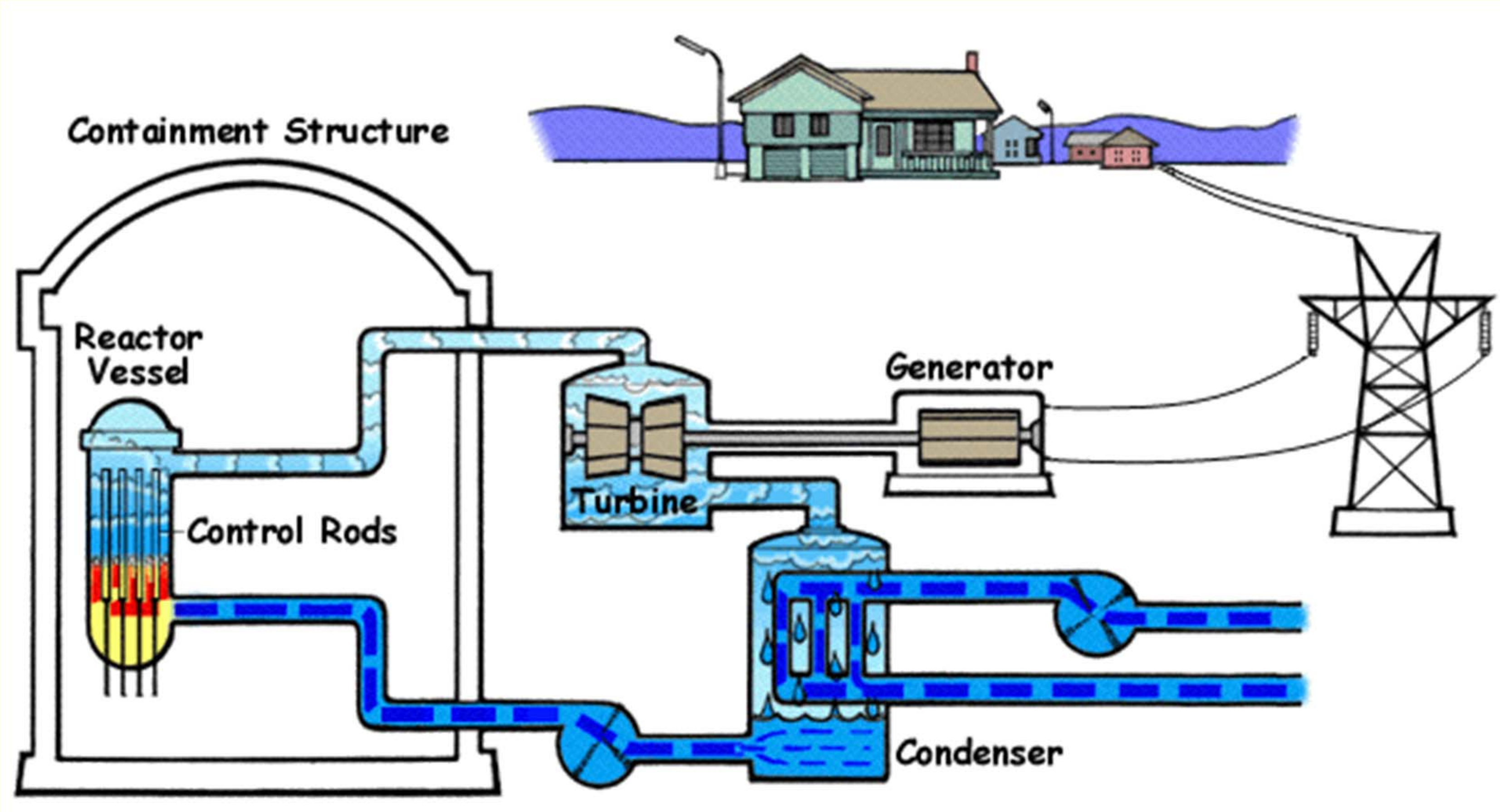
BWR Description

Jacopo Buongiorno
Associate Professor of Nuclear Science and Engineering

22.06: Engineering of Nuclear Systems

Center for Advanced Nuclear Energy Systems

Boiling Water Reactor (BWR)



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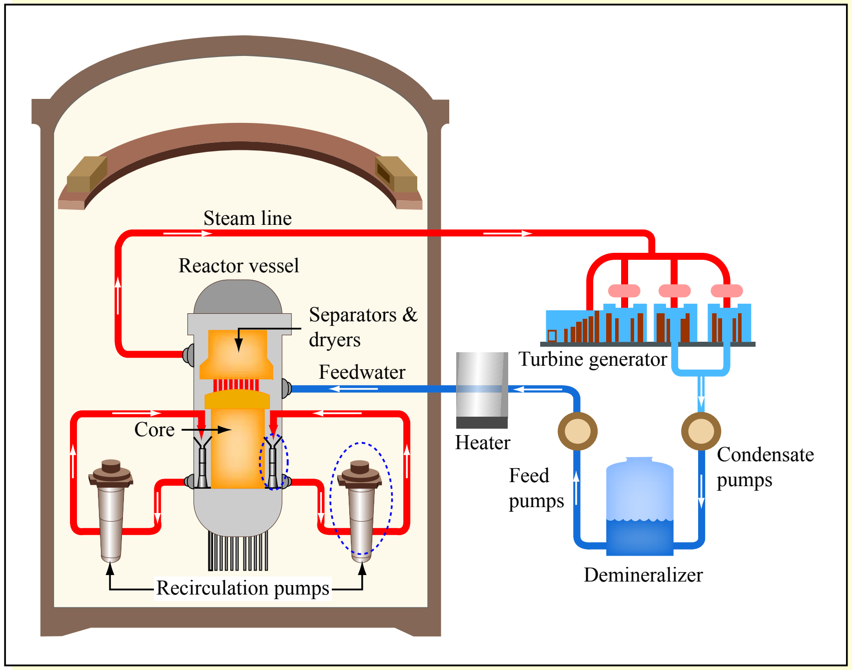
The BWR is a Direct Cycle Plant



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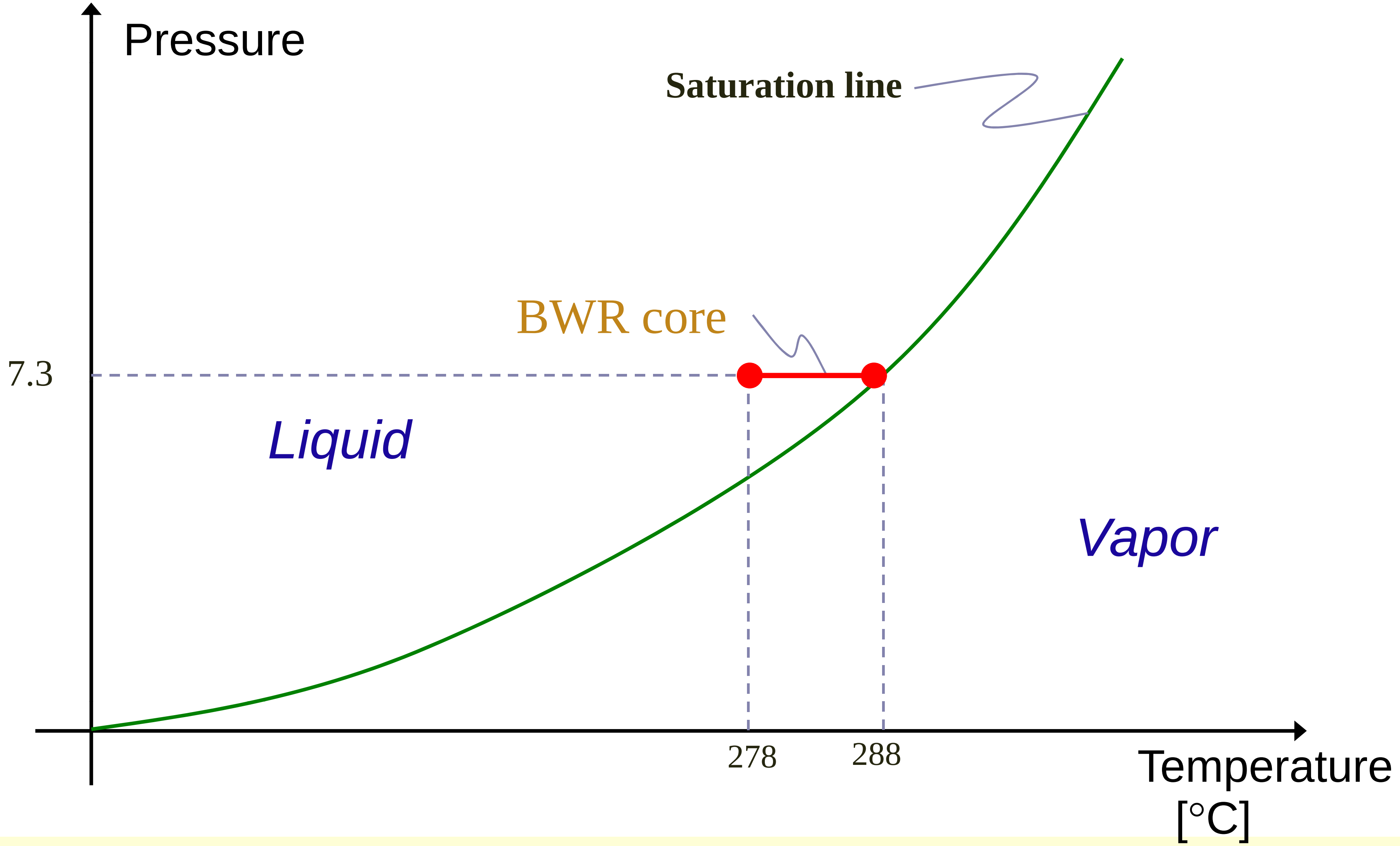
System pressure, MPa	7.136
Core thermal power, MW_{th}	3323
Electric power, MWe	1130
Thermal efficiency, %	34
Vessel ID / Thickness / Height, m	6.4 / 0.16 / 22
Core shroud diameter, m	5.2
Number of fuel assemblies	764
Core mass flow rate, kg/s	13702
Core inlet temperature, °C	278.3
Core outlet temperature, °C	287.2
Core exit quality, %	13.1
Feedwater flow rate, kg/s	1820
Feedwater temperature, °C	220
Steam flow rate, kg/s	1820
Steam temperature, °C	287.2
Core power density, kW/L	50.5
Core flow bypass	14 %

