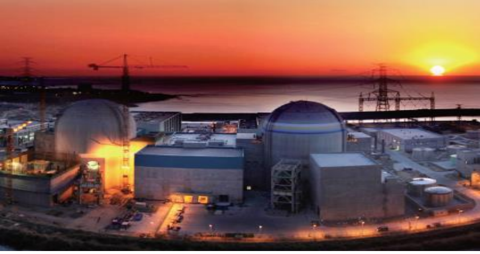
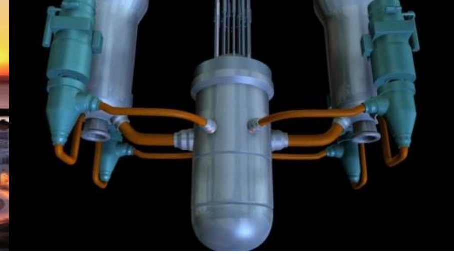
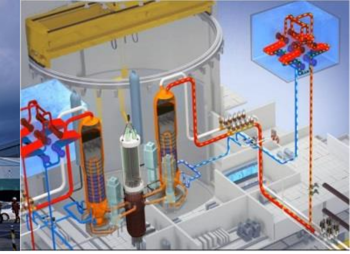





# NUCLEAR SYSTEMS ENGINEERING

***Cho, Hyoung Kyu***

***Department of Nuclear Engineering***

***Seoul National University***

NuTHEL
Nuclear Thermal Hydraulic Engineering Lab.

# Contents of Lecture

❖ Contents of lecture

- Chapter 1  Principal Characteristics of Power Reactors
  - Will be replaced by the lecture note
  - Introduction to Nuclear Systems
  - PWR (OPR1000 and APR1400)
  - CANDU
  - BWR and Fukushima accident

Nuclear system

- Chapter 4  Transport Equations for Single-Phase Flow (up to energy equation)
- Chapter 6  Thermodynamics of Nuclear Energy Conversion Systems: Nonflow and Steady Flow : First- and Second-Law Applications
- Chapter 7  Thermodynamics of Nuclear Energy Conversion Systems : Nonsteady Flow First Law Analysis

Thermodynamics

- Chapter 3  Reactor Energy Distribution
- Chapter 8  Thermal Analysis of Fuel Elements

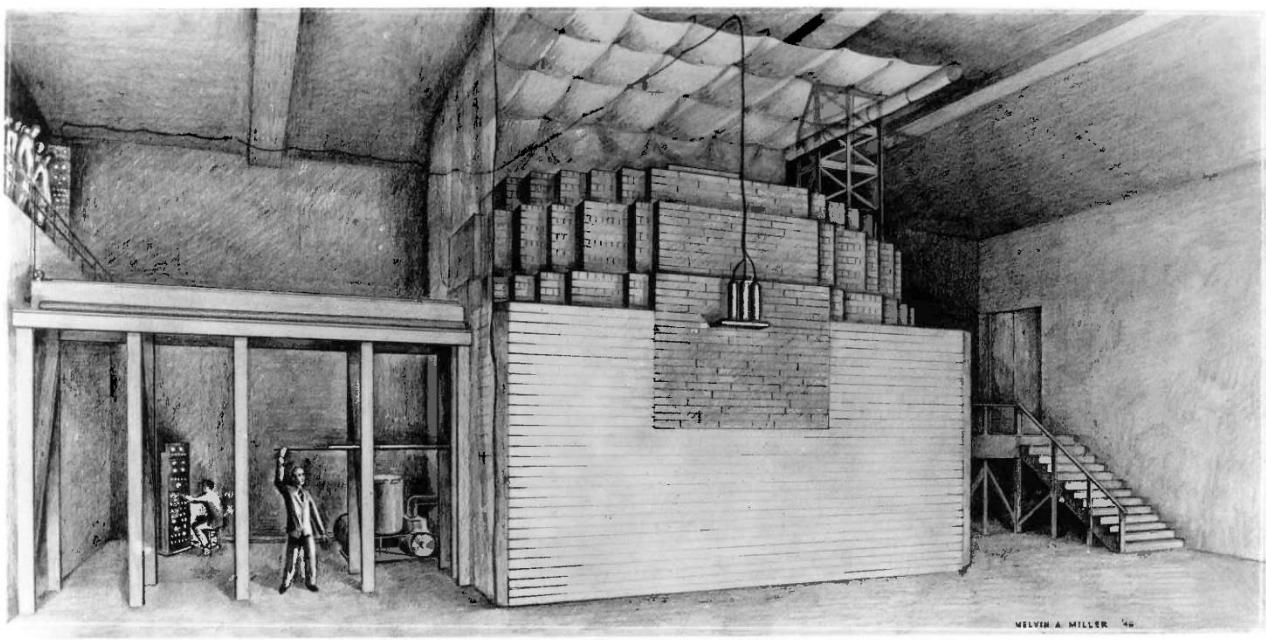
Heat transport
Conduction
heat transfer

# 3. PRESSURIZED WATER REACTOR

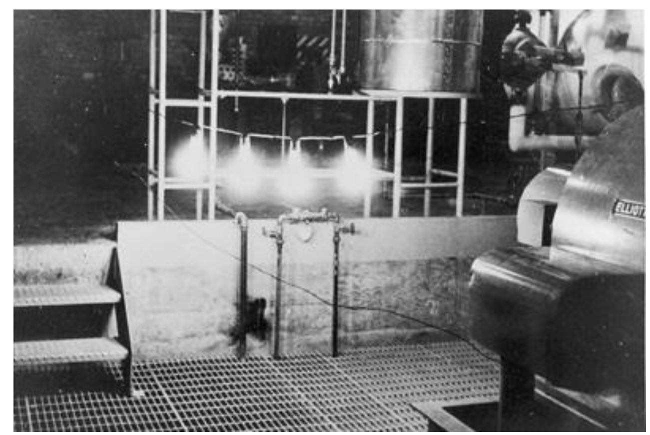
# Contents

# History of PWR

- 1939: Nuclear fission was discovered.
- 1942: The world's first chain reaction
  - Achieved by the Manhattan Project (1942.12.02)
- 1951: Electricity was first generated from nuclear power
  - EBR (Experimental Breeder Reactor-1), Idaho, USA
  - Power: 1.2 MWt, 200 kWe


Chicago Pile I (CP-I), World's First Reactor

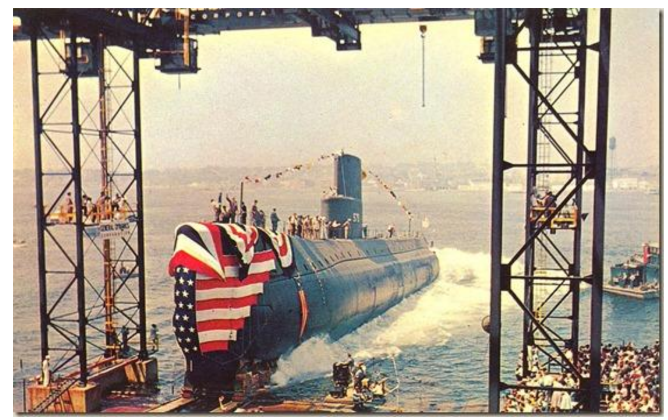


## ❖ Nuclear  Energy (sculpture)

- The location commemorates the exact location where the Manhattan Project team devised the first nuclear reactor to produce the first self-sustaining controlled nuclear reaction under the now demolished west stands of the old Stagg Field.

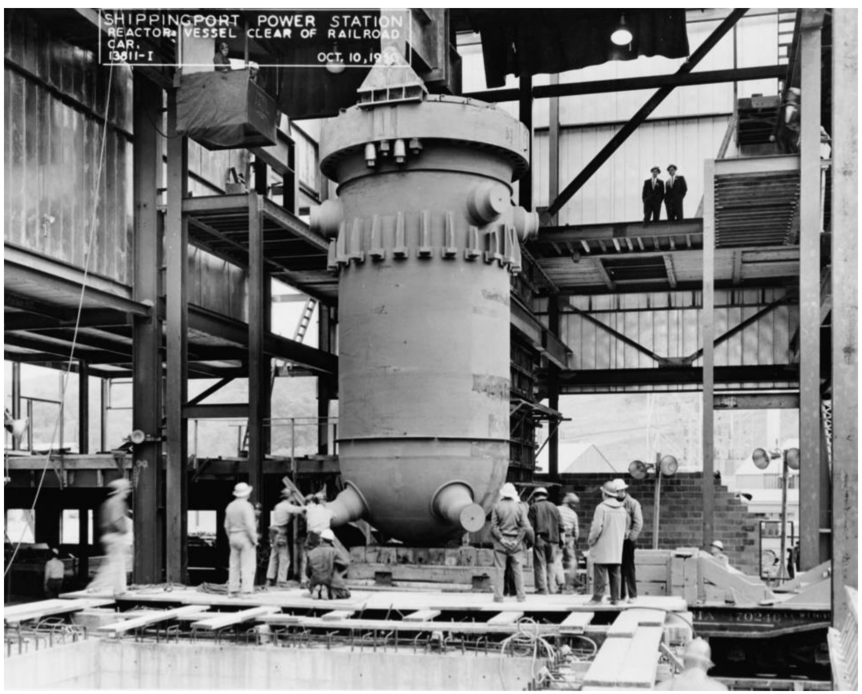

# History of PWR

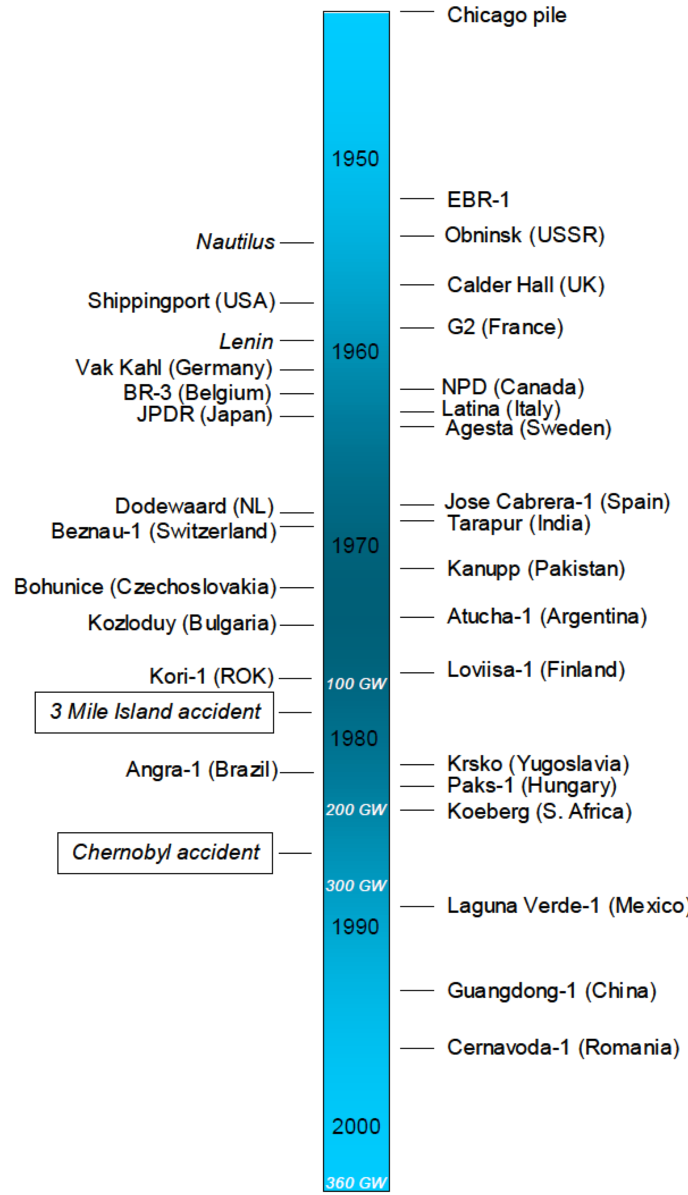
- 1950s: R&D
  - USA: light water reactor
    - PWR: Westinghouse
    - BWR: General Electric (GE)
  - USSR: graphite moderated light water reactor and WWER (similar to PWRs)
  - UK and France: natural uranium fueled, graphite moderated, gas cooled reactor
  - Canada: natural uranium fueled, heavy water reactor.
- 1954: initial success
  - USSR: 5 MWe graphite moderated, light water cooled reactor was connected to grid.
  - USA: the first nuclear submarine, the Nautilus (PWR)



# History of PWR

- 1956~1959
  - UK: Calder Hall-1, 50 MWe GCR (1956)
  - USA: Shippingport, 60 MWe PWR (1957)
  - France: G-2, 38 MWe GCR (1959)
  - USSR: the ice breaker Lenin (1959)
    - The world's first non-military nuclear powered ship

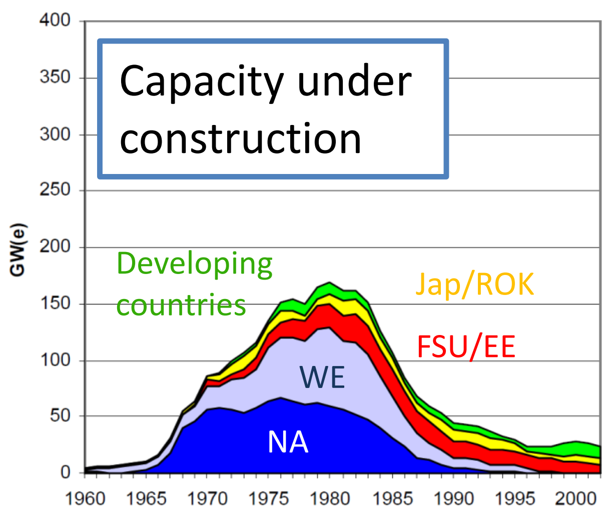


# History of PWR

❖ 1960s~1970s: golden age

- Westinghouse: 48 operational reactors, 9 shut down reactors
- B&W (Babcock & Wilcox)
  - 1961~: 7 operational reactors, 4 shut down reactors including TMI-2
- CE (Combustion Engineering)
  - 1972~:  14 operational reactors, 3 shut down reactors
- Framatome (France)
  - Technology from Westinghouse,  1978~

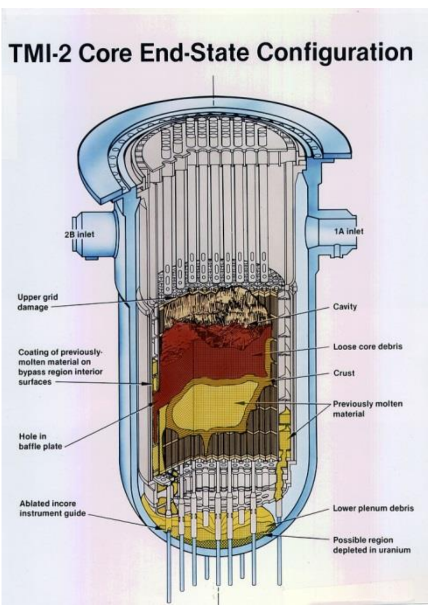



The US Atomic Energy Commission foresaw 1000 nuclear plants on line in the USA by the year 2000.

# History of PWR

- 1979~1990s
  - 1979: TMI-2 (B&W PWR)
  - 1986: Chernobyl (RBMK-1000)
  - Technology transfer
    - Framatome from Westinghouse (1981)
    - KEPCO from CE (1987)

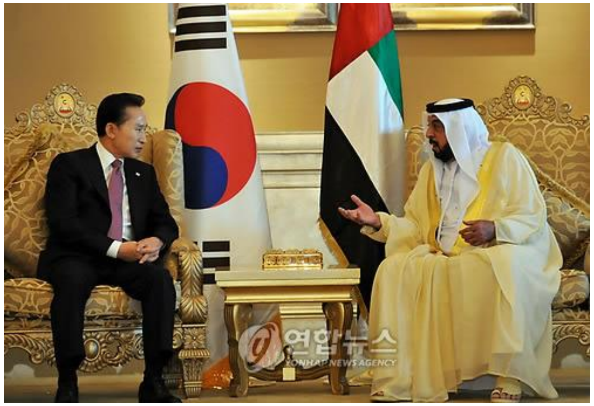





# History of PWR

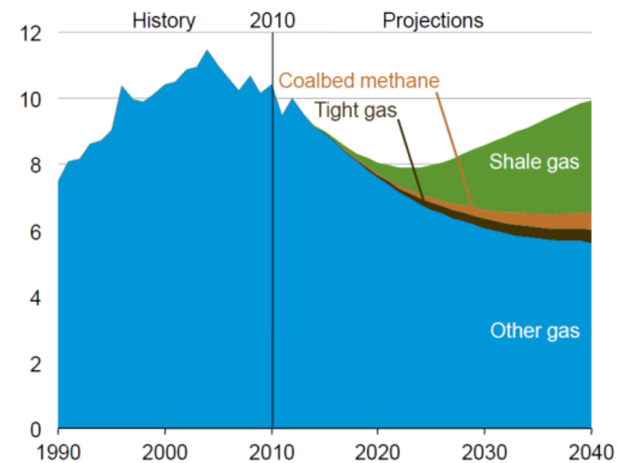
❖ 2000s~2011: Nuclear Renaissance

- Climate change, fossil fuel price
- US: No new reactor after TMI-2 accident, approval for new reactor construction
  - Northeast blackout in 2003
- Toshiba ⇐(2007) Westinghouse ⇐ (2000) CE
- AREVA: Framatome ⇐ SIEMENS (2001)
- Consortium: AREVA-MHI, WEC-TOSHIBA, GE-Hitachi (BWR)
- KEPCO consortium: won the UAE bid (2009)
  - KHNP, KEPCO E&C (KOPEC), KEPCO NF (KNF), KEPCO KPS (KPS) etc.



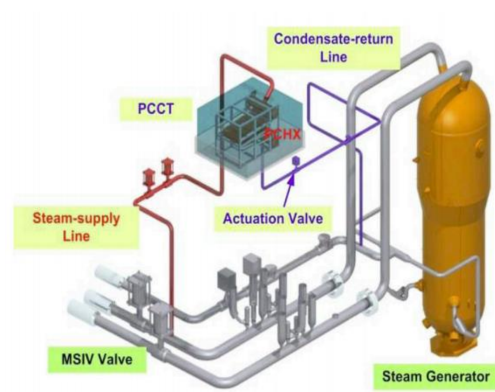
# History of PWR

- 2011.3~
  - Fukushima Daiichi accident
  - Domestic issues
    - Coverup of the serious incident: Station blackout for 12 minutes during regular inspections
    - License renewal: Wolsong Unit 1 (approved), Kori Unit 1 (2018)
    - Documentation scandal, corruption scandal, nuclear mafia
    - Lawsuit regarding thyroid cancer
  - Opportunities
    - Finland, Saudi Arabia (SMART), Vietnam etc.
    - APR+, IPOWER , SMR etc.

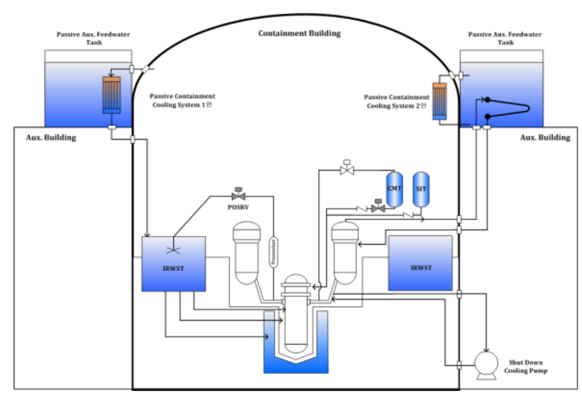




Passive Auxiliary Feedwater System




Passive Containment Cooling System



# History of PWR

❖ 2017~


연합뉴스, 2017.04.25

법원, "월성원전 1호기 수명연장 처분 취소하라"

조선일보, 2017.02.07

| 전국 | 4,582,979 (100%) |
|---|---|


판도라, 2016

뉴스 ˅ 原電, 동해안에 18기 밀집... 1基만 사고 나도 연쇄참사 우려


조선비즈, 2016.09.14

한전의 영국 원전수출 반대 목소리 정치권에서 나와

탈핵에너지전환 국회의원모임 원전사업 반대...대선후보 탈원전 공약 부담

비즈니스포스트, 2017.04.11

영국 무어사이드 원전 조감도. Moorside nuclear plant in Cumbria source theguardian

- 2017~



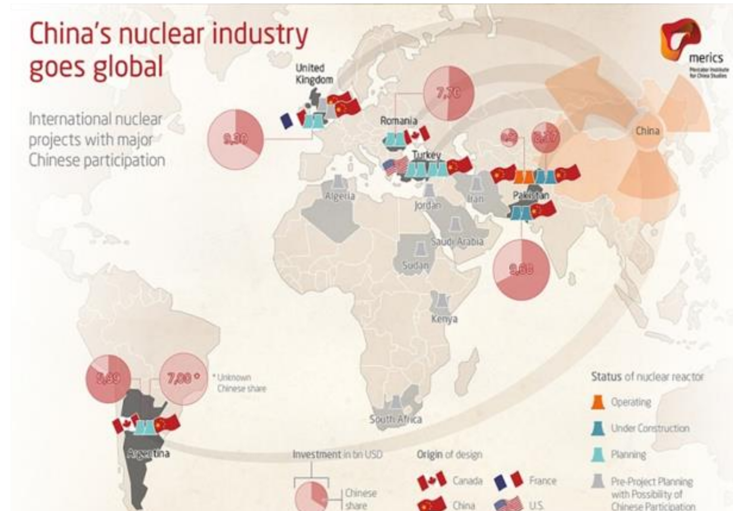

"우리 원전 기술의 우수성과 대한민국의 역량을 직접 눈으로 보니 자랑스럽다."

# History of PWR

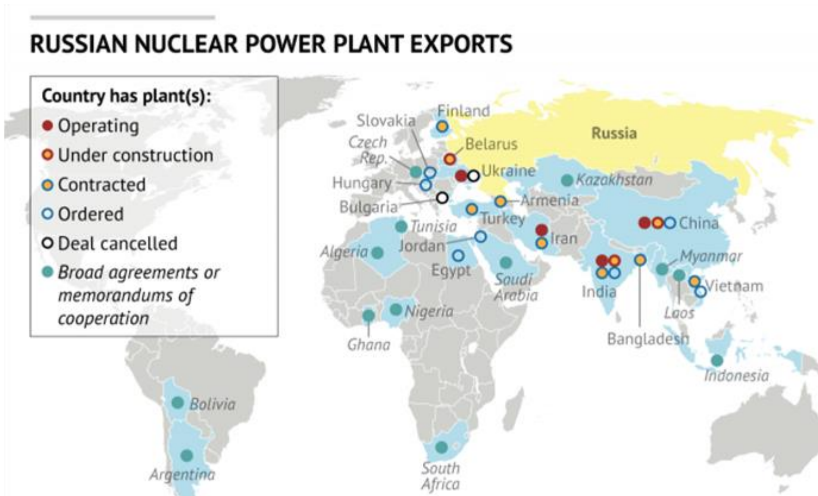
❖ 2017~

◆ Cliché fast follower – first mover – innovator

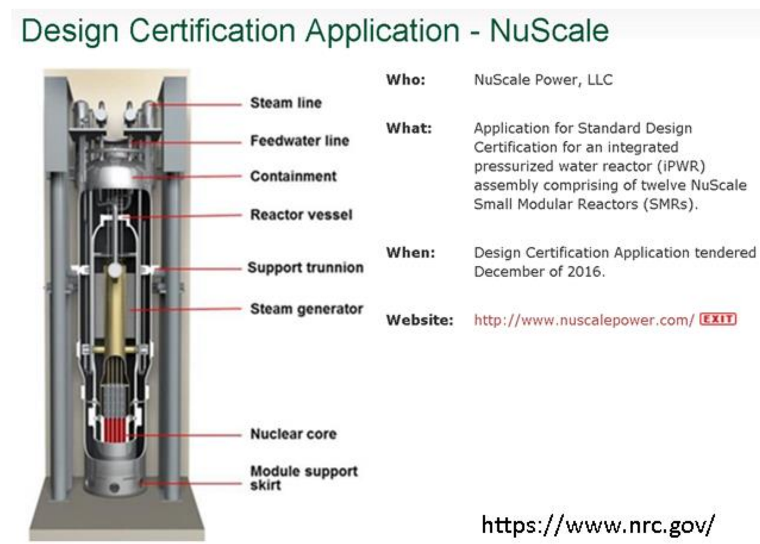

New York Times, 2017.03.29




http://www.merics.org




https://www.stratfor.com




https://www.nrc.gov/

# PWRs in Korea

Nuclear Power Plants in South Korea


*Source: World Nuclear Association*

Operating reactors in South Korea

| Reactor | Type | Net capacity (MWe) | Commercial operation | Planned close |
|---|---|---|---|---|
| Kori 2 | PWR – Westinghouse | 640 | 7/83 | 2023 |
| Kori 3 | PWR – Westinghouse | 1011 | 9/85 | 2024 |
| Kori 4 | PWR – Westinghouse | 1012 | 4/86 | 2025 |
| Hanbit 1, Yonggwang | PWR – Westinghouse | 996 | 8/86 | 2026 |
| Hanbit 2, Yonggwang | PWR – Westinghouse | 988 | 6/87 | |
| Hanul 1, Ulchin | PWR – Framatome | 968 | 9/88 | |
| Hanul 2, Ulchin | PWR – Framatome | 969 | 9/89 | |
| Hanbit 3, Yonggwang | PWR (System 80) | 994 | 12/95 | |
| Hanbit 4, Yonggwang | PWR (System 80) | 970 | 3/96 | |
| Wolsong 2 | PHWR – Candu | 647 | 7/97 | 2026 |
| Wolsong 3 | PHWR – Candu | 651 | 7/98 | |
| Wolsong 4 | PHWR – Candu | 653 | 10/99 | |
| Hanul 3, Ulchin | OPR-1000 | 997 | 8/98 | |
| Hanul 4, Ulchin | OPR-1000 | 999 | 12/99 | |
| Hanbit 5, Yonggwang | OPR-1000 | 998 | 5/02 | |
| Hanbit 6, Yonggwang | OPR-1000 | 993 | 12/02 | |
| Hanul 5, Ulchin | OPR-1000 | 998 | 7/04 | |
| Hanul 6, Ulchin | OPR-1000 | 997 | 4/05 | |
| Shin Kori 1 | OPR-1000 | 997 | 2/11 | |
| Shin Kori 2 | OPR-1000 | 997 | 7/12 | |
| Shin Wolsong 1 | OPR-1000 | 997 | 7/12 | |
| Shin Wolsong 2 | OPR-1000 | 993 | 7/15 | |
| Shin Kori 3 | APR1400 | 1383 | 12/16 | |
| Shin Kori 4 | APR1400 | 1383 | 09/19 | |
| Total: 24 | | **23,231 MWe** | | |

https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx

주요 원전 설계수명 현황

| 원전 | 설계수명 종료 | 수명 |
|---|---|---|
| 고리1 | [illegible] | 30+10 [illegible] |
| 월성1 | [illegible] | 30+10 연장 [illegible] |
| 고리2 | 2023 | 40 |
| 고리3 | 2024 | 39 |
| 고리4 | 2025 | 40 |
| 영광1 | 2026 | 40 |
| 영광2 | 2026 | 40 |
| 월성2 | 2027 | 30 |
| 월성3 | 2028 | 30 |
| 울진1 | 2028 | 40 |

# PWRs in Korea

Reactors under construction, planned, and proposed

| Reactor | Type | Gross capacity | Start construction | Commercial operation |
|---|---|---|---|---|
| Shin Hanul 1, Ulchin | APR1400 | 1400 MWe | **July 2012** | Mid-2020 |
| Shin Hanul 2, Ulchin | APR1400 | 1400 MWe | **June 2013** | Mid-2021 |
| Shin Kori 5 | APR1400 | 1400 MWe | **April 2017** | March 2023 |
| Shin Kori 6 | APR1400 | 1400 MWe | **September 2018** | June 2024 |
| Total under const: 4 | | **5600 MWe**<br>(5360 MWe net, 1340 each) | | |
| | | | | |
| Shin Hanul 3, Ulchin | APR1400 | 1400 MWe | (on hold) | |
| Shin Hanul 4, Ulchin | APR1400 | 1400 MWe | (on hold) | |
| Total proposed: 2 | | **2800 MWe** | | |
| Cheonji 1 | APR+ | 1500 MWe | 2022 (cancelled) | |
| Cheonji 2 | APR+ | 1500 MWe | 2023 (cancelled) | |
| Cheonji 3 or Daejin 1 | APR+ | 1500 MWe | 2025 (cancelled) | |
| Cheonji 4 or Daejin 2 | APR+ | 1500 MWe | 2026 (cancelled) | |

https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx

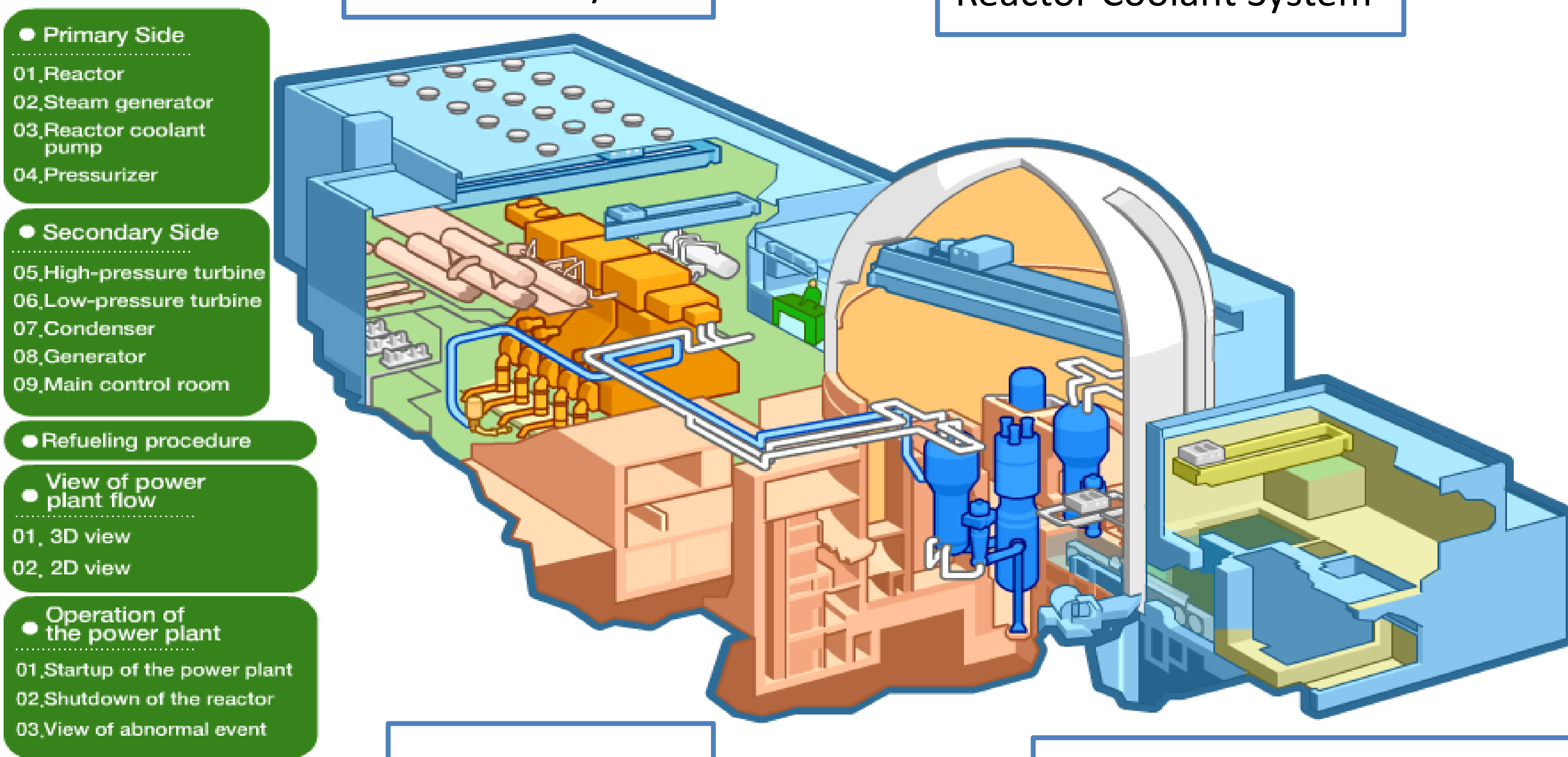
- Operating principles, construction, installation

# Plant Overall

❖ Operating principles, construction, installation

Steam and Power Conversion System

Reactor Coolant System




Auxiliary System

Radioactive Waste Management

Control and Protection System

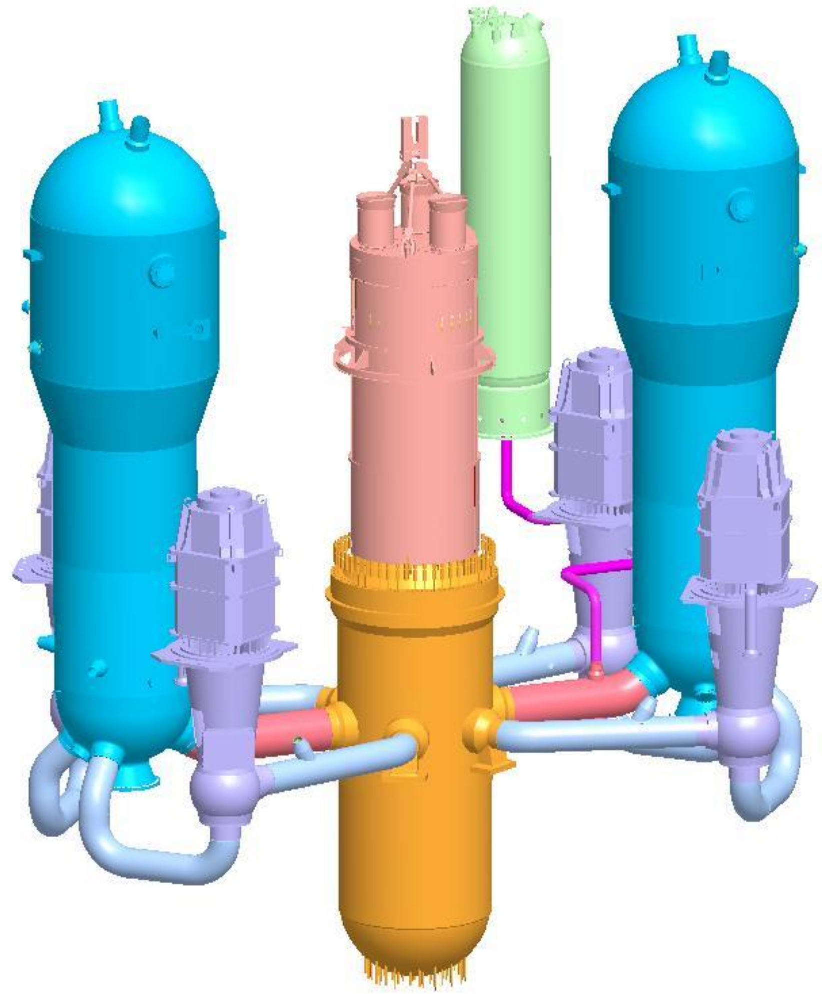
# Contents

- History of PWR
- Plant Overall
- Reactor Coolant System
- Steam and Power Conversion System
- Auxiliary System
- Plant Protection System
- Other systems

Reactor Vessel
Pressurizer
Reactor Coolant Pump
Steam Generator

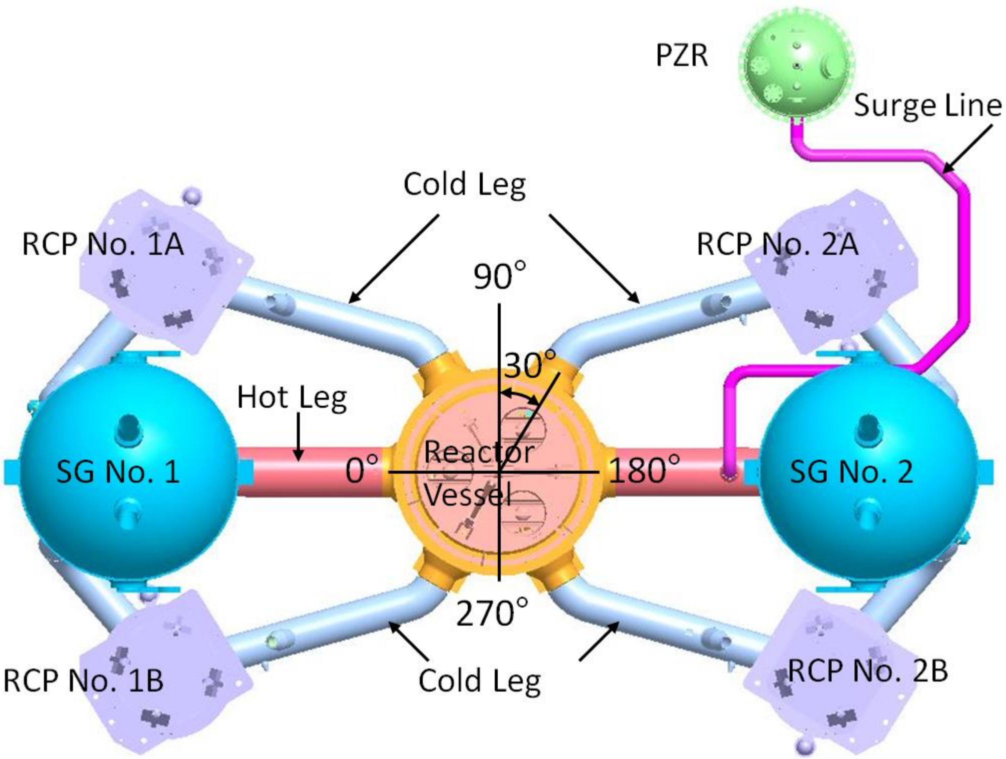
# Reactor Coolant System

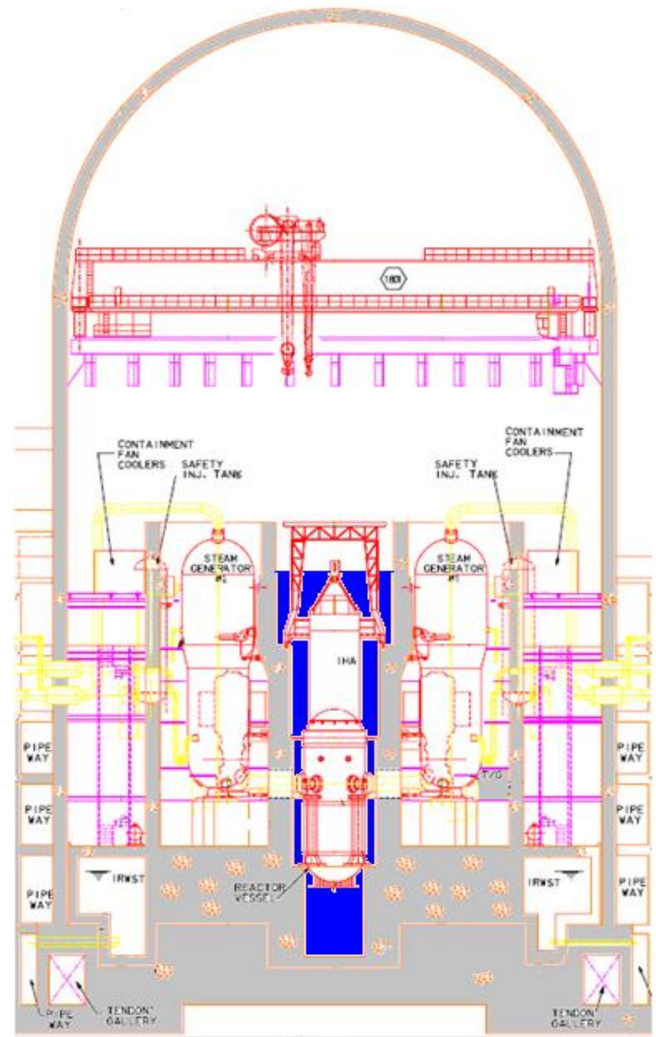
- RCS (Reactor Coolant System)
  - Primary system
  - Reactor pressure vessel (RPV)
  - Steam generator (SG)
  - Reactor coolant pump (RCP)
  - Pressurizer (PRZ)
  - Piping
    - Hot legs, cold legs, intermediate legs, surge line
  - Functions
    - Transfer the heat from the fuel to SG
    - Contain any fission products that escape the fuel



# Reactor Coolant System

❖ RCS (Reactor Coolant System)



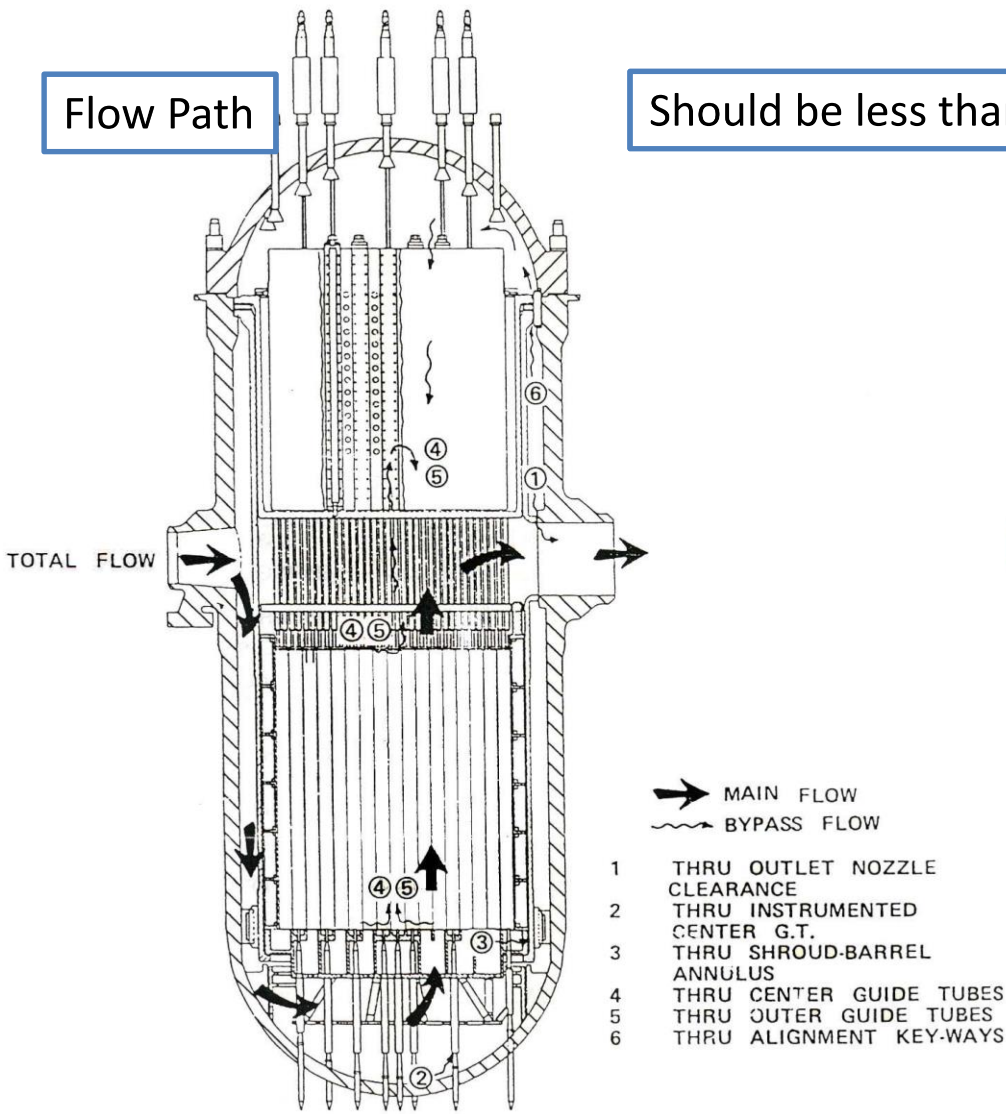



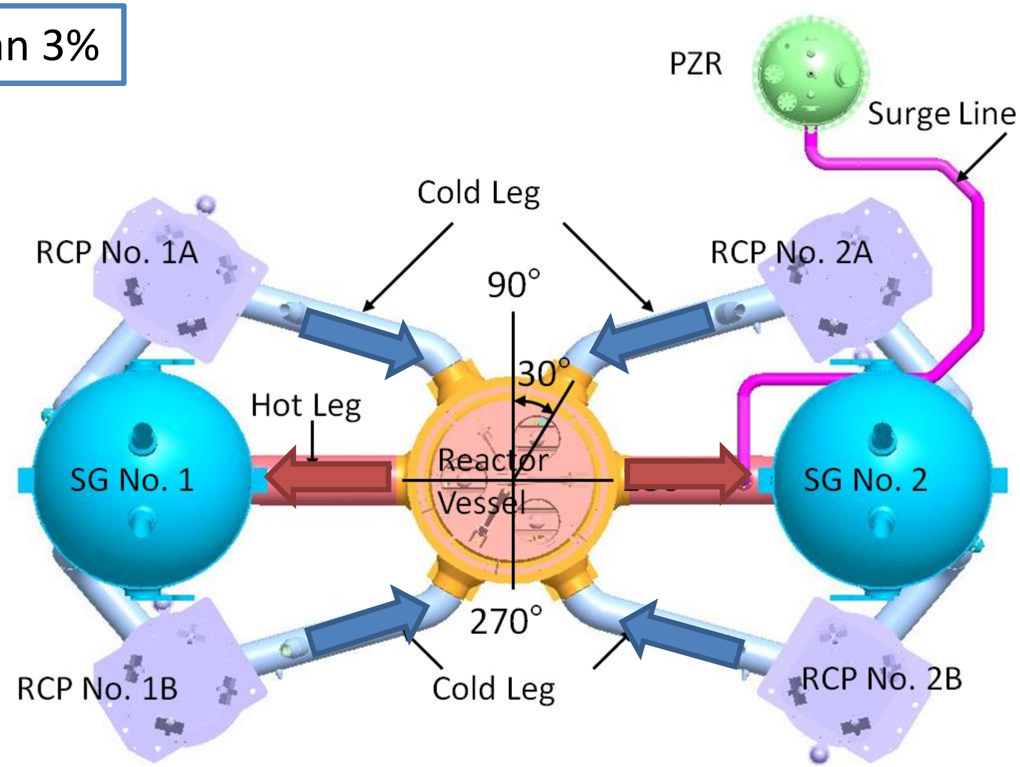
# Reactor Coolant System

❖ Reactor Vessel

Flow Path

Should be less than 3%

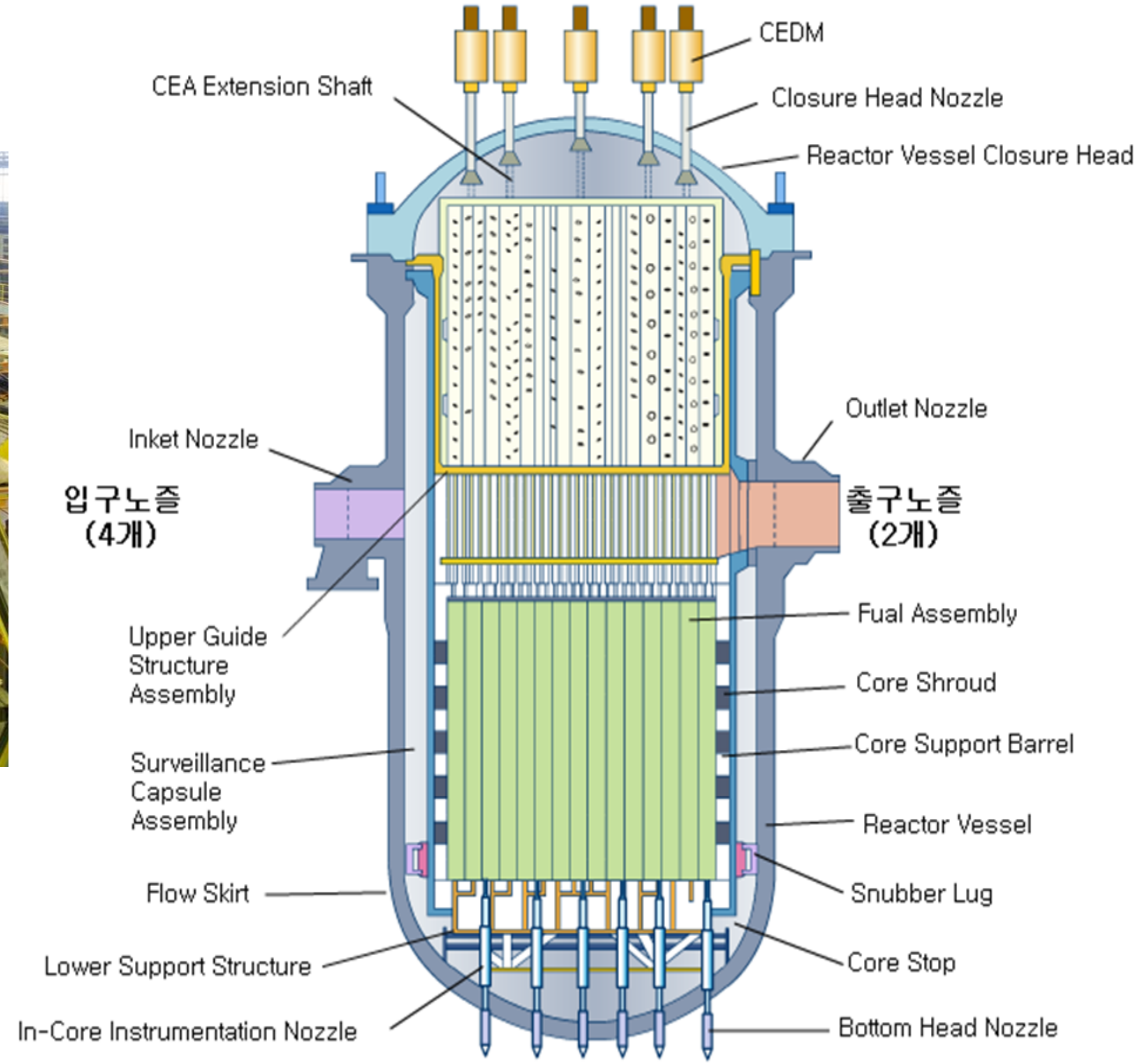


# Reactor Coolant System

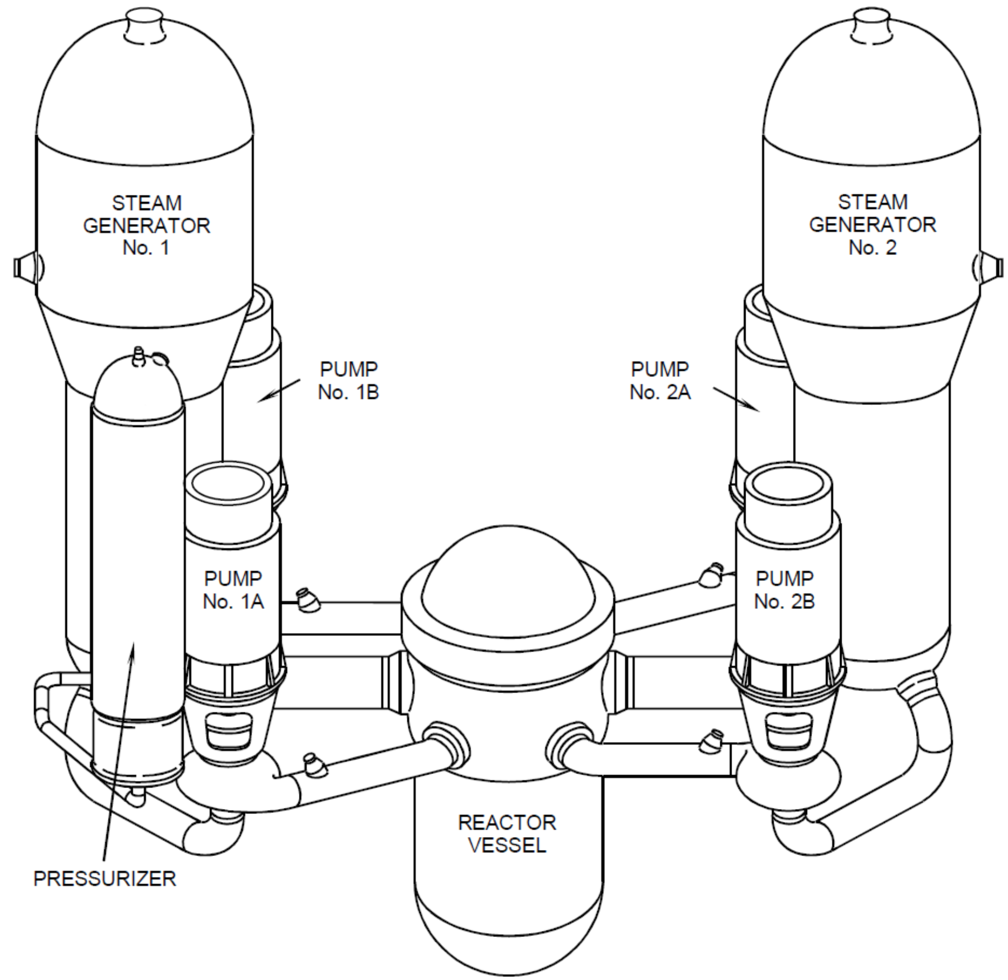
## ❖ Reactor Vessel





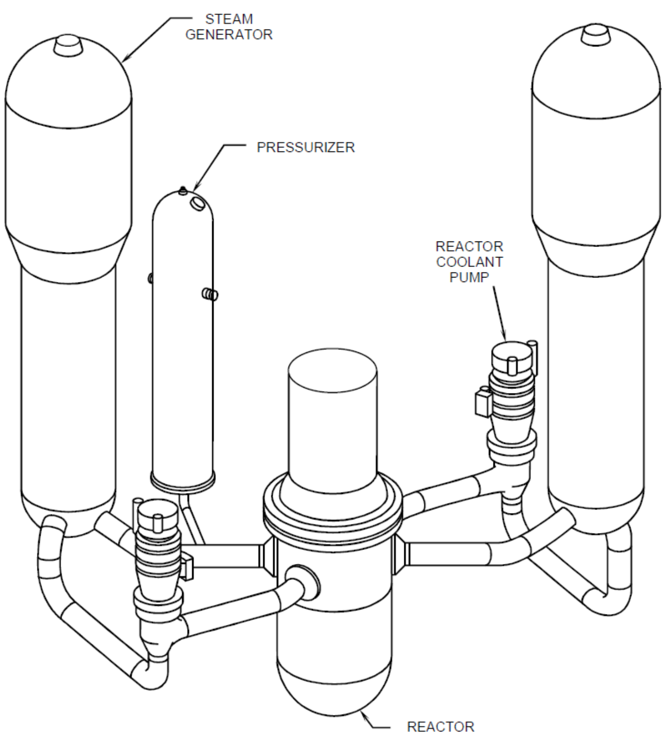
## Layout

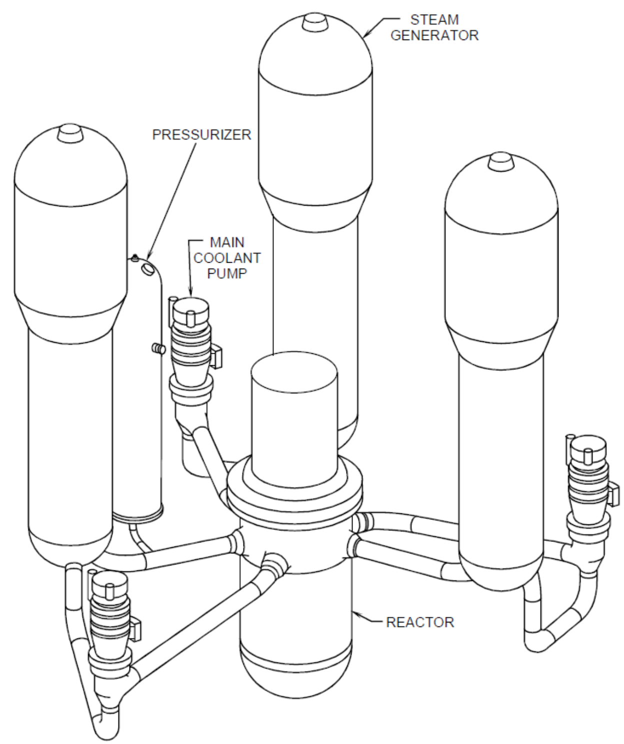
- System80, OPR1000, APR1400: 2 loop PWR
  - System80: Hanbit (YGN) Unit 3,4
  - OPR1000: Hanbit (YGN) Unit 5,6
    Hanul (Ulchin) Unit 3-6
    Shin Kori Unit 1,2
    Shin Wolsong Unit 1,2
  - APR1400: Shin Kori Unit 3-7
    Shin Hanul Unit 1-4
  - 2 SG, 2 hot legs
  - 4 RCP, 4 cold legs



# Reactor Coolant System

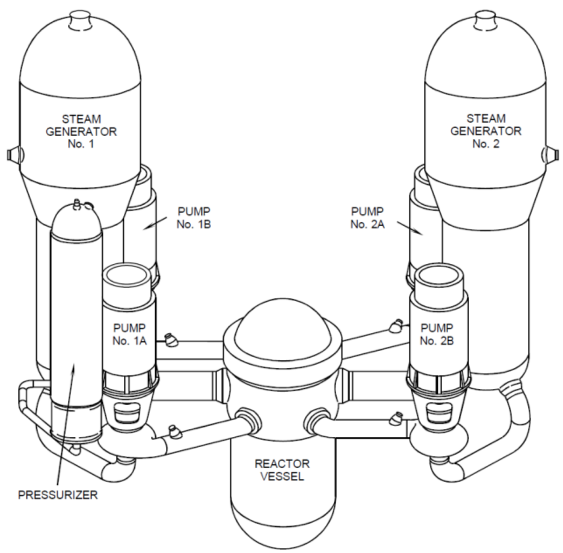
- Layout
  - WH-2 and WH-3
    - 2 loop:Kori Unit 1,2
    - 3 loop: Kori Unit 3,4, Hanbit (YGN) Unit 1,2
  - Framatome
    - 3 loop: Hanul (Ulchin) Unit 1,2

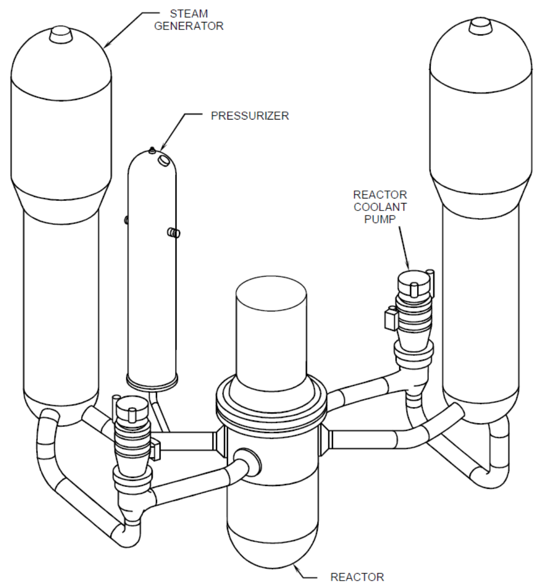


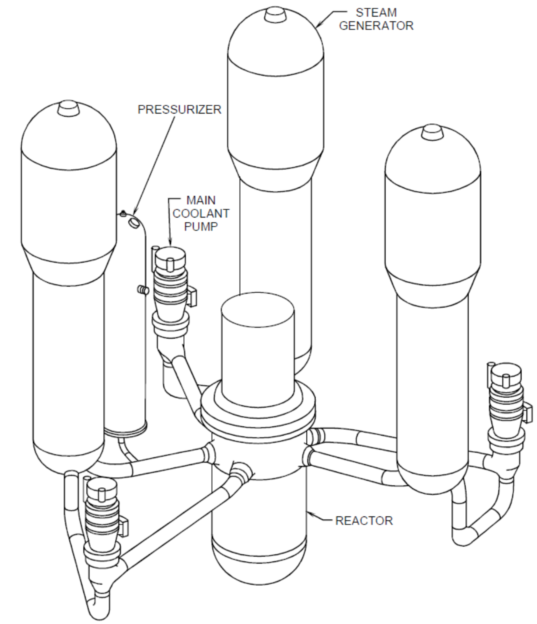



# Reactor Coolant System

❖ Loop configuration




Systme80: Hanbit (3,4)
OPR1000 & APR1400: Hanbit (5,6) Hanul (3-6)
Shin Kori (1,2,3) Shin Wolsong (1,2)

Kori Unit 1,2

Hanul (1,2), Kori (3,4), Hanbit (1,2)

In general, Westinghouse plants have either two, three or four steam generators depending on how powerful the plant is. Each steam generator has its own specific hot leg, cold leg and reactor coolant pump.

