PWR Description

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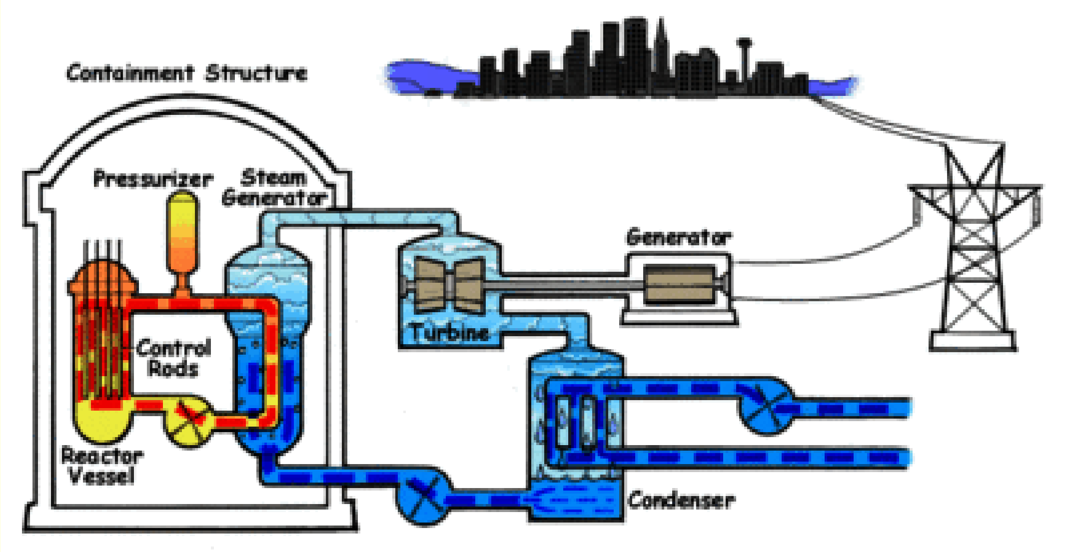
22.06: Engineering of Nuclear Systems

CENTER FOR ADVANCED NUCLEAR ENERGY SYSTEMS

Pressurized Water Reactor (PWR)



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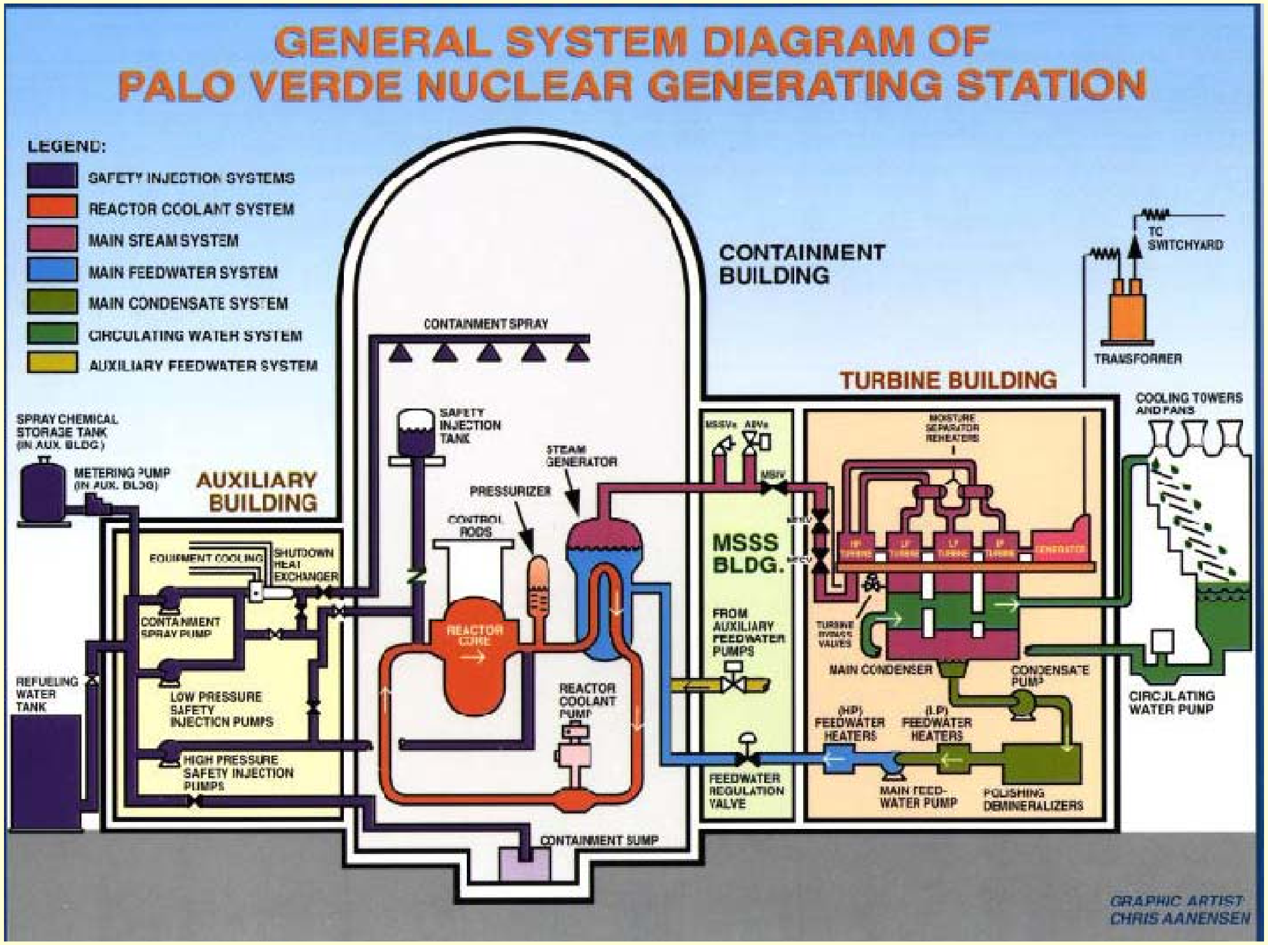
SCHEMATIC OF A PWR



Major PWR vendors include Westinghouse, Areva and Mitsubishi

PWR Coolant Circuits

- INDIRECT CYCLE: Primary and Secondary Coolant Loops
- Single Phase (Liquid) Reactor Coolant

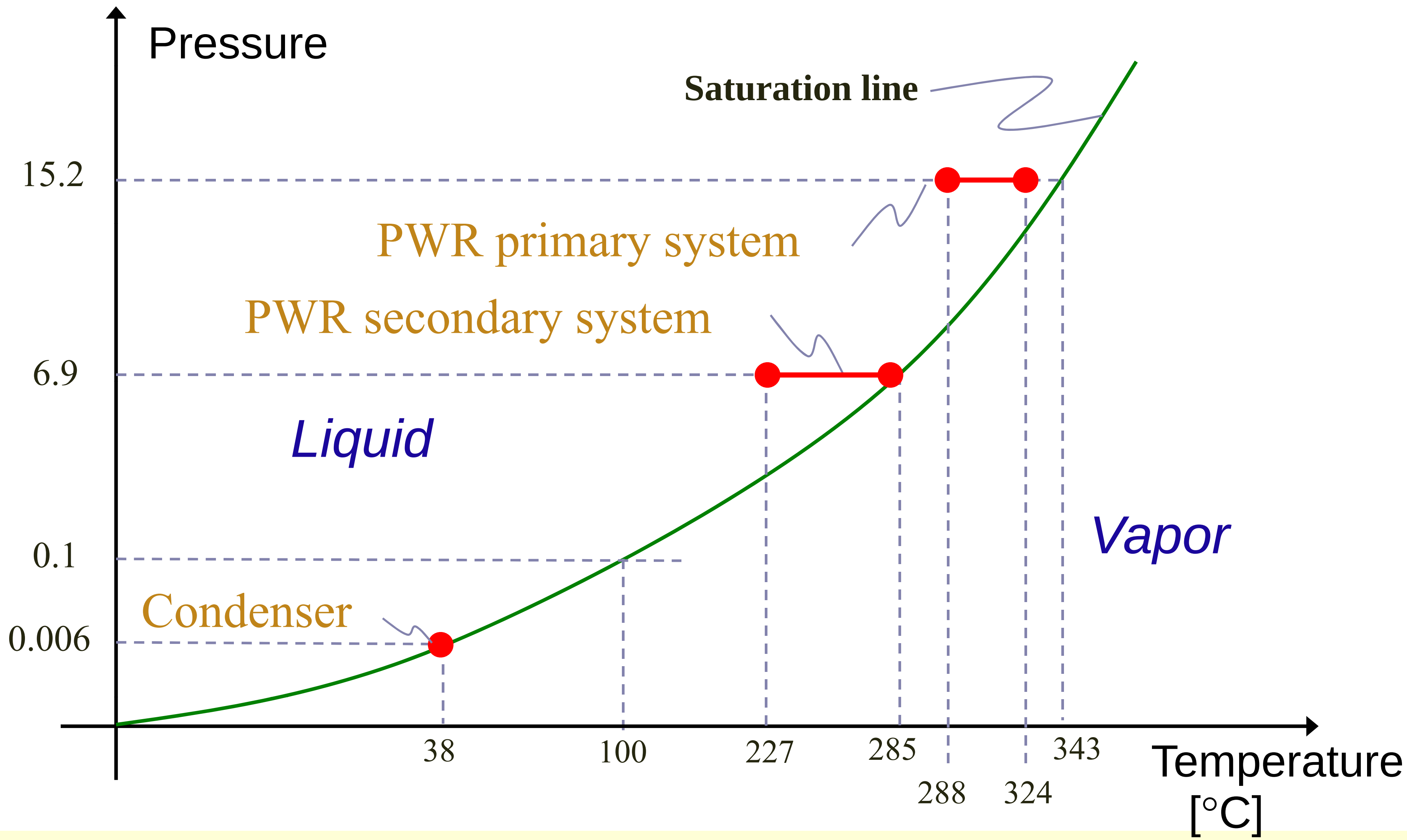
[T_{in}=287.7°C, T_{out}=324°C, P=15.2 MPa, T_{sat}= 343.3°C]

