Reactor Thermal-hydraulics

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Nuclear Reactor Systems

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Overview

Why is Nuclear fuel hot?

Heat storage and dissipation

Energy generation due to nuclear reaction and retention

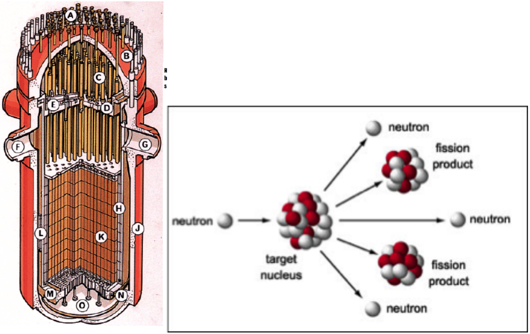


Figure: (Left)Typical nuclear fuel arrangement; (Right) A cartoon for fission reaction

How can this energy go out?

Heat Conduction

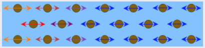


Figure: (Left)Typical nuclear fuel arrangement; (Right) A cartoon for fission reaction

Convection

Macroscopic displacement of atoms or molecules resulting in replacing the heated particles with colder ones.

Radiation

Every medium continuously emits electromagnetic radiation randomly into all directions.

Pressurized Water Reactor

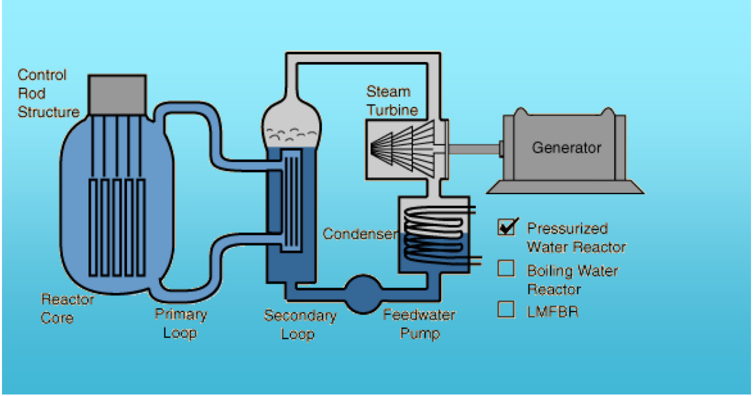


Figure: Schematic of a PWR plant showing how primary and secondary sides interact

