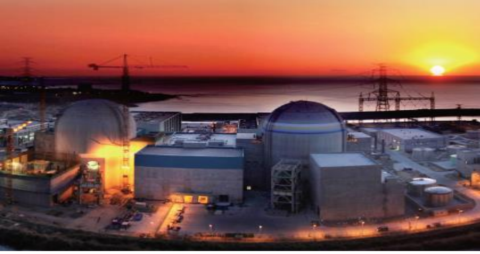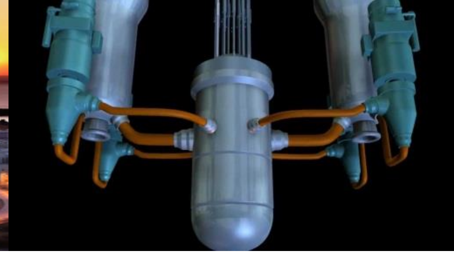

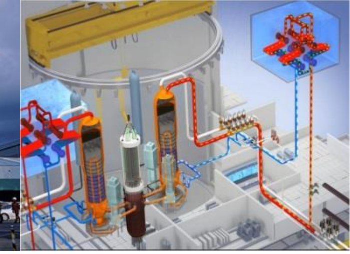

NUCLEAR SYSTEMS ENGINEERING

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NuTHEL
Nuclear Thermal Hydraulic Engineering Lab.

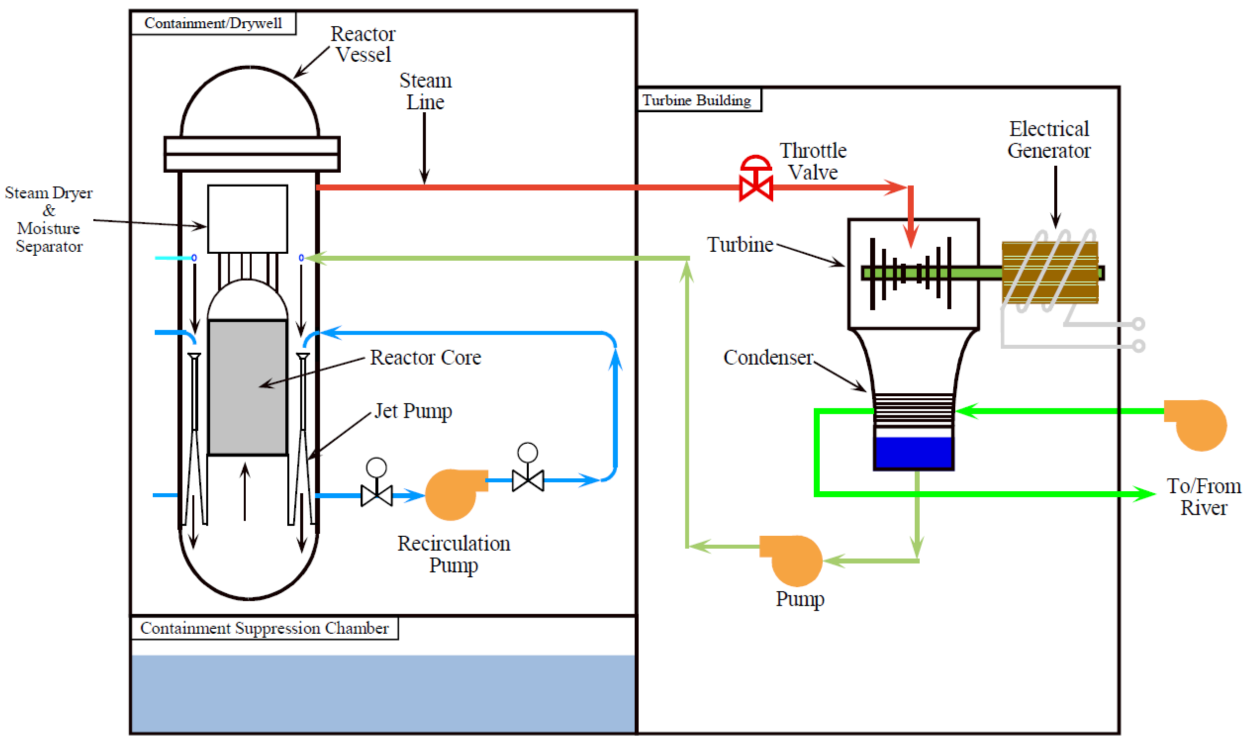
2. BOILING WATER REACTOR AND FUKUSHIMA DAIICHI NUCLEAR DISASTER

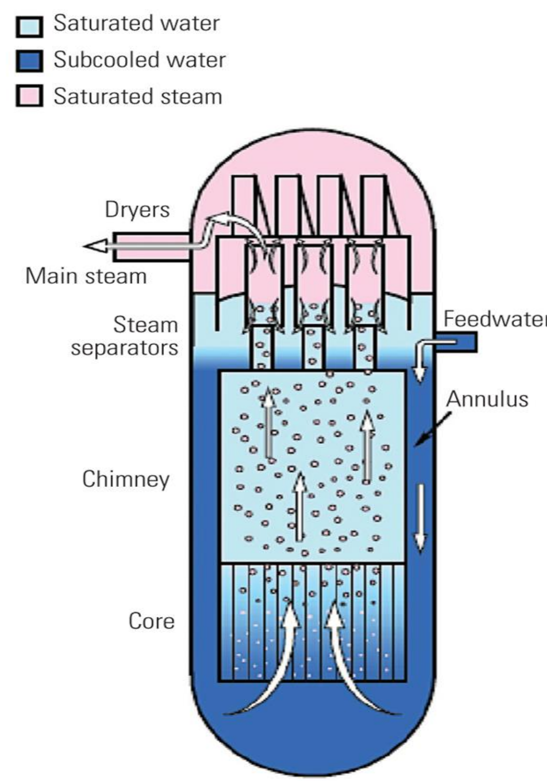
Nuclear Thermal Hydraulic Engineering Lab.

VERI TAS LUX MEA

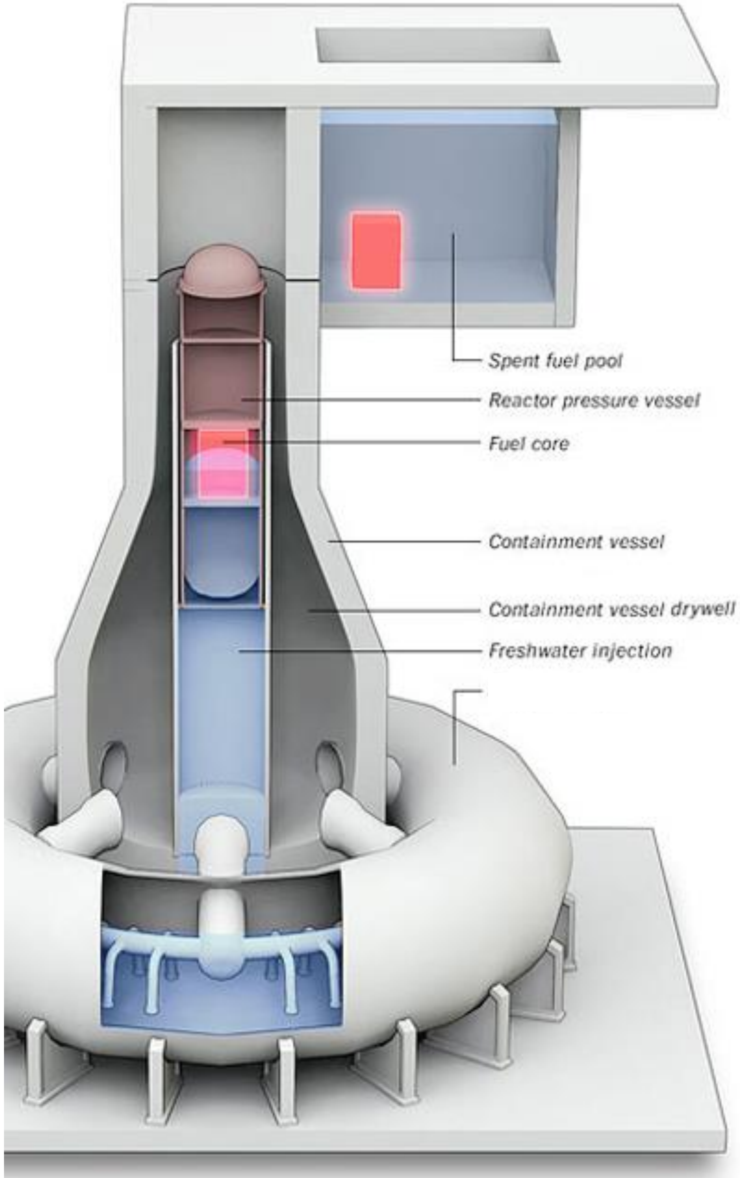
Boiling Water Reactor

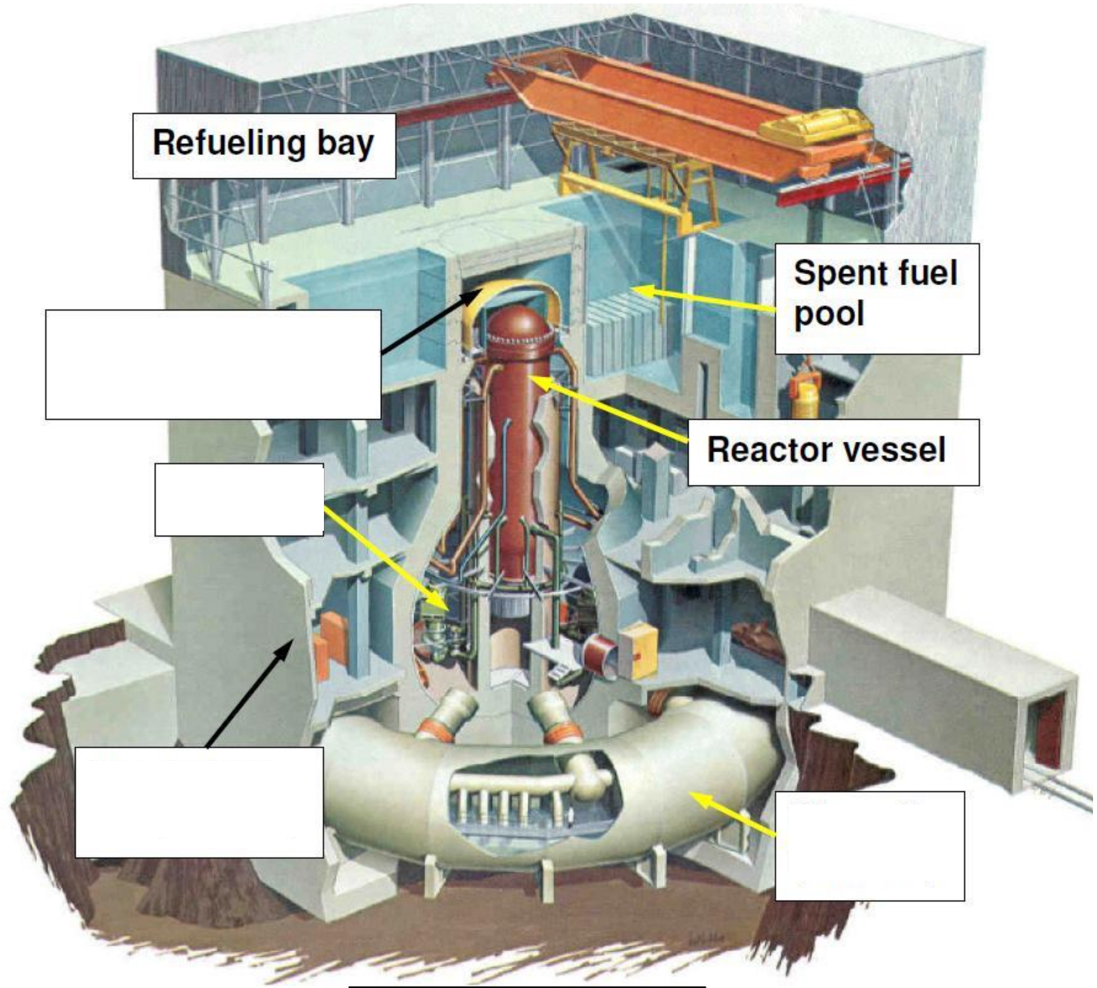
- Operates in essentially the same way as a fossil-fueled generating plant.
- Inside the reactor vessel, a steam/water mixture is produced absorbing core heat.
- Two stages of moisture separation: water droplets are removed before the steam line
- Steam line $\Rightarrow$ turbine $\Rightarrow$ condenser $\Rightarrow$ reactor vessel
- Recirculation pumps & jet pumps





Boiling Water Reactor





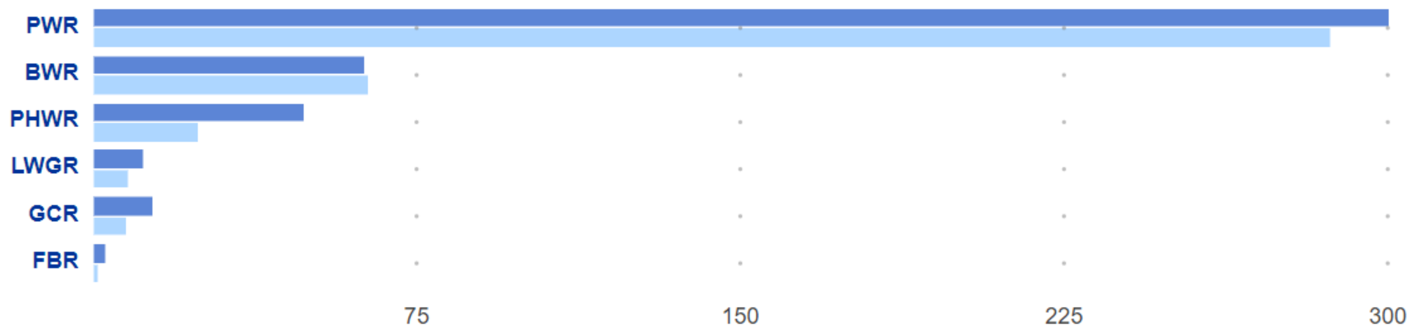
Mark I Containment

https://pris.iaea.org/PRIS/home.aspx

Boiling Water Reactor

Statistics

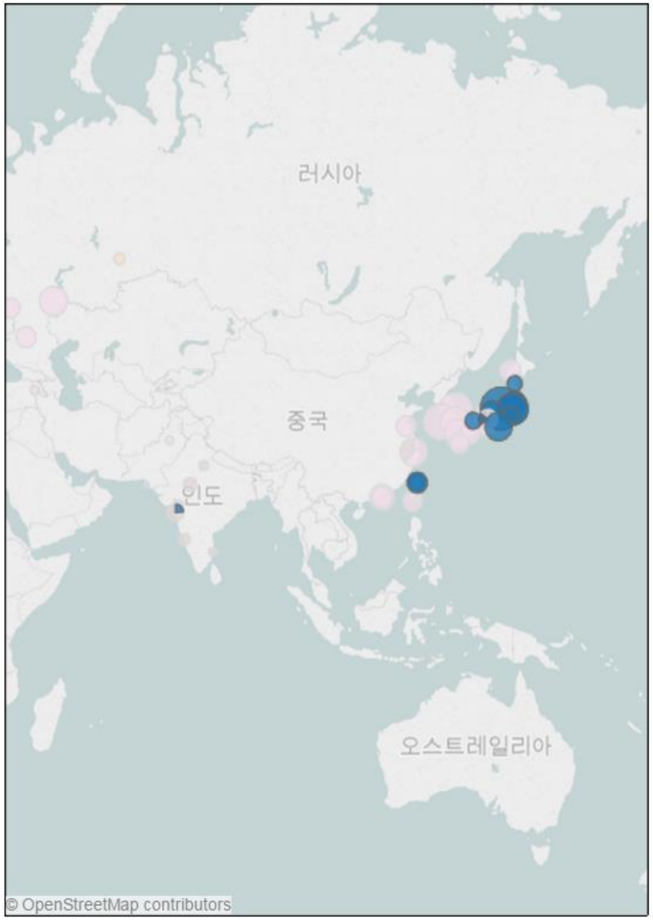
- 63 BWRs/443 NPPs

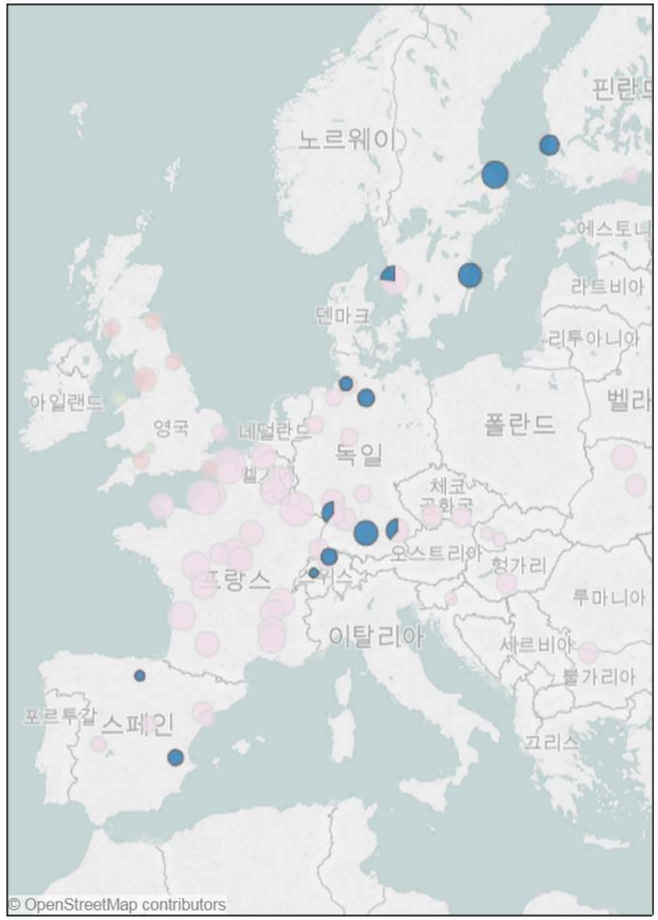


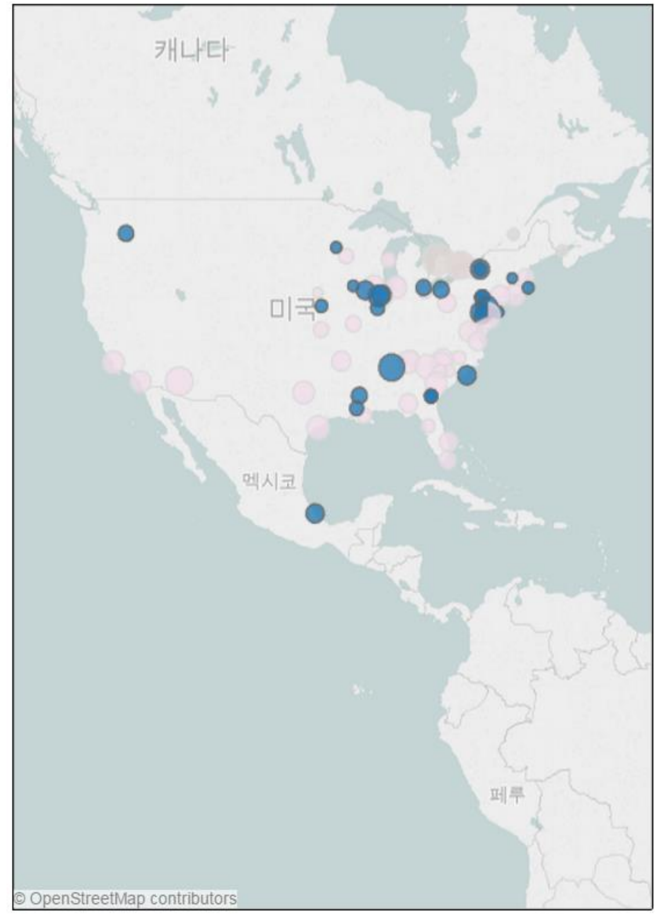
(2021-03-11)