- Two-Phase (Steam-Water) Power Conversion Cycle Loop

[$T_{SG,in}$=227°C, $T_{SG,out}$=285°C, P=6.9 MPa, T_{sat}=285°C]

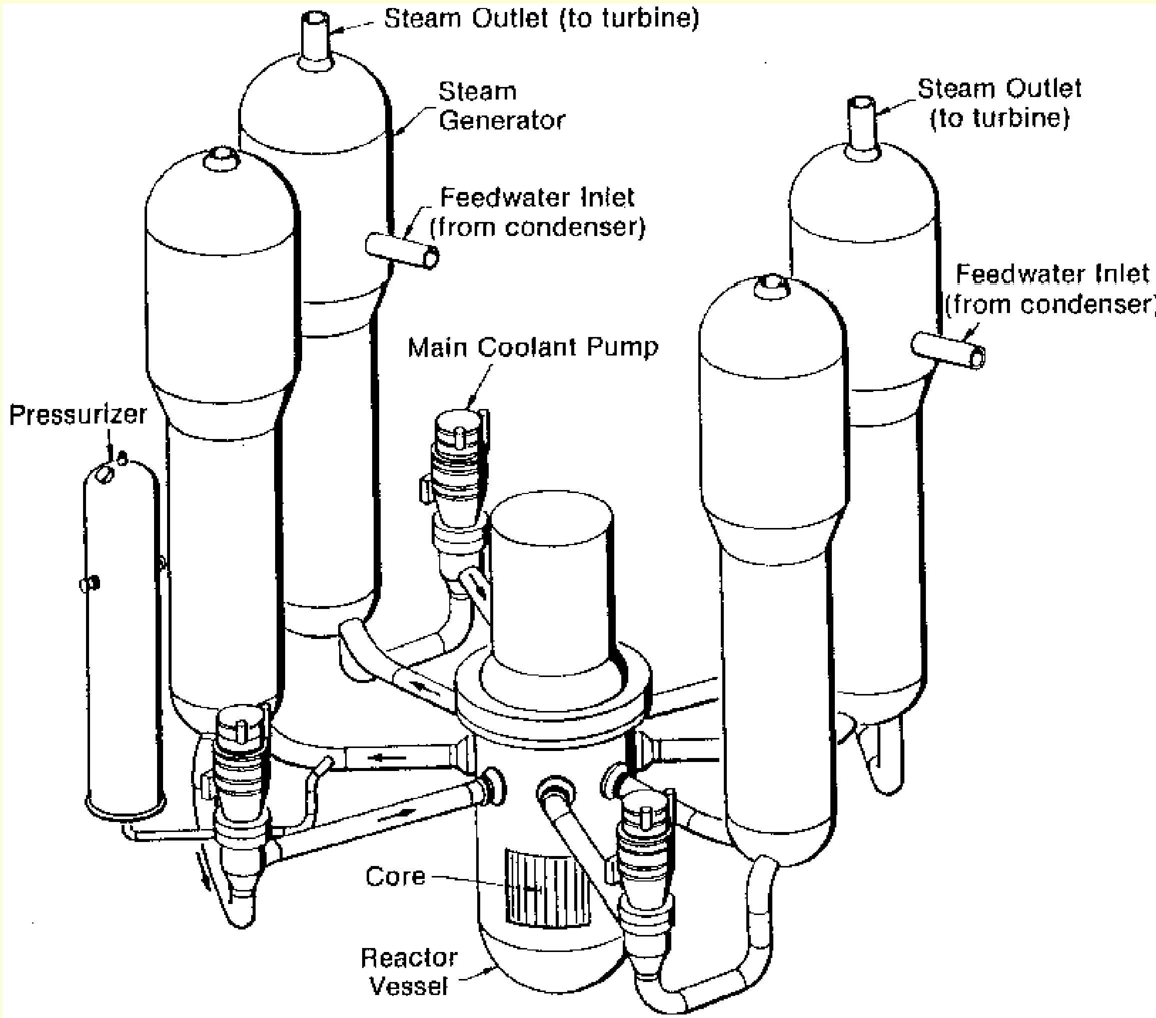
[$T_{Condenser}$= 37.8°C, P=6.6 kPa]

