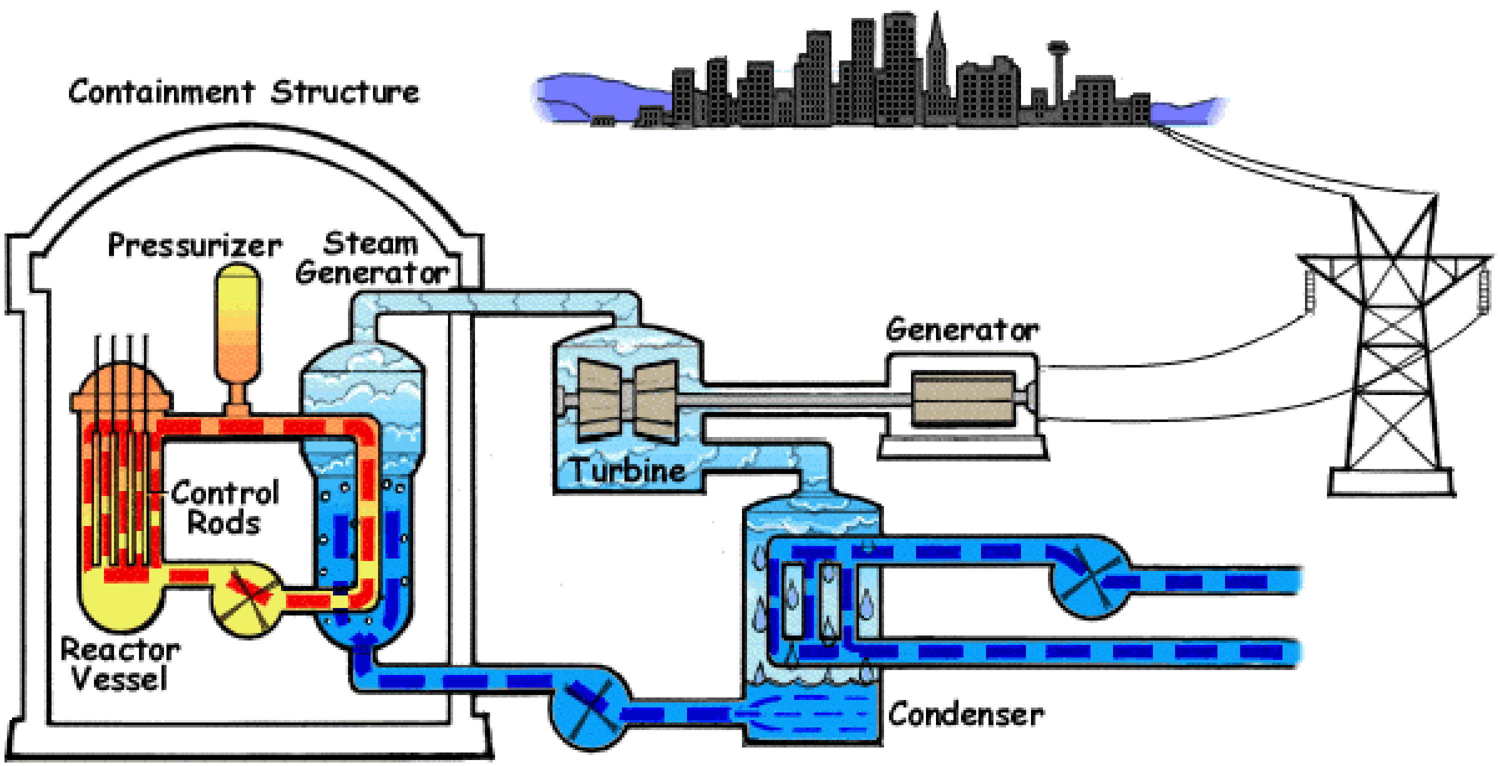
- High pressure injection
- Intermediate pressure injection
  - Provide water to the core when water pressure remains relatively high
- Cold leg accumulators
  - Doesn't require electrical power

    Borated water in a tank with a pressurized nitrogen bubble at the top
  - Kicks in when significant pressure drop
- Low pressure injection
  - Residual heat removal
  - Also takes water from sump pump and re-circulates in long outages.

BWR

- About 25-30% of commercial reactors in the US
- Only one cooling loop
- Up to 800 assemblies in a core
  - Roughly 15 cm by 15 cm
  - Approx 1000 MWe

BWR



Public domain image from wikipedia.