Reactor Type	Reactor Type Descriptive Name	Number of Reactors ▼
PWR	Pressurized Light-Water Moderated and Cooled Reactor	302
BWR	Boiling Light-Water Cooled and Moderated Reactor	63
PHWR	Pressurized Heavy-Water Moderated and Cooled Reactor	49
GCR	Gas Cooled, Graphite Moderated Reactor	14
LWGR	Light-Water Cooled, Graphite Moderated Reactor	12
FBR	Fast Breeder Reactor	3
Total		**443**

Statistics







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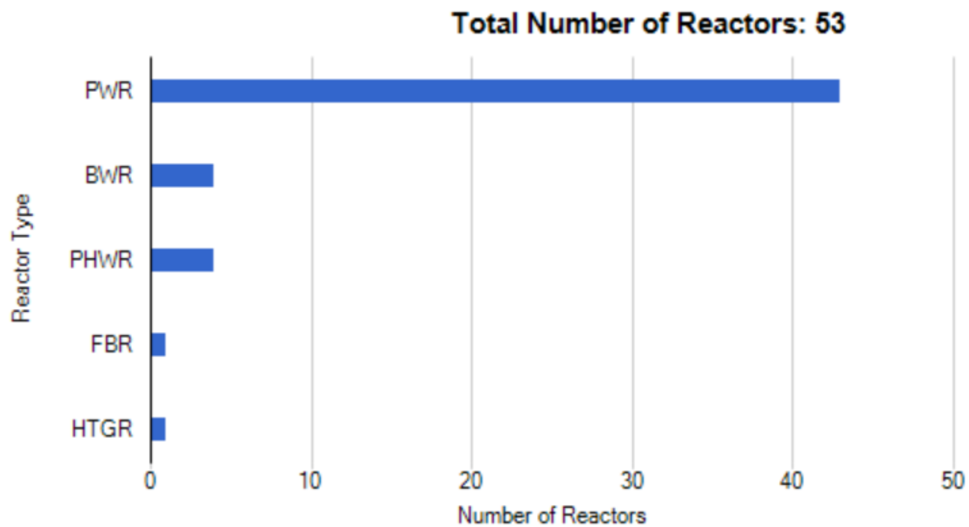
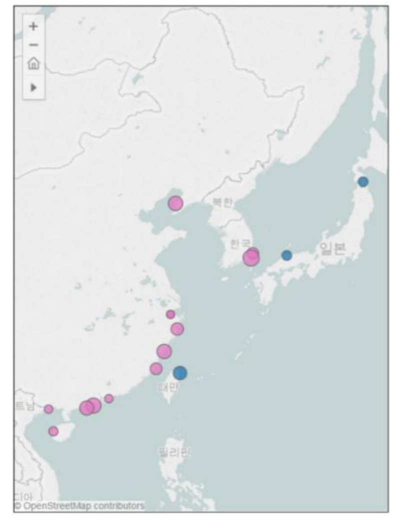
Boiling Water Reactor

Statistics

- 4 BWRs/60 NPPs: 2 in Japan, 2 in Taiwan

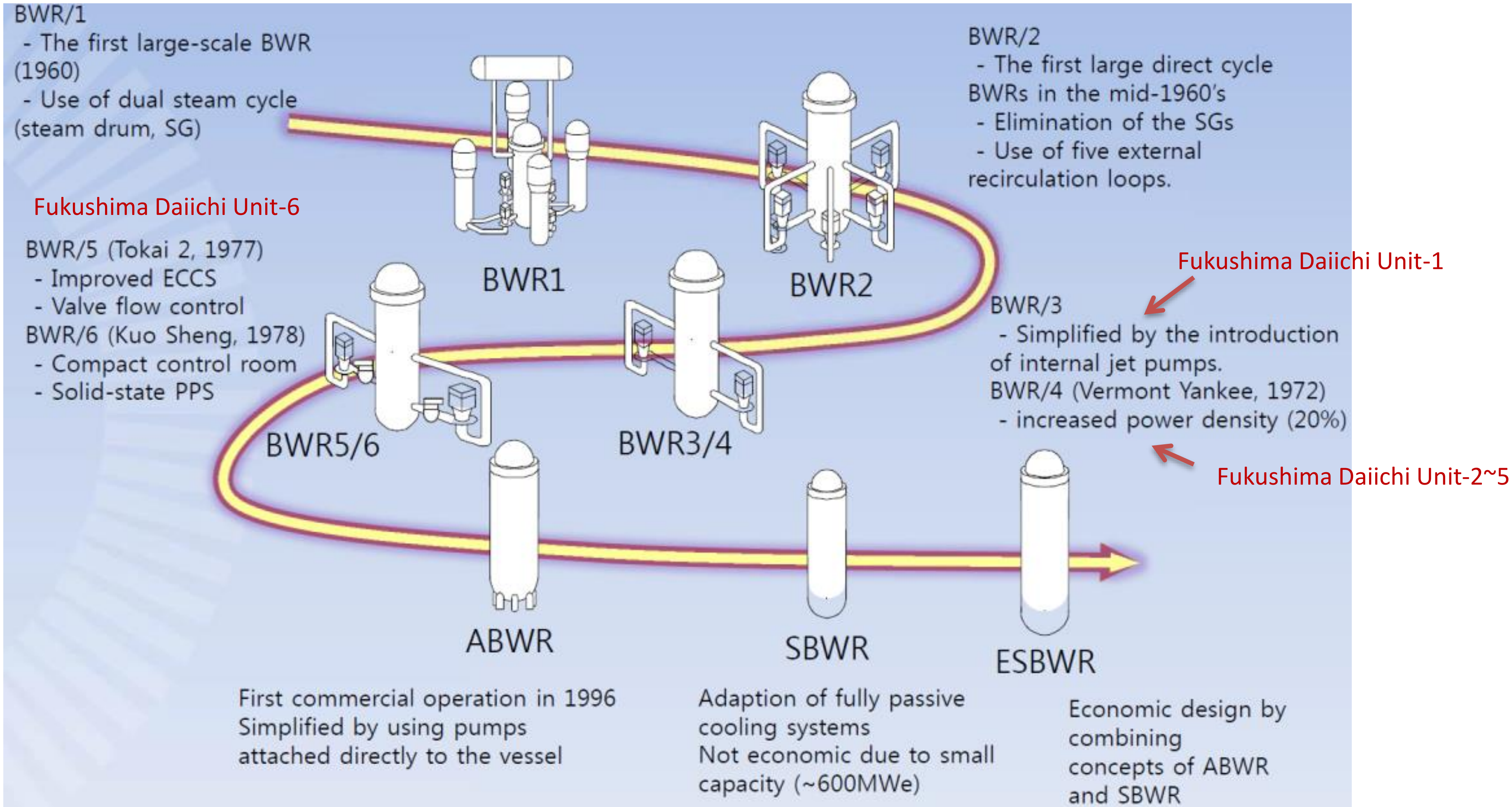




Reactor Type ▲	Reactor Type Descriptive Name	Number of Reactors
BWR	Boiling Light-Water Cooled and Moderated Reactor	4
FBR	Fast Breeder Reactor	1
HTGR	High Temperature Gas Cooled Reactor	1
PHWR	Pressurized Heavy-Water Moderated and Cooled Reactor	4
PWR	Pressurized Light-Water Moderated and Cooled Reactor	43
Total		**53**

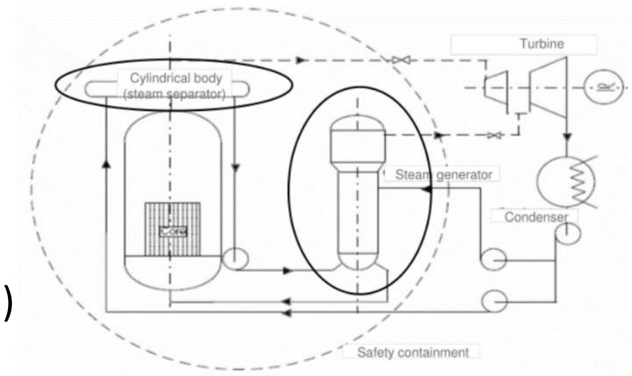
❖ History

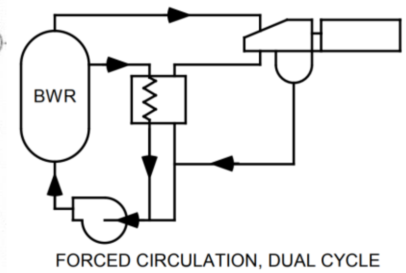
- Developed by the Idaho National Laboratory and General Electric (GE) in the mid-1950s.



History

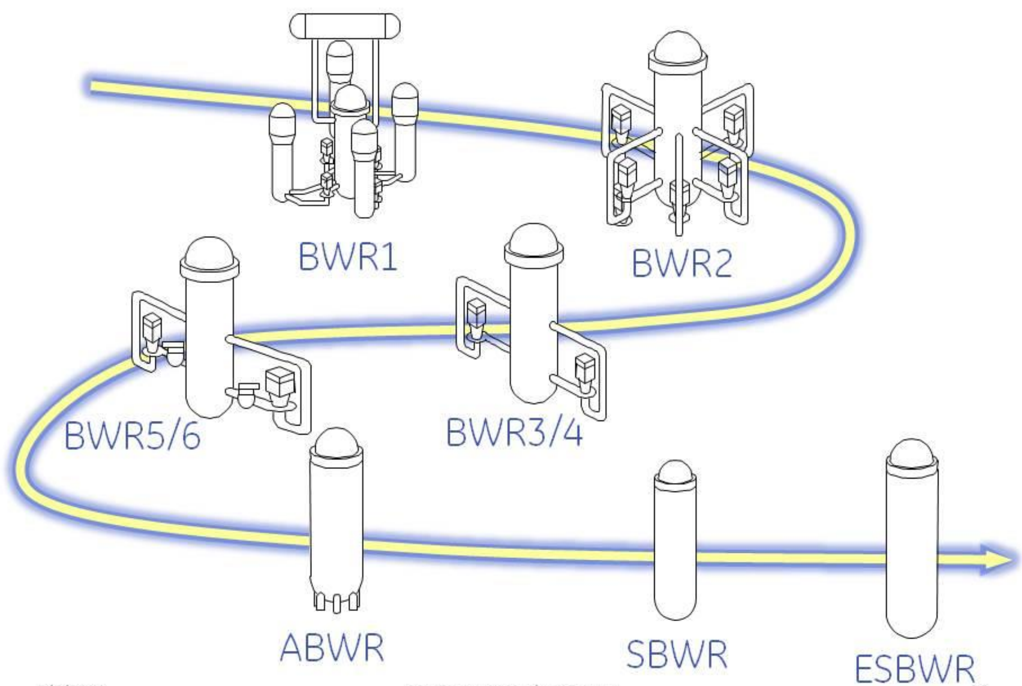
- VBWR (Vallecitos Boiling Water Reactor)
  - 1st General Electric BWR power plant
  - Built in 1957 (near San Jose, California)
  - 1st commercial BWR; 5 MWe supplied to Pacific Gas & Electric grid (through 1963)
  - 1000 psig (66.7 atm) operating pressure





- BWR-1
  - Introduced in 1955
  - 1st commercial plant in 1960 (Dresden 1)
  - 8 plants
  - Characteristics:
    - External or Internal steam separation
    - Low power density core

Evolution of BWR

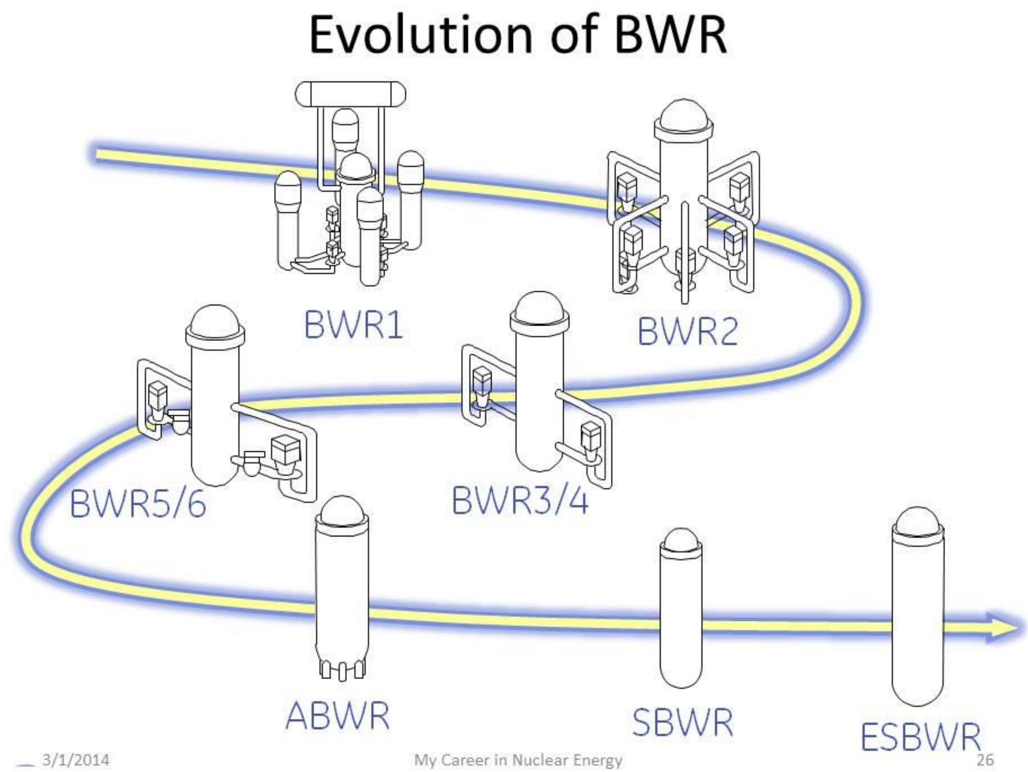


Boiling Water Reactor

History

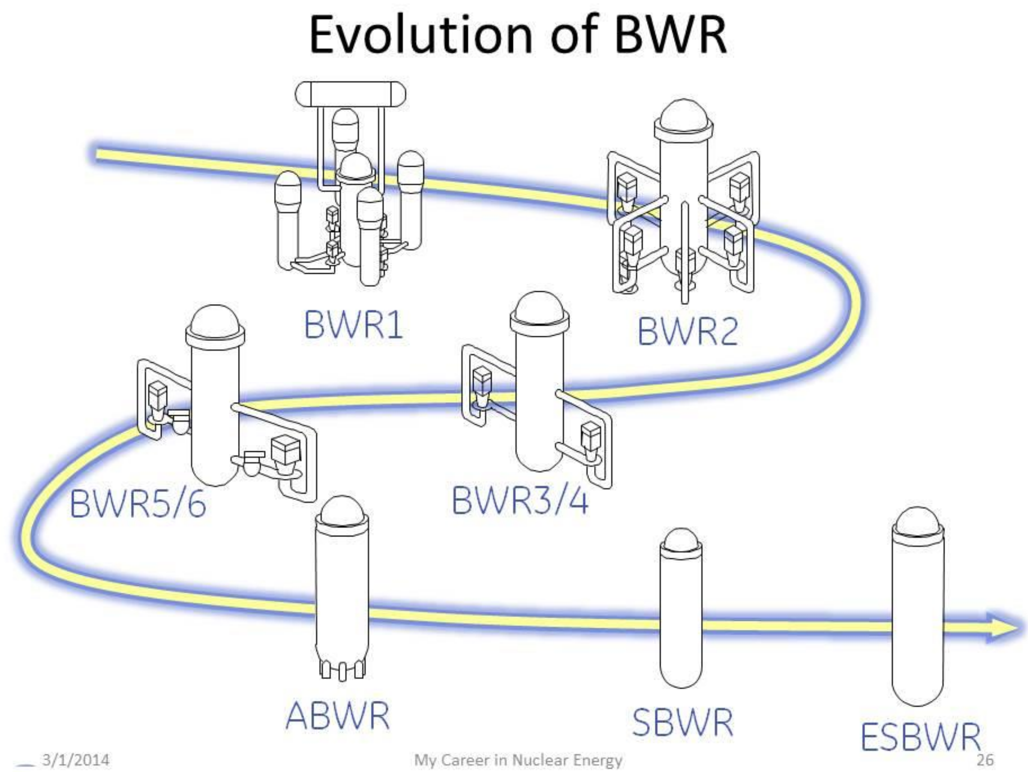
- BWR2
  - Introduced in 1963
  - 3 plants
  - Characteristics:
    - Internal steam separation
    - Low power density core
    - 5 Recirculation loops
    - Flow control load following