Phase Diagram of Water



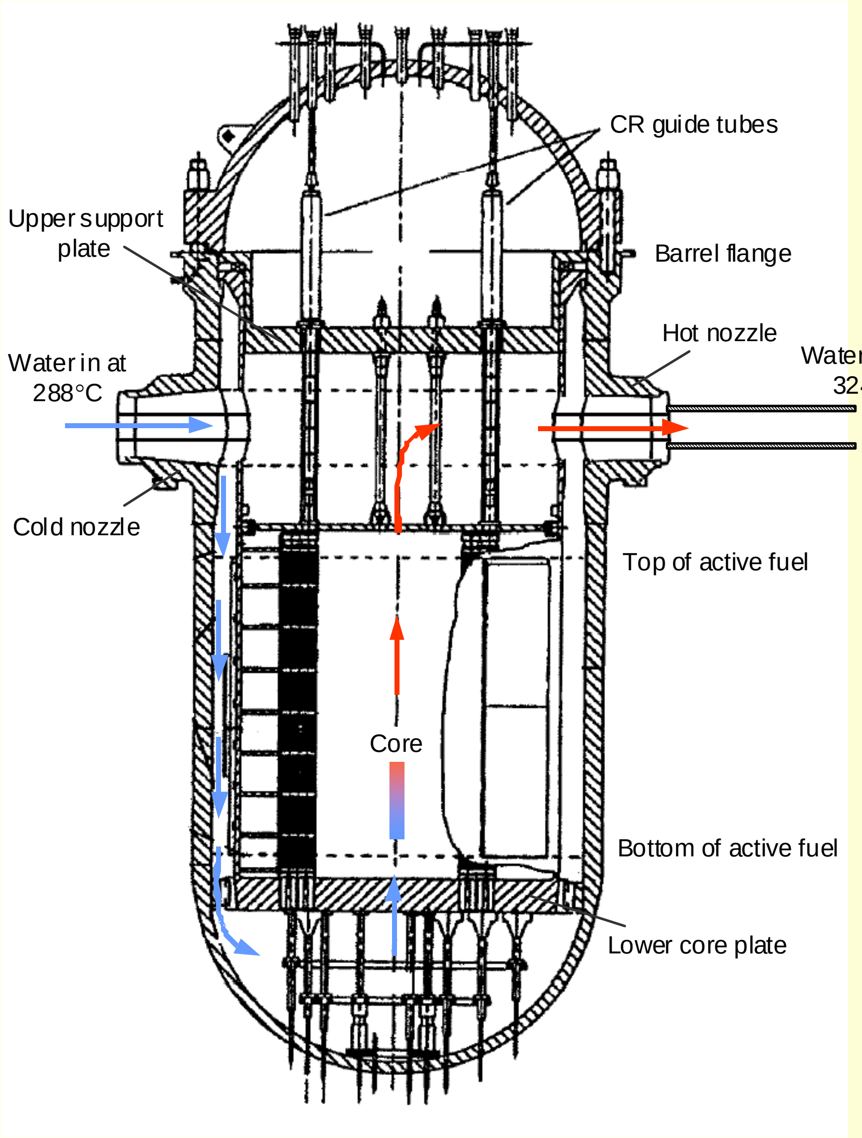
PWR Vessel, Core and Primary System

ARRANGEMENT OF THE PRIMARY SYSTEM FOR A WESTINGHOUSE 4-LOOP PWR

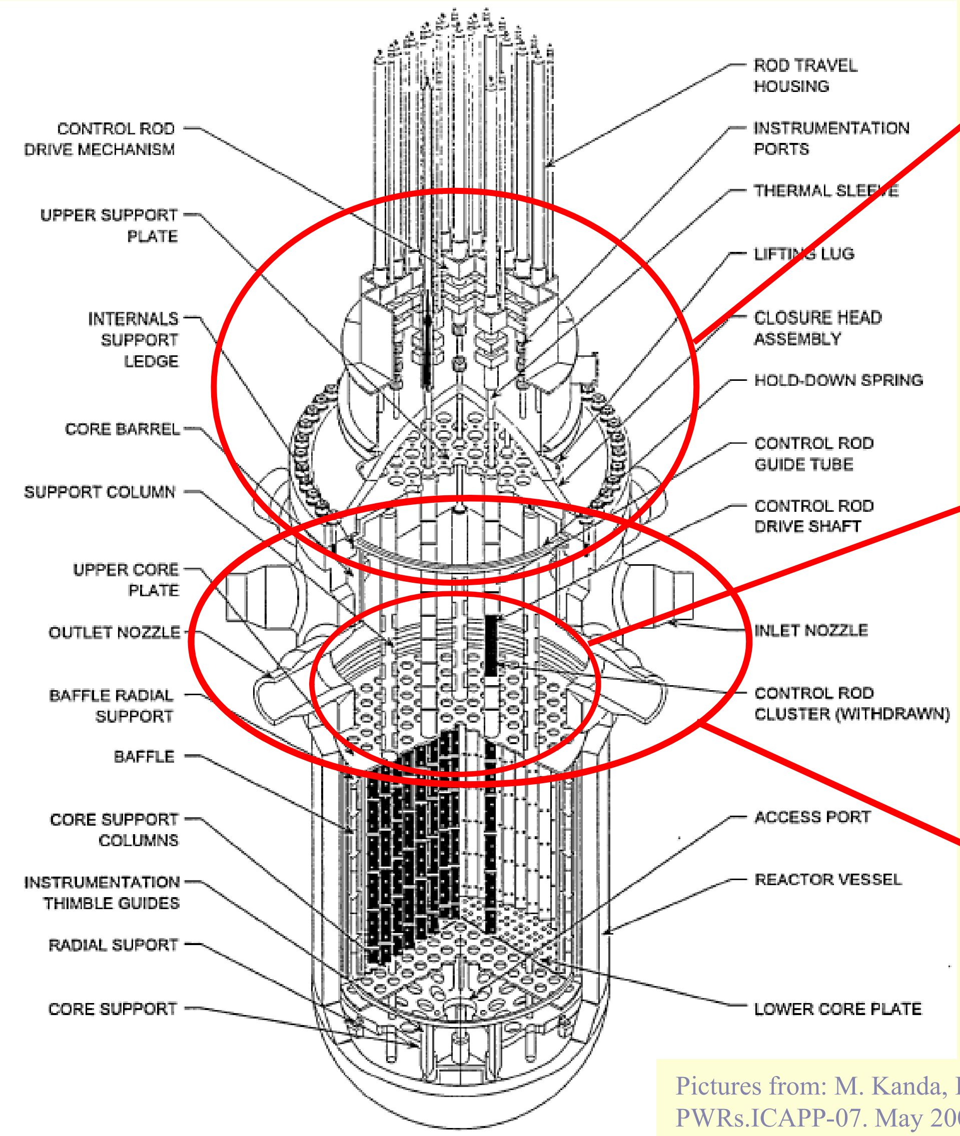


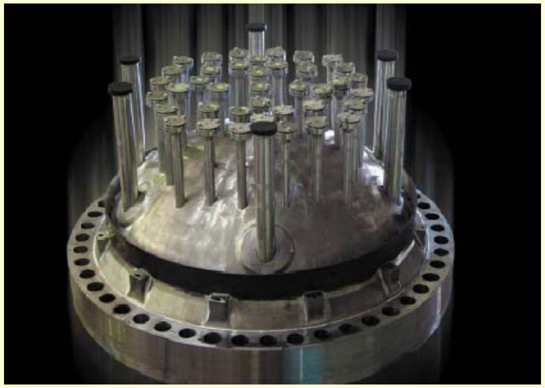
A.V. Nero, Jr., *A Guidebook to Nuclear Reactors*, 1979

FLOW PATH WITHIN REACTOR VESSEL



REACTOR VESSEL AND INTERNALS





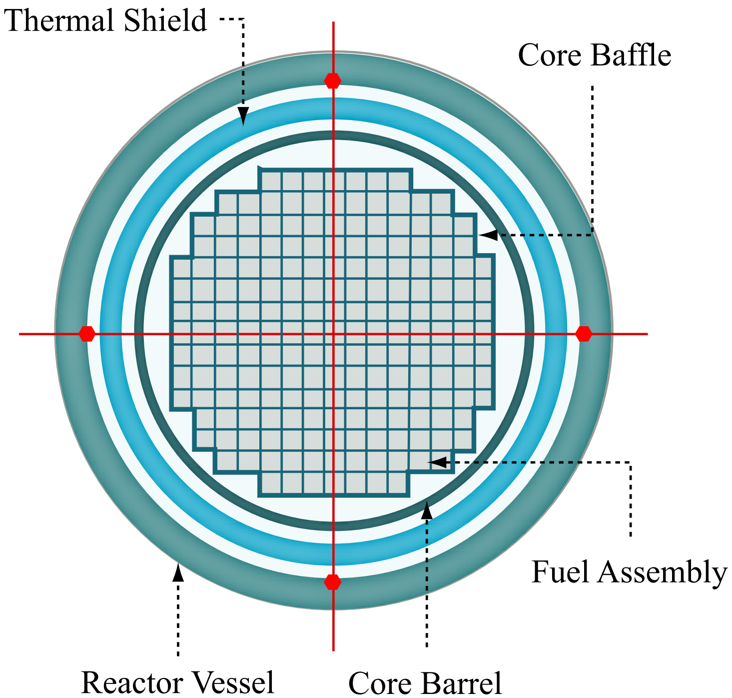
Pictures from: M. Kanda, Improvement in US-APWR design from lessons learned in Japanese PWRs.ICAPP-07. May 2007 (top), and EPR brochure available at www.areva.com (bottom two)

TYPICAL 4-LOOP REACTOR VESSEL PARAMETERS

Overall length of assembled vessel, closure head, and nozzles	13.36 m
Inside diameter of shell	4.39 m
Radius from center of vessel to nozzle face	
Inlet	3.33 m
Outlet	3.12 m
Nominal cladding thickness	5.56 mm
Minimum cladding thickness	3.18 mm
Coolant volume with core and internals in place	134.2 m^3
Operating pressure	15.51 MPa
Design pressure	17.24 MPa
Design temperature	343.3°C
Vessel material	Carbon steel
Cladding material Sta	inless steel
Number of vessel material surveillance capsules, total	8

TYPICAL 4-LOOP CORE

Cross Section (193 Fuel Assemblies)



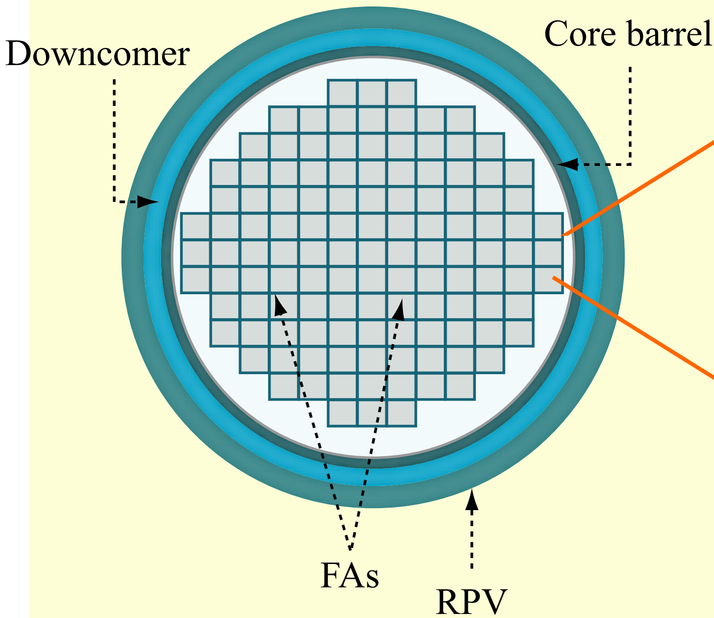
Parameters

Total heat output	~3250-3411 MWt
Heat generated in fuel	97.4%
Nominal system pressure	15.6 MPa
Total coolant flow rate	~1.74 x 10^4 kg/s
Coolant temperature	
Nominal inlet	291.9^{o}C
Average rise in vessel	33.9^{o}C
Outlet from vessel	325.8^{o}C
Equivalent core diameter	3.37 m
Core length, between fuel ends	3.66 m
Fuel weight, uranium (first core)	86,270 kg
Number of fuel assemblies	193

Image by MIT OpenCourseWare.