CE plants always have two steam generators, no matter how powerful the plant is.

- Discussion topic
  - 2x4 loop vs. 4x4 loop
    - Reactor vessel
      - –
      - –
    - Steam generator
      - Westinghouse: 250~350 Mwe
      - CE/OPR1000/APR1400: 500~700 MWe
      - –
      - Response under accident conditions ?

## ❖ Discussion topic

- 2x4 loop vs. 4x4 loop

I.C. Chu, KAERI/AR-663/2003
“Early fretting wear of U-tubes has been observed in the U-bend region above the central cavity in KSNP steam generator, and the main cause of the wear is expected to be FIV(Flow Induced Vibration). More specifically, Fluid Elastic Instability is the most probable mechanism considering that the progress of the wear is very rapid.”

(1) 기술적 측면

원자력 발전소 증기발생기 전열관의 마모현상은 크게 프레팅에 의한 마모, 이물질에 의한 마모, 슬라이딩에 의한 마모 등으로 나눌 수가 있다. 고리 2, 3, 4호기와 영광 1, 2호기와 같이 Westinghouse(WH)형 모델 F를 적용한 경우, 10년 이상의 가동기간에도 불구하고 프레팅 마모에 의한 관막음 전열관의 비율이 3% 이내에 머물고 있으나 Combustion Engineering(CE) 모델을 적용한 한국표준형 원전인 영광 3, 4호기와 울진 3, 4호기의 경우 가동연수가 짧음에도 불구하고 마모에 의해 관막음된 전열관 수가 수십 개에 이르고 있으며 특히 울진 3, 4호기의 경우 1주기 가동후 전열관이 관막음될 정도로 빠른 속도의 마모손상을 보이고 있다.

# Reactor Pressure Vessel

❖ Reactor Vessel

- Inner diameter: ~4.6 m, thickness: ~ 25 cm
- Height: ~14.8 m
- Material: manganese molybdenum steel
  - Surfaces that come into contact with reactor coolant are clad with stainless steel to increase corrosion resistance.

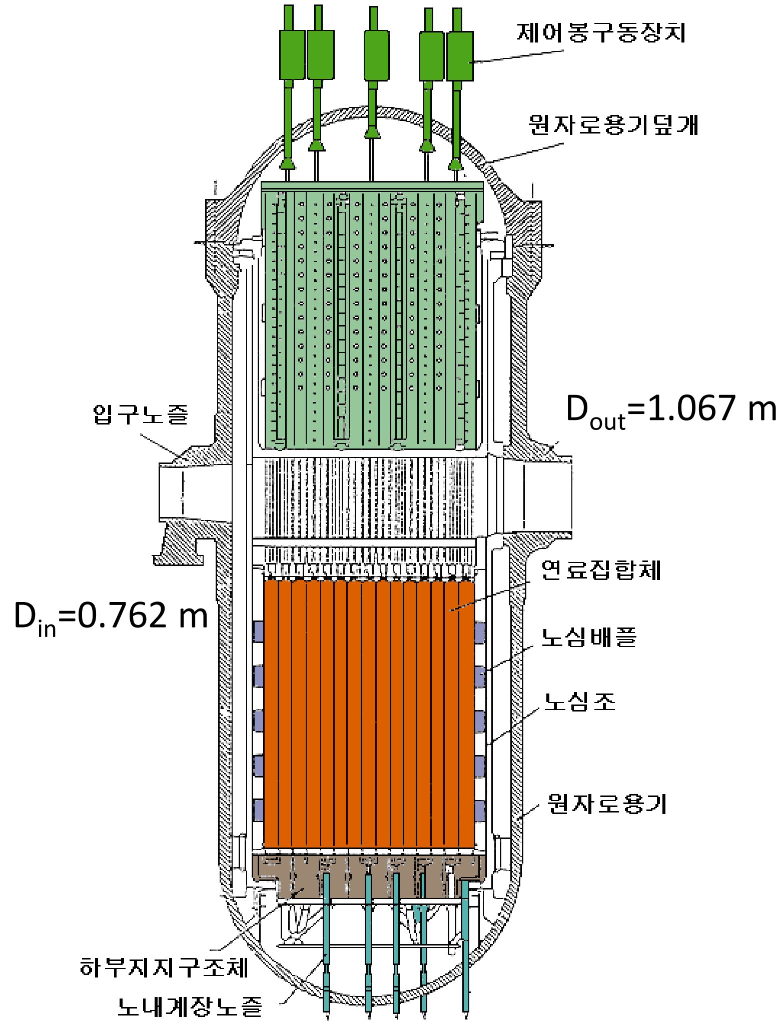
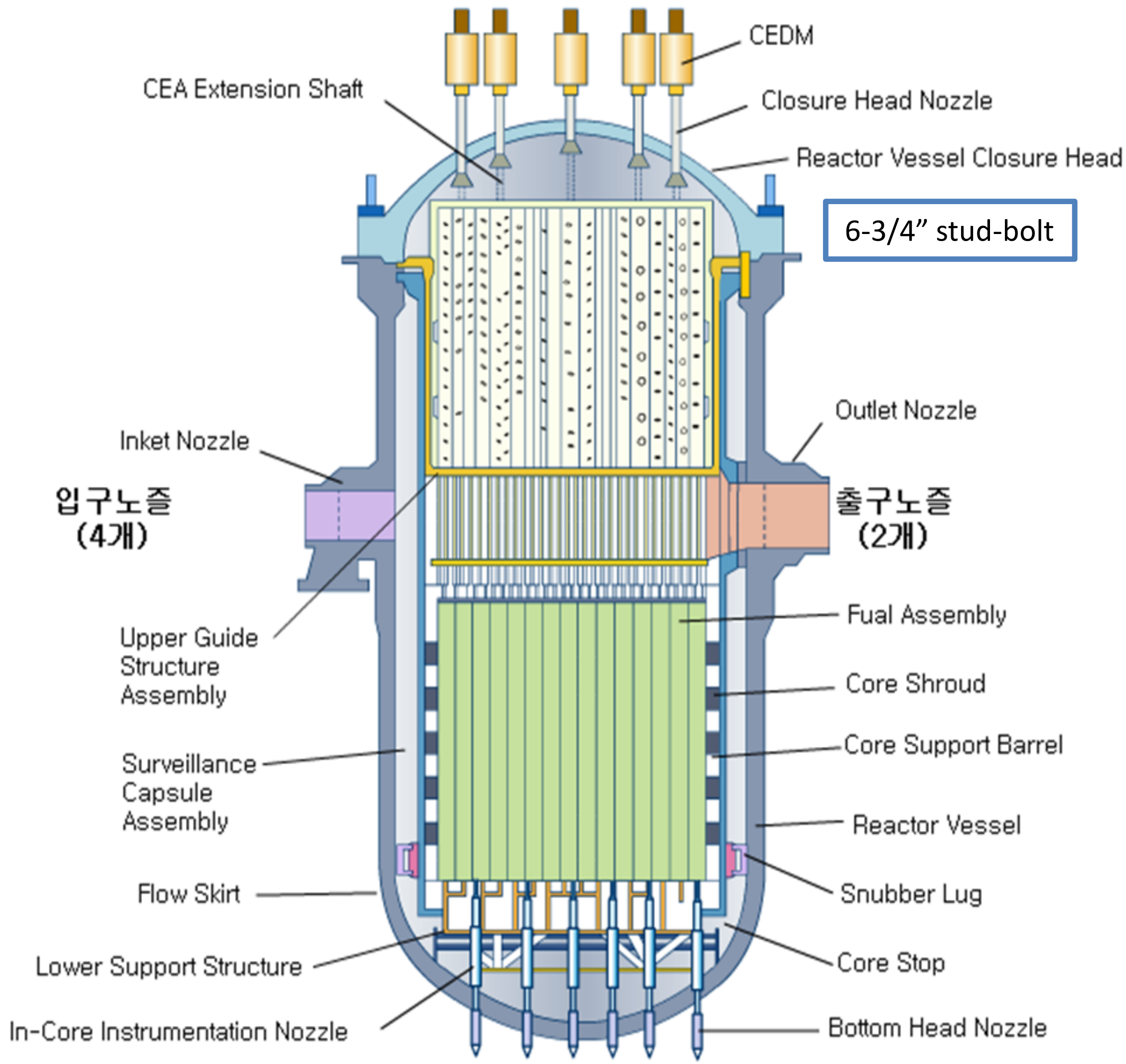




그림-3 한국표준형경수로의 원자로

[자료] Korea Electric Power Corporation : KOREAN STANDARD NUCLEAR POWER PLANT(KSNP), p.41

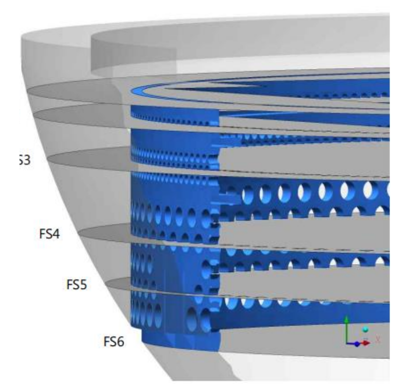
## Reactor Vessel




Closure head assembly

- 108 nozzles for CEDMs
- 54 studs and 2 O-rings

Flow skirt: 유량분배환, 유량 분배 균일화



# Reactor Pressure Vessel

❖ Reactor Vessel

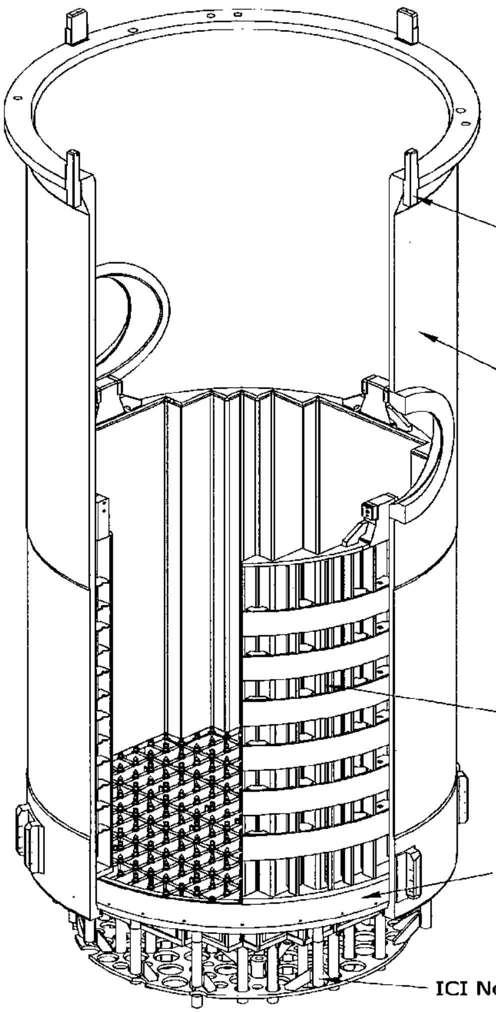
Doosan heavy industry

Ring Forging

Cladding

# Reactor Pressure Vessel

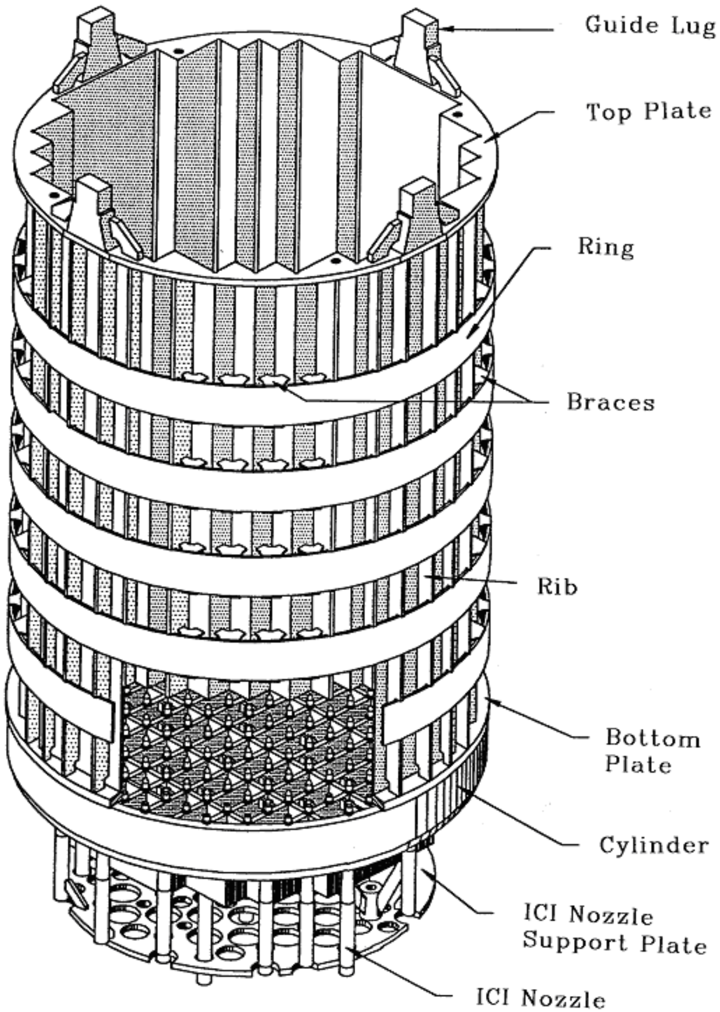
Core Support Barrel contains and supports the fuel assembly, core shroud and lower support structure, and shields from radioactivity along with coolant. Linked with reactor vessel's exit nozzle, the nozzle attached to the cylinder minimizes the coolant leakage.





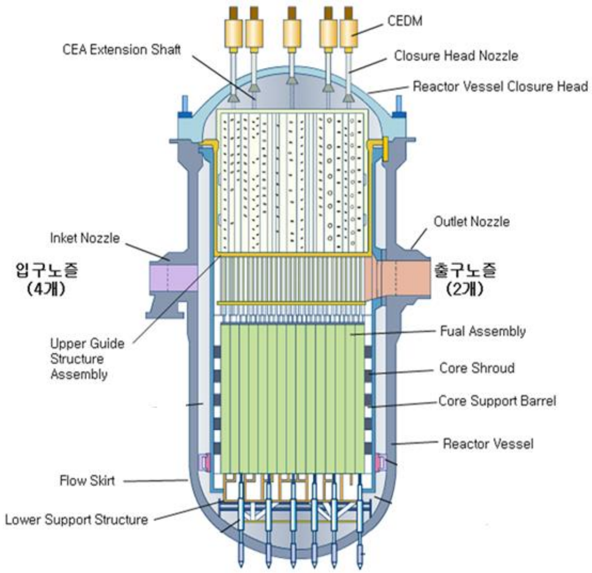

# Reactor Pressure Vessel

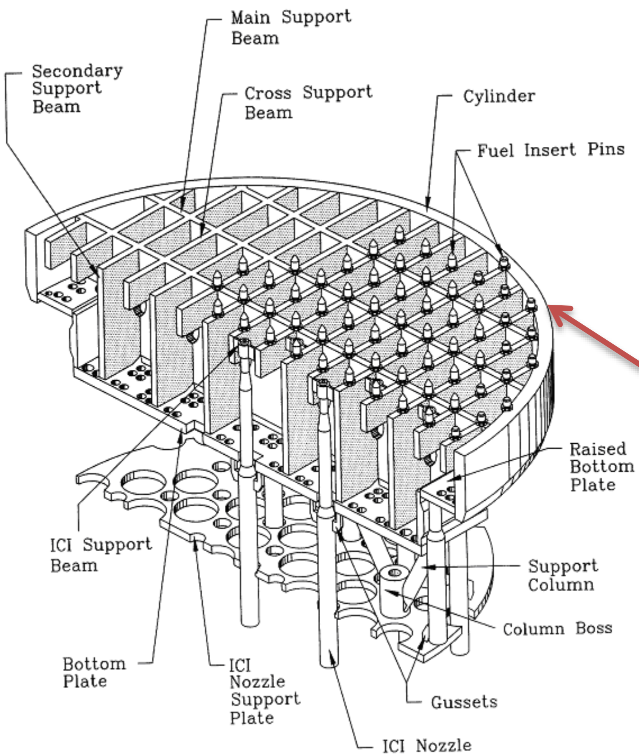
Core Shroud shelters the reactor fuel
and stabilizes the flow of coolant.



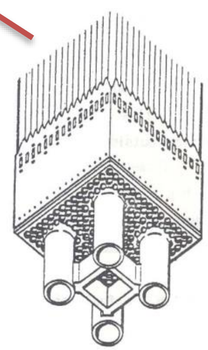


# Reactor Pressure Vessel



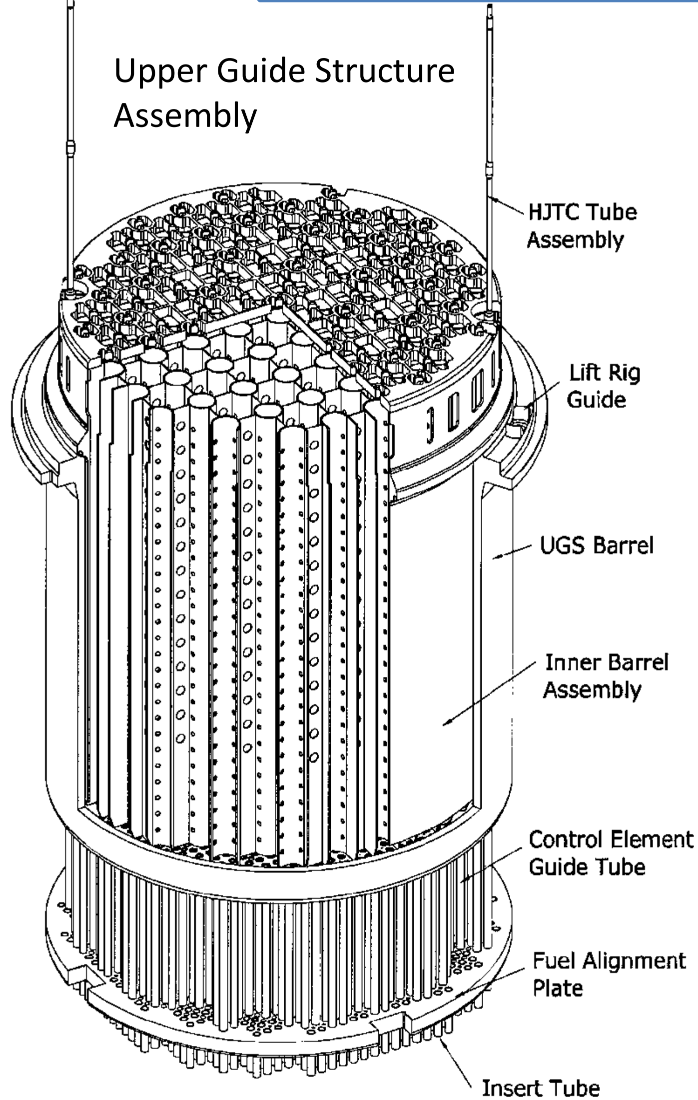




Lower support
Structure

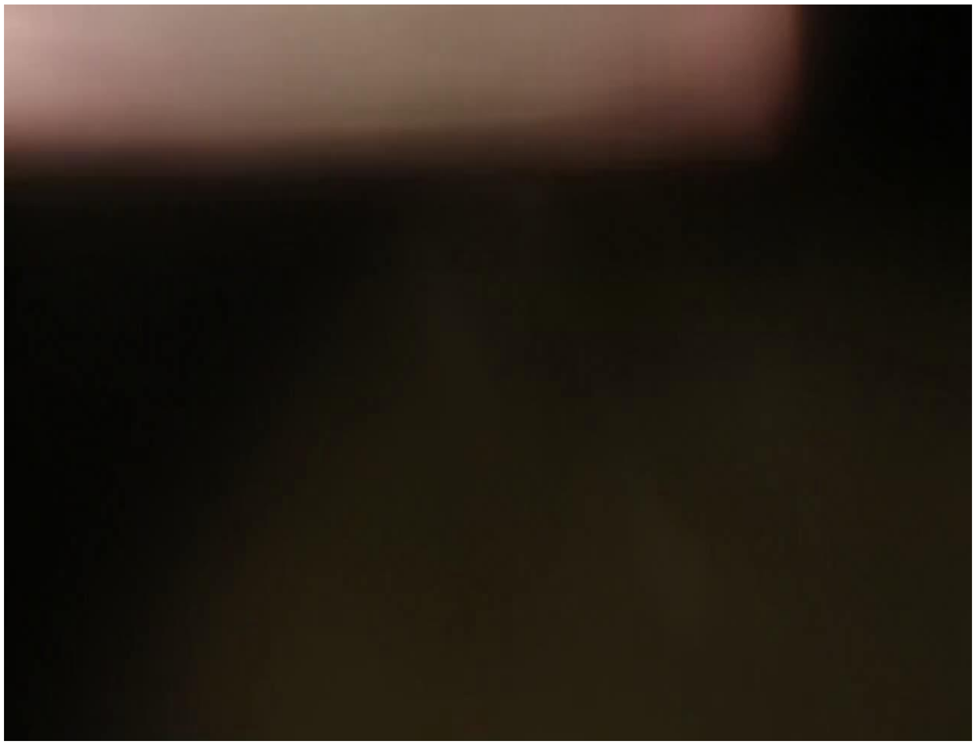


가열접점 열전대
(Heated Junction Thermocouple System)

Upper Guide Structure
Assembly



# Reactor Pressure Vessel

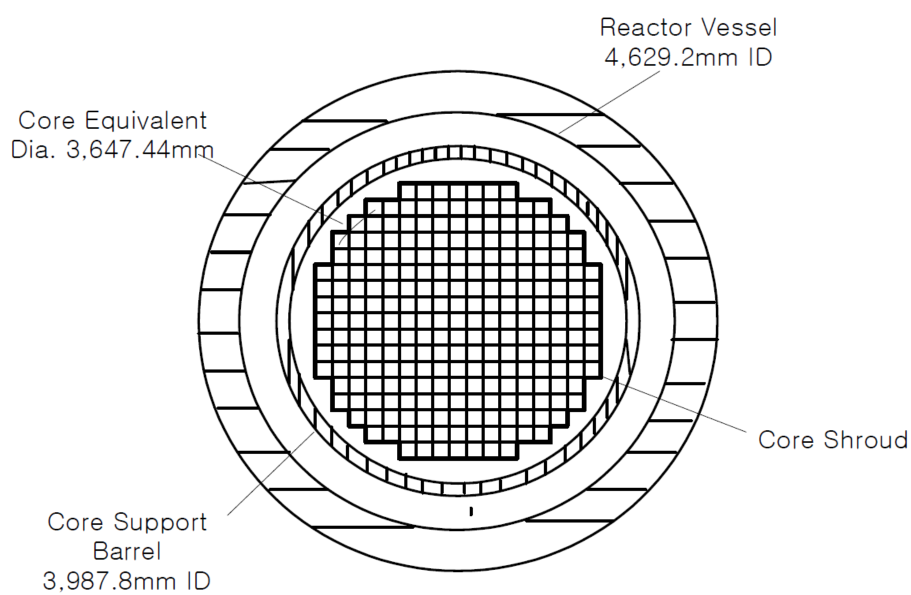


# Reactor Pressure Vessel

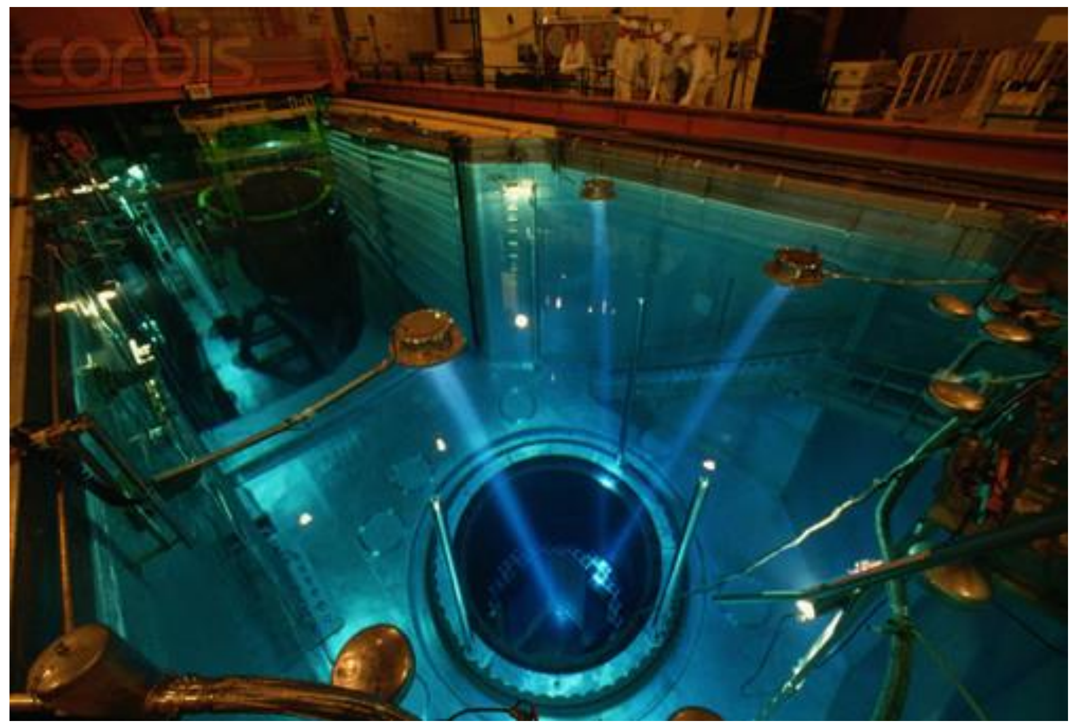
## Reactor core

*) 원자로 노심

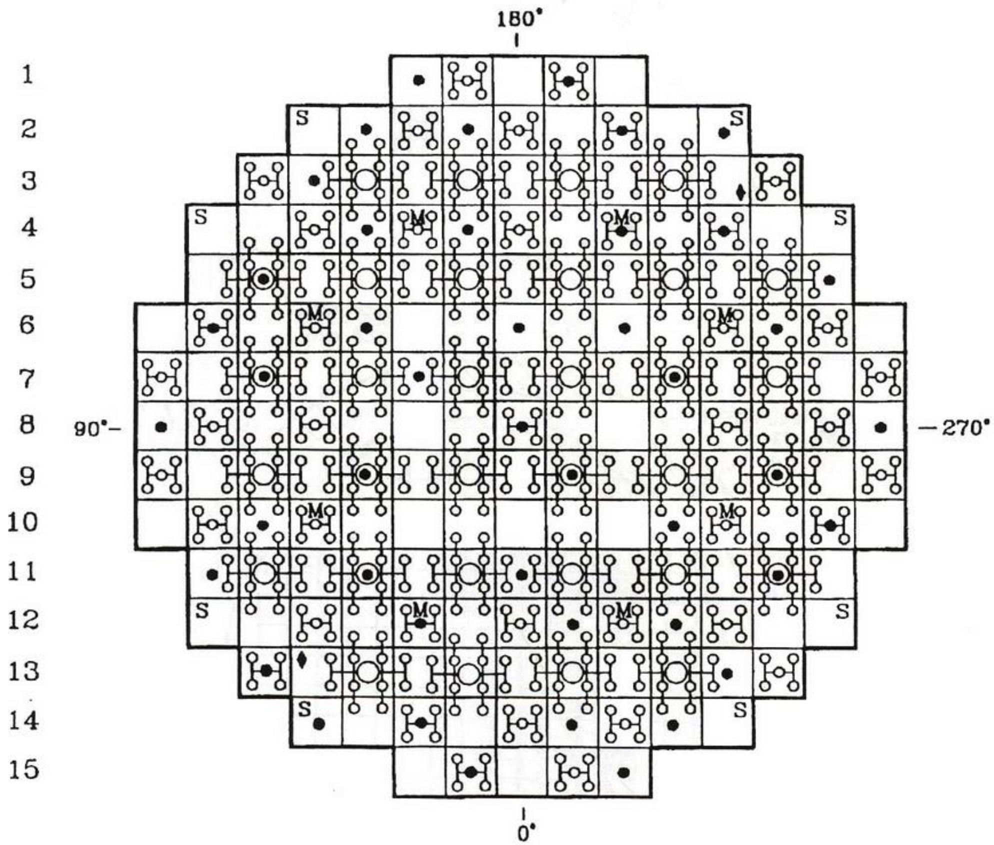
- At the nuclear power plant, the fuel assemblies are inserted vertically into the reactor vessel (a large steel tank filled with water with a removable top).
- The fuel is placed in a precise grid pattern known as the “reactor core.”
- 241 assemblies in APR1400 (3983 MWt), 177 in OPR1000 (2815 MWt)
  - 15.9~16.5 MWt/assembly



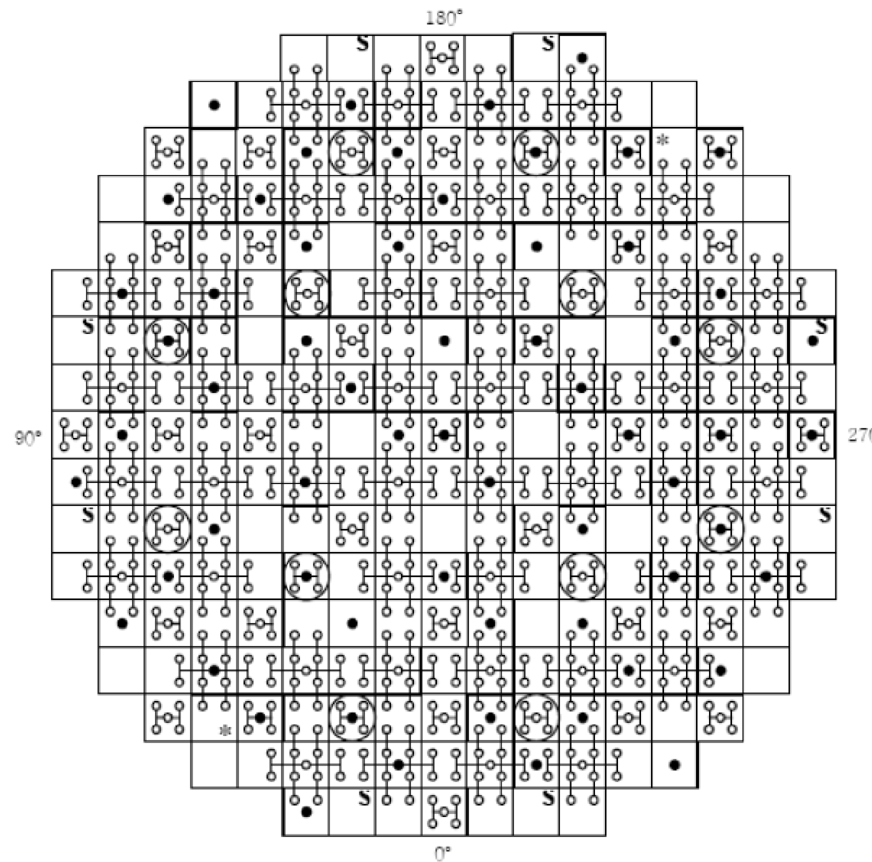

APR1400 Reactor Core



# Reactor Pressure Vessel




177 FUEL ASSEMBLIES
73 CEA's AND CEDM's
8 MANEUVERING CEA's (M)
8 ADDITIONAL LOCATIONS FOR SHUTDOWN CEA's (S)
45 FIXED IN-CORE DETECTOR ASSEMBLIES (●)
2 NEUTRON SOURCE ASSEMBLIES (M–3 AND D–13) (♦)



# Reactor Pressure Vessel

❖ Reactor Core: Thermal and Hydraulic Parameters

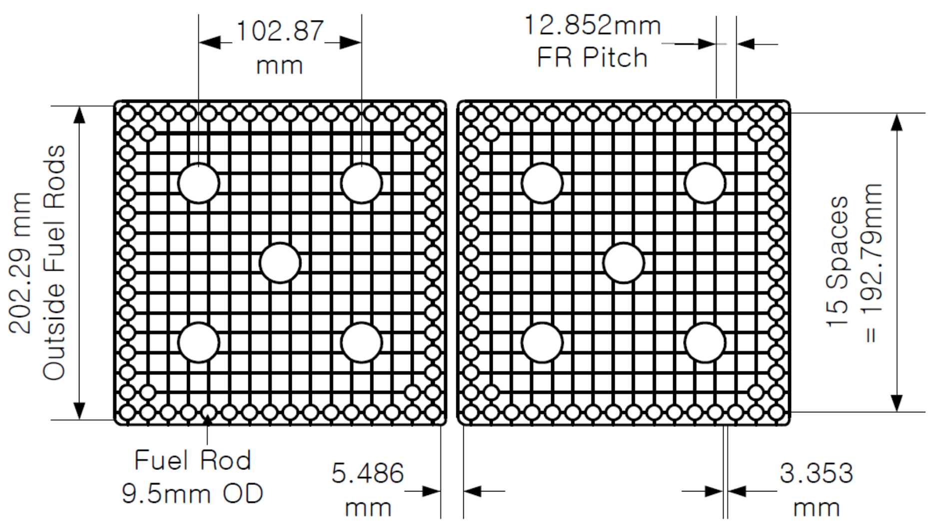
| Reactor Parameters | Ulchin 3&4 | SKN 3&4 |
|---|---|---|
| Core Average Characteristics at Full Power: | | |
| Total core heat output, MWt | 2815 | 3983 |
| Total core heat output, $10^6$ kcal/h (MBtu/h) | 2421 (9608) | 3425 (13,590) |
| Average fuel rod energy deposition fraction | 0.975 | 0.975 |
| Hot fuel rod energy deposition fraction | 0.975 | 0.975 |
| Primary system pressure, kg/cm$^2$ A (psia) | 158 (2250) | 158 (2250) |
| Reactor inlet coolant temperature, °C (°F) | 296 (564.5) | 291 (555) |
| Reactor outlet coolant temperature, °C (°F) | 327 (621) | 324 (615) |
| Core exit average coolant temperature, °C (°F) | 328 (623) | 325 (617) |
| Average core enthalpy rise, kcal/kg (Btu/lb) | 45.3 (81.5) | 46.7 (84.1) |
| Design minimum primary coolant flow rate, L/min (gpm) | 1,249,000 (330,000) | 1,689,000 (446,300) |
| Design maximum core bypass flow, % of primary | 3.0 | 3.0 |
| Design minimum core flow rate, L/min (gpm) | 1,211,000 (320,000) | 1,639,000 (432,900) |
| Hydraulic diameter of nominal subchannel, cm (in.) | 1.196 (0.471) | 1.265 (0.498) |
| Core flow area, m$^2$ (ft$^2$) | 4.165 (44.83) | 5.825 (62.7) |
| Core average mass velocity, million kg/h-m$^2$ (million lb/h-ft$^2$) | 12.84 (2.63) | 12.60 (2.58) |
| Core average coolant velocity, m/s (ft/s) | 5.10 (16.7) | 4.94 (16.2) |
| Core average fuel rod heat flux, Kcal/h-m$^2$ (Btu/h-ft$^2$) | 487,660 (179,750) | 517,361 (190,735) |
| Total heat transfer area, m$^2$ (ft$^2$) | 4840 (52,100) | 6454 (69,470) |
| Average fuel rod linear heat rate, W/cm, (kW/ft) | 172.6 (5.26) | 179.2 (5.46) |
| Power density, kW/L | 96.6 | 100.5 |
| No. of active fuel rods | 41,772 | 56,876 |

APR1400: 109.7m 461.3 m$^3$/min

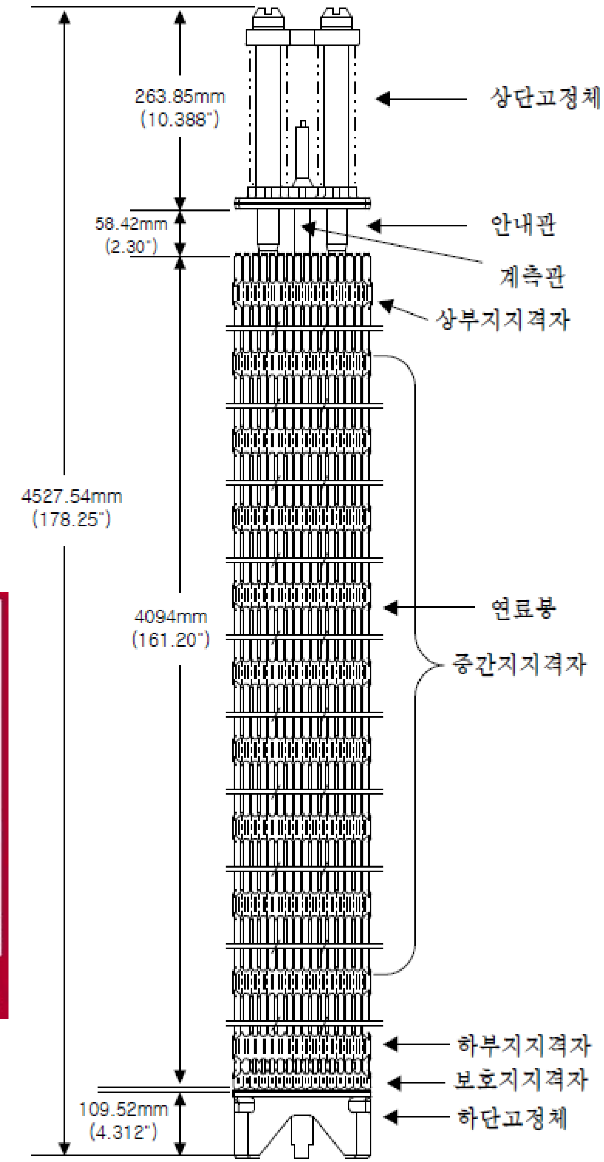
OPR1000: 102.7m, 323.3 m$^3$/min

# Reactor Core

- Equivalent diameter: ~3.647 m, active core height: 3.81 m
- APR1400: 241 Fuel assemblies (16×16)
- Coolant temperature: Inlet (~291°C), outlet: (~324 °C)
- Flow rate: 1,639,000 lpm ≈ 27.3 $m^3/s$ ≈ 4.94 m/s
- Linear power density of each rod: 17~18 kW/m



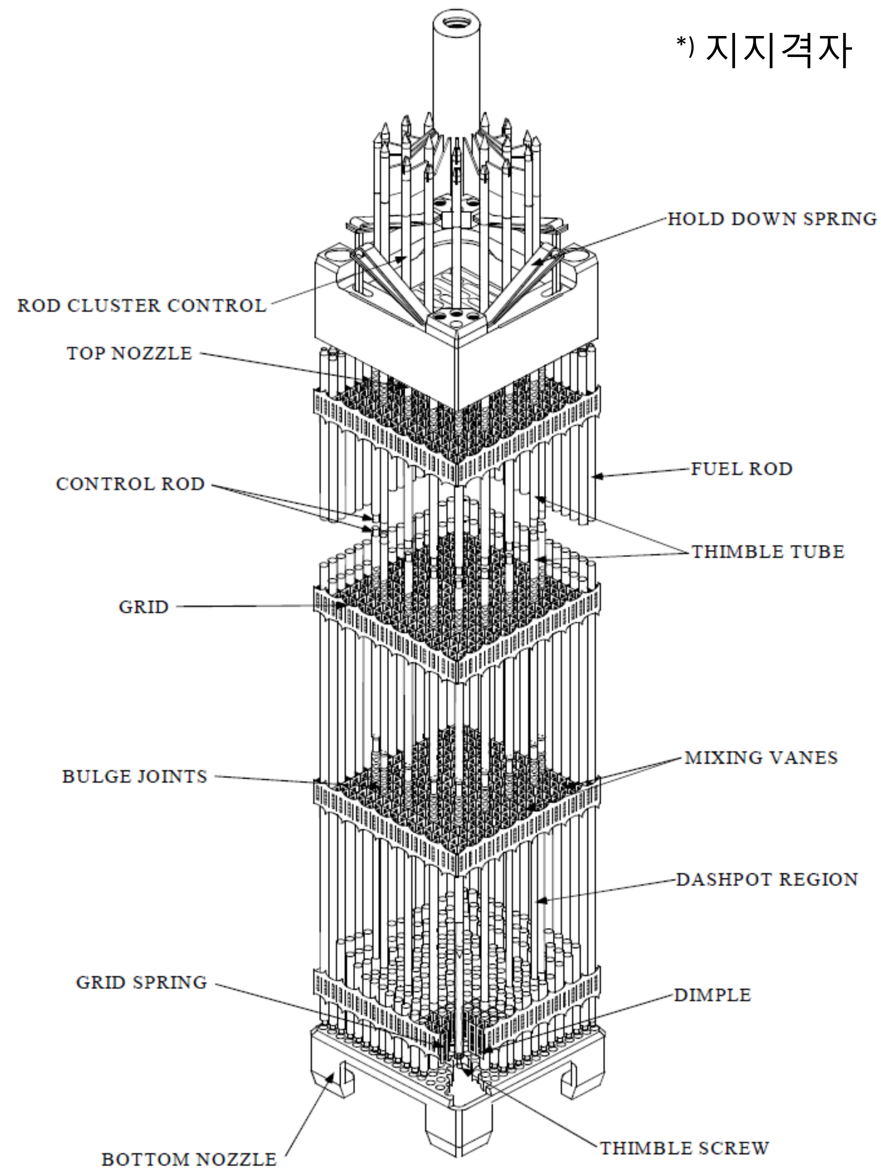

15 % 이용률 (3.5 시간)



# Reactor Pressure Vessel

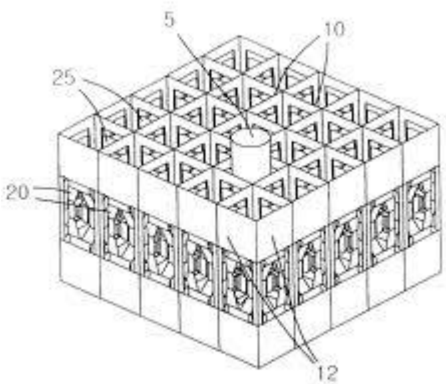
- Reactor fuel assemblies
  - Major components
    - Fuel rods
    - Spacer grids
    - Upper and lower end fittings
  - Fuel rods
    - Ceramic fuel pellets
    - Length: 3.81 m (APR1400)
    - Contain a space at the top for the collection of any gases produced by the fission process
      - For example, xenon and krypton
    - Arranged in a square matrix
      - 16×16 or 17×17 for PWRs
        - 236 in APR1400, why not 256?
      - 8×8 for BWRs
    - APR1400: 241 Fuel assemblies (16×16)
      56876 fuel rods

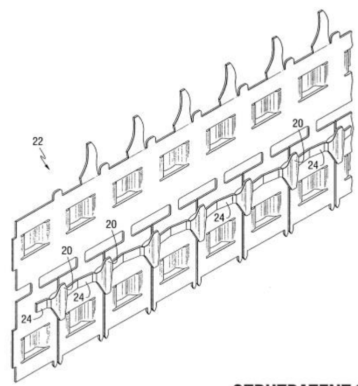
*) 지지격자

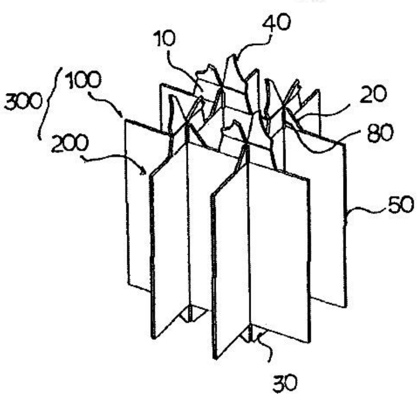


# Reactor Pressure Vessel

- Reactor fuel assemblies
  - Spacer grids*)
    - Separate the individual rods with pieces of sprung metal.
    - Provide the rigidity of the assemblies.
    - Allow the coolant to flow freely up through the assemblies and around the fuel rods.
    - Some spacer grids may have flow mixing vanes (or swirl vane) that are used to promote mixing of the coolant as it flows around and through the fuel assembly.