- BWR3
  - Introduced in 1965
  - First Jet Pump application
  - 9 plants
  - Characteristics:
    - Low power density core
    - Internal Jet Pumps
    - 2 Recirculation loops



History

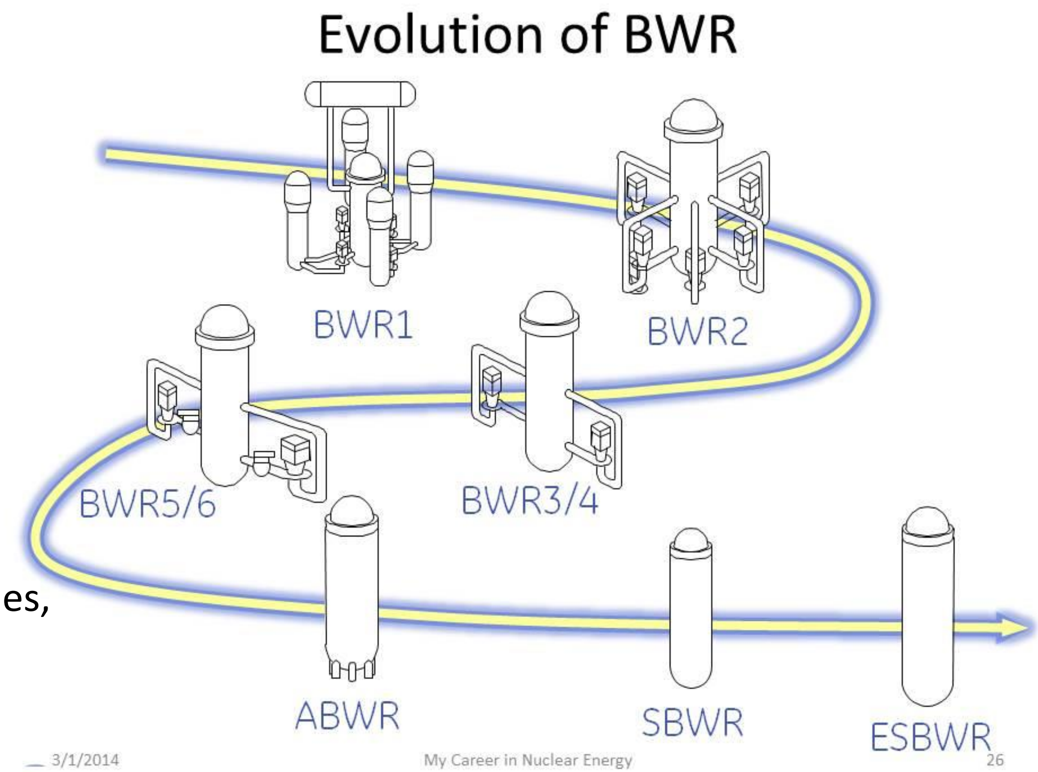
- BWR4
  - Introduced in 1966
  - Increased power density
  - 25 Plants
  - Characteristics:
    - High power density core
    - Mark I or II containment
- BWR5
  - Introduced in 1969
  - Improved safeguards (ECCS)
  - Recirculation flow control valves
  - 8 plants
  - Characteristics:
    - Valve flow control load following
    - ECCS injects into core shroud



Boiling Water Reactor

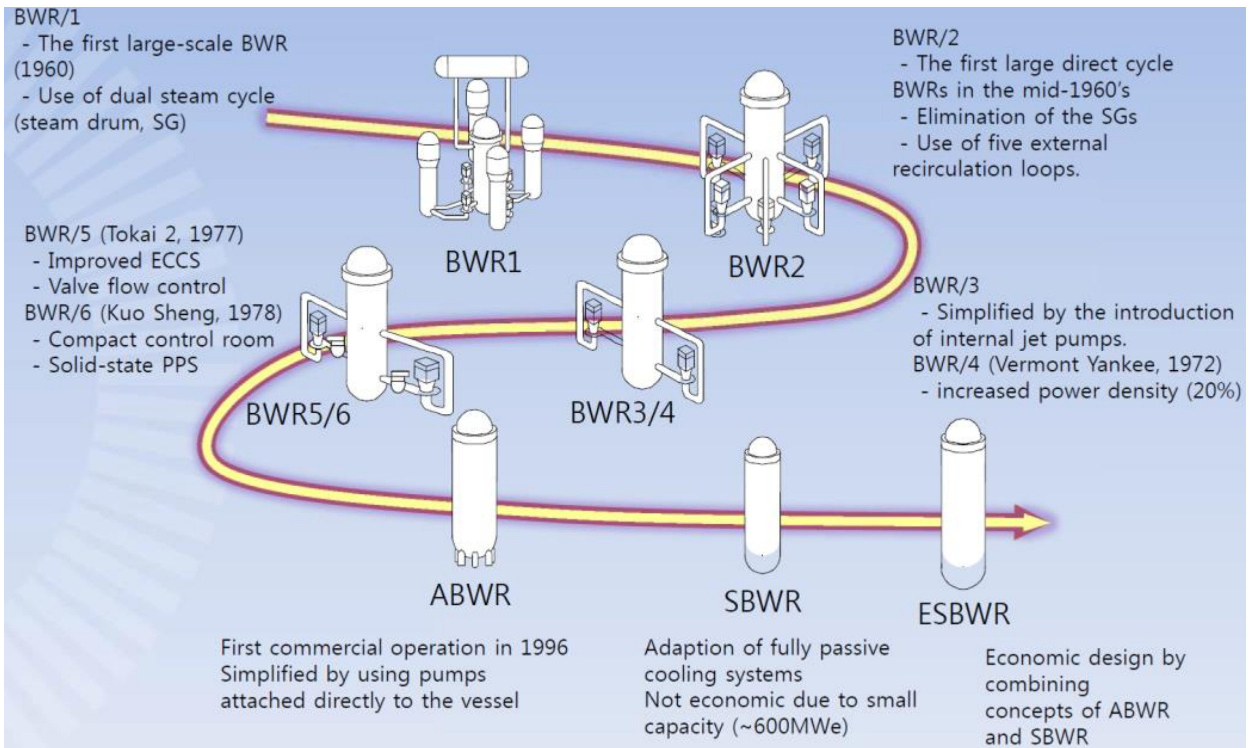
History

- BWR6
  - Introduced in 1972
  - Added fuel bundles; increased output;
  - Improved fuel safety margins
  - Improved Recirc system performance
  - 8 plants
  - Characteristics:
    - Valve flow control, 8 x 8 fuel bundle
- ABWR
  - Introduced in 1991
  - Blend of best features:
  - operating BWRs, available new technologies, & modular construction techniques
  - 4 plants
  - Characteristics:
    - Safety improvements (reduced core damage frequency)
    - Design life 60 years
  - No external Recirc Loops; Reactor Internal Pumps



History

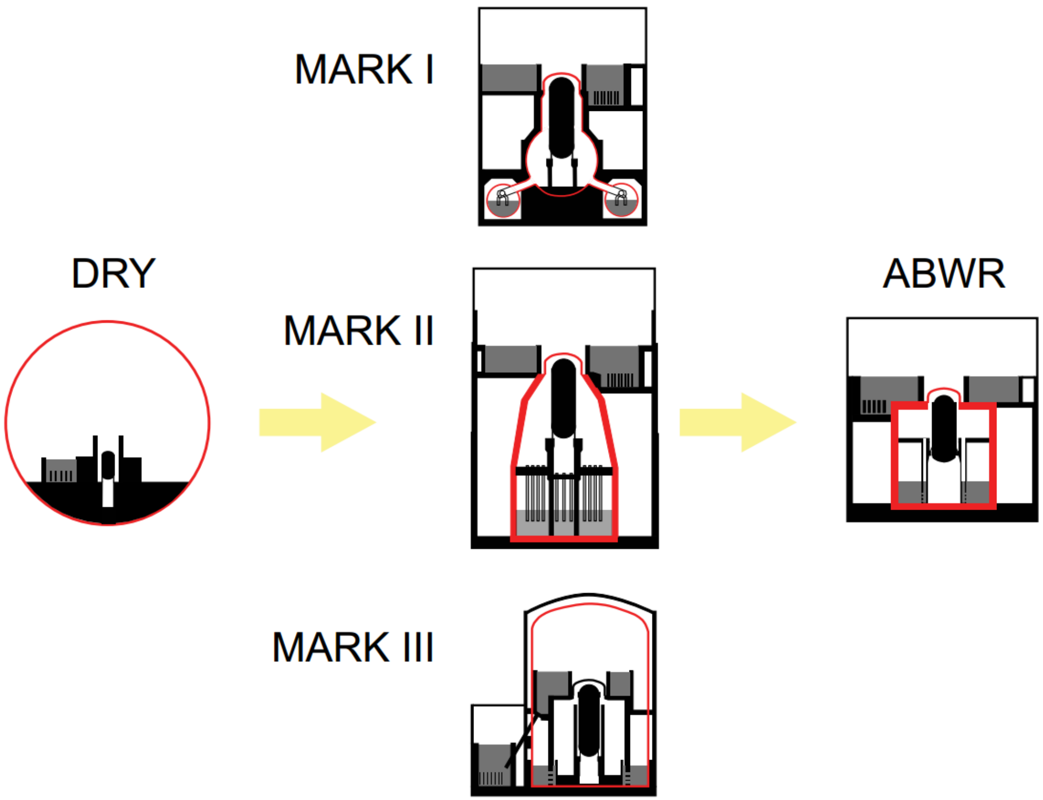
- ESBWR
  - Currently in licensing and design
  - Characteristics:
    - Passive Safety
    - Natural Circulation; No Recirc loops or Pumps
    - Safety improvements (reduced core damage frequency)
    - Design life 60 years
    - Larger Main Generator (~1600 MWe)



Boiling Water Reactor

❖ History

- Containment design evolution



History

- Containment design

The first BWR containments were spherical "dry" structures, similar to those still used today in PWR designs. The BWR, however, quickly moved to the "pressure suppression" containment design for its many advantages. Among these are:

- High heat capacity
- Lower design pressure
- Superior ability to accommodate rapid depressurization
- Unique ability to filter and retain fission products
- Provision of a large source of readily available makeup water in the case of accidents
- Simplified, compact design

It is the reduction in containment design pressures, together with the elimination of the external recirculation loops, that allows the containment (and, by extension, the reactor building) to be more compact.

The Mark I containment was the first of the new containment designs. The torus used to house a large water inventory in the Mark I gives this design its characteristic light bulb configuration. The conical Mark II design has a less-complicated arrangement, based on steel-lined reinforced concrete. A key feature is the large containment drywell that provides more room for the steam and ECCS piping. The Mark III containment design, used worldwide with BWR/6s and some BWR/5s, represented a major improvement in simplicity. Its steel containment structure is a right circular cylinder that is easy to construct, and provides ready access to equipment and ample space for maintenance activities. Other

Japan's Nuclear Safety Commission did not require improvements implemented in U.S. in 1980s.

History

- Flaw in MARK-1 containment

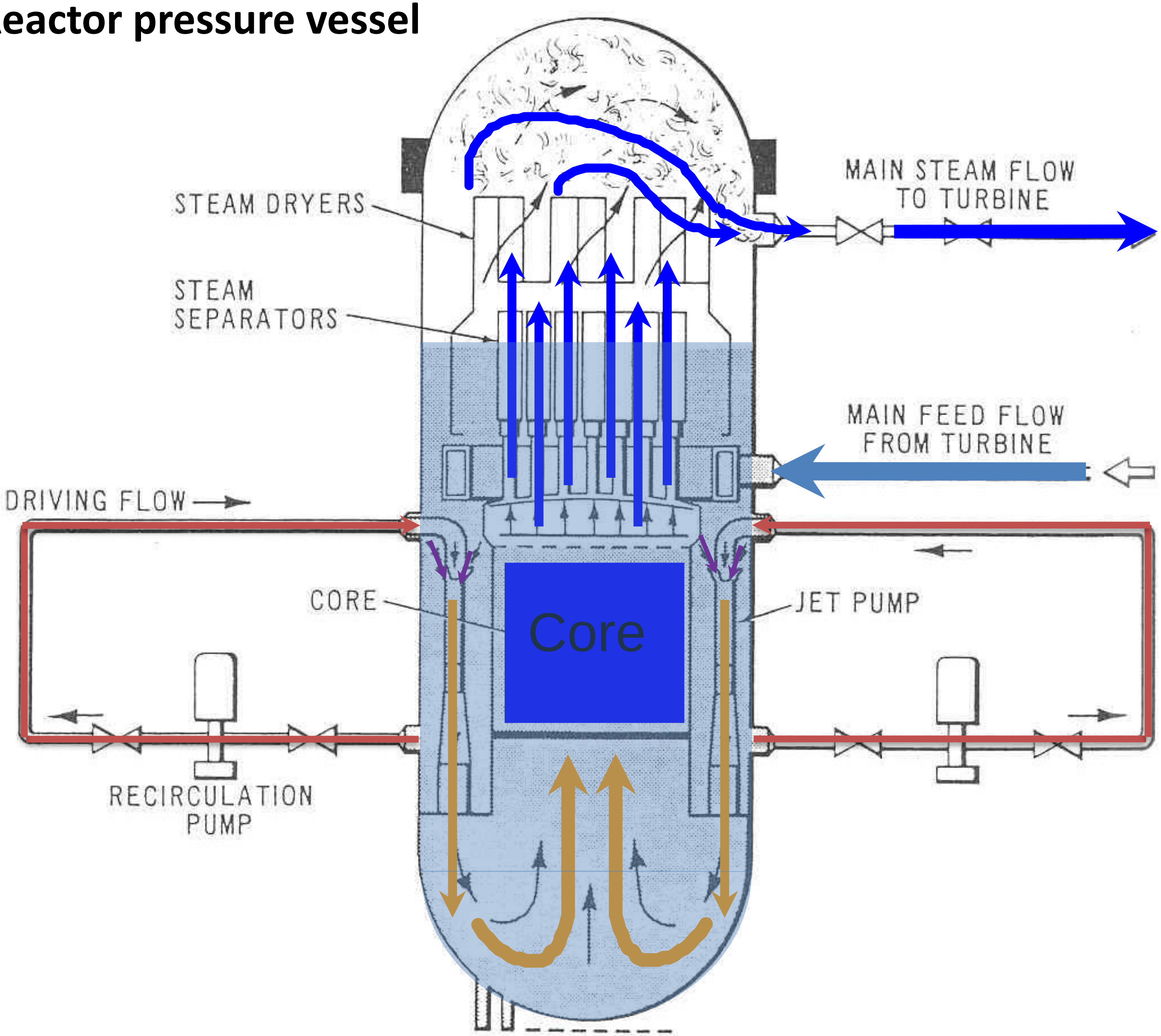
Boiling Water Reactor

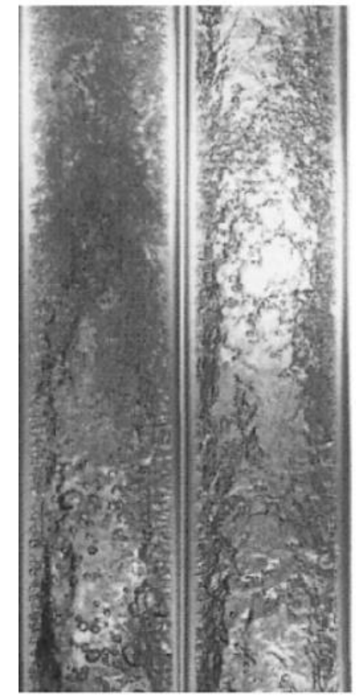
Basics

- Pressure in water/steam cycle: 70 bar (7 MPa) (PWR: 155 bar)
- Temperature about 288°C (PWR: 326°C)

Parameter	BWR/4 (Browns Ferry 3)	BWR/6 (Grand Gulf 1)	ABWR	ESBWR
Power (MWt / MWe)	3293/1098	3900/1360	3926/1350	4500/1590
Vessel height / diameter (m)	21.9/6.4	21.8/6.4	21.1/7.1	27.6/7.1
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-8
Safety Bldg Vol (m^3/MWe)	120	170	180	135

❖ **Reactor pressure vessel**

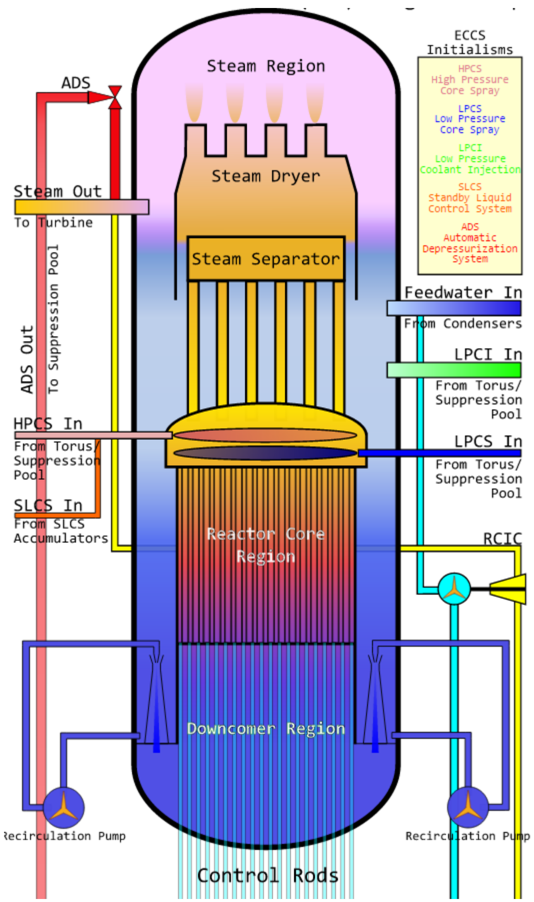




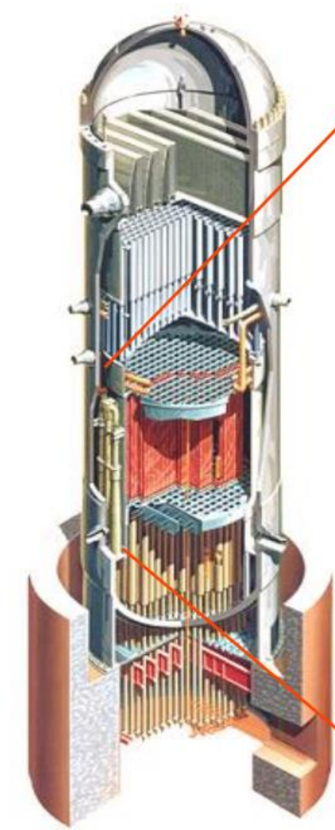
Review

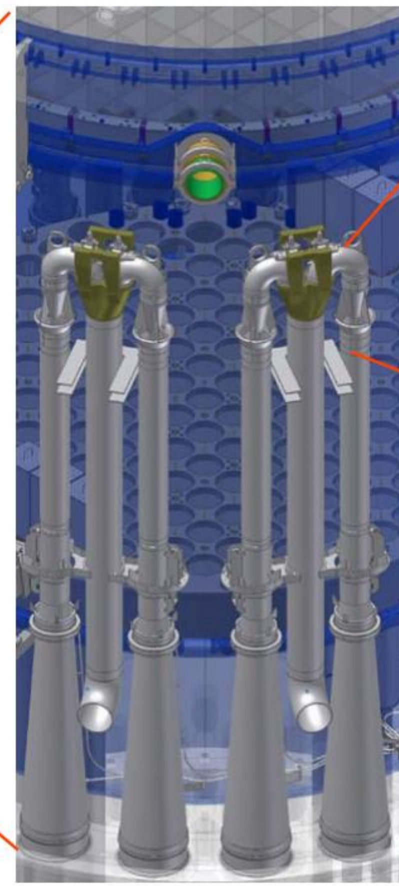
- BWR statistics
- Evolution of BWR
- Containment design evolution
- Main flow/ jet pump/ recirculation pump