PWR nuclear power plant

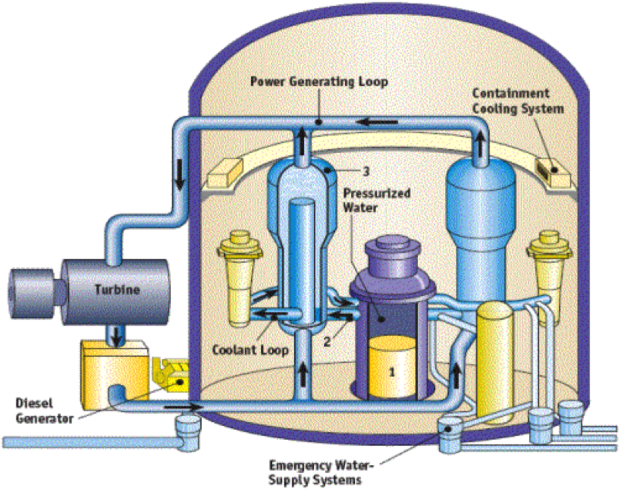


Figure: Reactor building cartoon with PWR system layout

PWR reactor coolant system

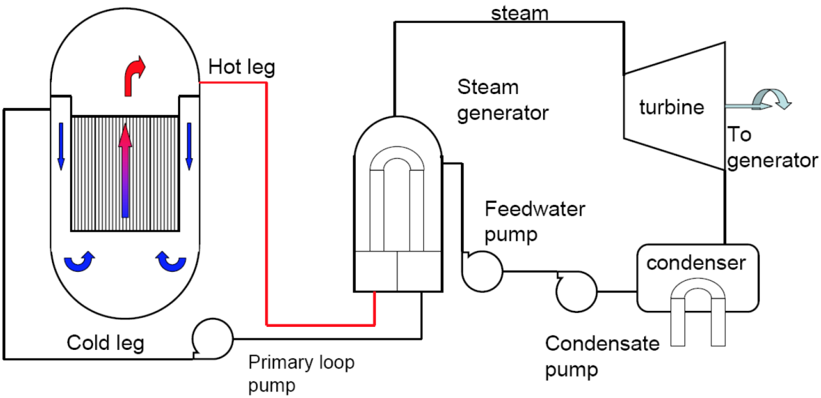


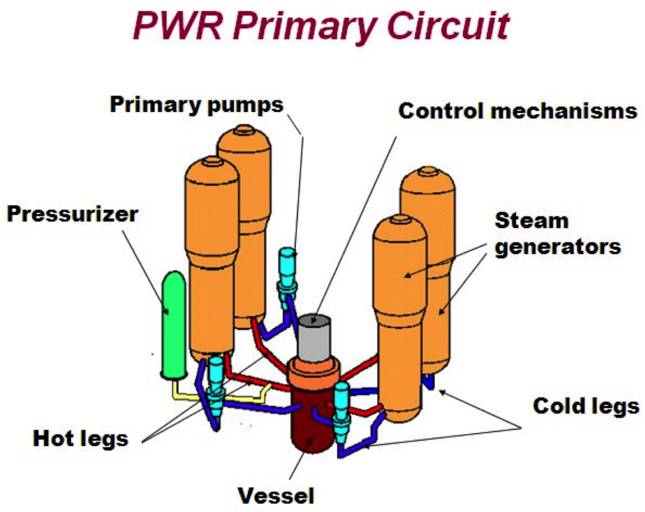
Figure: Simplified PWR flow diagram

PWR parameters

TABLE 2-1
TYPICAL REACTOR CORE PARAMETERS

	2-Loop Plant	3-Loop Plant	4-Loop Plant
Total heat output, MWt	1882	2785	3411
Heat generated in fuel, %	97.4	97.4	97.4
Nominal system pressure, psia (bar)	2250 (155)	2250 (155)	2250 (155)
Total coolant flow rate, lb/hr (kg/sec)	~71.03 x 10^6 (8950)	~109.0 x 10^6 (13734)	~138.4 x 10^6 (17438)
Coolant temperature			
Nominal inlet, °F (°C)	549.9 (287.7)	557.0 (291.7)	557.5 (291.9)
Average rise in vessel, °F (°C)	66.2 (36.8)	62.9 (34.9)	61.0 (33.9)
Outlet from vessel, °F (°C)	616.1 (324.5)	619.9 (326.6)	618.5 (325.8)
Equivalent core diameter, ft (cm)	8.4 (256)	9.98 (304)	11.06 (338)
Core length, between fuel ends, ft (cm)	12.0 (365.8)	12.0 (365.8)	12.0 (365.8)
Fuel type	16 x 16 Std	17x17 OFA	17x17 OFA
Fuel weight, uranium in core, kg	49,702	66,411	81,639
Number of fuel assemblies	121	157	193