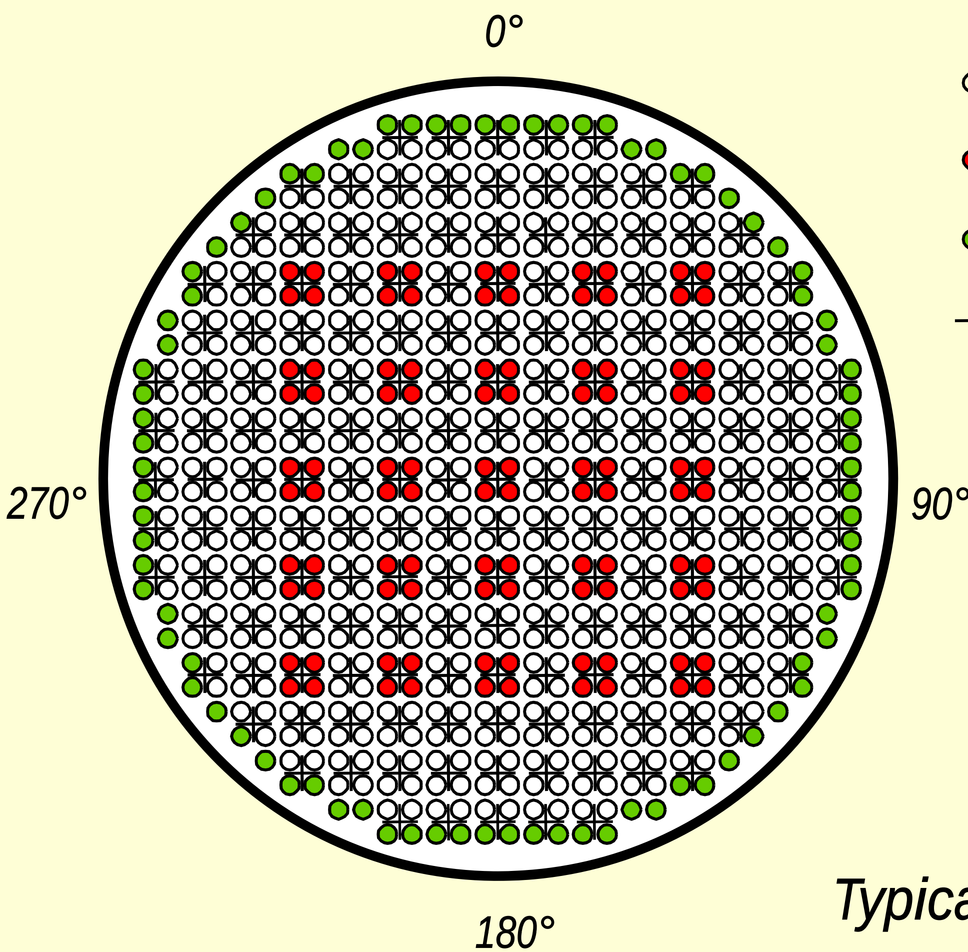
A.V. Nero, Jr., *A Guidebook to Nuclear Reactors*, 1979

Phase Diagram of Water



BWR Core

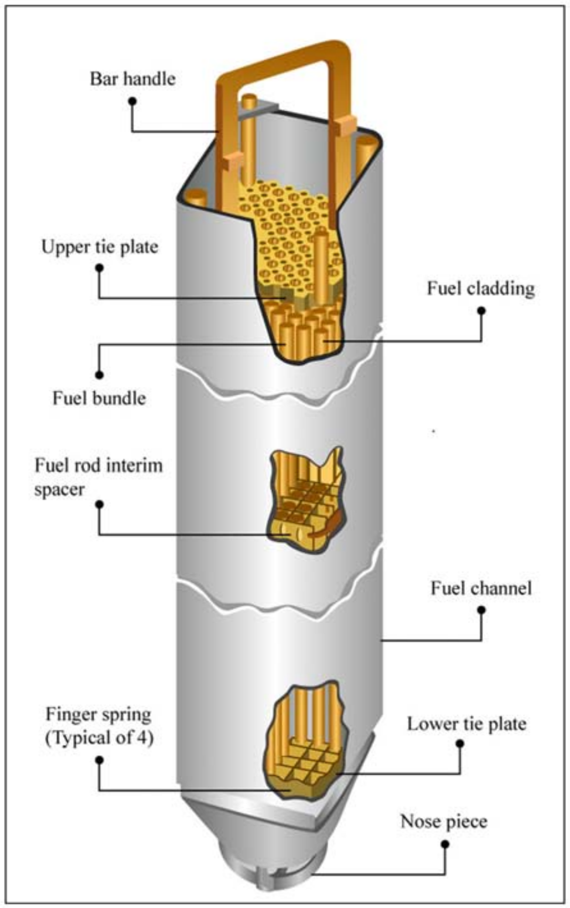
BWR Core Layout



- ○ *Fuel Bundle*
- ● *Control Cell Bundle*
- ● *Peripheral Bundle*
- \+ *Control Blade*

Typical Control Cell Core Layout

BWR Fuel Assembly



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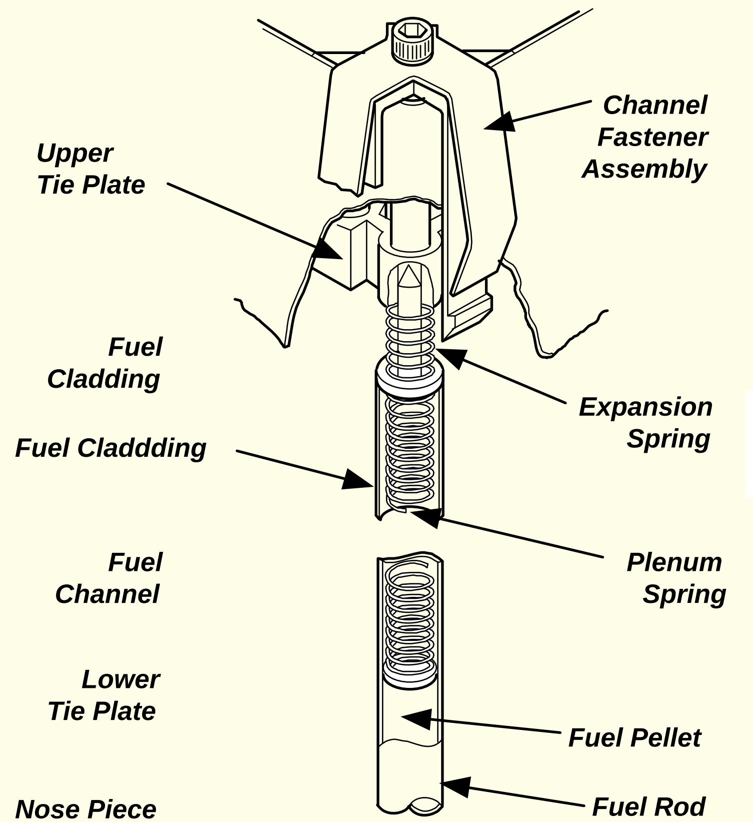
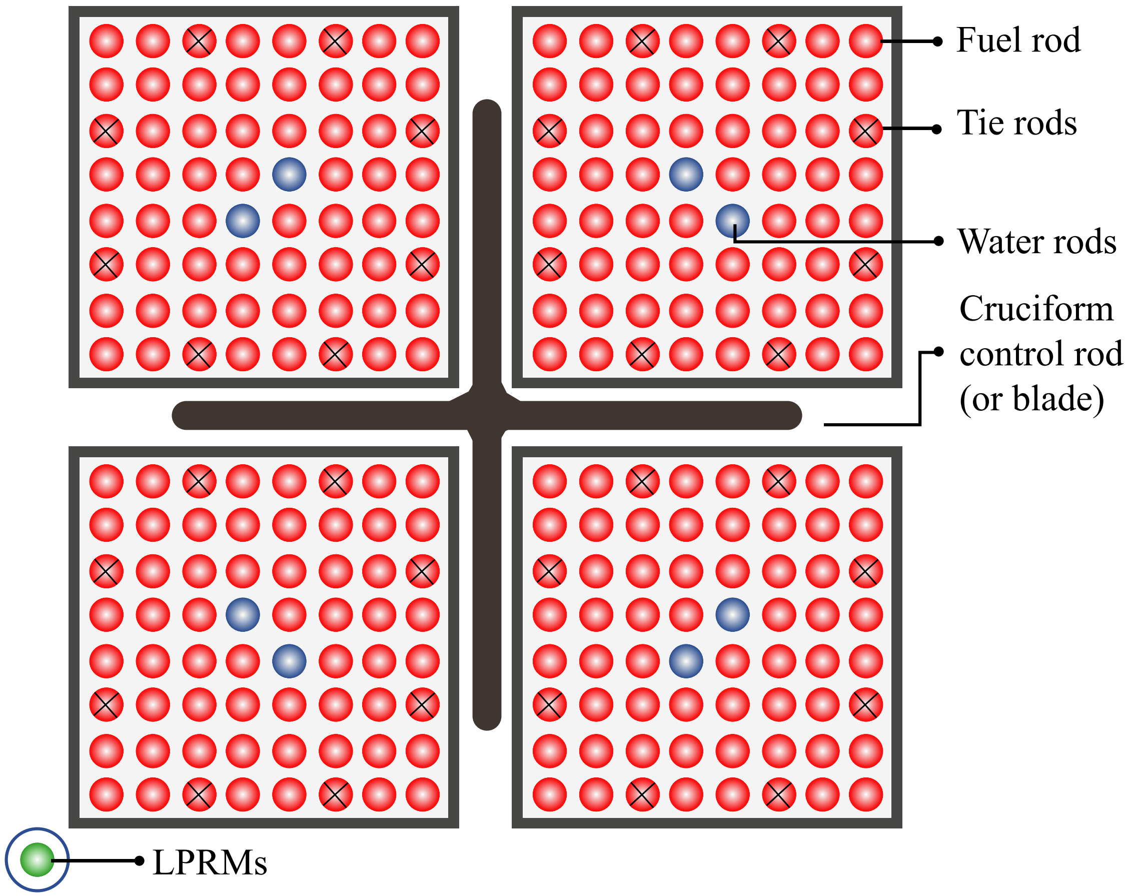


