Chemical Engineering 612

Reactor Design and Analysis

Lecture 9

Nuclear Reactor Concepts

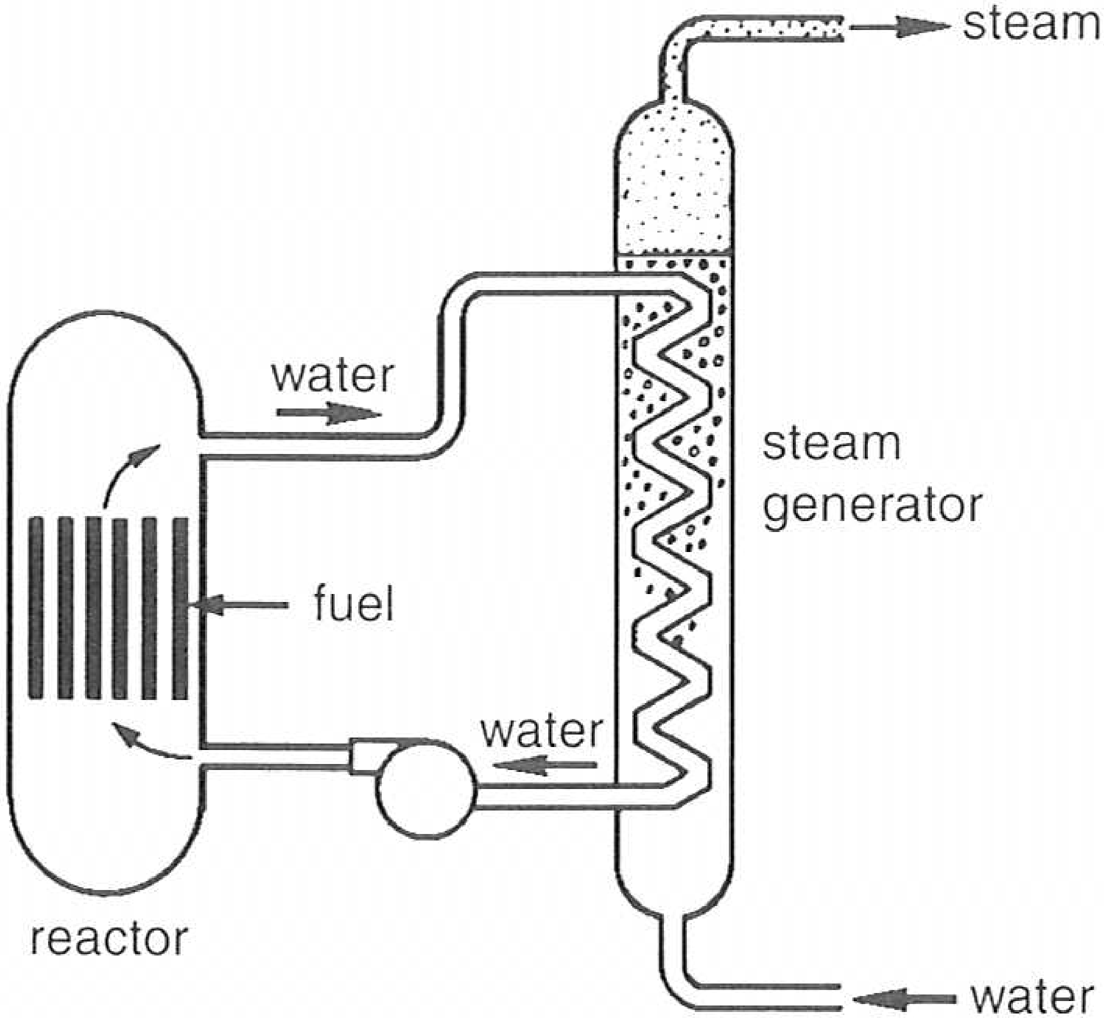
Spiritual Thought

“Historically, fear has often been used as a means to get people to take action. Parents have used it with their children, employers with employees, and politicians with voters. Experts in marketing understand the power of fear and often employ it… It is true that fear can have a powerful influence over our actions and behavior. But that influence tends to be temporary and shallow. Fear rarely has the power to change our hearts, and it will never transform us… People who are fearful may *say* and do the right things, but they do not *feel* the right things. They often feel helpless and resentful, even angry. Over time these feelings lead to mistrust, defiance, even rebellion.”

Dieter F. Uchtdorf

Perfect Love Casteth Out Fear

Pressurized Water Reactor (PWR)



Pressurized Water Reactor (PWR)

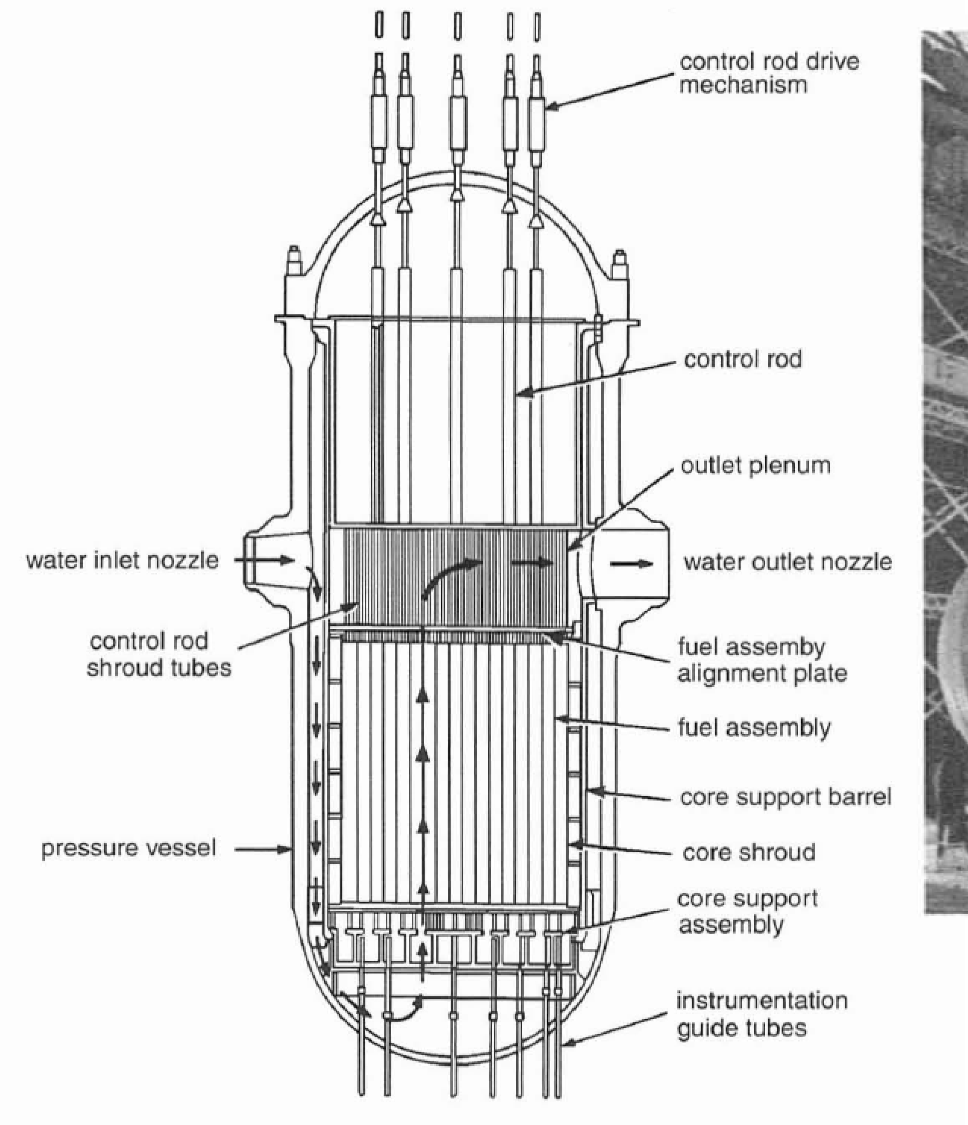
- Most widely used reactor worldwide.
- Water never boils in the core (which is pressurized – typically 150-200 atm).
- Heat exchanged in a second lower-pressure loop to generate turbine steam.
- Minimizes equipment exposure to ionizing radiation and radioactive waste production.