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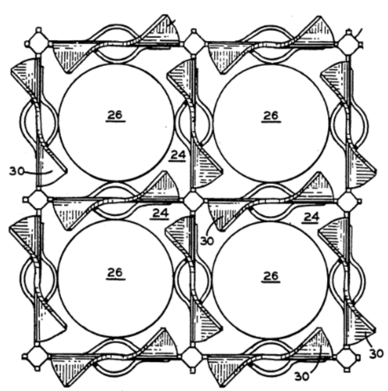
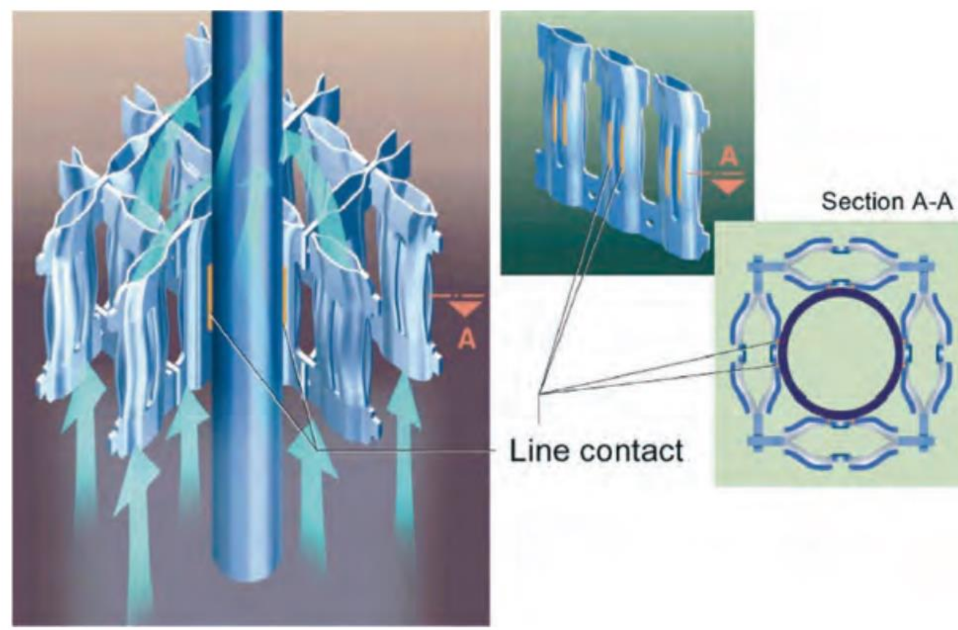
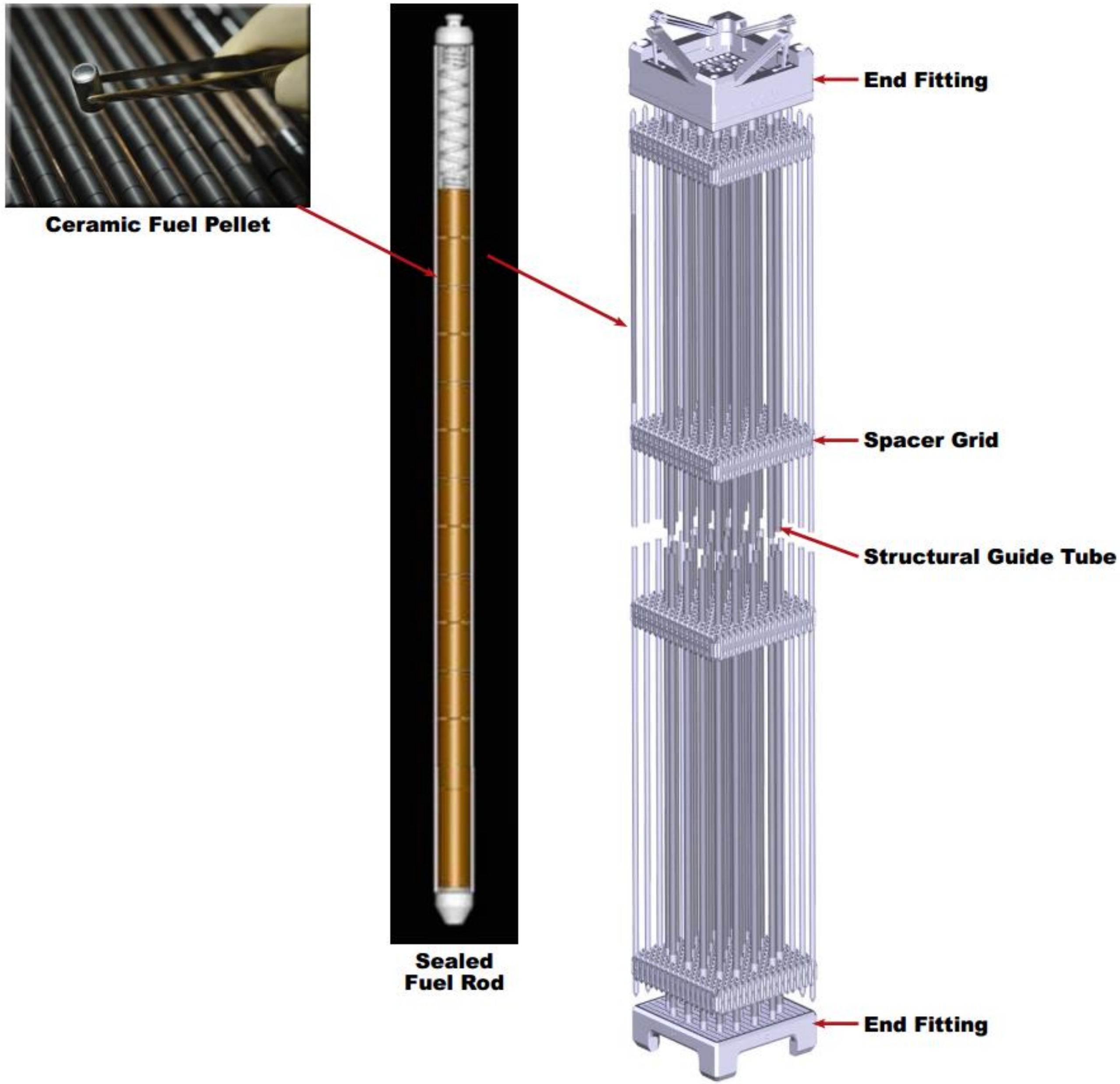


# Reactor Pressure Vessel

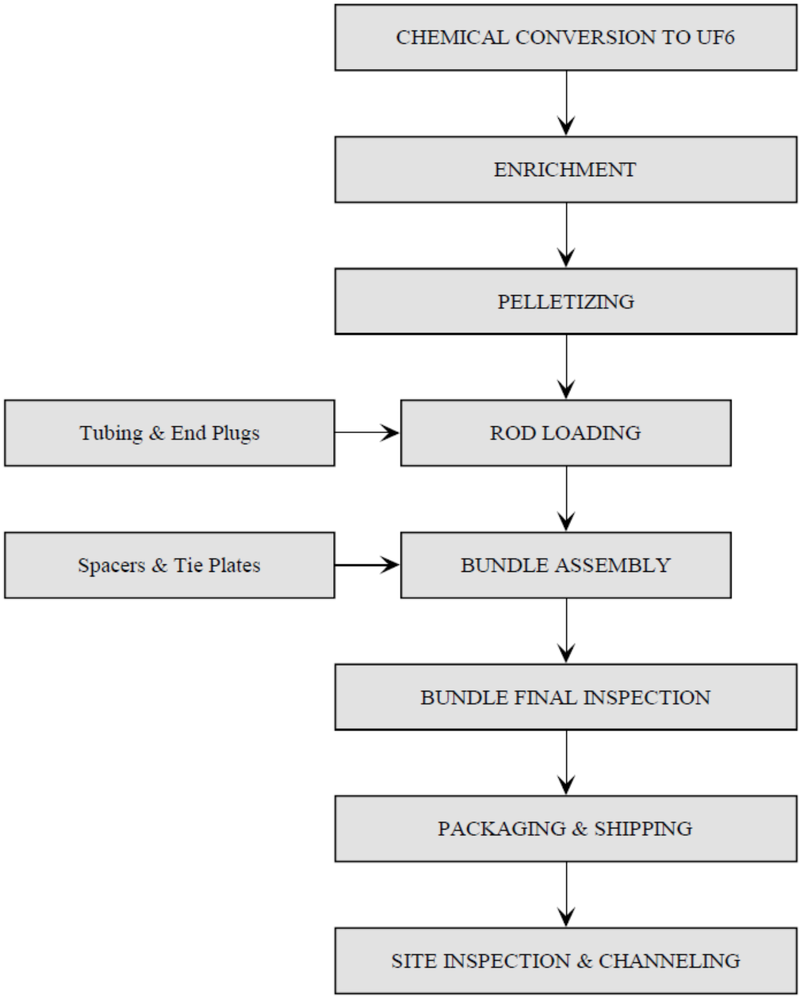


# Reactor Pressure Vessel

| Fuel Assemblies (Cont'd) | |
|---|---|
| Pellet diameter (nominal), cm (in) | 0.819 (0.3225) |
| Pellet length , cm (in) (Enriched Uranium) | 0.983 (0.387) |
| Pellet density (nominal), $g/cm^3$ | 10.44 |
| Pellet theoretical density, $g/cm^3$ | 10.96 |
| Pellet density (nominal) (% theoretical) | 95.25 |
| Stack height density (nominal), $g/cm^3$ | 10.313 |
| Clad material | ZIRLO |
| Clad ID, cm (in) | 0.836 (0.329) |
| Clad OD, (nominal), cm (in) | 0.950 (0.374) |
| Clad thickness, (nominal), cm (in) | 0.05715 (0.0225) |
| Diametral gap, (cold, nominal), cm (in) | 0.01651 (0.0065) |
| Active length, cm (in) | 381 (150) |
| Plenum length (nominal), cm (in) | 22.568 (8.885) |

# Reactor Coolant System

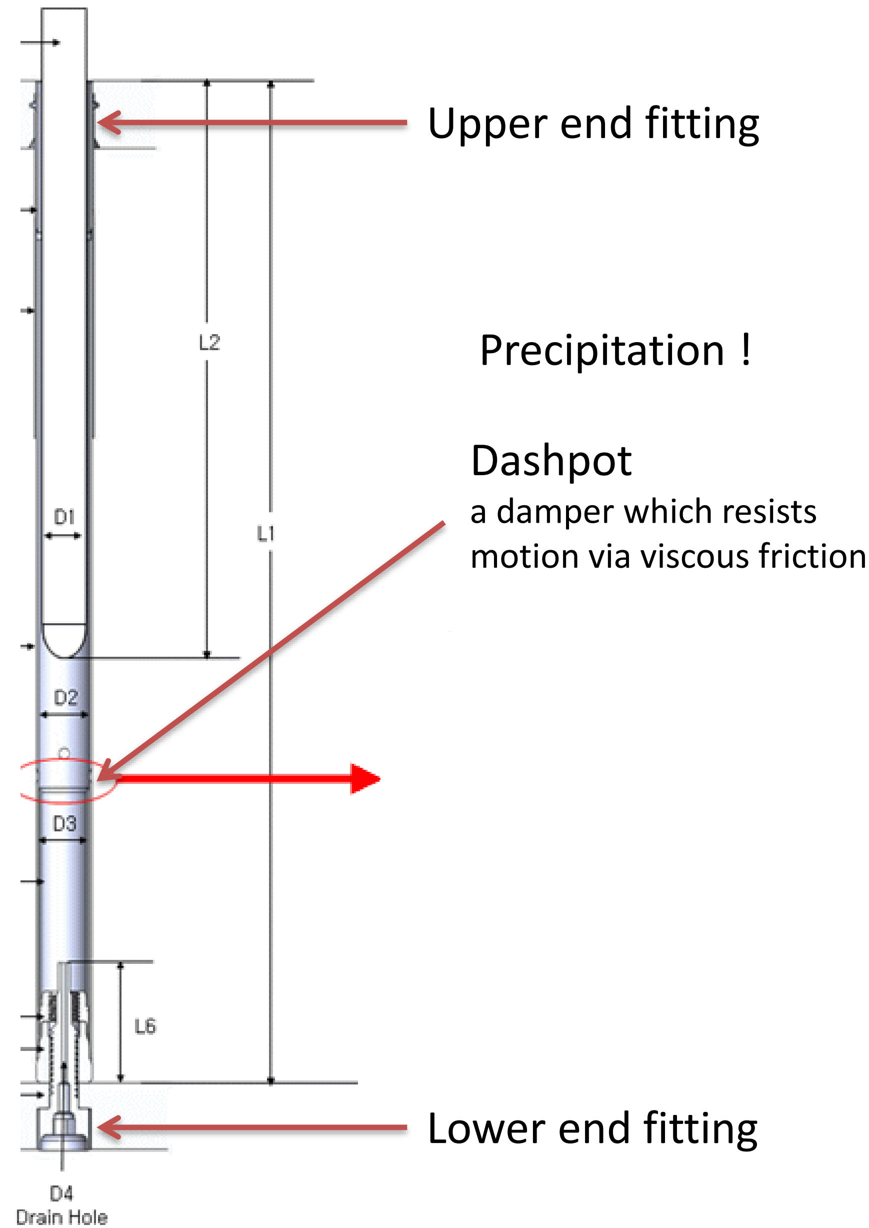
- Nuclear fuel
  - Ceramic pellets
  - The pellets are stacked into 12-foot long, slender metal tubes, generally made of a zirconium alloy.
  - The tube is called the "fuel cladding."
  - When a tube is filled with the uranium pellets, it is pressurized with helium gas, and plugs are installed and welded to seal the tube.
    - ~400 psig ≈ 27 bar (why?)
  - The filled rod is called a "fuel rod."
  - The fuel rods are bundled together into "fuel assemblies" or "fuel elements."
  - The completed assemblies are now ready to be shipped to the plant for installation into the reactor vessel.




*) 핵연료피복재, 핵연료봉, 핵연료집합체

## Guide Tube

- Design parameters
  - Control rod drop velocity
  - Bypass minimum
  - Bypass maximum



# Contents

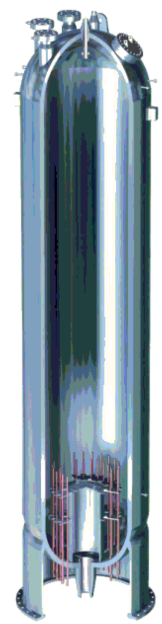


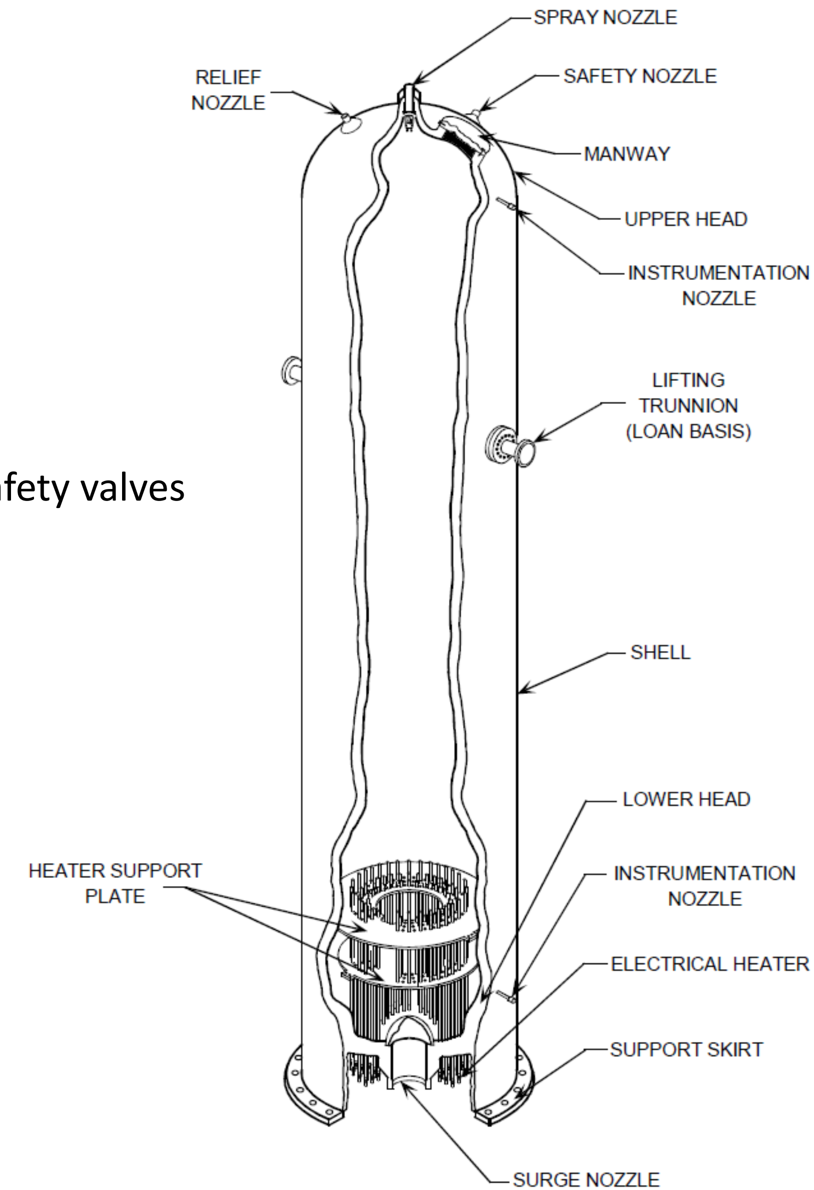
Reactor Vessel
Pressurizer
Reactor Coolant Pump
Steam Generator

# Reactor Coolant System

## Pressurizer

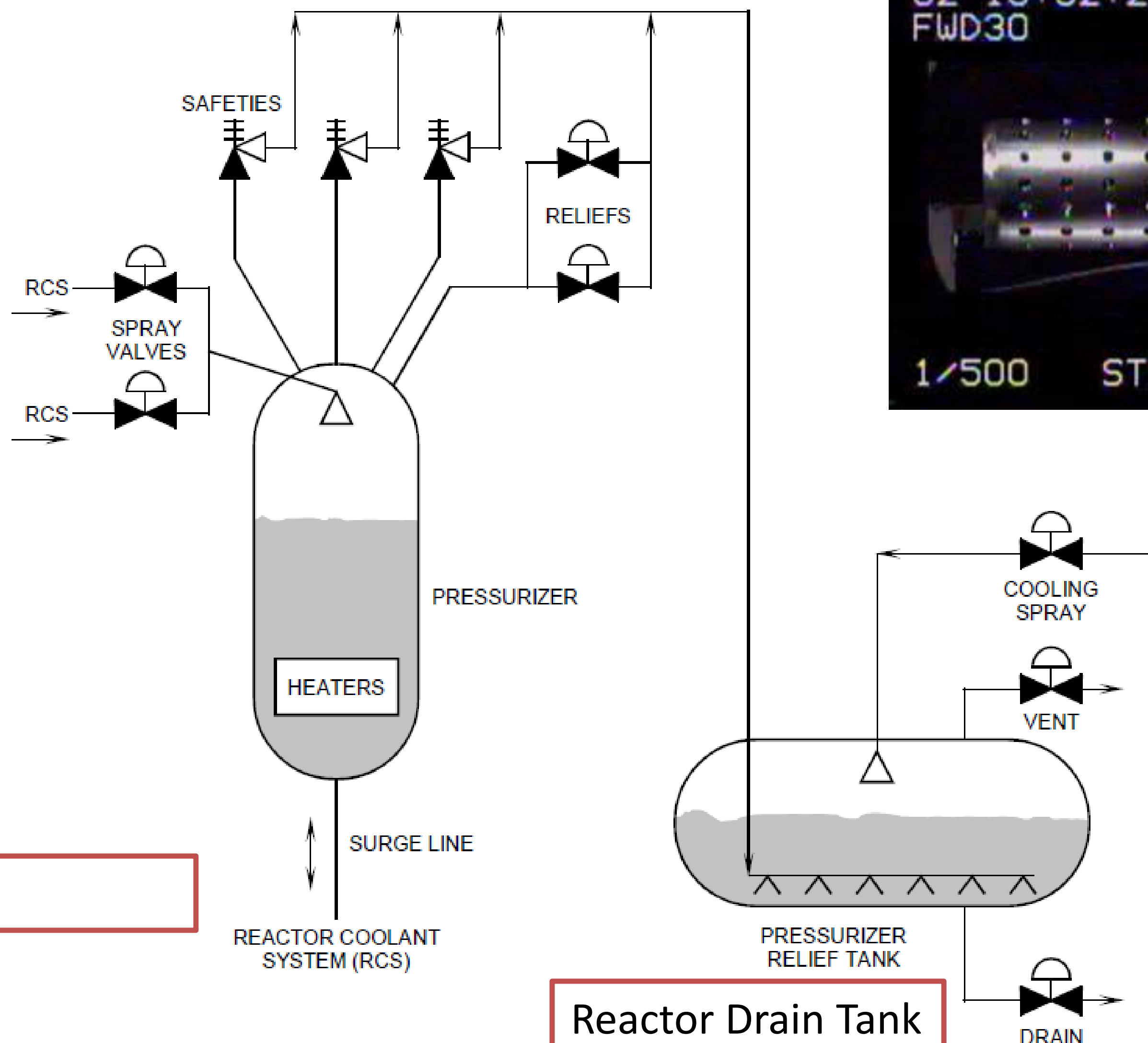
- Provides a means of controlling the system pressure
- Pressure is controlled by
  - Electrical heaters
  - Pressurizer spray
  - Power operated relief valves/ safety valves.
- Operation
  - High pressure: spray ($\rho_l$=588.5, $\rho_g$=105.2) $\Rightarrow$ PORV $\Rightarrow$ safety valves
  - Low pressure: heaters $\Rightarrow$ trip
- Dimensions
  - Height: ~ 13 m
  - Inner diameter: ~ 2.4 m
  - Outer diameter: ~ 2.7 m
  - Surge nozzle: ~ 0.3 m
- Installed heater
  - Total 1800 kW (50 kW × 36 ea)





# Reactor Coolant System

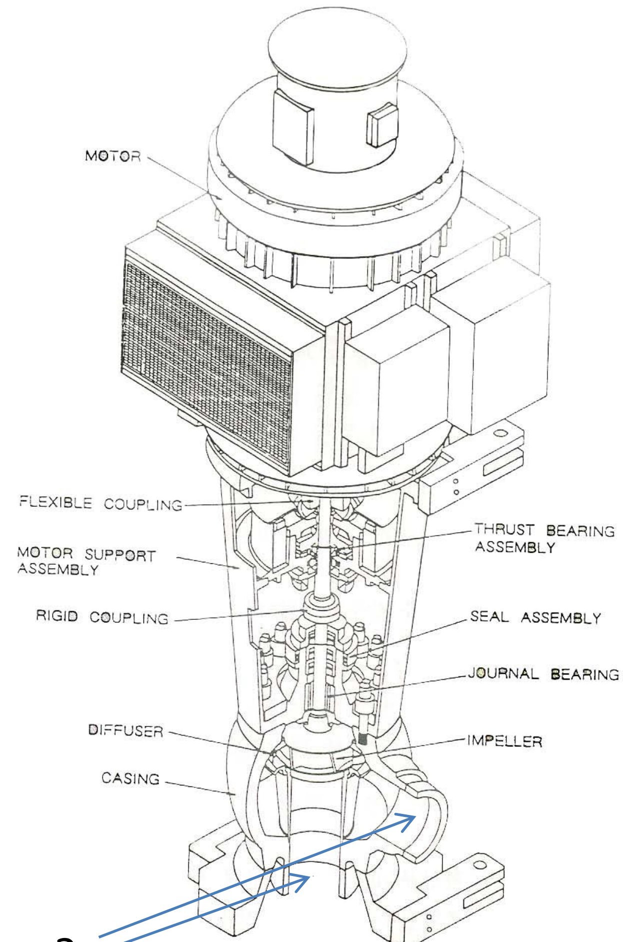
- **Pressurizer**


Reactor Drain Tank

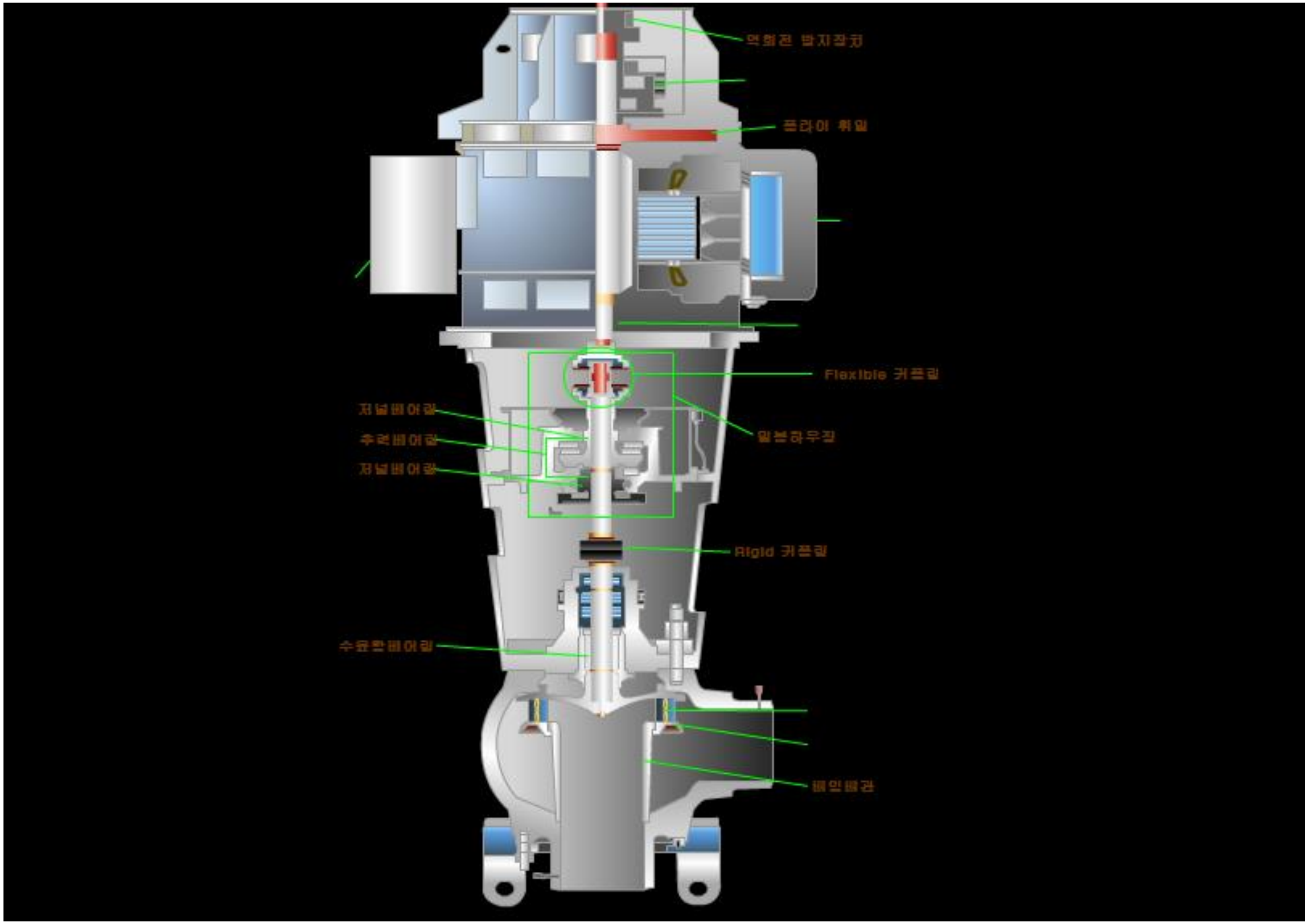
## RCP (Reactor Coolant Pump)

- Provide forced primary coolant flow to remove the heat generated by the fission process
  - Natural circulation: sufficient for heat removal when the plant is shutdown
- Increase pressure: 90 psi ≈ 6.2 bar
- Components
  - Motor, hydraulic section, seal package
  - Motor
    - Air cooled, 1190 RPM, 4.5~6 MW (10~20 MWt)
    - Flywheel for coastdown
  - Hydraulic section
    - Impeller, shaft, suction and discharge nozzles etc.
- Height: ~ 11 m, ~$ 20~30 M



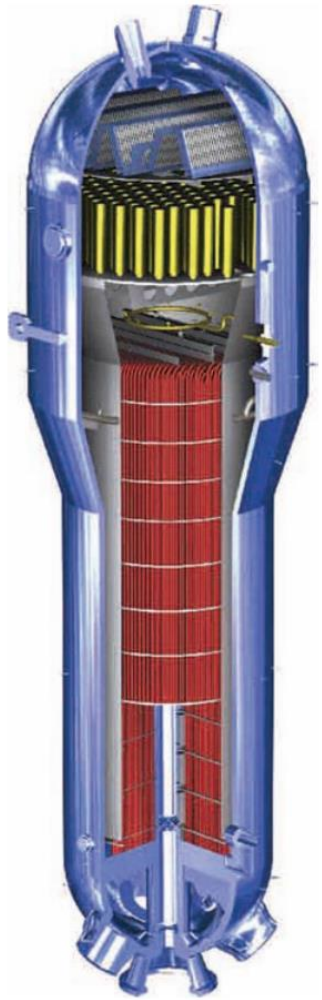

Suction?
or Discharge?

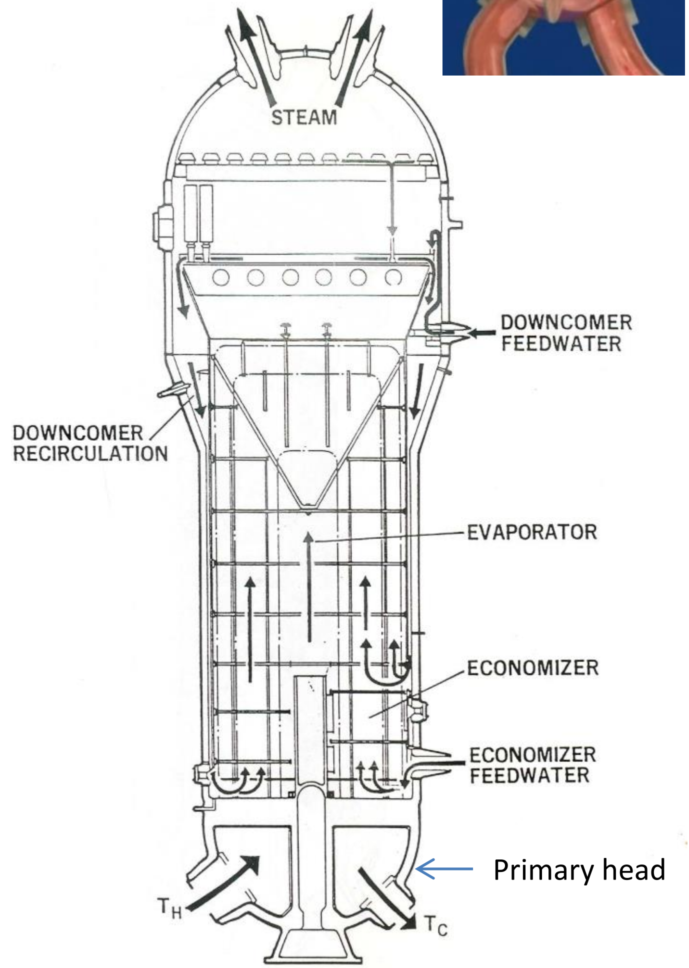
## ❖ RCP (Reactor Coolant Pump)

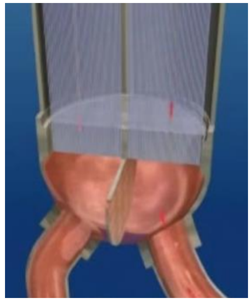


## Steam Generator

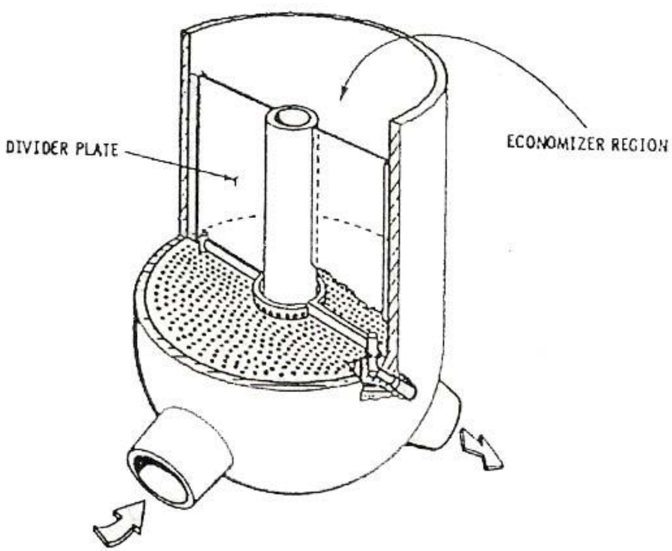
- Primary side (tube)
  - U-tubes: 19.05 mm I.D., 1.07 mm thickness
  - Length: ~ 19.4 m
  - OPR1000: ~ 8,214 tubes/SG
  - APR1400: ~ 13,102 tubes/SG
  - 1 Inlet: 323 °C, 2 outlets: 290 °C
  - Inconel-600
- Secondary side (shell)
  - Height: 20~23 m, diameter: 4.5~6 m
  - Pressure: 70~75 Bars
  - 3 Inlets: ~232 °C, 2 outlets: ~285 °C
- Operation
  - Steam-water mixture ⇒ separator⇒ drier
  - Separator: mixture spin (exit water < 2 %)
    - Centrifugal separator
  - Drier: rapid direction change
  - Exit water content < 0.25 wt %
    - To prevent damage to the turbine blading

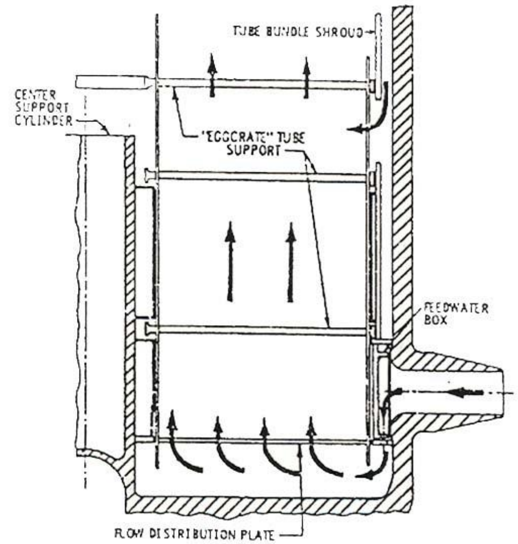




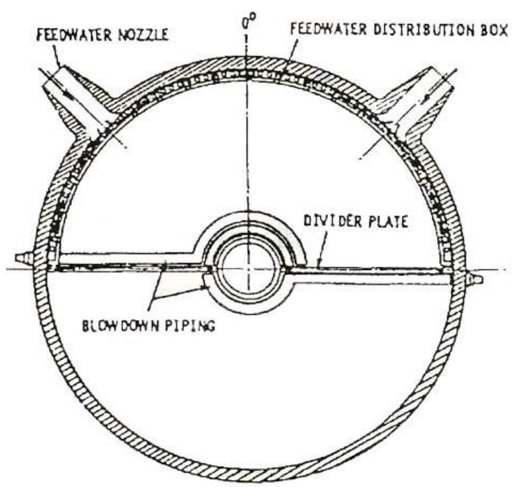



## ❖ Steam Generator



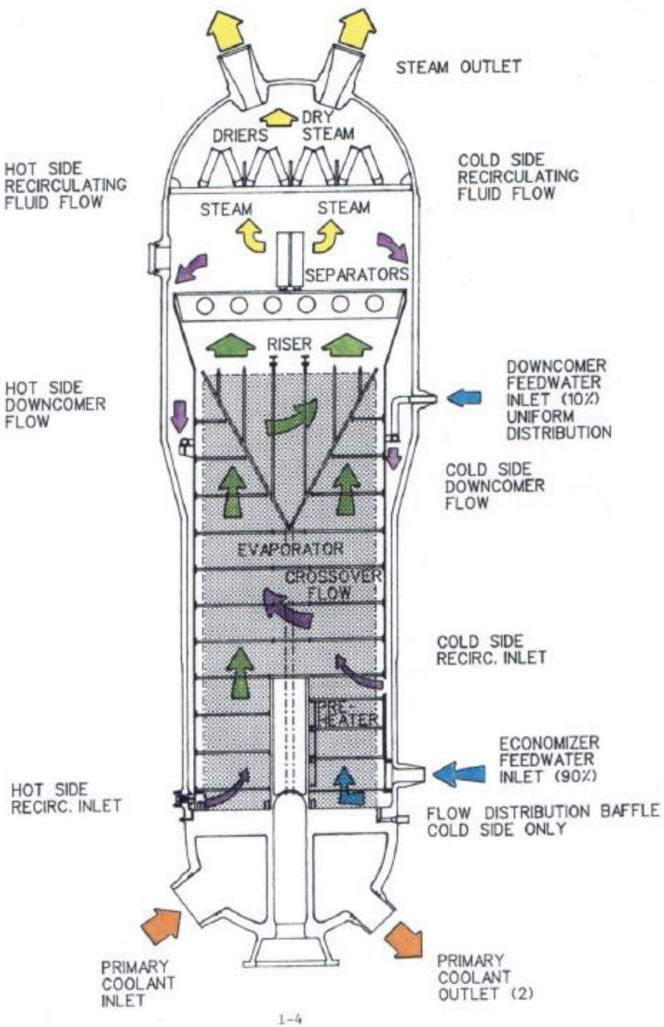



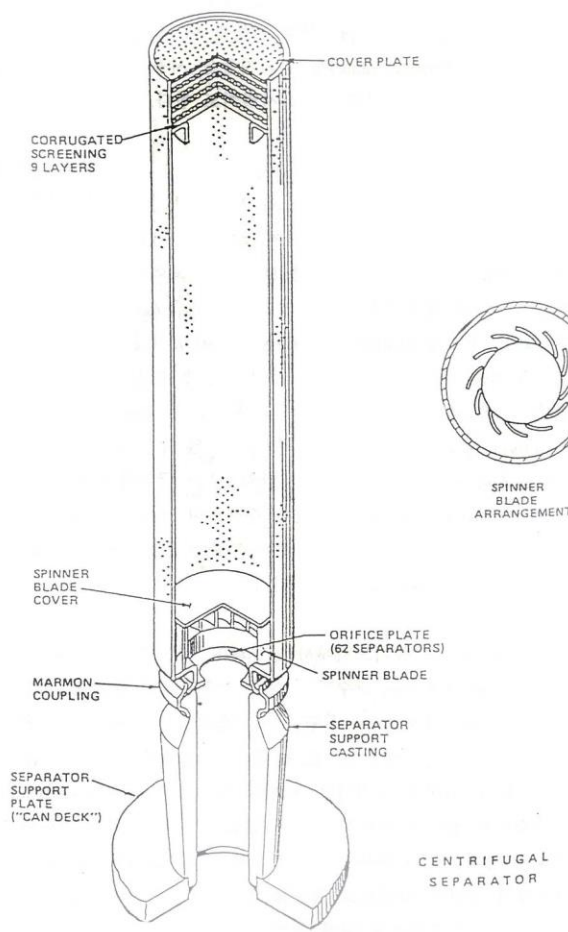

350 mm

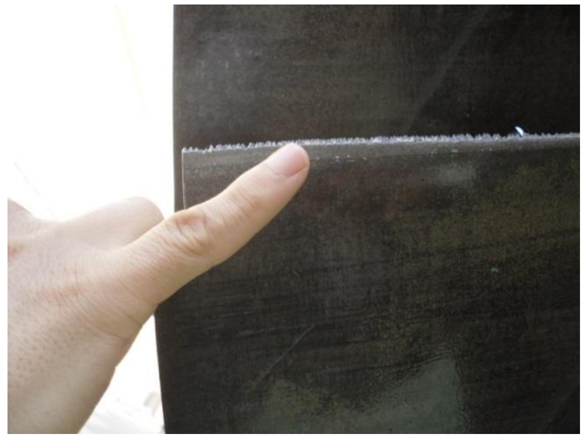


## ❖ Steam Generator

Recirculation ratio : 3.9
(100 (Steam) + 290 (Saturated water)) / 100 (Feedwater)

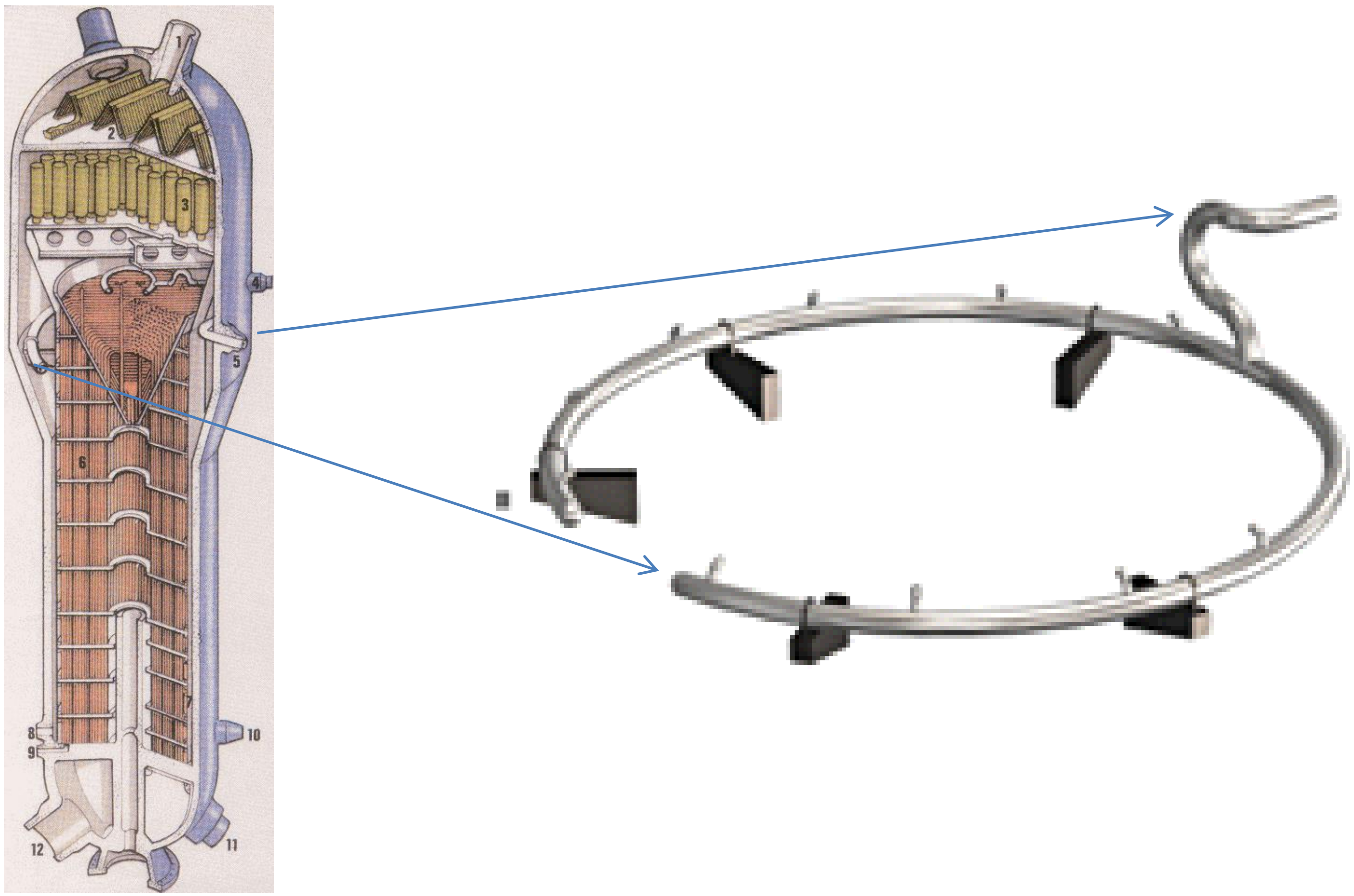


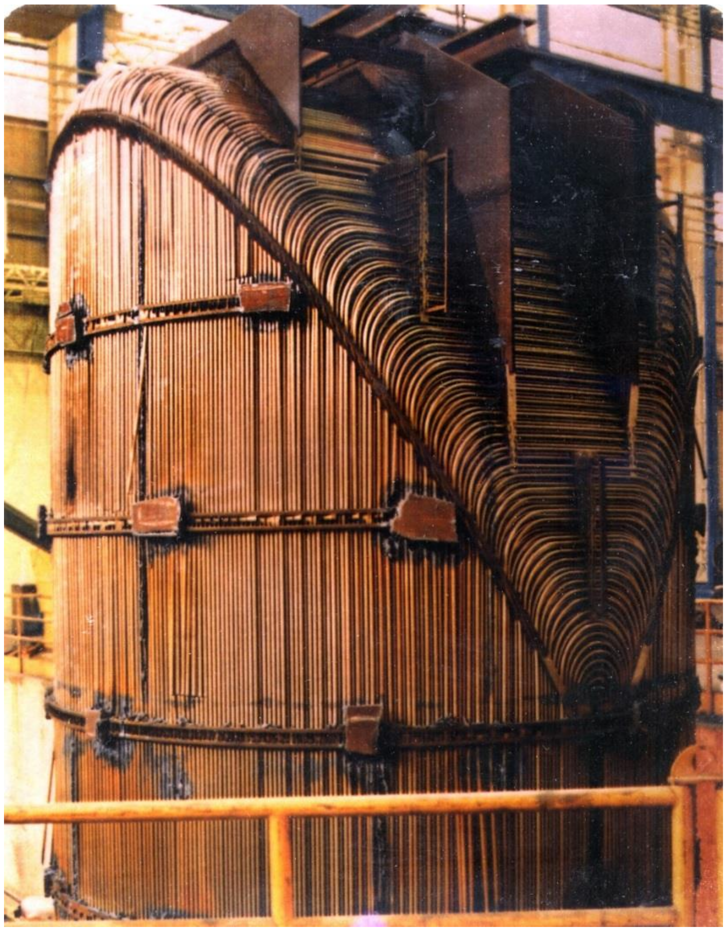



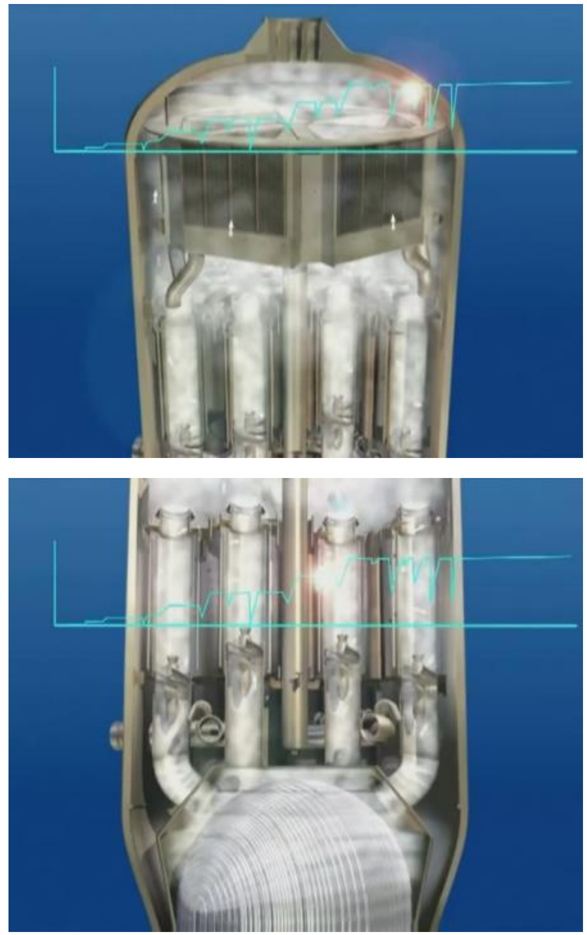
## Steam Generator

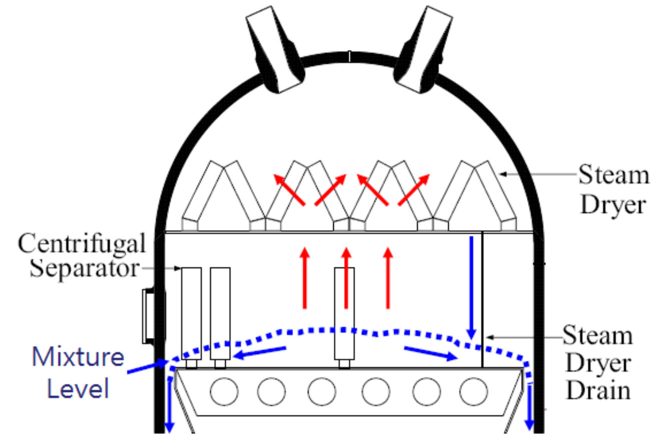
- Inverted J-Nozzle
  - To prevent condensation-induced water hammer



## Steam Generator







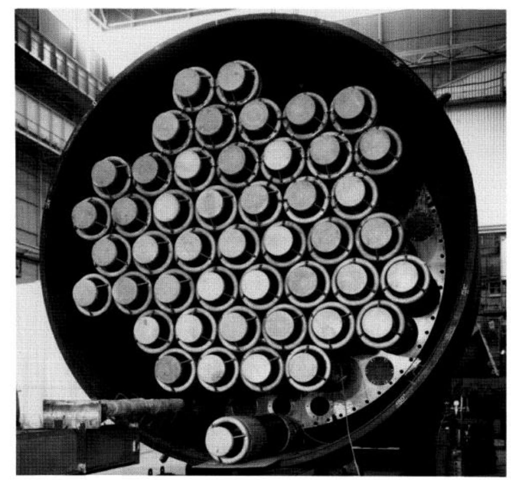
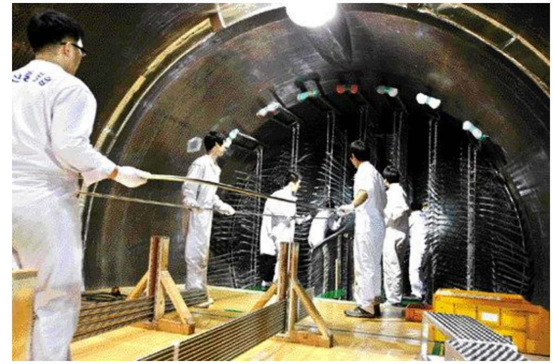
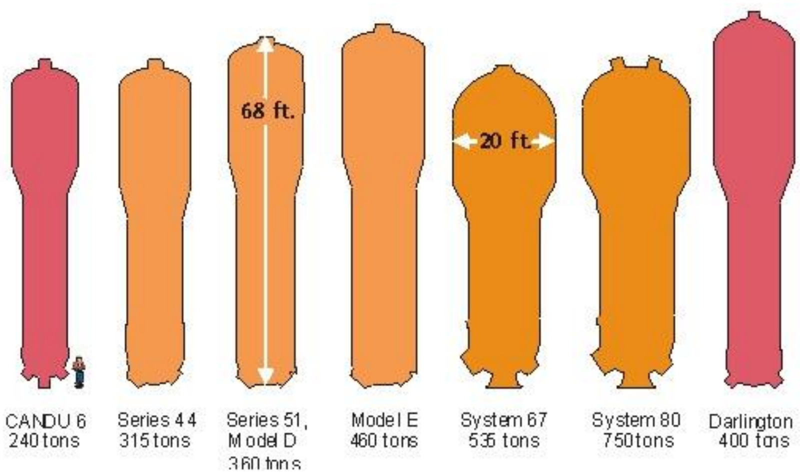



FIGURE 51. Moisture separator arrangement in a KWU SG.