Single bundle 3D view

Fuel assemblies have a duct wall to prevent vapor radial drifting

BWR Fuel Assemblies



2D view of four bundle module, 8 x 8 lattice, with control blade

Image by MIT OpenCourseWare.

Fuel Assembly Parameters for 9x9 Fuel Assembly

Parameter	**Value**
Fuel Pellet OD (mm)	9.55
Fuel Pin OD (mm)	11.18
Clad Thickness (mm)	0.71
Fuel Pin Pitch (mm)	14.27
Active Fuel rod height (mm)	3707.9
Total Fuel Rod height (mm)	4178.7
Part Length Rod Height (mm)	2436
Fuel Pins / Water Rods per Fuel Assembly	74/2
Number of Part Length Rods	8
Inner/Outer diameter of the water rods (mm)	23.37/24.89
Duct Thickness (mm)	2.54
Clearance between duct and peripheral fuel rods (mm)	3.53
Clearance between water rods and fuel rods (mm)	1.79
Assembly Outer Dimension (mm)	137.54
Inter-Assembly Gap (mm)	14.86
Average Linear Power (kW/m)	16.46
Pressure Drop (kPa)	160
Average enrichment (wt%)	4.31
Average Discharge Burnup (GWd/t)	56
Refueling scheme	4 batches
Number of rods with gadolinia	8
Gadolinia concentration (wt%)	5
Hydrogen to Heavy Metal Ratio	4.53
Void Coefficient (pcm/% void)	-144
Fuel Temperature Coefficient (pcm/K)	-1.7
Approximate Assembly Weight (kg)	281

Control Blade

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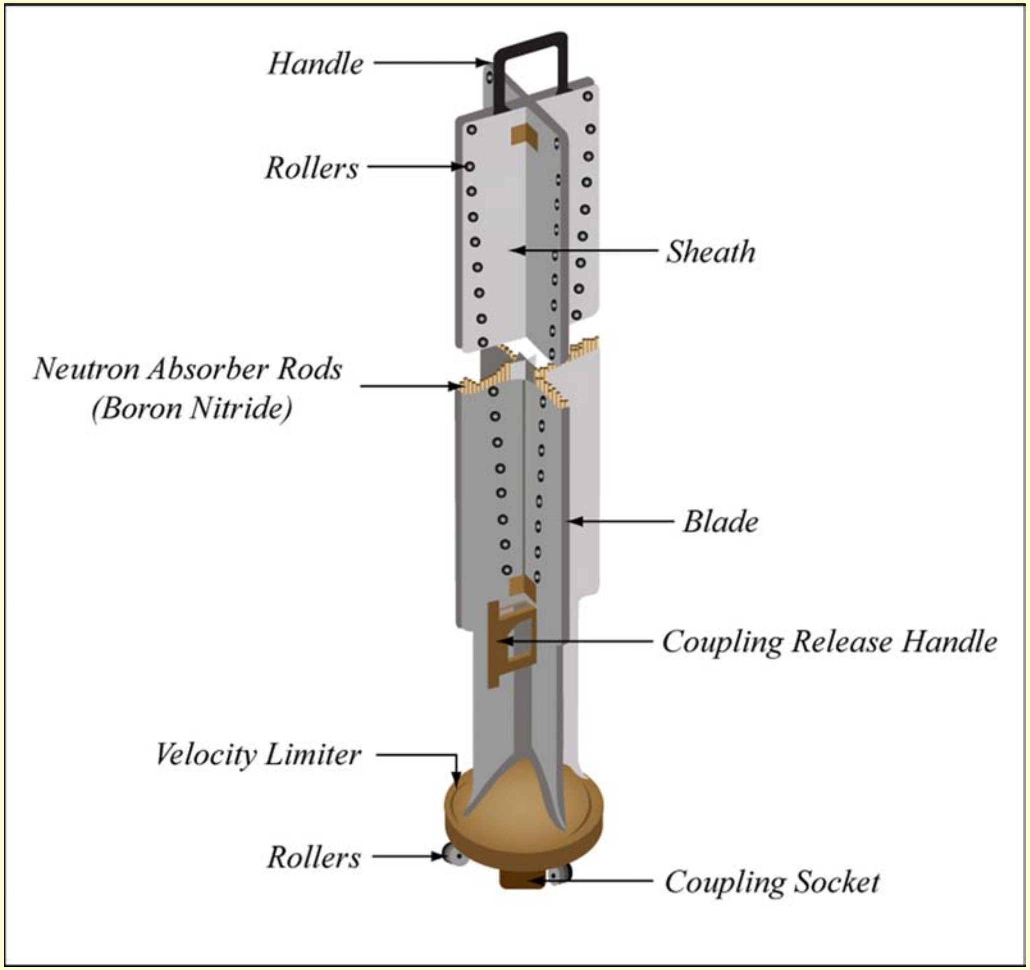

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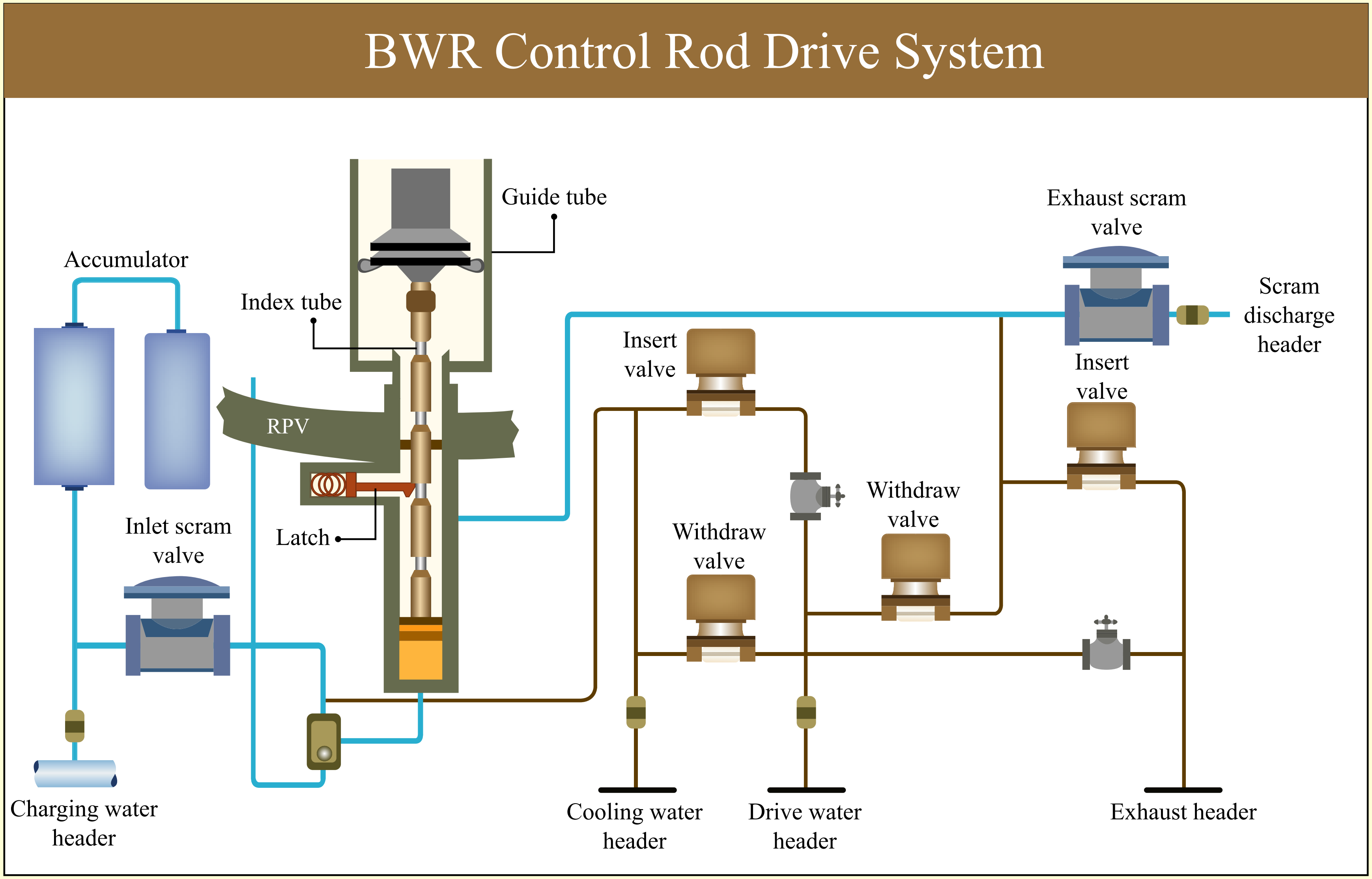
BWR Control Rod Drive System