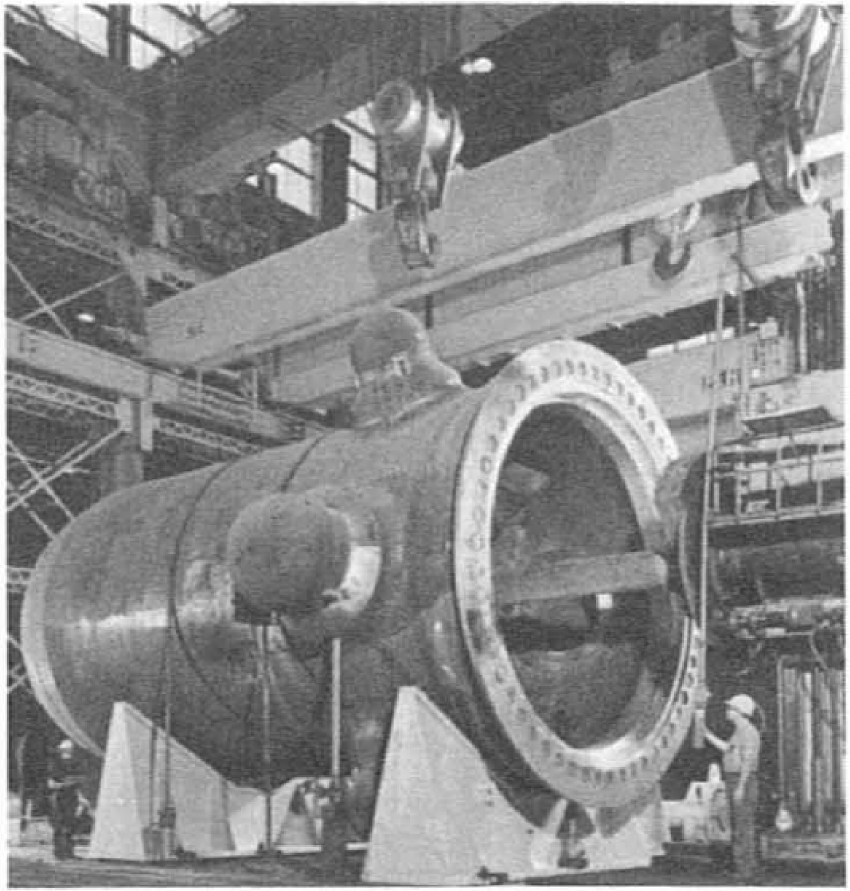
Typical PWR Specs

POWER	
thermal output	3800 MW
electrical output	1300 MW(e)
efficiency	0.34
CORE	
length	4.17 m
diameter	3.37 m
specific power	33 kW/kg(U)
power density	102 kW/L
av. linear heat rate	17.5 kW/m
rod surface heat flux	
average	0.584 MW/m^2
maximum	1.46 MW/m^2
REACTOR COOLANT SYSTEM	
operating pressure	15.5 MPa (2250 psia)
inlet temperature	292 °C
outlet temperature	329 °C
water flow to vessel	65.9×10^6 kg/h
STEAM GENERATOR (SG)	
number	4
outlet steam pressure	1000 psia
outlet steam temp.	284 °C
steam flow at outlet	1.91×10^6 kg/h

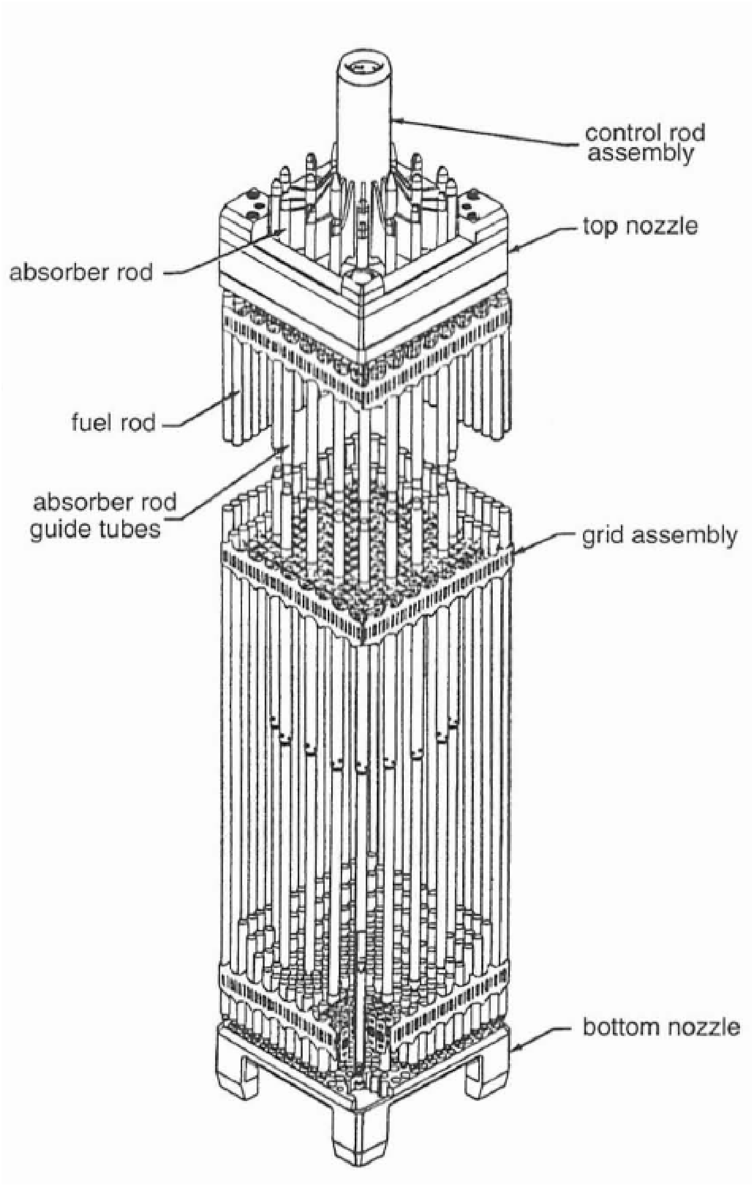
REACTOR PRESSURE VESSEL	
inside diameter	4.4 m
total height	13.6 m
wall thickness	22.0 cm
FUEL	
cylindrical fuel pellets	UO_2
pellet diameter	8.19 mm
rod outer diameter	9.5 mm
zircaloy clad thickness	0.57 mm
rod lattice pitch	12.6 mm
rods/assembly (17 × 17)	264
assembly width	21.4 cm
fuel assemblies in core	193
fuel loading	115×10^3 kg
initial enrichment % ^{235}U	1.5/2.4/2.95
equil. enrichment % ^{235}U	3.2
discharge fuel burnup	33 GWd/tU
REACTIVITY CONTROL	
no. control rod assemblies	68
shape	rod cluster
absorber rods per assembly	24
neutron absorber	Ag-In-Cd and/or B_4C
soluble poison shim	boric acid H_3BO_3