BWR

- Light water coolant and moderator: no physical separation
  - Inlet: single phase
  - Outlet: 285 C, boils, two-phase
  - Pressure: 7.5 MPa

BWR Fuel Assembl

- UO2 fuel: ceramic form
- Enrichment 3-4.5% (max of 5% in US)
- Zircaloy cladding
- 6 x 6 to 10 x 10 fuel rods
- 4 meters long

BWR Control Mechanism

- Cruciform control blades
  - Control rods move to adjust core power
  - Shutdown mechanism
  - Driven from the bottom of the core
- Coolant feed flow
  - Increase
    - Less void, more moderation, power increases
  - Decrease
    - More void, less moderation, power decreases

BWR: Emergency Core Cooling

- High pressure injection
  - Provide water to the core when water pressure remains relatively high
- Automatic Depressurization system
  - Reduces pressure of the core if high pressure injection is not working
- Low pressure injection
  - Provides water to the core in large breaks
- Core spray
  - Sprays water on the top of the core

Advantages

- PWR
  - Negative Doppler coefficient
  - Negative coolant void coefficient
  - Uses light water
  - No radioactive contamination of steam generators
  - Less complex to operate than BWR
  - Smaller footprint than BWR
- BWR
  - Negative Doppler coefficient
  - Negative coolant void coefficient
  - Uses light water
  - No boric acid in the moderator
  - Less pressure than PWR
  - Lower fuel temperature than PWR

New designs – AP1000

- Advanced PWR ~1100 MWe
- Proposed and designed by Westinghouse
- Simpler designs
  - Less piping
  - Fewer valves
  - Fewer pumps
  - …

AP 1000

- Passive safety system
  - Relies on natural convection to cool the core in the event of an accident
  - "… the AP1000 relies on the natural forces of gravity, natural circulation and compressed gases to keep the core and containment from overheating."
- Results of the Probabilistic Risk Assessment (PRA) show a very low core damage frequency (CDF) that is 1/100 of the CDF of currently operating plants and 1/20 of the maximum CDF deemed acceptable for new, advanced reactor designs.

AP 1000

- 6 units under construction in China
- Combined License (COL) applications filed for 14 units in the US

New design - EPR

- European Pressurized Reactor ~1600MWe

- Design features
  - Core catcher in the event of a core meltdown
  - Four independent emergency cooling systems (300% redundancy)
  - Double containment to resist airplane crash

EPR

- Proposed and design (and under construction) by AREVA
  - One unit in Finland
  - One unit in France
- 4 COL applications filed in the US

Images removed due to copyright restrictions.

New design – ABWR

- Advanced BWR
  - Passive safety
  - Shorter construction time (39 months)
  - Designed by GE
- NRC approved ABWR in 1997
  - 4 units already operating in Japan
  - COL applications filed for 2 ABWRs in Texas

New design – ESBWR

- Economic Simplified BWR
  - Designed by GE- Hitachi
  - ~1600MWe
  - Natural circulation only, no pumps
  - Very low risk
    - CDF less than 1/10 of the AP1000’s
  - Much lower costs
  - COL applications filed for 6 units in the US

Summary from this class

- Neutron Multiplication Factor
- Essential features of PWR and BWR
- Understand how and when the pressurizer operates
- Advantages and Disadvantages of PWR and BWR
- Control Mechanisms of PWR and BWR

k: six factor formula

$$P_{NL} = P_{FNL} P_{TNL}$$

$P_{FNL} \equiv$ probability that fast neutron will not leak out

$P_{TNL} \equiv$ probability that thermal neutron will not leak out

$$k = \eta f \varepsilon p P_{FNL} P_{TNL}$$

k-infinity: four factor formula

$$k_{\infty} = \eta f \varepsilon p$$

Summary from this class

- Neutron life cycle in a thermal reactor
- Four factor formula
  - Definitions of the terms
  - Range of the terms
- Six factor formula

CANDU - History

- UK war scientists moved to Canada; research laboratory created at the Université de Montréal in 1942. Also came Lew Kowarski, Russian émigré physicist who had worked in France and then had fled to England.
- Kowarski came with very valuable cargo: almost entire world’s supply of heavy water, spirited out of Norway and then out of France.

- 1943: Meeting between Roosevelt, Churchill, and Mackenzie King. Canada enters into wartime collaboration on research into nuclear fission with UK and USA.
- The importance of heavy water as a neutron moderator was understood, and since Canada now had an inventory of it, Canada was given the responsibility for developing a heavy-water reactor to eventually produce plutonium for an atomic bomb for the war effort.

- The Montréal Laboratory was moved to Chalk River in 1944.
- Work began on designing NRX, which was to be the production reactor for plutonium for the war effort.
- However, Lew Kowarski was able to get authorization, as a first step, to build a research reactor: ZEEP (Zero Energy Experimental Pile).