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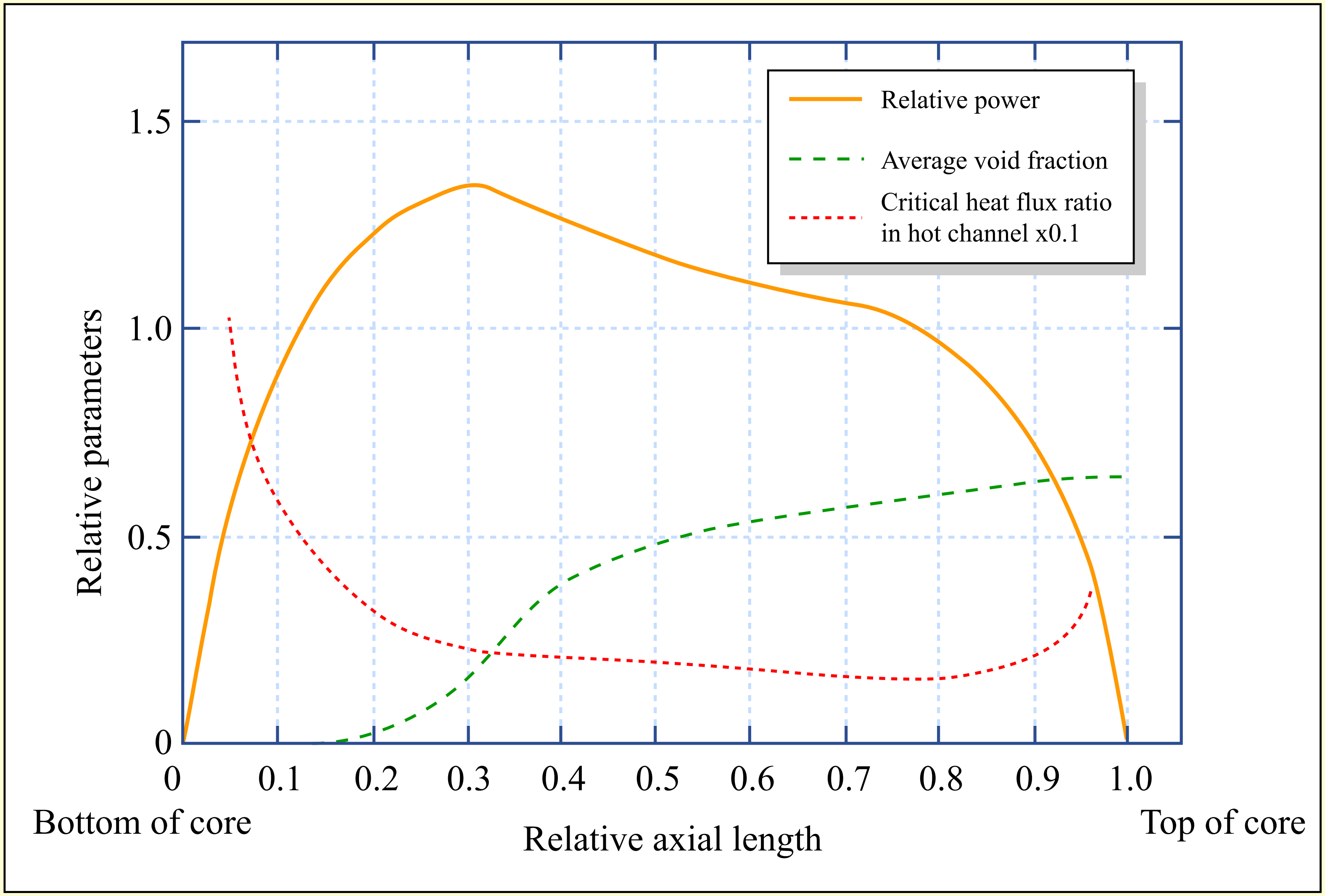
BWR SPATIAL CORE PROPERTIES

(WITH CONTROL RODS PARTIALLY INSERTED)



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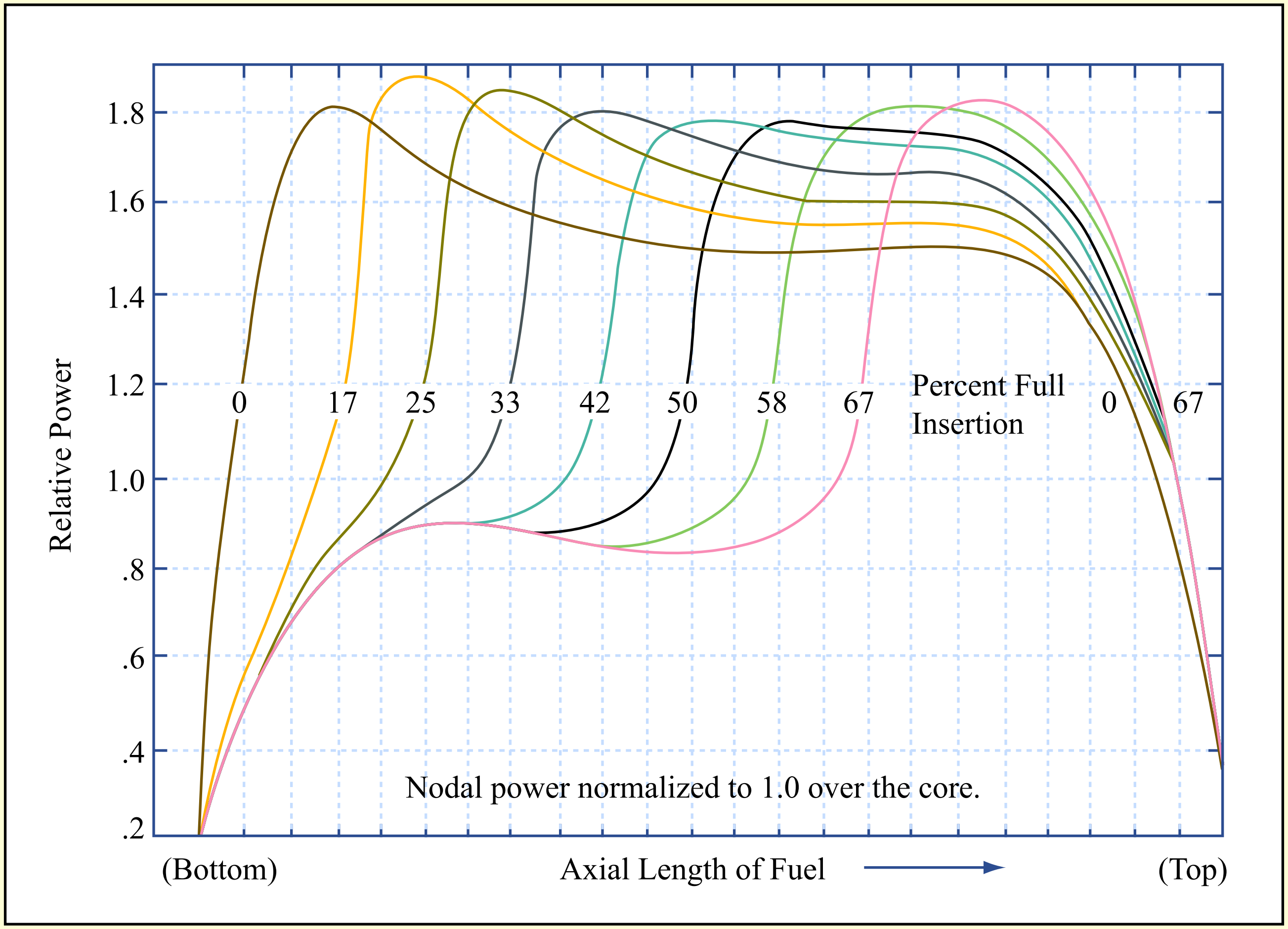
POWER IN FRESH FUEL ASSEMBLY AS ADJACENT CONTROL ROD IS WITHDRAWN TOWARD BOTTOM



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"BWR/6: General Description of a BWR," GE, 1980.