Reactor Core

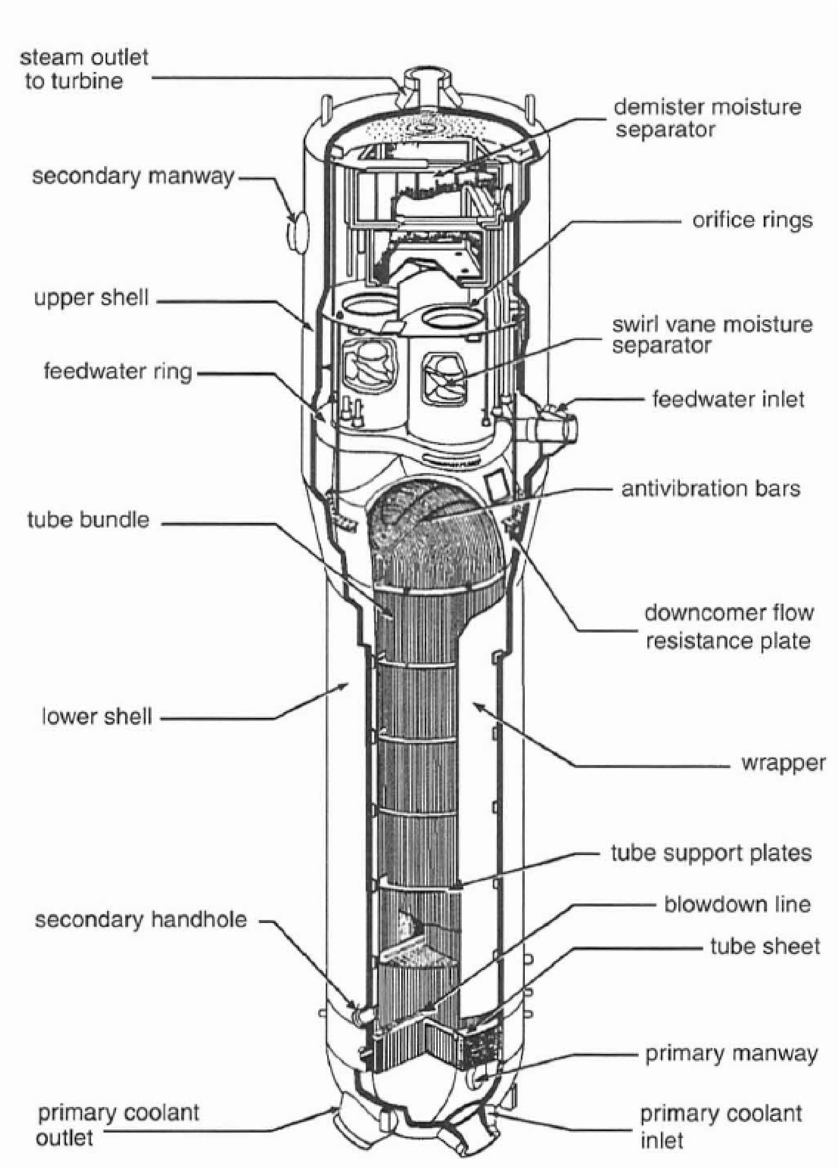


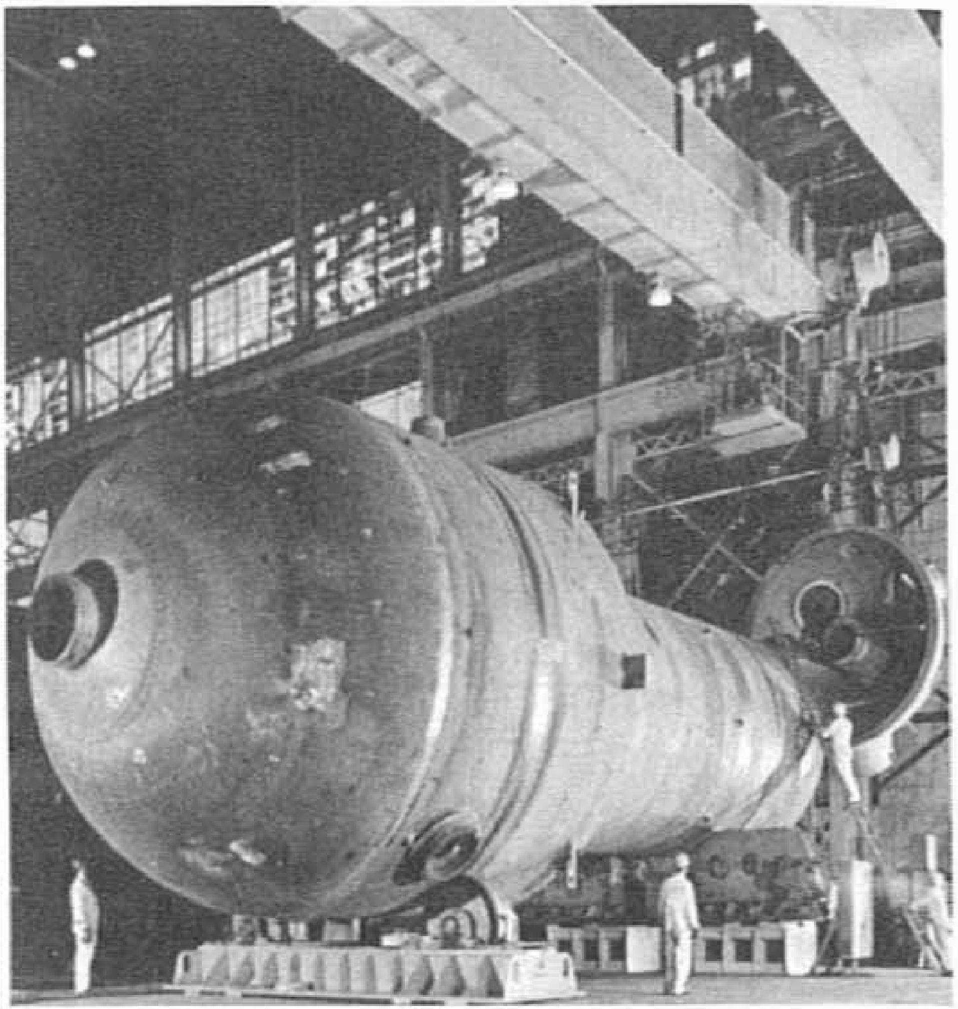


Fuel Assembly

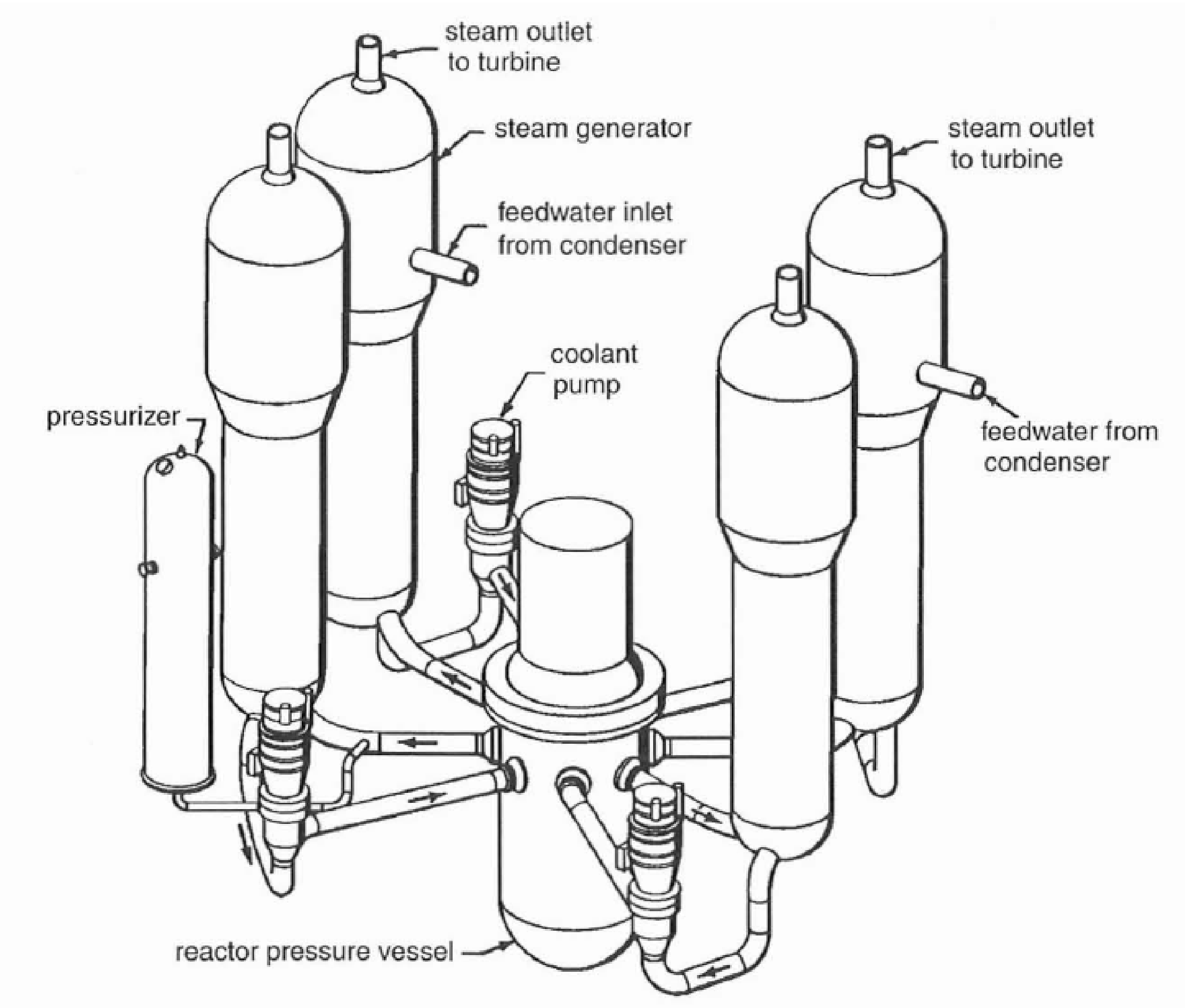


Steam Generator (Heat Exchanger)