## ❖ Steam Generator




# Contents

- History of PWR
- Plant Overall
- Reactor Coolant System
- Steam and Power Conversion System
- Auxiliary System
- Plant Protection System
- Other systems

Main Steam System
Condensate System
Main Feedwater System

# Contents

- History of PWR
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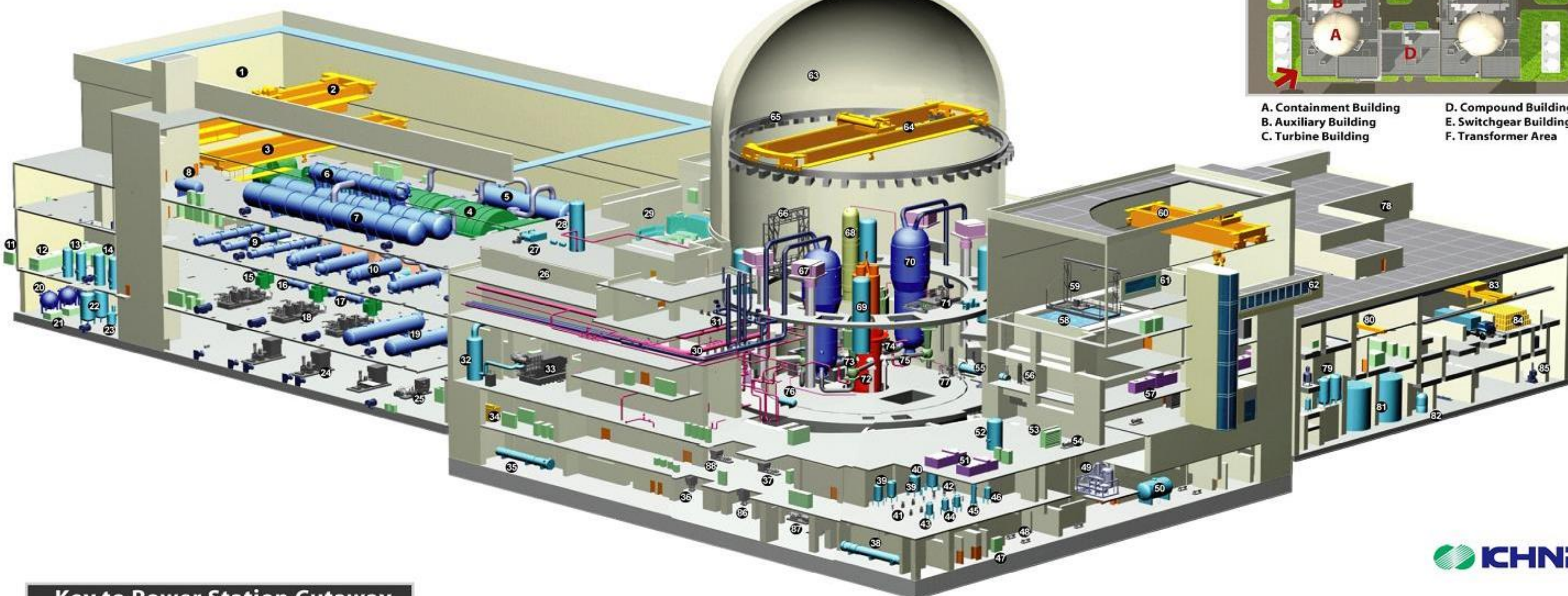
Main Steam System
Condensate System
Main Feedwater System

# Steam and Power Conversion System


A. Containment Building
B. Auxiliary Building
C. Turbine Building
D. Compound Building
E. Switchgear Building
F. Transformer Area



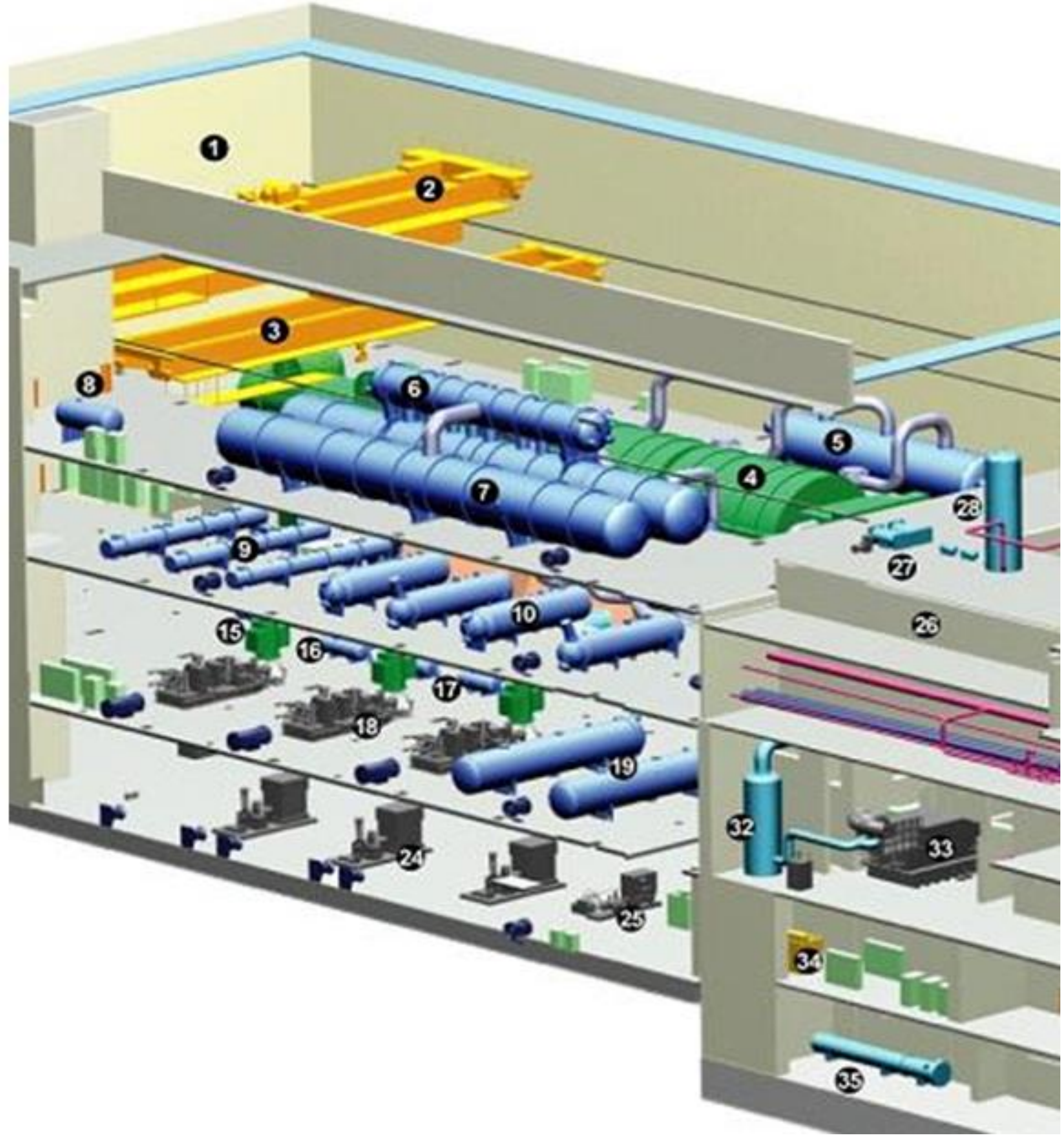
KHNP

## Key to Power Station Cutaway

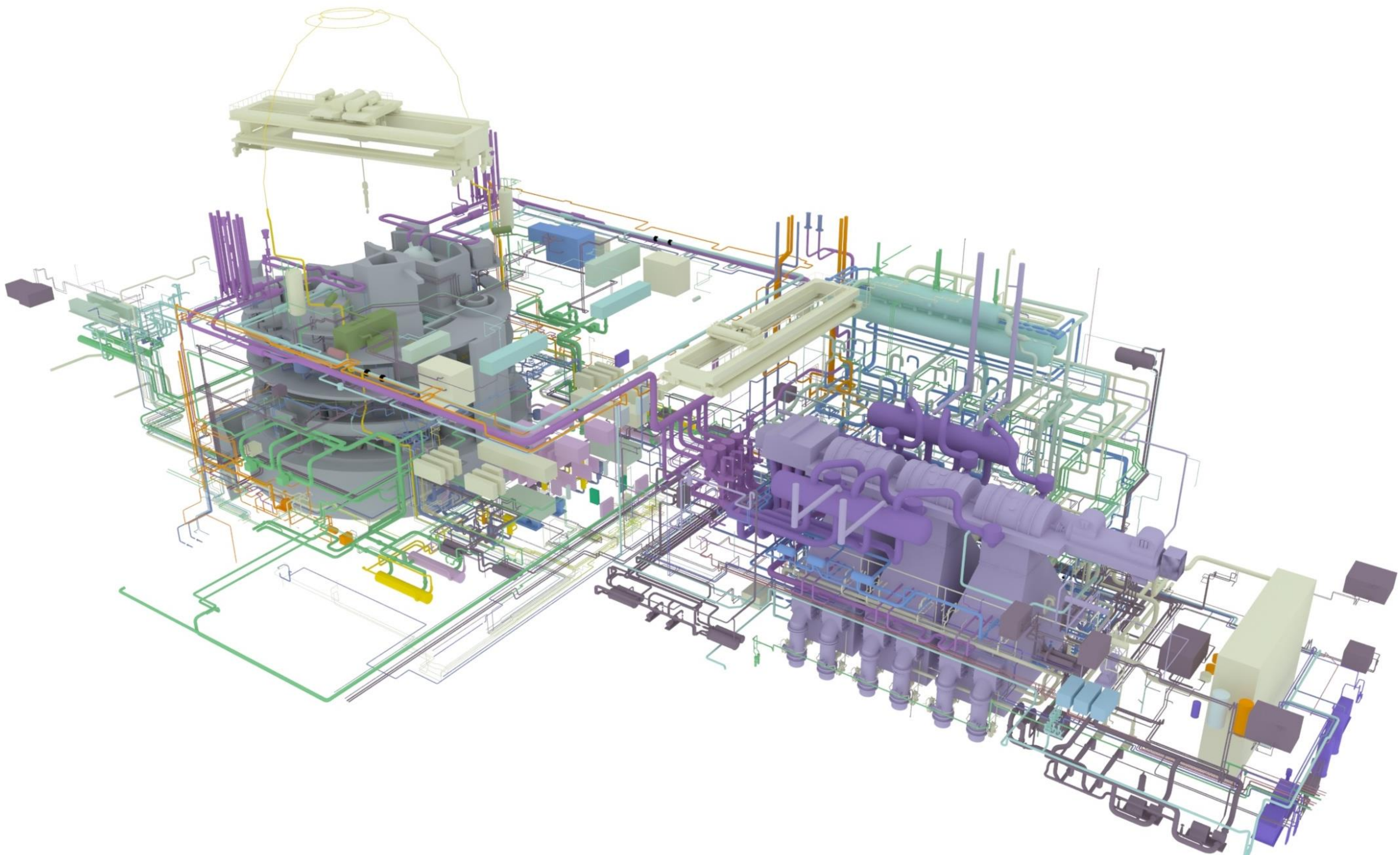
1. Turbine Building
2. Main Overhead Crane
3. Aux. Overhead Crane
4. Generator
5. Moisture Separator Reheater
6. Deaerator
7. Deaerator Storage Tank
8. TBCCW Surge Tank
9. LP Feedwater Heaters
10. HP Feedwater Heaters
11. Closed Loop Cooling System
12. Air Compressor
13. Air Receivers
14. Service Air Receiver
15. Feedwater Pumps Turbine Driven
16. Moisture Separator Drain Tank
17. Stage Reheater Drain Tank
18. Feedwater Pumps Turbine "A""B""C"
19. HP Feedwater Heaters
20. Cond. Polishing Mixed Bed Vessels
21. Cond. Polishing Resin Traps
22. Cation Regen. & Hold Tanks
23. Ammonia Day Tank
24. Feedwater Booster Pumps
25. Start-up FW Pump
26. Auxiliary Building
27. D/G Room Emergency Exhaust Fan
28. CCW Surge Tank
29. Main Control Room
30. Main Steam Line
31. Main Steam Safety Valve
32. Exhaust Silencer
33. Diesel Generator
34. 480V PNS Loadcenter
35. CS Heat Exchanger
36. CS Pump
37. Motor Driven Aux. Feedwater Pumps
38. SC Heat Exchanger
39. Spent Fuel Pool Clean-up Demin
40. SG Blowdown Mixed Bed Demin
41. Reactor Drain Filter
42. SGBD Filter
43. Pre-Holdup Ion Exchanger
44. Purification Ion Exchanger
45. Boric Acid Cond Ion Exchanger
46. Deborating Ion Exchanger
47. Process Radiation Monitor
48. Holdup Pump
49. Boric Acid Conc.
50. Equip. Drain Tank
51. Aux. Bldg. Controlled Area Exhaust ACU
52. Volume Control Tank
53. SFP Cooling Exchanger
54. SFP Cooling Pump
55. Fuel Transfer Tube
56. Fuel Transfer Carriage & Upender in Fuel Handling Area
57. Fuel Handling Area Emer Exhaust ACU
58. Spent Fuel Pool
59. Spent Fuel Handling Machine
60. Fuel Handling Area Overhead Crane
61. Viewing Area
62. Walkway
63. Containment Building
64. Polar Crane
65. Crane Rail
66. CEA Change Platform
67. RCFC Duct
68. Pressurizer
69. Safety Injection Tank
70. Steam Generator
71. Refueling Machine
72. Reactor Vessel
73. Reactor Coolant Pump
74. Reactor Coolant Piping Hot Leg
75. Reactor Coolant Piping Cold Leg
76. RCP Lube Oil Collector Tank
77. Fuel Transfer System Upender
78. Compound Building
79. Charcoal Delay Beds
80. Suspension Crane
81. Long Term Storage Tank
82. Low Activity Spent Resin
83. Traveling Bridge Crane
84. Waste Drum Storage Area
85. Solid Waste Compactor
86. SC Pump
87. SI Pump
88. Turbine Driven Aux. Feedwater Pump

# Steam and Power Conversion System

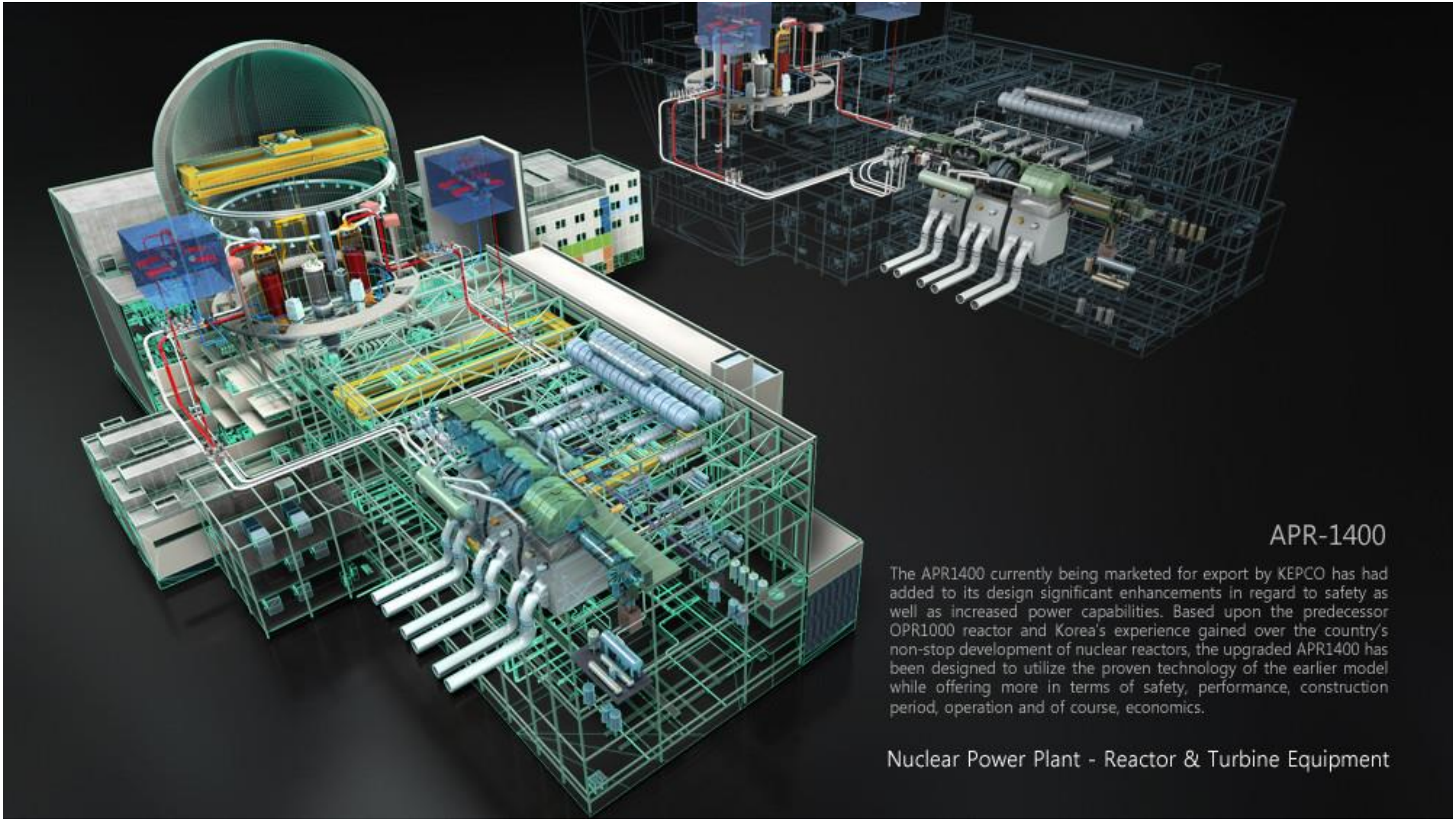
1. Turbine Building
2. Main Overhead Crane
3. Aux. Overhead Crane
4. Generator
5. Moisture Separator Reheater
6. Deaerator
7. Deaerator Storage Tank
8. TBCCW Surge Tank
9. LP Feedwater Heaters
10. HP Feedwater Heaters
11. Closed Loop Cooling System
12. Air Compressor
13. Air Receivers
14. Service Air Receiver
15. Feedwater Pumps Turbine Driven
16. Moisture Separator Drain Tank
17. Stage Reheater Drain Tank
18. Feedwater Pumps Turbine "A""B""C"
19. HP Feedwater Heaters
20. Cond. Polishing Mixed Bed Vessels
21. Cond. Polishing Resin Traps
22. Cation Regen. & Hold Tanks
23. Ammonia Day Tank
24. Feedwater Booster Pumps
25. Start-up FW Pump
26. Auxiliary Building
27. D/G Room Emergency Exhaust Fan
28. CCW Surge Tank
29. Main Control Room
30. Main Steam Line



# Steam and Power Conversion System

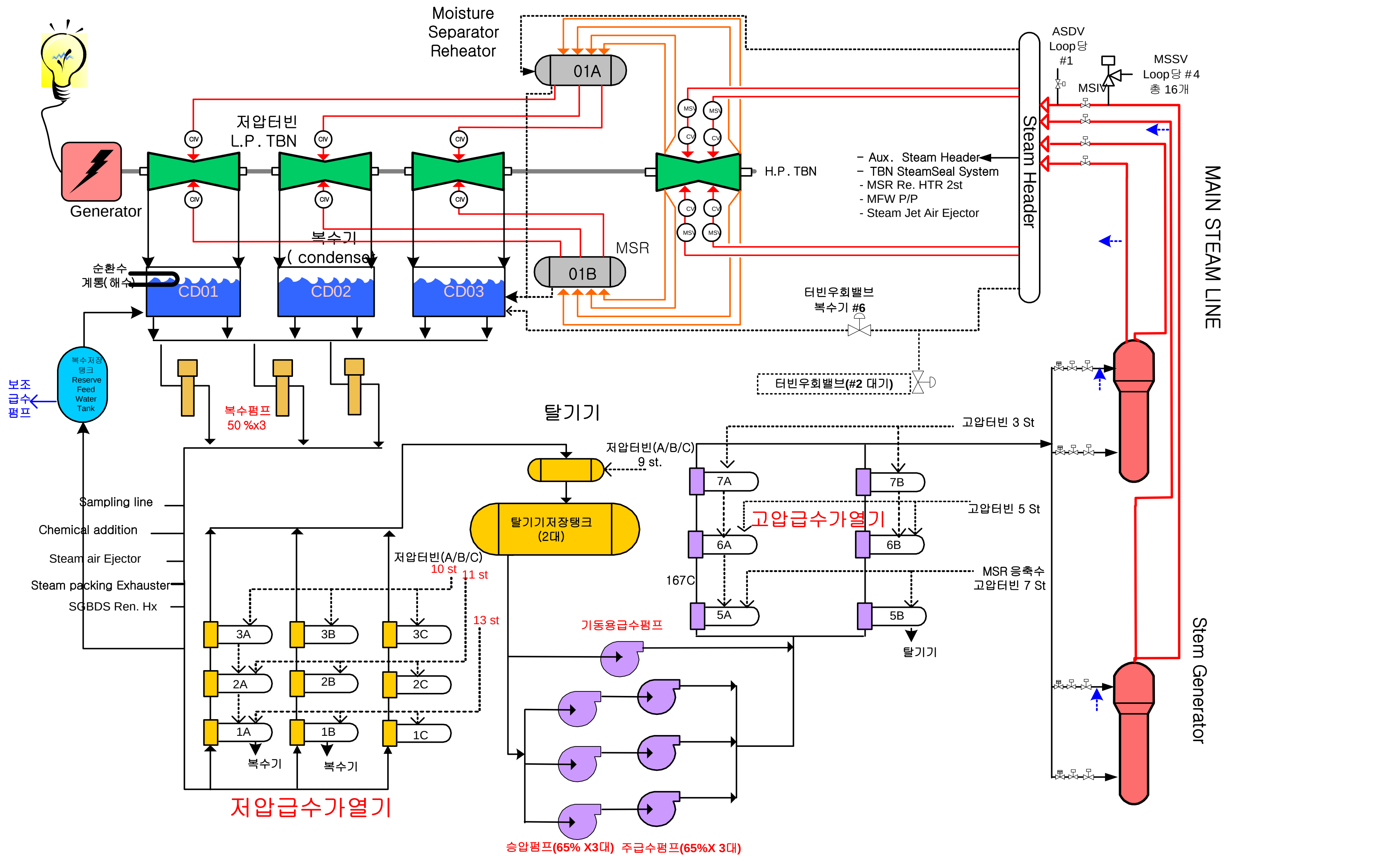


# Steam and Power Conversion System

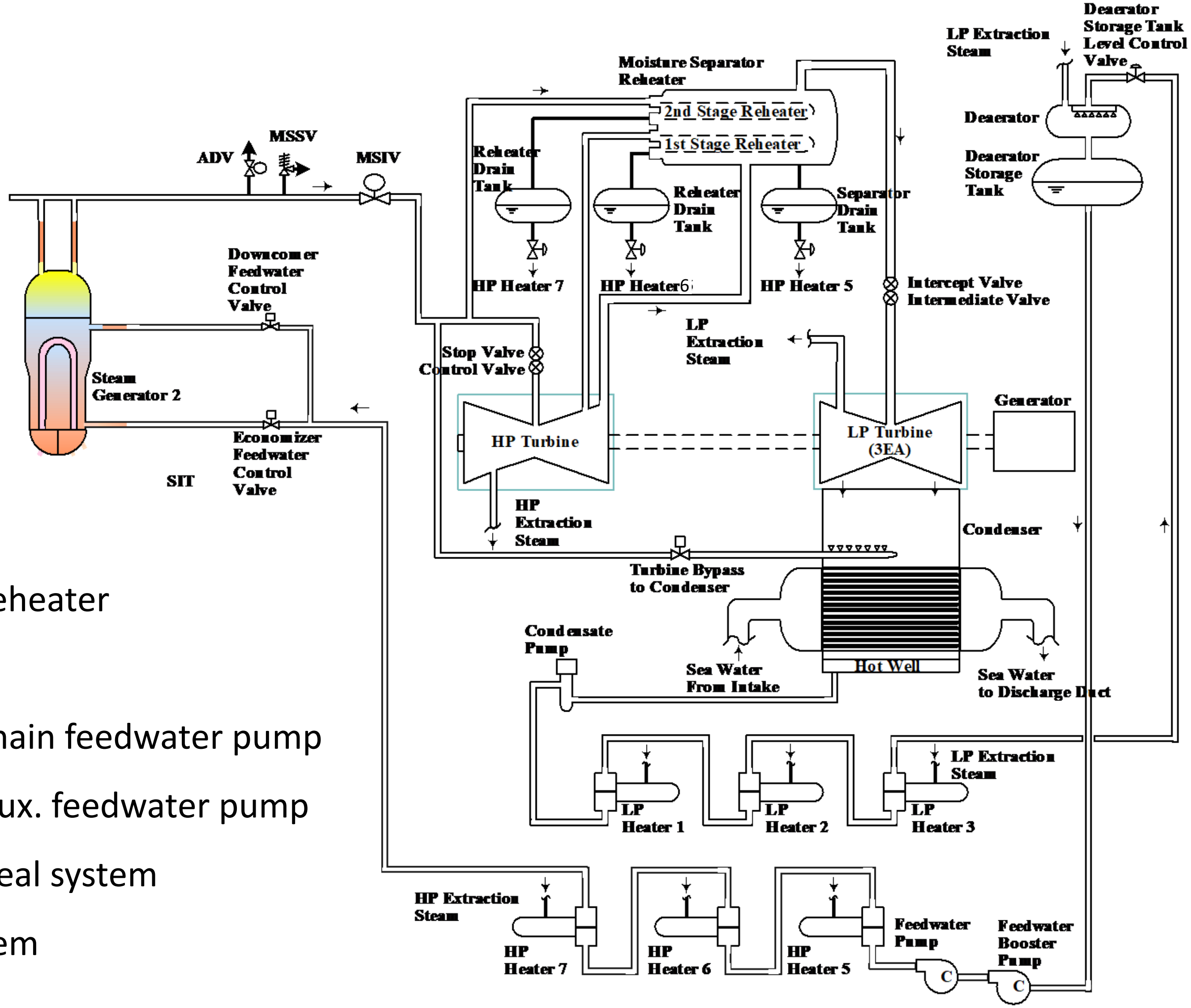


# Steam and Power Conversion System

## ❖ Condensate / main feedwater system (복수 및 주급수 계통)



## ❖ Condensate / main feedwater system (복수 및 주급수 계통)

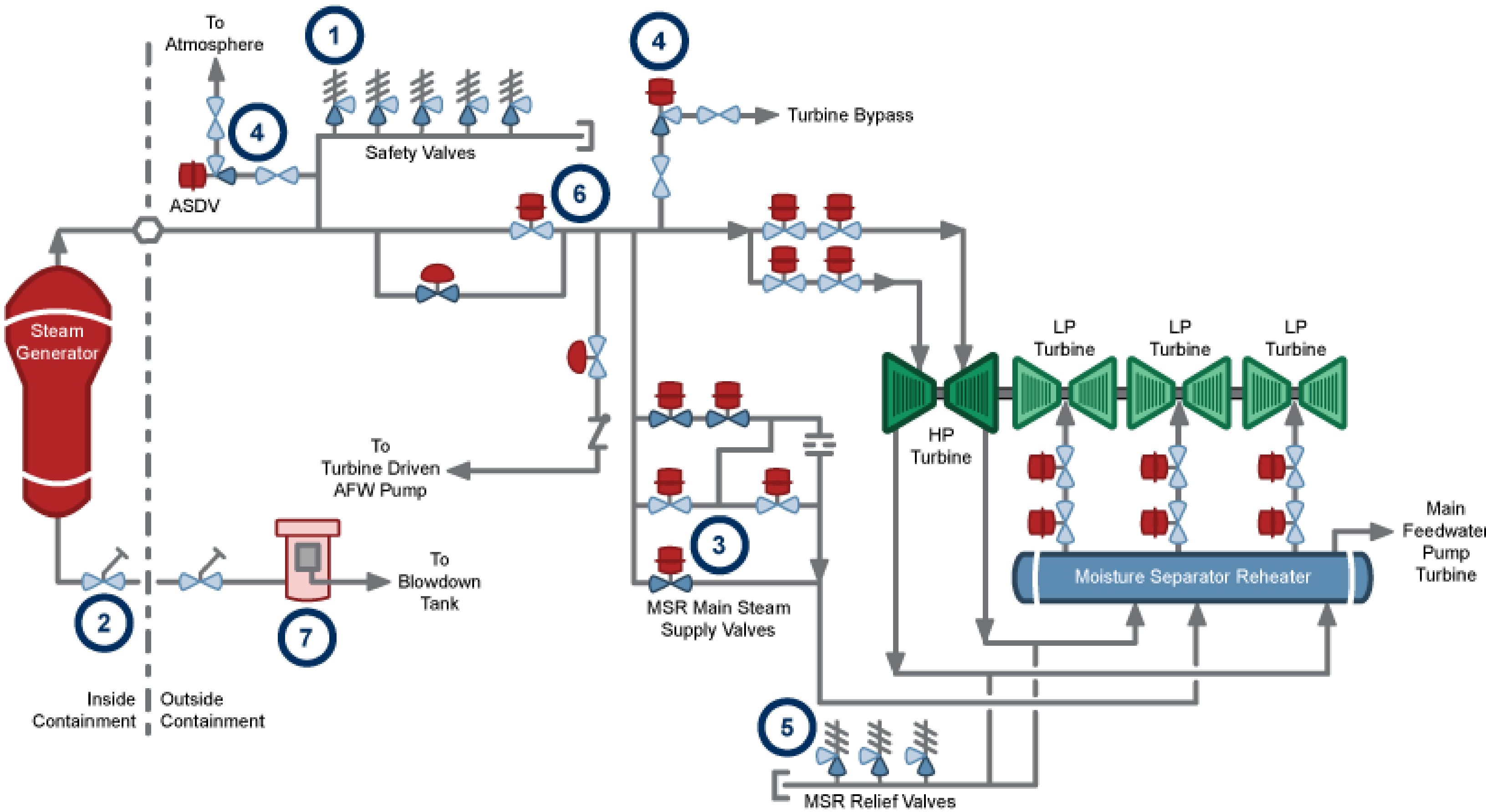



- HP Turbine
- MSR 2nd stage reheater
- Turbine bypass
- Turbine of the main feedwater pump
- Turbine of the aux. feedwater pump
- Turbine steam seal system
- Aux. steam system
- Sampling line

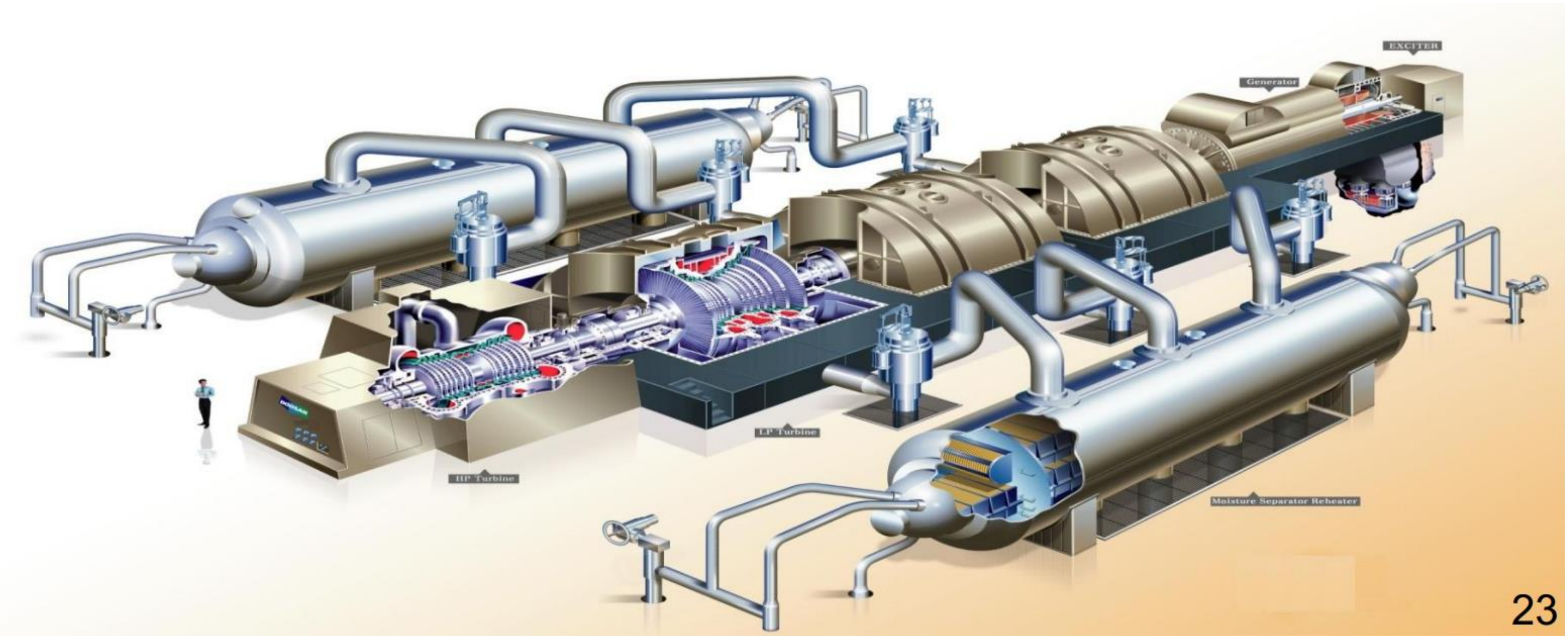
# Steam and Power Conversion System

## Main steam system

- Main steam line ⇒ High pressure turbine ⇒ Moisture separator/reheater ⇒ low pressure turbines (3) ⇒ main condenser (operated at a vacuum)

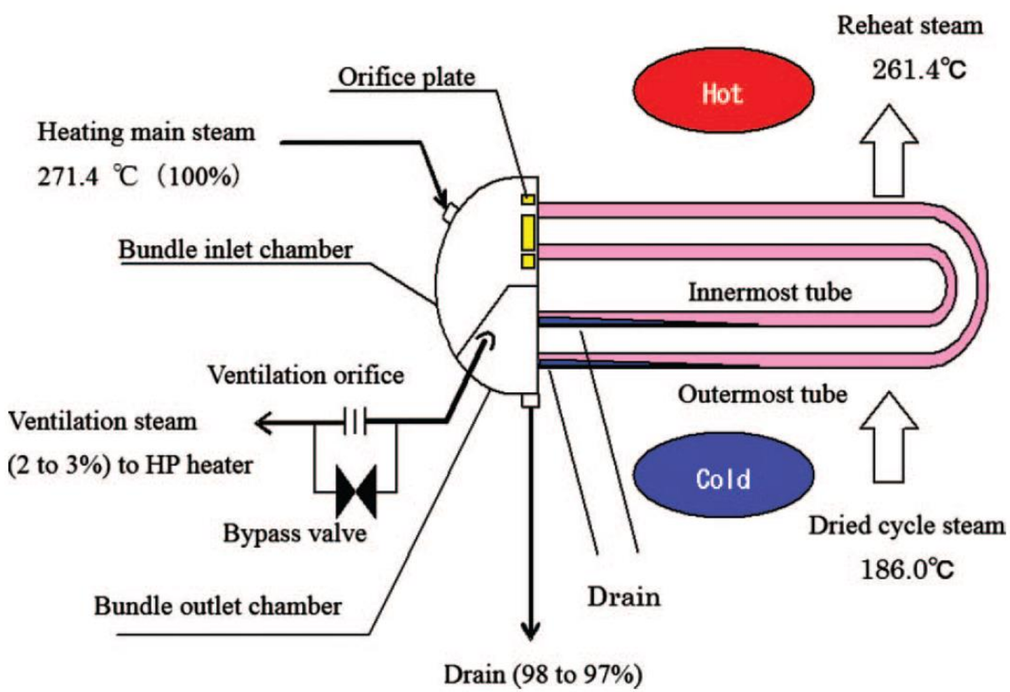


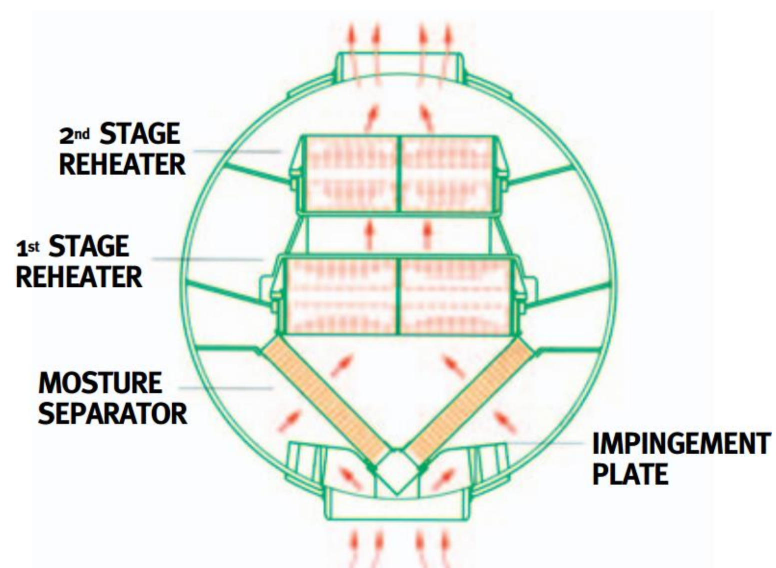
# Steam and Power Conversion System



## Main steam system

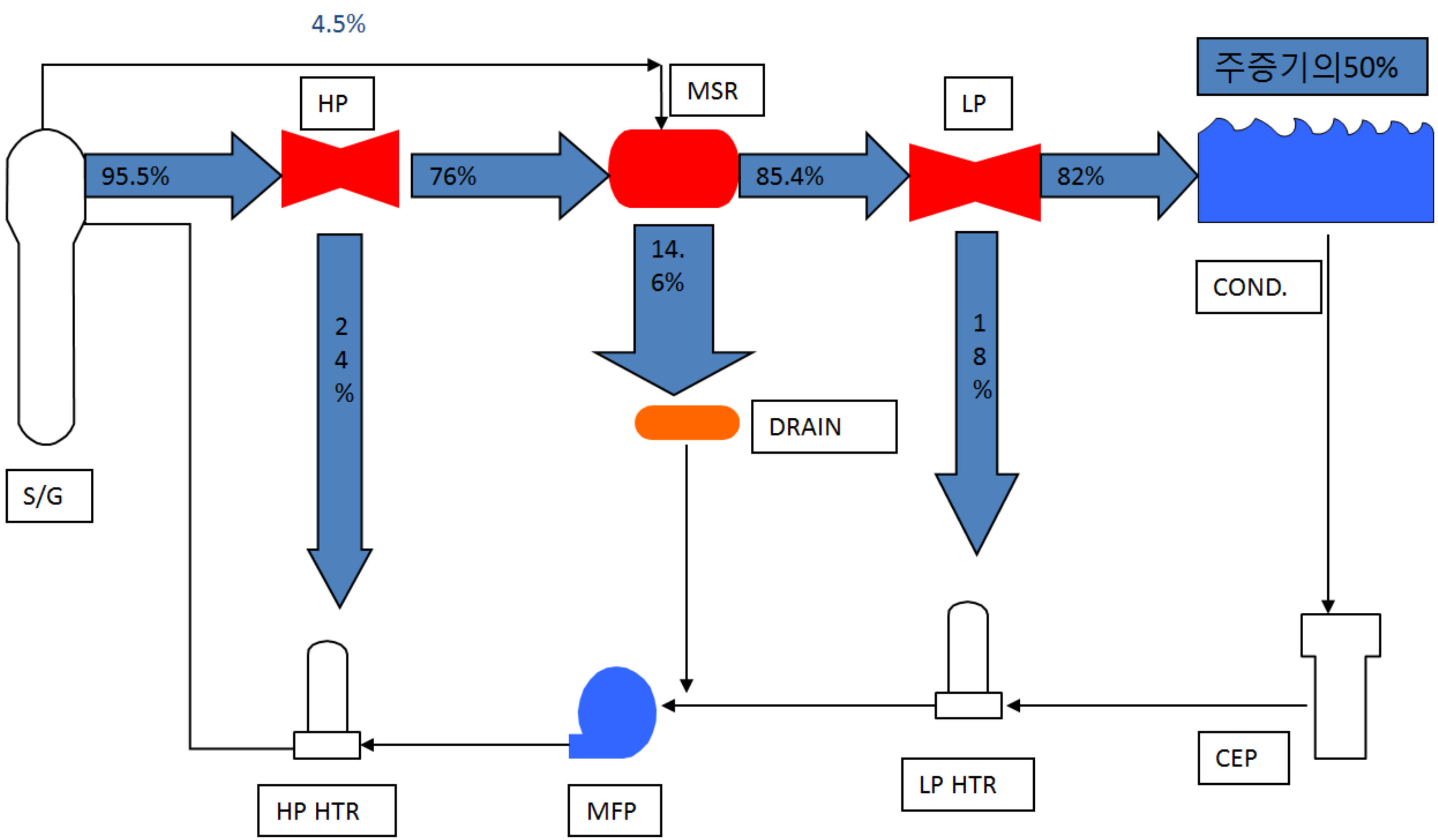
- Moisture separator/reheater



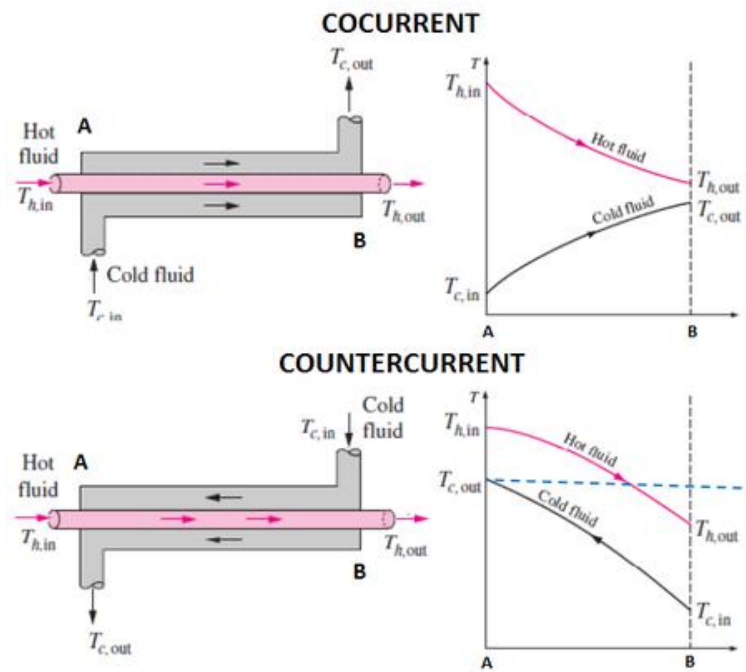
## Main steam system

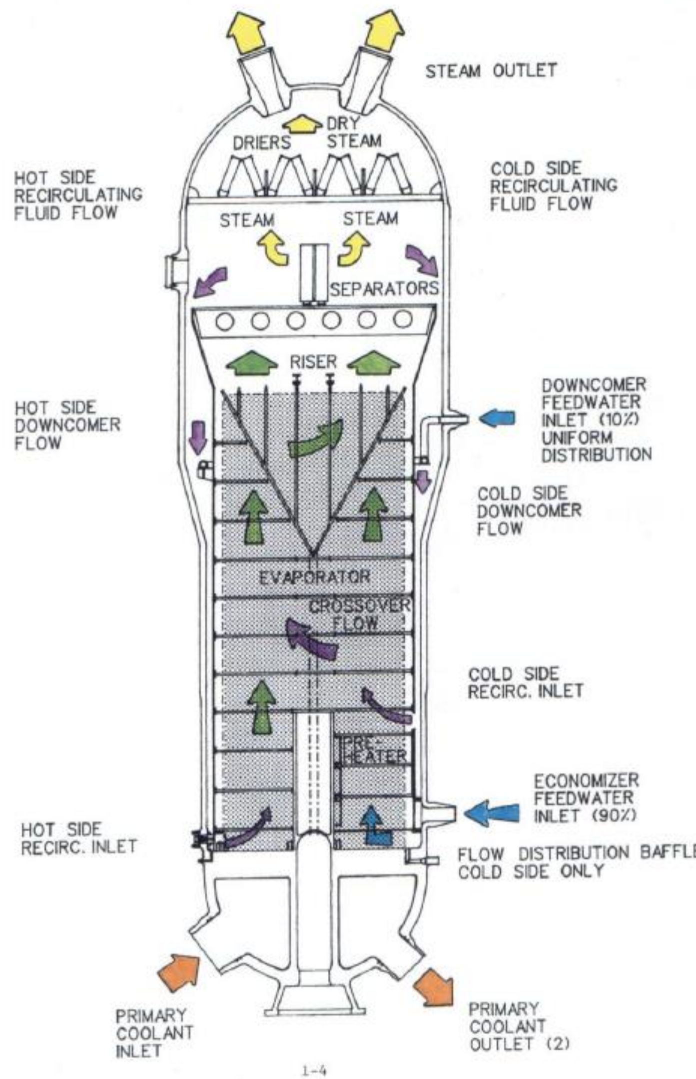
- High pressure turbine



## ❖ Counter-current heat exchanger

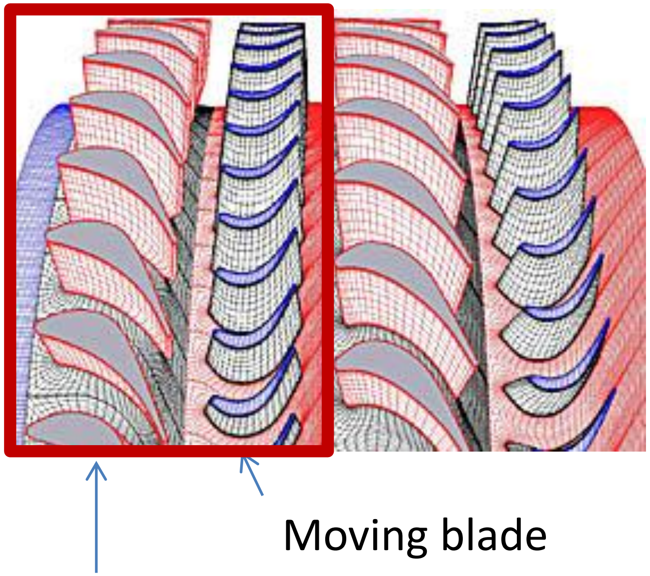
- **Why is it better ? (explain using LMTD)**
- **Check the following heat exchangers' flow directions**
  - Steam generator
  - Moisture separator reheater
  - Feedwater heater
  - Deaerator



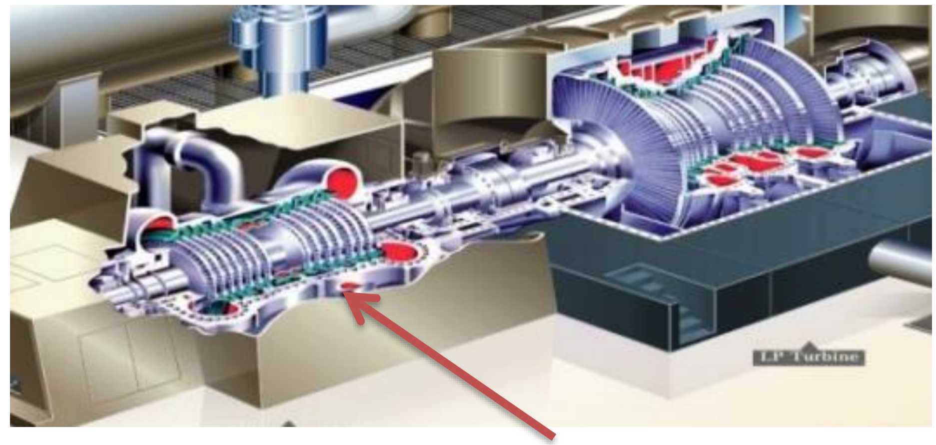
## ❖ Turbine

Stage



Moving blade

Stationary blade



HP Turbine: 7 stages (OPR1000)

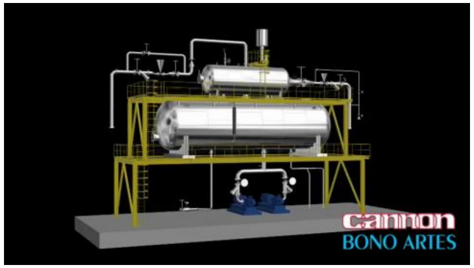
- 3rd or 10th stage: steam extraction for MSR / high pressure feedwater heater #7
- 5th or 12th stage: high pressure feedwater heater #6
- 7th or 14th stage: high pressure feedwater heater #5

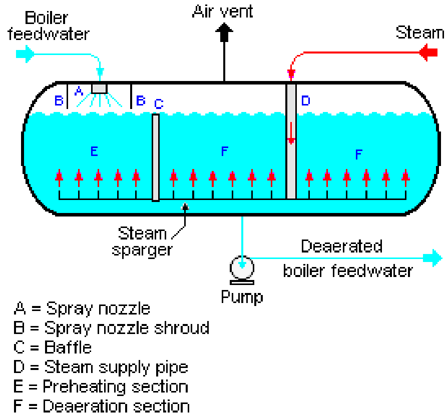
LP Turbine: 7 stages (OPR1000)

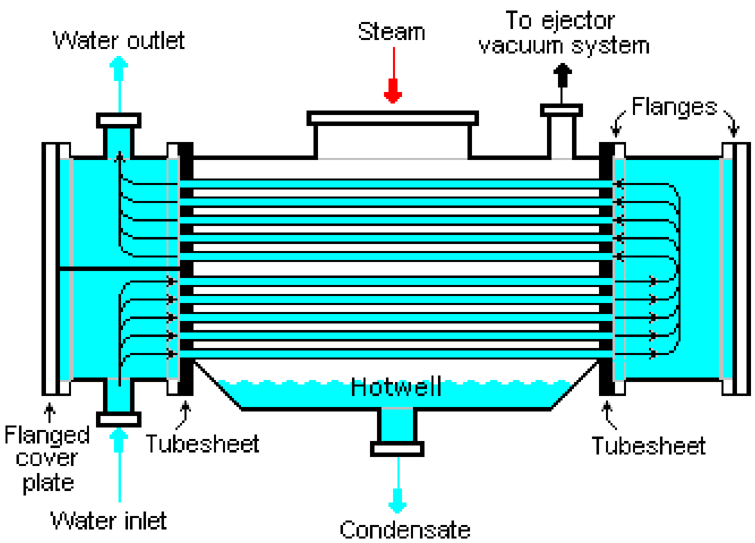
- 2nd or 9th stage: for deaerator
- 3rd or 10th stage: for low pressure feedwater heater #3
- 4th or 11th stage: for low pressure feedwater heater #2
- 6th or 13th stage: for low pressure feedwater heater #1

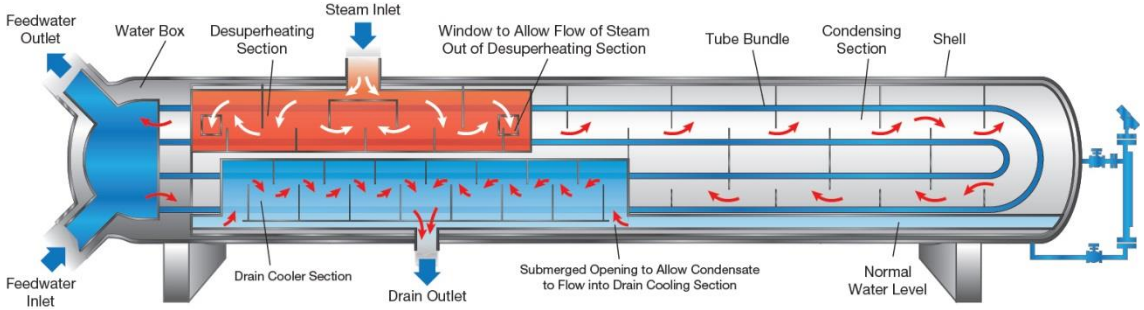
## Condensate system

- Main condenser/ Condenser vacuum system/ Condensate pump
- Condensate polishing system (복수탈염계통)
- Low pressure feed water heater
- Deaerator (탈기기)



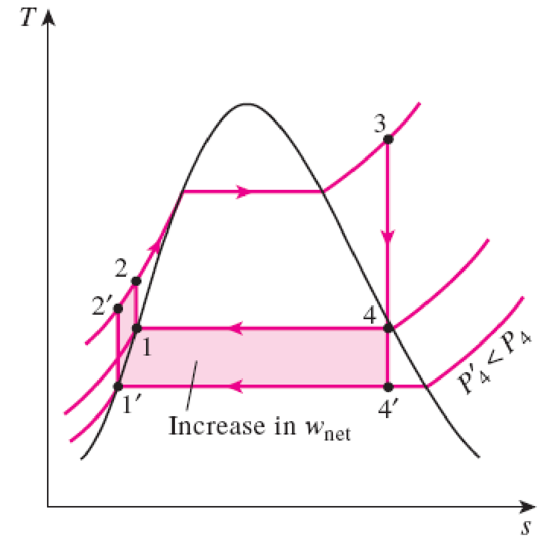



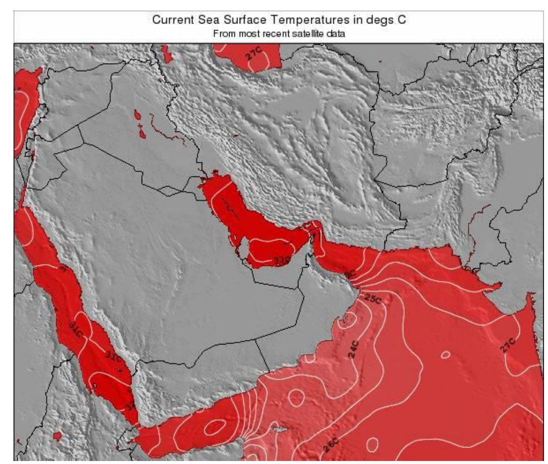



## Condenser

- To condense the exhaust steam from the turbine and recover the high-quality feedwater for reuse in the cycle
- To create a low back pressure (vacuum, 5 kPa, 33 °C)
  - The enthalpy drop, and hence, turbine work, per unit pressure drop
    - At low pressure >> at high pressure
  - Increased plant efficiency
  - Important to use cooling-water temperature that are the lowest available
- Heat sink: sea water, circulating water system



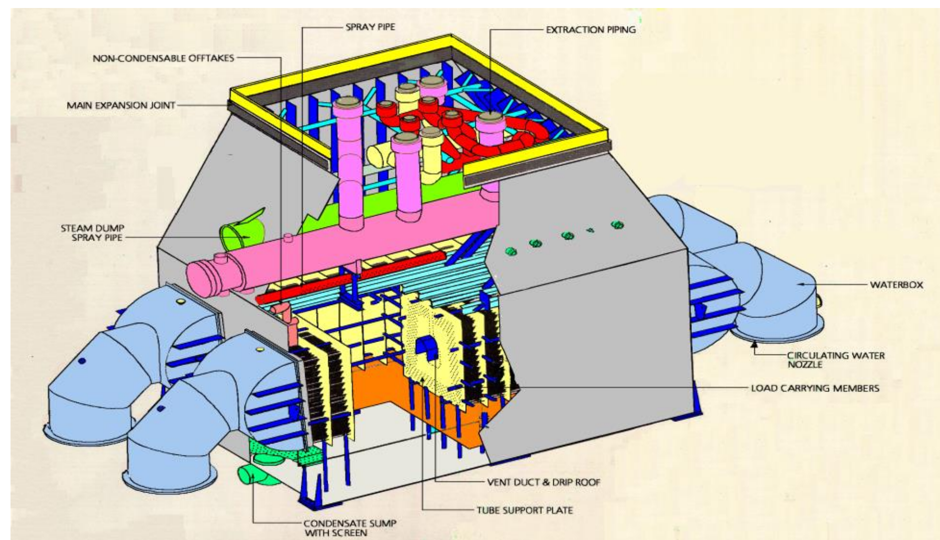

## Type of condenser

- Direct-contact condenser
- Surface condenser

## Surface condenser

- Most common type used in powerplants
  - Shell-and-tube heat exchangers
  - Condensing of saturated steam on the outside of the tubes
  - Forced-convection heating of the circulating water inside the tube
- Schematic of a surface condenser
  - Steel shell with water boxes
  - Tube sheets and support plates to prevent tube vibration

- OPR1000 main condenser
  - 3 shells
  - Single-pressure, single pass, surface condenser
  - Located below the low pressure turbines
  - Tubes are arranged perpendicular to the turbine shaft