Connection of BWR Core Design to Neutronics

Why are the fuel rods spaced out more in a BWR than in a PWR?

Why is the core power density lower in a BWR core than in a PWR?

What is the purpose of spatial fuel enrichment zoning throughout a BWR fuel assembly?

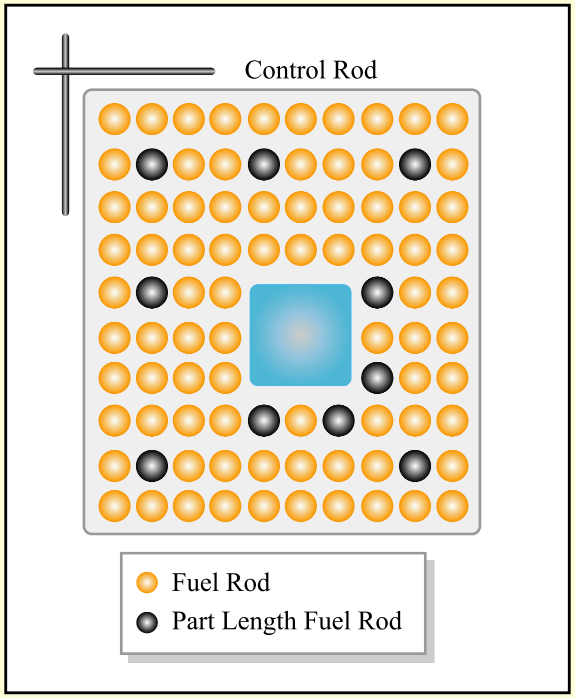
What function do the water rods perform?

Why are the BWR control rods inserted from the bottom of the core?

Can dissolved boron be used as a means to control reactivity in a BWR core?

BWR Bundle Design Advances

- Extended burnup features
  - More fuel pins (10×10) for a lower heat flux
  - Heavier fuel loadings
- Improved mechanical performance
  - “Barrier” cladding
  - Low growth, wear resistant materials
- Improved operational performance
  - Natural uranium blankets
  - Flow mixing grids to enhance margin to critical power
  - Part-Length Fuel Rods (Stability, SDM)
  - Large Central Water Channels (Stability, SDM)
  - Sophisticated poison & enrichment zoning



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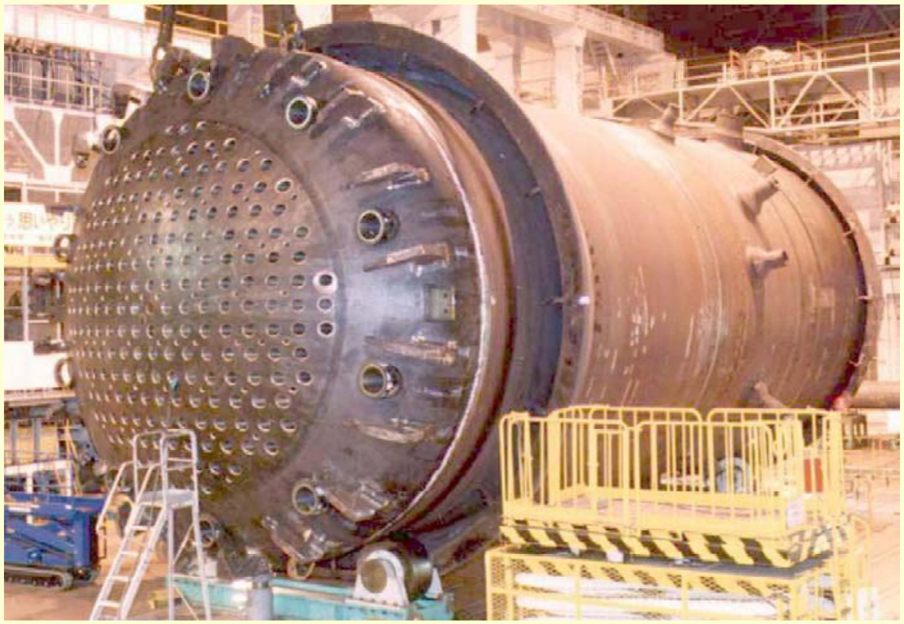
BWR Vessel and Vessel Internals

BWR Vessel



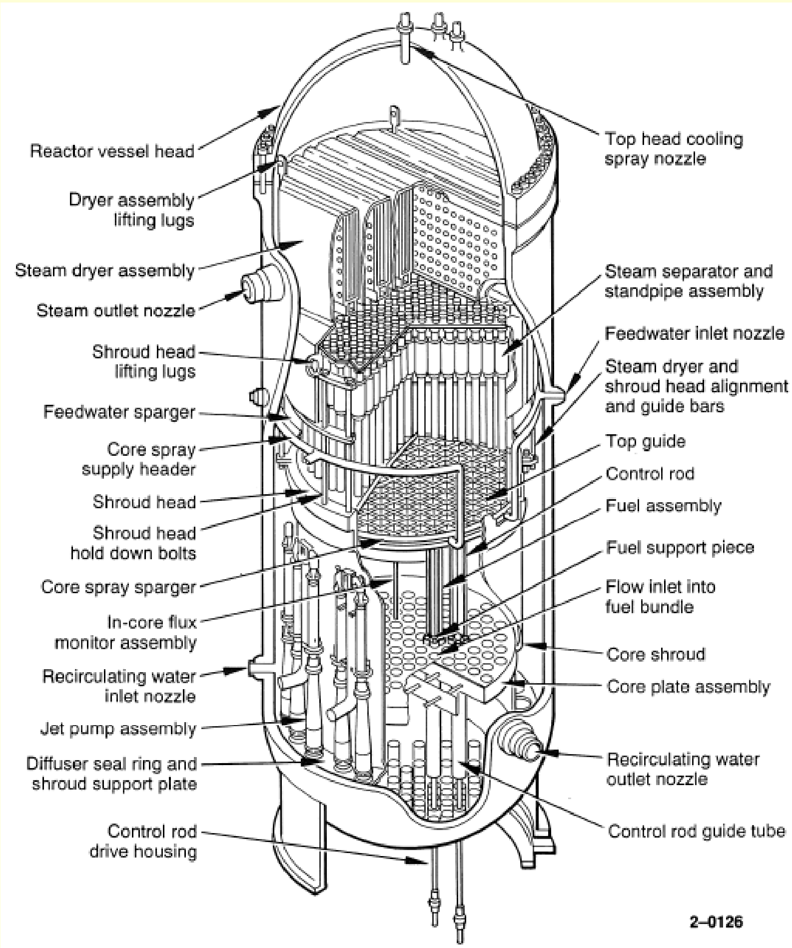
Large vessel made of ring forgings to avoid welds in the core region

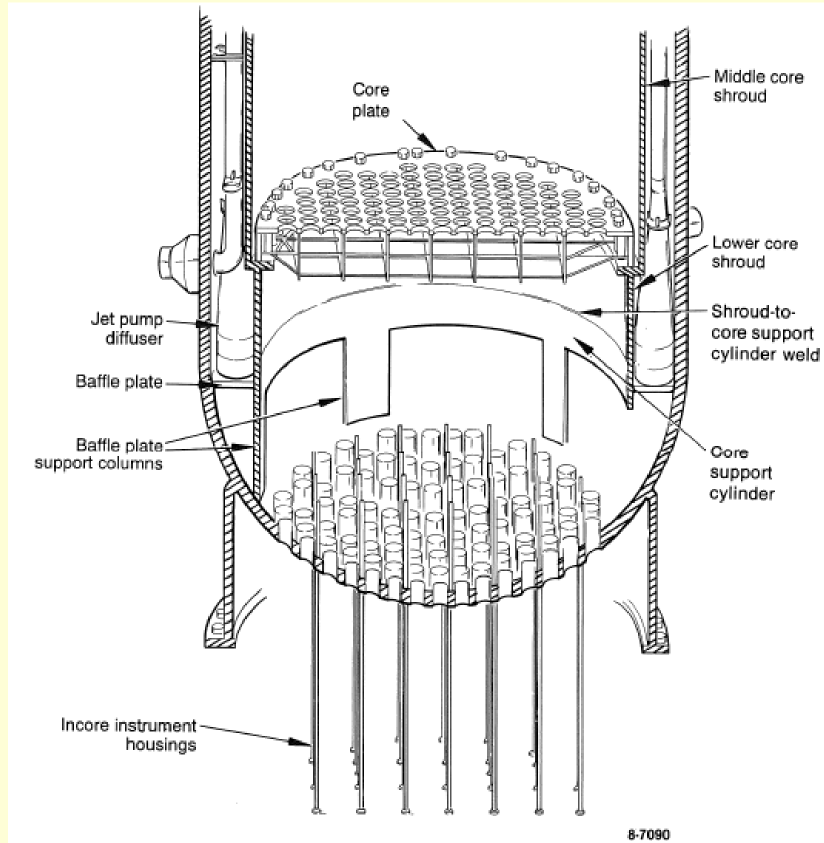
Vessel bottom head accommodates CR penetrations

ABWR RPV beltline forging, weight: 127 tons; dimensions: 7.48 m outside diameter, 7.12 m inside diameter, 3.96 m high; material: ASME SA 508, Class 3 EQ.