Masche, G., Systems Summary: W PWR NPP, 1971

Geometry of the fuel



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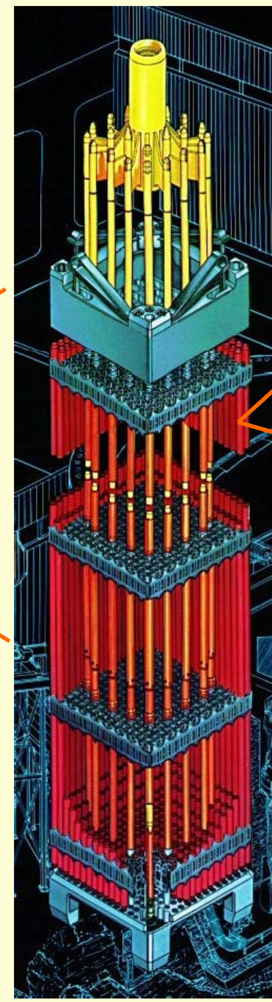


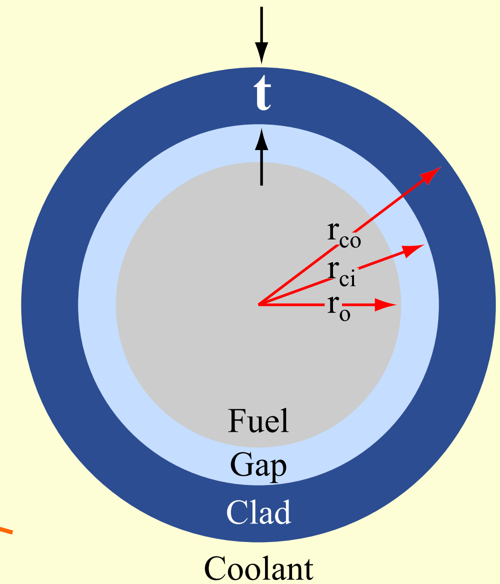


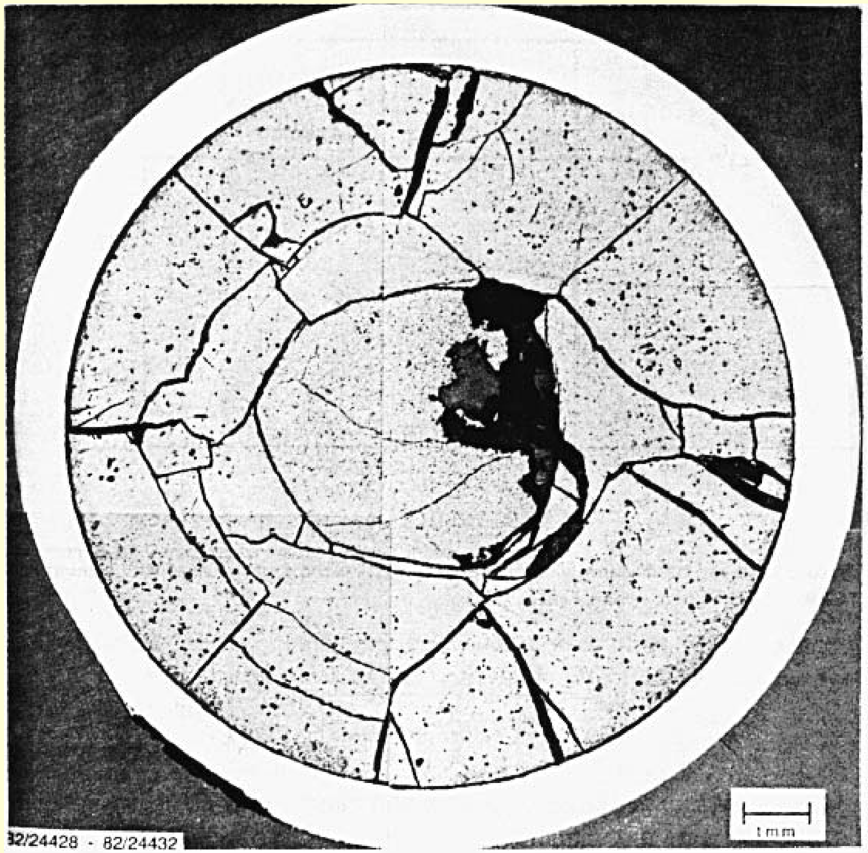
Image by MIT OpenCourseWare.

Cross Section of a Representative Fuel Pin (not drawn to scale)

mm (in.)	BWR	PWR
$2r_o$	10.40 (0.409)	8.20 (0.323)
$2r_{co}$	12.27 (0.483)	9.50 (0.374)
t	0.813 (0.032)	0.57 (0.023)

Why the fuel/clad gap?

- Provides clearance for fuel pellet insertion during fabrication
- Accommodates fuel swelling without breaking the clad
- Filled with helium gas

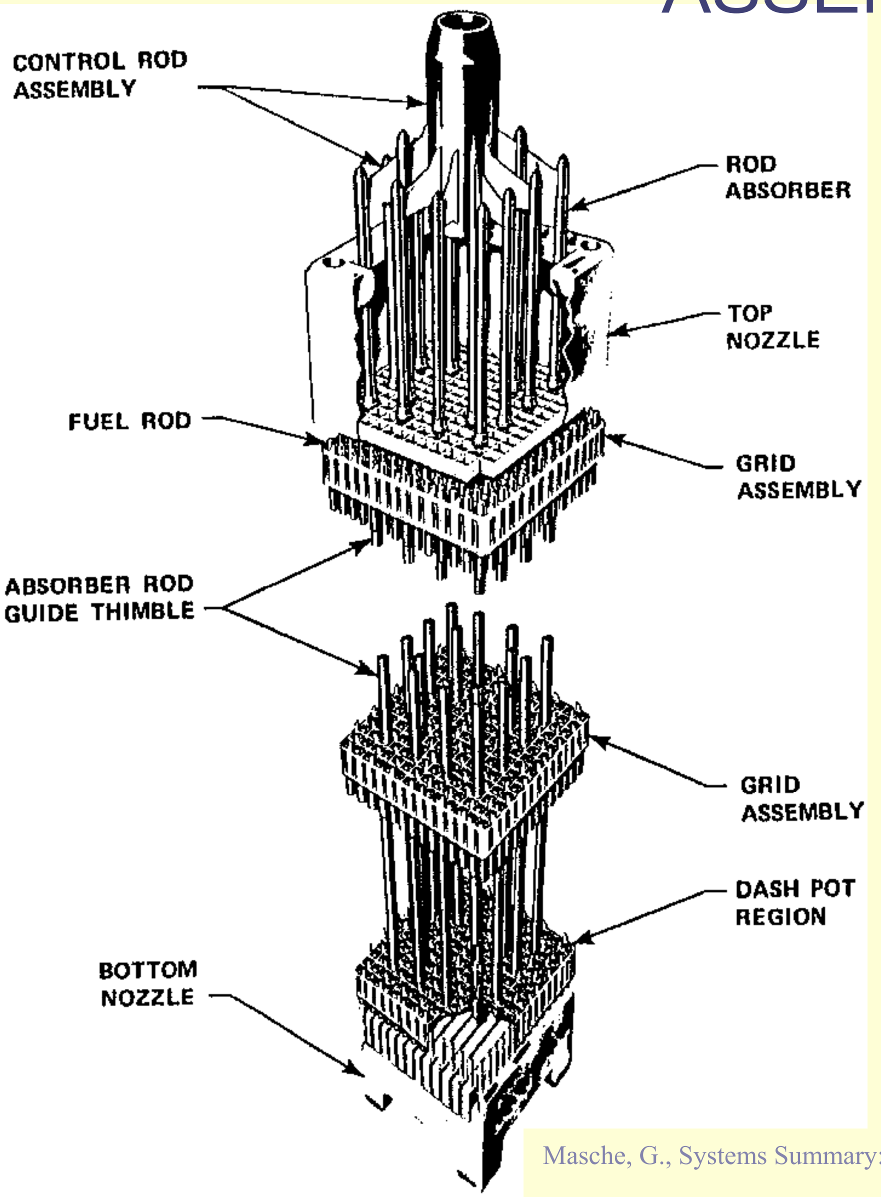


Example of a Cracked Fuel Cross Section
Source: Todreas & Kazimi, Vol. I, p. 333

TYPICAL FUEL ROD PARAMETERS

Outside diameter	9.50 mm
Cladding thickness	0.57 mm
Diametral gap	0.166 mm
Pellet diameter	8.19 mm
Pitch	12.6 cm
Rods array in assembly	17x17
Fuel rods per assembly	264
Total number of fuel rods in core	50,952

CUTAWAY OF TYPICAL ROD CLUSTER CONTROL ASSEMBLY (RCCA)