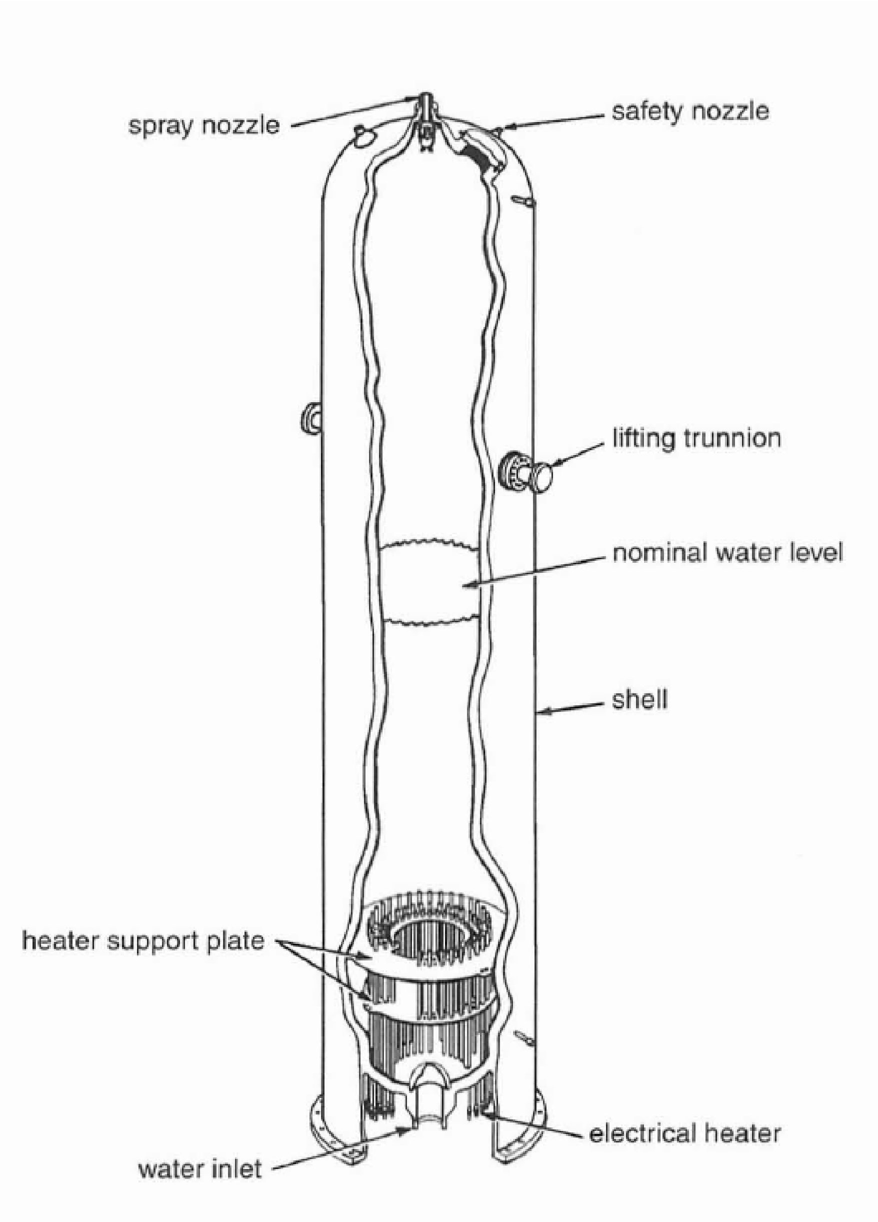




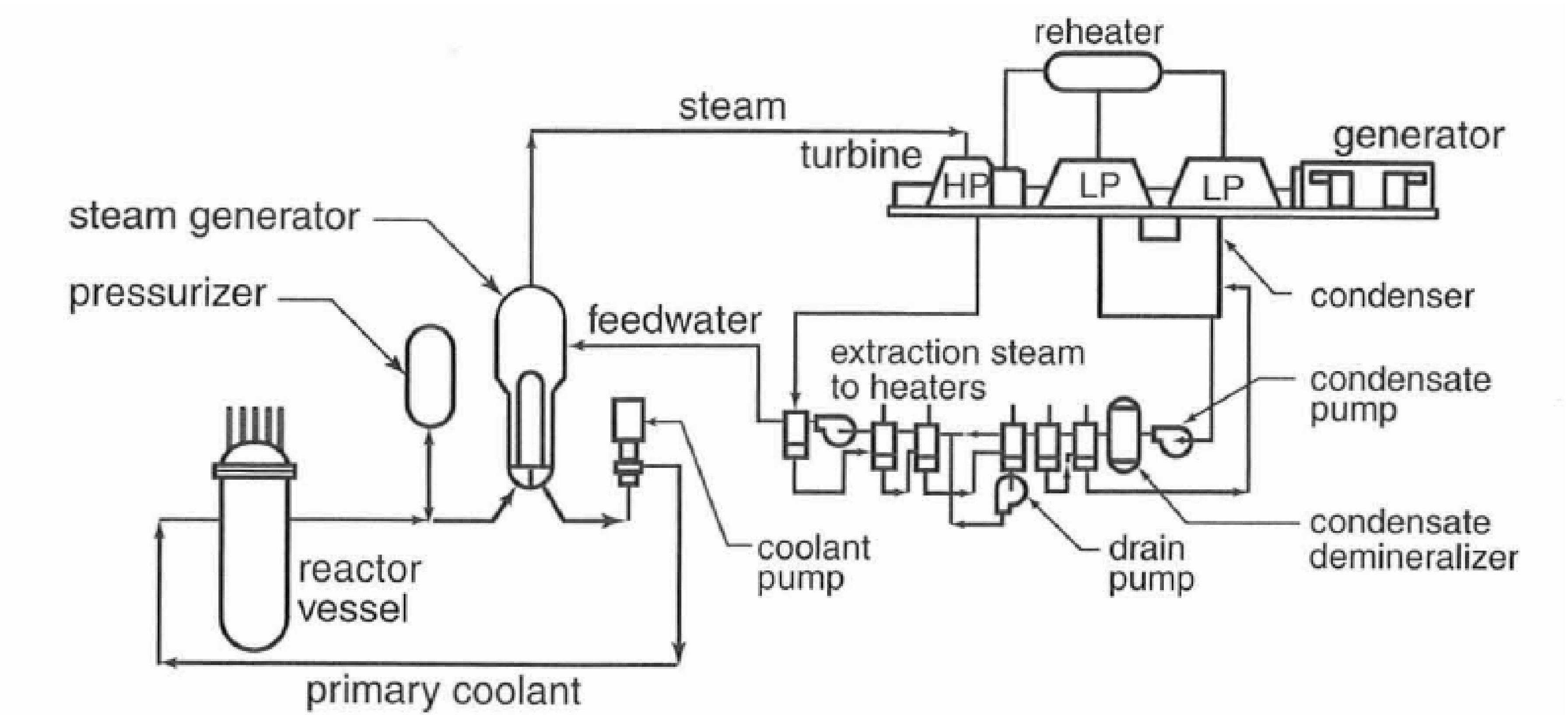
Overall Equipment Arrangement



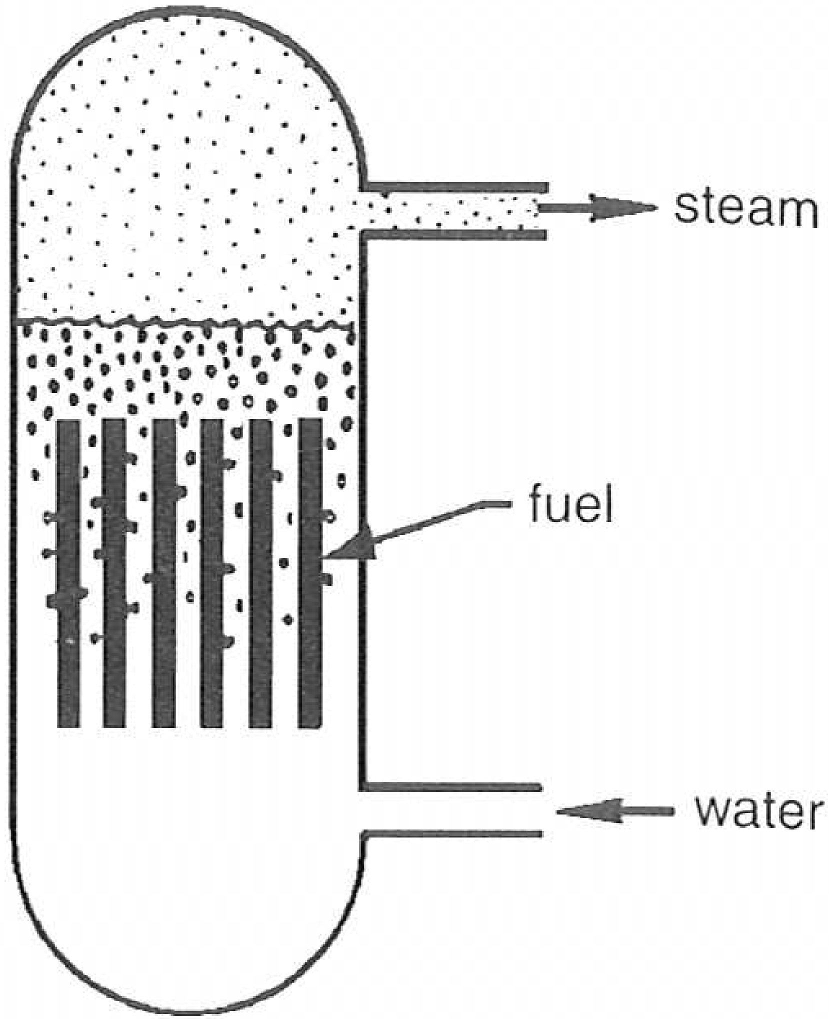
Pressurizer



PWR Steam Cycle



Boiling Water Reactor (BWR)



Boiler Water Reactor (BWR)

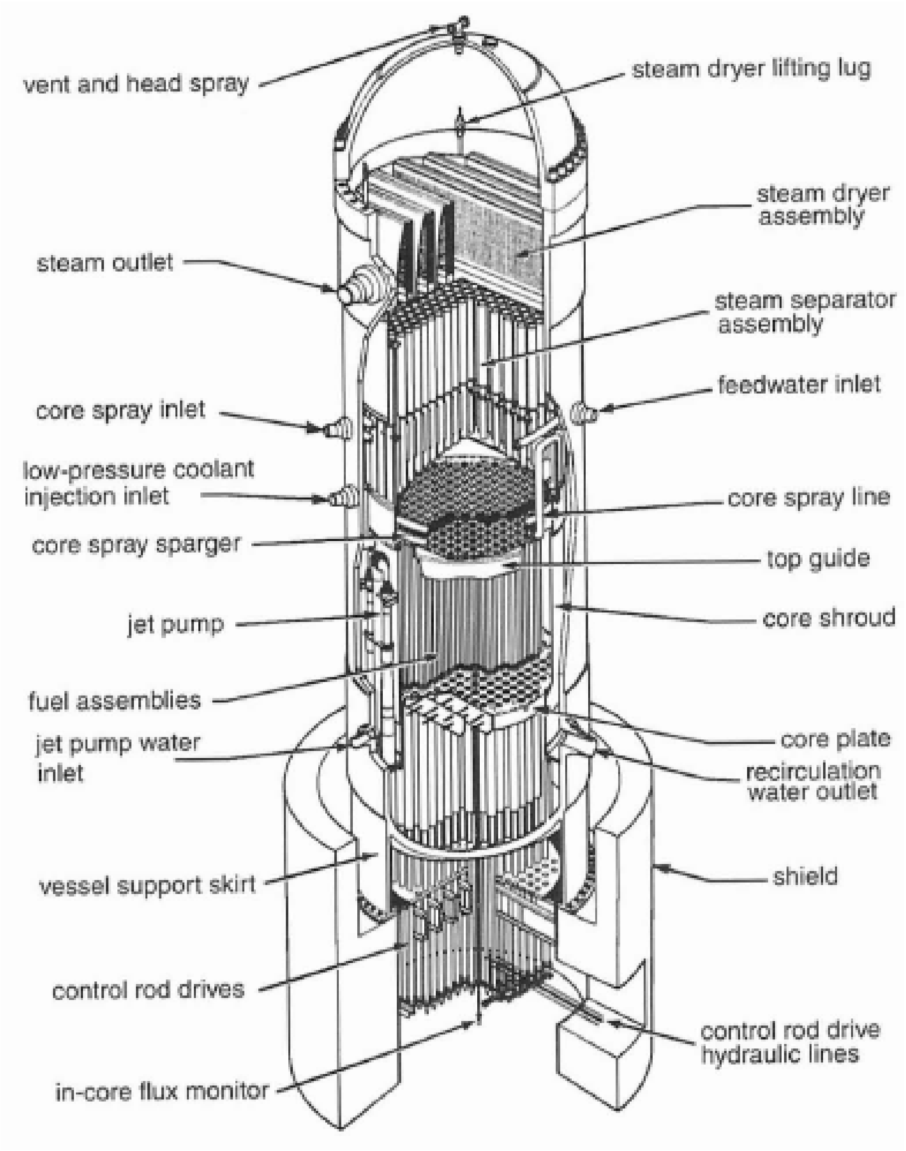
- Water boils directly in the core.
- Steam passes directly to turbine.
- After turbine, steam recondenses and returns to reactor.
- Large variations in heat transfer coefficients on the fuel rods.
- Turbine exposed to radioactive products from fluid, complicating maintenance and decommissioning.