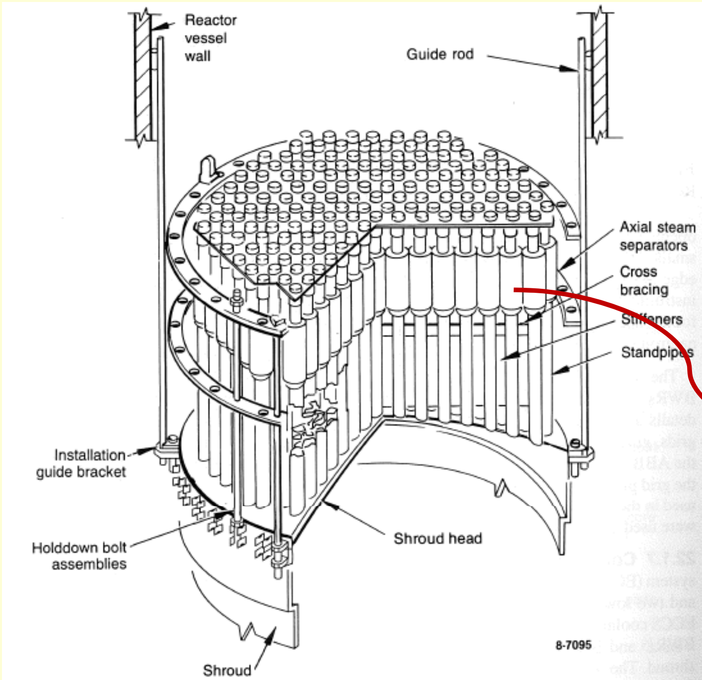
From: L.E. Fennern, ABWR Seminar – Reactor, Core & Neutronics. April 13, 2007.

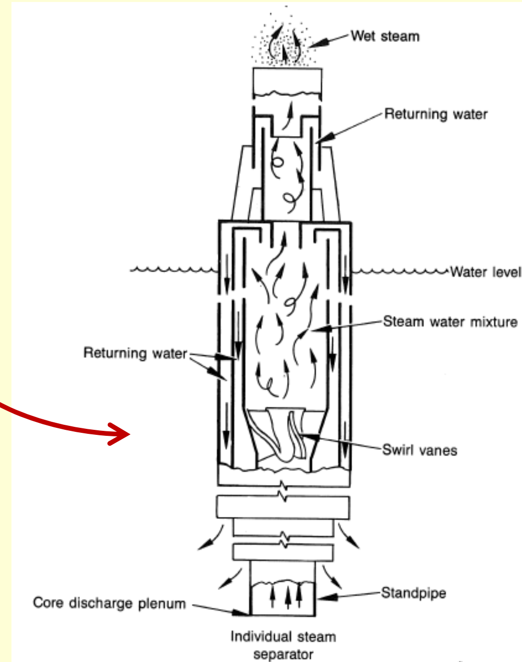
BWR Vessel Internals





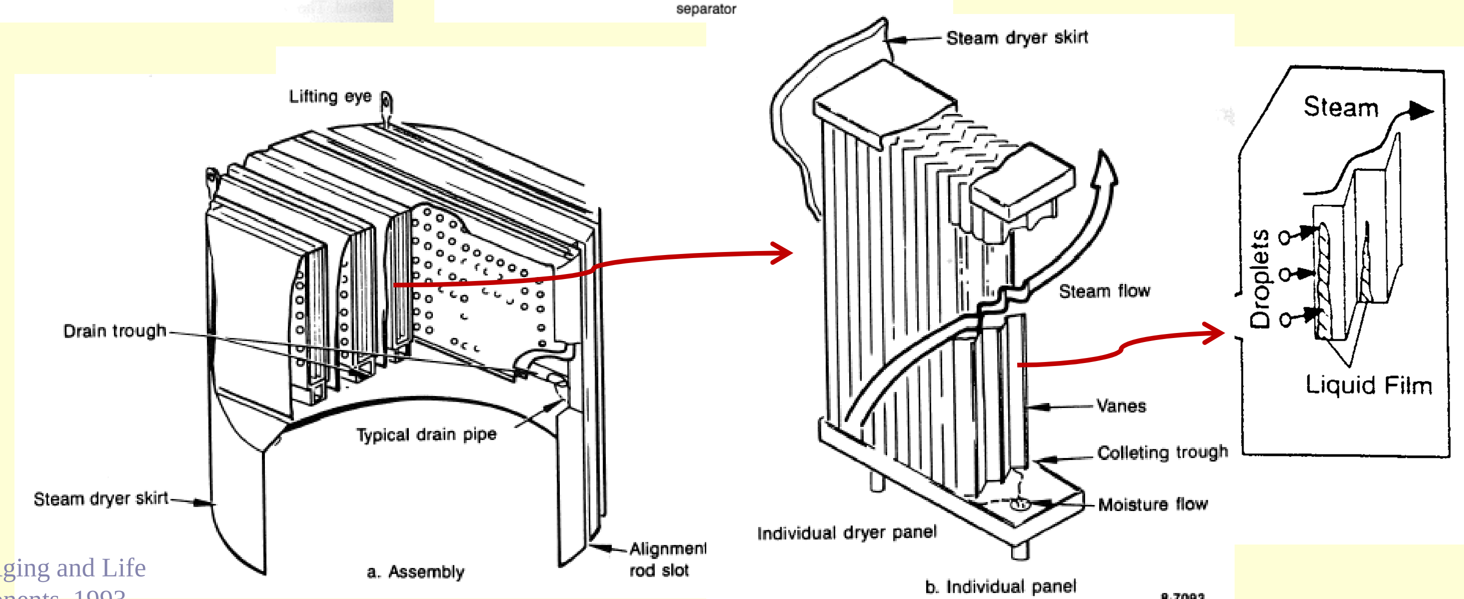
From: V. Shah, P. MacDonald, Aging and Life Extension of Major LWR Components, 1993.





Steam Separators

Steam Dryers



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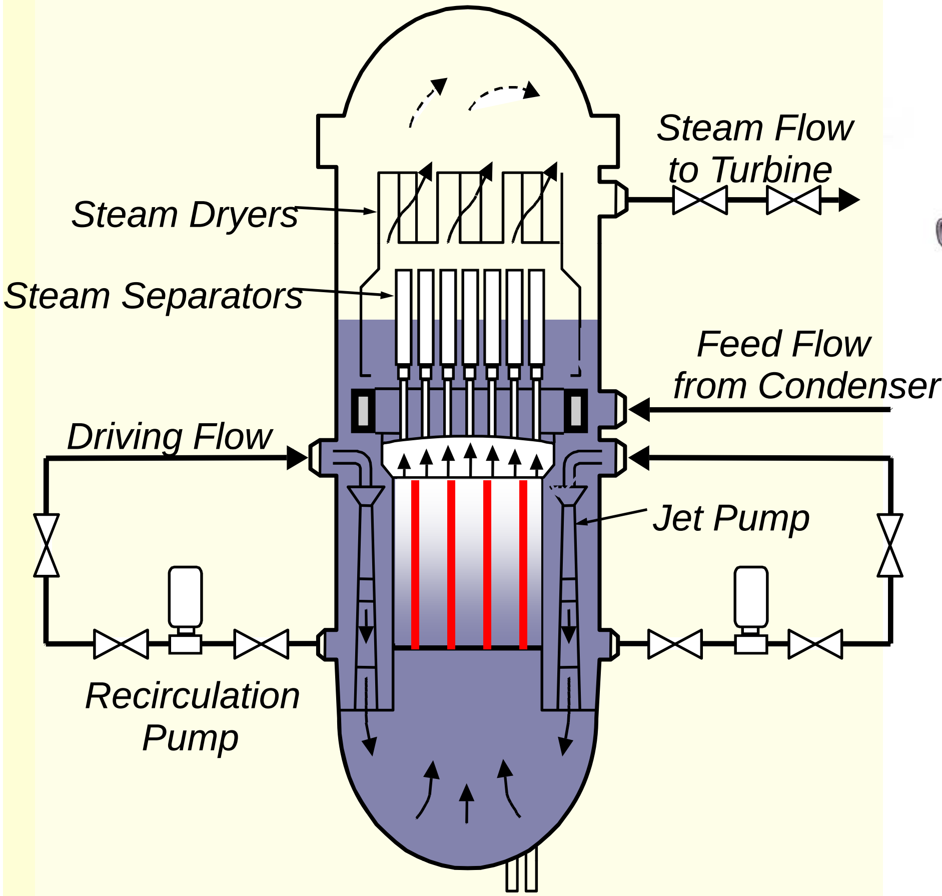
BWR Recirculation System