- Following end of war, in the early 1950s, several visionaries, among them Bennett Lewis, head of Chalk River Nuclear Laboratories (which eventually became AECL in 1952), lobbied hard to apply Canada’s nuclear knowledge to peaceful ends: the production of electricity.
- Bennett, a man of purpose and eloquence, convinced the Government to give AECL that mandate.

- Excellence and success of ZEEP development made it natural to continue in the heavy-water “path” for the moderator.
- This was in contrast to the US decision to develop light-water reactors for power, which followed from the successful American nuclear-submarine program.
- A distinctive, world-class Canadian reactor design was born – a great technological success and a proud feat for a country with a small population.

Basic Characteristic

- Heavy water moderator
  - The neutron economy of heavy water is such that natural uranium can be used as fuel.
  - With light water as moderator, this is not the case: the rate of neutron absorption is sufficiently high that the reactor cannot go critical with natural uranium fuel; the uranium must first be enriched in the 235U isotope to increase the probability of fission relative to that of absorption.

- Natural Uranium Fuel
  - Important for Canada: self-sufficient in its very large uranium resources, it did not have to develop the complex and costly enrichment capability or rely on external sources of enriched fuel.
  - Remains important factor for other small countries not willing to depend on foreign sources for reactor fuel.

- CANDU fuel is uranium dioxide.
- Each element consists of UO_2 pellets encased in a zircaloy sheath.
- A number of fuel elements are assembled together to form a bundle of length ~ 50 cm.
- The elements are held together by bundle end plates.

Public domain image from wikipedia.

- The CANDU fuel bundle is short and easy to handle.
  - No need for special borated casks
- It has few (7) different components.
- CANDU fuel is much cheaper than light water reactor fuel
- CANDU fuel-manufacturing capability can readily be developed by even small countries which purchase CANDU reactors.
  - No need for enrichment

- Note: although natural uranium has been the fuel for CANDU since the beginning, the heavy-water moderator does not **demand** natural uranium.
- In fact, CANDU is extremely flexible - can burn enriched uranium, mixed-oxide (U/Pu) fuels, or even irradiated fuel from light-water reactors.
  - DUPIC cycle
  - Th cycle
  - MA burning
- Latest CANDU design, the Advanced CANDU Reactor (ACR), will use slightly-enriched uranium.

Pressure Tube Design

- Canada did not have a heavy industry capable of manufacturing a pressure vessel of the required size, so a contract was signed to purchase the vessel from the UK.
- However, the fathers of CANDU then started to be concerned about the size of the pressure vessel, not only for NPD, but even more so for the larger reactors that would follow. The pressure vessels would really have to become enormous.

- As a result of these misgivings, the pressure-vessel design for NPD was scrapped (with penalty to tear up contract for vessel).
- NPD was changed to a pressure-tube design – the tubes would be the pressure boundary for the hot coolant, the reactor vessel (renamed a **calandria)** would not be at pressure, and would be much simpler to manufacture.
- In fact, it could be manufactured domestically, another important plus for Canada.

- NPD designers, and those of all currently operating CANDUs, opted for horizontal pressure tubes.
- This was in the interest of symmetry – there would be no “preferred” direction for the coolant flow, as there would be if the pressure tubes were vertical.
- With horizontal pressure tubes, the coolant could be made to flow in opposite directions in alternate channels, which would further enhance axial symmetry.

- Very important to note that what made the pressure tube concept viable was zirconium.
- The large mass of metal in the pressure-tube design could absorb too many neutrons - definitely the case with steel pressure tubes: the fission chain reaction could not be made self-sustaining.
- Zirconium, “magic” nuclide with a very low neutron absorption cross section, came on the scene in time.
- This as the result of materials research in Chalk River for the US nuclear program.

- Note: while the pressure tubes are the pressure boundary, they would tend to conduct heat from the fuel out into the moderator.
- In order to provide insulation for the moderator and prevent it from boiling in contact with the hot pressure tube, each pressure tube is surrounded by a concentric calandria tube of larger diameter.
- The gap between pressure tube and calandria tube is filled with insulating gas (CO_2), allowing it to operate at relatively low temperature (~ 70 ^oC).

- In the pressure-tube design, the moderator and coolant are separated, in contrast to the situation in the pressure-vessel design. In principle, this allows the moderator and coolant to be different.
  - ACR uses light water as a coolant
- In spite of this, all operating CANDUs have heavy water as the coolant. The idea for retaining heavy water as the coolant too is to maximize the neutron economy.