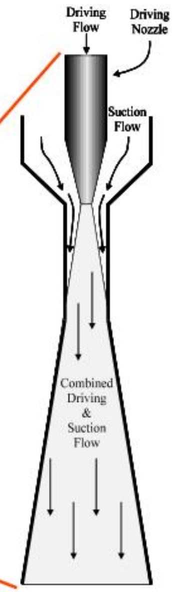
❖ Reactor pressure vessel



BWR Jet Pump



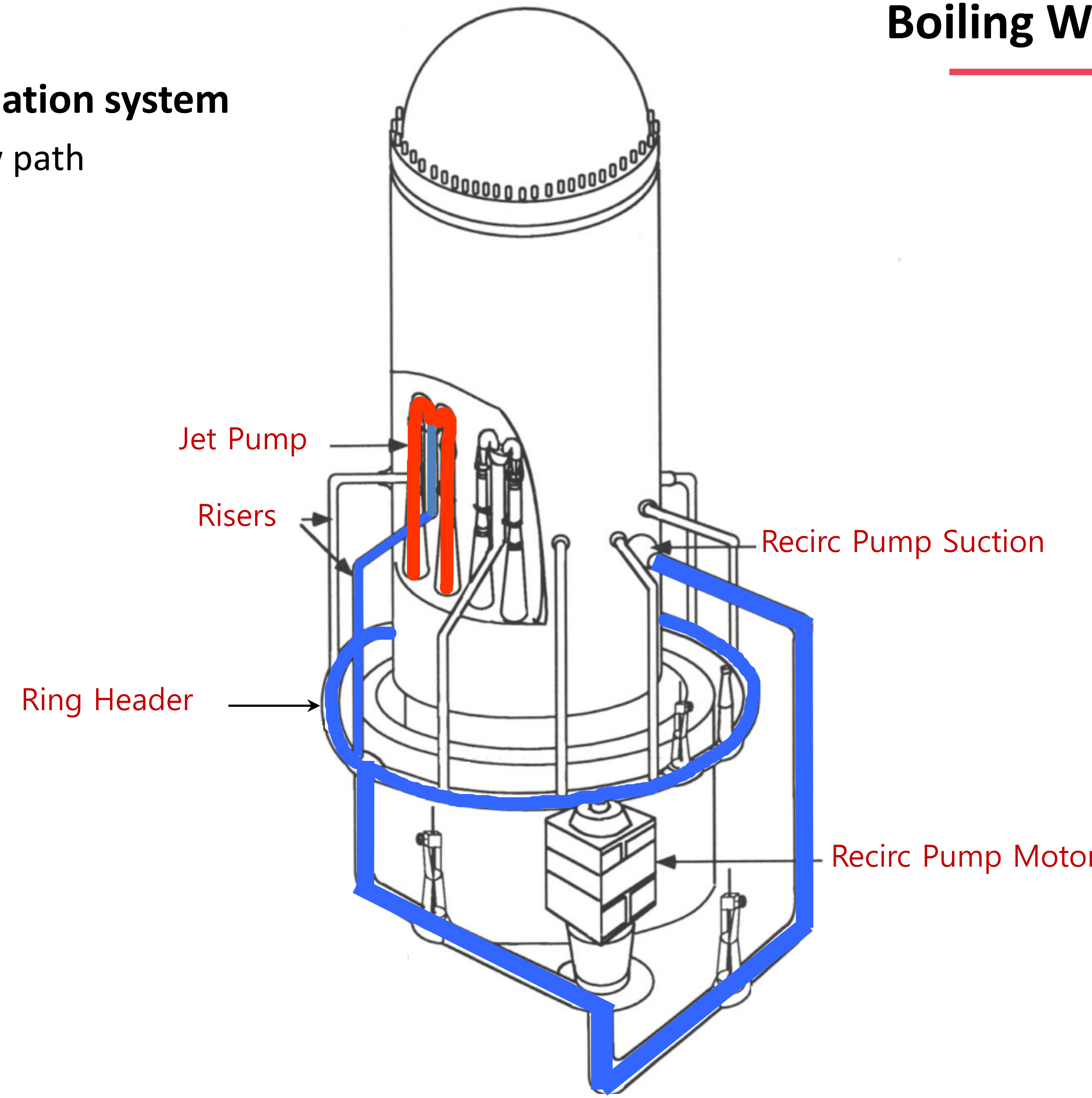




- Provide core flow to control reactor power which yields higher power level without increasing the Rx size
- Provide part of the boundary required to maintain 2/3 core height following a recirculation line break event

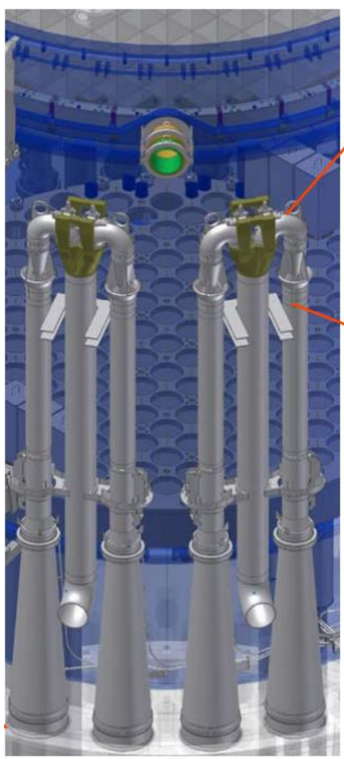
Boiling Water Reactor

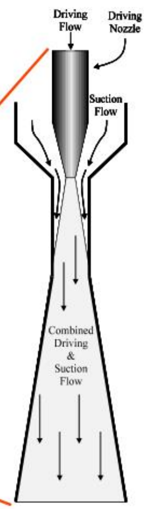
- **Recirculation system**
  - Flow path



Recirculation system

- Jet pump





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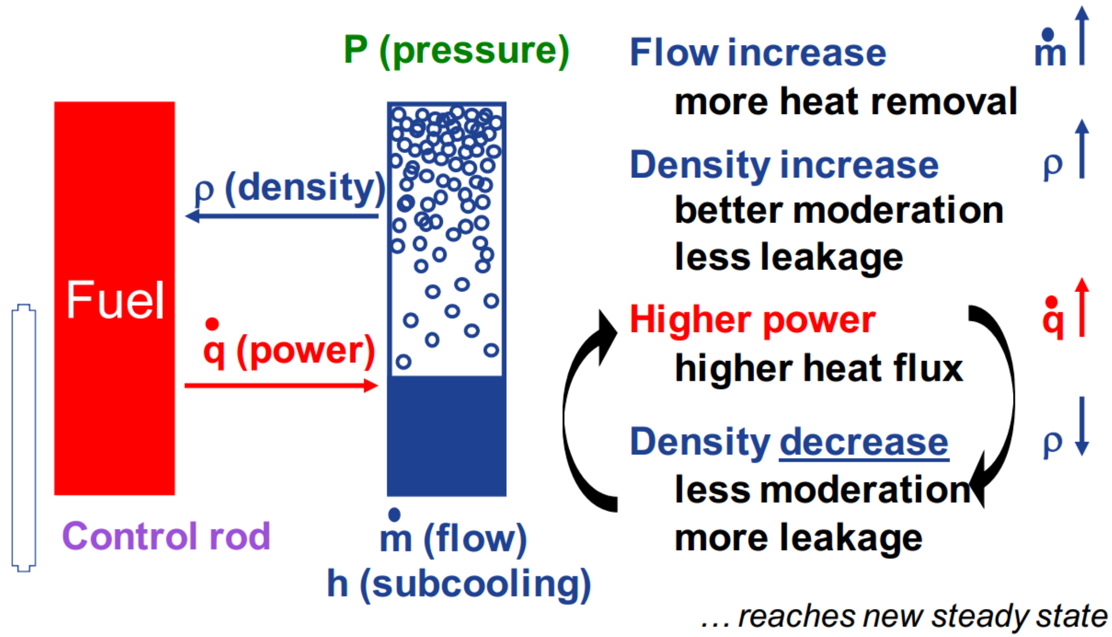
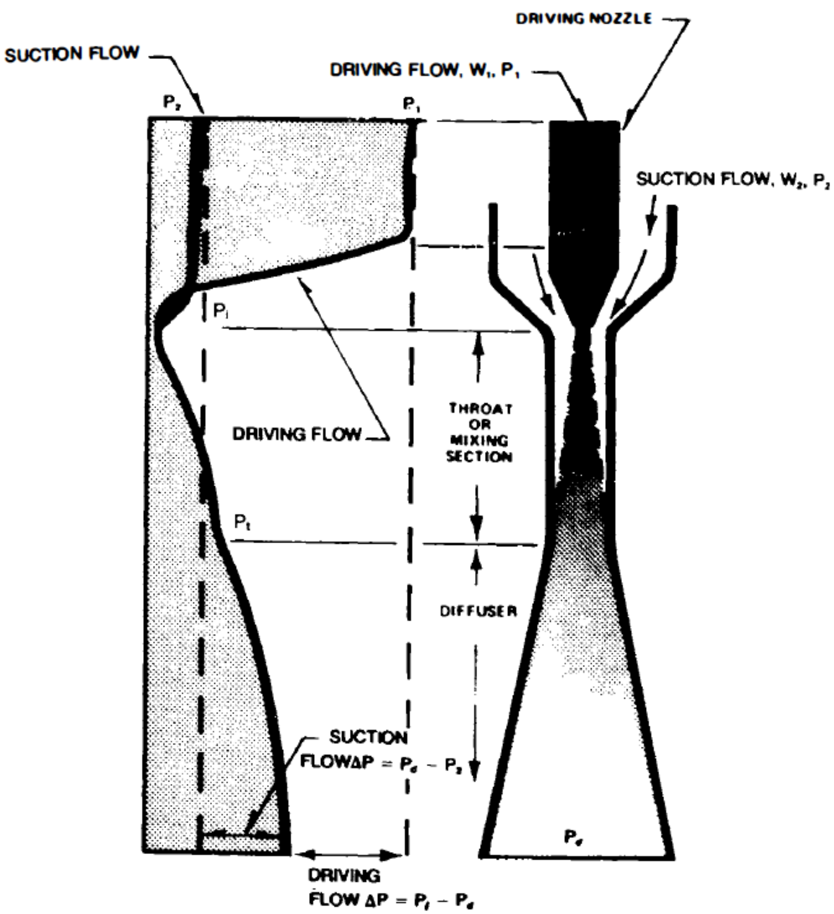


Recirculation system

- Working principle: power control
  - The recirculation system simply takes water from the reactor vessel and returns it to the reactor vessel where it flows through jet pumps into the lower dome beneath the reactor core.
  - Changing (increasing or decreasing) the flow of water through the core is the normal and convenient method for controlling power from approximately 30% to 100% reactor power.
    - Power may be varied from approximately 30% to 100% of rated power by changing the reactor recirculation system flow by varying the speed of the recirculation pumps or modulating flow control valves.
  - As flow of water through the core is increased,
    -
    -
    -
    -
    -
  - As flow of water through the core is decreased,
    - Steam voids remain longer in the core,
    - The amount of liquid water in the core decreases,
    - Neutron moderation decreases,
    - Fewer neutrons are slowed down to be absorbed by the fuel,
    - Reactor power decreases.

Recirculation system

- Working principle: flow rate control



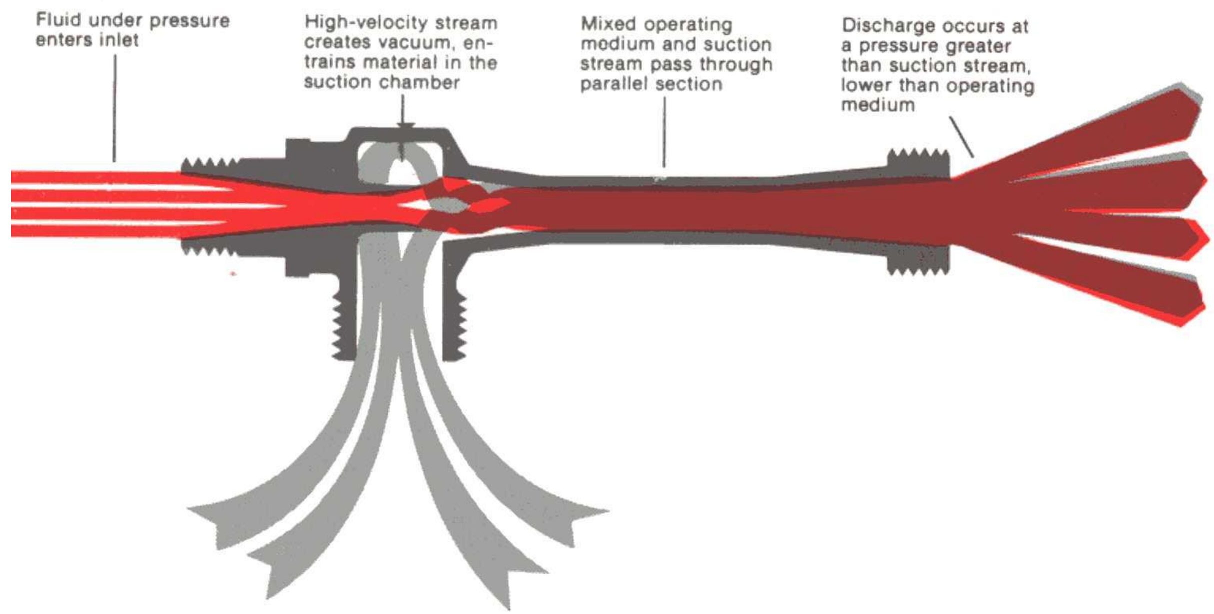


Fig. A: Jet pumps operate simply and effectively.

Recirculation system

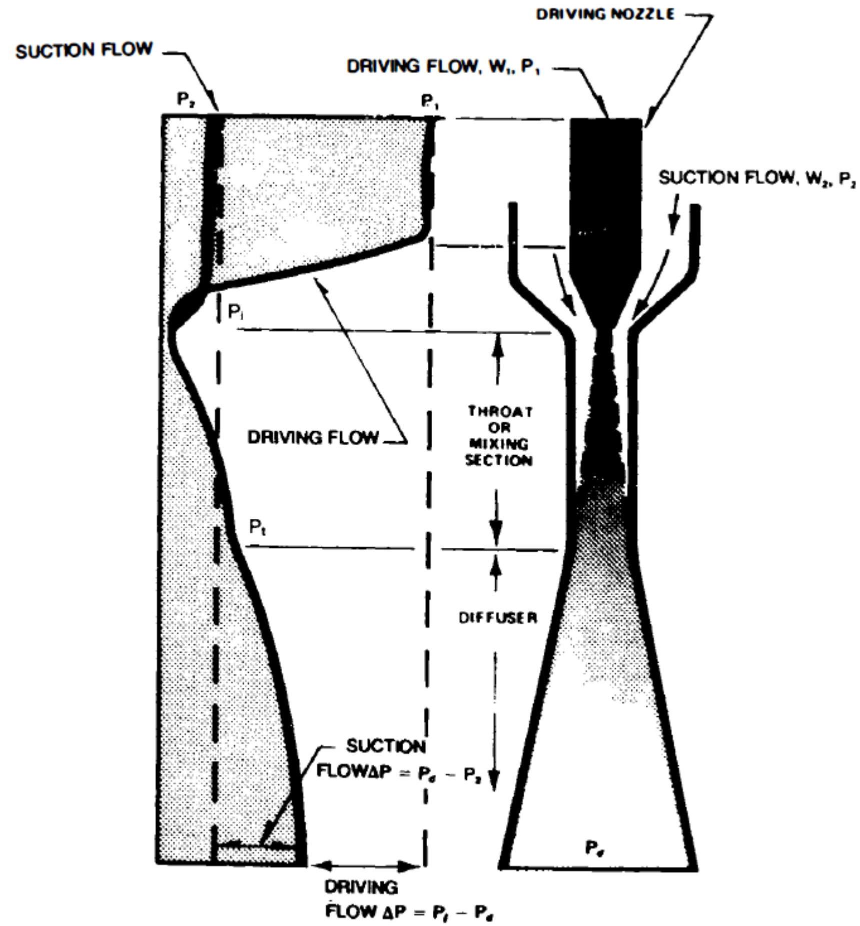
- Working principle: flow rate control
  - Mass conservation equation

$$v_t = (v_1 A_1 + v_2 A_2)/A_t$$

  - Momentum conservation

$$p_i\left(A_1 + A_2\right) + A_1\rho_f v_1^2 + A_2\rho_f v_2^2 = p_t A_t + A_t\rho_f v_t^2$$

$$p_t = p_i(A_1 + A_2)/A_t - \frac{\rho_f}{A_t g_c}\left[A_t v_t^2 - A_1 v_1^2 - A_2 v_2^2\right]$$