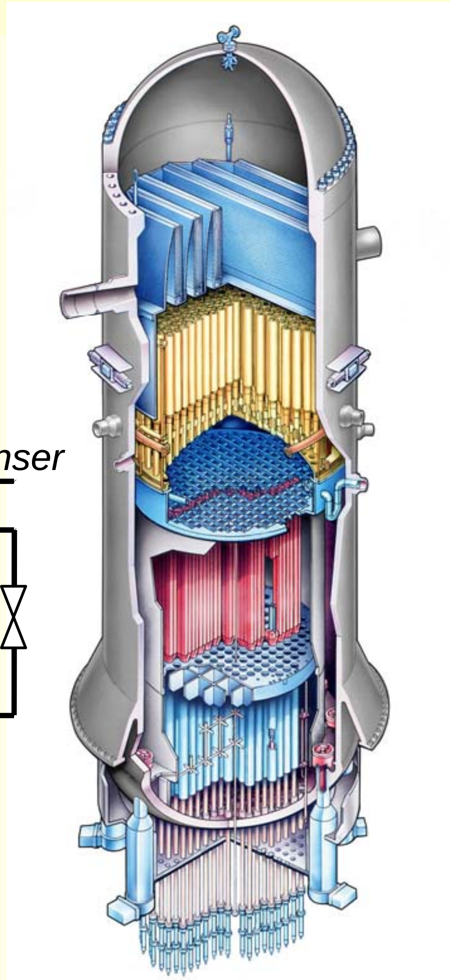
BWR Recirculation System

BWR/6



External recirculation pumps + jet pumps

ABWR



Ten internal recirculation pumps

ESBWR

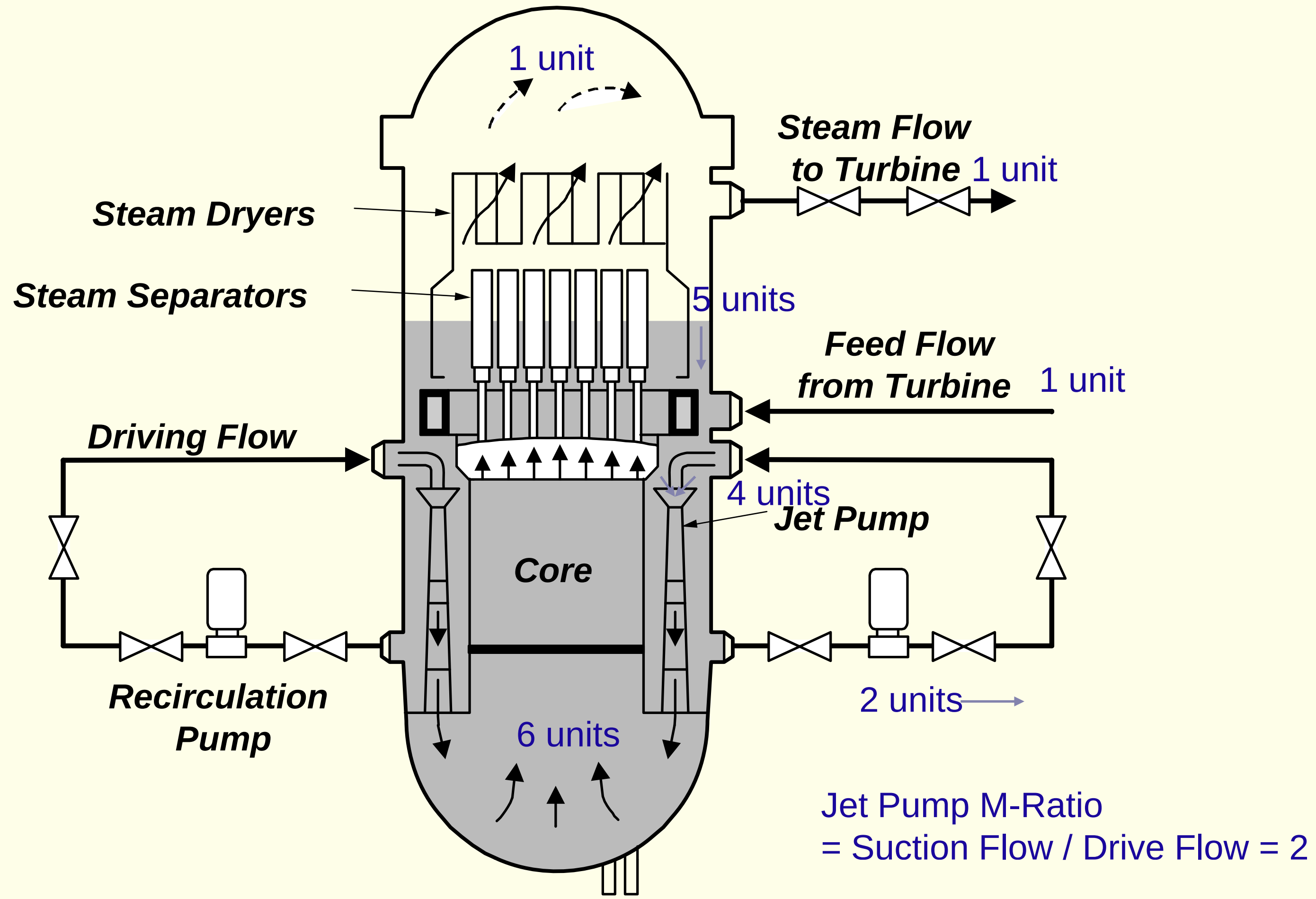
Relies on natural circulation

Traditional BWR vs ABWR and ESBWR

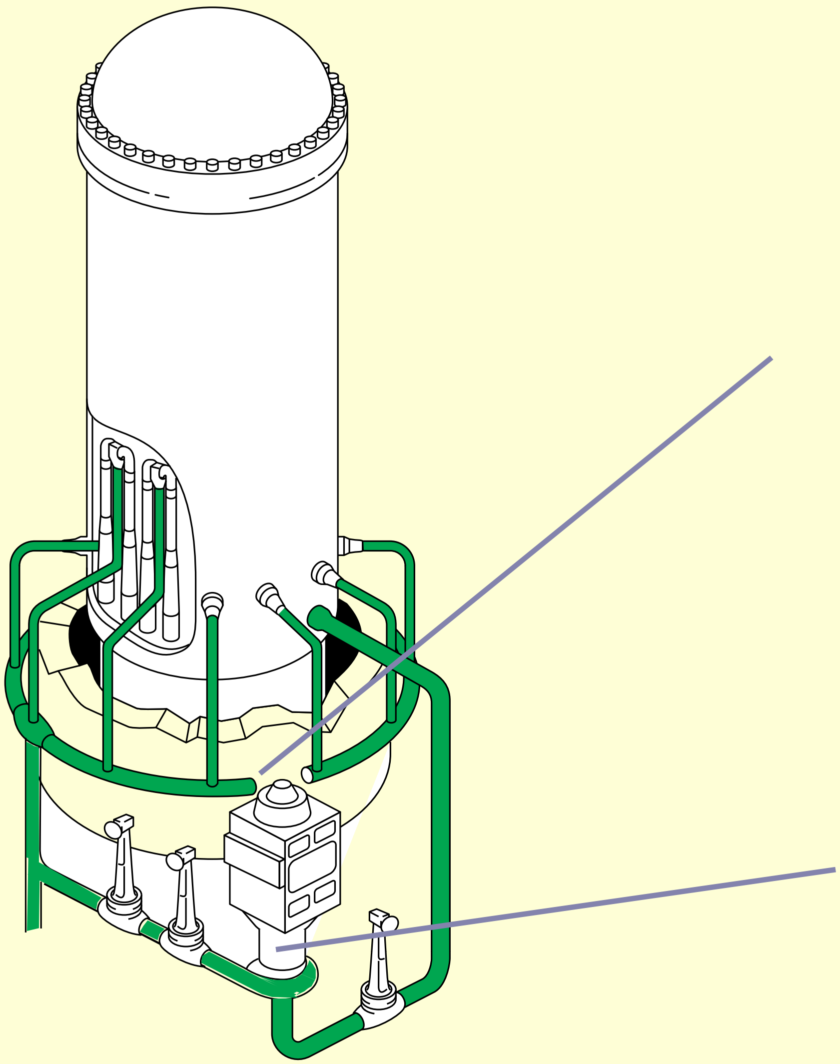
Parameter	BWR/4-Mk I (Browns Ferry 3)	BWR/6-Mk III (Grand Gulf)	ABWR	ESBWR
Power (MWt/MWe)	3293/1098	3900/1360	3926/1350	4500/1550
Vessel height/dia. (m)	21.9/6.4	21.8/6.4	21.1/7.1	27.7/7.1
Fuel bundles (number)	764	800	872	1132
Active fuel height (m)	3.7	3.7	3.7	3.0
Power density (kW/L)	50	54.2	51	54
Recirculation pumps	2(large)	2(large)	10	Zero
Number of CRDs/type	185/LP	193/LP	205/FM	269/FM
Safety system pumps	9	9	18	Zero
Safety diesel generator	2	3	3	Zero
Core damage freq./yr	1E-5	1E-6	1E-7	1E-7
Safety Bldg Vol (m^3/MWe)	115	150	160	<100

Image by MIT OpenCourseWare.