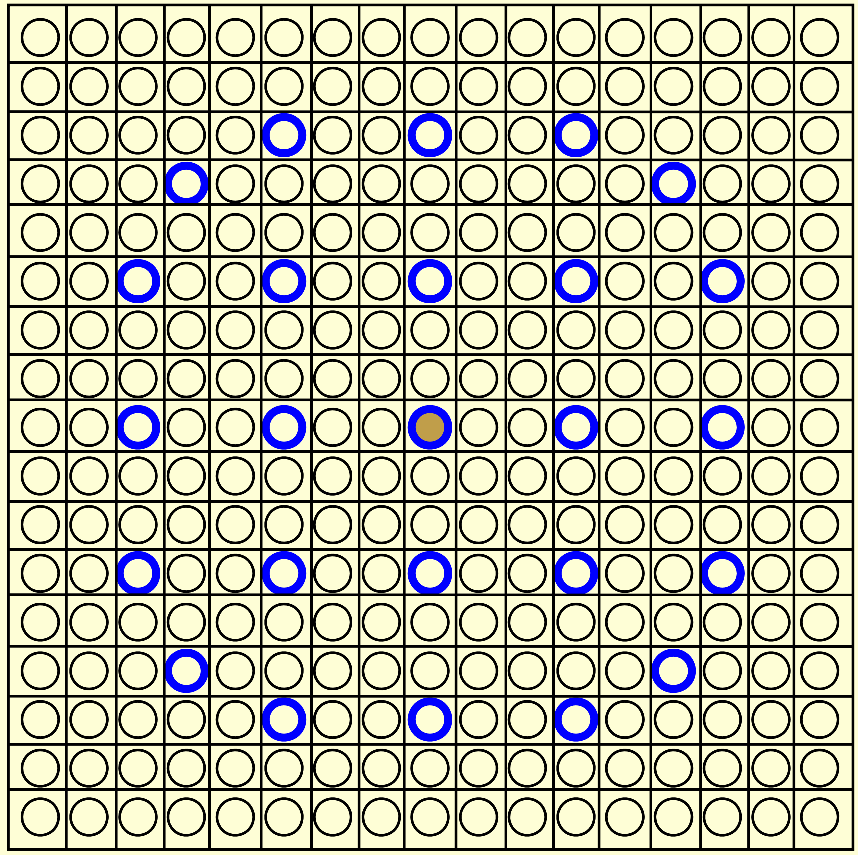
Masche, G., Systems Summary: W PWR NPP, 1971

From: EPR brochure. Available at www.areva.com

PWR Control Rod (Westinghouse RCCA)

Made of Ag-In-Cd (“black” rods for scram) or Inconel (“gray” rods for fine tuning)

Public domain image from wikipedia.



Control rod guide tube (24)

Instrument thimble

Other means to control reactivity in PWRs

Boron (boric acid, H_3BO_3) **dissolved in coolant**. Compensates for loss of reactivity due to fuel burnup. High concentration at BOC (beginning of cycle), progressively decreased to zero at EOC (end of cycle)

Pros: uniform absorption throughout core, concentration is easily controlled

Cons: makes coolant slightly acidic (requires addition of other chemicals to re-equilibrate pH), can deposit (come out of solution) as crud on fuel rods, can make moderator reactivity feedback positive at high concentration

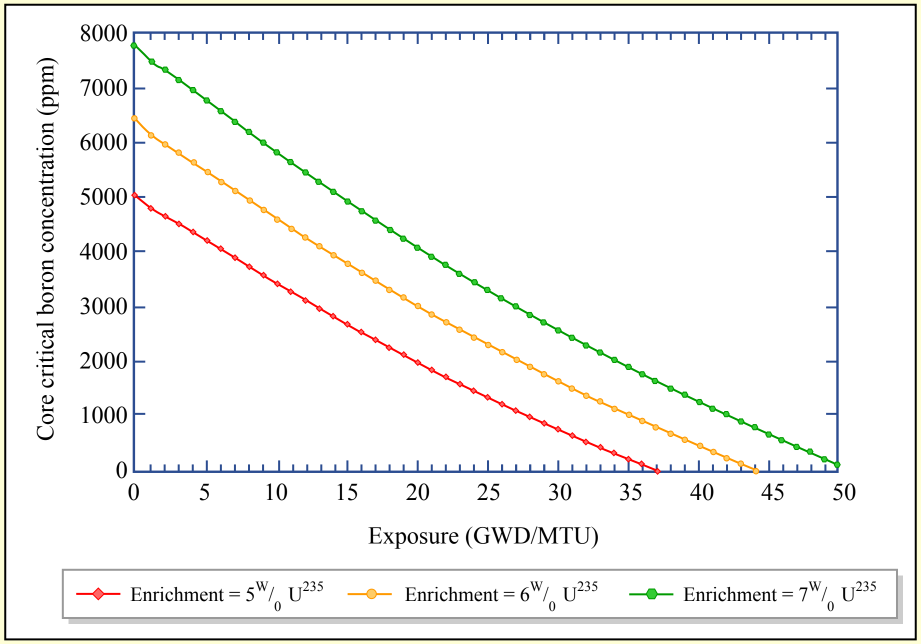
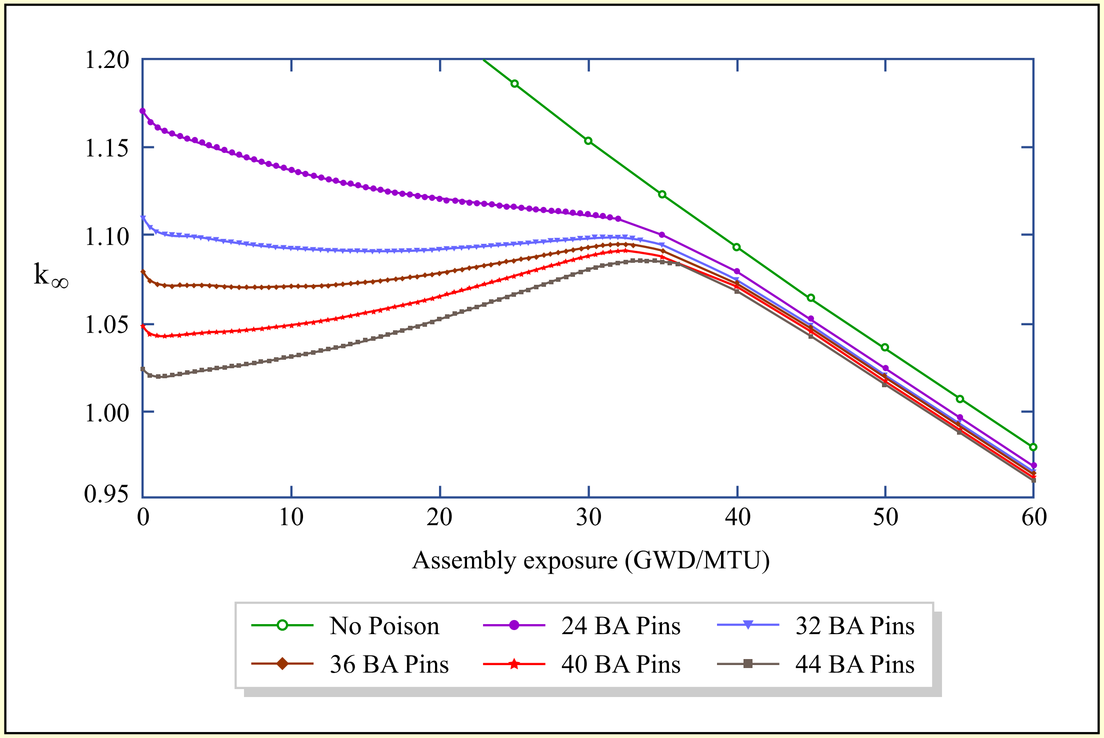


Image by MIT OpenCourseWare.

Other means to control reactivity in PWRs (2)

Burnable absorbers ("poisons") loaded in fuel. Gd (Gd_2O_3) has higher σ_a than ^{235}U, thus it "burns" faster than fuel, which tends to increase k_{eff} over time.