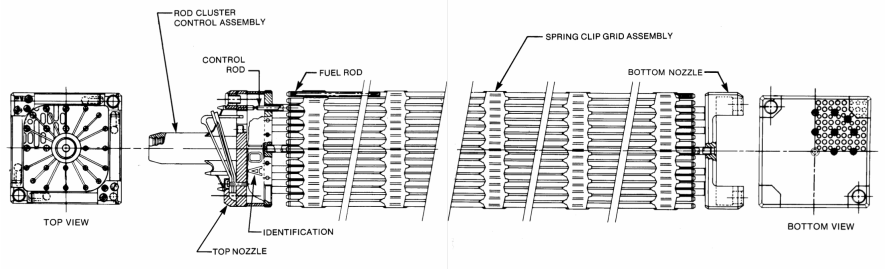
PWR reactor coolant system



PWR-Fuel

Figure 2-4. Fuel Pellets

PWR-Fuel

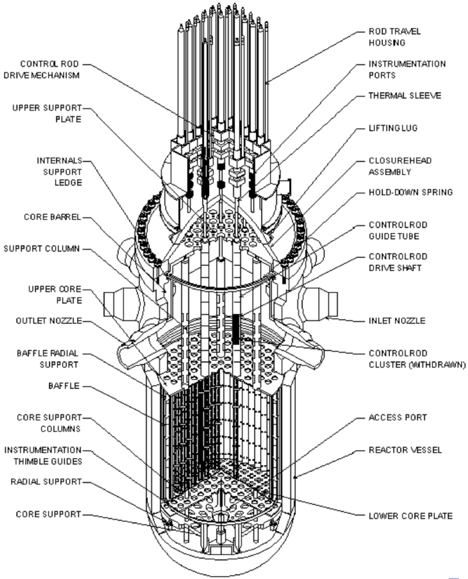

ROD CLUSTER
CONTROL ASSEMBLY
CONTROL
ROD
FUEL ROD
SPRING CLIP GRID ASSEMBLY
BOTTOM NOZZLE
TOP VIEW
IDENTIFICATION
TOP NOZZLE
BOTTOM VIEW

PWR-Fuel

TABLE 2-2
FUEL ROD PARAMETERS
(Four-Loop Plant)

Fuel rod length	12 ft (365.8 cm)
Outside diameter	0.360 in. (0.914 cm)
Cladding thickness	0.0225 in. (0.0572 cm)
Cladding material	Zircaloy-4
Diametrical gap	0.0062 in. (0.0157 cm)
Pellet diameter	0.3088 in. (0.7844 cm)
Lattice pitch	0.496 in. (1.260 cm)
Rods array in assembly	17 x 17
Rods in assembly	264
Total number of fuel rods in core	50,952

PWR Reactor Vessel

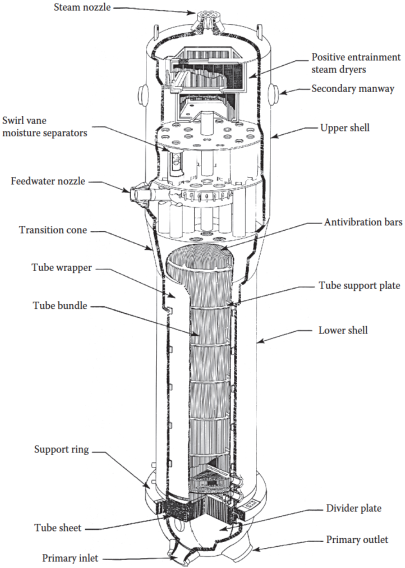


PWR Reactor Vessel- Design specifications

TABLE 3.1-1
REACTOR VESSEL PRINCIPAL PARAMETERS

Parameter	2-Loop-Plant	3-Loop Plant	4-Loop Plant
Overall length of assembled vessel, closure head, and nozzles	39 ft, 9 in. (12.1 m)	43 ft, 4 in (13.2 m)	44 ft, 7 in. (13.6 m)
Inside diameter of shell	132 in. (3.4 m)	157 in. (4.0 m)	173 in. (4.4 m)
Radius from center of vessel to nozzle face:			
Inlet	9 ft, 7 in. (2.9 m)	10 ft, 6 in. (3.2 m)	10 ft, 11 in. (3.3 m)
Outlet	9 ft, 2 in. (2.8 m)	10 ft, 2 in. (3.1 m)	10 ft, 3 in. (3.1 m)
Nominal cladding thickness	7/32 in. (0.56 cm)	7/32 in. (0.56 cm)	7/32 in. (0.56 cm)
Minimum cladding thickness	1/8 in. (0.32 cm)	1/8 in. (0.32 cm)	1/8 in. (0.32 cm)
Coolant volume with core and internals in place	2491 ft^3 (71 m^3)	3734 ft^3 (106 m^3)	4885 ft^3 (138 m^3)
Operating pressure	2332 psia (160 bar)	2332 psia (160 bar)	2332 psia (160 bar)
Design pressure	2500 psia (172 bar)	2500 psia (172 bar)	2500 psia (172 bar)
Design temperature	650°F (343°C)	650°F (343°C)	650°F (343°C)
Vessel material	Low alloy steel	Low alloy steel	Low alloy steel
Cladding material	Stainless steel	Stainless steel	Stainless steel
Number of vessel material surveillance capsules	6	6	6