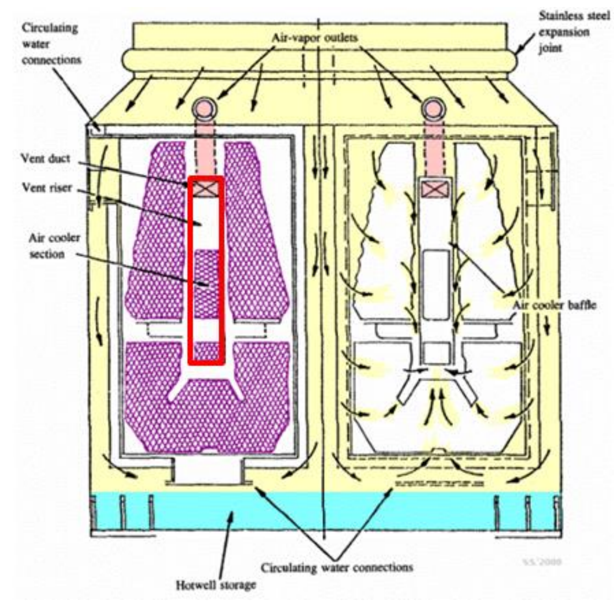


## ❖ Deaeration in condenser

- Deaeration (탈기)
- Removal of air molecules (usually meaning oxygen) from another gas or liquid
  - Deaerator (탈기기)
  - To remove the non-condensable gases
    - Otherwise, it can accumulate in the system.
- Non-condensable gases
  - Leak from atmosphere into the cycle
    - Condenser: operates below atmospheric pressure
    - Decomposition of water into oxygen and hydrogen by thermal or influence of nuclear radiation
    - Chemical reactions between water and materials
- Effect of non-condensable gases
  - Raise the total pressure of the system $\Rightarrow$ lower plant efficiency
  - Blanket the heat transfer surfaces (condenser outside surface) $\Rightarrow$ decrease condensing HTC
  - Cause various chemical activities $\Rightarrow$ corrosion (most severely in SG), hydriding by hydrogen, combustible

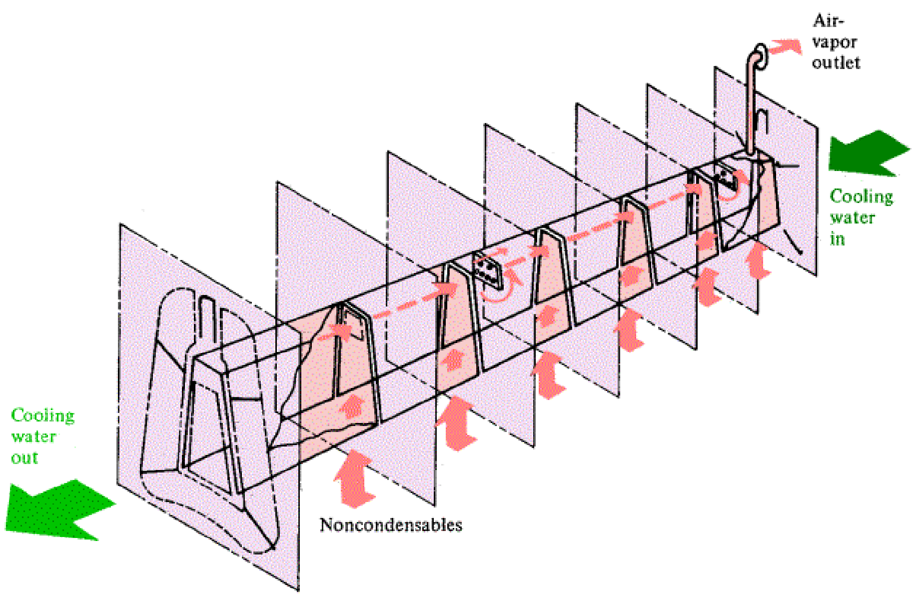
## Deaeration in condenser

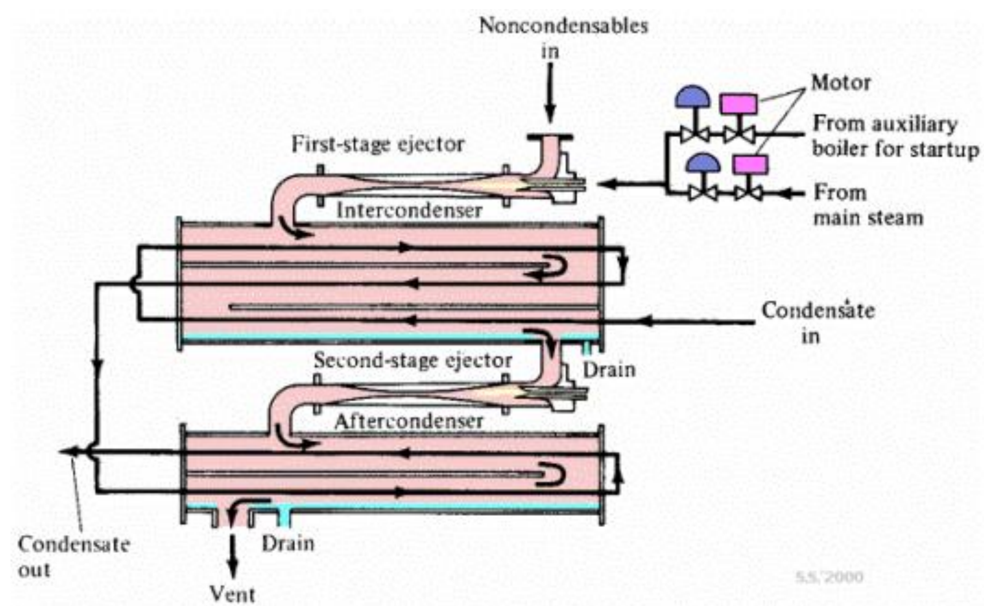
- Condenser
  - It is essential that the condenser itself be the place of good deaeration.
- Procedure
  - The cold condensate falling from the lower tubes with sufficient falling height and scrubbing steam
  - The scrubbing steam reheats the condensate.
    - Non-condensables are more easily released from a hotter than a colder liquid.
  - The released non-condensables are cooled to reduce their volume before being pumped out
    - 6~8 % of tubes are set aside
    - Air cooler section, baffled to separate the NCs from the main steam flow.
    - NCs flow toward the cold end of the condenser.
    - Connected to a vent duct
  - Venting equipment
    - Jet pump
    - Universal acceptance because of simplicity and lack of moving parts
    - Low maintenance and good reliability



## Deaeration

- Jet pump used on condensers: Steam-Jet Air Ejector (SJAE)
  - The condensed steam: returned to a low-pressure part of the cycle.
  - Second stage ejector
    - Compressed further and passed to an after condenser
  - Third stage ejector
    - May or may not necessary
    - To bring the system to the off-gas system in nuclear power plants



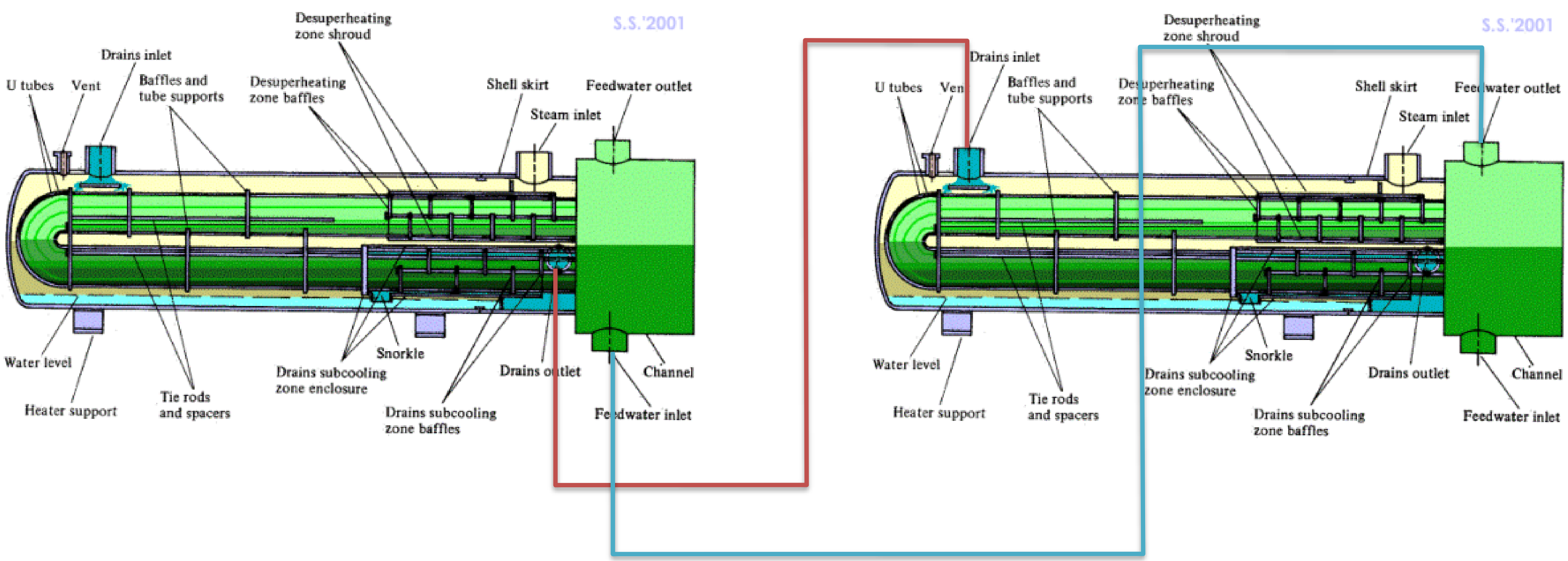
# Deaeration

- Jet pump used on condensers: Steam-Jet Air Ejector (SJAE)
  - Uses steam as their motive or driving flow
  - Usually two or three stages

- Principle
  - Steam enters a driving-flow nozzle in the first-stage ejector.
    - Exits with high velocity and momentum and reduced pressure.
  - Reduced pressure draws in the NCs from the condenser.
    - By a process of momentum exchange, the gases are entrained by steam jet
  - The combined flow of steam and NCs is compressed in the diffuser.
  - Discharged into a small intercondenser
    - Steam is condensed by passing across cooling pipes.
    - Cooling is accomplished by the main condenser condensate.
    - Part of the feedwater heating system
    - Improvement in efficiency

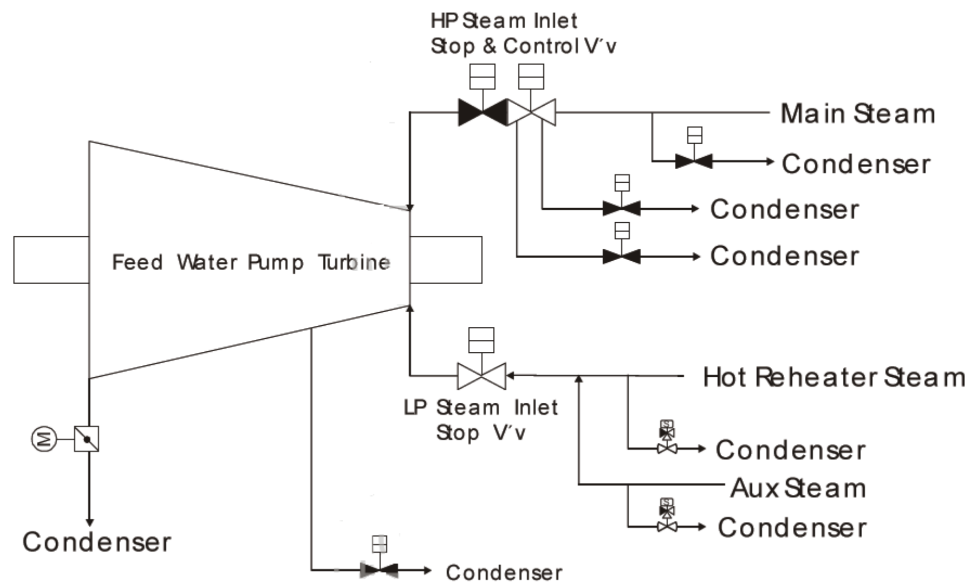
## Condensate system

- Main condenser/ Condenser vacuum system/ Condensate pump
- Condensate polishing system (복수탈염계통)
- Low pressure feed water heater
- Deaerator (탈기기)



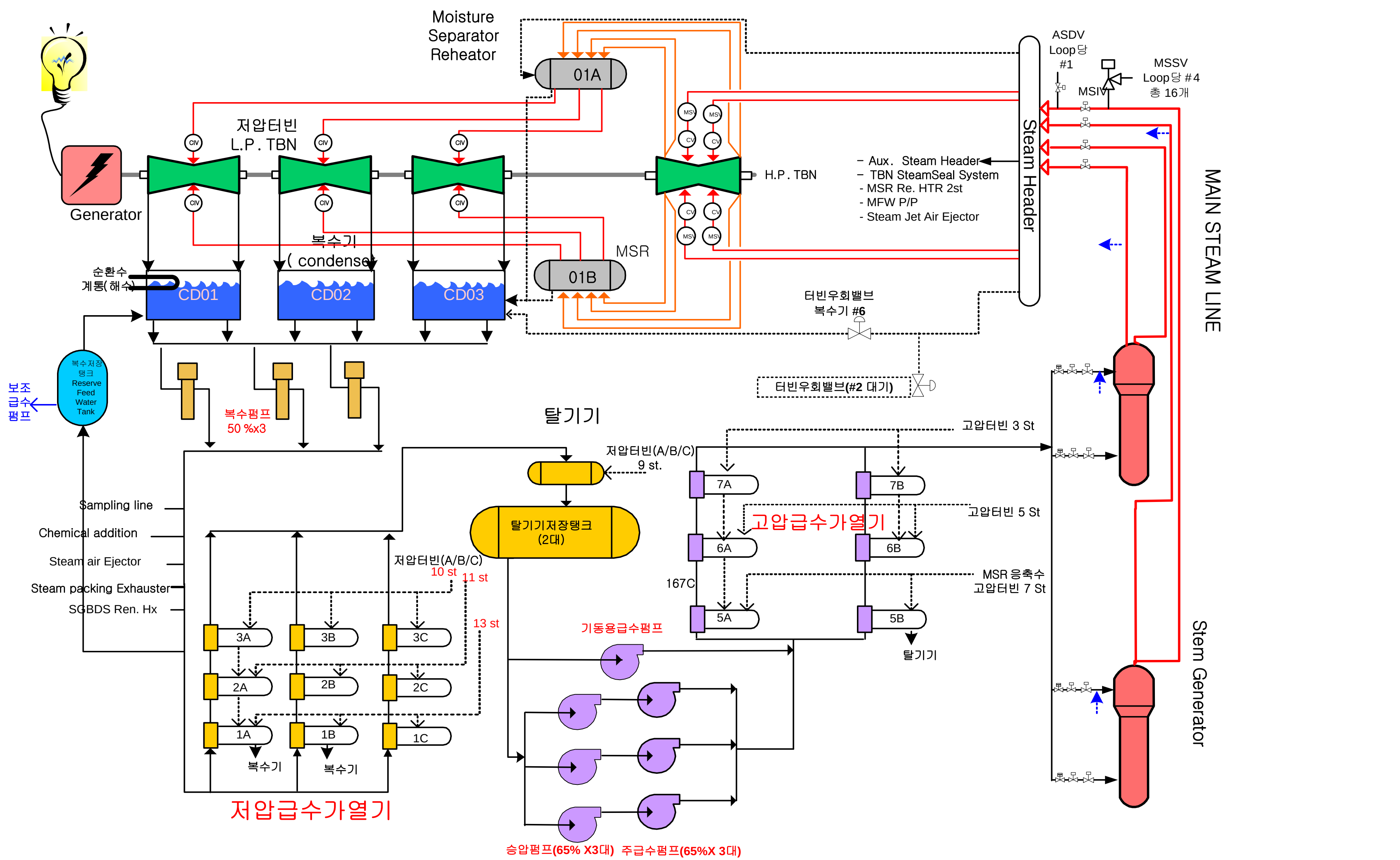
## Main feedwater system

- Feedwater booster pump (급수승압펌프)
- Main feedwater pump (주급수펌프)
  - 2 Turbine driven pumps, 1 motor driven pump
  - Steam: from main steam line (power<40% ), from MSR (otherwise)
- Startup feedwater pump (기동용 급수 펌프)
- High pressure feedwater heater
- Steam generator feedwater line
  - Downcomer feedwater
  - Economizer feedwater

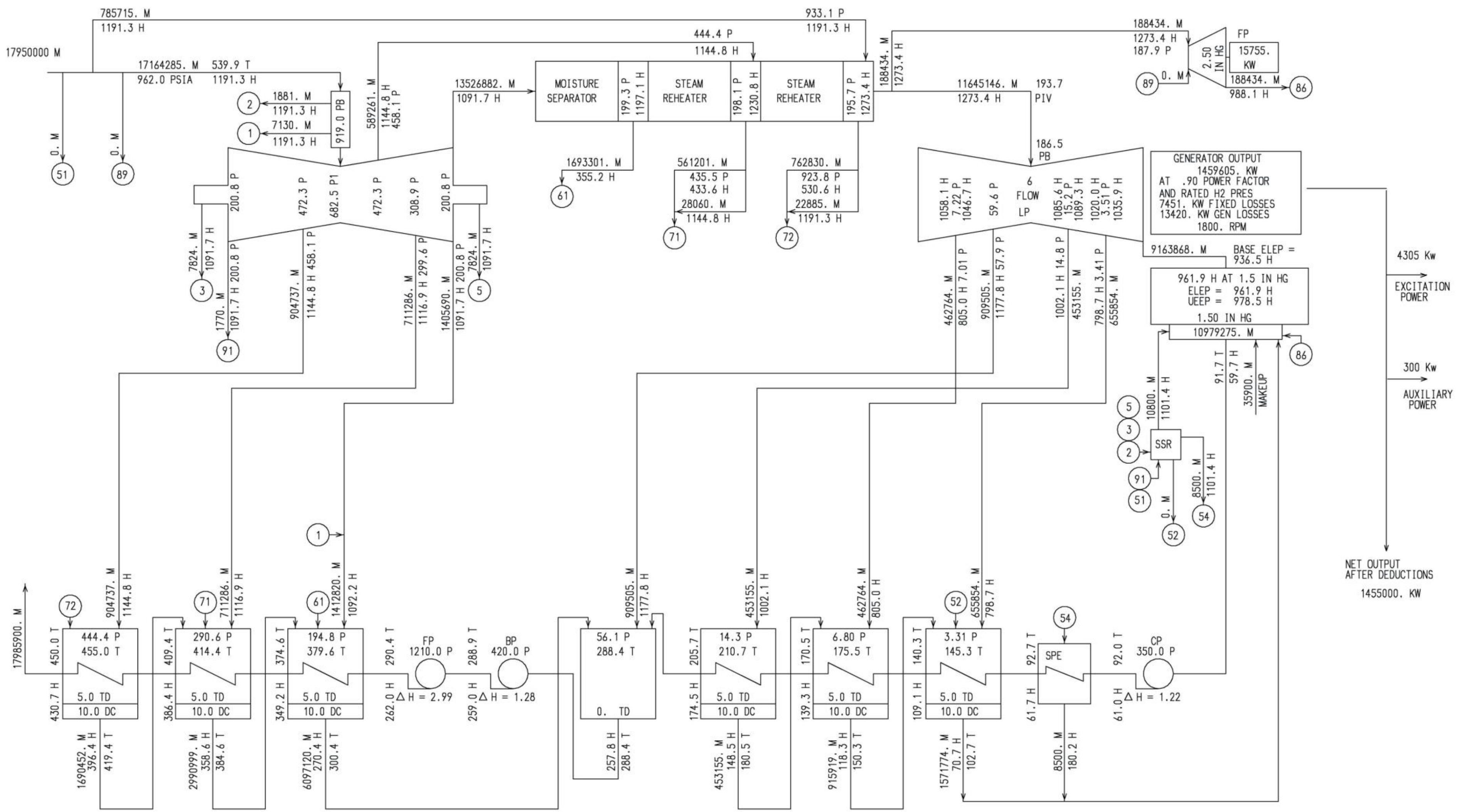


# Steam and Power Conversion System

## ❖ Condensate / main feedwater system (복수 및 주급수 계통)



# APR1400 Steam and Power Conversion System




* VALVE BEST POINT NET HEAT RATE $= \dfrac{17164286.\ (1191.3 - 430.7) + 785715.\ (1191.3 - 430.7)}{1459605} = 9353$ $\dfrac{\text{BTU}}{\text{KW-HR}}$

* VALVE BEST POINT GROSS HEAT RATE $= \dfrac{17164286.\ (1191.3 - 430.7) + 785715.\ (1191.3 - 430.7)}{1475360} = 9254$ $\dfrac{\text{BTU}}{\text{KW-HR}}$

LEGEND – CALCULATIONS BASED ON 1967 ASME STEAM TABLES
M – FLOW-LB/HR
P – PRESSURE-PSIA
H – ENTHALPY-BTU/LB
T – TEMPERATURE-F DEGREES

1455000. KW 1.50 IN HG ABS .20 PCT MU
TC6F 52.0 IN LSB 1800 RPM
962.0 PSIA 1191.3 BTU / LB 2 STAGE REHEAT
GEN- 1690000. KVA .90 PF LIQ

17164286. ( 1191.3 – 430.7 )

# Contents

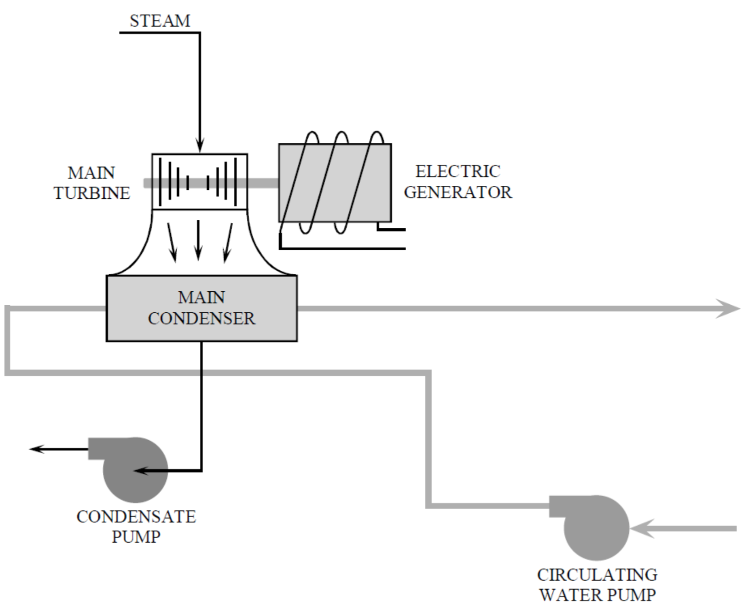
- **History of PWR**
- **Plant Overall**
- **Reactor Coolant System**
- **Steam and Power Conversion System**
- **Auxiliary System**
- **Plant Protection System**
- **Other systems**

Main Steam System
Condensate System
Main Feedwater System

CWS
CVCS
CCWS
ESWS
Fuel Storage and Handling System
Spent Fuel Pool Cooling and Clean up System (SFPCCS)
ESF (Engineered Safety Features)

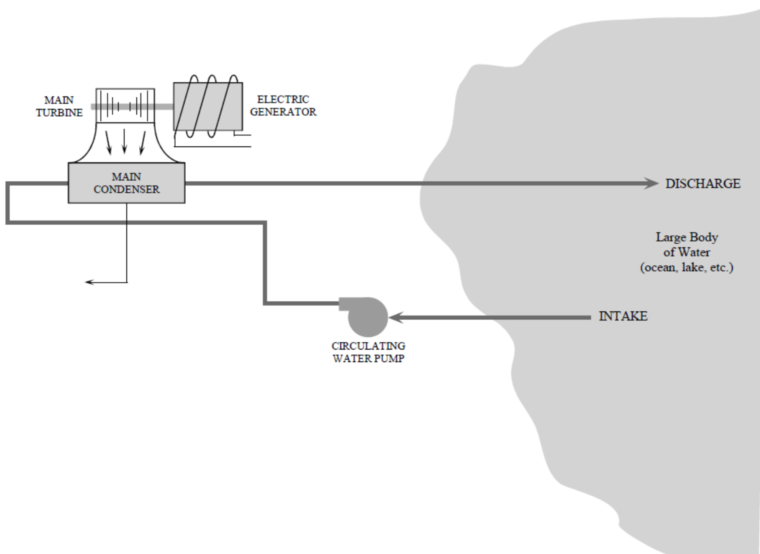
## Circulating water system

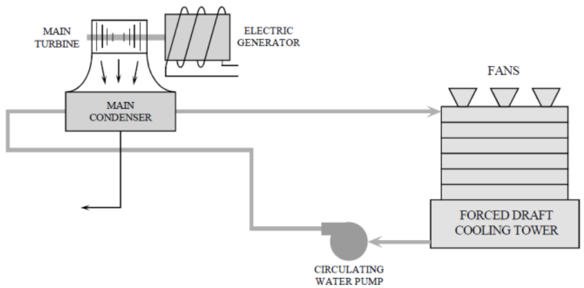
- To condense the steam and transfer that heat to the environment
- Main condenser
  - Steam condensation on thousands of condenser tubes
  - No physical contact between steam and the environment
  - In vacuum: any tube leakage will produce an inflow of water into condenser

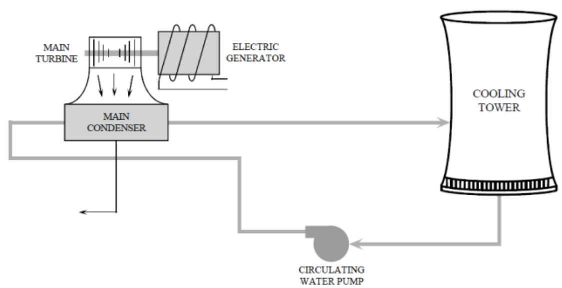


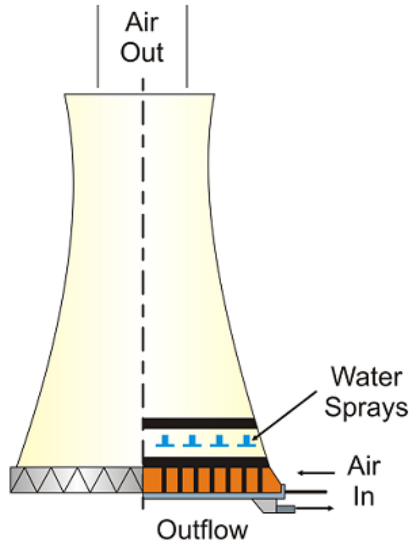

## Circulating water system

- Takes water from the ocean/lake and discharges back into it
  - Expected temperature increase: 5~10°C (for 1000 MW)
  - Flow rate: ~ 50 ton/sec.
- Cooling tower
  - Forced draft cooling tower
  - Natural convection cooling tower



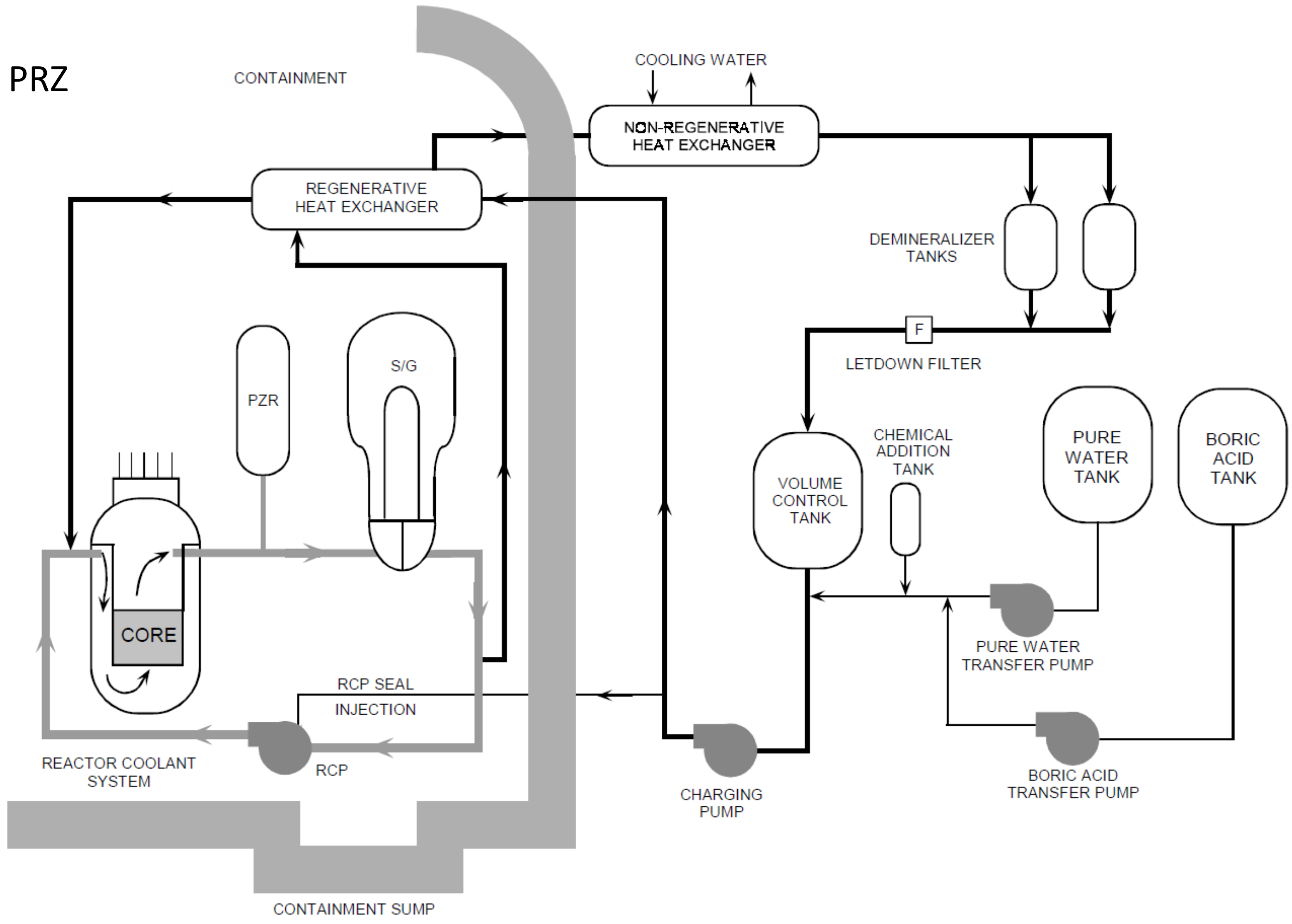




## ❖ CVCS (Chemical and Volume Control System)

- Major support system for RCS
  - Purify RCS using filters and demineralizers, minimize the amount of radioactive material in coolant
  - Add/remove boron
  - Maintain the level of PRZ
- Volume control tank
- Letdown line
- Charging line



## CCWS (Component Cooling Water System)

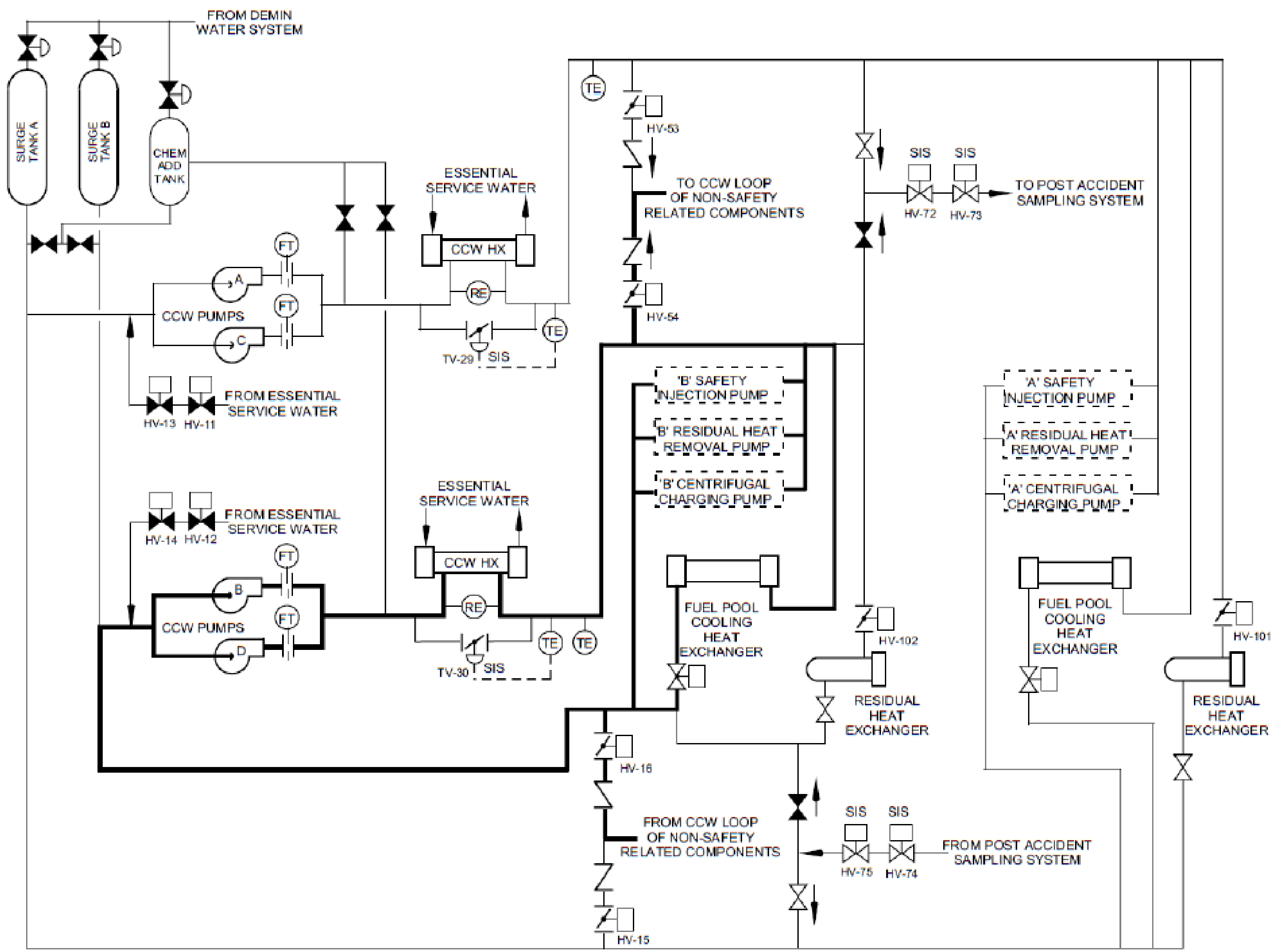
- Closed loop, two independent trains
- Provide coolant to components
- Cooled by ESWS (Essential Service Water System)
- CCW pumps
- CCW heat exchanger
  - Tube: ESWS
  - Shell: CCW
- Surge tank (완충 탱크)

**발전소 기기냉각수 요구 설비 [울진5,6호기]**

| 기기냉각수가 요구되는 설비 | 1차 기기냉각수 | | 2차 기기 냉각수 |
|---|---|---|---|
| | 안전등급 | 비안전등급 | |
| 1. 격납건물 살수 열교환기[주1)] | ✓ | | |
| 2. 정지냉각 열교환기[주2)] | ✓ | | |
| 3. 안전주입 펌프 모타 냉각기 | ✓ | | |
| 4. 보조급수 펌프 모타 냉각기 | ✓ | | |
| 5. 기기냉각수 펌프 모타 냉각기 | ✓ | | |
| 6. 비상디젤 발전기 냉각기 | ✓ | | |
| 7. 필수냉동기 응축기 | ✓ | | |
| 8. 사용후연료저장조 열교환기 | ✓ | | |
| 1) 원자로냉각재펌프 밀봉수 냉각기[주3)] | | ✓ | |
| 2) 유출수 열교환기 | | ✓ | |
| 3) 탈기기 | | ✓ | |
| 4) 붕산농축기 | | ✓ | |
| 5) 일차시료채취계통 시료 냉각기(정상 및 사고후 시료냉각기) | | ✓ | |
| 6) 방사선감시기 열교환기 | | ✓ | |
| 7) 격납건물 냉동기 응축기 | | ✓ | |
| 8) 복수회수탱크 배기 응축기 | | ✓ | |
| 9) 증기발생기 취출 비재생열교환기 | | ✓ | |
| 10)방사성폐기물건물 냉동기 응축기 | | ✓ | |
| 11)충전펌프 최소유량 열교환기 | | ✓ | |
| 12)액체방사성폐기물계통 밀봉수 열교환기 | | ✓ | |
| 13)기체방사성폐기물계통 냉동기 스키드 | | ✓ | |
| ① 공정시료채취계통 냉각기 | | | ✓ |
| ② 터빈건물 냉방기 | | | ✓ |
| ③ 2차측 기기냉각해수 펌프 전동기 베어링 냉각기 | | | ✓ |
| ④ 급수펌프 터빈 윤활유 냉각기 | | | ✓ |
| ⑤ 급수 승압펌프 윤활유/기계적 밀봉 냉각기 | | | ✓ |
| ⑥ 동기구동 급수펌프 윤활유/작동유 냉각기 | | | ✓ |
| ⑦ 기동 급수펌프 윤활유/기계적 밀봉 냉각기 | | | ✓ |
| ⑧ 복수펌프 전동기베어링 냉각기 | | | ✓ |
| ⑨ 공기압축기 중간냉각기, 후단냉각기 및 윤활유 냉각기[주4)] | | | ✓ |
| ⑩ 주 터빈 윤활유 냉각기 | | | ✓ |
| ⑪ 발전기 수소 냉각기 | | | ✓ |
| ⑫ 발전기 고정자 냉각기 | | | ✓ |
| ⑬ 상분리모선 덕트 냉각기 | | | ✓ |

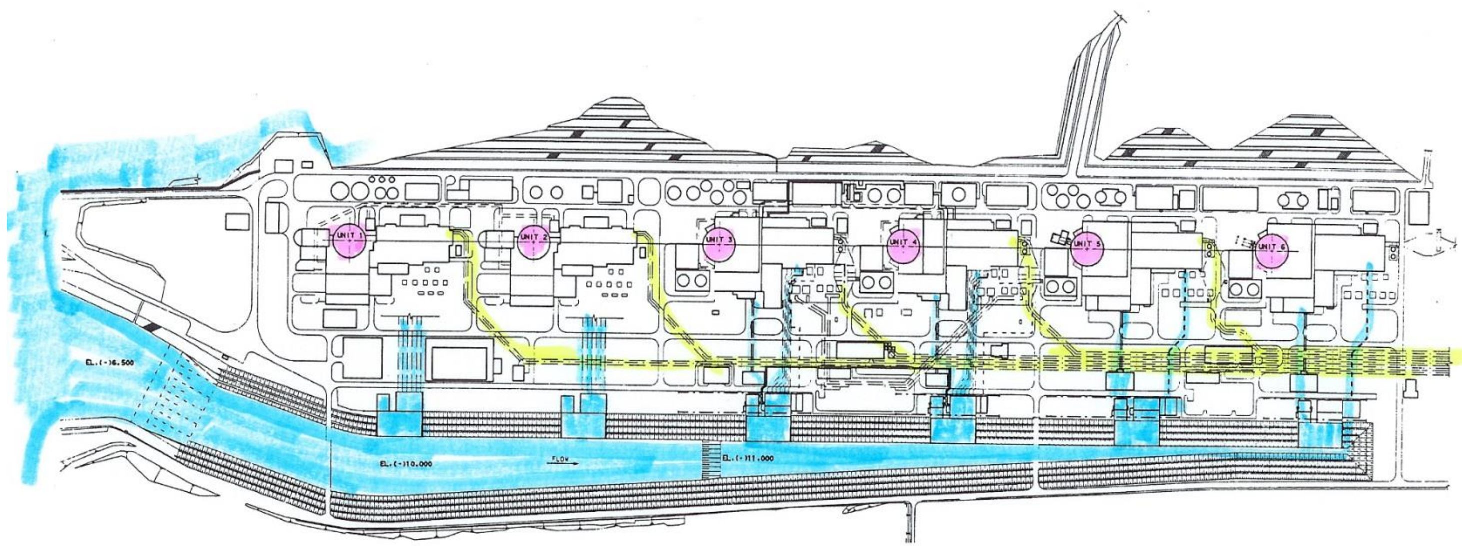
주 1) RHR : 펌프 모타 열교환기, Miniflow 열교환기 포함
2) CV : 격납용기 살수펌프 모타 열교환기, Miniflow 열교환기 포함
3) RCP : 오일냉각기, 고압냉각기, 펌프모터 오일냉각기, 펌프모터 공기냉각기 포함
4) IA : 1대의 공기압축기 냉각수 제공을 위한 독립적인 폐회로 냉각계통 포함

## ❖ CCWS (Component Cooling Water System)

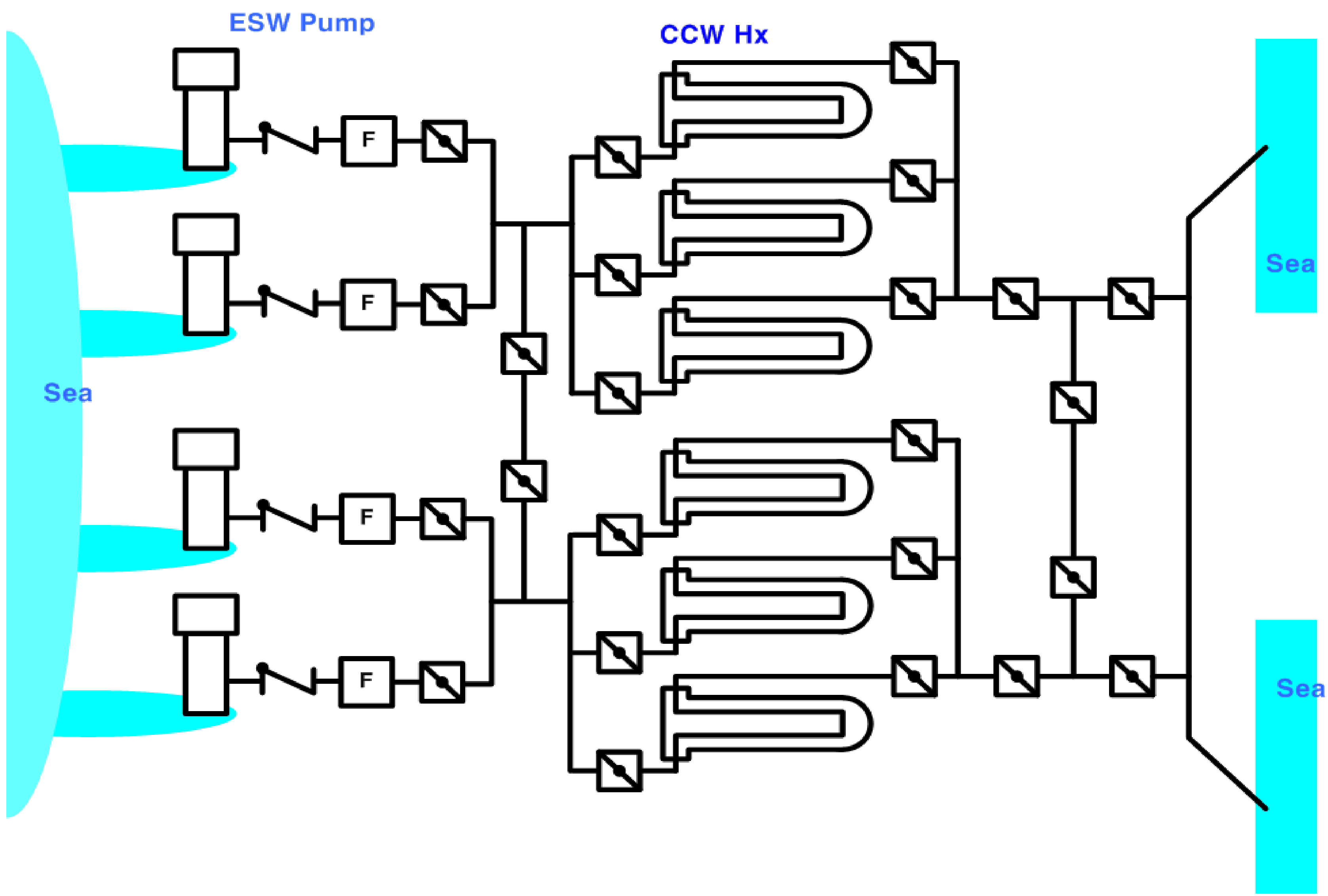


## ESWS (Essential Service Water System)

- Open loop, two independent trains
- Provide cooling water
  - CCWS HX, emergency diesel generator HXs, ESW pump room coolers
- Since the water is frequently drawn from an adjacent river, the sea, or other large body of water, the system can be endangered by large volumes of seaweed, marine organisms, oil pollution, ice and debris.
- In locations without a large body of water in which to dissipate the heat, water is recirculated via a cooling tower.

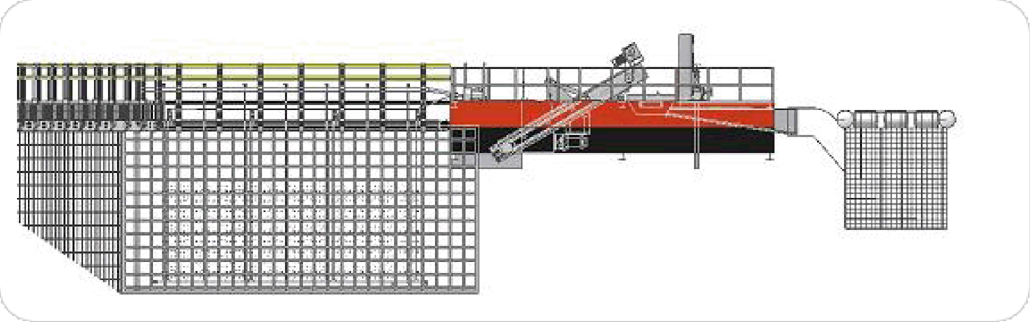


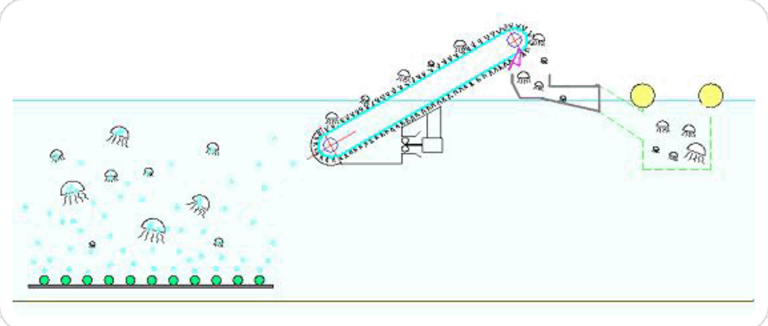
## ❖ ESWS (Essential Service Water System)



## ❖ ESWS (Essential Service Water System)

- 운전경험
  - 해수 취수구 이물질, 가시고기, 해파리, 새우 떼 유입에 의한 발전정지 및 원자로 정지
  - 1988 고리4호기
    - 가시고기떼 유입으로 순환수계통 압력 상승 ⇒ 원자로 수동정지
  - 1991 고리4호기
    - 태풍 글래디스의 영향으로 취수구에 다량의 오물이 유입
    - 2차 기기냉각해수 유량상실 ⇒ 2차측 기기온도 증가 / 복수기 진공 저하 ⇒ 터빈 및 원자로 정지
  - 2001 울진1,2호기, 2006 울진1,2호기
    - 새우떼 취수구 유입 ⇒ 순환수펌프 정지 ⇒ 복수기 진공 저하 ⇒ 주급수펌프 정지 ⇒ 원자로 정지
  - 2014 월성 3호기
    - 월성3호기 계획예방정비 중 취수구 잠수작업자 인명사고 발생



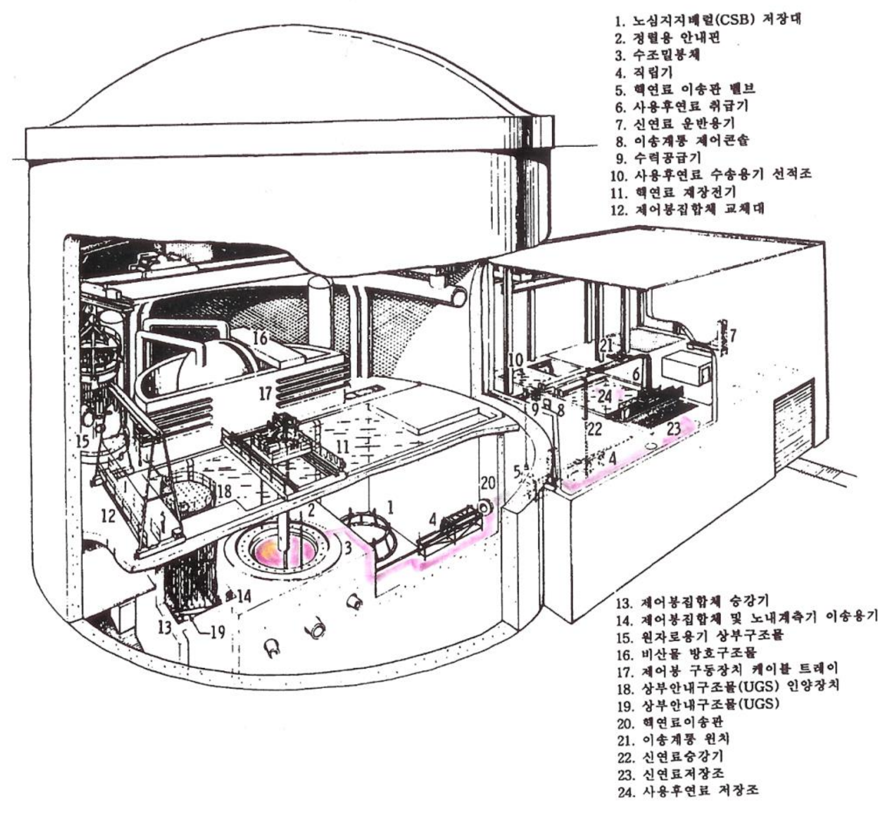


## Fuel Storage and Handling System

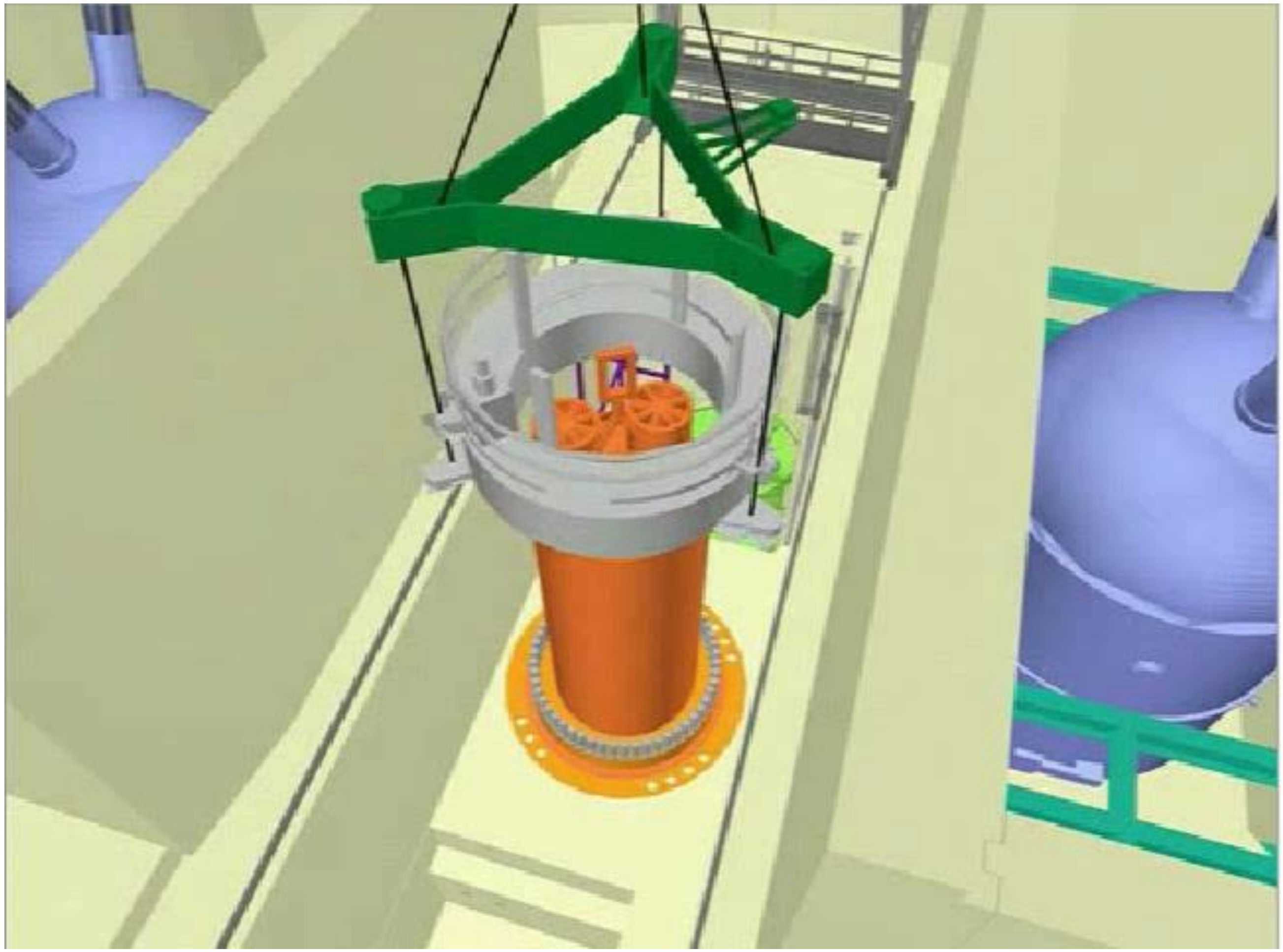
- Nuclear fuel
  - Contains fissile material and, after irradiation, highly radioactive fission and activation products.
- The most significant design features
  - Provide the necessary assurances that the fuel and core components can be received, handled, stored and retrieved without undue risk to health, safety or the environment.
  - Maintaining subcriticality of the fuel
  - Ensuring the integrity of the fuel
  - Cooling irradiated fuel
  - Ensuring radiation protection and safety

    in accordance with the Basic Safety Standards
  - Preventing unacceptable releases of

    radioactive material to the environment.