Pros: no impact on coolant corrosion or moderator reactivity feedback
Cons: lowers melting point and thermal conductivity of UO_2, cannot burn out completely by EOC



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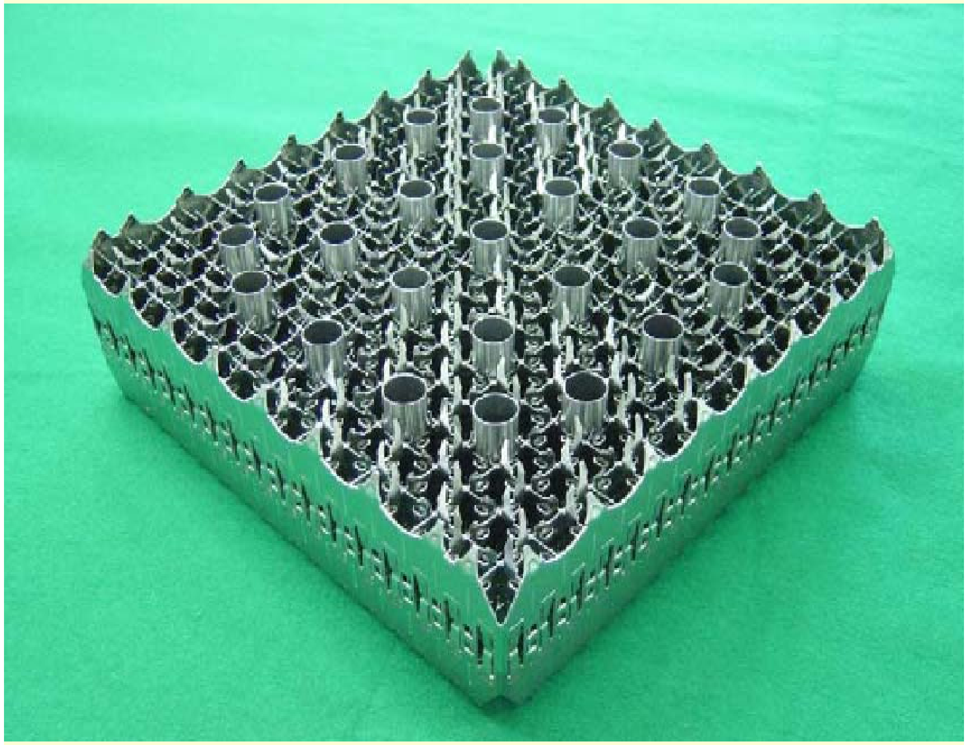
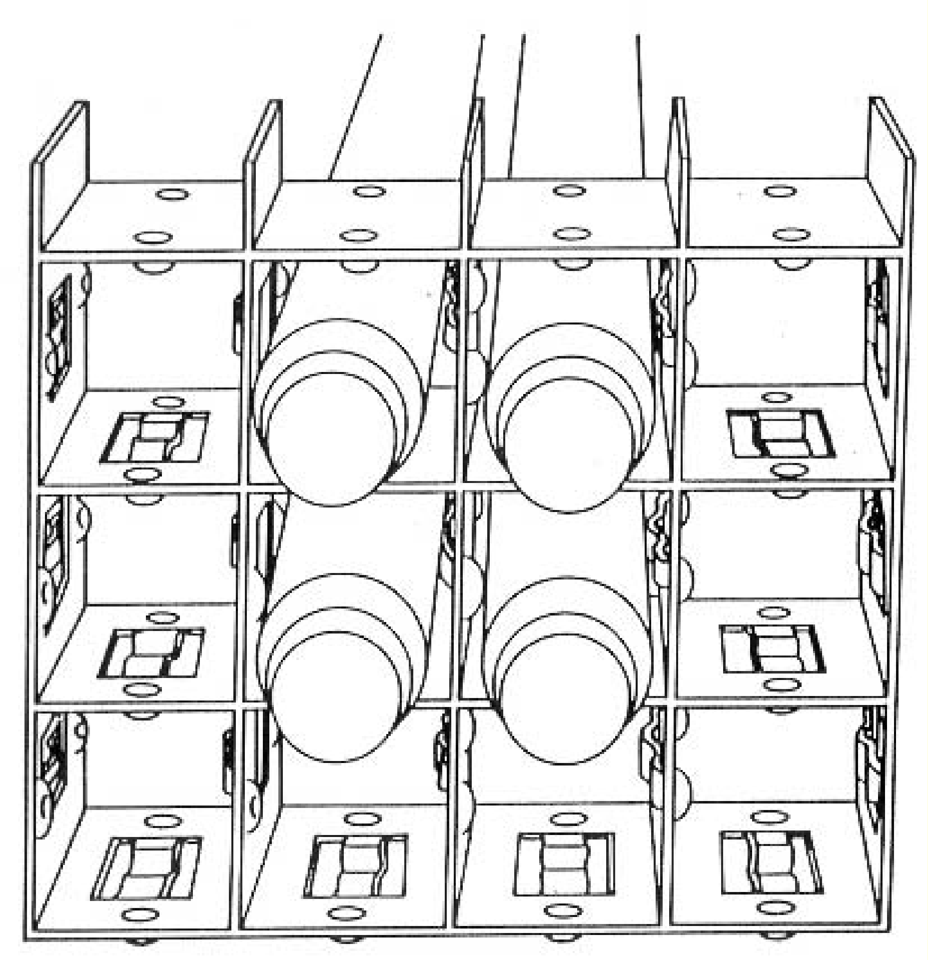
PWR GRID SPACERS



From: Mitsubishi US-APWR Fuel and core design. DOE Technical session UAP-HF-07063. June 29, 2007.



Masche, G., Systems Summary: W PWR NPP, 1971

Hold fuel rods in place ⇒ prevent excessive vibrations

Have mixing vanes ⇒ enhance coolant mixing and heat transfer

Connection of PWR Core Design to Neutronics

Why is Zr used as structural material in fuel assemblies?

What functions does water perform?

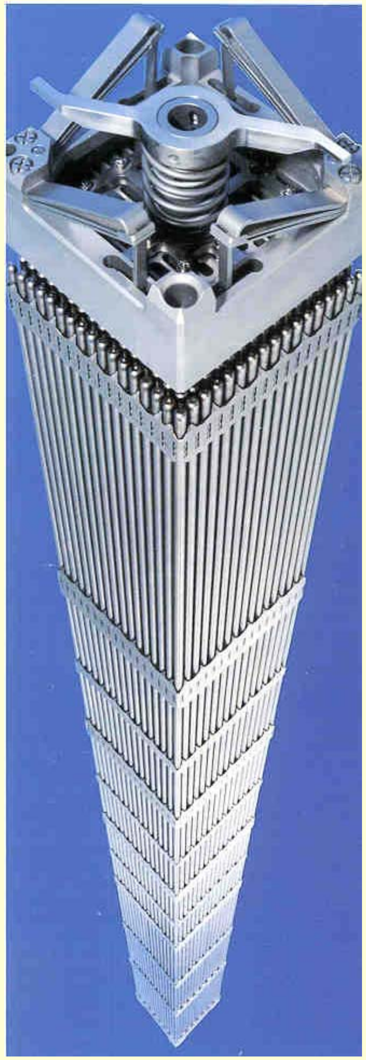
What determines the fuel rod spacing?

Why are the fuel rods so small?

Why are the control rods arranged in clusters?

Why is boron dissolved in the coolant? What is Gd used for?

PWR Bundle Design Advances



- Extended burnup features
  - Advanced cladding (ZIRLO™, M5)
  - Annular blankets
  - Larger gas plena
- Improved mechanical performance
  - Improved debris filters
  - Low growth, wear-resistant materials
- Improved economic and operational performance
  - Natural uranium blankets
  - Flow mixing grids to enhance margin to DNB
- Reduced O&M costs
  - Low cobalt steel alloys to reduce exposure
  - Reduced inspection requirements

REPRESENTATIVE CHARACTERISTICS OF PWRs

Parameter	4-loop PWR
1. Plant	
Number of primary loops	4
Reactor thermal power (MWth)	3411
Total plant thermal efficiency (%)	34
Plant electrical output	1150
Power generated directly in coolant (%)	2.6
Power generated in the fuel (%)	97.4
2. Core	
Core barrel inside diameter/outside diameter (m)	3.76/3.87
Rated power density (kW/L)	104.5
Core volume (m^3)	32.6
Effective core flow area (m^2)	4.747
Active heat transfer surface area (m^2)	5546.3
Average heat flux (kW/m^2)	598.8
Design axial enthalpy rise peaking factor ($F_{\Delta h}$)	1.65
Allowable core total peaking factor (F_Q)	2.5
3. Primary Coolant	
System pressure (MPa)	15.51
Core inlet temperature (^oC)	292.7
Average temperature rise in reactor (^oC)	33.4
Total core flow rate (Mg/s)	18.63
Effective core flow rate for heat removal (Mg/s)	17.7
Average core inlet mass flux (kg/m^2-s)	3,729
4. Fuel Rods	
Total number	50,952
Fuel density (% of theoretical)	94
Fuel pellet diameter (mm)	8.19
Fuel rod diameter (mm)	9.5
Cladding thickness (mm)	0.57
Cladding material	Zircaloy-4
Active fuel height (m)	3.66

Parameter	4-loop PWR
5. Fuel Assemblies	
Number of assemblies	193
Number of heated rods per assembly	264
Fuel rod pitch (mm)	12.6
Fuel assembly pitch (mm)	215
Number of grids per assembly	7
Fuel assembly effective flow area (m^2)	0.02458
Location of first spacer grid above beginning of heated length (m)	0.3048
Grid spacing (m)	0.508
Grid type	L-grid*
Number of control rod thimbles per assembly	24
Number of instrument tubes	1
Guide tube outer diameter (mm)	12.243
6. Rod Cluster Control Assemblies	
Neutron absorbing material	Ag-In-Cd
Cladding material	Type 304 SS
Cladding thickness (mm)	0.46
Number of clusters Full/Part length	53/8
Number of absorber rods per cluster	24