PWR Steam Generator



PWR Steam Generator

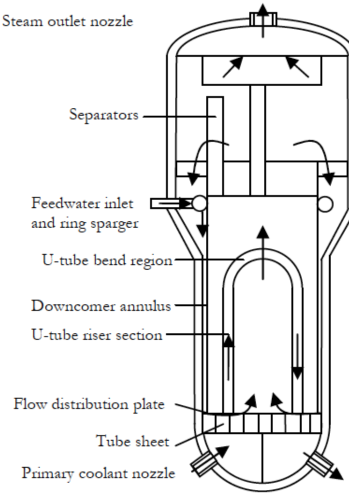
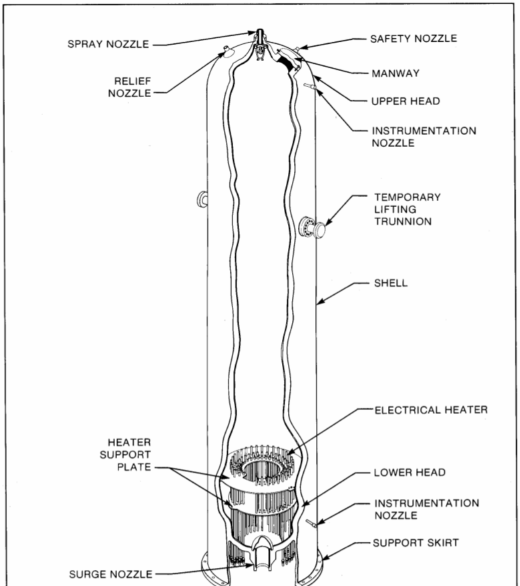


TABLE 3.4-1 STEAM GENERATOR PRINCIPAL DESIGN DATA	
Number and type	1 vertical, U-tube steam generator with integral steam-drum per loop
Height overall	67 ft, 8 in. (20.6 m)
Upper shell OD	14 ft, 7-3/4 in. (4.5 m)
Lower shell OD	11 ft, 3 in. (3/4m)
Operating pressure, tube side	2250 psia (155 bar)
Design pressure, tube side	2500 psia (172 bar)
Design temperature, tube side	650°F (343°C)
Full load pressure, shell side	
2-Loop Plant	920 psia (63 bar)
3-Loop Plant	964 psia (66 bar)
4-Loop Plant	1000 psia (69 bar)
Steam flow per steam generator	3,813,000 lb/hr (480 kg/sec)
Maximum moisture at outlet (full load)	0.25 %
Design pressure, shell side	1200 psia (82.7 bar)
Reactor coolant flow rate	35,075,000 lb/hr (4419 kg/sec)
Reactor coolant inlet temperature	621°F (327°C)
Reactor coolant outlet temperature	558°F (292°C)
Shell material	Mn-Mo steel
Channel head material	Carbon steel clad internally with stainless steel
Tube sheet material	Ni-Mo-Cr-V clad with Inconel on primary face
Tube material	Thermally treated Inconel
Steam generator weights	
Dry weight, in place	346 tons (314,000 kg)
Normal operating weight, in place	422 tons (384,000 kg)
Flooded weight (cold)	560 tons (508,000 kg)