BWR/6 Recirculation Flow



BWR Recirculation Pumps



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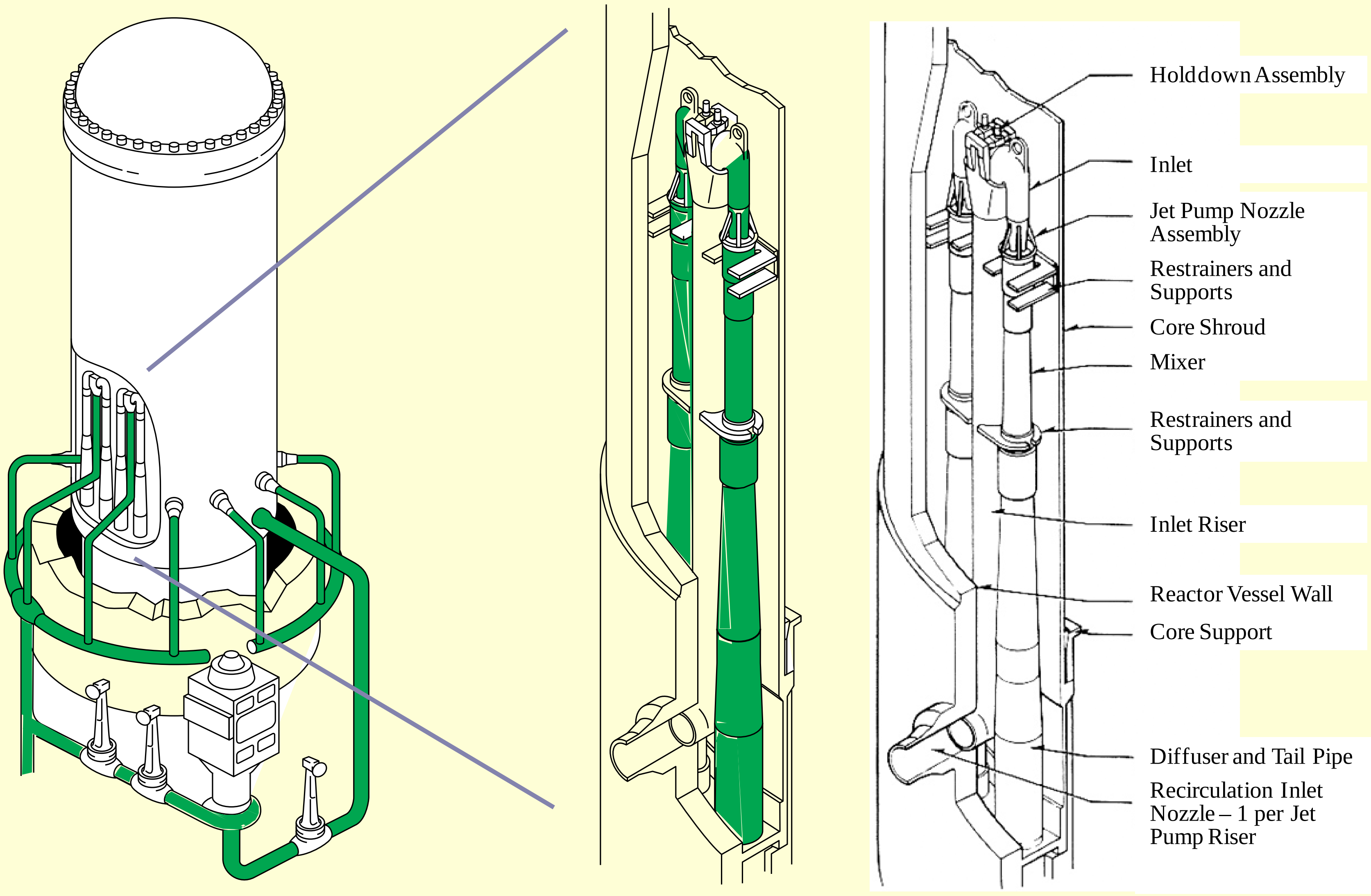
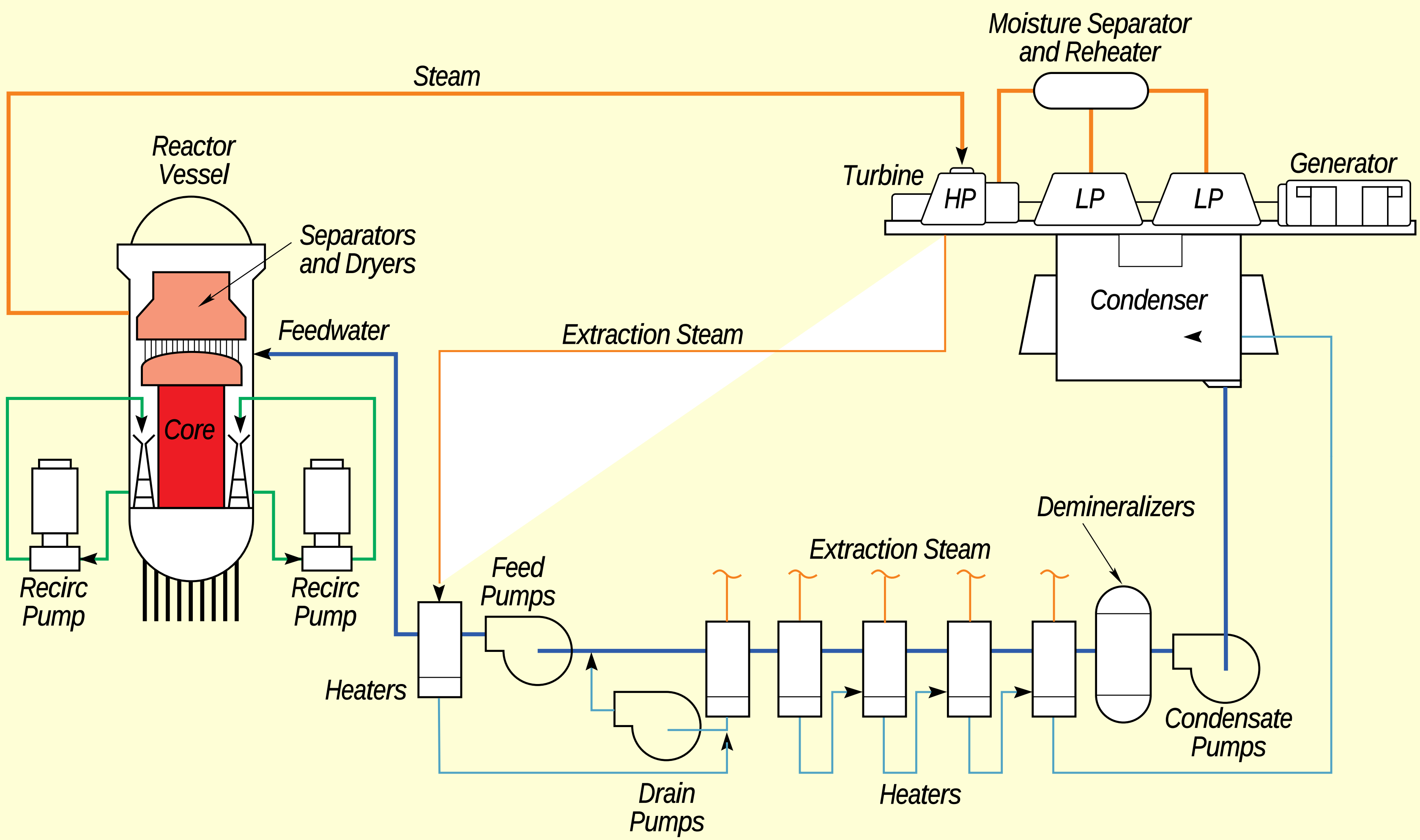
BWR Jet Pumps



BWR Balance Of Plant (BOP)

BWR Power Cycle



Courtesy of GE Hitachi Nuclear Systems. Used with permission.

"BWR/6, General Description of a BWR," GE, 1980

Radioactive Steam

Entire Power Conversion System becomes Radioactive $\Rightarrow$ Shielding is Needed

Reaction products from water:

$$O^{16} + n \rightarrow N^{16} + H^{1},\ \ T_{1/2} = 7.2\ s;\ \ \gamma, \beta$$
$$O^{17} + n \rightarrow N^{17} + H^{1},\ \ T_{1/2} = 4.2\ s;\ \ \gamma, \beta$$
$$O^{18} + n \rightarrow O^{19} \rightarrow F^{19},\ \ T_{1/2} = 29\ s;\ \ \gamma, \beta$$

Activation of corrosion products:

$$Fe^{54} + n \rightarrow Fe^{55},\ \ T_{1/2} = 2.7\ y;\ \ \gamma$$
$$Fe^{58} + n \rightarrow Fe^{59},\ \ T_{1/2} = 44.6\ d;\ \ \gamma, \beta$$
$$Co^{59} + n \rightarrow Co^{60},\ \ T_{1/2} = 5.3\ y;\ \ \gamma, \beta$$
$$Ni^{58} + n \rightarrow Ni^{59},\ \ T_{1/2} = 8x10^{4}\ y;\ \ \gamma, \beta$$
$$Ni^{62} + n \rightarrow Ni^{63},\ \ T_{1/2} = 100\ y;\ \ \gamma, \beta$$

Air Ejector

Removes Any Gases in Coolant Downstream of Condenser

They Must be Held Up and Stabilized

Nobel Gas Fission Products Escaped from Faulty Fuel Pins
(Xe, Kr isotopes)

$$Xe^{135} \rightarrow Cs^{135} + b^{-} + g, \ \ T_{1/2} = 9.2 \text{ h}$$
$$Kr^{88} \rightarrow Rb^{88} + b^{-} + g, \ \ T_{1/2} = 2.8 \text{ h}$$
$$Kr^{85} \rightarrow Rb^{85} + b^{-1} + g, \ \ T_{1/2} = 10.7 \text{ y}$$

H_2 from Radiolysis of H_2O
N Isotopes Produced by (O + n) Reactions
Gases Leaking into Condenser

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