***Employs mixing vanes**

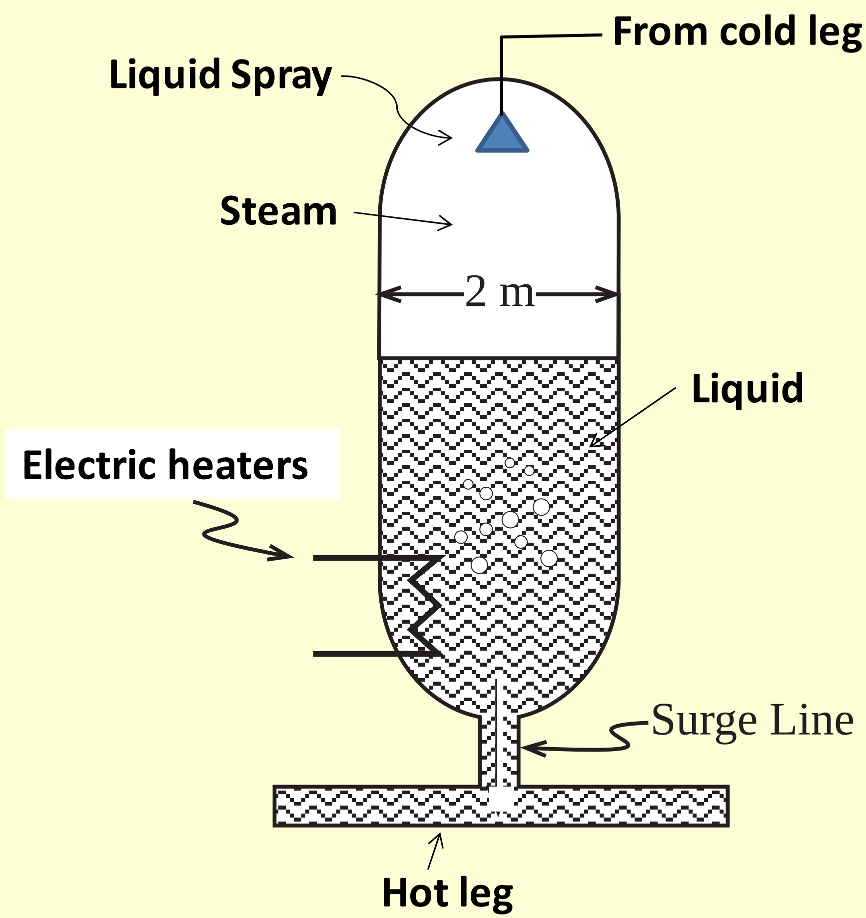
Image by MIT OpenCourseWare.

A. V. Nero, Jr., *A Guidebook to Nuclear Reactors*, 1979.

PWR PRESSURIZER

Pressurizer (Saturated Liquid-Steam System: P=15.5 MPa, T=344.7°C)

Controls pressure in the primary system



- Pressure can be raised by heating water (electrically)

- Pressure can be lowered by condensing steam (on sprayed droplets)

PRESSURIZER TYPICAL DESIGN DATA

Number and type	1 Two-phase water and steam pressurizer
Overall height	16.08 m
Overall diameter	2.35 m
Water volume	30.58 cu m
Steam volume	20.39 cu m
Design pressure	17.2 MPa
Design temperature	360°C
Type of heaters	Electric immersion
Number of heaters	78
Installed heater power	1800 kW
Number of relief valves	2 Power-operated
Number of safety valves	3 Self-actuating
Spray rate	
• *Pressure transient*	3028 L/m
• *Continuous*	3.79 L/m
Shell material	Mn-Mo steel, clad internally with stainless steel
Dry weight	106,594 kg
Normal operating weight	125, 191 kg
Flooded weight (21.1°C)	157,542 kg

Image by MIT OpenCourseWare.

Masche, G., Systems Summary: W PWR NPP, 1971

Reactor Coolant Pumps

- Large centrifugal pumps

- Utilize controlled leakage shaft seal

- Have large flywheel to ensure slow coast-down upon loss of electric power to the motor

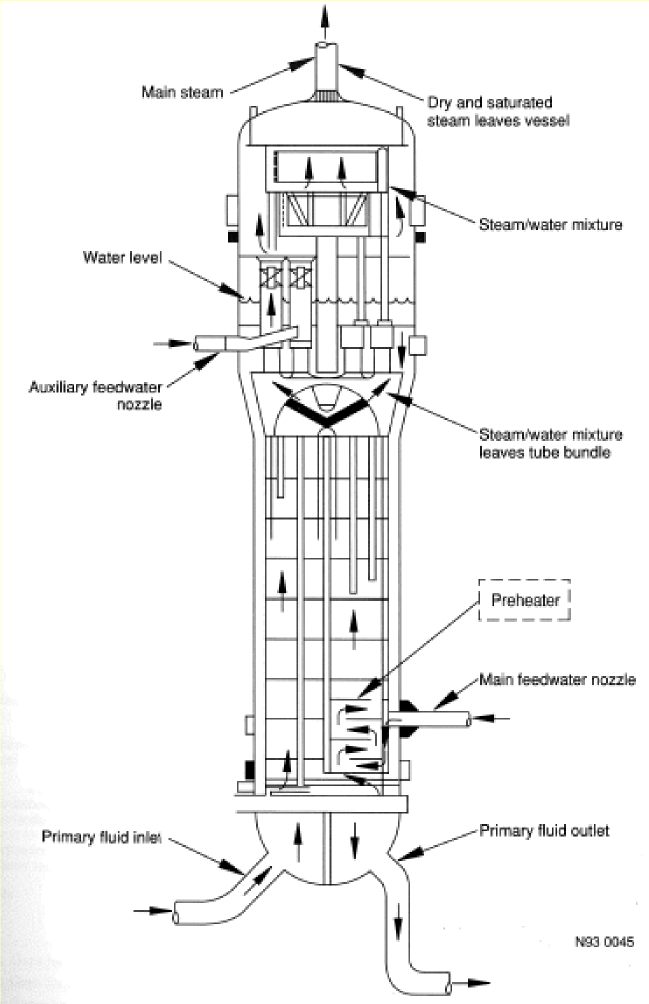
PWR Secondary System

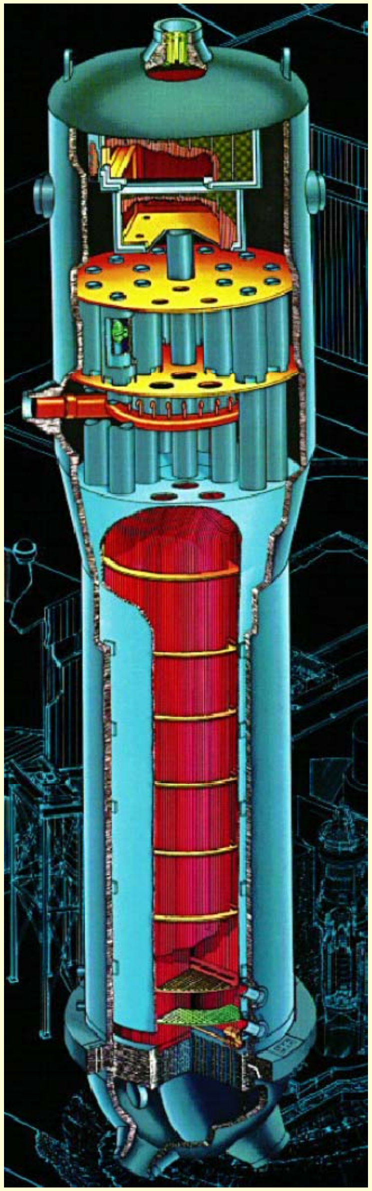
PWR STEAM GENERATORS

Primary side, Hot (T_{in} = 324˚C, T_{out} = 288˚C): High Pressure Liquid
Secondary side, Cold (T_{sat} = 285˚C): Lower Pressure Steam and Liquid

- Water Boils on Shell Side of Heat Exchanger
- Steam Passes through Liquid Separators, Steam Dryers
- Liquid Water Naturally Recirculates via Downcomer
- Level Controlled via Steam and Feedwater Flowrates