PWR Pressurizer



PWR Pressurizer

TABLE 3.5-1
PRESSURIZER PRINCIPAL DESIGN DATA

	2-Loop Plant	3-Loop Plant	4-Loop Plant
Number and type	1 two-phase water and steam pressurizer	1 two-phase water and steam pressurizer	1 two-phase water and steam pressurizer
Overall height	31 ft, 5 in. (9.6 m)	42 ft,1 in. (12.8 m)	52 ft, 9 in. (16.1 m)
Overall diameter	7 ft, 7-1/2 in. (2.3 m)	7 ft, 7-1/2 in. (2.3 m)	7 ft, 8in. (2.3 m)
Water volume	600 ft^3 (17.0 m^3)	840 ft^3 (23.8 m^3)	1080 ft^3 (30.6 m^3)
Steam volume	400 ft^3 (11.3 m^3)	560 ft^3 (15.9 m^3)	720 ft^3 (20.4 m^3)
Design pressure	2500 psia (172 bar)	2500 psia (172 bar)	2500 psia (172 bar)
Design temperature	680°F (360°C)	680°F (360°C)	680°F (360°C)
Type of heaters	Electric immersion	Electric immersion	Electric immersion
Number of heaters	78	78	78
Installed heater power	-1000 kw	1400 kw	1800 kw
Number of relief valves	2 power-operated	2 power-operated	2 power-operated
Number of safety valves	3 self-actuating	3 self-actuating	3 self-actuating
Spray rate			
Pressure transient	500 gpm (32 l/sec)	700 gpm (44 l/sec)	900 gpm (57 l/sec)
Continuous	1 gpm (63 ml/sec)	1 gpm (63 ml-/sec)	1 gpm (63 ml/sec)
Shell material	Mn-Mo steel, clad internally with stainless steel	Mn-Mo steel, cald internally with stainless steel	Mn-Mo steel, clad internally with stainless steel
Dry weight	116,000 lb (52,600 kg)	155,300 lb (70,400 kg)	195,500 lb (88,700 kg)

PWR reactor auxiliary subsystems

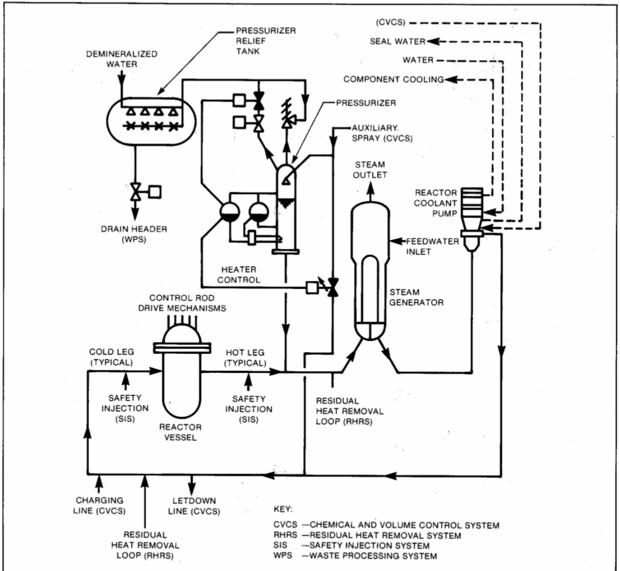


Figure 3-1. Reactor Coolant System, Flow Diagram

PWR reactor auxiliary subsystems

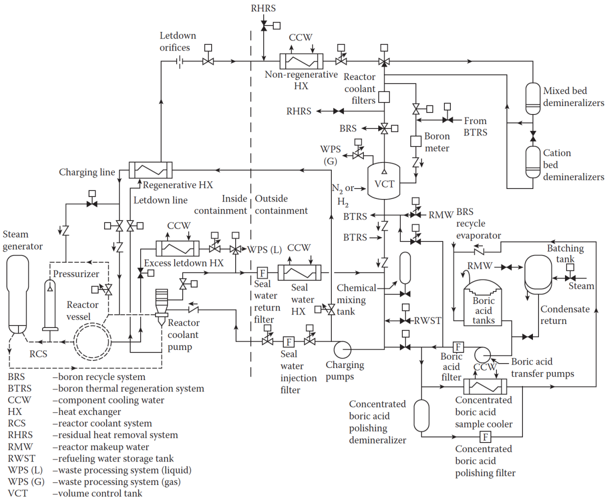


Figure: Chemical and Volume Control System

Boiling – Latent heat

Latent means 'Hidden'