- CANDU-6
  - 380 channels
  - ~ 7 m diameter
  - ~ 6m long active core
  - ~ 2200 MWth
  - ~ 650 MWe
  - ~ 30-32 % efficiency
  - 10 MPa
  - Outlet = 310 C

Online refuelling

- With pressure tubes, on-power refuelling becomes possible - fuel channels can be “opened” individually and at full power to replace some of the fuel. On power refuelling was therefore adopted for CANDU.
- On-power refuelling also means that “old” fuel is replaced by fresh fuel nearly continuously. Thus, very little excess reactivity is required. Batch refuelling would require a large excess reactivity at the start of each cycle (as in LWR).

- The short CANDU fuel bundle facilitates on-power refuelling - can then replace part of the fuel in a channel at each refuelling operation (
  - 8-bundle shift refuelling scheme in CANDU 6
  - 2-bundle shift refuelling scheme in ACR
  - Refuel about 1-2 channels per day
- Also, horizontal channels simplify refuelling – the bundles need not be “tied” together. In Gentilly-1, with vertical channels, a central tie-rod was needed to hold the entire fuel-string together.
- Horizontal channels allow axial symmetry (no difference in coolant density between the 2 ends).

Advantages of online refuelling

- Constant global power shape, with localized “ripples” as channels are refuelled and go through their burnup cycle
- Constant in-core burnup
- Constant shutdown-system effectiveness
- Possibility of on-power removal of failed fuel, and therefore clean HTS

Safety Advantage

- Unpressurized calandria - no risk of catastrophic vessel “break-up”
- Reactivity devices in unpressurized environment – no “rod ejection”
- Low excess reactivity – potential for reactivity addition small
- Very long prompt-neutron lifetime
- Redundant, independent safety systems

- Separation between control and safety systems
- Large volume of cool moderator “water” – excellent heat sink in hypothetical severe accidents
- Low fissile content in fuel – no criticality concern outside the reactor

Differences in Reactor-Core Design

<u>CANDU</u>

- Natural-uranium fuel
- Heavy-water moderator & coolant
- Pressure tubes; calandria <u>not</u> a pressure vessel
- Coolant physically separated
- Small/Simple fuel bundle
- On-power refuelling
- No boron/chemical reactor control in coolant system

<u>PWR</u>

- Enriched-uranium fuel
- Light-water moderator/coolant
- Pressure vessel
- No separation of coolant from moderator
- Large, more complex fuel assembly
- Batch (off-power) refuelling
- Boron/chemical reactor control in coolant system

Safety Systems

- Shutdown System 1
  - Spring loaded shutdown rod
- Shutdown System 2
  - Rapid injection of poison (Gd nitrate solution)
- Emergency Core Cooling System
- Containment

- Liquid zone controllers
  - 21 water rods that are filled with light water
    - 3 zones with 7 controllers
  - Light water acts as a poison in CANDU reactors
- Permanent control rods are inserted
  - 21 rods in total
    - Usually stainless steel
    - At Gentilly-2, they irradiated Co-59 to produce the Co-60 source
      - Radioactive tracer
      - Cancer treatment

Disadvantages

- Positive void coefficient
- Low fuel burnup
  - Large amount of waste
- Easy to produce Pu239
  - Proliferation issue
- Heavy water
  - Expensive to make

CANDU ACR

- ACR: Advanced CANDU Reactor
- Heavy water moderated
- Light water cooled
  - 12.5 MPa, Outlet T = 319 C
- Tighter lattice
  - From 28.5 to 24
- Same core size as the CANDU-6
  - Except higher power density
  - 1000-1100 MWe vs 600-650 MWe

- CANFLEX bundle
  - 43 fuel pins
  - Slightly enriched uranium
  - Dyprosium in fuel
- Higher fuel burnup
- Flatter power profile
- Reduction in void coefficient
  - Almost negative, recent studies indicate slightly positive