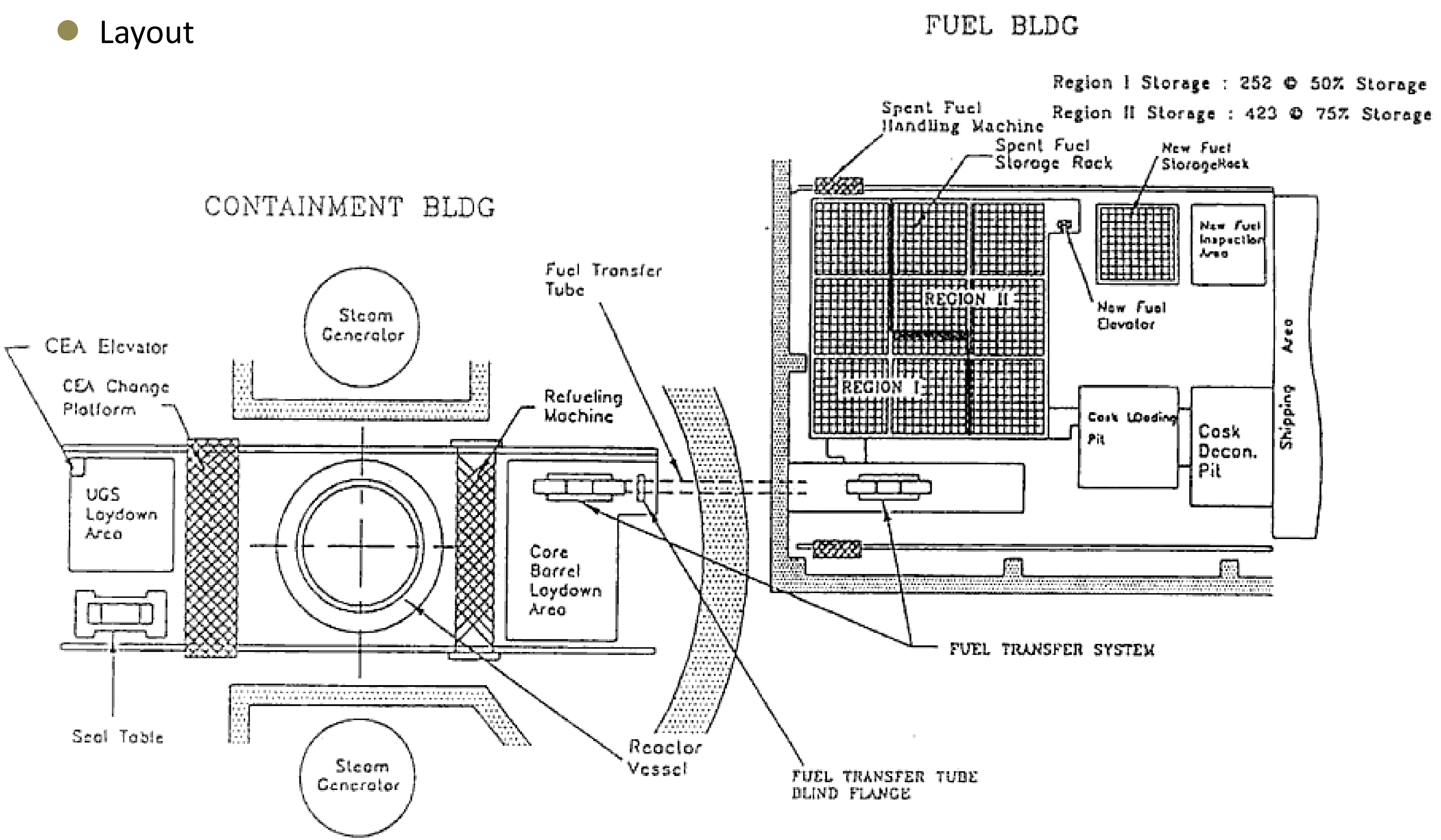


❖ **Fuel Storage and Handling System**

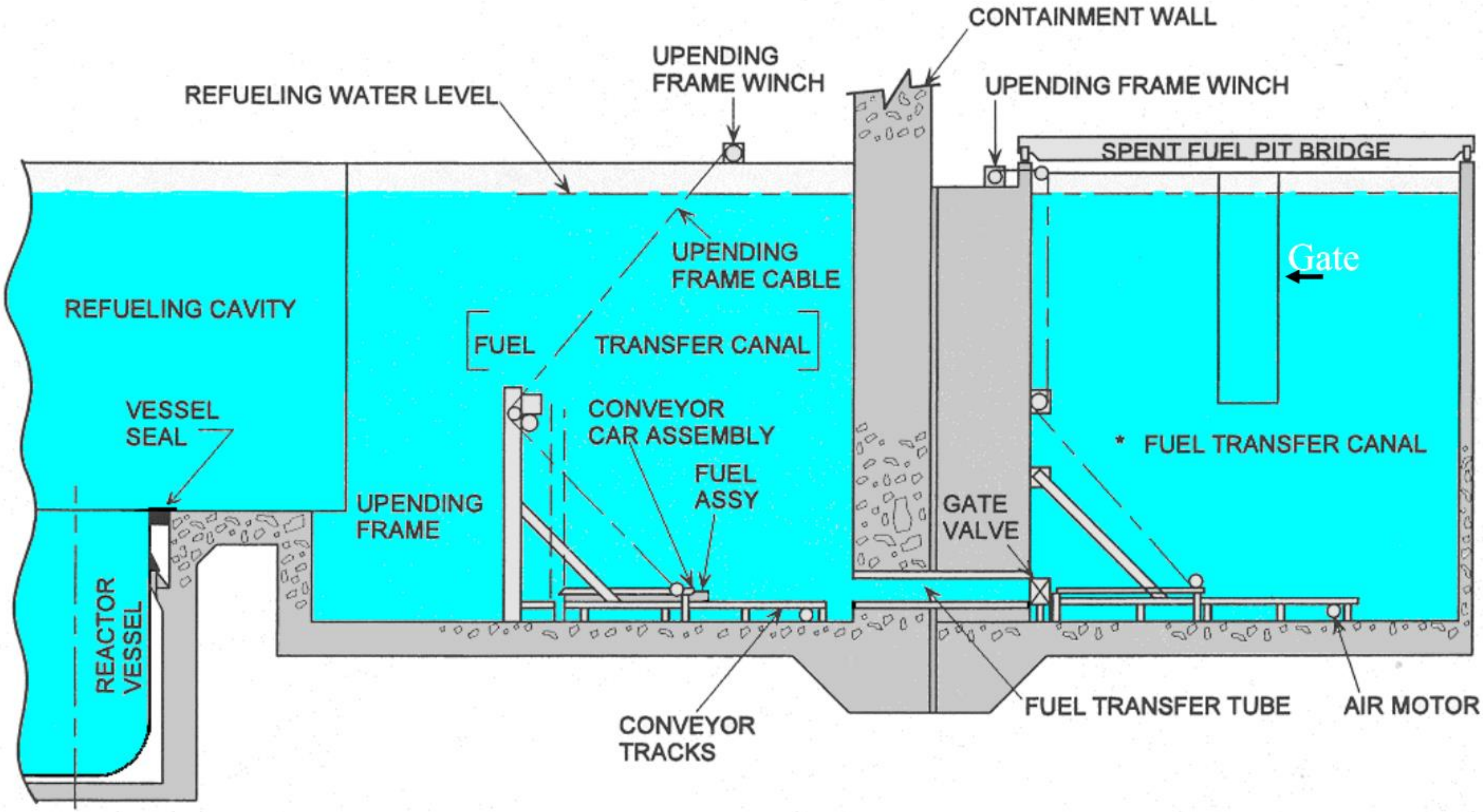


## ❖ Fuel Storage and Handling System

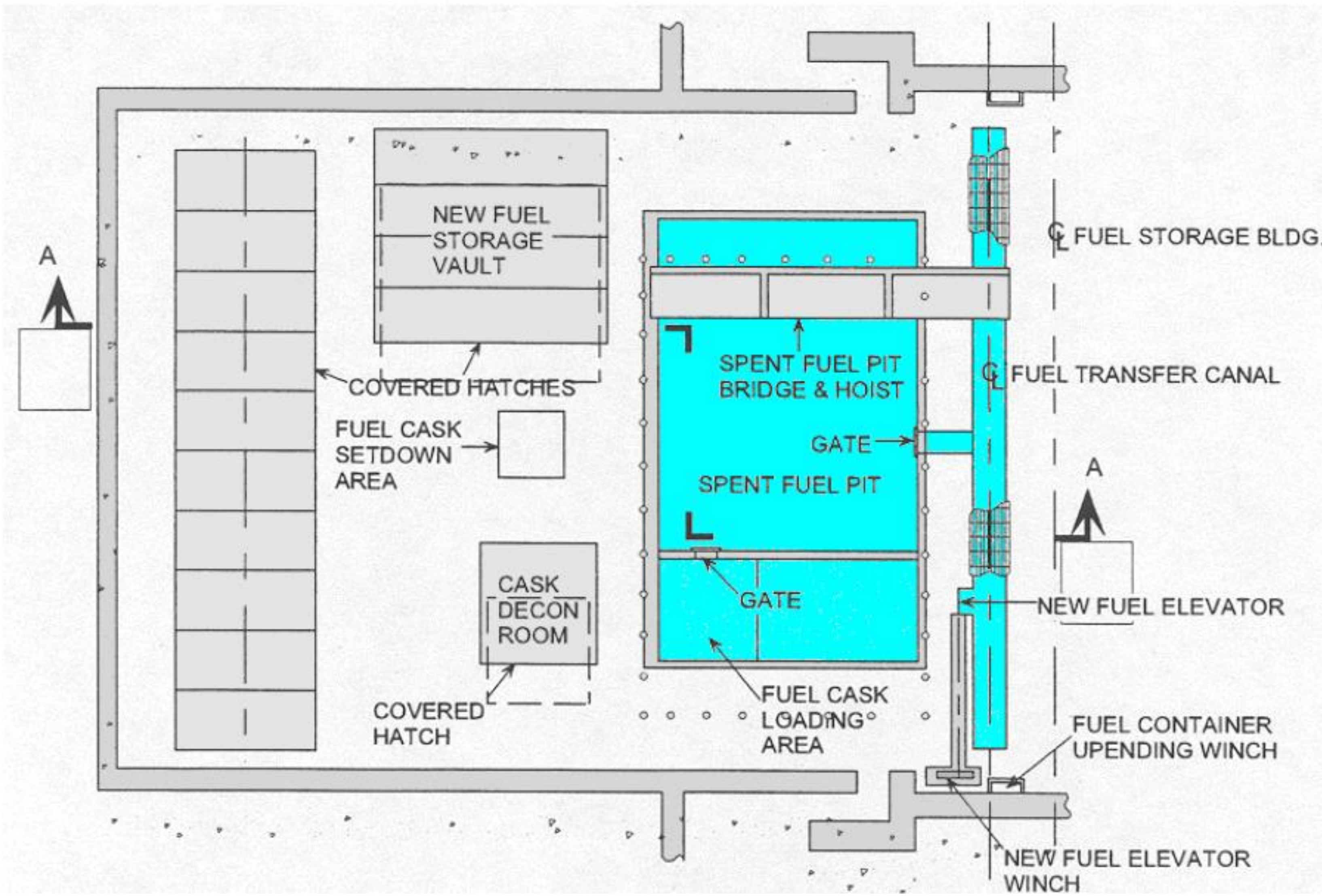
- Layout



## ❖ Fuel Storage and Handling System

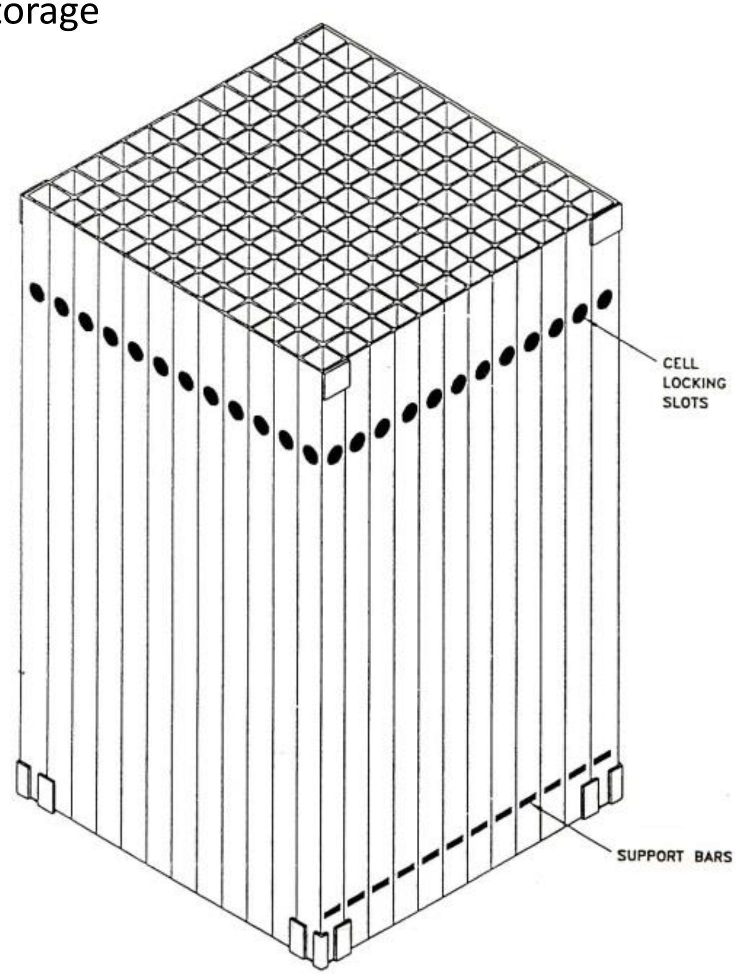


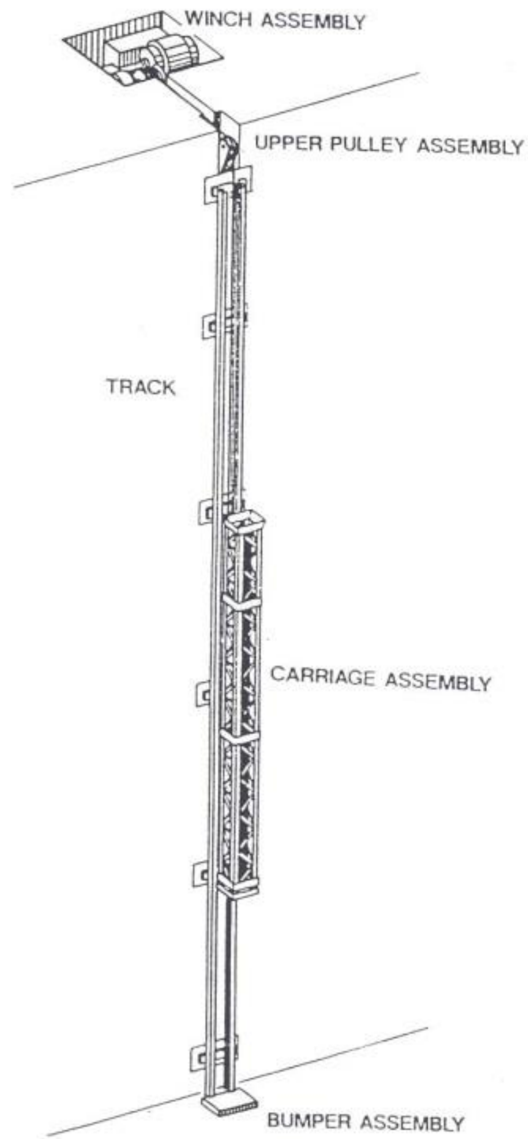
## ❖ Fuel Storage and Handling System



## ❖ Fuel Storage and Handling System

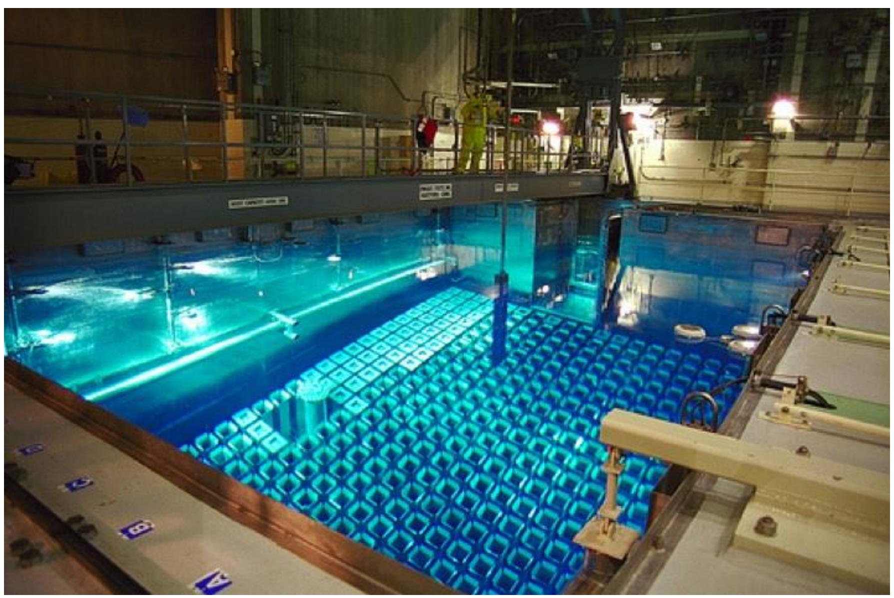
- Fresh fuel (new fuel)
  - Fuel storage racks/ New fuel elevator
  - Dry storage

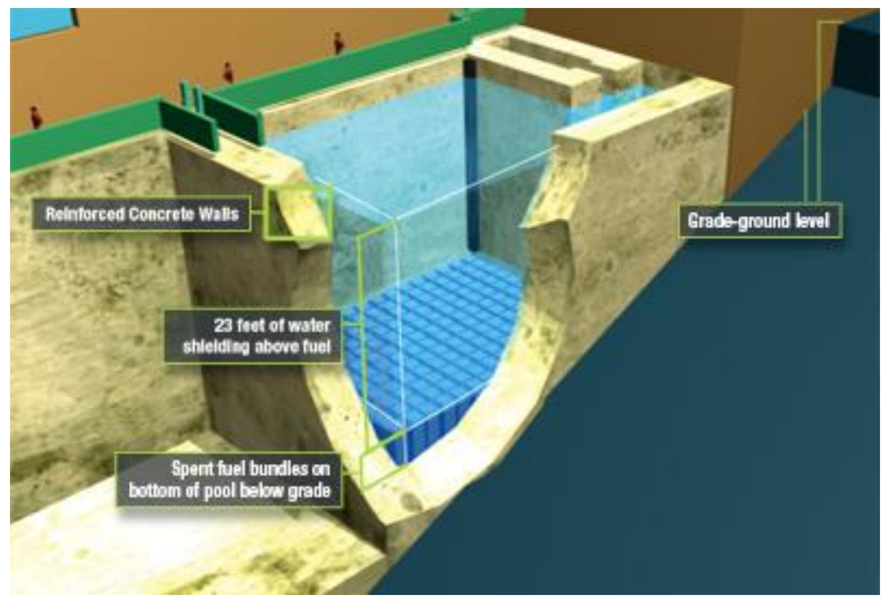


## Fuel Storage and Handling System

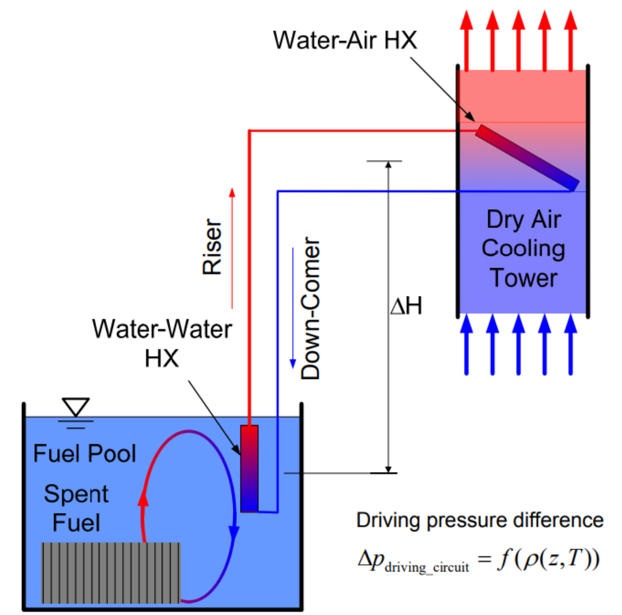
- Spent fuel pools
  - Located inside the plant's protected area.
  - Contain an enormous quantity of water, which acts to cool the fuel and provide radiation shielding.
  - Have no drains that would allow the water to drain out. Can be filled using a variety of water sources, if needed.
  - Have large safety margins, including about 20 feet of water above the top of the fuel
  - Are robust, with very thick, steel-reinforced concrete walls and stainless-steel liners.
  - May be located below ground level, shielded by other structures, or surrounded by walls that would protect the pool from a plane crash or other impact.

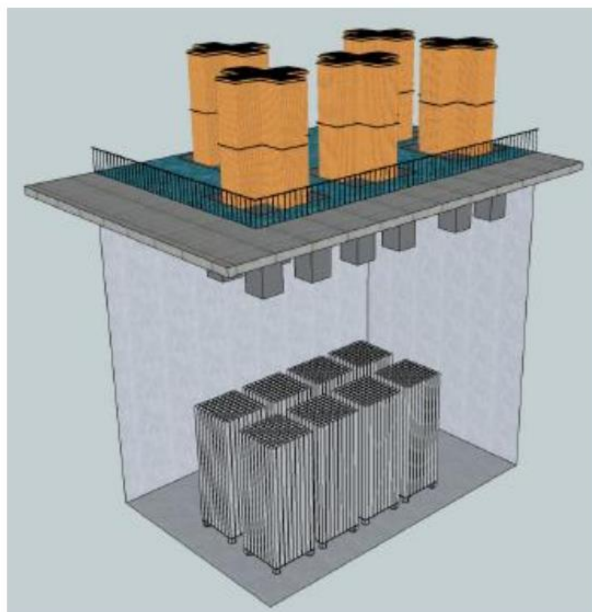


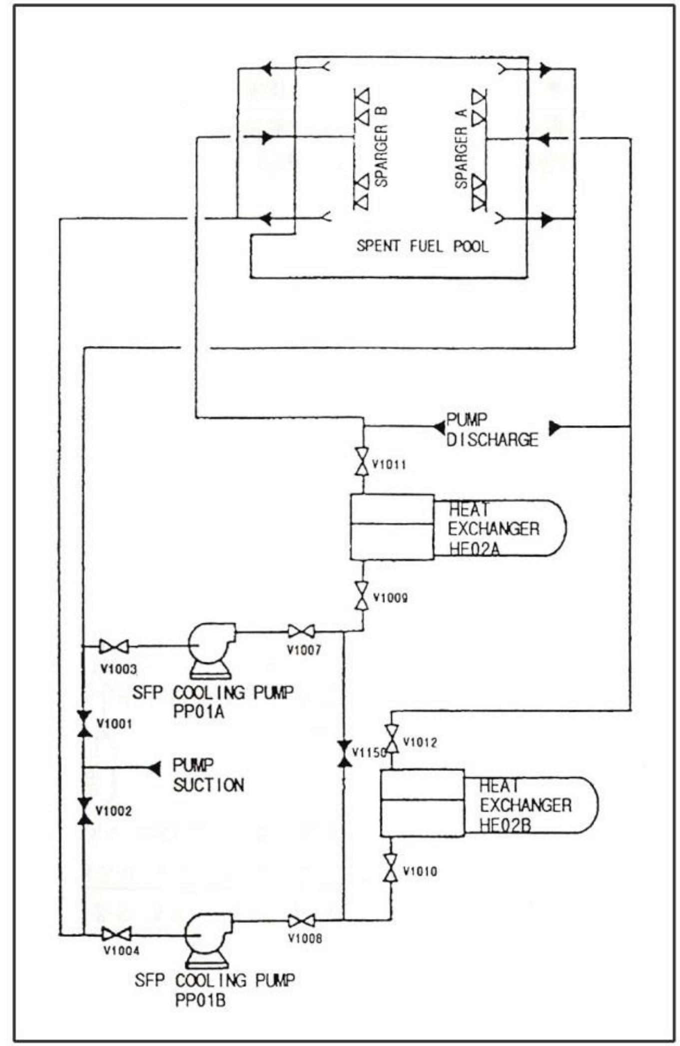


## Spent Fuel Pool Cooling and Clean up System (SFPCCS)

- Spent fuel pool cooling
  - To remove decay heat from the spent fuel
  - To maintain the water pool temperature, $T_{bulk}$<60°C





# Contents

- **History of PWR**
- **Plant Overall**
- **Reactor Coolant System**
- **Steam and Power Conversion System**
- **Auxiliary System**
- **Plant Protection System**
- **Other systems**

Main Steam System
Condensate System
Main Feedwater System

CWS
CVCS
CCWS
ESWS
Fuel Storage and Handling System
Spent Fuel Pool Cooling and Clean up System (SFPCCS)
ESF (Engineered Safety Features)

# Engineered Safety Features

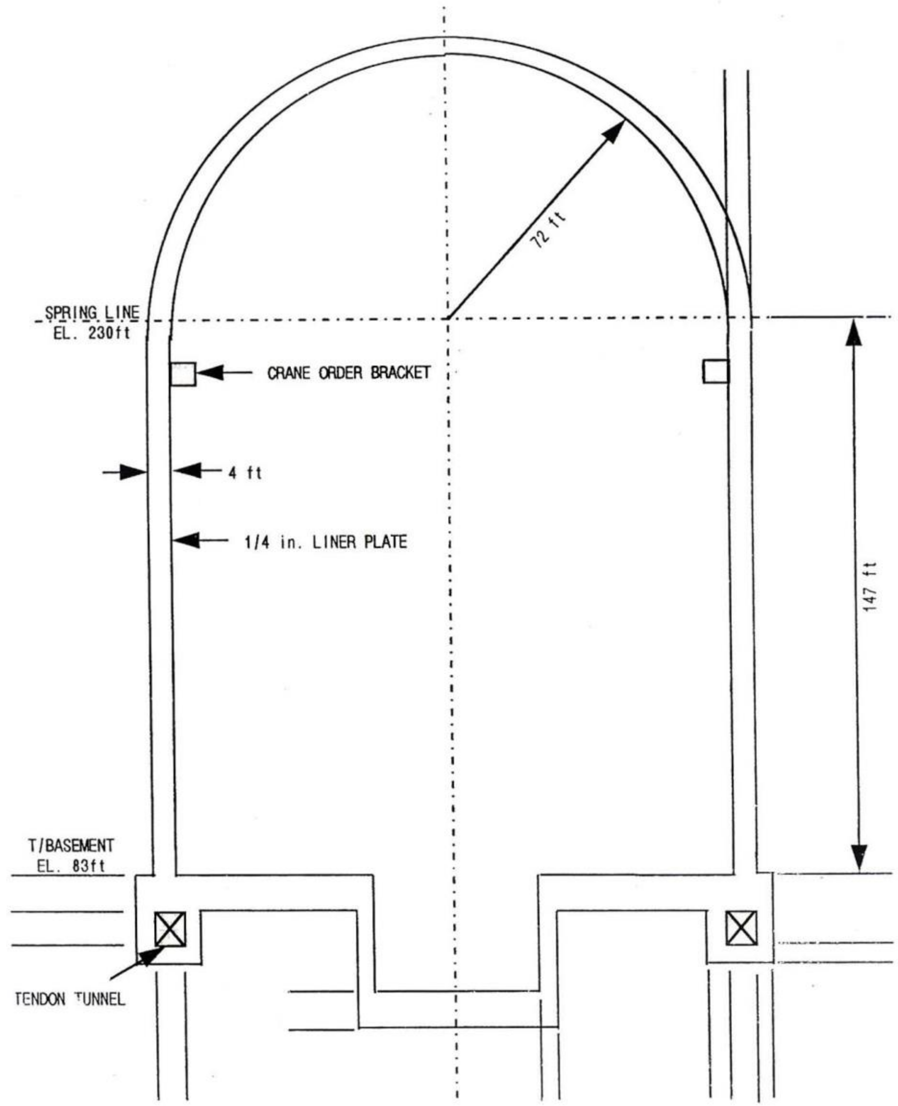
## ESF (Engineered Safety Features)

- Reactor shut down
- Remove decay heat
- Minimize the radioactivity release

- Functions
  - To localize, control, mitigate and terminate accidents
  - To hold exposure levels below the limits
- Containment system
  - The containment structure which forms a virtually leak tight barrier to the escape of fission product
- Containment spray system
  - To reduce containment pressure and remove iodine from the containment atmosphere after a primary or secondary pipe break inside containment.
- Safety injection system
  - To provide borated water to cool the reactor core in the event of an accidental depressurization
  - The combination of control rods and the boron in the injection water provides the necessary negative reactivity to maintain the reactor shutdown.
- Shutdown cooling system
  - To maintain the RCS at refueling temperature for extended period.
- Auxiliary feedwater system
  - To provide emergence heat removal capability upon loss of normal feedwater.
- Safety depressurization system
  - To provide a manual means of rapidly depressurizing the RCS

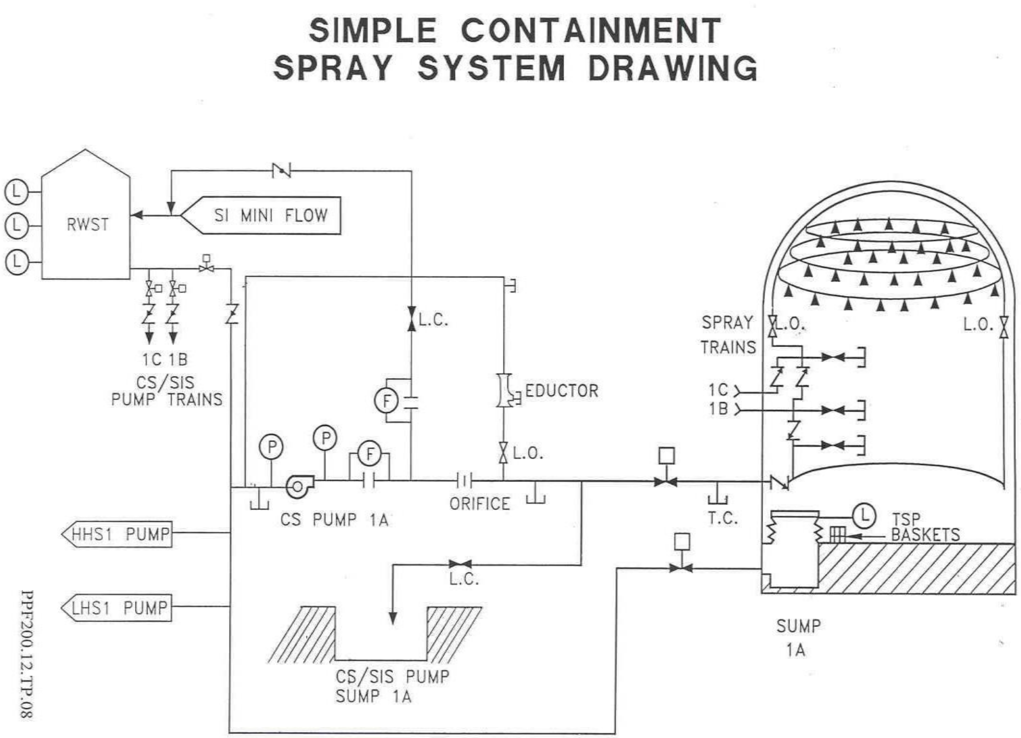
## ESF (Engineered Safety Features)

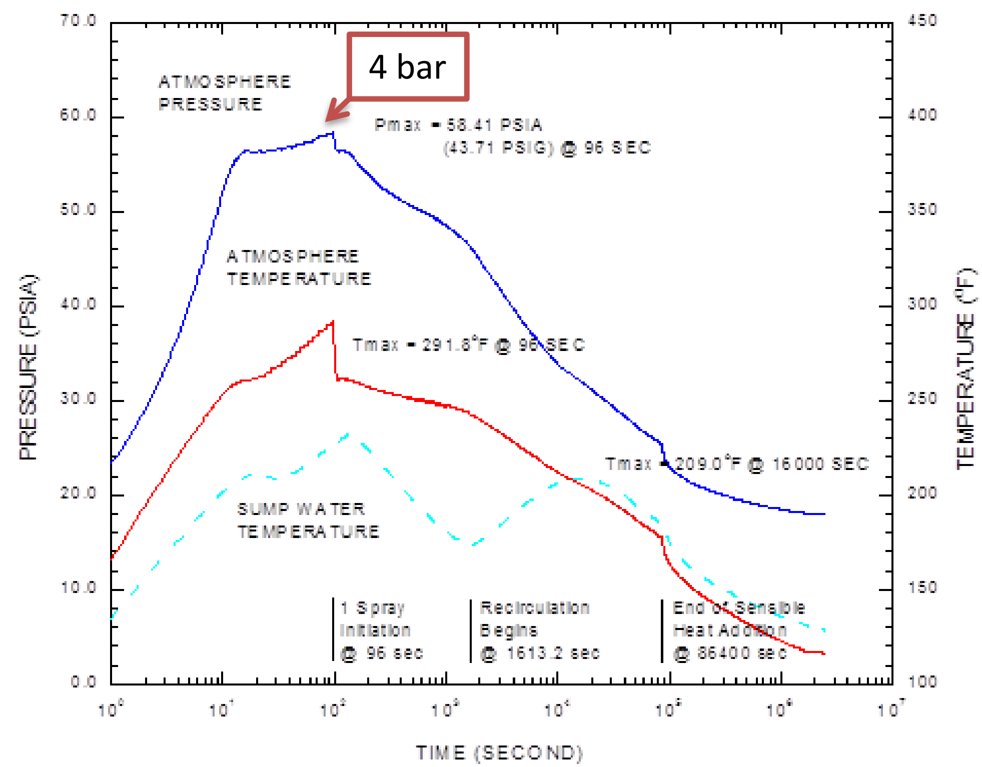
- Containment system
  - Design pressure: ~ 4 bar
  - Internal diameter: ~ 44 m, thickness: ~ 1.2 m
  - Dome radius: ~ 21.9 m
  - Height: ~ 66 m



## ESF (Engineered Safety Features)

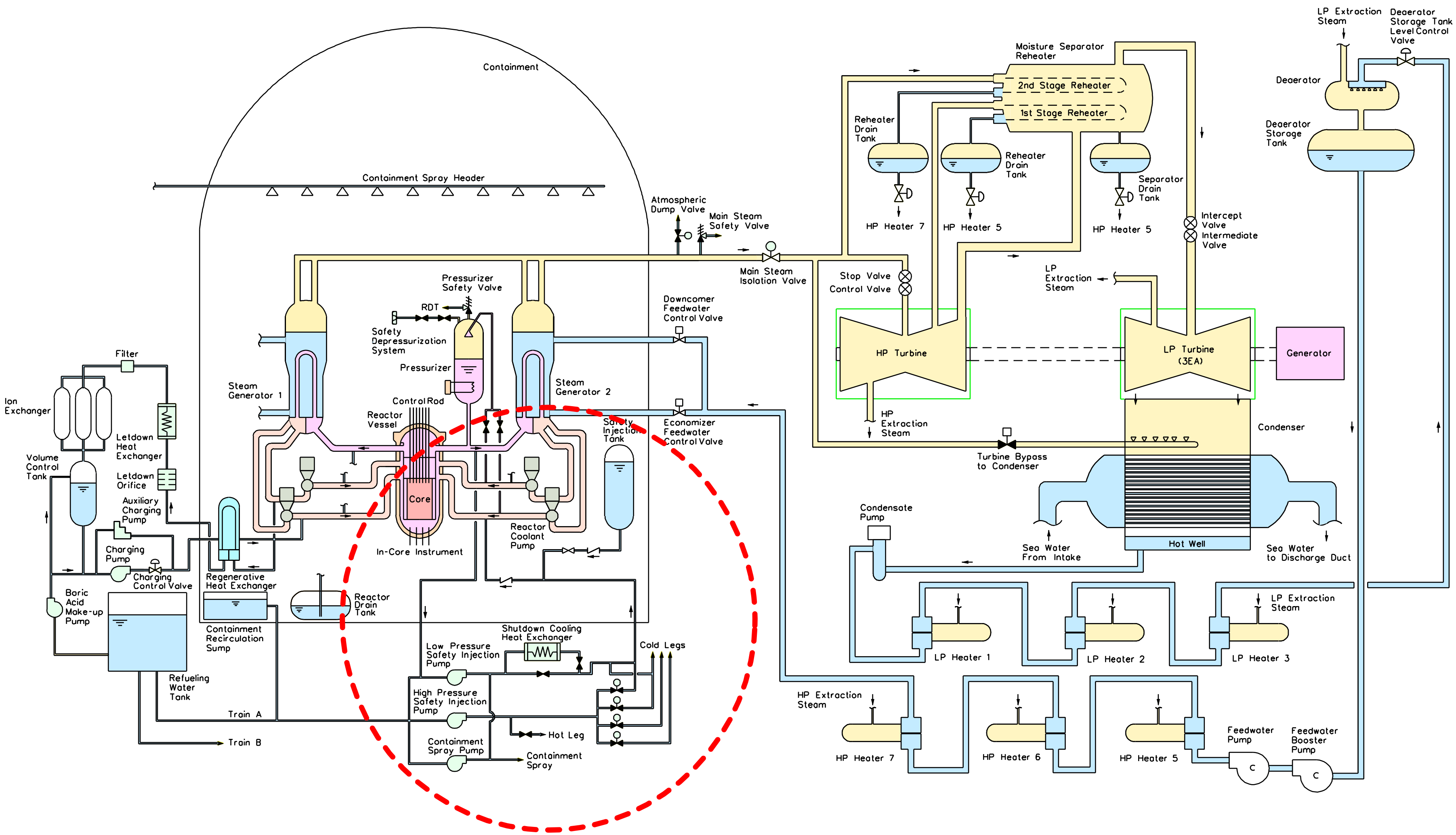
- Containment spray system



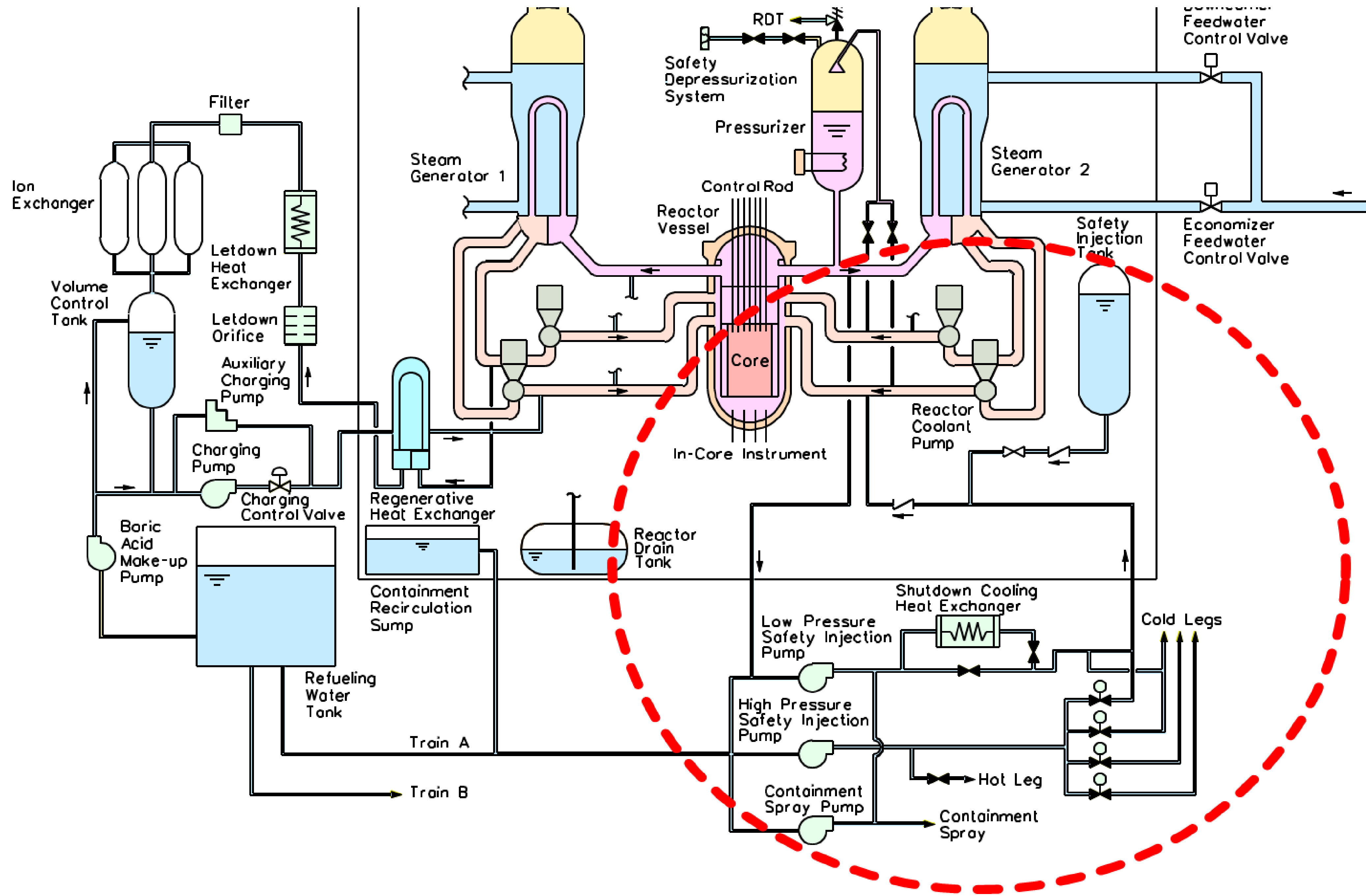



## ESF (Engineered Safety Features)

- SIS (Safety Injection System)/ ECCS (Emergency Core Cooling System)

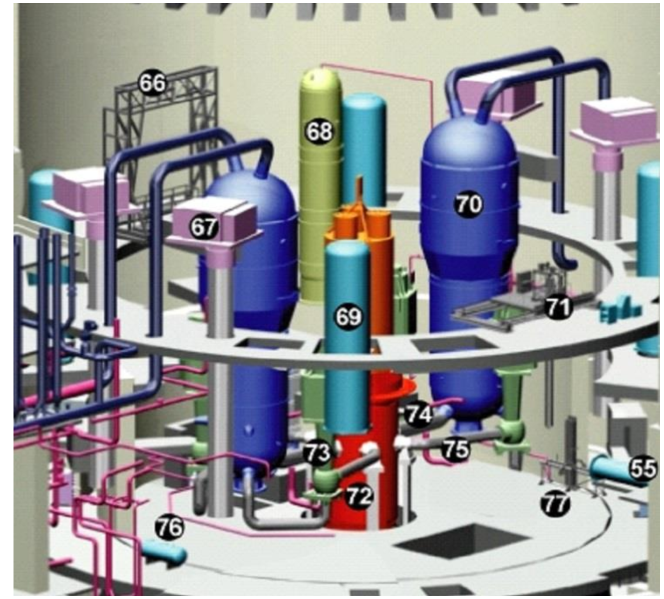


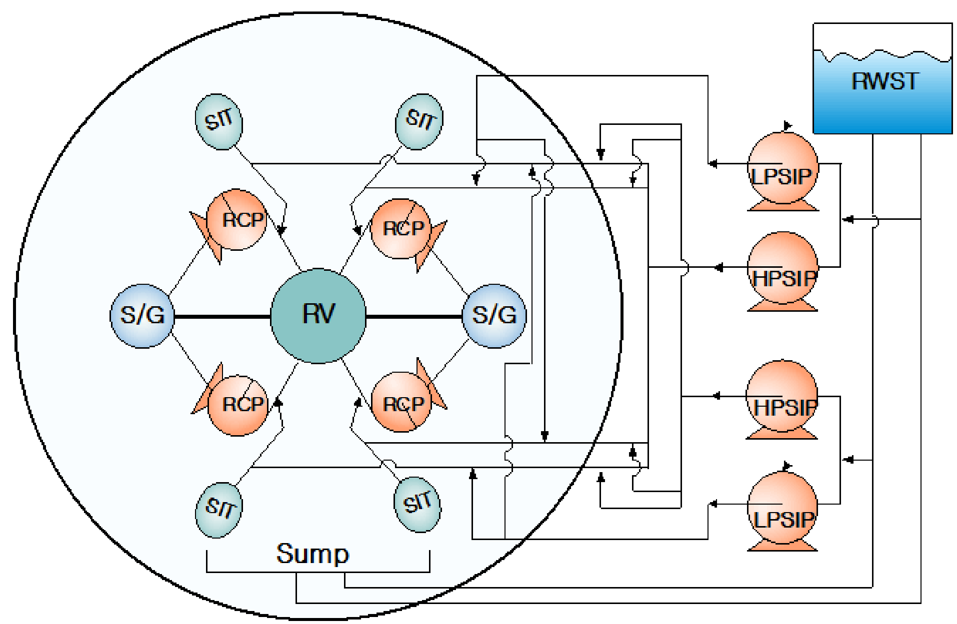

Safety Injection Systems


RDT
Safety Depressurization System
Feedwater Control Valve
Filter
Steam Generator 1
Pressurizer
Steam Generator 2
Ion Exchanger
Control Rod
Reactor Vessel
Letdown Heat Exchanger
Volume Control Tank
Letdown Orifice
Safety Injection Tank
Economizer Feedwater Control Valve
Auxiliary Charging Pump
Core
Reactor Coolant Pump
Charging Pump
In-Core Instrument
Charging Control Valve
Regenerative Heat Exchanger
Boric Acid Make-up Pump
Reactor Drain Tank
Containment Recirculation Sump
Shutdown Cooling Heat Exchanger
Low Pressure Safety Injection Pump
Cold Legs
Refueling Water Tank
High Pressure Safety Injection Pump
Train A
Hot Leg
Containment Spray Pump
Train B
Containment Spray

## Engineered Safety Features

- **ESF (Engineered Safety Features)**
  - SIS (Safety Injection System)
    - OPR1000: HPSI, SIT, LPSI
    - APR1400: HPSI, SIT
  - High pressure safety injection pump
    - 1 pump: connected to 4 cold legs & 1 hot leg
  - Safety injection tank
    - 1 tank: connect to 1 cold leg
    - D=2.74 m
    - H=13.6 m
  - Low pressure safety injection pump
    - 1 pump: connected to 2 cold legs

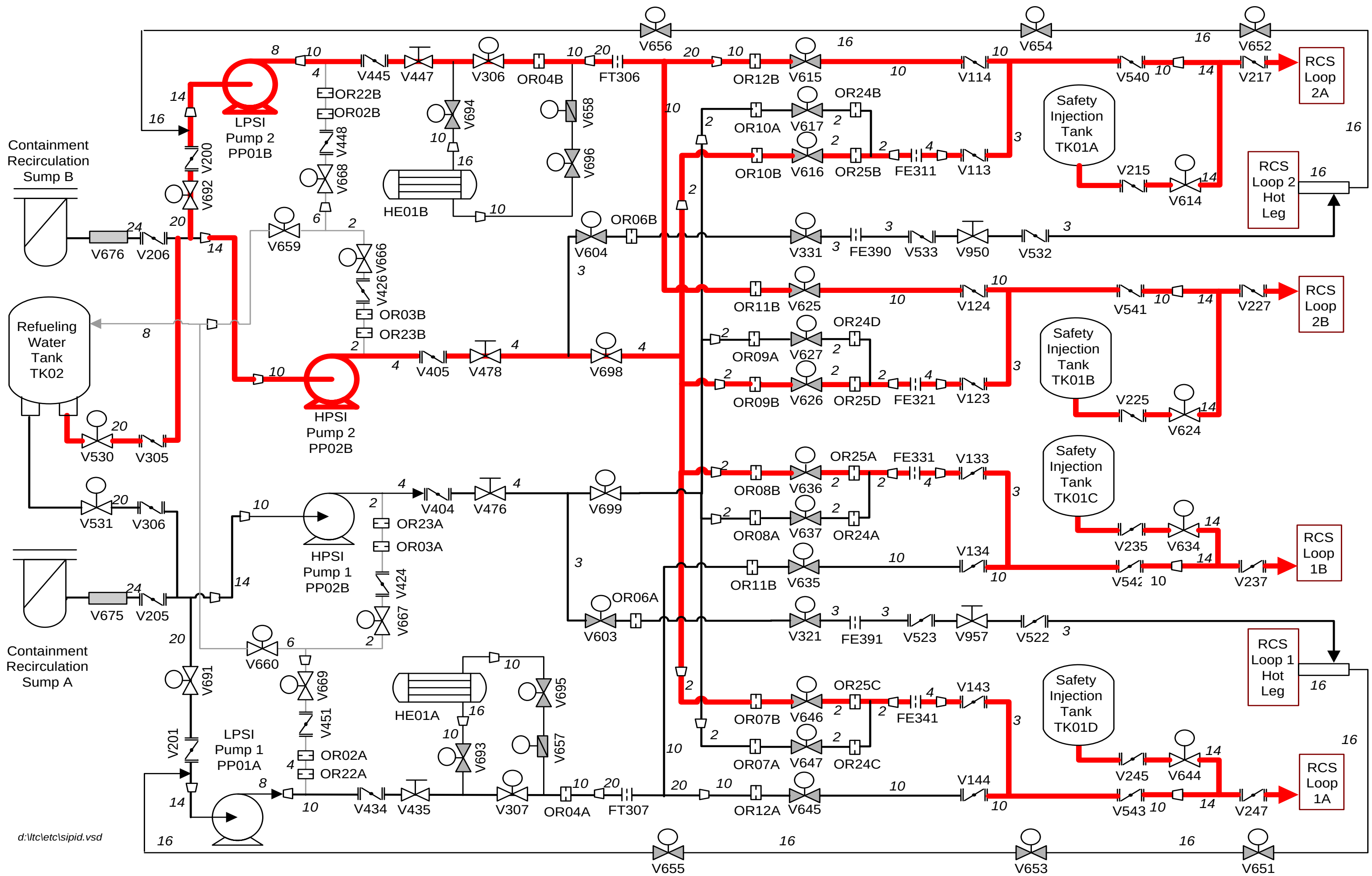


# Engineered Safety Features

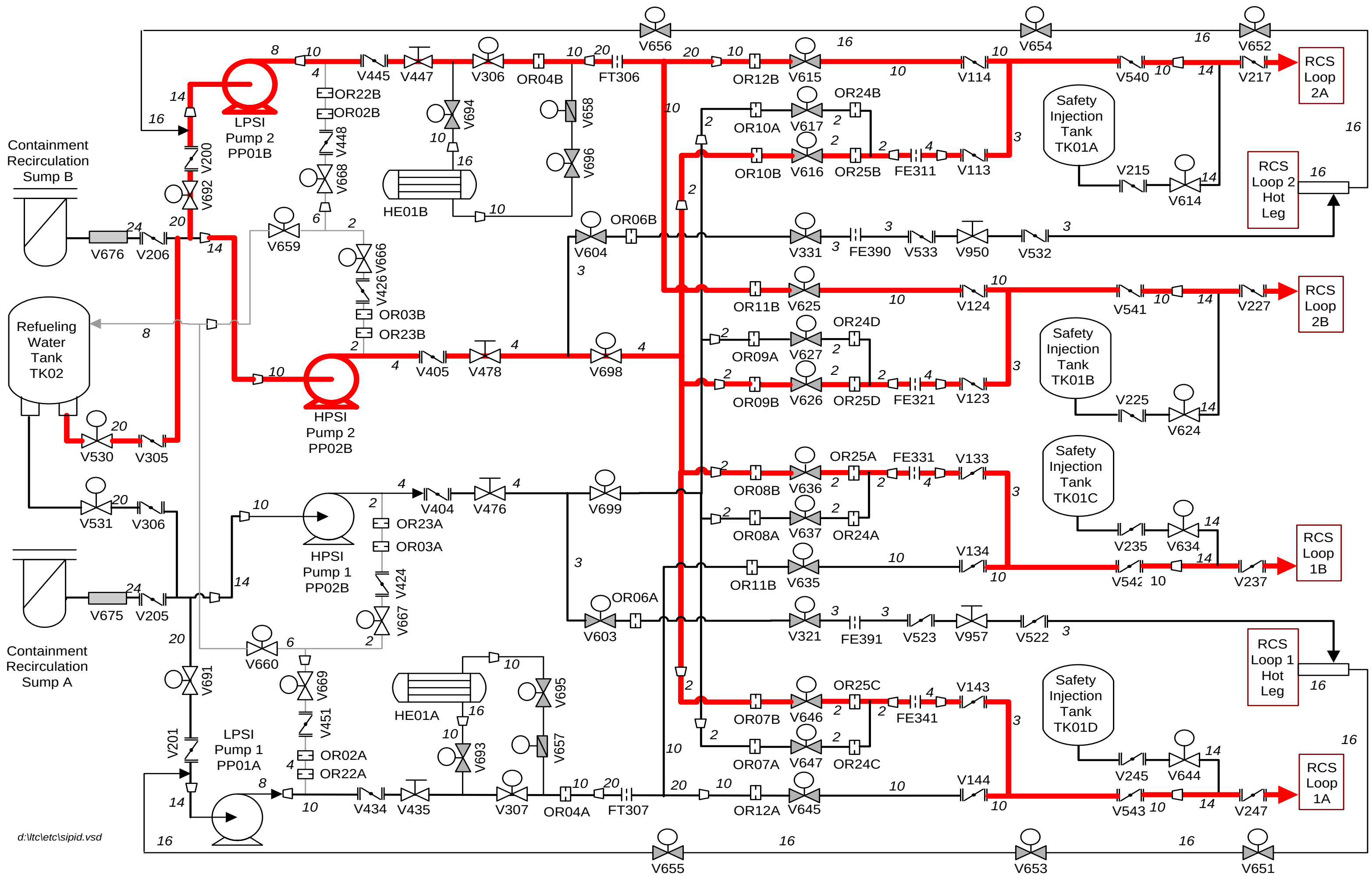
## ❖ ESF (Engineered Safety Features)