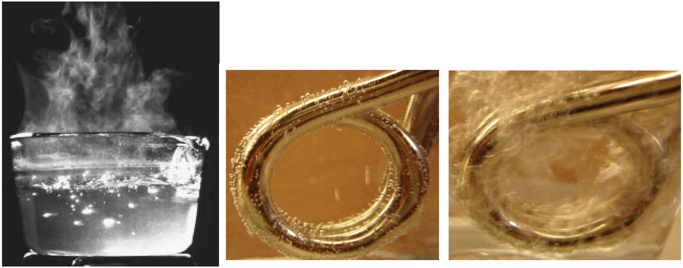
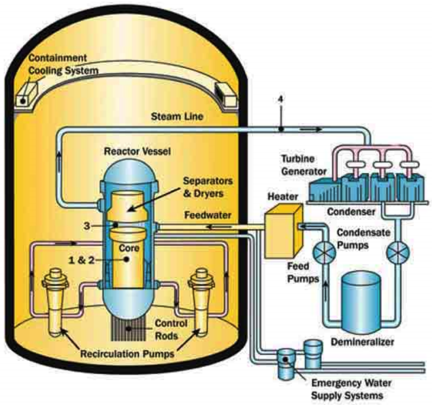
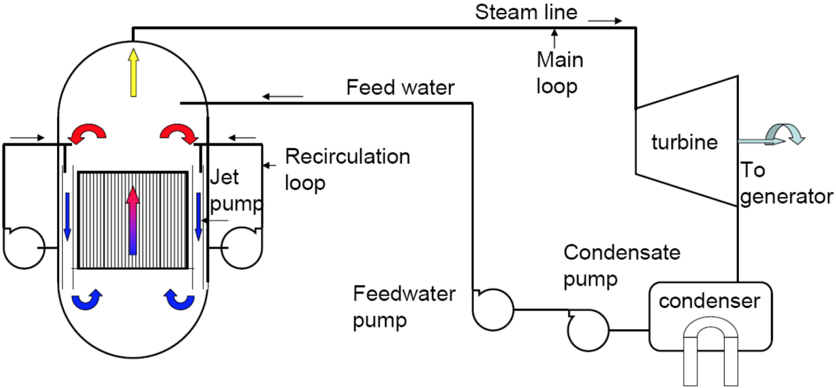