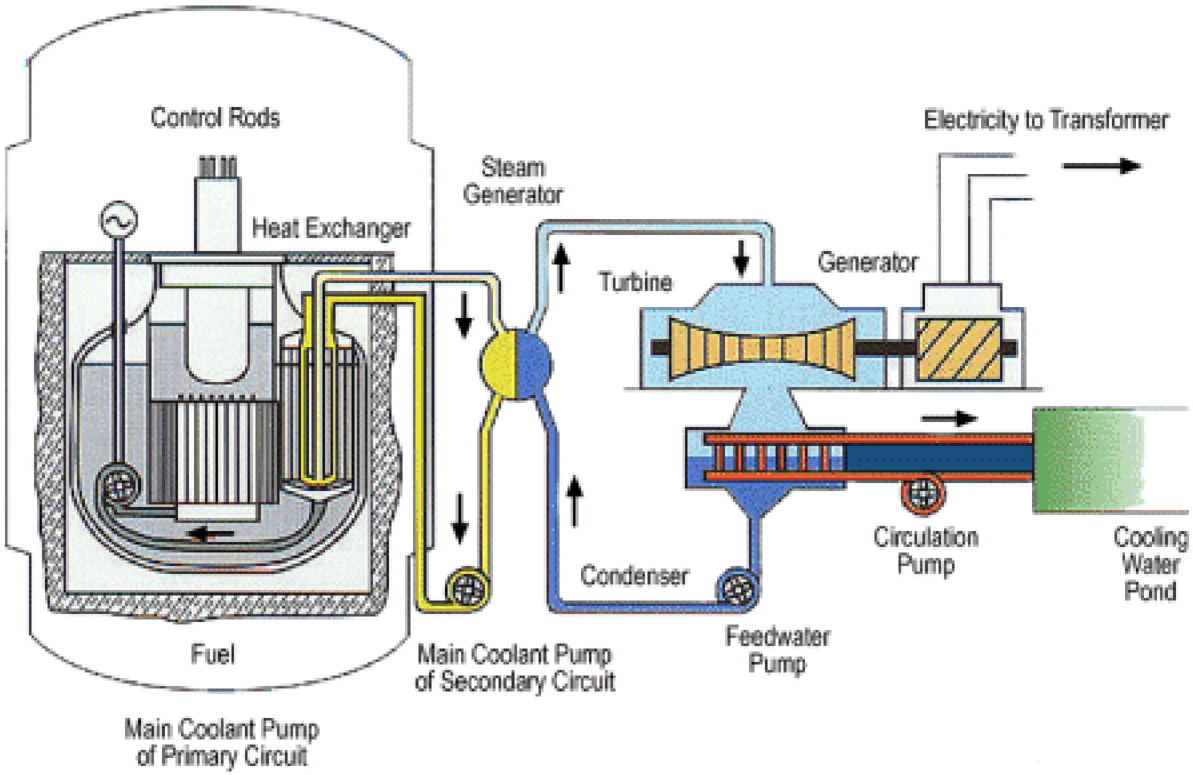
Fast Reactors

- Initially developed for *breeding*
  - Uncertainty on how much U-235 was present
  - Fear that nuclear might not be sustainable
- Breeding: Convert fertile materials into fissile
  - Th-232 to U-233
  - U-238 to Pu-239
- First fast breeder reactor
  - Clementine, built at LANL in 1946
  - EBR-I, built in Idaho, first to produce electricity

Design considerations

- No moderator
  - Avoid low mass materials
- High enrichments are required
  - 10-30% either U-235 or Pu-239
- Hexagonal lattices
  - Reduces coolant-to-fuel ratio
- Fuel can be either metal of ceramic
- Coolant is usually a liquid metal (some designs use gas)
  - Na, NaK, Lead-Bismuth
  - Low pressure, ~ 1MPa