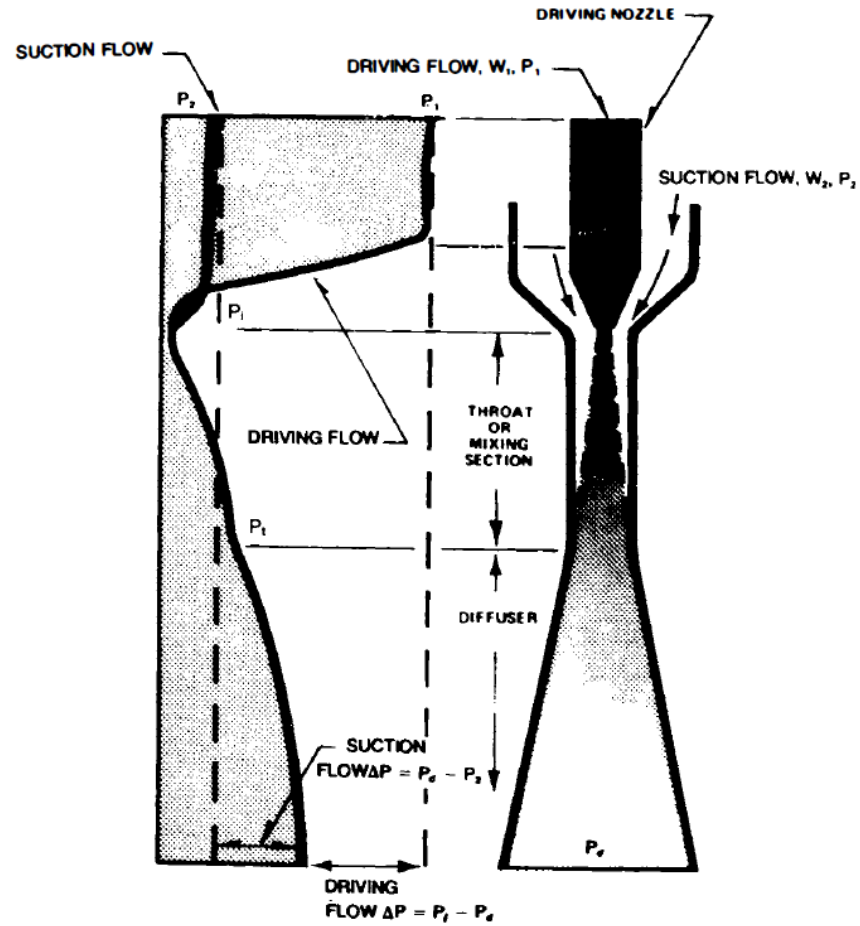


Recirculation system

- Working principle: flow rate control
  - Bernoulli equation for diffuser

$$\frac{p_t g_c}{\rho_f g} + \frac{v_t^2}{2g} = \frac{p_d g_c}{\rho_f g} + \frac{v_d^2}{2g}$$

$$v_d = \frac{\rho_f A_t v_t}{\rho_f A_d}$$



Recirculation system

Working principle: flow rate control

- Example

A water jet pump has a jet area of 0.010 m^2 and jet speed of 30.0 m/s. The jet is within a secondary stream of water having a speed of 3.00 m/s at section 1 as shown. The total area of the duct is 0.0750 m^2. The water is thoroughly mixed and leaves the jet pump in a uniform stream at section 2. The pressures of the jet and secondary stream are the same at the pump inlet. Determine the following:

(a) the velocity at the pump exit and
(b) the pressure rise.

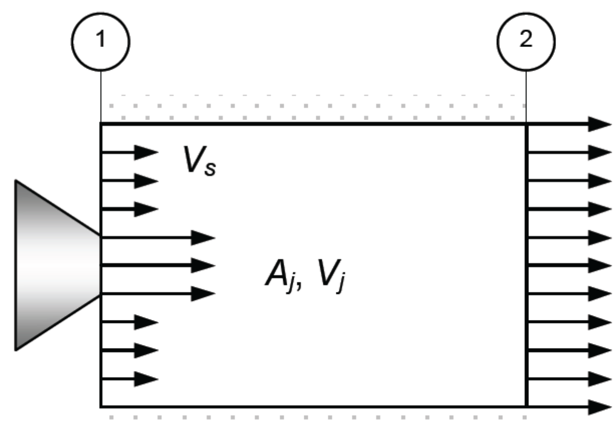
Known: Water jet pumped into flow, A_j = 0.010 m^2, V_j = 30.0 m/s, V_s = 3.00 m/s, A = 0.0750 m^2

Assumptions: Steady flow, incompressible liquid, uniform flow at inlets and exit, uniform pressure at sections 1 and 2, negligible friction at walls

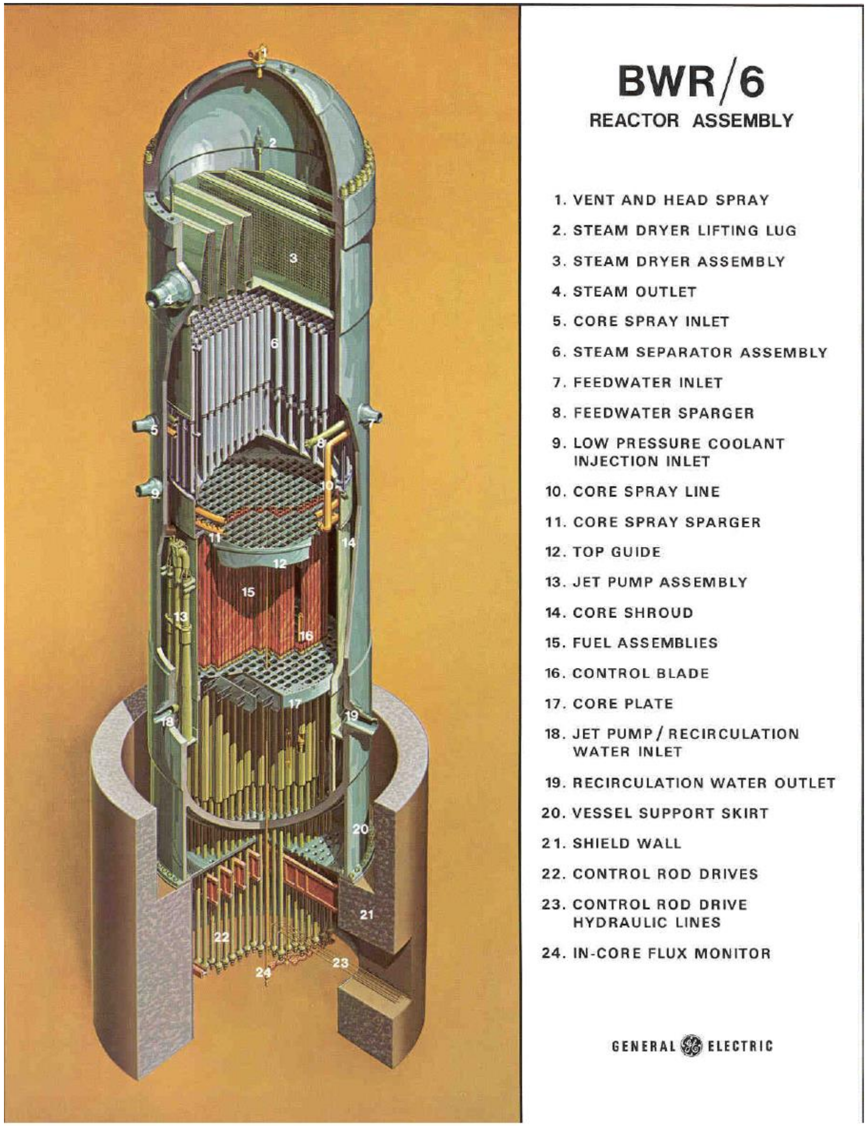
Find: (a) V_2, (b) $p_2 - p_1$

Solution:

Properties: ρ_{water} = 1000 kg/m^3

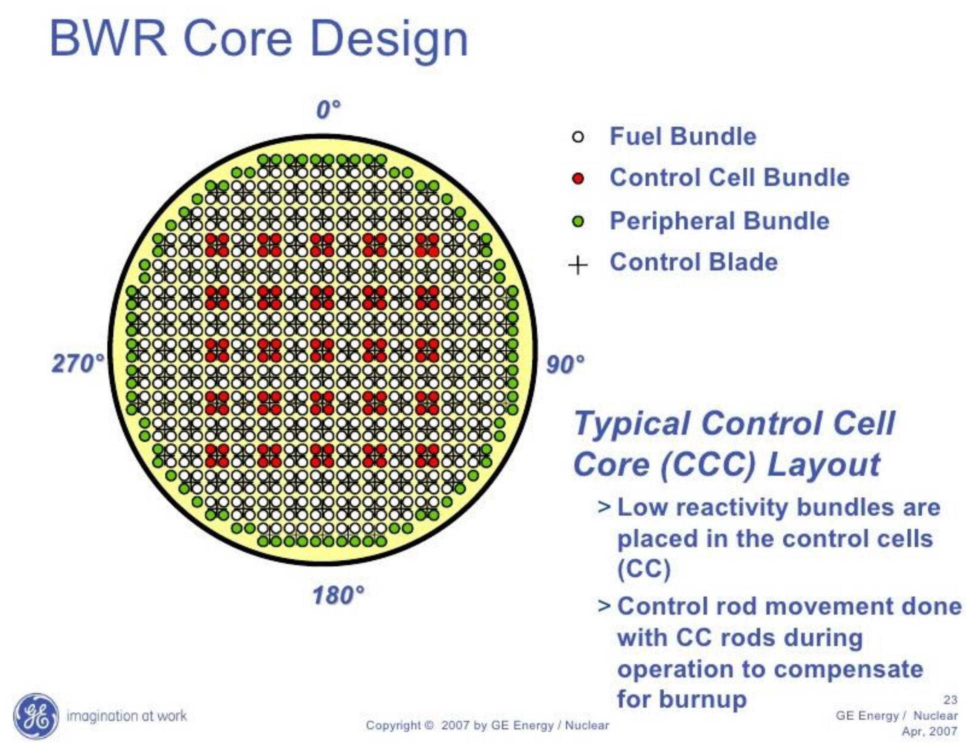


Reactor core



BWR 6 Reactor Vessel

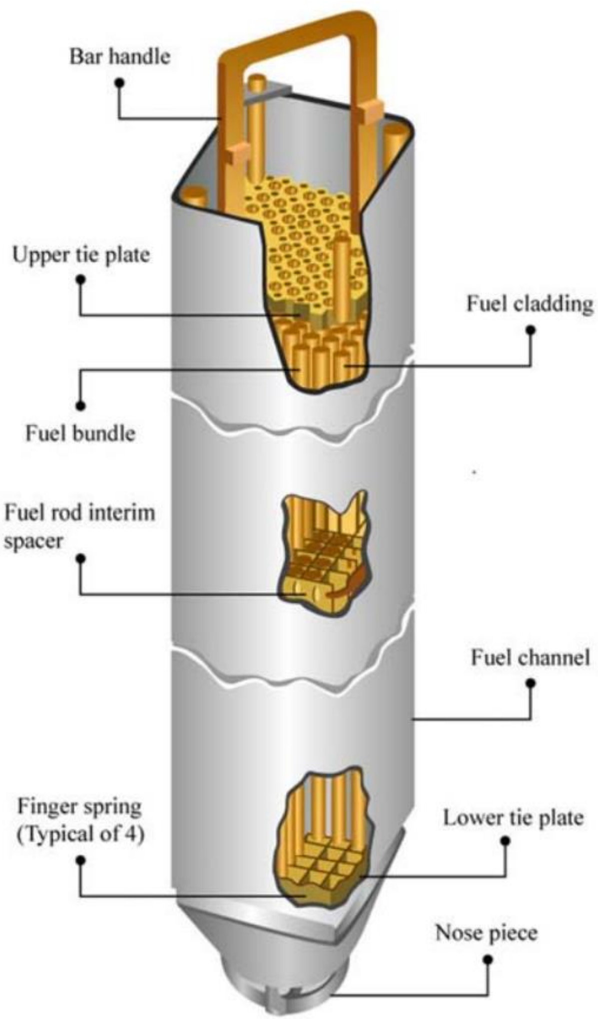
Core equivalent diameter: 5.16 m (PWR: 3.64 m)
Active core height: 3.81 m