Figure: Liquid to Vapor phase change; Nucleate Boiling

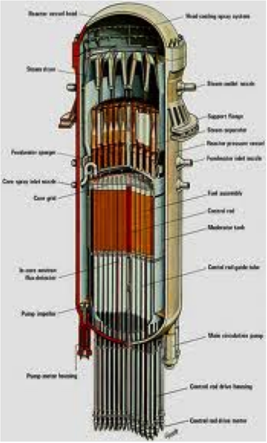
BWR nuclear power plant

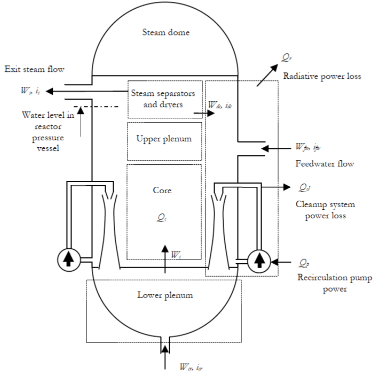


BWR reactor coolant system

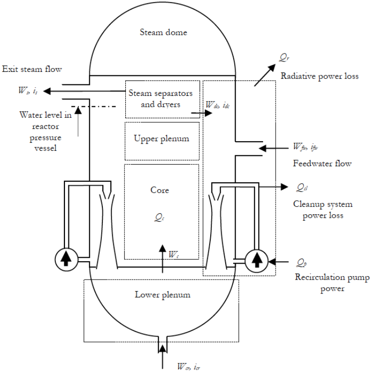


BWR reactor vessel

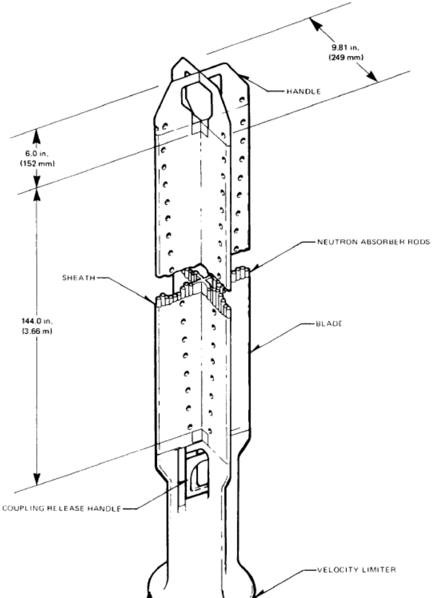




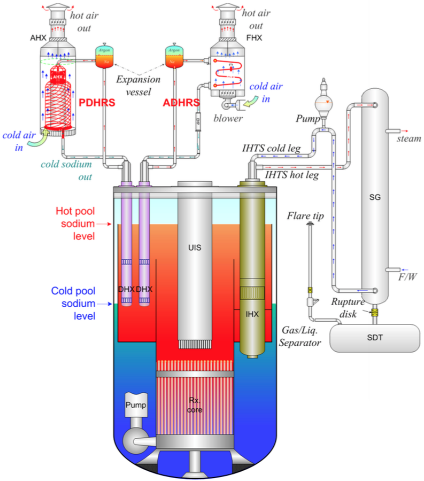
BWR reactor vessel



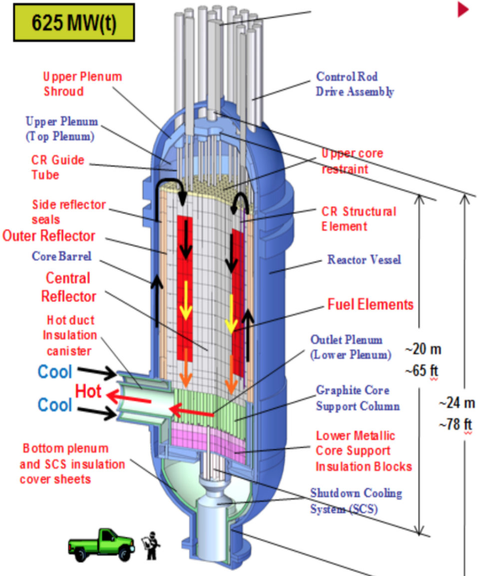
BWR reactor vessel



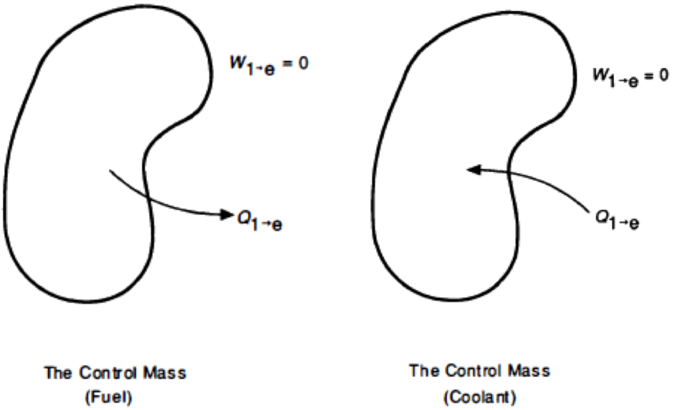
Sodium-cooled Fast Reactor



High Temperature Gas-cooled Reactor



Basics- Fuel Coolant thermal interaction



Basics- Fuel Coolant thermal interaction

Conservation of energy

$$Q = \pm \Delta U \quad (1)$$

Example- Fuel Coolant thermal interaction

Lumped heat addition

Compute equilibrium temperature in a fuel-coolant system where coolant mass is 1/10th of fuel mass. Ratio of specific heat of coolant to fuel is 2.