- SIS (Safety Injection System)/ ECCS (Emergency Core Cooling System)
  - 



## ESF (Engineered Safety Features)

- SIS (Safety Injection System)/ ECCS (Emergency Core Cooling System)
  - 



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- SIS (Safety Injection System)/ ECCS (Emergency Core Cooling System)
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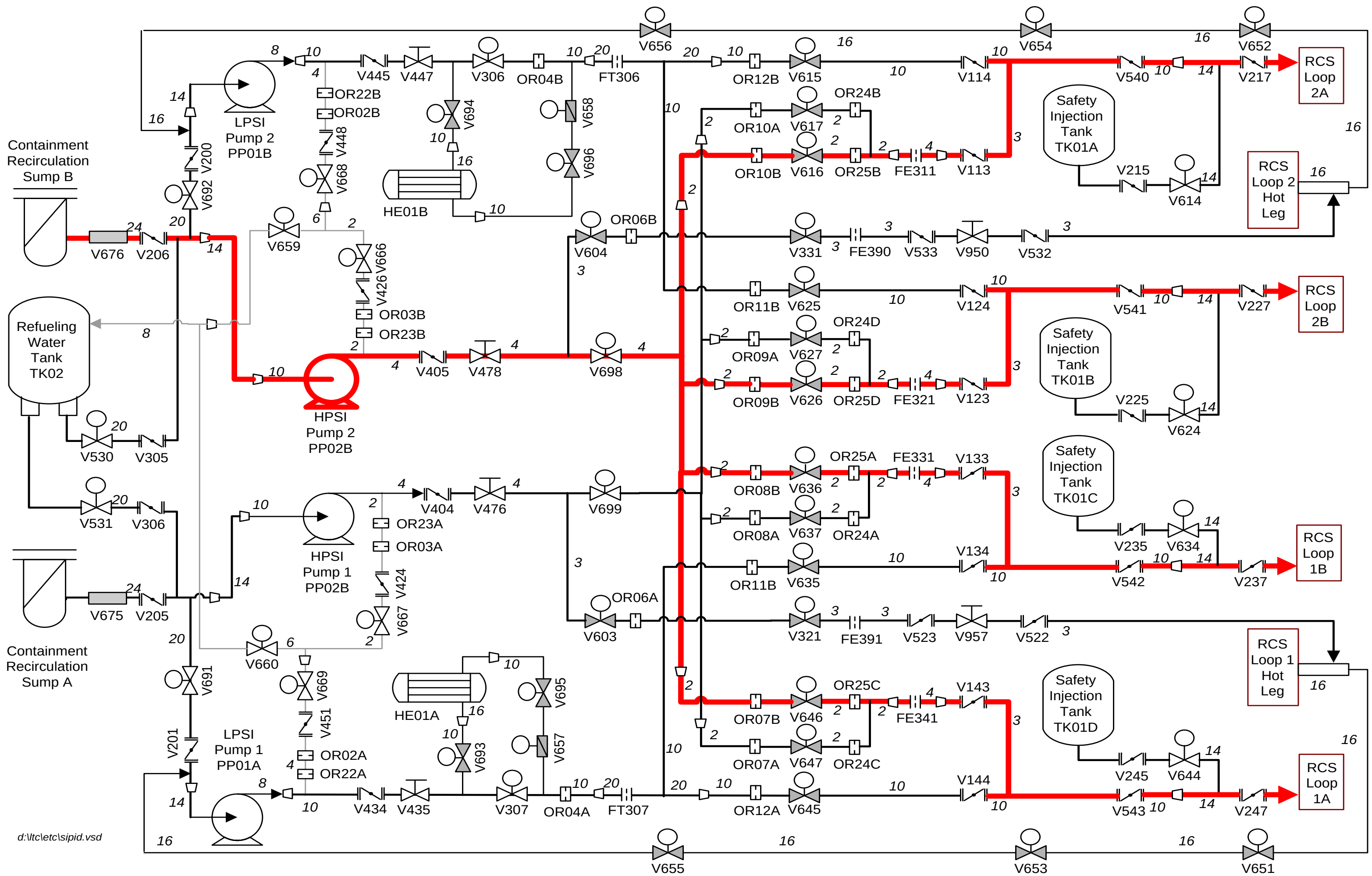
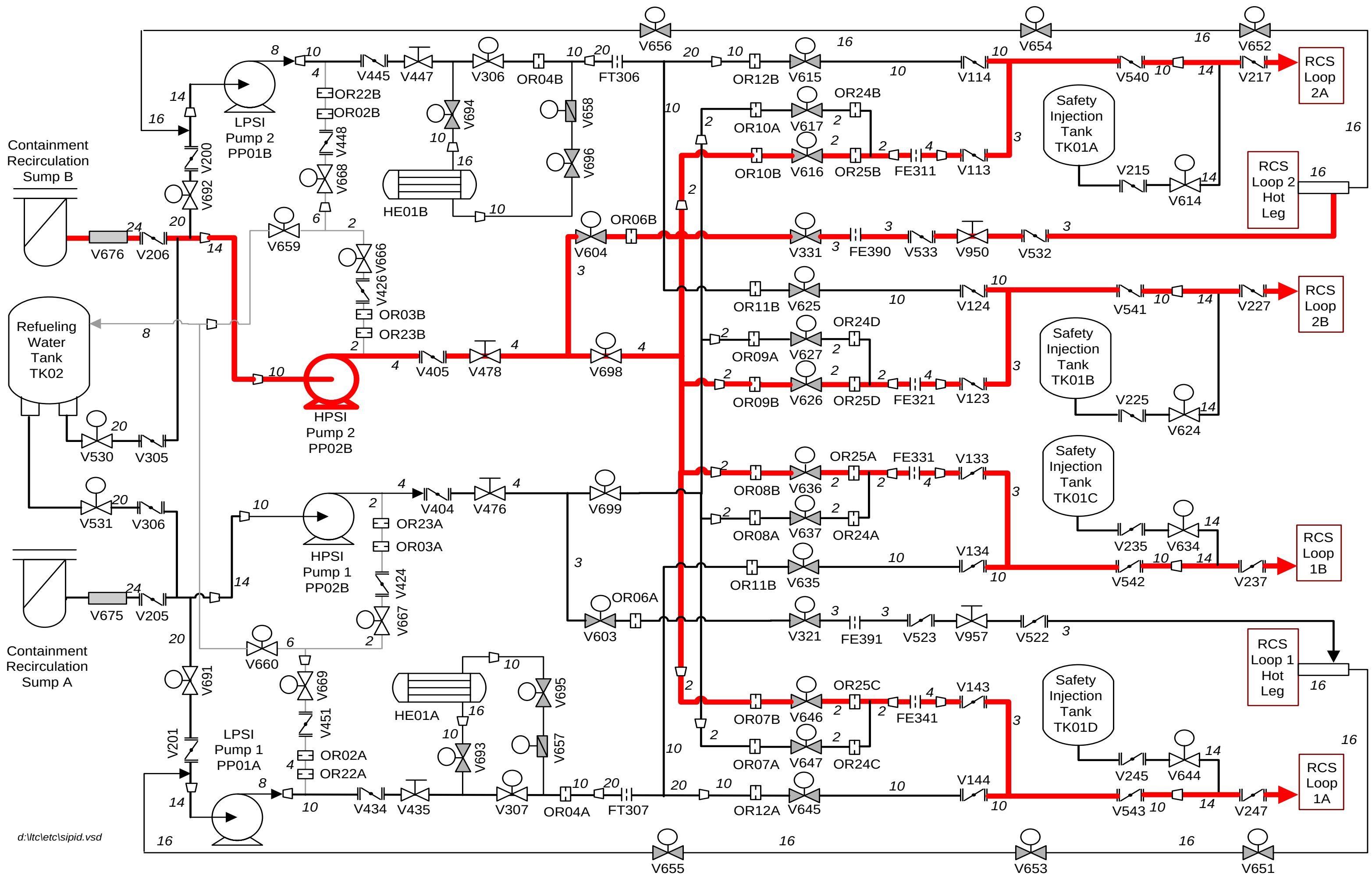


## ESF (Engineered Safety Features)

- SIS (Safety Injection System)/ ECCS (Emergency Core Cooling System)
  - 



# Safety injection mode

- Injection mode
  - HPSI : 안전주입신호로 기동, 124 bars
  - SIT: 42~44 bars
  - LPSI: 안전주입신호로 기동, 14 bars

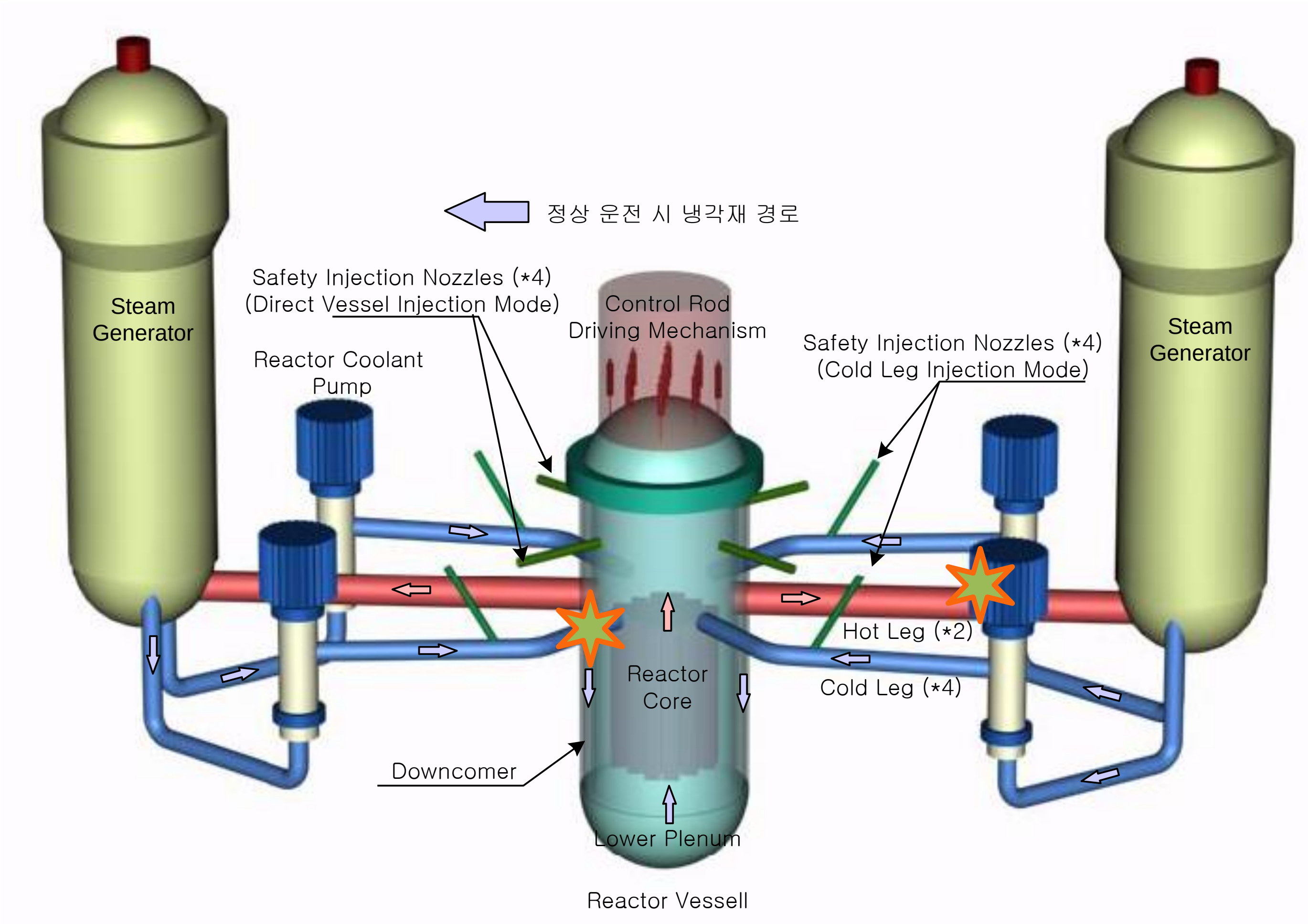
- Short-term recirculation mode
  - RWT 저수위 (7.6 %)
  - HPSI: cold leg injection
  - LPSI 정지

- Long-term recirculation mode
  - 안전주입 발생 후 4시간 이내에 정지냉각 불만족 시
  - HPSI: simultaneous injection

| 안전주입신호(SIAS) | | | |
|---|---|---|---|
| 작 동 신 호 | 설 정 치 | 동시성 | 비고 |
| 격납용기 고-압력 | 133cm$H_2$0 | 2/4 | |
| 가압기 저-압력 | 124kg/cm$^2$a | 2/4 | WR |
| 수 동 | 수동 스위치 | 2/4 | |

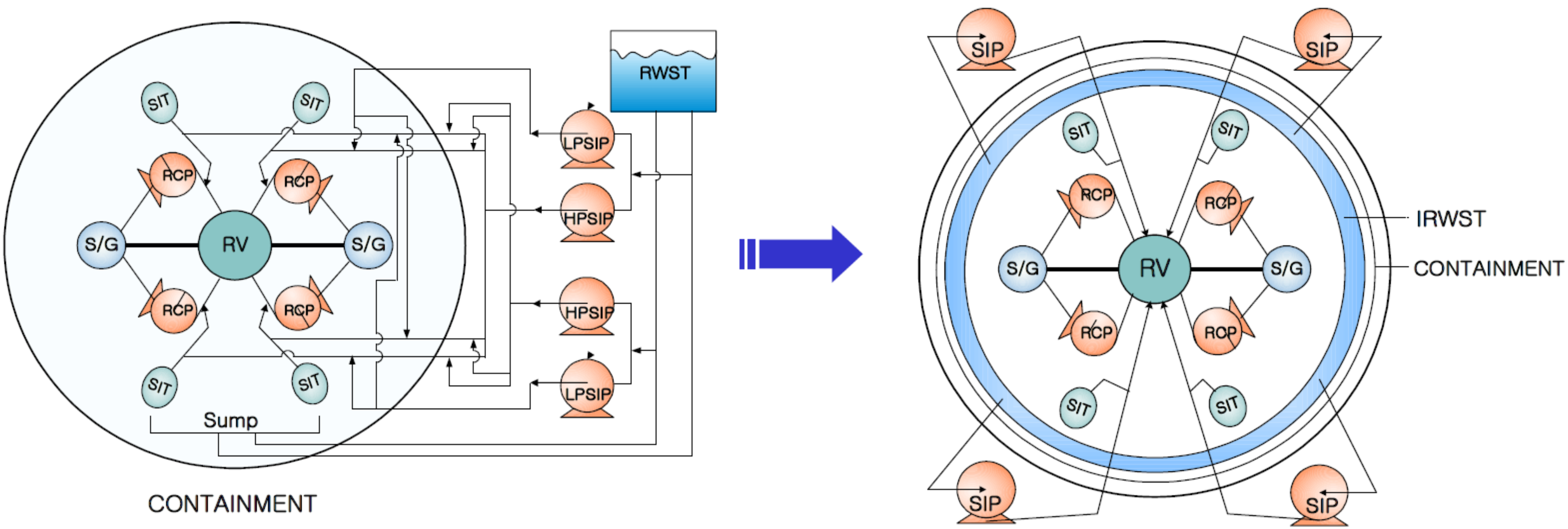
## ESF (Engineered Safety Features)

- SIS (Safety Injection System)/ ECCS (Emergency Core Cooling System)
  - OPR1000: HPSI, SIT, LPSI
  - APR1400: HPSI, SIT



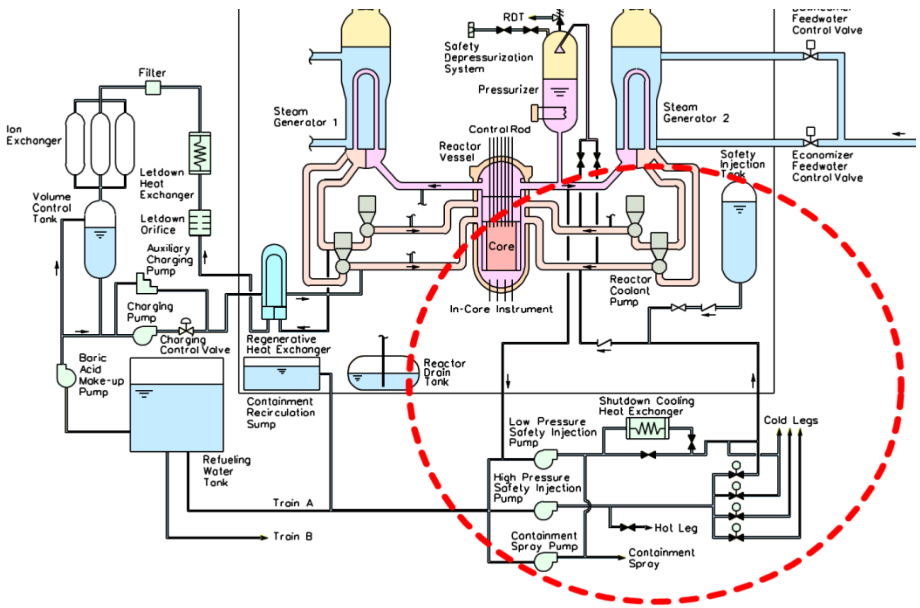
## ESF (Engineered Safety Features)

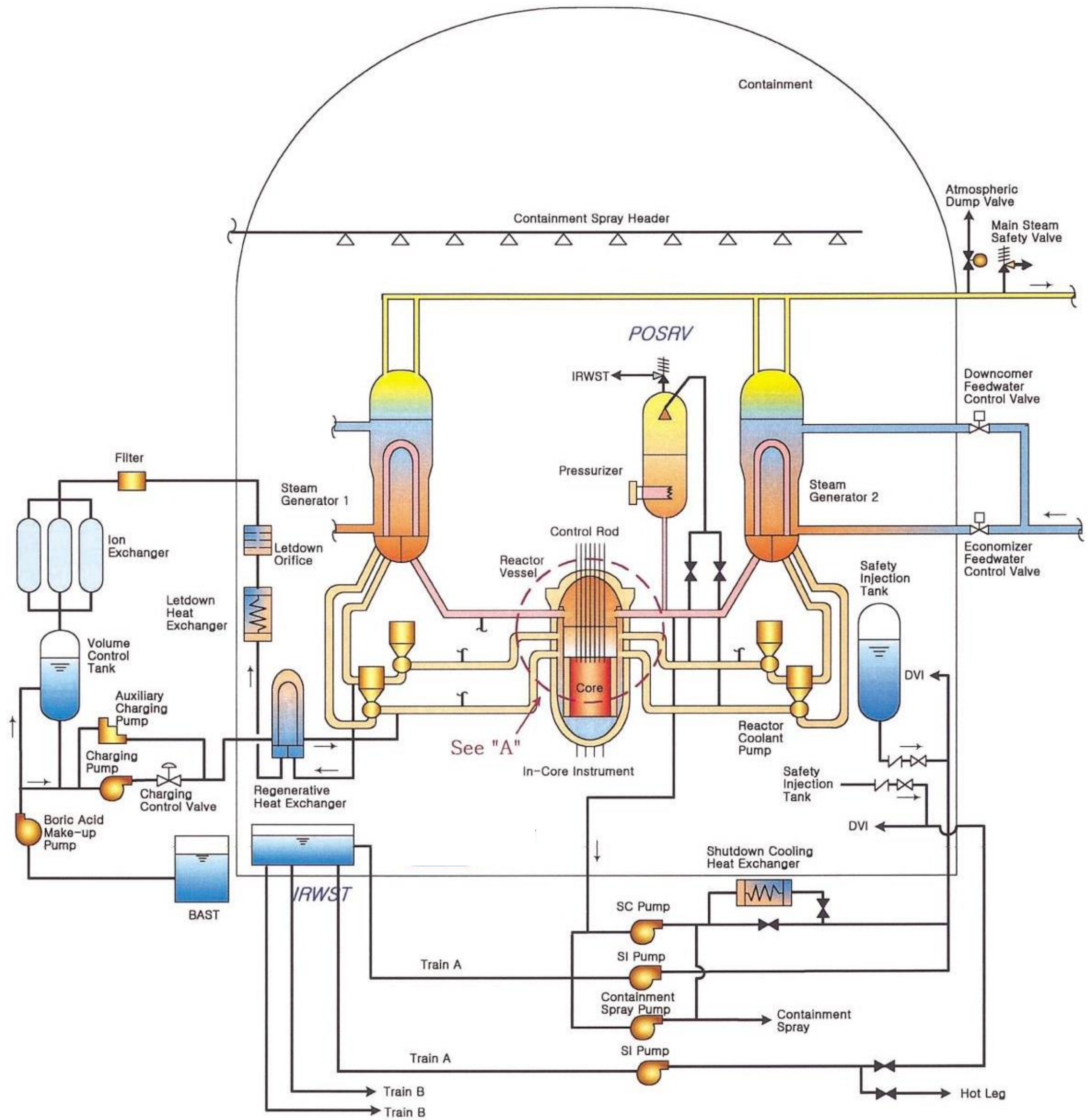
- SIS (Safety Injection System)/ ECCS (Emergency Core Cooling System)
  - OPR1000: HPSI, SIT, LPSI
  - APR1400: HPSI, SIT
  - Simplified SIS
  - 4 mechanical trains with 2 electrical trains



## ESF (Engineered Safety Features)

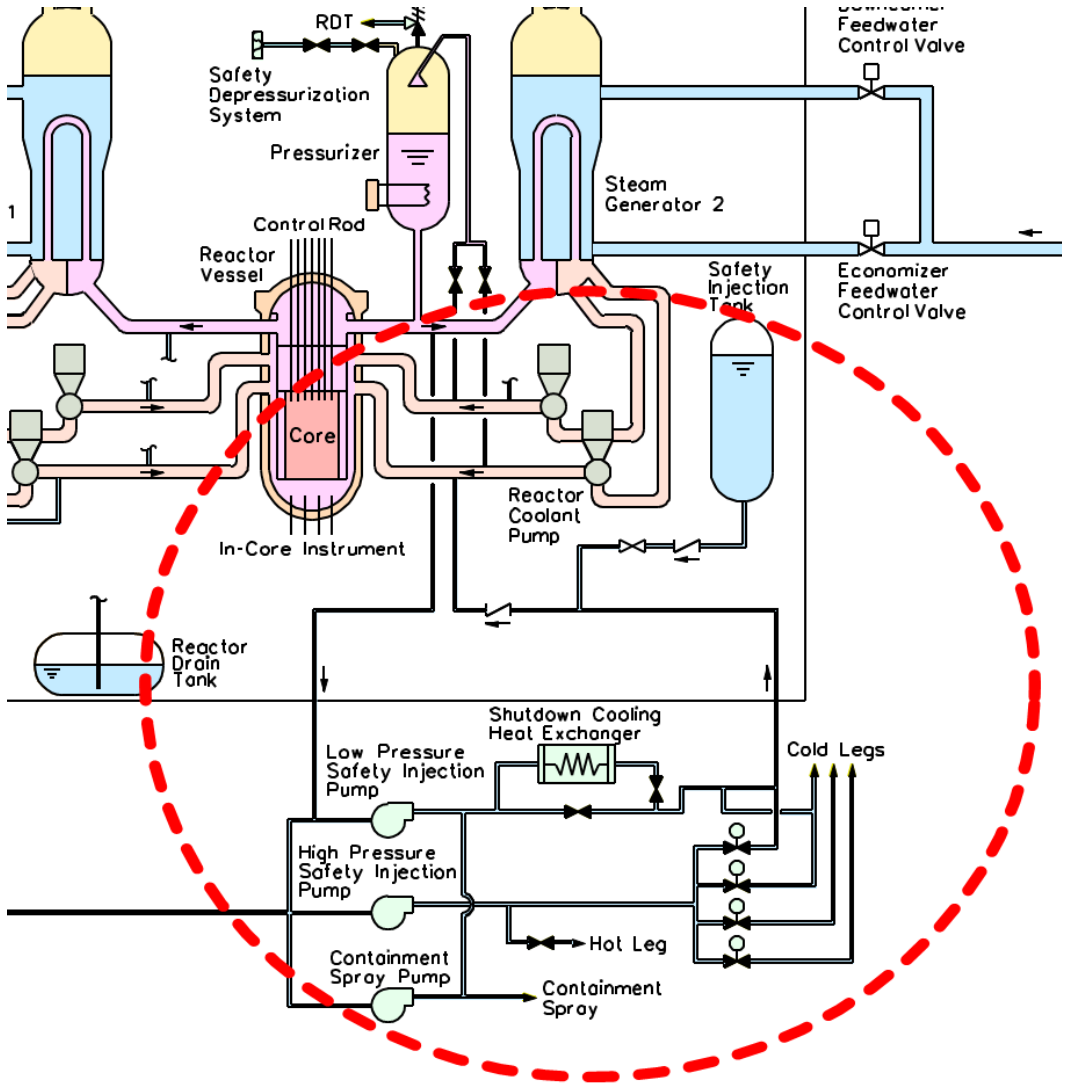
- OPR1000 vs. APR1400



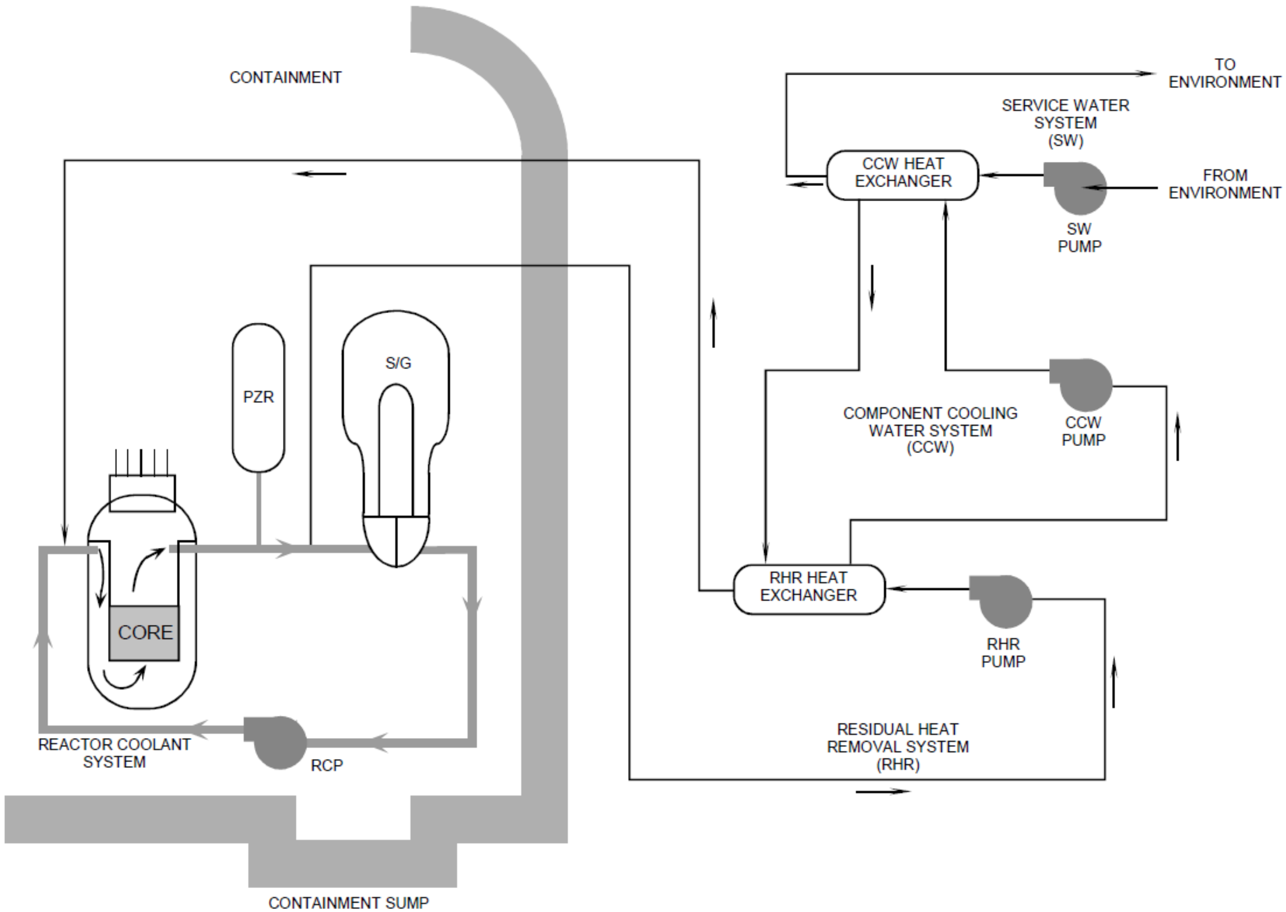
## ESF (Engineered Safety Features)

- SCS (Shutdown Cooling System)/ RHRS (Residual Heat Removal System)



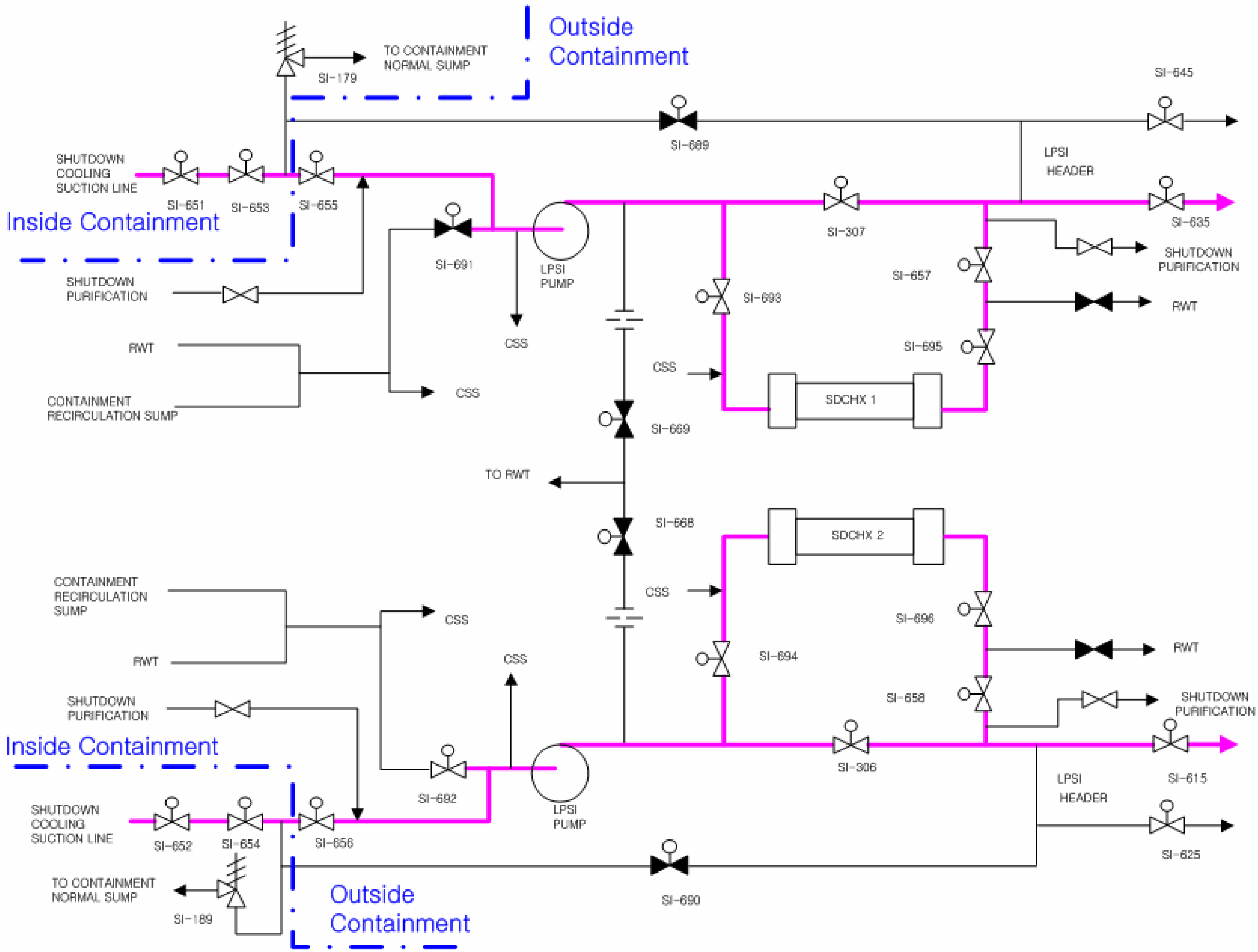
## ESF (Engineered Safety Features)

- SCS (Shutdown Cooling System)/ RHRS (Residual Heat Removal System)
  - To continue the cooldown by removing heat from the core and transferring it to the environment.



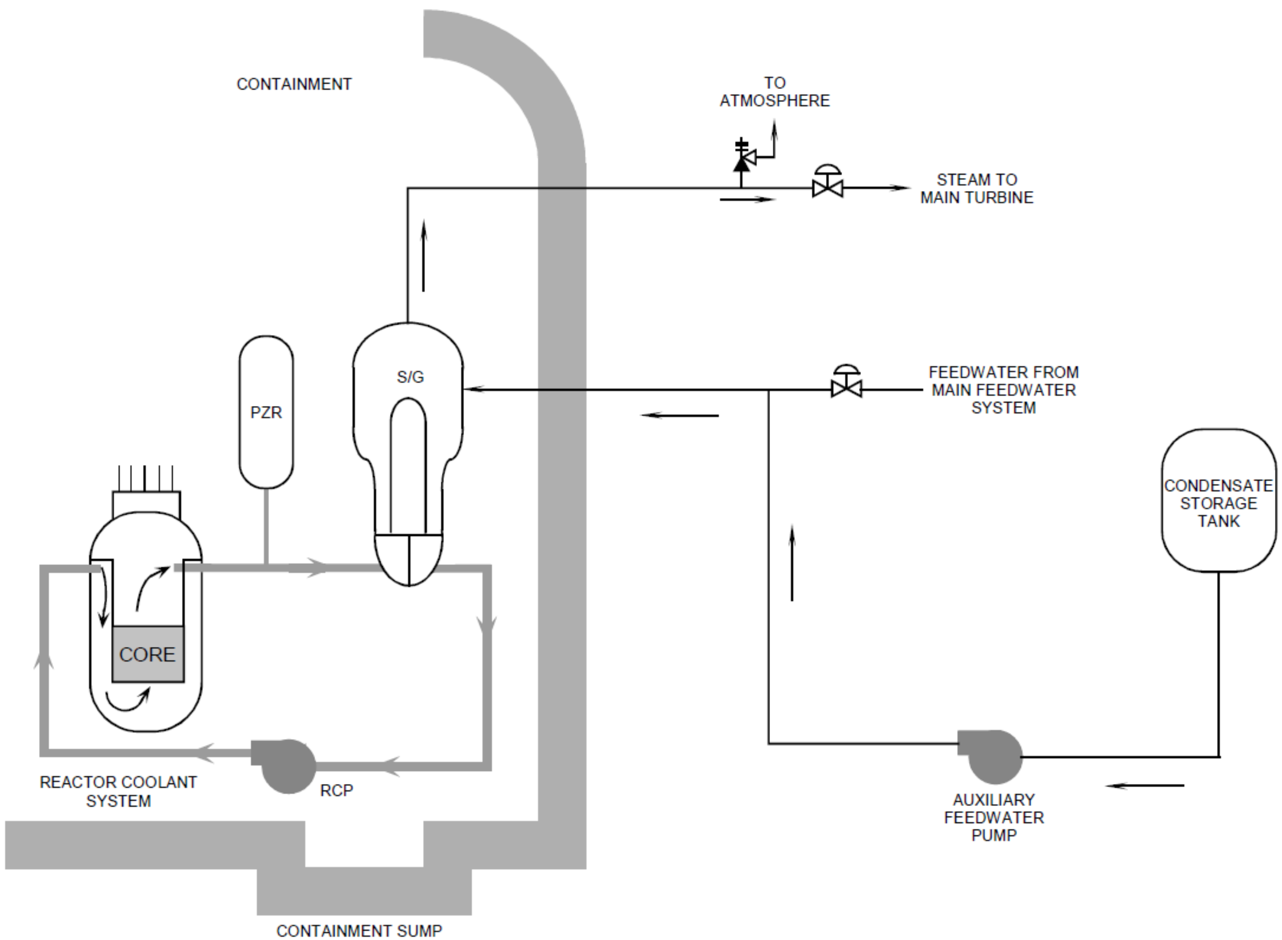
## ESF (Engineered Safety Features)

- SCS (Shutdown Cooling System)/ RHRS (Residual Heat Removal System)



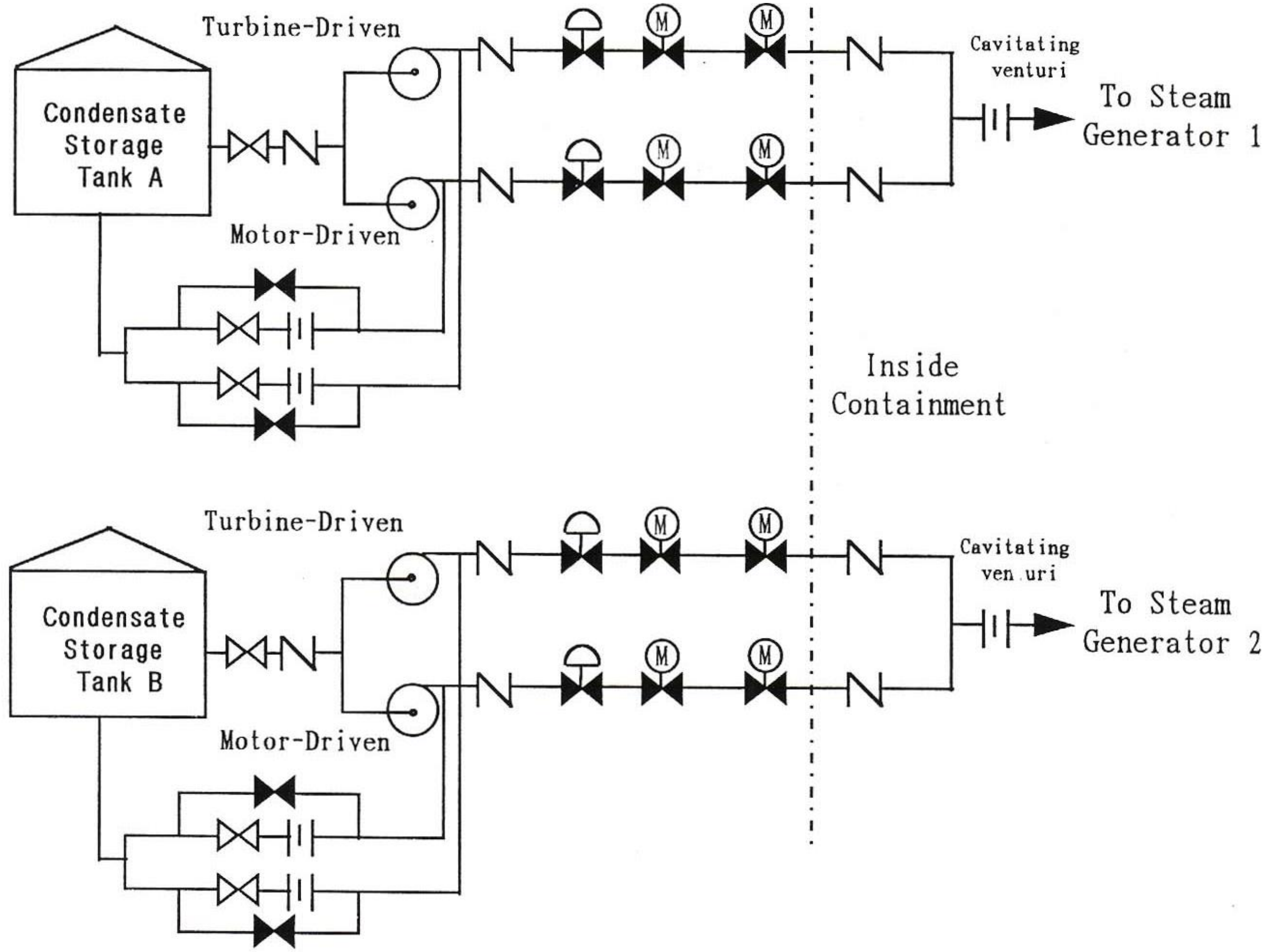
## ESF (Engineered Safety Features)

- Auxiliary feedwater system
  - To provide emergence heat removal capability upon loss of normal feedwater.



## ESF (Engineered Safety Features)

- Auxiliary feedwater system
  - To provide emergence heat removal capability upon loss of normal feedwater.
  - Replaced by PAFS in APR+



# Plant Protection System

- **PPS (Plant Protection System)**
  - RPS(Reactor Protection System)
    - To provide an emergency shutdown of the reactor to protect the core and the reactor coolant system pressure boundary
  - ESFAS(Engineered Safety Features Actuation System)
    - To provide those functions required to prevent the release of significant amounts of radioactive material to the environment in the event of pressure boundary rupture.
  - The PPS continuously monitors selected safety-related parameters
    - Such as neutron flux, pressurizer pressure, steam generator pressure and level
  - The PPS automatically initiates plant protective action in the form of initiation of the appropriate function whenever a monitored plant parameter reaches a predetermined level.
    - RPS trip and/or ESF actuation

## PPS (Plant Protection System)

- Monitored parameters
  - Core power (neutron flux and core inlet/outlet temperatures)
  - Reactor coolant system pressure
  - Departure from nucleate boiling ratio (DNBR) in the limiting coolant channel of the core
  - Peak local power density in the limiting fuel pin of the core
  - Steam generator water level
  - Steam generator pressure
  - Containment pressure
  - Refueling water tank water level
  - Reactor coolant system flow
    - Reactor coolant pump speed and steam generator primary differential pressure

# PPS (Plant Protection System)

- Trip functions
  - Variable Overpower
    - To limit the plant's maximum steady state power level, in conjunction with the DNBR/LPD trips.
  - High Logarithmic Power Level
    - To ensure the integrity of the fuel cladding and coolant system boundary in the event of unplanned criticality from a shutdown condition, resulting from either dilution of soluble boron or withdrawal of CEAs.
  - High Local Power Density
    - To prevent the linear heat rate (kW/ft or w/cm) in the limiting fuel pin in the core from exceeding the fuel design limit in the event of defined anticipated operational occurrences.
  - Low Departure From Nucleate Boiling Ratio (DNBR)
    - To prevent the DNBR in the limiting coolant channel in the core from exceeding the fuel design limit in the event of defined Anticipated Operational Occurrences.
  - High Pressurizer Pressure
    - To help assure the integrity of the Reactor Coolant Pressure Boundary for design basis events
  - Low Pressurizer Pressure
    - To assist the Engineered Safety Features System in the event of a coolant accident and to provide a reactor trip in the event of reduction in pressurizer pressure.
  - Low Steam Generator Water Level
    - To assist the Engineered Safety Features System by assuring that there is sufficient time for actuating the auxiliary feedwater pumps to remove decay heat from the reactor in the event of a reduction of steam generator water inventory.

## PPS (Plant Protection System)

- Trip functions
  - High Steam Generator Water level
    - To provide protection in conjunction with the MSIS to protect Main Steam System components from being damaged by excessive moisture carryover from the steam generators.
  - Low Steam Generator Pressure
    - To provide protection against excess secondary heat removal events
  - High Containment Pressure
    - To assist the Engineered Safety Features System by tripping the reactor coincident with an event which results in significant mass and energy releases into the containment.
  - Low Reactor Coolant Flow
    - To limit the consequences of a sheared reactor coolant pump shaft and steam line break.
  - Manual Trip

## PPS (Plant Protection System)

- ESFAS Functions
  - Safety Injection Actuation Signal (SIAS)
  - Containment Isolation Actuation Signal (CIAS)
  - Containment Spray Actuation Signal (CSAS)
  - Recirculation Actuation Signal (RAS)
  - Main Steam Isolation Signal (MSIS)
  - Auxiliary Feedwater Actuation Signal (AFAS)

# Other Systems

## Plant Monitoring System

- Core operating Limit Supervisory System
- In-core Instrumentation System
- Ex-core Neutron Flux Monitoring System
- Inadequate Core Cooling Monitoring
- NSSS Integrity Monitoring System
- Radiation Monitoring System
- Containment Vessel Monitoring System
- Post Accident Monitoring System
- Bypass and Inoperable Status Indications

# Other Systems

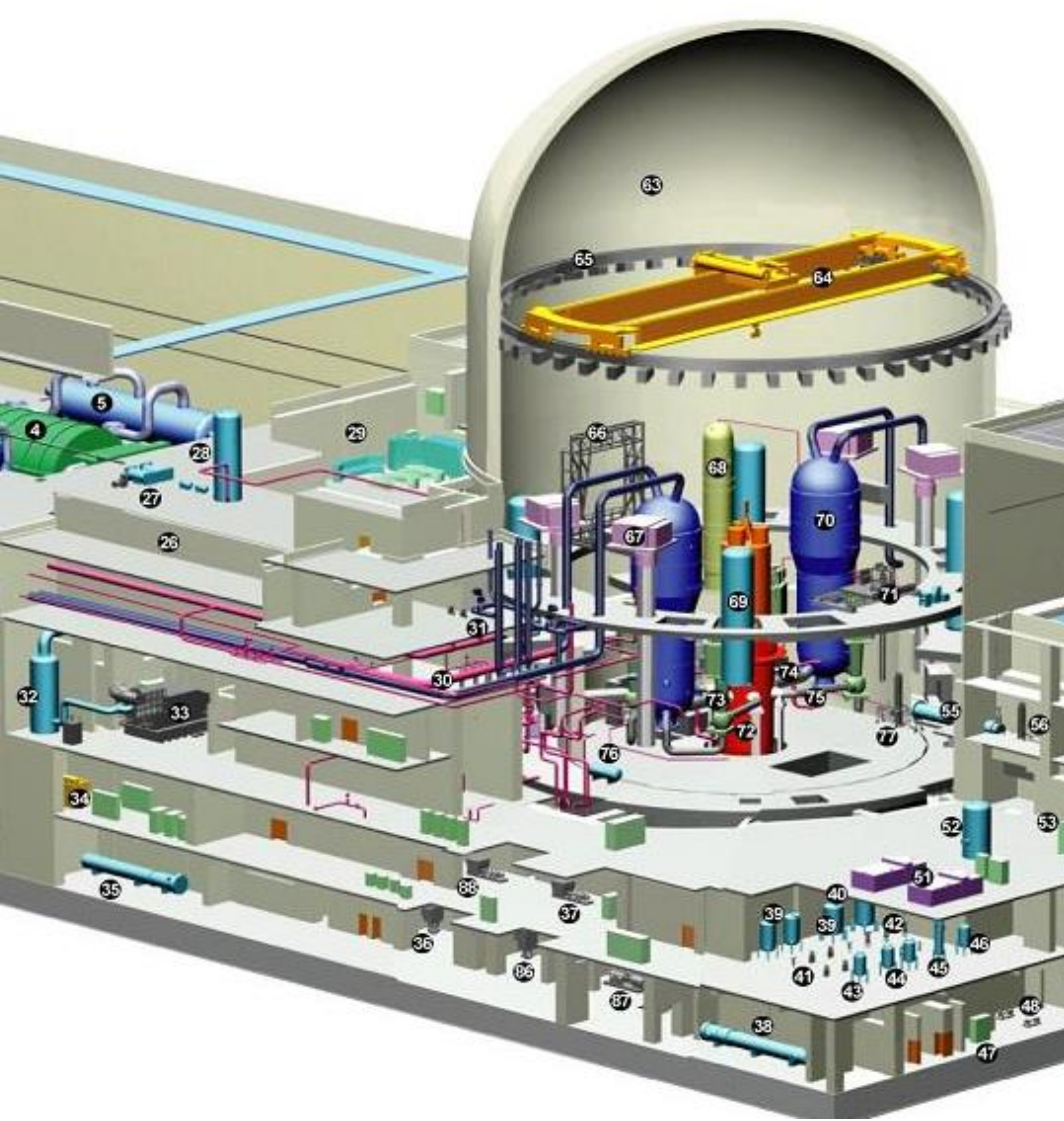
## Plant Control System

- Reactor Regulating System
- Control Element Drive Mechanism Control System
- Main Feedwater Contorl System
- Steam Bypass Control System
- Reactor Power Cutback System
- Pressurizer Pressure Control System
- Pressurizer Level Control System

# Other Systems

- **Radioactive Waste Management System**
  - Gaseous Radioactive Waste System
  - Liquid Radioactive Waste System
  - Solid Radioactive Waste System

- **Compressed Air System**
- **Chilled Water System**



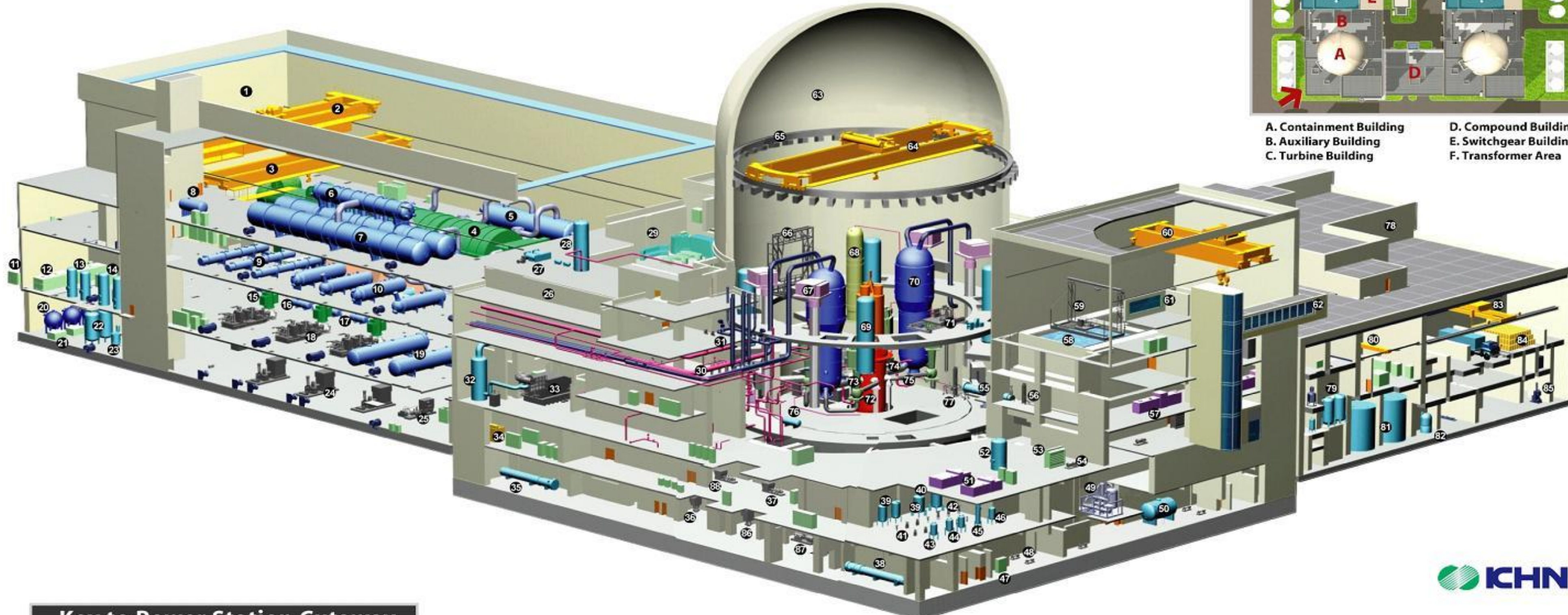
31. Main Steam Safety Valve
32. Exhaust Silencer
33. Diesel Generator
34. 480V PNS Loadcenter
35. CS Heat Exchanger
36. CS Pump
37. Motor Driven Aux. Feedwater Pumps
38. SC Heat Exchanger
39. Spent Fuel Pool Clean-up Demin
40. SG Blowdown Mixed Bed Demin
41. Reactor Drain Filter
42. SGBD Filter
43. Pre-Holdup Ion Exchanger
44. Purification Ion Exchanger
45. Boric Acid Cond Ion Exchanger

46. Deborating Ion Exchanger
47. Process Radiation Monitor
48. Holdup Pump
49. Boric Acid Conc.
50. Equip. Drain Tank
51. Aux. Bldg. Controlled Area Exhaust ACU
52. Volume Control Tank
53. SFP Cooling Exchanger
54. SFP Cooling Pump
55. Fuel Transfer Tube
56. Fuel Transfer Carriage & Upender in Fuel Handling Area
57. Fuel Handling Area Emer Exhaust ACU
58. Spent Fuel Pool
59. Spent Fuel Handling Machine

75. Reactor Coolant Piping Cold Leg
76. RCP Lube Oil Collector Tank
77. Fuel Transfer System Upender
78. Compound Building
79. Charcoal Delay Beds
80. Suspension Crane
81. Long Term Storage Tank
82. Low Activity Spent Resin
83. Traveling Bridge Crane
84. Waste Drum Storage Area
85. Solid Waste Compactor
86. SC Pump
87. SI Pump
88. Turbine Driven Aux. Feedwater Pump

## Site Plan Key


A. Containment Building
B. Auxiliary Building
C. Turbine Building
D. Compound Building
E. Switchgear Building
F. Transformer Area



KHNP

## Key to Power Station Cutaway

1. Turbine Building
2. Main Overhead Crane
3. Aux. Overhead Crane
4. Generator
5. Moisture Separator Reheater
6. Deaerator
7. Deaerator Storage Tank
8. TBCCW Surge Tank
9. LP Feedwater Heaters
10. HP Feedwater Heaters
11. Closed Loop Cooling System
12. Air Compressor
13. Air Receivers
14. Service Air Receiver
15. Feedwater Pumps Turbine Driven
16. Moisture Separator Drain Tank
17. Stage Reheater Drain Tank
18. Feedwater Pumps Turbine "A""B""C"
19. HP Feedwater Heaters
20. Cond. Polishing Mixed Bed Vessels
21. Cond. Polishing Resin Traps
22. Cation Regen. & Hold Tanks
23. Ammonia Day Tank
24. Feedwater Booster Pumps
25. Start-up FW Pump
26. Auxiliary Building
27. D/G Room Emergency Exhaust Fan
28. CCW Surge Tank
29. Main Control Room
30. Main Steam Line
31. Main Steam Safety Valve
32. Exhaust Silencer
33. Diesel Generator
34. 480V PNS Loadcenter
35. CS Heat Exchanger
36. CS Pump
37. Motor Driven Aux. Feedwater Pumps
38. SC Heat Exchanger
39. Spent Fuel Pool Clean-up Demin
40. SG Blowdown Mixed Bed Demin
41. Reactor Drain Filter
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54. SFP Cooling Pump
55. Fuel Transfer Tube
56. Fuel Transfer Carriage & Upender in Fuel Handling Area
57. Fuel Handling Area Emer Exhaust ACU
58. Spent Fuel Pool
59. Spent Fuel Handling Machine
60. Fuel Handling Area Overhead Crane
61. Viewing Area
62. Walkway
63. Containment Building
64. Polar Crane
65. Crane Rail
66. CEA Change Platform
67. RCFC Duct
68. Pressurizer
69. Safety Injection Tank
70. Steam Generator
71. Refueling Machine
72. Reactor Vessel
73. Reactor Coolant Pump
74. Reactor Coolant Piping Hot Leg
75. Reactor Coolant Piping Cold Leg
76. RCP Lube Oil Collector Tank
77. Fuel Transfer System Upender
78. Compound Building
79. Charcoal Delay Beds
80. Suspension Crane
81. Long Term Storage Tank
82. Low Activity Spent Resin
83. Traveling Bridge Crane
84. Waste Drum Storage Area
85. Solid Waste Compactor
86. SC Pump
87. SI Pump
88. Turbine Driven Aux. Feedwater Pump

# SAFETY FEATURES OF ADVANCED NUCLEAR REACTORS

# Contents

- APR+ Safety Features
- AP1000 Safety Features
- Plan for IPOWER

# APR+ Safety Features

## APR+ Overall Specification (project name)

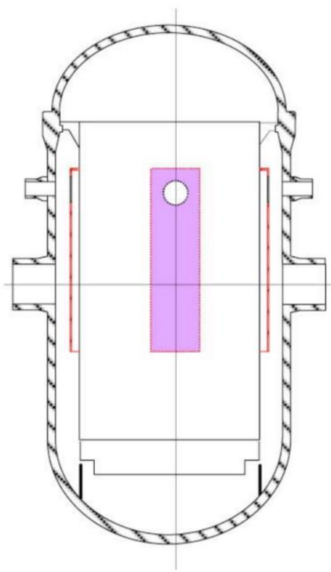
- Developer: KHNP
- Thermal power: 4290 MWth
- Electrical power: 1505 Mwe
- Design life: 60 years
- Construction period: 36 months
- Core damage frequency:
  - $<1.0 \cdot 10^{-6}$/year
- Construction plan
  - Shin Kori 7
  - 2022/2023 ?