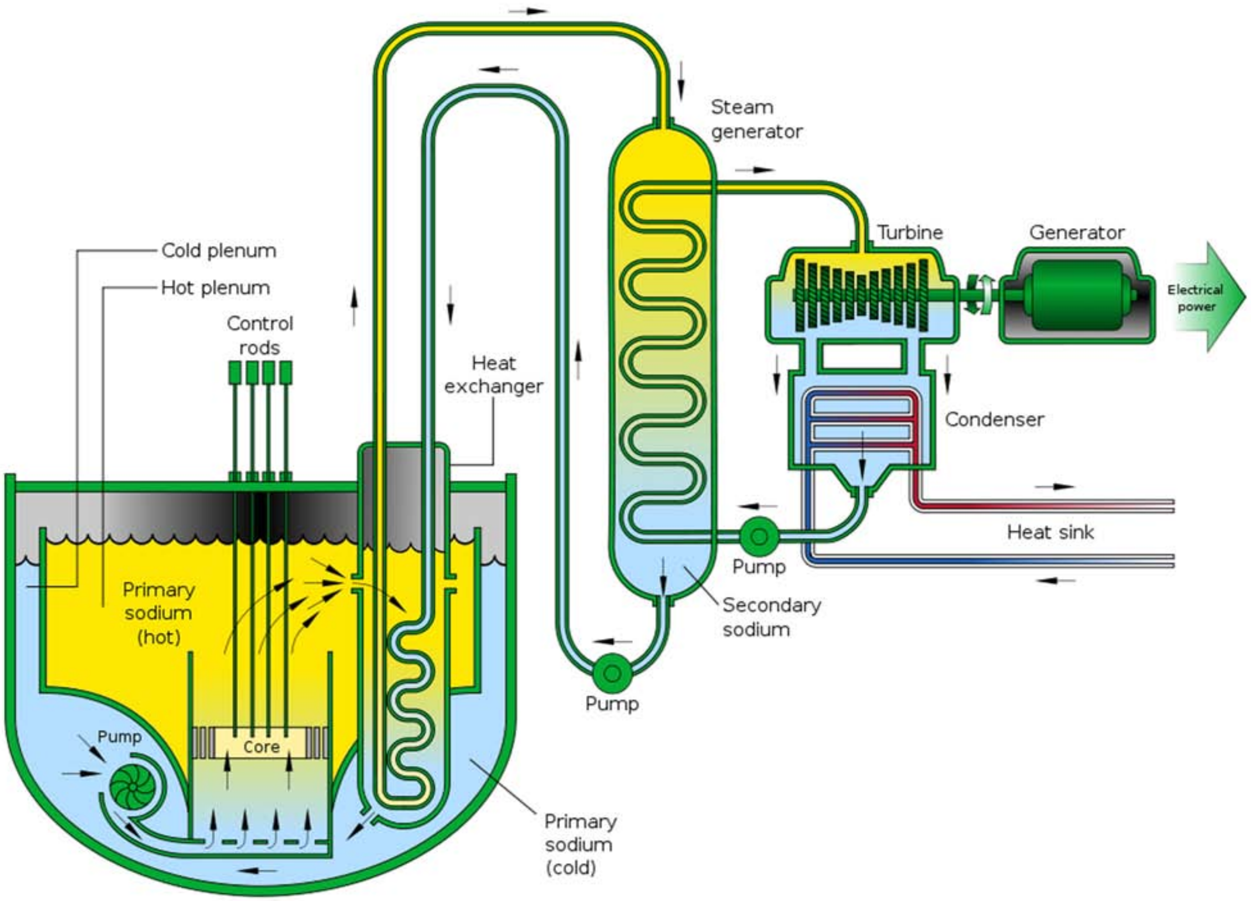
BN-600 Reactor Design



Public domain image from wikipedia.

Designs

- Loop design
- Pool design
- Three loops
  - Primary
  - Intermediate
  - Steam Generator
- Breeding usually occurs in a blanket of U-238 that surrounds the core



Public domain image from wikipedia.

Fuels

- Metal
  - Faster (Harder) neutron spectrum
    - No moderation from oxygen
  - High thermal conductivity, which compensates for low meting point
  - Lots of swelling, which prevents high burnup
- Oxide
  - Lots of experience at high burnup
  - High melting point (2750 C)
  - Poor Thermal Conductivity
- Nitride and Carbide
  - High thermal conductivity

Fuel lattice

- Wire wrap
- Cladding
  - Zirconium is not suitable, does not behave well at high temperatures
  - Steel is usually preferred

Control Mechanisms

- Control rods
  - Absorbing material such as boron carbide
  - Much less effective than in thermal reactors
- Removing fuel
  - Method has been used in EBR-II, but it is not common

Need for fast reactors

- Transmutation of MA
  - Most MAs are fissile to fast neutrons
  - Higher ratio of fission/absorption
- Breeding
- Power Production

Problems with SFR

- Cost
  - Much more expensive than LWRs
- Positive void coefficient
- High Pu content
  - Proliferation issue
- High MA content
- Core meltdown can lead to reactivity excursion
- Reprocessing
  - Cost
  - Proliferation issue

Important Ratios

- Fissile Conversion Ratio (CR)

  Fissile material produced / Fissile material destroyed

- Breeding Ratio
  - Same as conversion ratio, but only when CR > 1
- TRU Conversion Ratio