Initial temperature of fuel is 1100 K and of coolant is 400 K

Example- Fuel Coolant thermal interaction

Lumped heat addition

$$\Delta U_c = -\Delta U_f \tag{2}$$

Solution

$$m_c C_{pc}(T_e - T_c) = -m_f C_{pf}(T_e - T_f) \tag{3}$$

Answer

980 K

Basics- Fuel Coolant thermal interaction

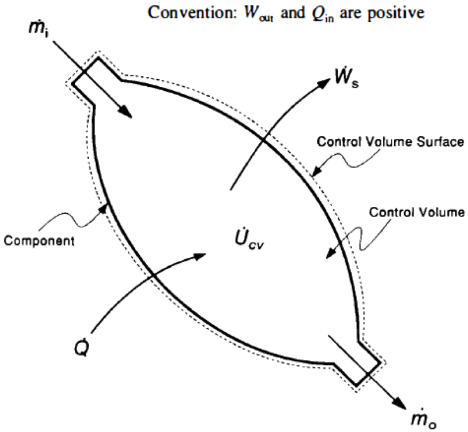


Figure: Coolant is moving and continuously extracting heat from the fuel

Basics- Fuel Coolant thermal interaction

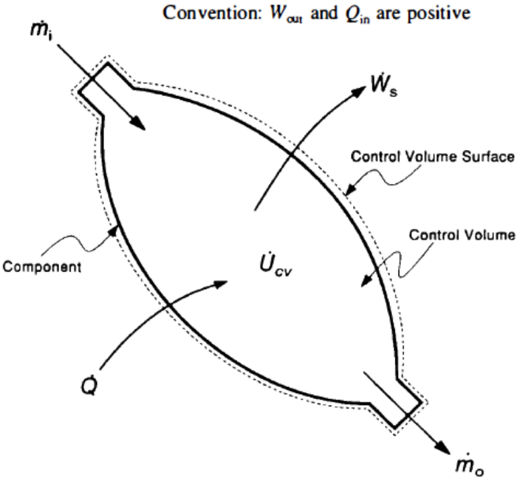
Fuel energy rate balance

$$\dot{Q}_f = \dot{Q}_{fc} \tag{4}$$

Coolant energy rate balance

$$\dot{m}_c C_{pc}(T_{c,out} - T_{c,in}) = \dot{Q}_{fc} \tag{5}$$

Basics- Fuel Coolant thermal interaction



Basics- Fuel Coolant thermal interaction

Fuel energy rate balance

$$\dot{Q}_f = \dot{Q}_{fc} \tag{6}$$

Coolant energy rate balance

$$\dot{m}_c(h_{v,out} - h_{l,in}) = \dot{Q}_{fc} \tag{7}$$

Overall Energy Balance of the system

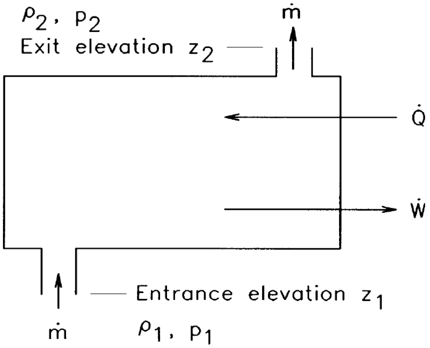


Fig. 2.1. Steady flow through a stationary control volume.

$$\dot{m}\left(\Delta u^o + \Delta\frac{p}{\rho} + g\Delta z\right) = \dot{m}\left(\Delta i^o + g\Delta z\right) = \dot{Q} - \dot{W}.$$