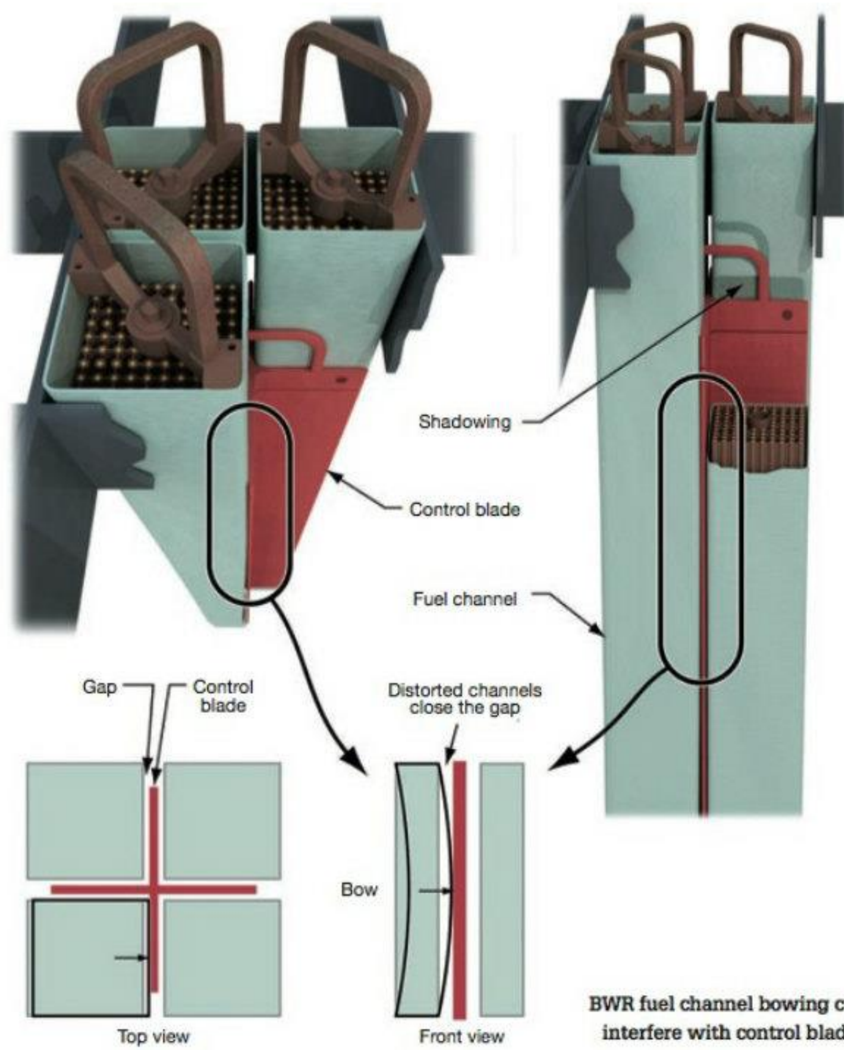


Boiling Water Reactor

- Reactor core

- **Reactor core**
  - Boxed fuel channel

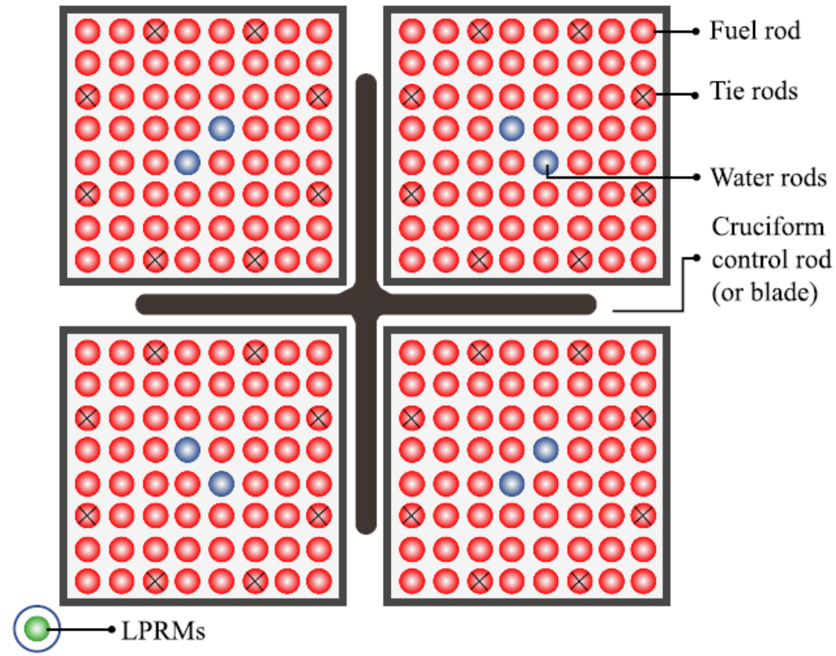


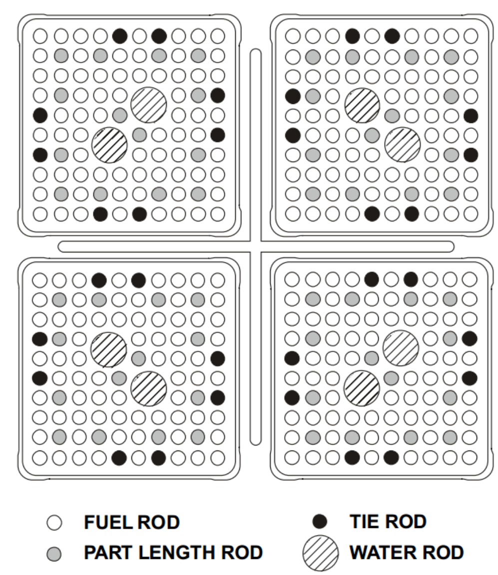


BWR fuel channel bowing can interfere with control blades

Boiling Water Reactor

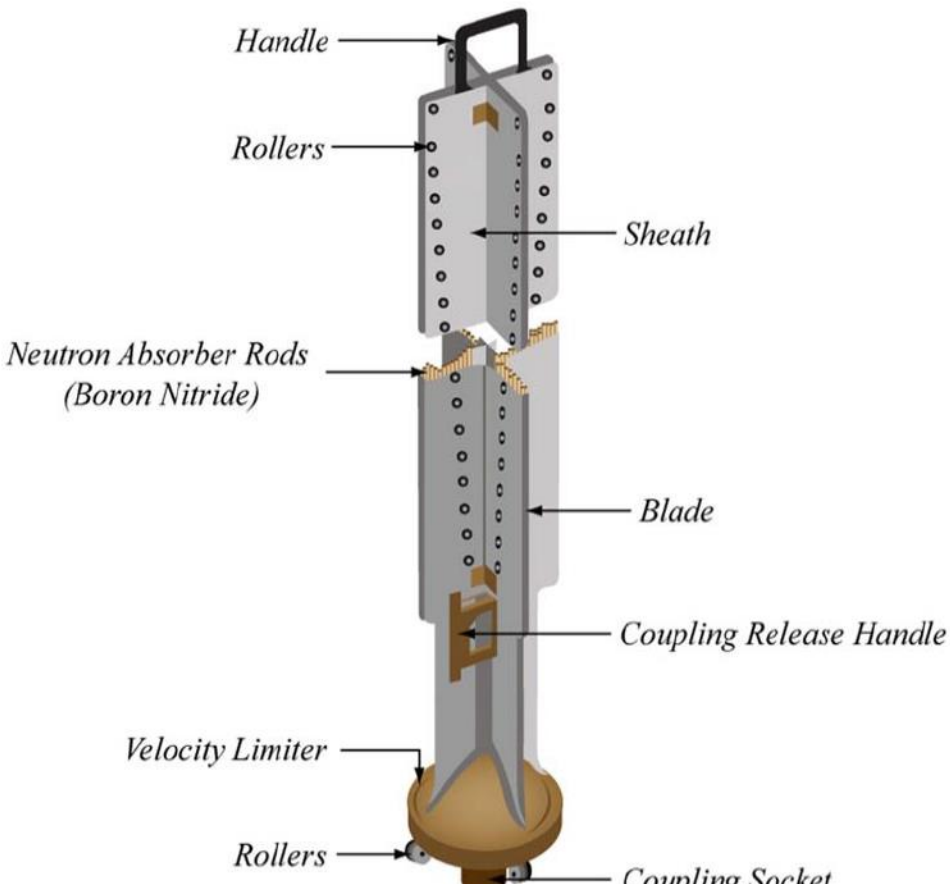
- **Reactor core**
  - Closed channel
  - 8x8 fuel array
  - 62 active rods, 2 water rods
  - Standard fuel rods, tie rods, water rods
  - Water rod?
    - Hollow Zircaloy-2 tubes.
    - Small holes are provided at both the lower and upper ends allowing water to flow through these rods, thus introducing moderating material within the bundle interior.
    - The water rods also serve as spacer-capture rods, mechanically locked to each of the seven grid spacers, thereby fixing the axial position of each spacer.

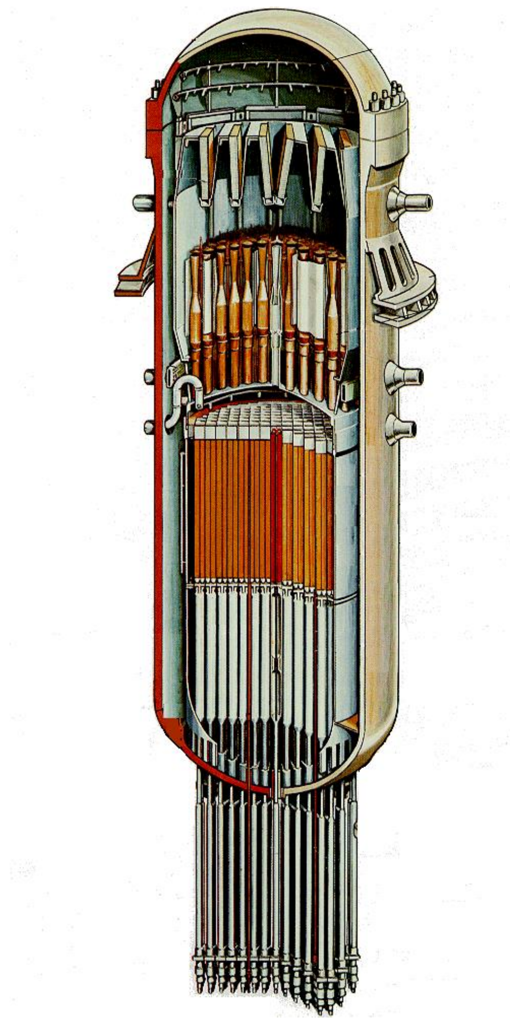




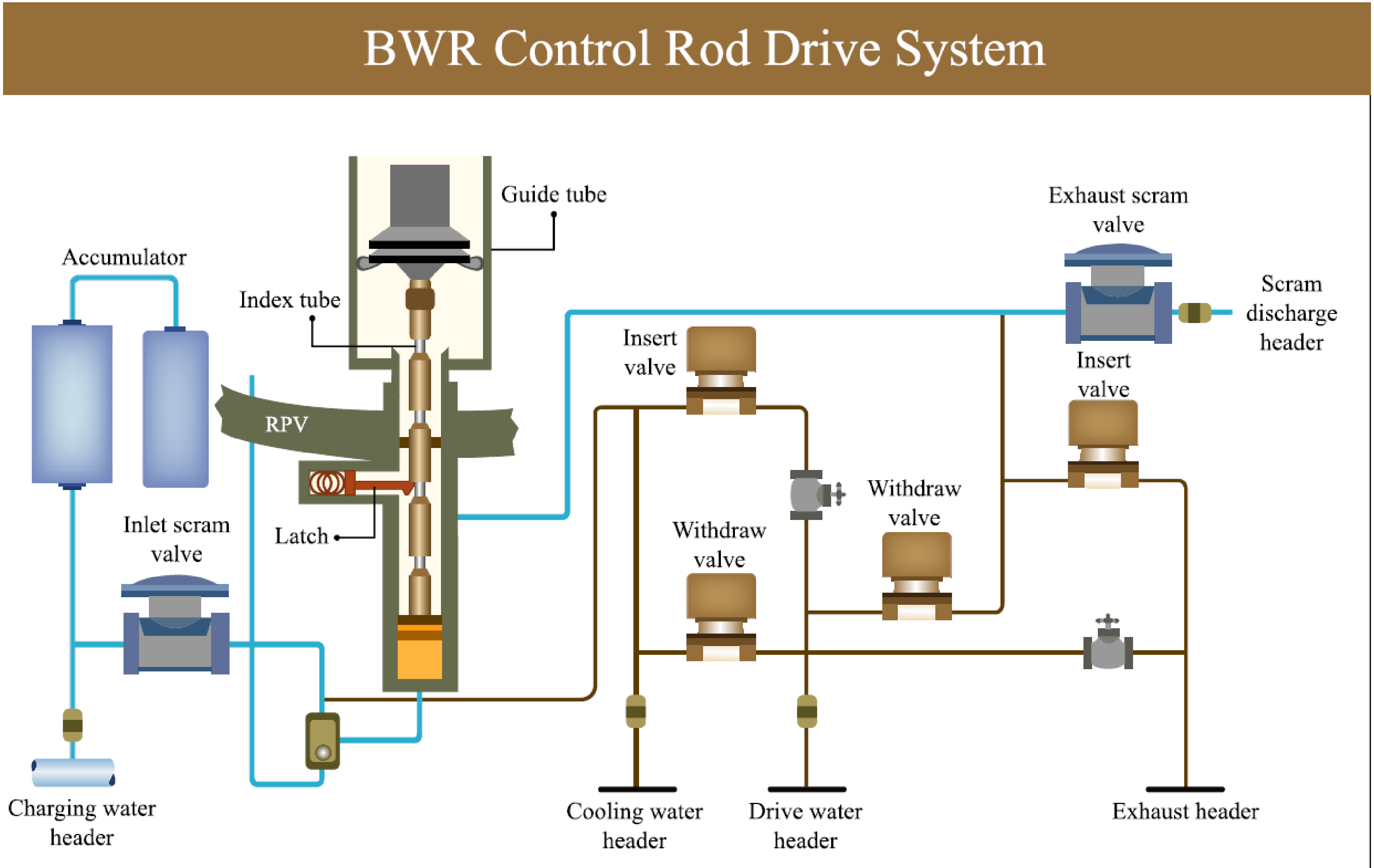
Control rod

- Cruciform control rod
  - 72 stainless steel tube filled with boron carbide or nitride
  - Inserted from the bottom





❖ Control rod drive system



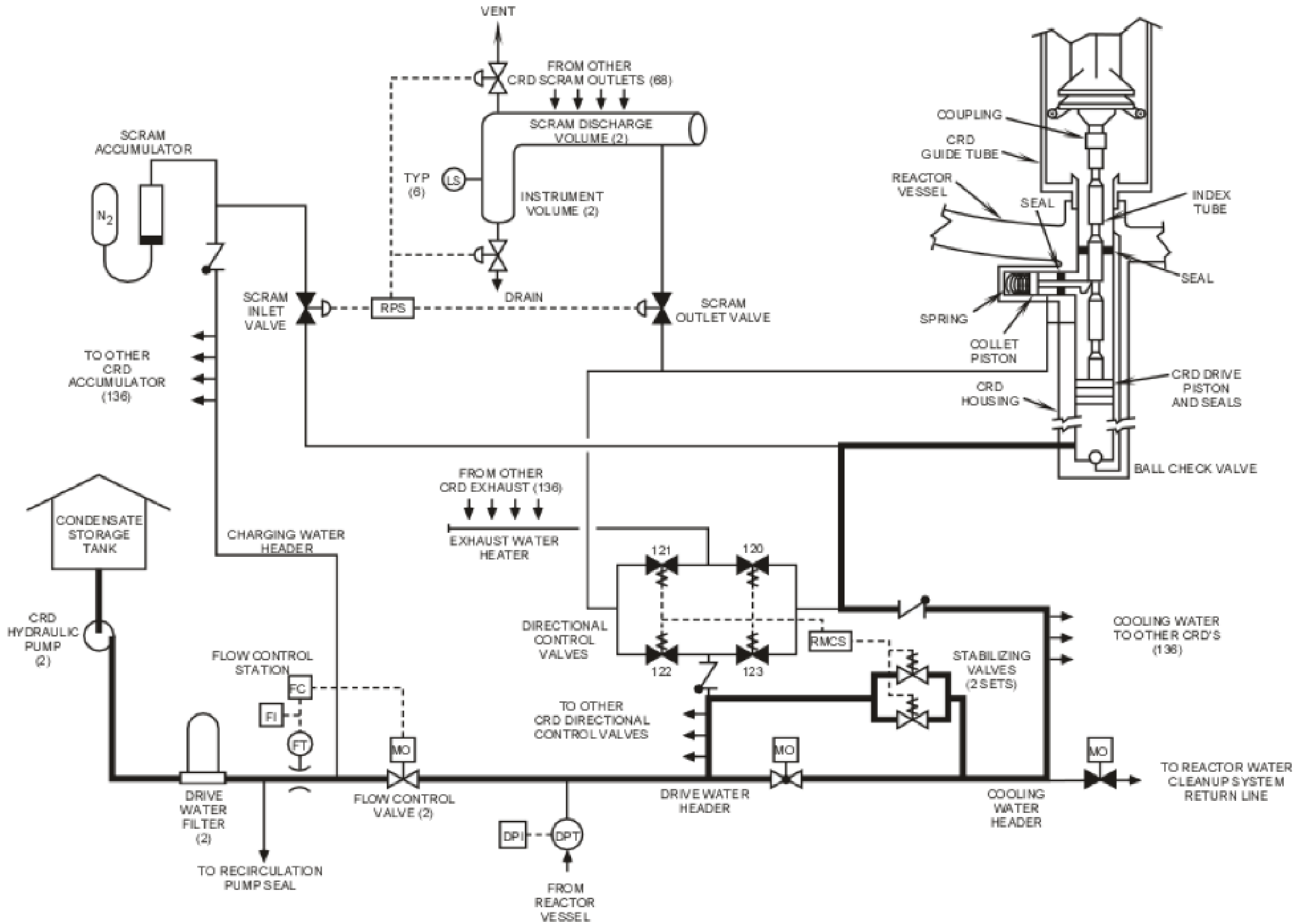
Boiling Water Reactor

Control rod

- Cruciform control rod
    - 72 stainless steel tube filled with boron carbide or nitride
    - Inserted from the bottom

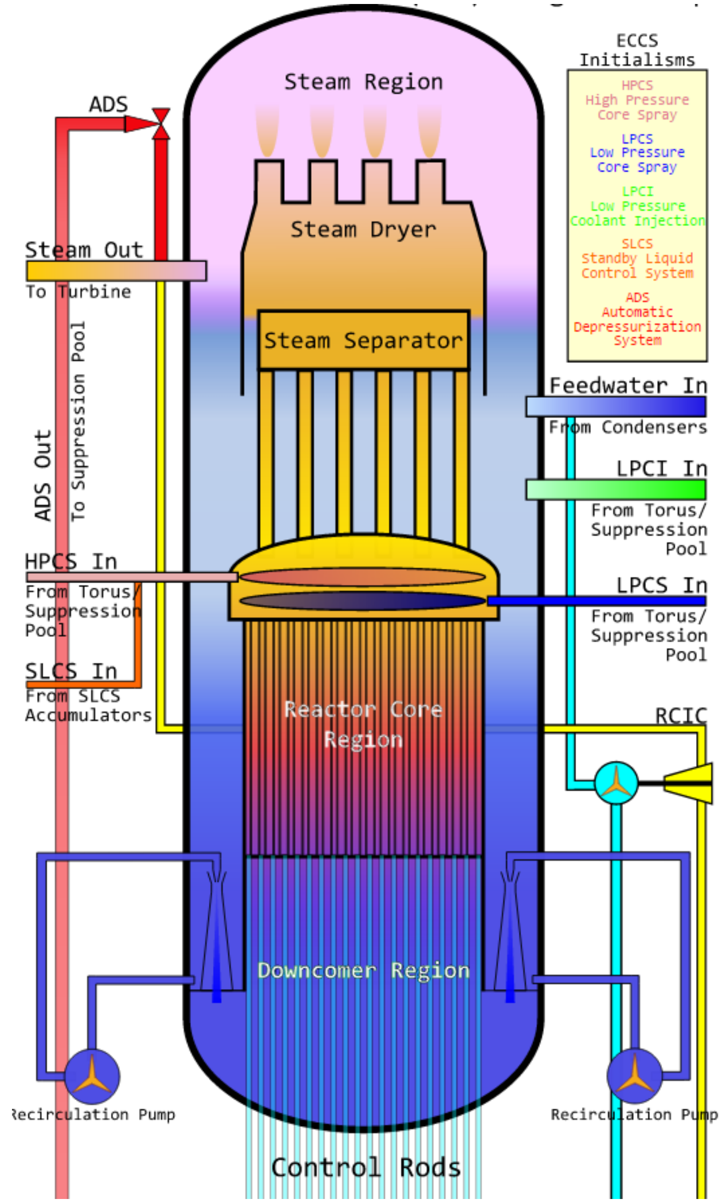
The BWR is the only light water reactor system that employs bottom-entry control rods. Bottom-entry and bottom-mounted control rod drives allow refueling without removal of control rods and drives, and allow drive testing with an open vessel prior to initial fuel loading or at each refueling operation. The hydraulic control rod drive system, which incorporates mechanical locking of the rod at the selected position, provides positive driving, and positioning of the control rods. Pressurized accumulators that provide a rod insertion force far greater than any gravity or mechanical system carry out rapid control rod insertion.