BWR Specifications

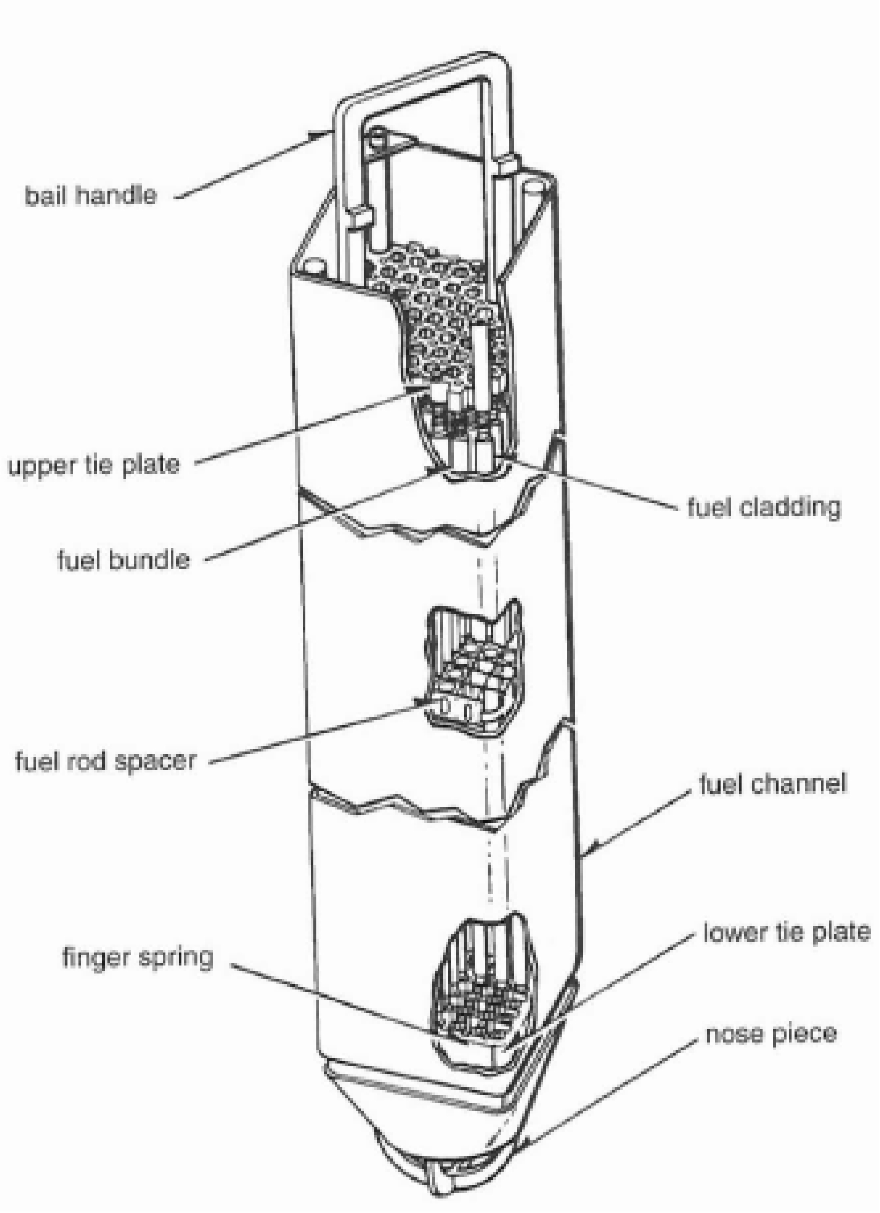
POWER	
thermal output	3830 MW
electrical output	1330 MW(e)
efficiency	0.34
CORE	
length	3.76 m
diameter	4.8 m
specific power	25.9 kW/kg(U)
power density	56 kW/L
av. linear heat rate	20.7 kW/m
rod surface heat flux	
average	0.51 MW/m^2
maximum	1.12 MW/m^2
REACTOR COOLANT SYSTEM	
operating pressure	7.17 MPa (1040 psia)
feedwater temperature	216 °C
outlet steam temperature	290 °C
outlet steam flow rate	7.5×10^6 kg/h
core flow rate	51×10^6 kg/h
core void fraction (av.)	0.37
core void fraction (max.)	0.75
no. in-core jet pumps	24
no. coolant pumps/loops	2

REACTOR PRESSURE VESSEL	
inside diameter	6.4 m
total height	22.1 m
wall thickness	15 cm
FUEL	
cylindrical fuel pellets	UO_2
pellet diameter	10.57 mm
rod outer diameter	12.52 mm
zircaloy clad thickness	0.864 mm
rod lattice pitch	16.3 mm
rods/assembly (8 × 8)	62
assembly width	13.4 cm
assembly height	4.48 m
fuel assemblies in core	760
fuel loading	168×10^3 kg
av. initial enrichment % ^{235}U	2.6%
equil. enrichment % ^{235}U	1.9%
discharge fuel burnup	27.5 GWd/tU
REACTIVITY CONTROL	
no. control elements	193
shape	cruciform
overall length	4.42 m
length of poison section	3.66 m
neutron absorber	boron carbide
burnable poison in fuel	gadolinium

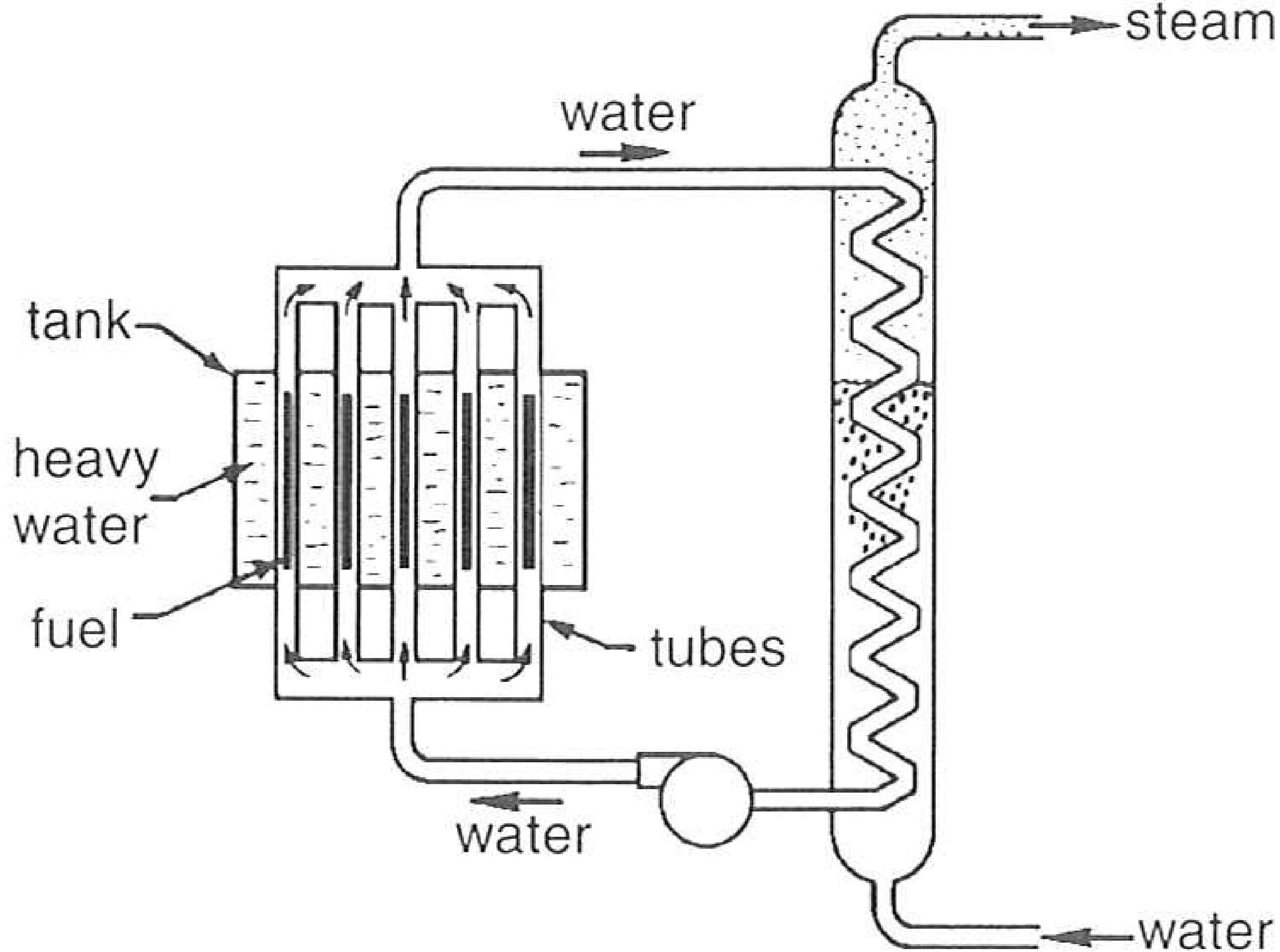
BWR Core


vent and head spray
steam dryer lifting lug
steam dryer assembly
steam outlet
steam separator assembly
feedwater inlet
core spray inlet
low-pressure coolant injection inlet
core spray line
core spray sparger
top guide
jet pump
core shroud
fuel assemblies
core plate
jet pump water inlet
recirculation water outlet
vessel support skirt
shield
control rod drives
control rod drive hydraulic lines
in-core flux monitor