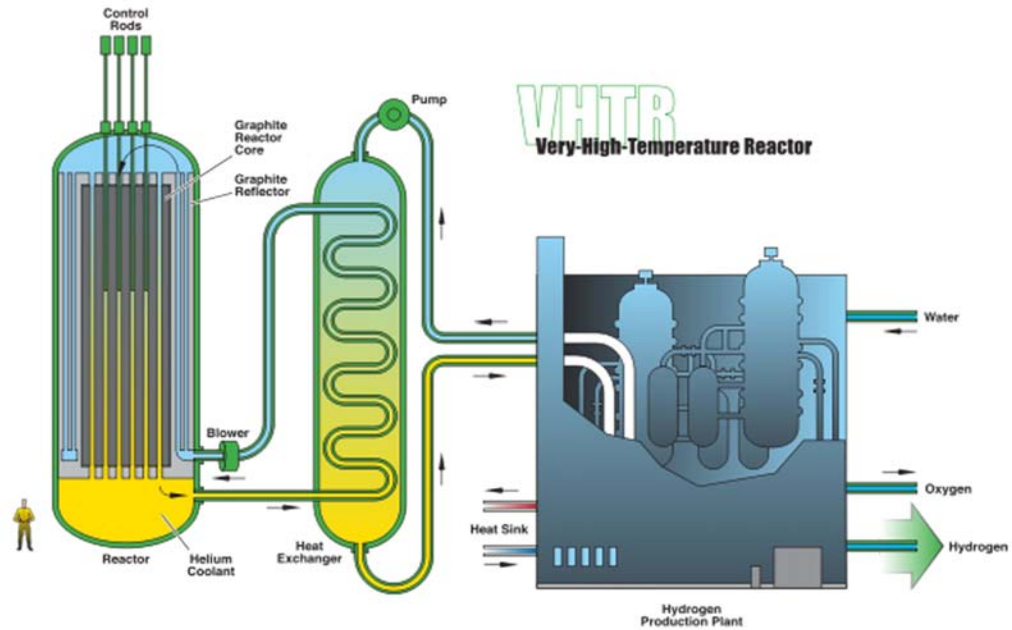
  TRU Produced / TRU destroyed

    - Equivalent to the absorption rate in U-238 divided by the total fission rate in TRU

High Temperature Gas Reactors

Basic Gas Reactor Design

- Moderator – Graphite
- Coolant – CO_2; Helium; Molten Salt
- Fuel – $(U,Th)O_2$,C,or CO
- Vessel – steel or prestressed concrete
- Cycle – Indirect Steam or Direct Brayton

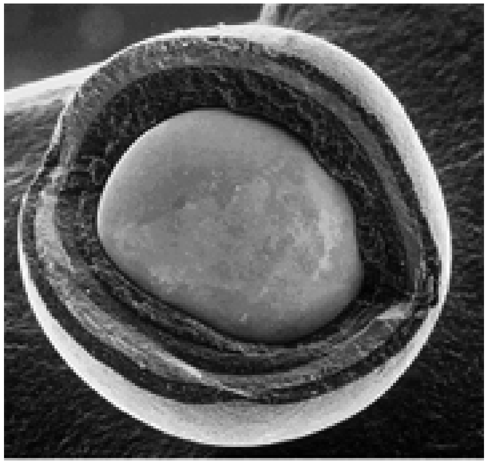


Public domain image from Wikipedia.

New Design Premise?

- Commercial
  - – Magnox reactors in Britain (60s-90s); Gen I
  - – UNGG reactors in France (60s-90s); Gen I
  - – Fort St. Vrain in US (70’s-80’s)
  - – AGR in Britain (80s-Present); Gen II
- Research
  - – Pebble Bed in Germany ()
  - – HTTR in Japan (1999-Present)
  - – HTR-10 in China (2003-Present)

Fuel Particles



Public domain image from wikipedia.

- TR(istructural) ISO(tropic) coating
  - Porous Carbon, IPyC, SiC, OPyC
  - Cracking Resistant beyond 1600^{o}C
    - Thermal stress
    - Fission Product Buildup
  - O.D. of .5-1.0 mm.
  - Fuel Kernel Encased
    - Enrichment 7-15%