❖ Control rod drive system



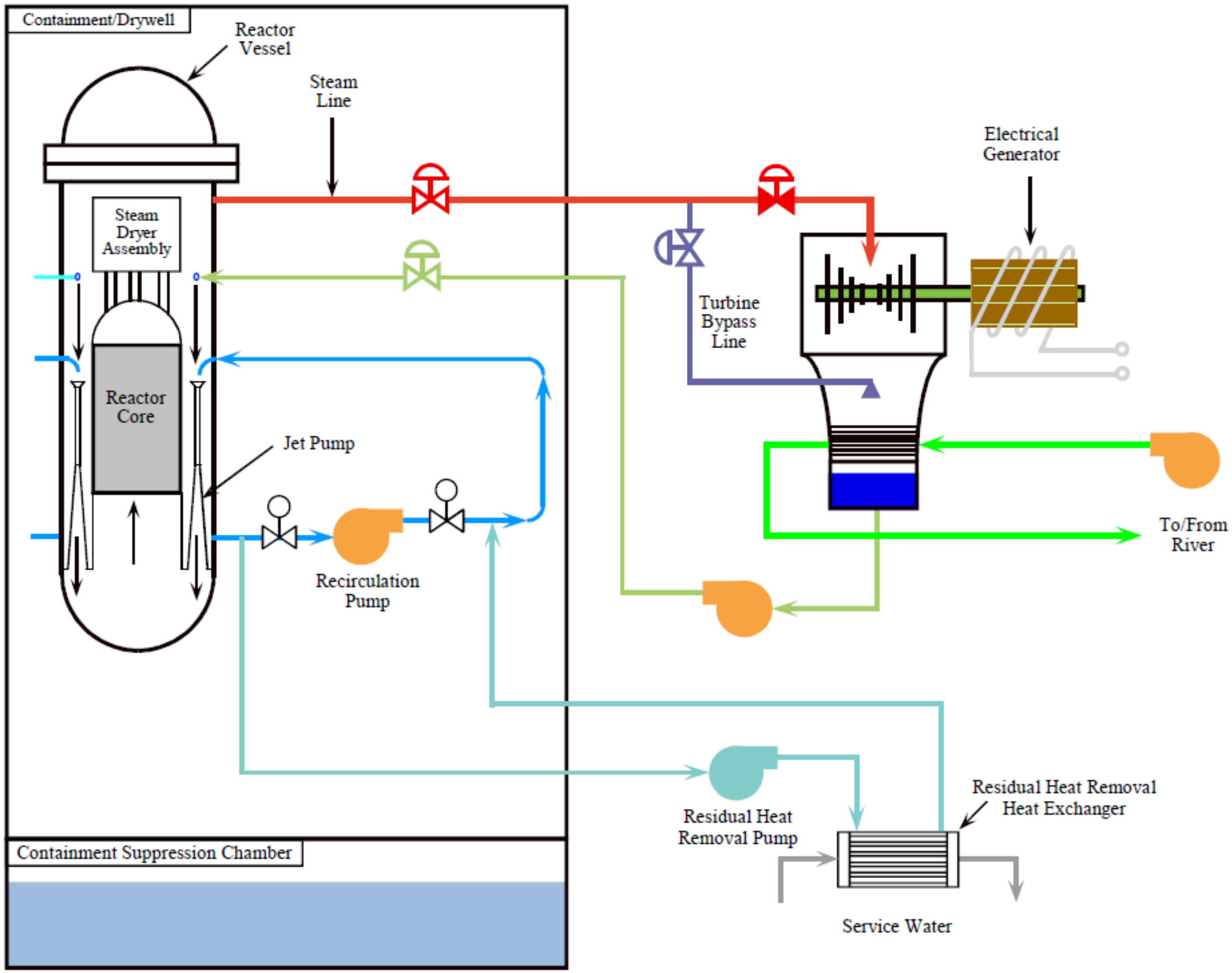
Boiling Water Reactor

- **Safety systems**
  - RHRS (Residual Heat Removal System)
  - RCIC (Reactor Core Isolation Cooling)
  - HPCI (High Pressure Coolant Injection)
  - ADS (Automatic Depressurization System)
  - LPCI (Low Pressure Coolant Injection)
  - HPCS (High Pressure Core Spray)
  - LPCS (Low Pressure Core Spray)
  - IC (Isolation Condenser)

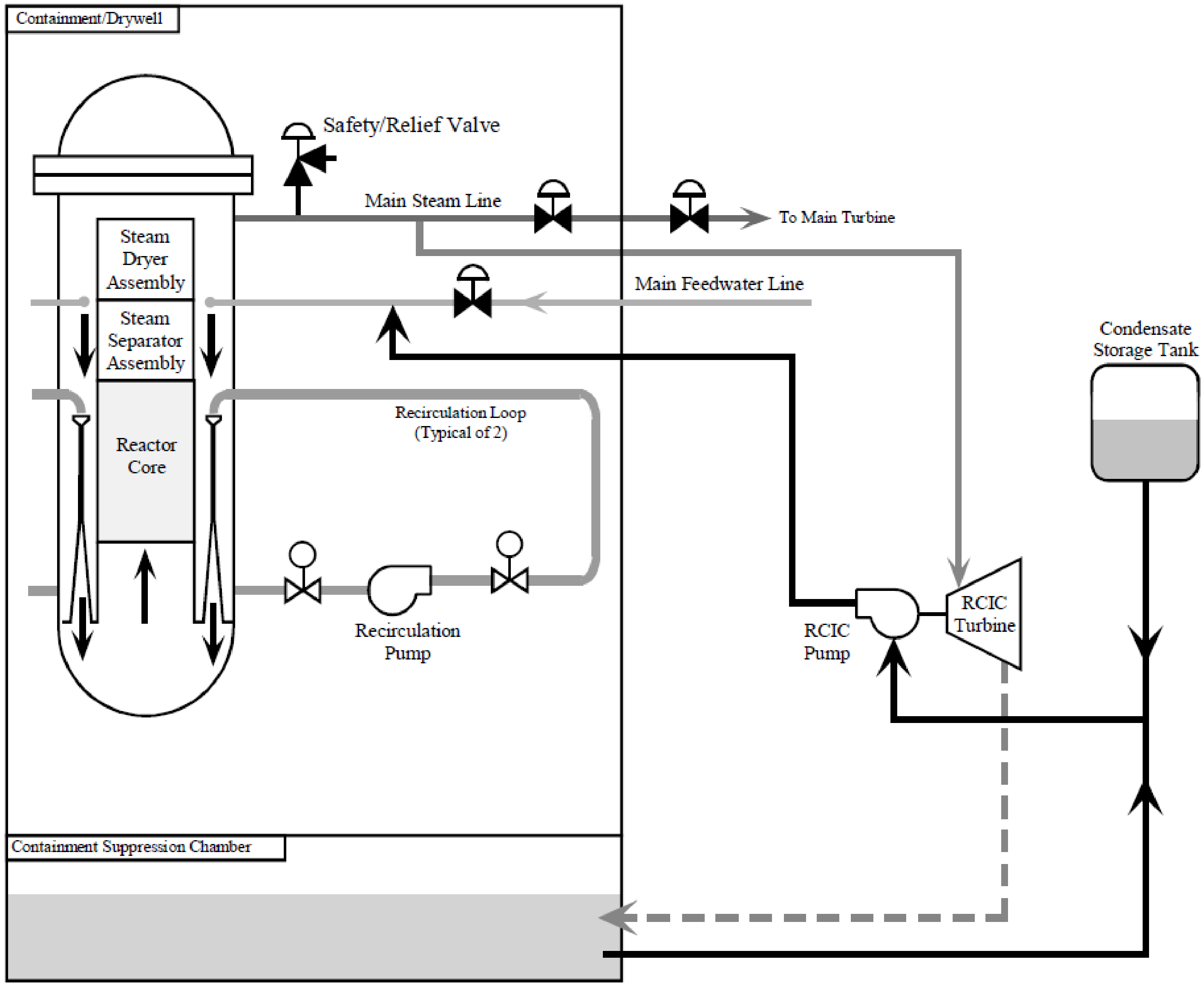


RHRS (Residual Heat Removal System)

- The shutdown cooling mode of the residual heat removal (RHR) system is used to complete the cooldown process when pressure decreases to approximately 50 psig.



❖ RCIC (Reactor Core Isolation Cooling)



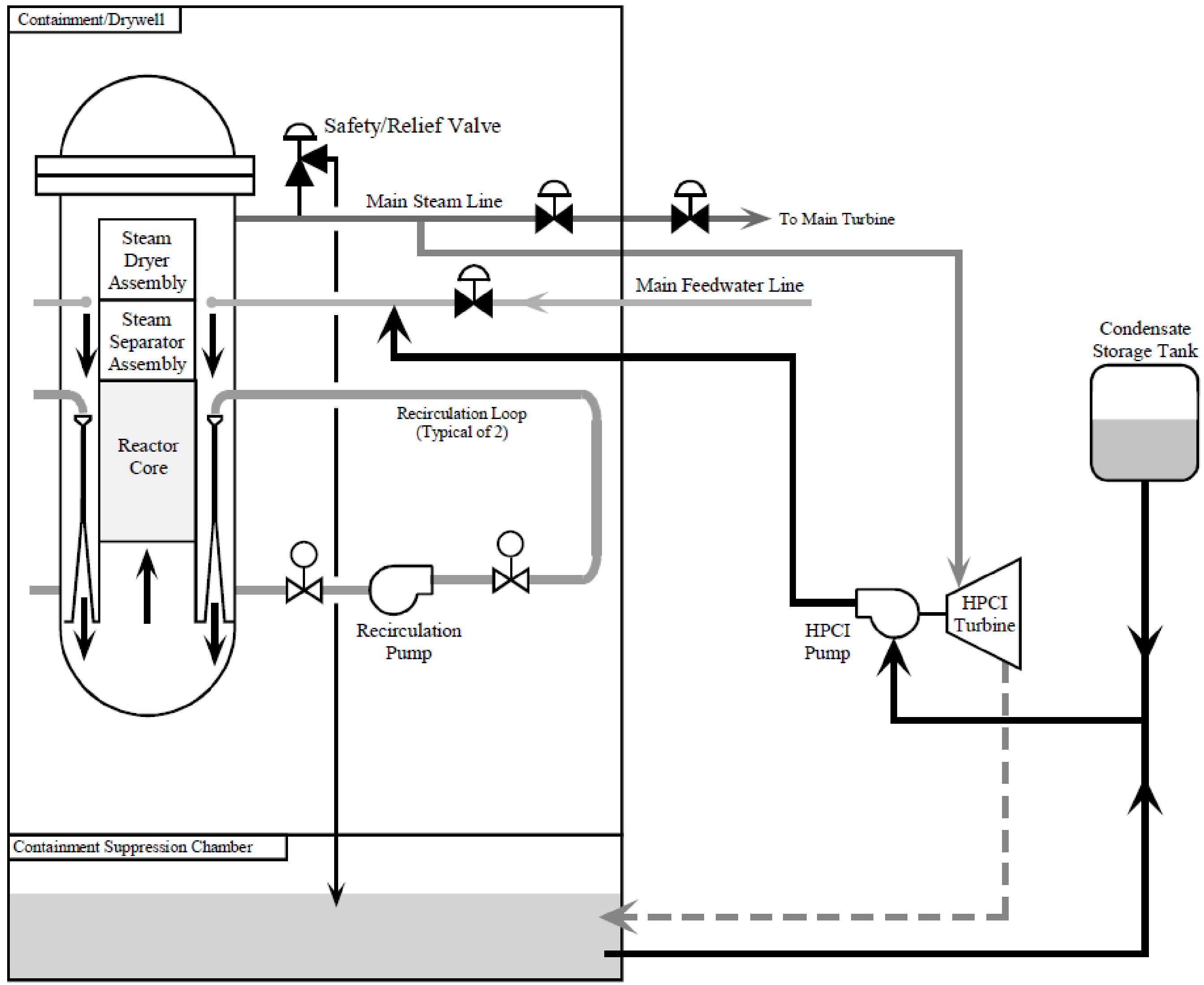
RCIC (Reactor Core Isolation Cooling)

- Provides makeup water to the reactor vessel for core cooling when the main steam lines are isolated and the normal supply of water to the reactor vessel is lost.
- Components
  - Turbine-driven pump, piping, and valves necessary to deliver water to the reactor vessel at operating conditions.

- Working principle
  - The turbine is driven by steam supplied by the main steam lines.
  - The turbine exhaust is routed to the suppression pool.
  - The turbine-driven pump supplies makeup water from the condensate storage tank, with an alternate supply from the suppression pool, to the reactor vessel via the feedwater piping.
  - The system flow rate is approximately equal to the steaming rate 15 minutes after shutdown with design maximum decay heat.
  - Initiation of the system is accomplished automatically on low water level in the reactor vessel or manually by the operator.

Boiling Water Reactor

❖ HPCI (High Pressure Coolant Injection)



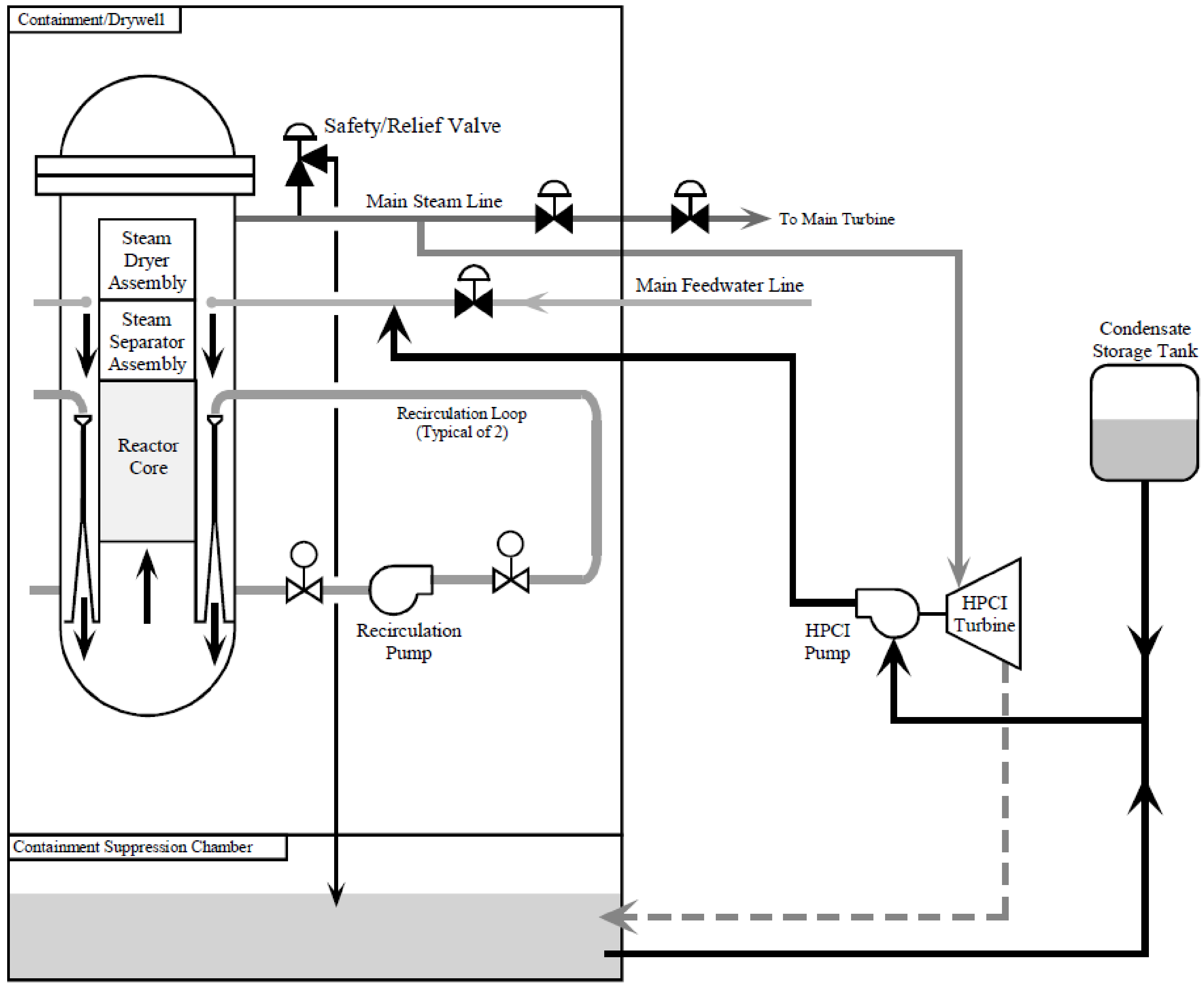
HPCI (High Pressure Coolant Injection)

- Similar to RCIC
- The high pressure coolant injection (HPCI) system is an independent emergency core cooling system requiring no auxiliary ac power, plant air systems, or external cooling water systems to perform its purpose of providing make up water to the reactor vessel for core cooling under small and intermediate size loss of coolant accidents.

- The high pressure coolant injection system can supply make up water to the reactor vessel from above rated reactor pressure to a reactor pressure below that at which the low pressure emergency core cooling systems can inject.

RCIC: capacity of 2.3 m^3/min at 10.0 to 7.9 MPa
HPCI: capacity of 18.9 m^3/min

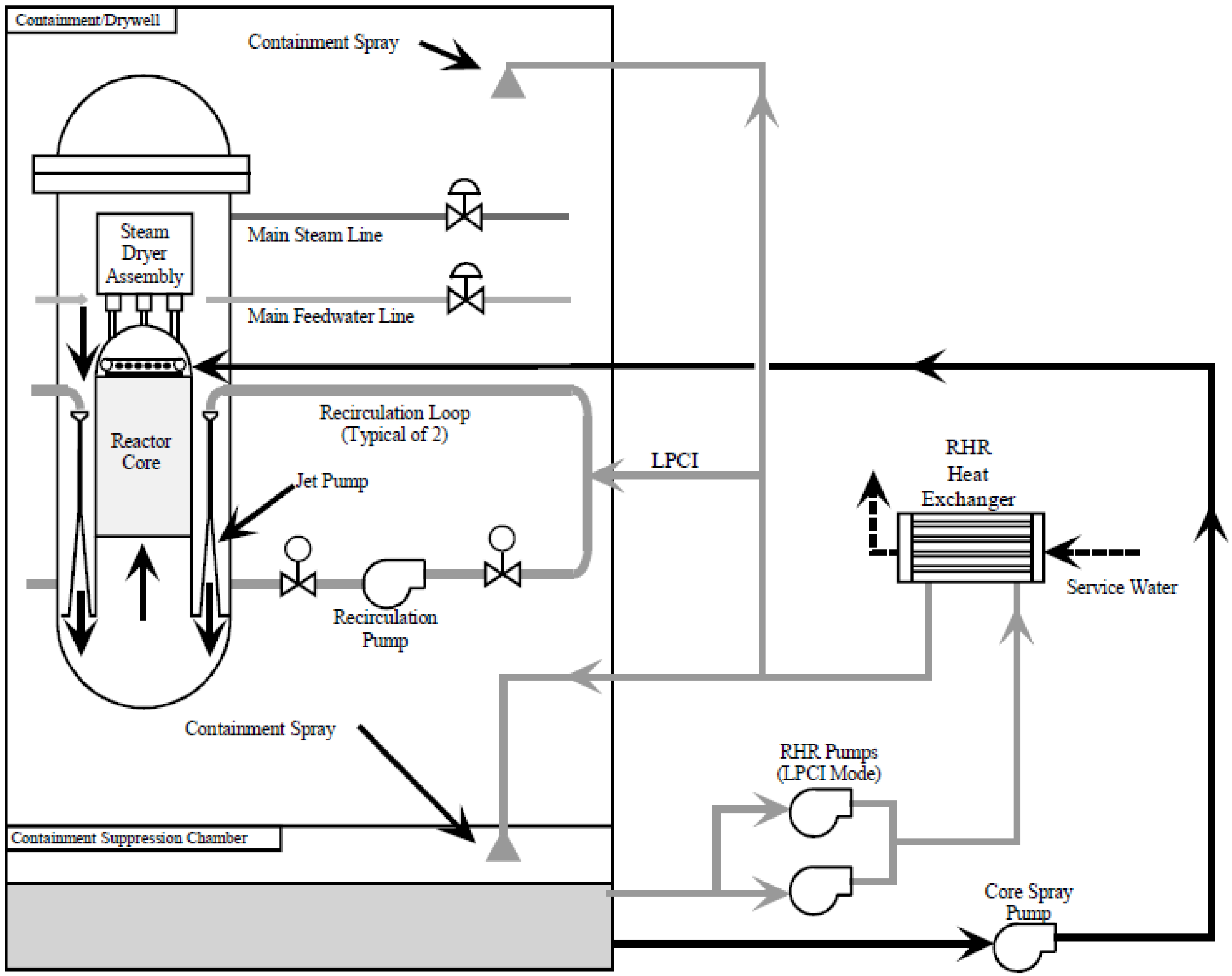
- ADS (Automatic Depressurization System)



ADS (Automatic Depressurization System)

- Designed to activate in the event that there is either a loss of high-pressure cooling to the vessel or if the high-pressure cooling systems cannot maintain the RPV water level.
- ADS can be manually or automatically initiated.
- The system rapidly releases pressure from the RPV in the form of steam through pipes that are piped to below the water level in the suppression pool (the torus/wetwell).
- Brings the reactor vessel below 32 atm (3200 kPa, 465 psi), allowing the low-pressure cooling systems to restore reactor water level.
- During an ADS blowdown, the steam being removed from the reactor is sufficient to ensure adequate core cooling even if the core is uncovered.
- The water in the reactor will rapidly flash to steam as reactor pressure drops, carrying away the latent heat of vaporization and providing cooling for the entire reactor.
- Low pressure ECCS systems will re-flood the core prior to the end of the emergency blowdown, ensuring that the core retains adequate cooling during the entire event.