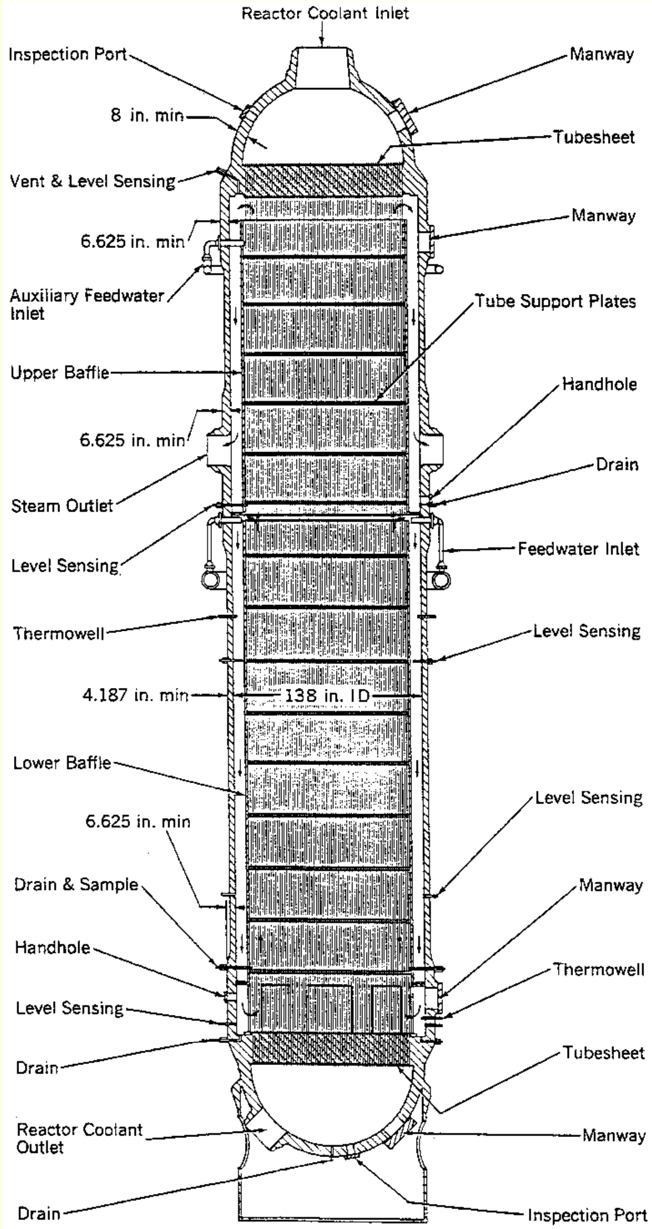
U-TUBE STEAM GENERATOR



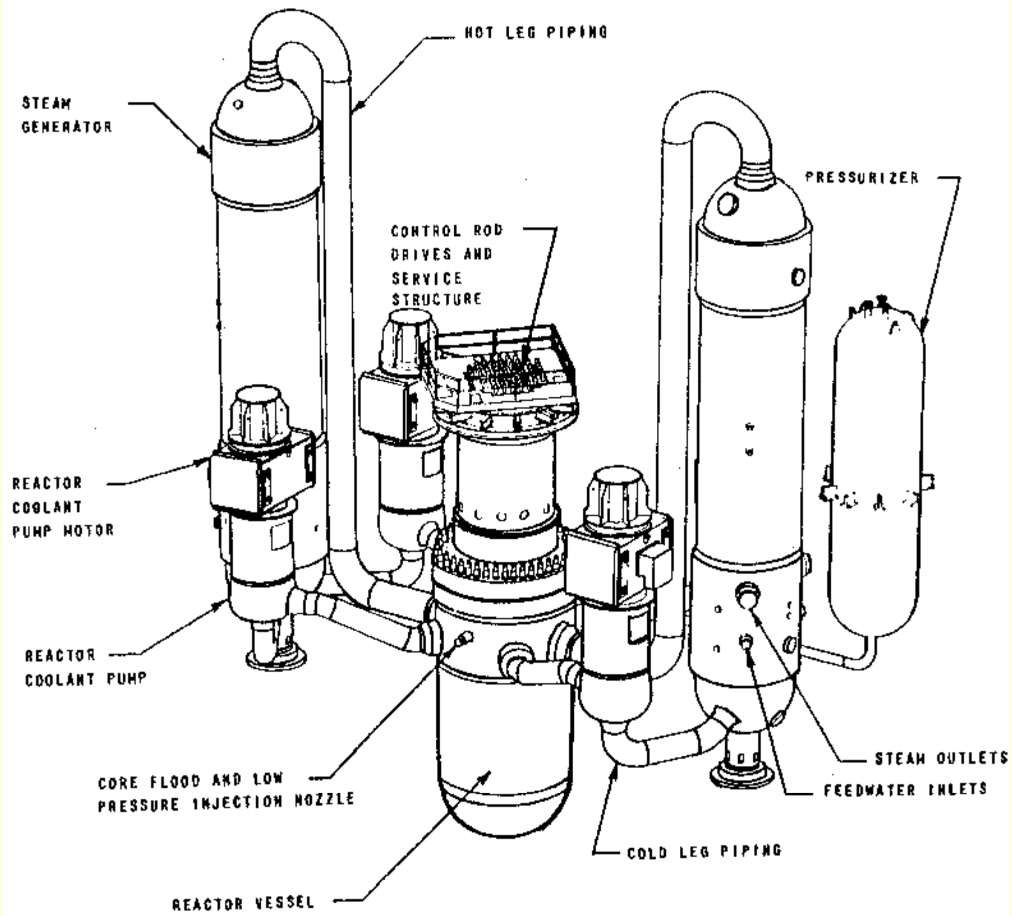


From: EPR brochure. Available at www.areva.com

ONCE-THROUGH NUCLEAR STEAM GENERATOR



Used only in old B&W plants



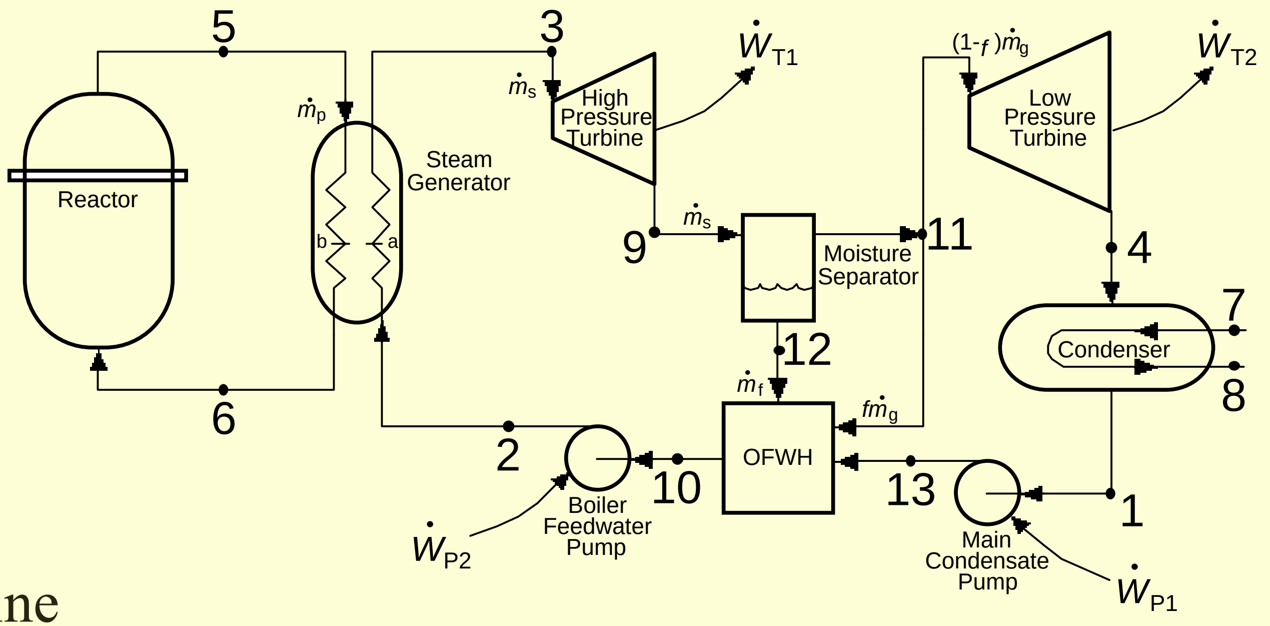
B&W, *Steam, Its Generation & Use*, 1972.

TYPICAL DESIGN DATA FOR STEAM GENERATORS

Number and type	4 Vertical, U-tube steam generators with integral steam-drum
Height overall	20.62 m
Upper shell OD	4.48 m
Lower shell OD	2.44 m
Operating pressure, tube side	15.5 MPa
Design pressure, tube side	17.2 MPa
Design temperature, tube side	343.3^{o}C
Full load pressure, shell side	6.90 MPa
Maximum moisture at outlet (full load)	0.25%
Design pressure, shell side	8.27 MPa
Reactor coolant flow rate	4360 kg/s
Reactor coolant inlet temperature	325.8^{o}C
Reactor coolant outlet temperature	291.8^{o}C
Shell material	Mn-Mo steel
Channel head material	Carbon steel clad internally with stainless steel
Tube sheet material	Mo-Cr-Ni steel clad with Inconel on primary face
Tube material	Inconel
Tube OD	2.22 cm
Average tube wall thickness	1.27 mm
Steam generator weights	
• *Dry weight, in place*	312,208 kg
• *Normal operating weight, in place*	376,028 kg
• *Flooded weight (cold)*	509,384 kg

Masche, G., Systems Summary: W PWR NPP, 1971

PWR power cycle (secondary$_S$ ystem)



Turbine

- Low Steam Pressure Requires:
  - Large turbine
  - Lower rotational speed (1800 RPM)

Condenser

- Steam Side at Low Pressure
- Cooling water from sea, river or cooling tower

PWR safety systems and containment to be discussed later in the course

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