BWR Fuel Assembly



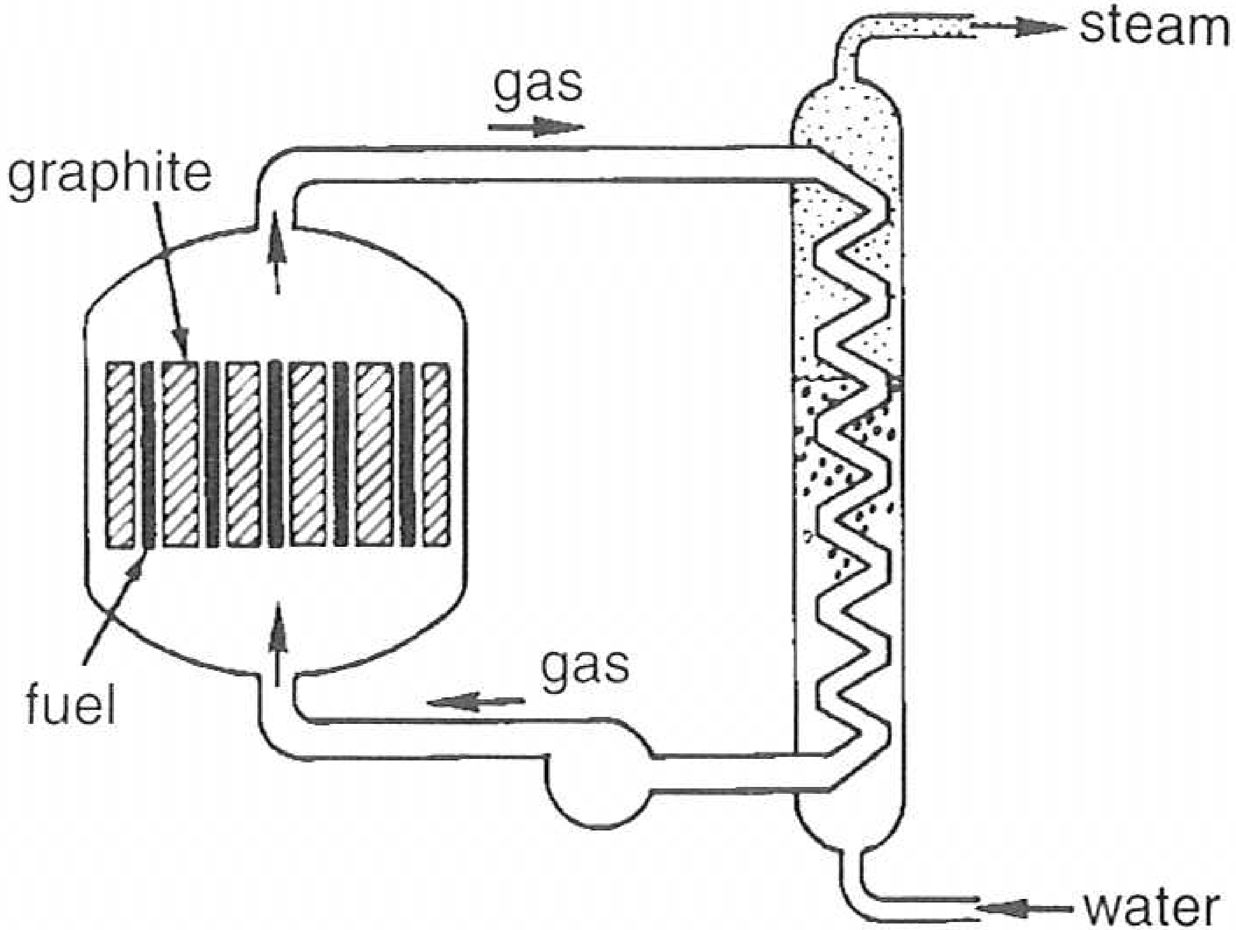
Heavy Water Reactor (PHWR)



Heavy Water Reactor

- Heavy water (deuterium- or tritium-based water) passes through pressurized fuel tubes surrounded by a non-pressurized heavy water bath.
- Operates on natural uranium
- Avoids pressurized reactor vessel (major expense).
- Steam generated in second loop.
- Basis of the CANDU (Canadian) reactor designs.
- Variant is the heavy-water-moderated, light-water-cooled reactor (HWLWR) that uses light water in the fuel tubes and no heat exchanger.

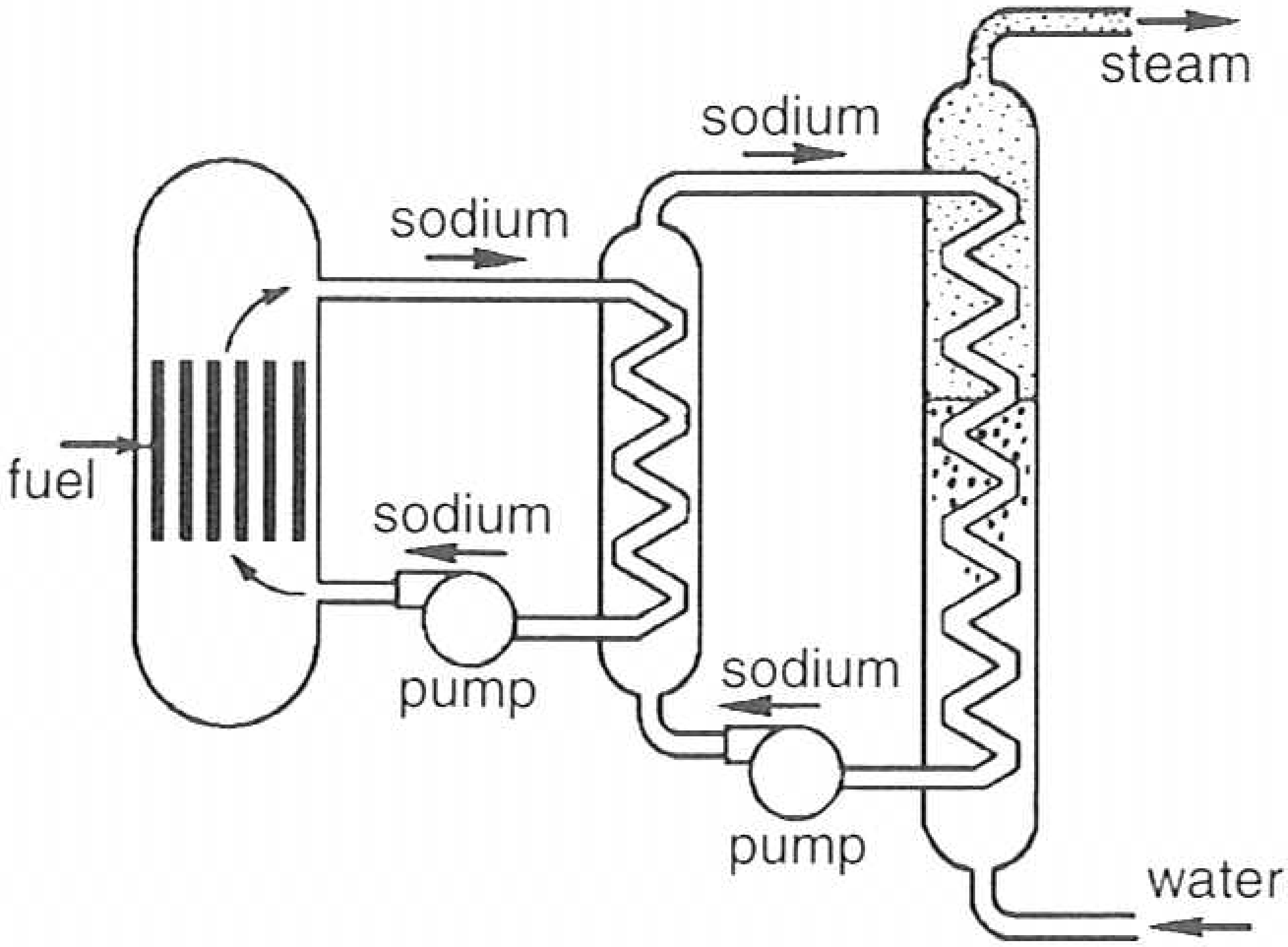
Gas-cooled Reactor (GCR)



Gas-cooled Reactor (GCR, HTGR)

- Gas (He or CO_2) used as coolant.
- Graphite typically used as moderator.
- Graphite (which remains solid) and gas need not be pressurized
  - No expensive pressure vessel
  - No Blowdown in accident
- Gas heats steam in secondary loop.
- In a gas-cooled reactor (GCR), gas passes through holes in graphite moderator.
- In a high-temperature gas-cooled reactor (HTGR), fuel channels and gas channels are drilled in graphite core.