Fuel Pebble Type

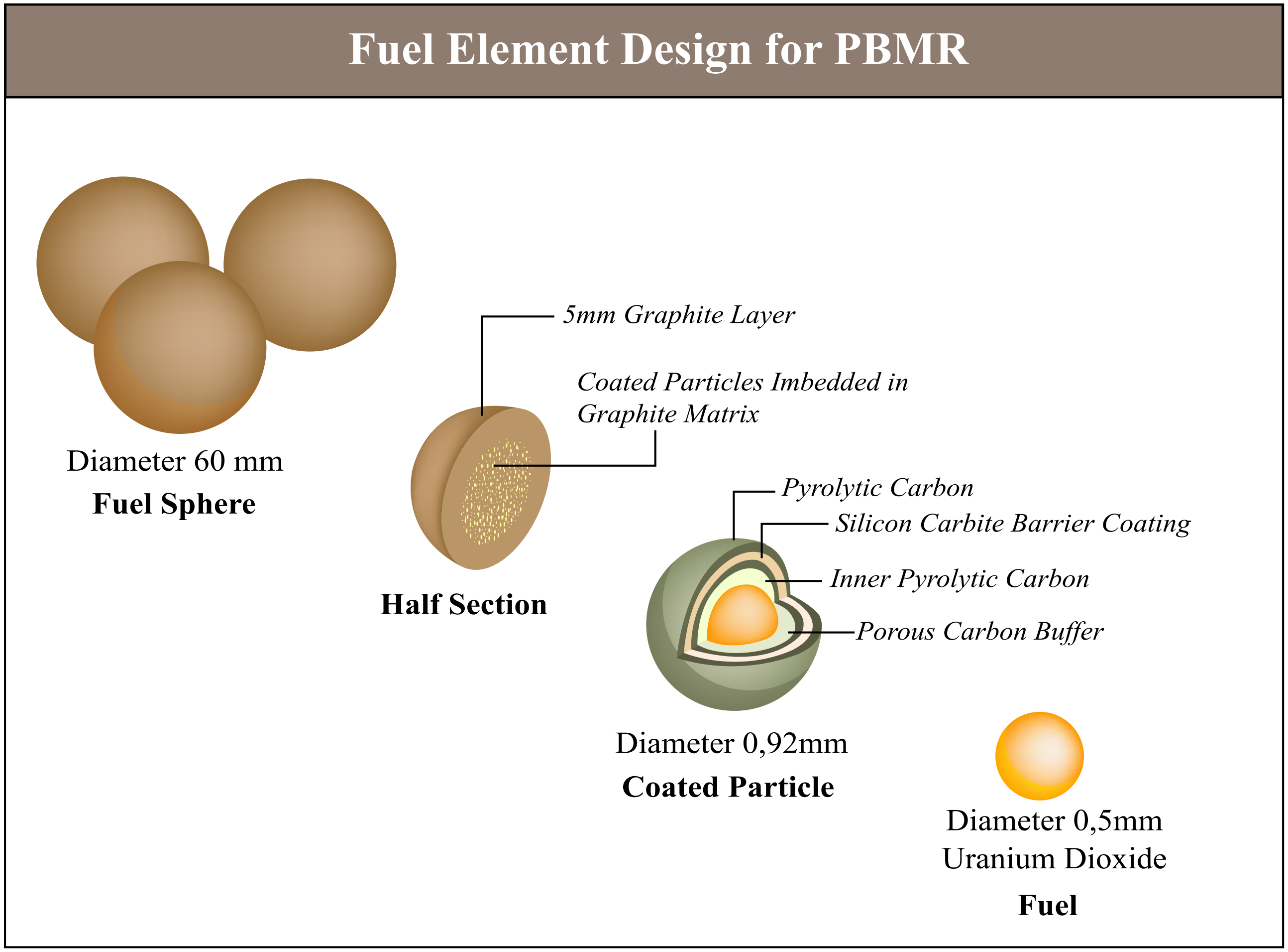


Image by MIT OpenCourseWare.

Comparison

- Prismatic
  - Pros
    - Operating/Fabrication Experience (Ft. St. Vrain)
    - Coolant flow and fuel positions well known -> more accurate modelling
    - Control rod placement easier
  - Cons
    - High excess reactivity
    - Hot spots not mobile
    - Need periodic shut down for refueling
    - Water ingress -> strong reactivity increase

Comparison

- Pebble Bed
  - Pros
    - Can keep excess reactivity to minimum
    - More effective fuel utilization
    - Few S.D.'s required
    - Enrichment lower
    - Peak fuel temperature lower
  - Cons
    - Difficult to calculate flow and temperature
    - Carbon dust production (3 kg/year)
    - Complications due to uncertainty in fuel position

Factors in Neutronics

- Block and/or pebbled bed packing fraction
- Reactivity effects of working fluid (He)
- Dependence of k on temperature, enrichment, core geometry
- Water ingress effects on reactivity
- Temperature coefficients of reactivity
- Fuel burnup effect on k over time

Safety Considerations

- Events leading to Reactivity Insertion
  - Water Ingress, Control Rod ejection, Repacking of fuel pebbles
- Air Ingress coupled with Carbon dust formation
- Decay Heat Removal (due to FPs)

Air Ingress Experiments

- Open Air Chimney Test Results; He to Air at 850^{o}C

Images removed due to copyright restrictions.

HTGR vs. Other Reactors

- Graphite moderator well suited for transient scenarios (high thermal inertia)
- Primary coolant less radioactive
- Very high burnup possible (to 200 GWd/t)
- Applications for high outlet temperatures
  - Oil Extraction from Shale and Oil Sands
  - Hydrogen Production, Coal Gasification
  - Desalinization
- Lower Power Density (~1/30 of PWR)
- Proliferation Resistant