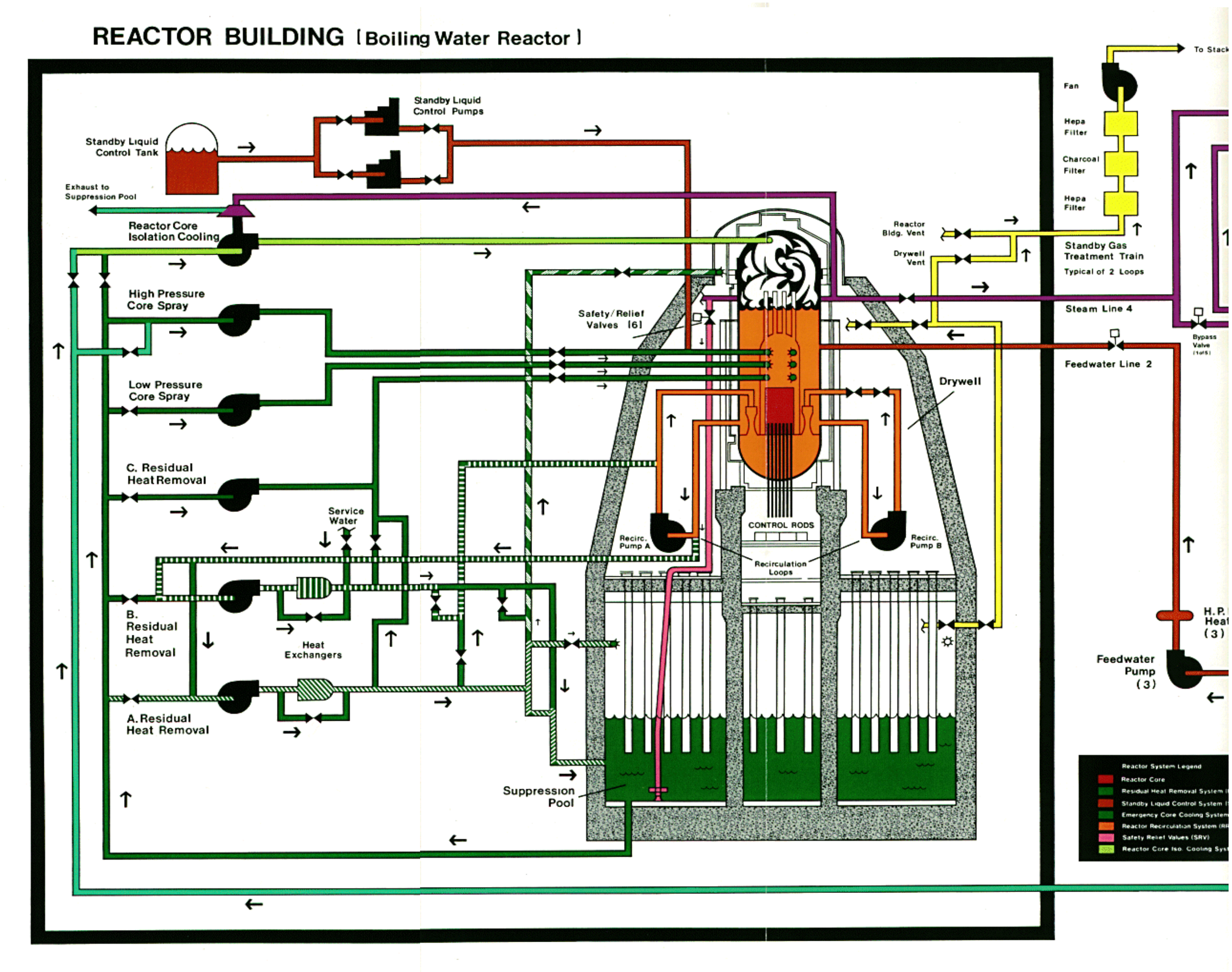
- LPCI (Low Pressure Coolant Injection)
- LPCS (Low Pressure Core Spray) / (High Pressure Core Spray)



LPCI (Low Pressure Coolant Injection)/LPCS (Low Pressure Core Spray)

- HPCS (High Pressure Core Spray)
  - The core spray system consists of two separate and independent pumping loops, each capable of pumping water from the suppression pool into the reactor vessel.
- LPCS (Low Pressure Core Spray)
  - The core spray system consists of two separate and independent pumping loops, each capable of pumping water from the suppression pool into the reactor vessel.
  - Core cooling is accomplished by spraying water on top of the fuel assemblies.
- LPCI (Low Pressure Coolant Injection)
  - The low pressure coolant injection mode of the residual heat removal system provides makeup water to the reactor vessel for core cooling under loss of coolant accident conditions.
  - Pumped by residual heat removal system

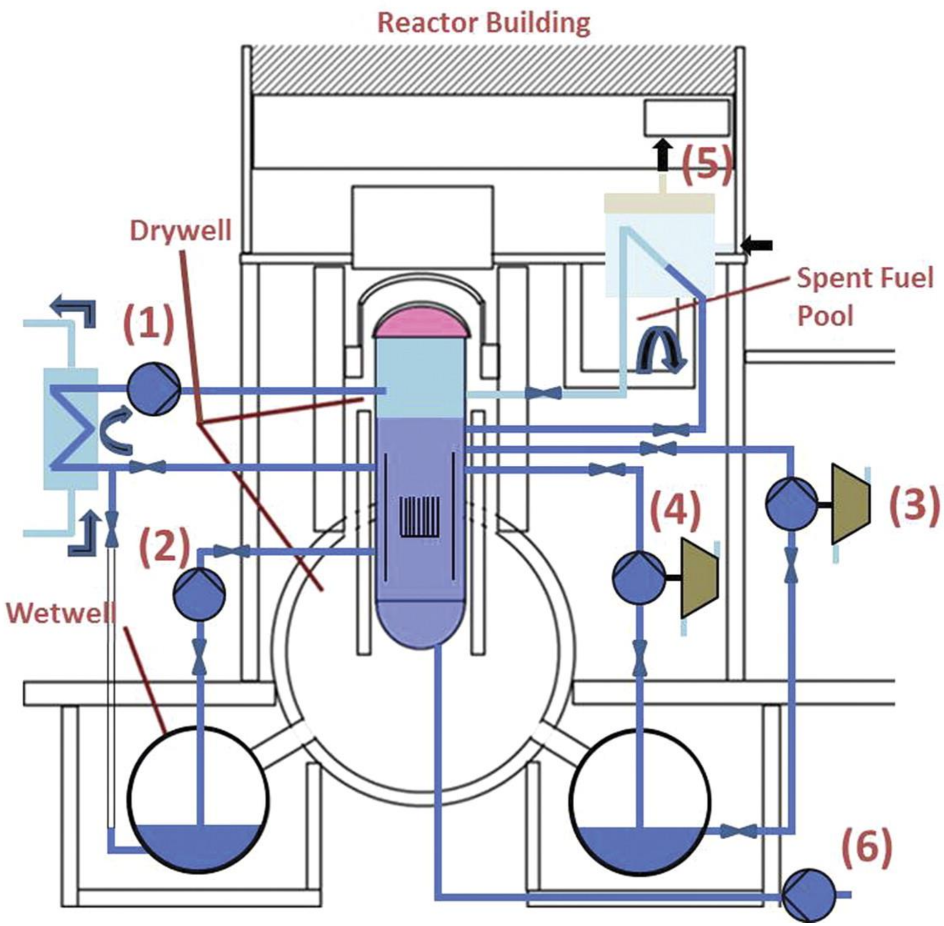
❖ LPCI (Low Pressure Coolant Injection)/LPCS (Low Pressure Core Spray)



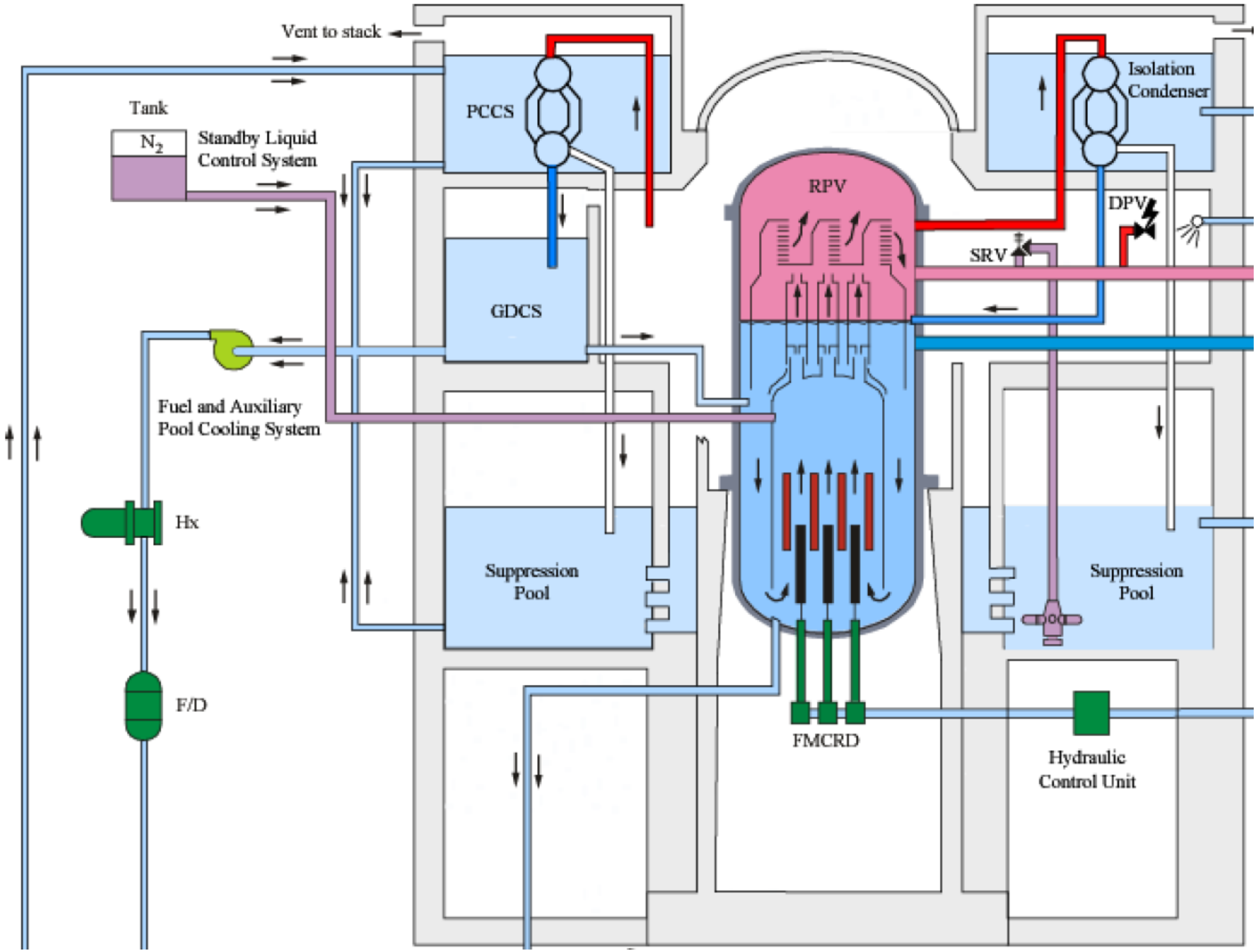
IC (Isolation Condenser)

- IC
  - Similar purpose to RCIC
  - Passive system
  - located above containment in a pool of water open to atmosphere
  - Decay heat boils steam , which is drawn into the heat exchanger and condensed
  - Then it falls by weight of gravity back into the reactor.
  - This process keeps the cooling water in the reactor, making it unnecessary to use powered feedwater pumps.
  - The water in the open pool slowly boils off, venting clean steam to the atmosphere. This makes it unnecessary to run mechanical systems to remove heat.

Notional diagram showing key safety cooling systems and differences among the various units (not drawn to scale). Systems are depicted by number: (1) residual-heat-removal system, (2) low-pressure core spray, (3) high-pressure core injection, (4) reactor core isolation cooling (Units 2, 3), (5) isolation condenser (only Unit 1), and (6) borating system. ADAPTED FROM U. STOLL, ENEF SPECIAL RISK WORKING GROUP ON SAFETY OF NUCLEAR FACILITIES, BRUSSELS, MARCH 24, 2011

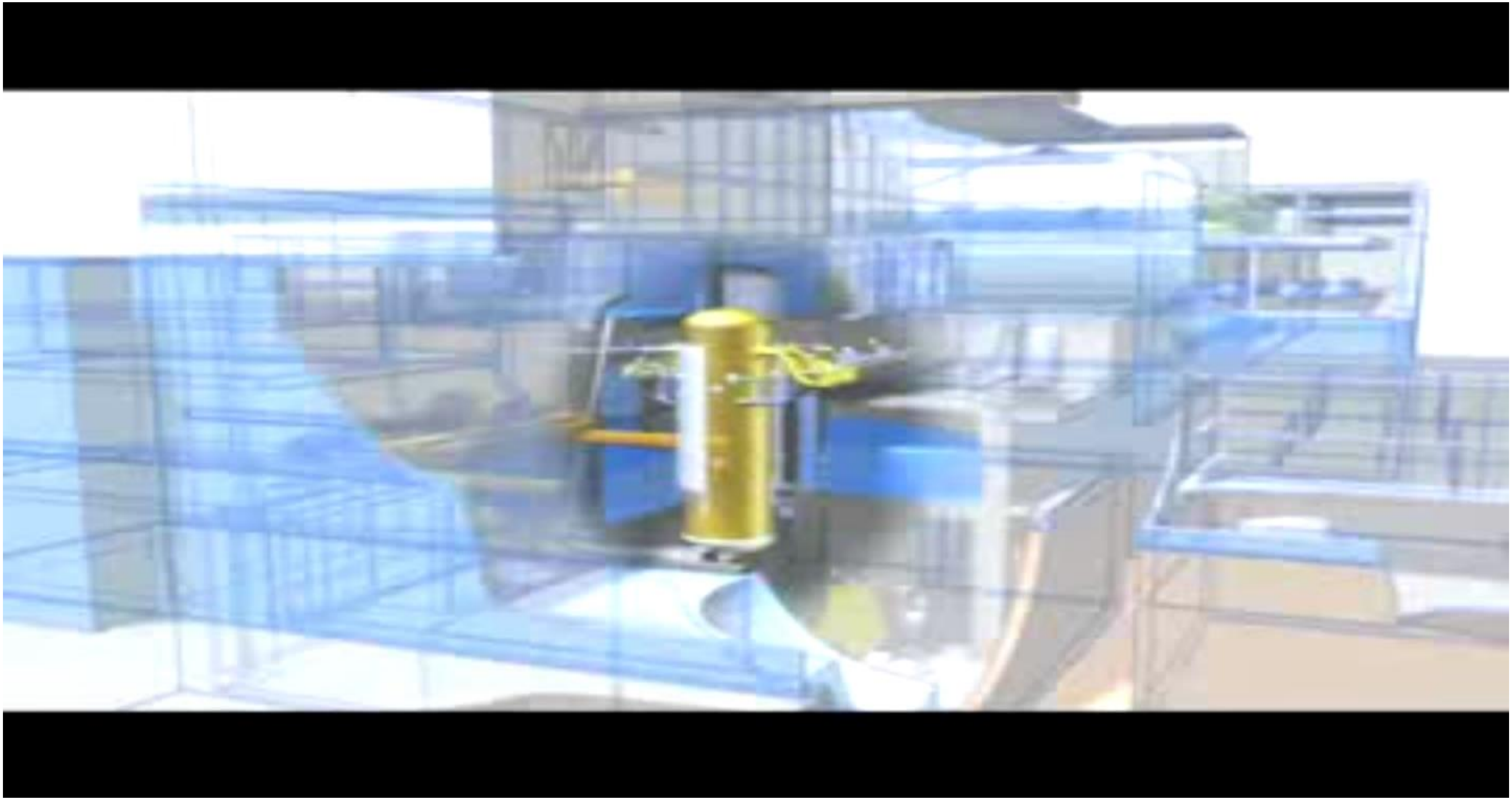


- ESBWR



Vent to stack
Tank
N_2
Standby Liquid Control System
PCCS
Isolation Condenser
RPV
DPV
SRV
GDCS
Fuel and Auxiliary Pool Cooling System
Hx
Suppression Pool
Suppression Pool
F/D
FMCRD
Hydraulic Control Unit

- **ESBWR**



RCIC: capacity of 2.3 m³/min at 10.0 to 7.9 MPa
HPCI: capacity of 18.9 m³/min

Safety system of BWR

- RHRS
- RCIC
- HPCI
- ADS
- LPCI
- HPCS
- LPCS
- IC
- GDCS