Liquid-metal fast breeder reactor



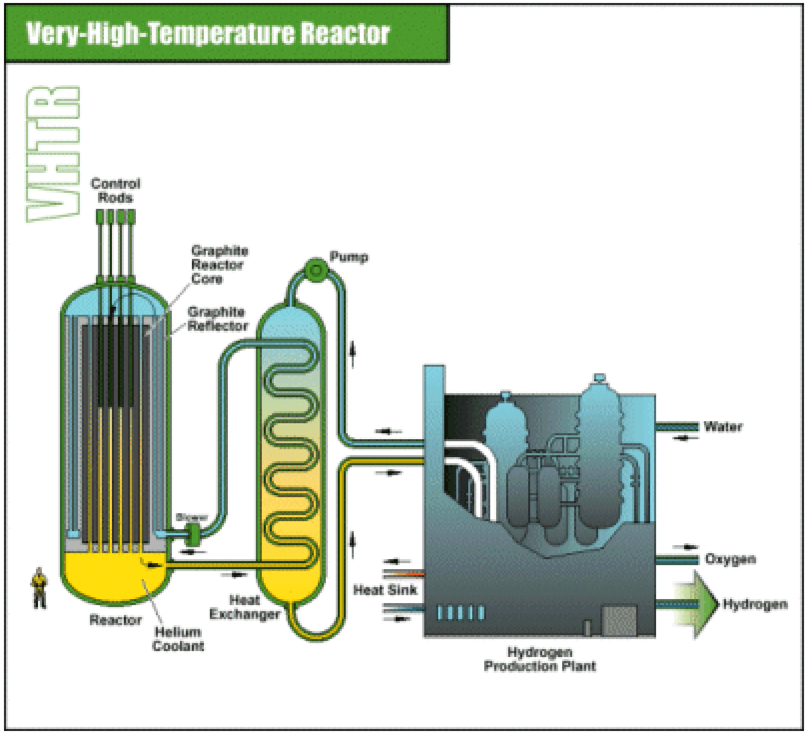
Liquid Metal Fast Breeder Reactor (LMFBR)

- Fast-neutron-based reactor scheme.
- No moderator (no light elements).
- Na or K-Na molten metal used as coolant.
- No pressurization, very high heat transfer coefficients.
- Na becomes radioactive and Na and K react violently with water (moderately with air).
- Second Na heat exchanger isolates Na/K coolant in core from turbine steam.
- New fuel to consumed fuel ratio raises from 0.6-0.8 in typical reactors to over 1 if designed as a breeder reactor.
- One in commercial operation (in Russia), though they are aggressively pursuing new designs.

Small Modular Reactors

- Small is < 300 MW_e (IAEA definition) or < 500 MW_e (conventional definition).
- Modular means systems can be almost entirely fabricated in shops rather than on site, decreasing security and other risks.
- Primary advantage is decrease in capital cost, reducing financial risk, construction at a single location, ability to add incremental power.
- Primary disadvantage is loss of economies of scale. Four small reactors are more expensive to build and operate than one large reactor of equivalent size.
- Include III, III+, and IV or other designs

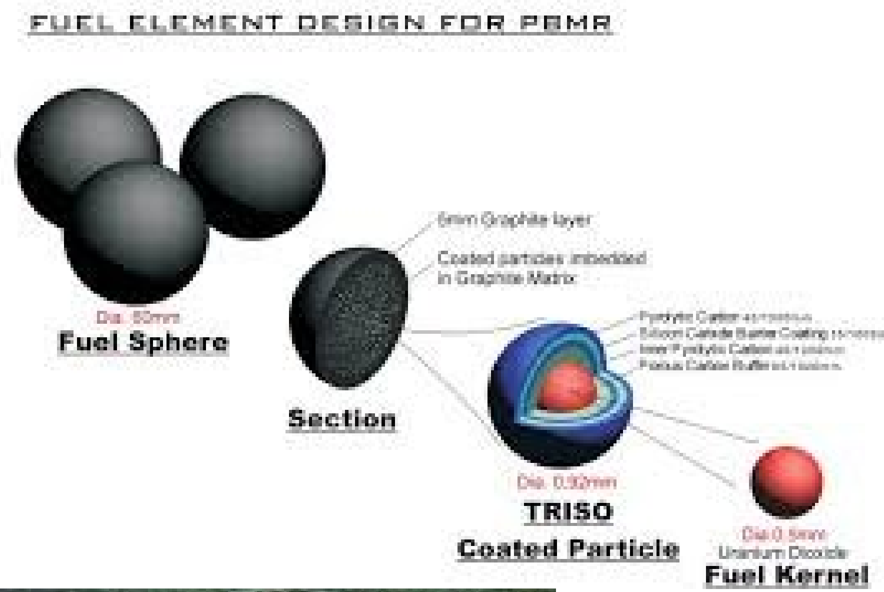
Very-High Temperature Reactor

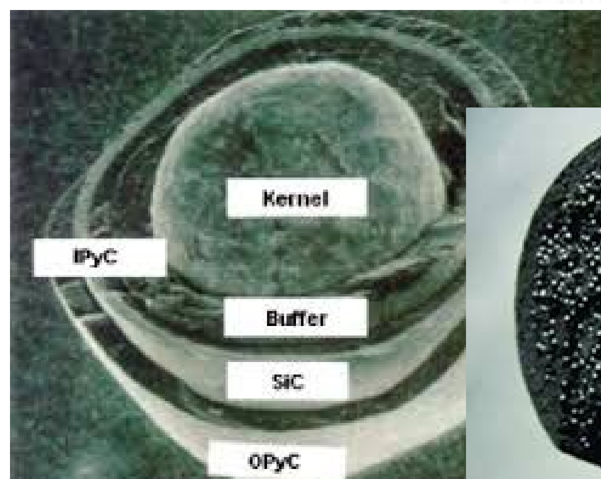


- Graphite-moderated core
- Once-through U fuel cycle
- 1000 ° C steam outlet temperature
- Possible H_2 production

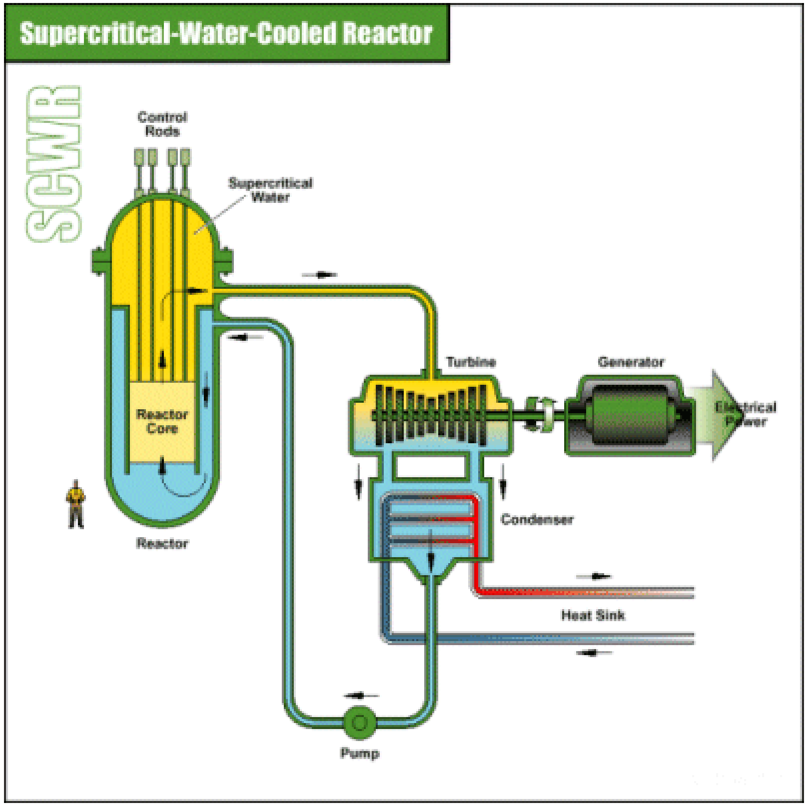
VHTR Fuel

- TRISO fuel
  - Man tiny pellets into graphite matrix sphere
  - Melt-down proof
  - Failure specs?
- Susceptible to air-ingress accidents (fire)
- Also used in FHR



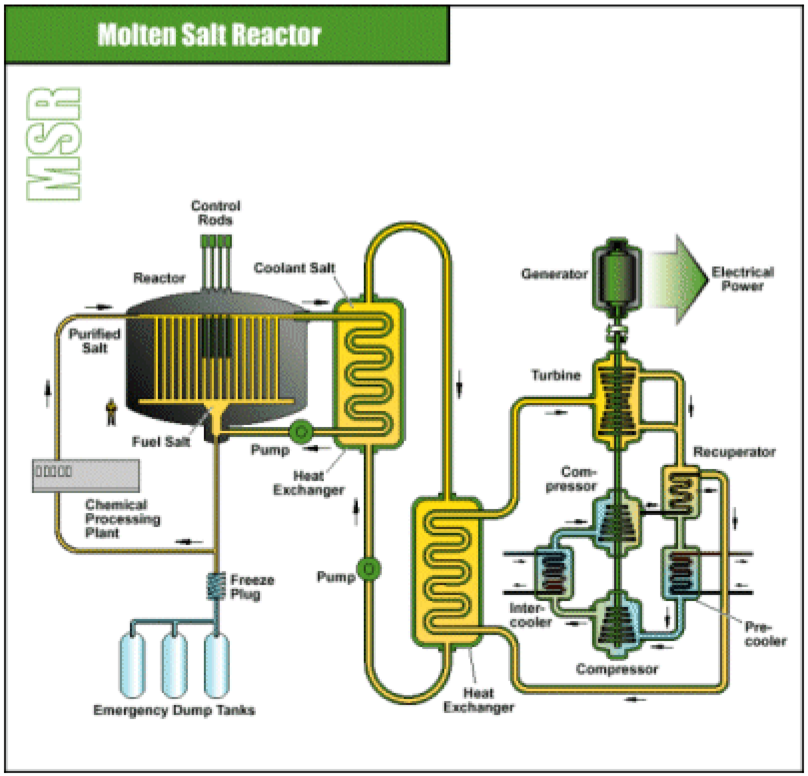


Supercritical-Water-Cooled Reactor



- SC Water (> 240 atm) for working fluid (similar to most modern coal boilers)
- 45% efficienct (compared to 33% in most current technologies)
- Combines LWR and fossil technology.

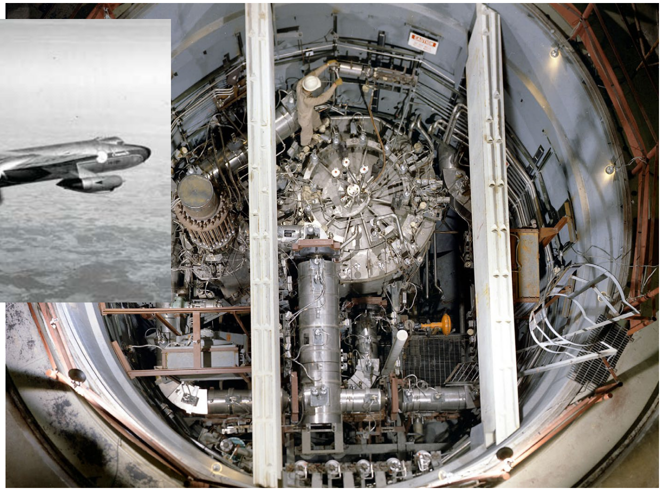
Molten Salt Reactor



- Low-pressure, high-temperature core cooling fluid
- Fuel either dissolved in salt (typically as UF_6) or dispersed in graphite moderator.
- Perhaps gas-driven (He) turbine.

MSR Fuel

- Liquid fuel
  - UF4
  - Suspended Directly in Salt
- No melt-down (already liquid)
- Fission products in coolant
  - COMPLEX chemistry
  - Online separation
  - Unknown behavior of salt



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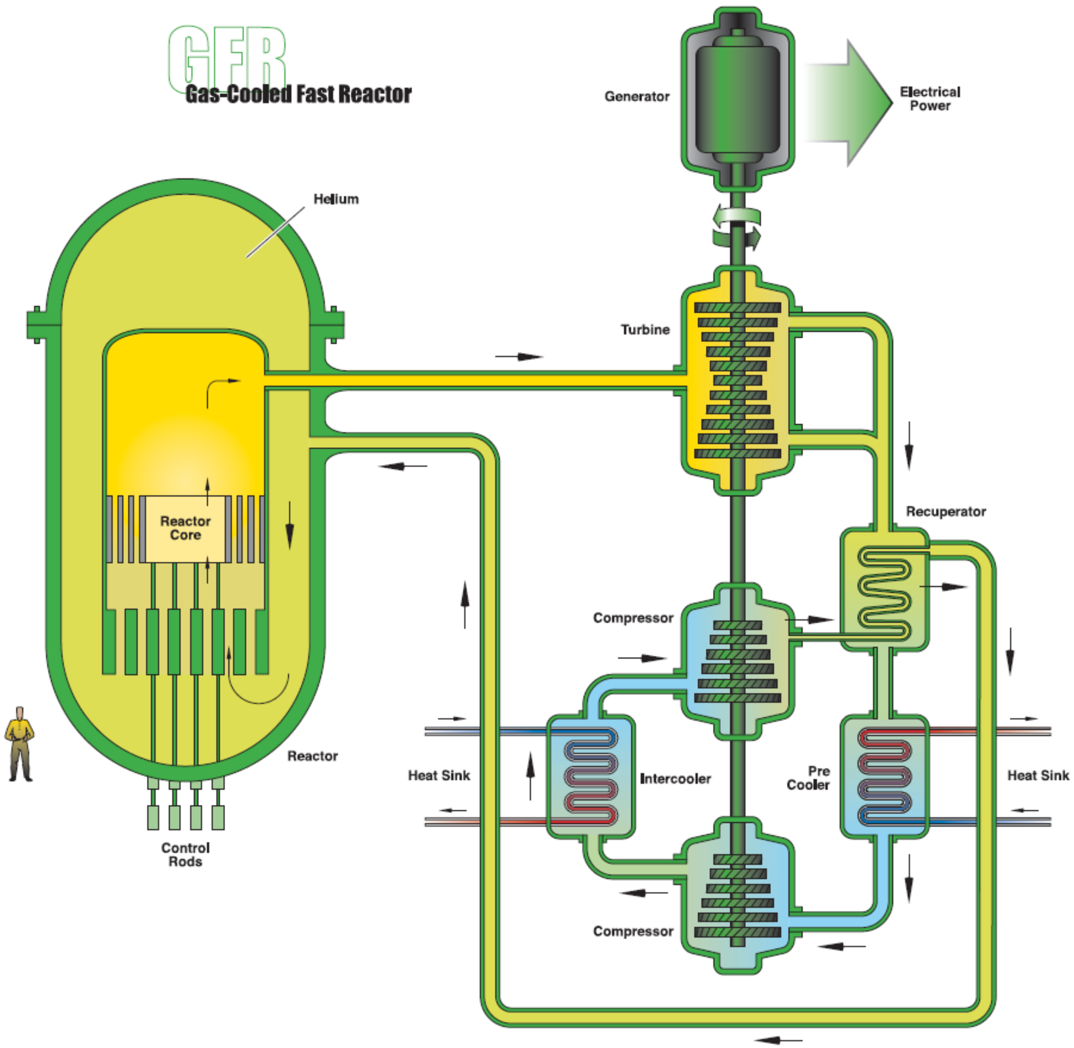
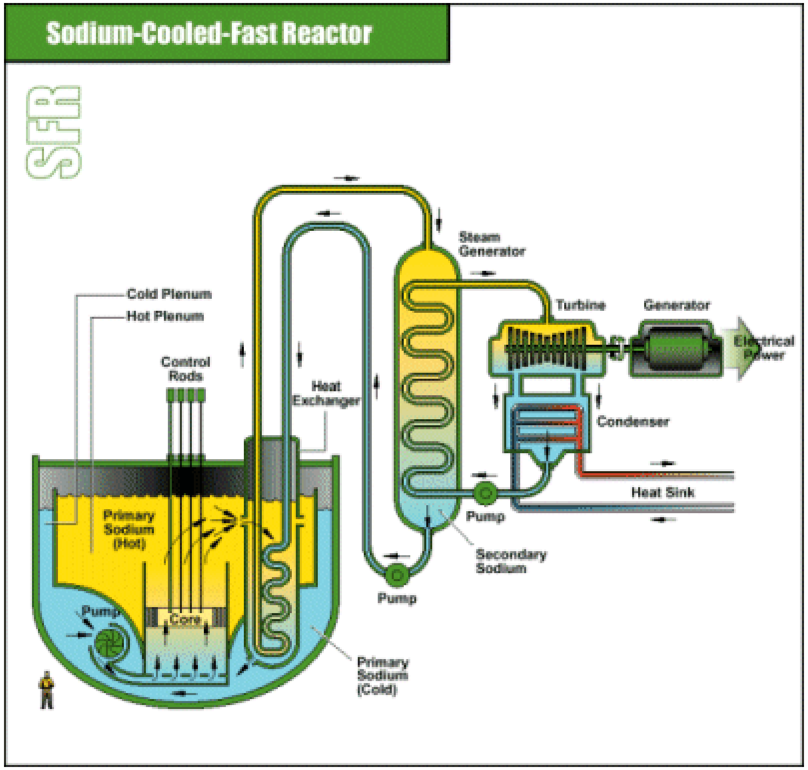
Gas-cooled Fast Reactor



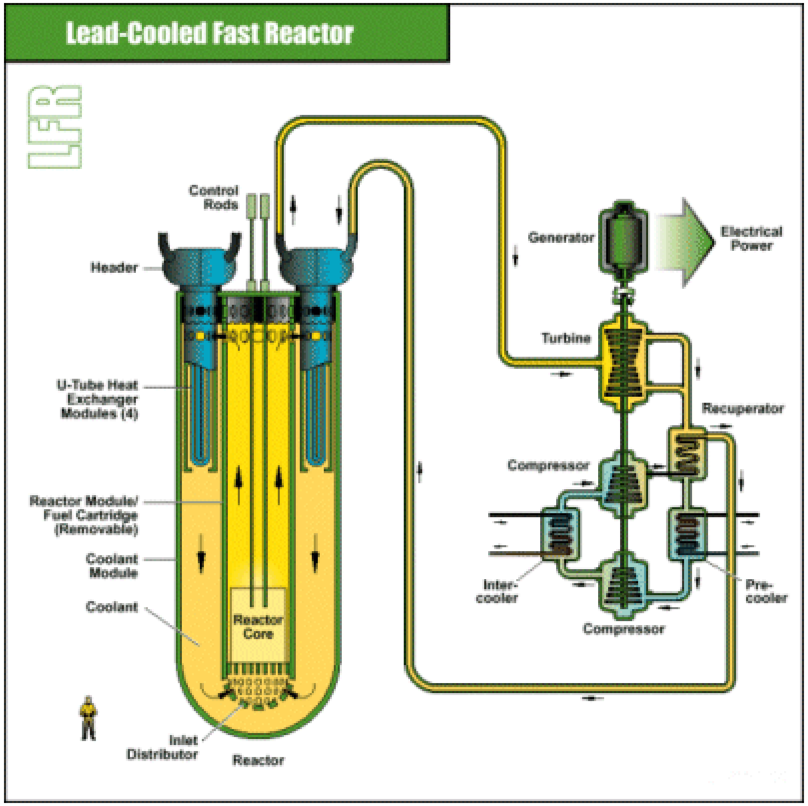
- He cooled with direct Brayton cycle for high efficiency
- Closed fuel cycle
- Low Power Density

Sodium-Cooled Fast Reactor



- Eliminates the need for transuranic (Pu) isotopes from leaving site (by breeding and consuming Pu)
- Liquid sodium cooled reactor
- Fueled by U/Pu alloy

Lead-cooled Fast Reactor



- Molten lead or lead-eutectic as core coolant
- Heat exchanged to gas-driven turbine
- Natural convection core cooling (cannot fail unless gravity fails)
- WEC Choice (12/2015), but called Gen V