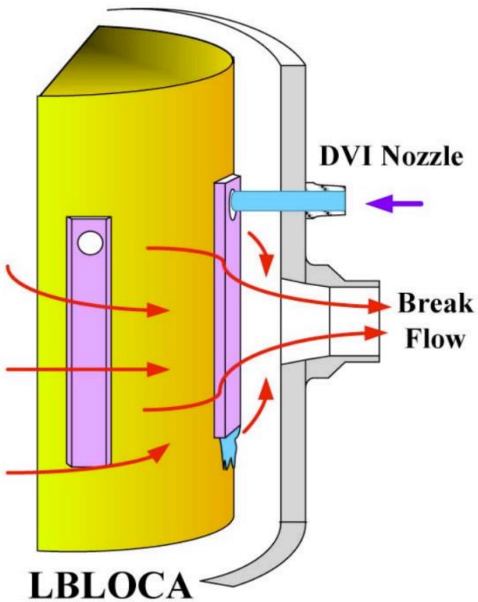
**Primary Characteristics**

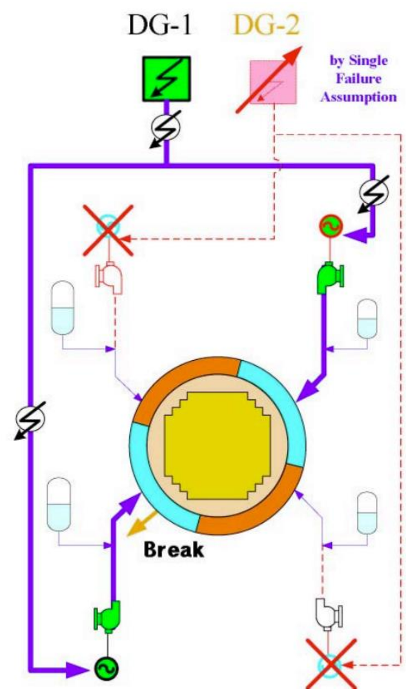
| Category | APR1400 | APR+ |
|---|---|---|
| Developer | KHNP | KHNP |
| Power output (MWe) | 1,400 | 1,500 |
| Design life | 60 years | 60 years |
| Safe Shutdown Earthquake (SSE) | 0.3 g | 0.3 g |
| Core Damage Frequency (CDF) | 6.22 E-6 | 1.0 E-6 |
| LOOP (RCP/SG) | 2 Loop (4/2) | 2 Loop (4/2) |
| Fuel Assembly<br>· Number of fuel assemblies<br>· Fuel assembly type<br>· Height of fuel assembly | <br>241<br>16×16<br>12.5' | <br>257<br>16×16<br>12.5' |
| Emergency Core Cooling System (ECCS)<br>· Safety injection<br>· Composition<br>· IRWST | <br>Direct Vessel Injection(DVI)<br>SIS(4), Accumulator(4) Fluid Device<br>Yes | <br>Direct Vessel Injection(DVI)<br>SIS(4), Accumulator(4) Fluid Device<br>Yes |
| Containment Building<br>· Type<br>· Cooling method | <br>Single<br>Active | <br>Single<br>Active |
| I&C | Full Digital | Full Digital |
| Emergency D/G (EDG) | 2 | 4 |

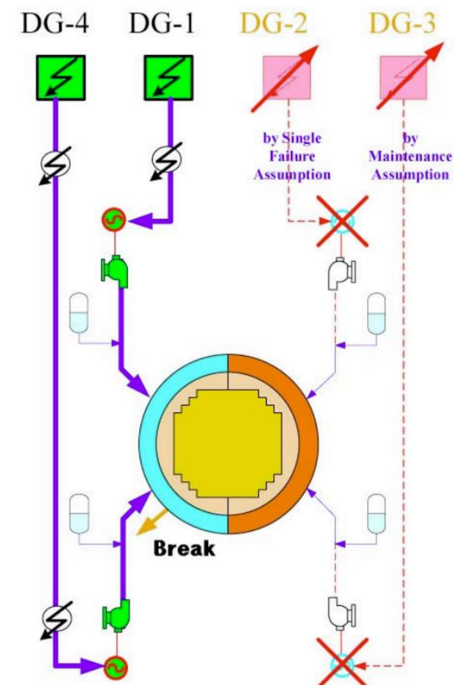
## New Safety Features

- DVI+
  - Prevention of ECC bypass (ECBD, Emergency Core Barrel Duct)
- 4 electrical trains of safety injection system
  - 3 safety systems are available with the single failure assumption
  - N+2
- FD+
  - Fluid Device: passively control the safety injection flow rate
  - Advanced SIT



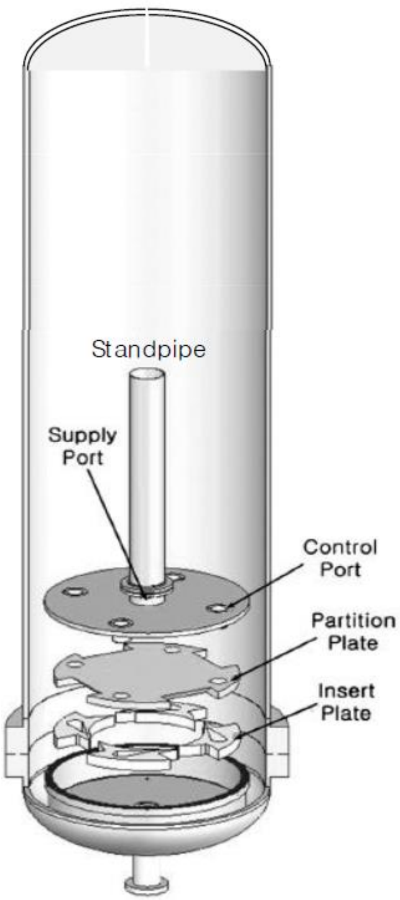


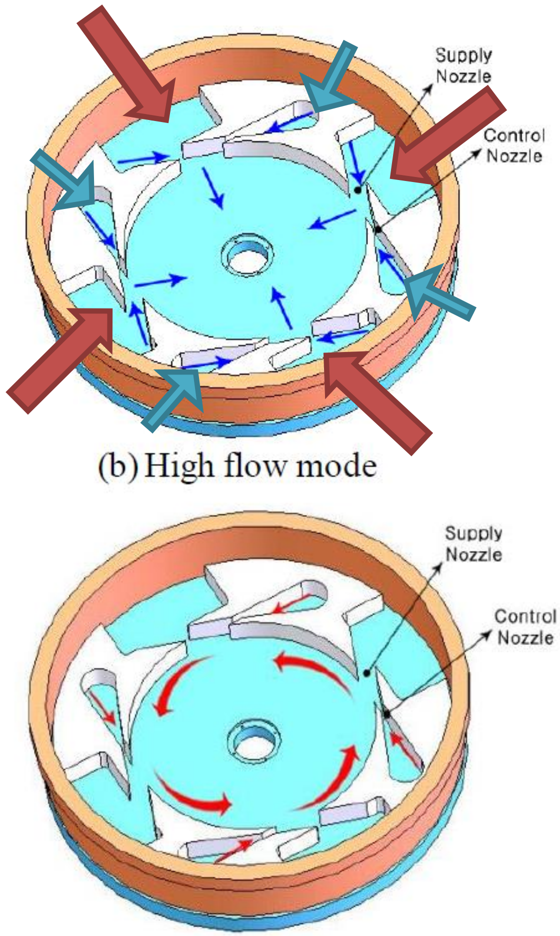



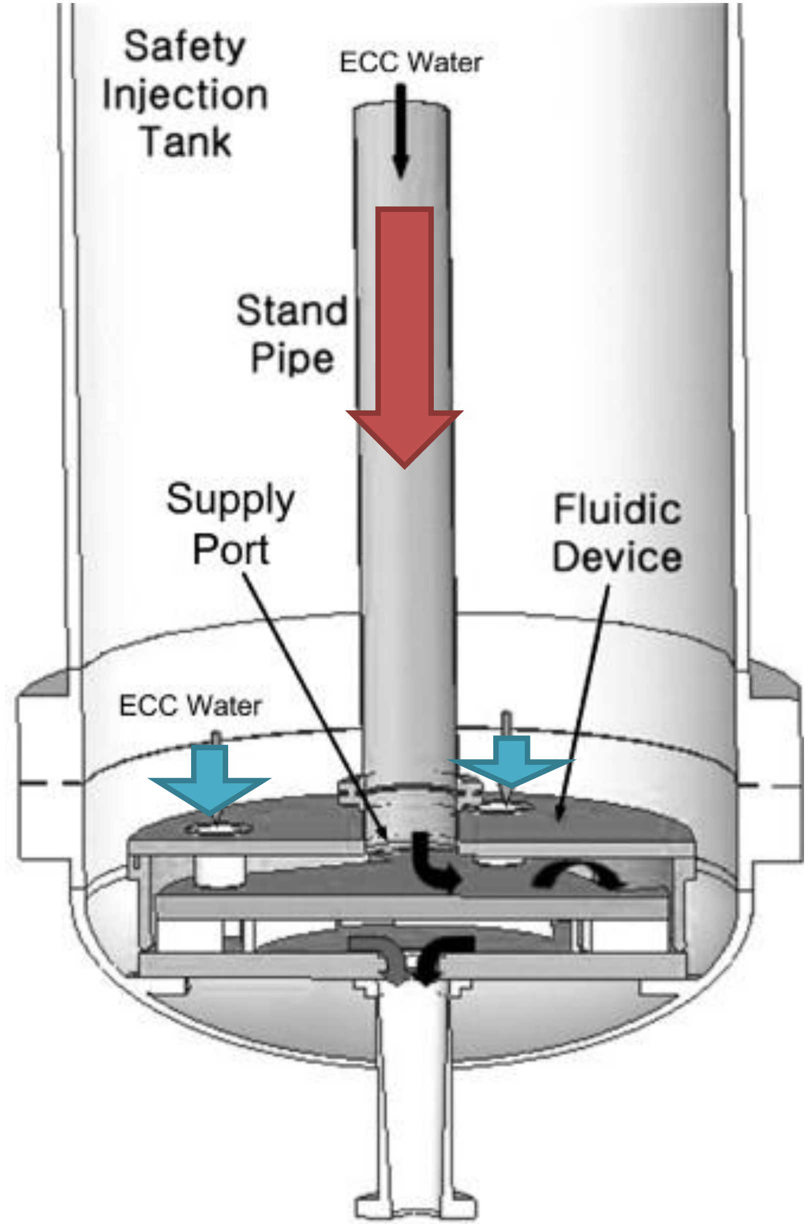
# APR+ Safety Features

- New Safety Features
  - Fluidic device



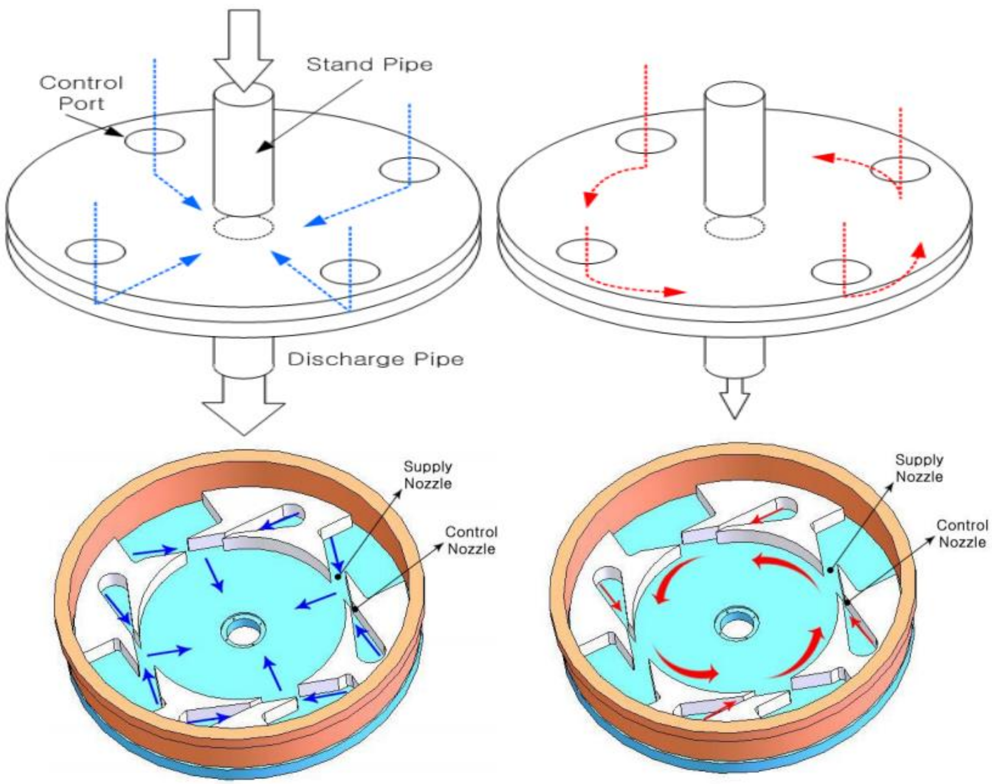

Vortex Chamber



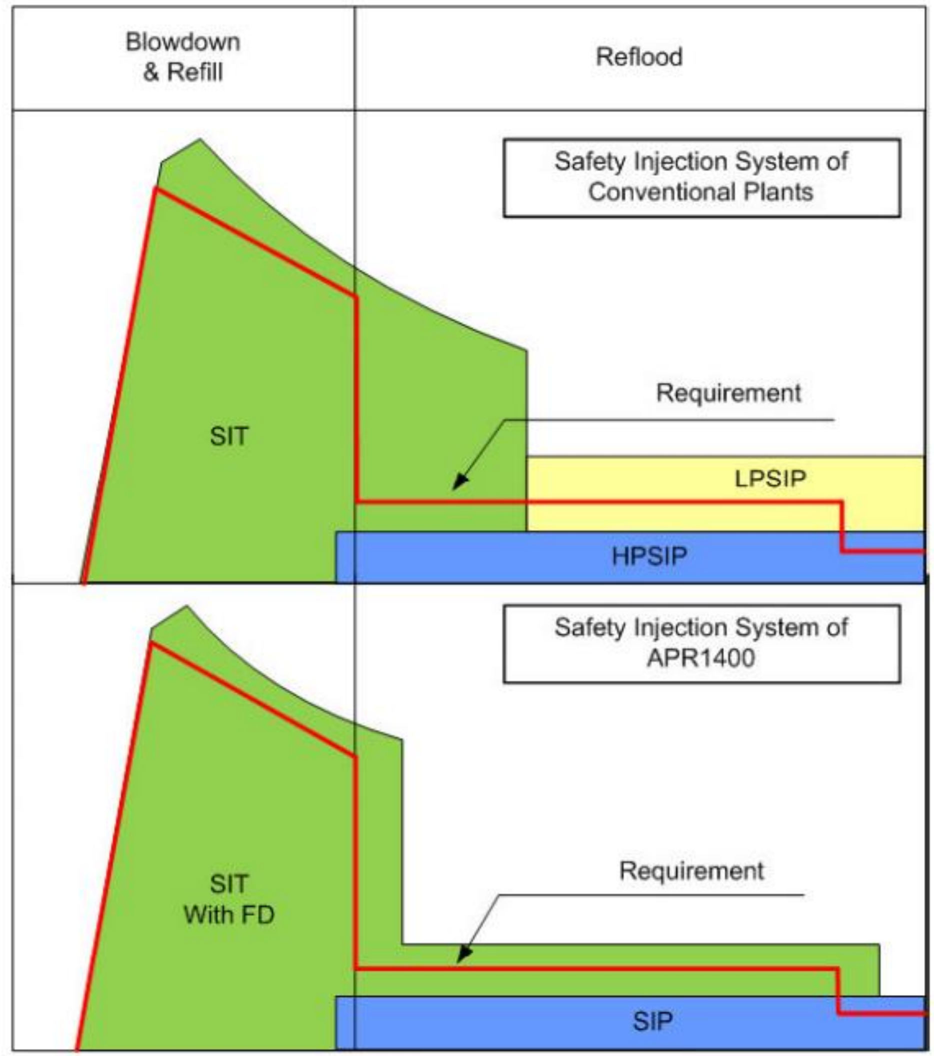
# APR+ Safety Features

- New Safety Features
  - Fluidic device



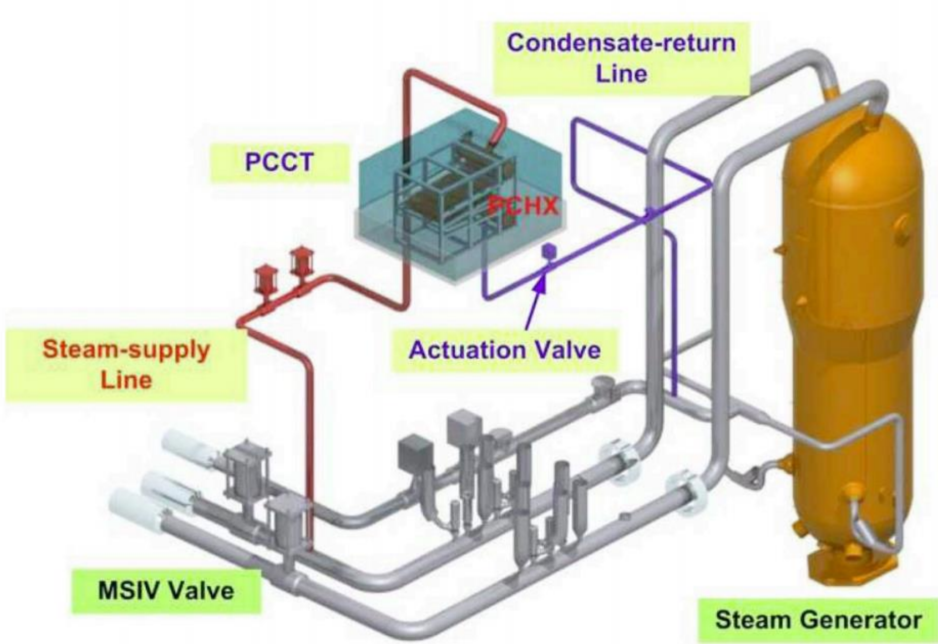

Large Flow Rate

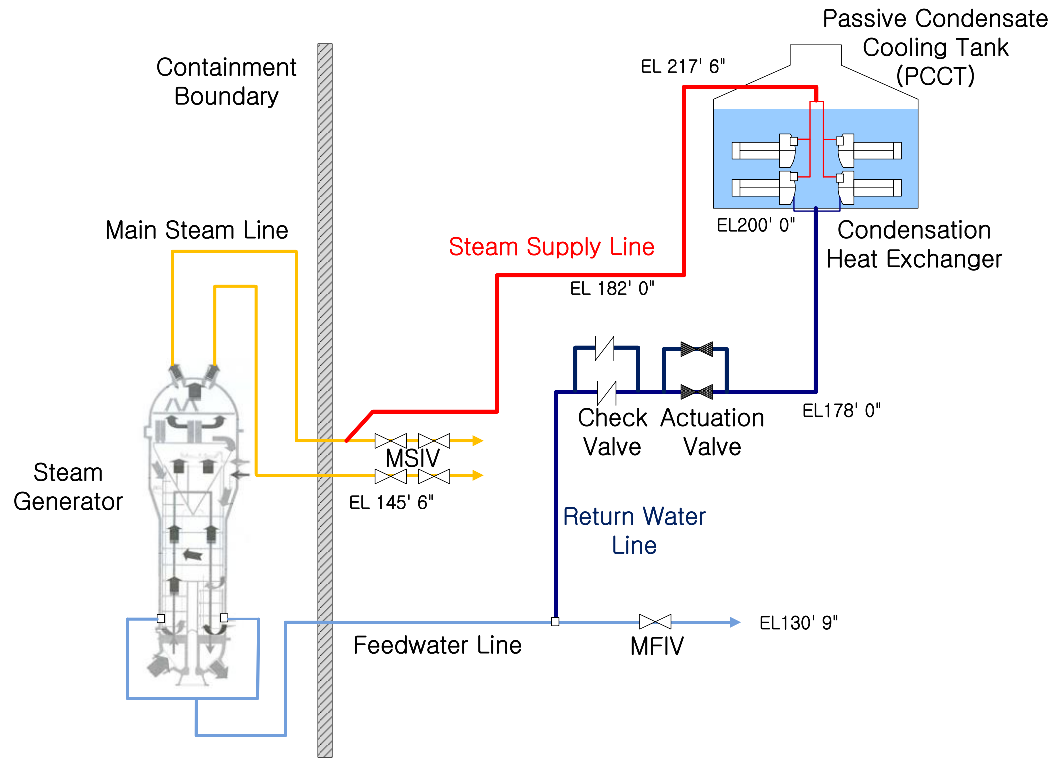
Small Flow Rate



- New Safety Features
  - Passive Auxiliary Feedwater System (PAFS)
    - Replacement of previous active auxiliary feedwater system
    - Reduced core damage frequency
    - Independent two-trains for two steam generators

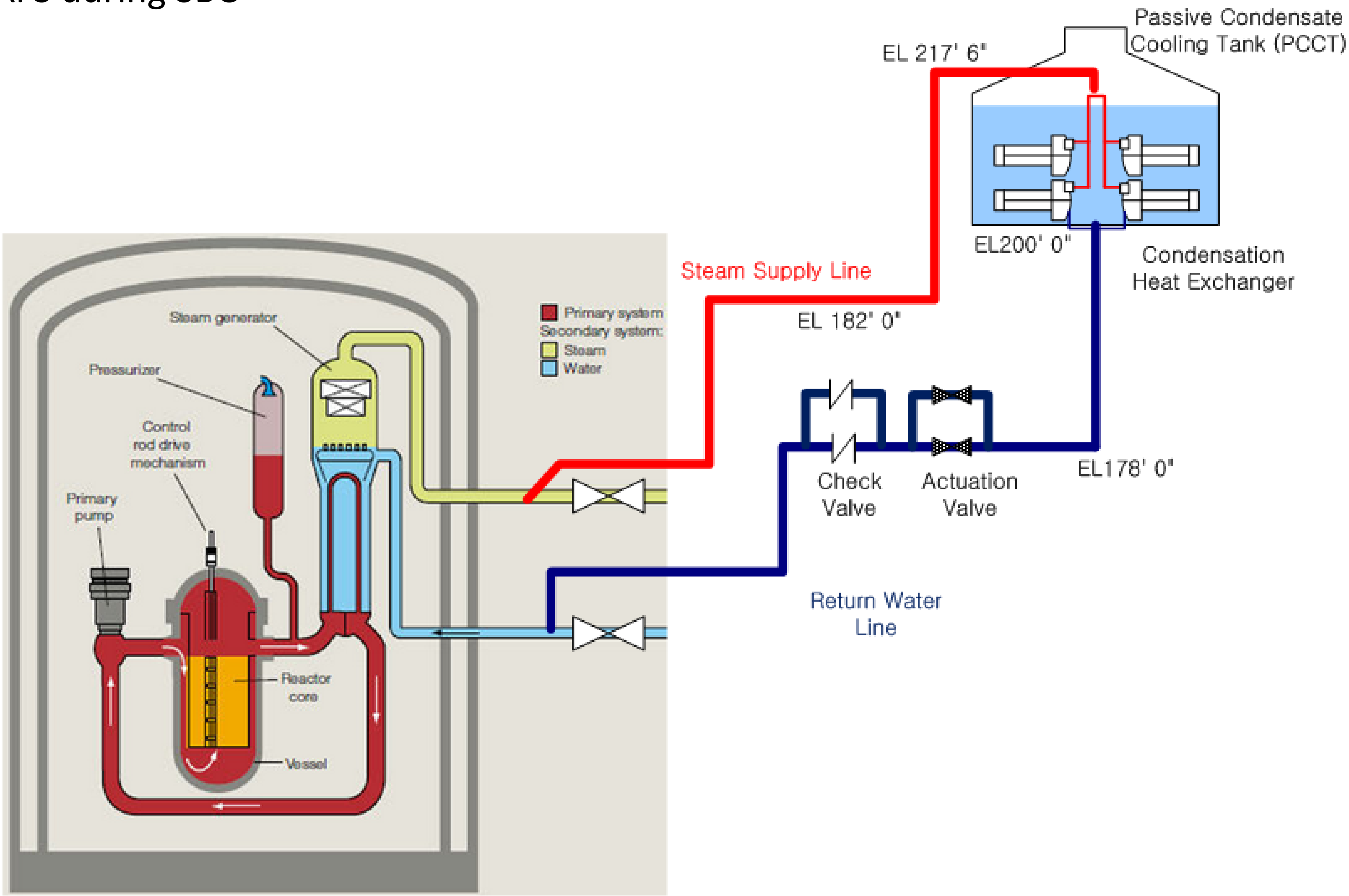
    - Driving force: gravity, free convection, condensation
    - Over 8 hours operation capability during SBO
    - 100% volume heat exchanger per SG



# APR+ Safety Features

- New Safety Features
  - PAFS during SBO



- New Safety Features
  - During SBO

Decay heat

↓ Natural circulation

U-tube

↓ Evaporation

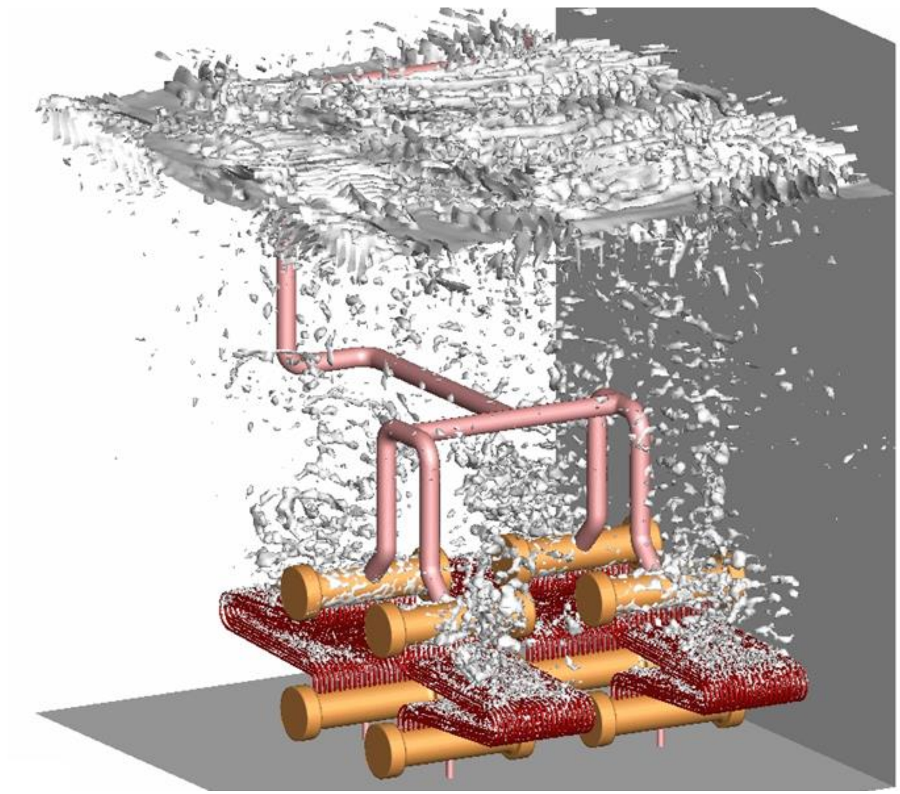
Secondary side

↓ Natural circulation

Heat exchanger tube

↓ Condensation/boiling

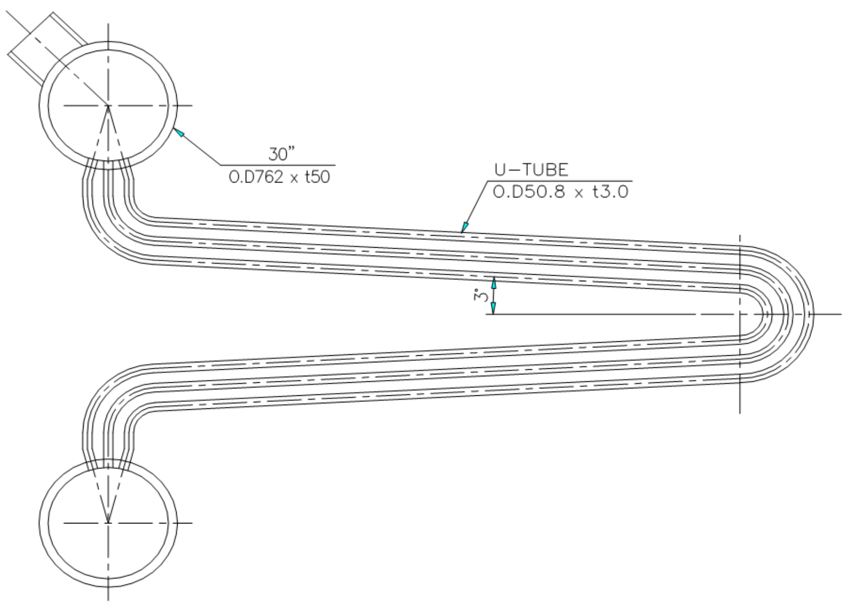
Water pool



# APR+ Safety Features

- New Safety Features
  - Safety issues
    - Condensation/boiling heat transfer rate
    - Water hammer $\Rightarrow$ differential shock

Water Hammer (differential shock)



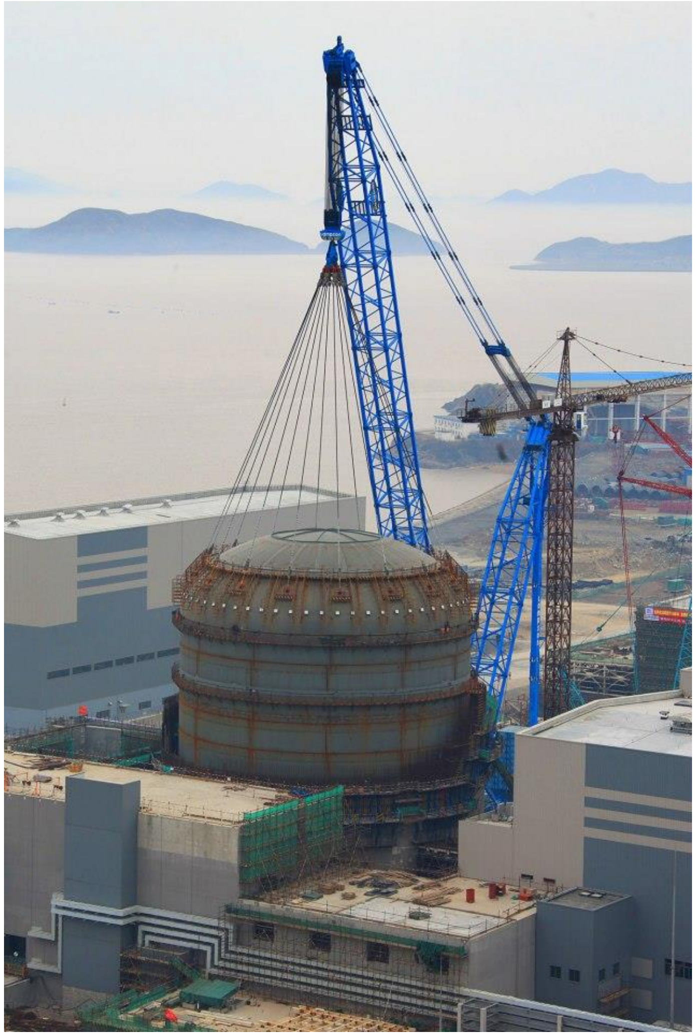

- Velocity of Steam is 10-100 times greater than the velocity of liquid
- Steam moving over the condensate will start manufacturing waves
- Waves will grow until they block the pipe completely forming a "Slug"
- Stopping only when suddenly impacted by equipment, tee, elbow, valve, or any bend in the piping

# APR+ Safety Features

- New Safety Features
  - ECBD, Emergency Core Barrel Duct
  - Electrical 4 trains of safety injection system
  - FD+
  - PAFS

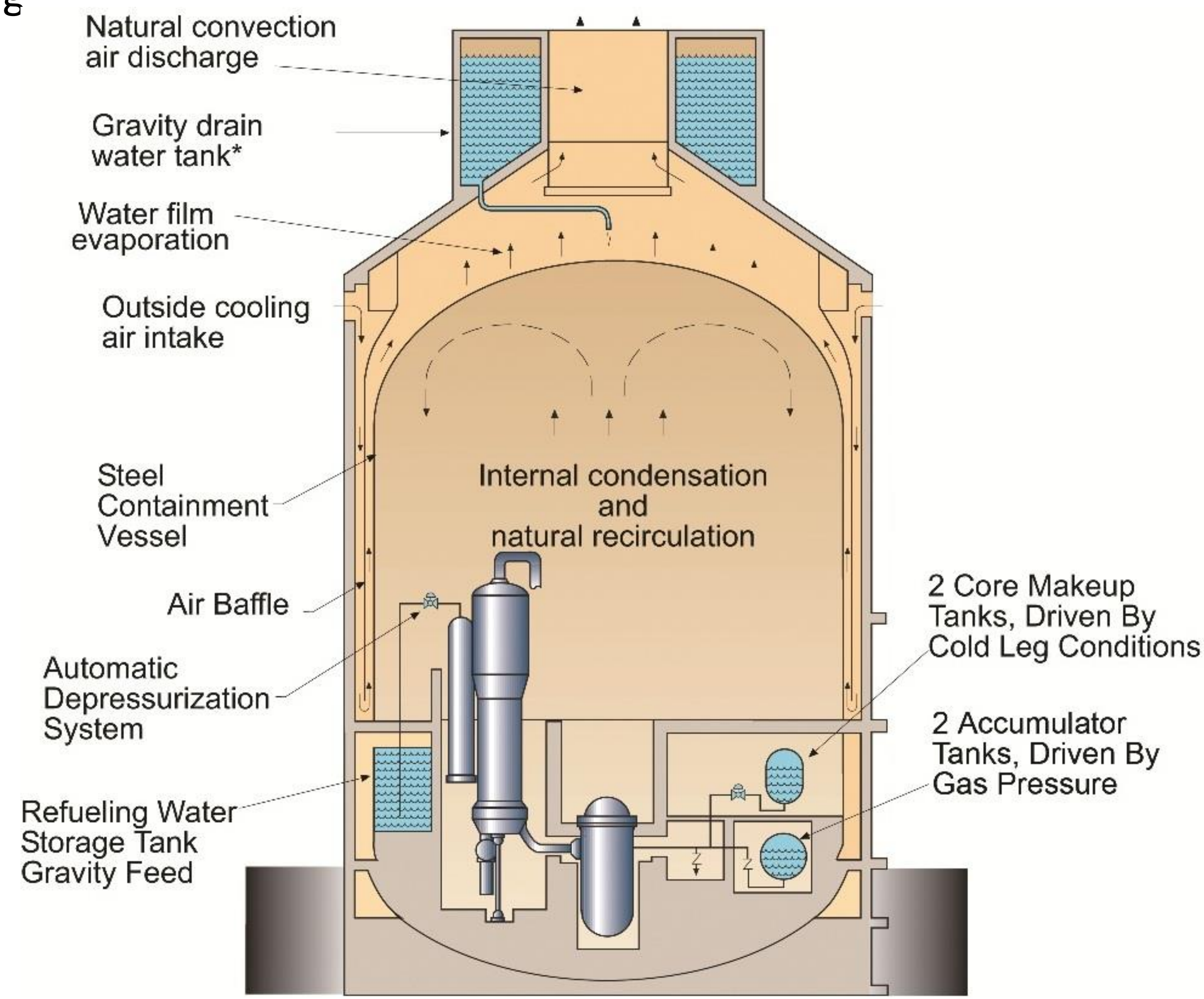
# AP1000 Safety Features

- AP1000 Overall Specification
  - Developer: Westinghouse, USA
  - Thermal power: 3415 MWth
  - Electrical power: 1117 MWe
  - Design life: 60 years
  - Construction period: 36 months
  - Core damage frequency:
    - $<5 \cdot 10^{-7}$/year
  - Under construction
    - In China: 4 units
    - In US: 4 units



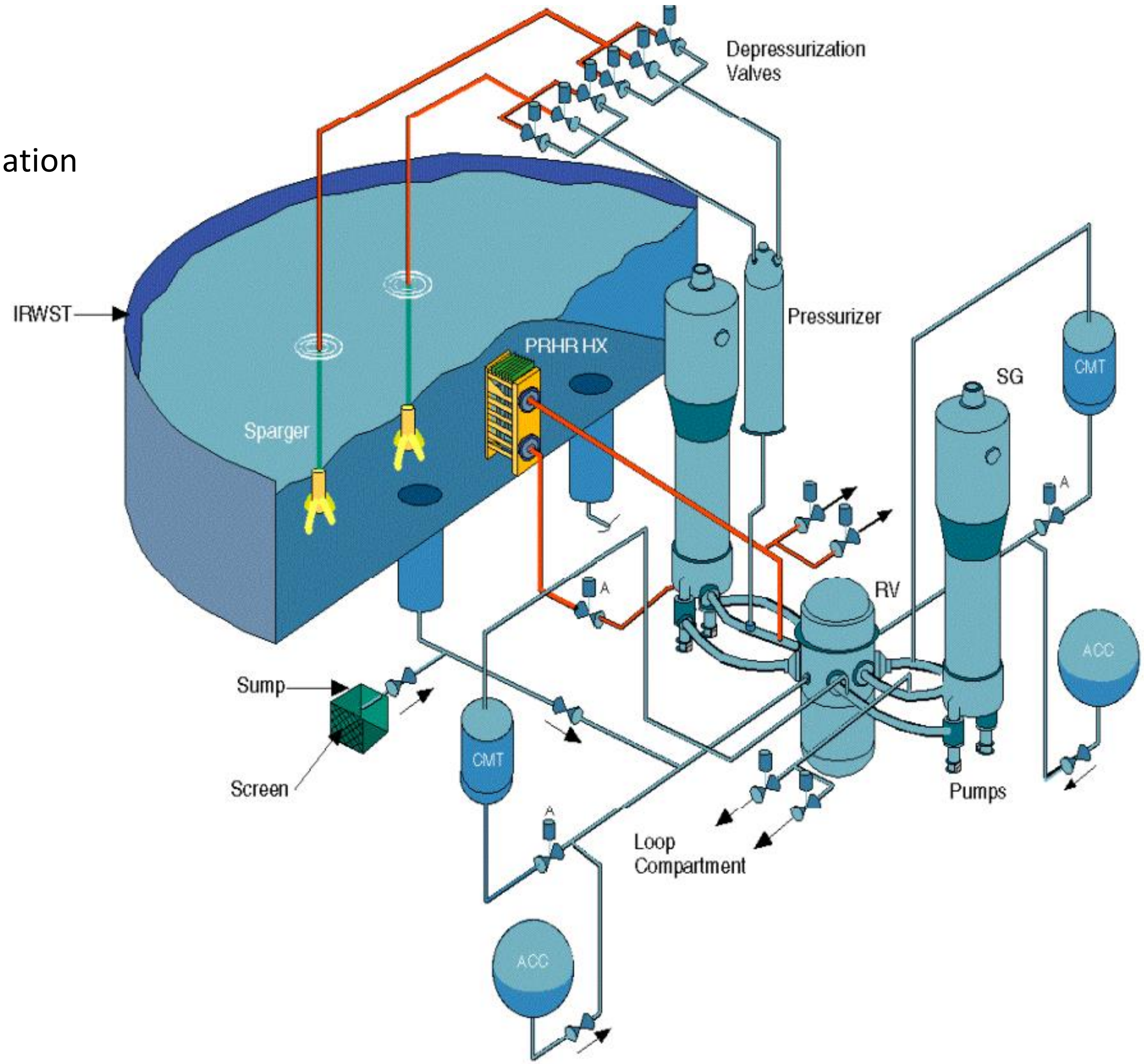
# AP1000 Safety Features

- New safety features
  - PCC: Passive containment cooling
    - Steel containment
    - Concrete shield
    - Safety concern?
  - CMT: Core make-up tank
  - PRHR: Passive residual heat removal system
  - ADS: Automatic depressurization system
  - Accumulator tanks
  - IRWST: In-containment Refueling Water Storage Tank



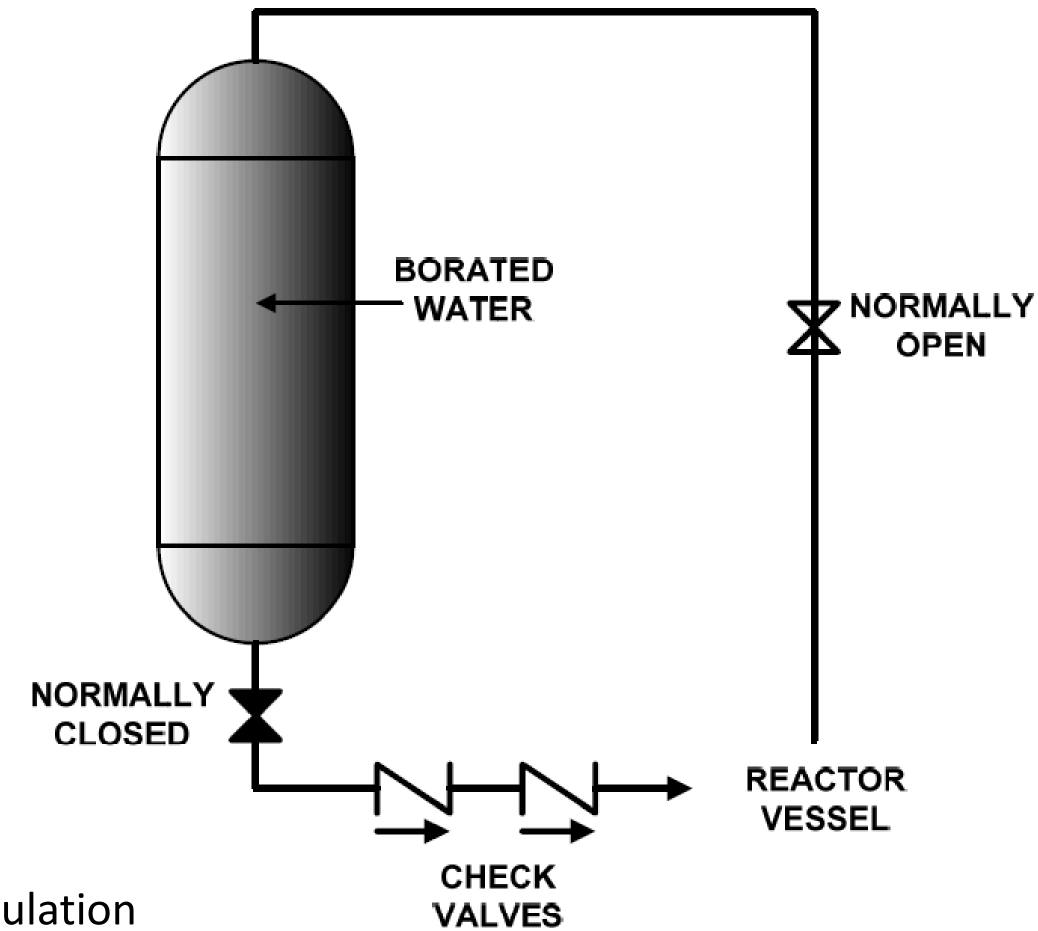
# AP1000 Safety Features

- New safety features
  - CMT: Core make-up tank
    - Full pressure
    - Injection by natural circulation
    - Replace HPSI pumps
  - PRHR: Passive residual heat removal system
  - ADS: Automatic depressurization system
  - IRWST: In-containment Refueling Water Storage Tank



# AP1000 Safety Features

- New safety features
  - CMT: Core make-up tank
    - Full pressure
    - Injection by natural circulation
    - Replace HPSI pumps
    - Filled with cold borated water
    - Connected at the top and bottom by balance lines.
    - Always at primary pressure
    - Natural circulation is established when valves are open
    - Cold borated water enters reactor
    - Hot primary water flows to CMT head.




High pressure safety injection by natural circulation

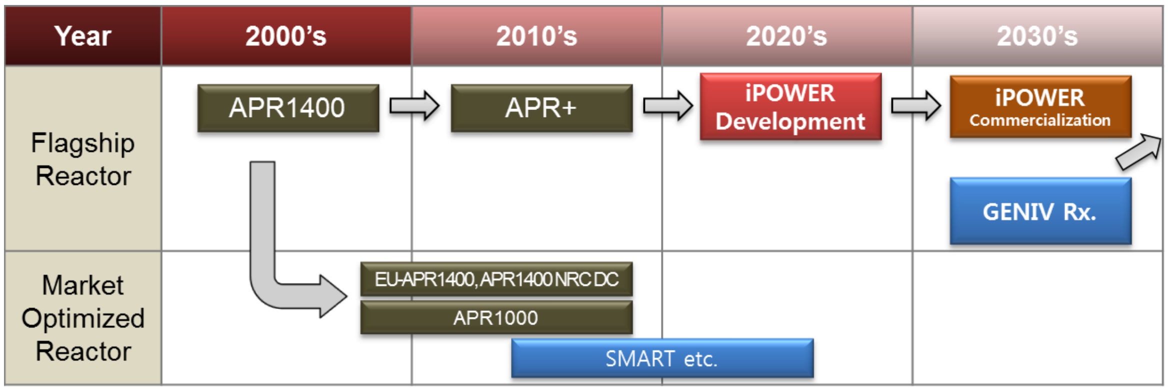
# AP1000 Safety Features

- New safety features
  - SBO: Station Black-Out
    - Passive core cooling
    - Passive containment cooling
  - LOCA
    - Passive core cooling

# iPOWER

## iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)

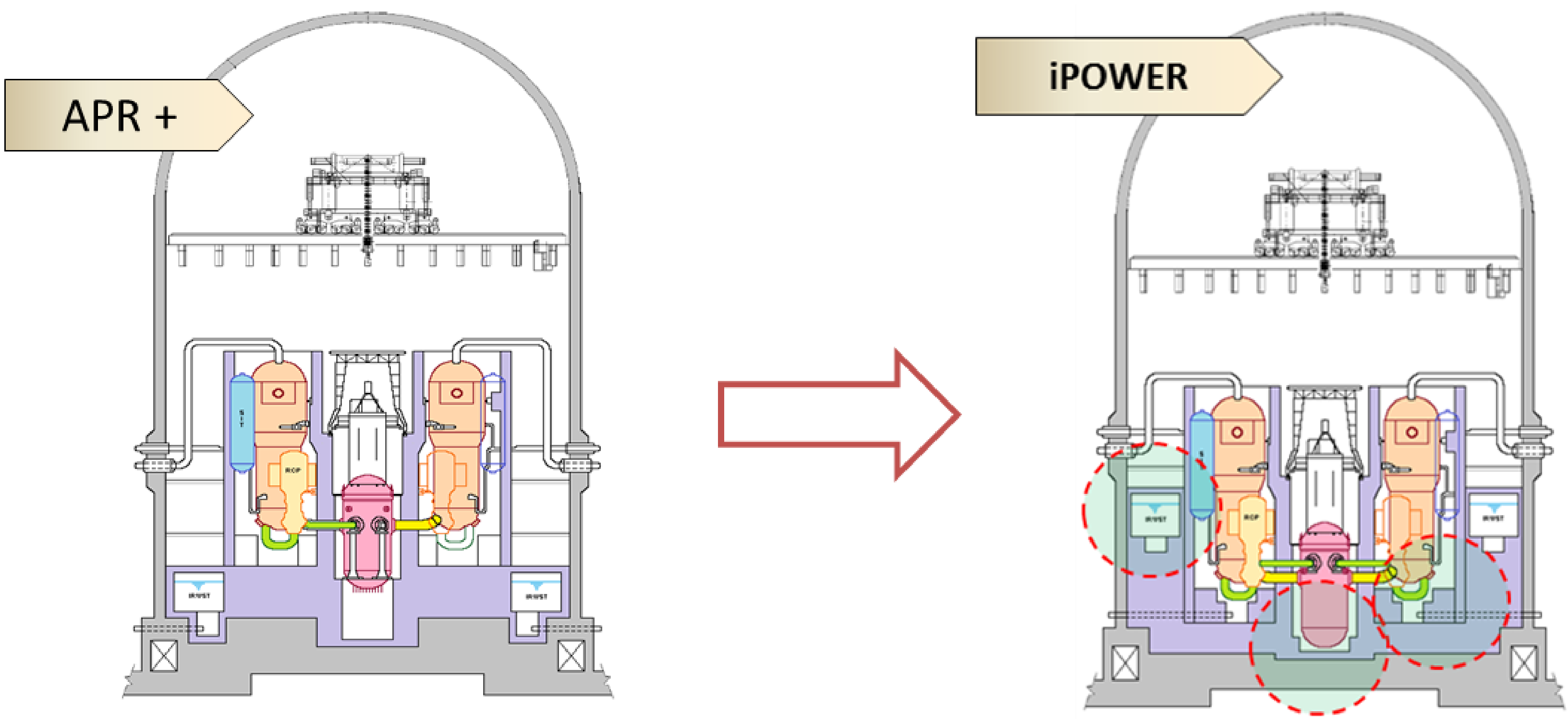
- Background
  - To secure the competitiveness of Korean NPP in 2020's




| Category | Development Strategy |
|---|---|
| Design life | Longer than 80 years |
| Power output | 1200~1500MWe (1250MWe) |
| CDF | < 1 X $10^{-7}$ /RY (5 X $10^{-8}$ /RY) |
| Containment Failure Frequency | ~ 0 (<1 X $10^{-9}$ /RY 이하) |
| Operator's grace time | > 72 hours (1 week) |
| Safety System | Fully passive |

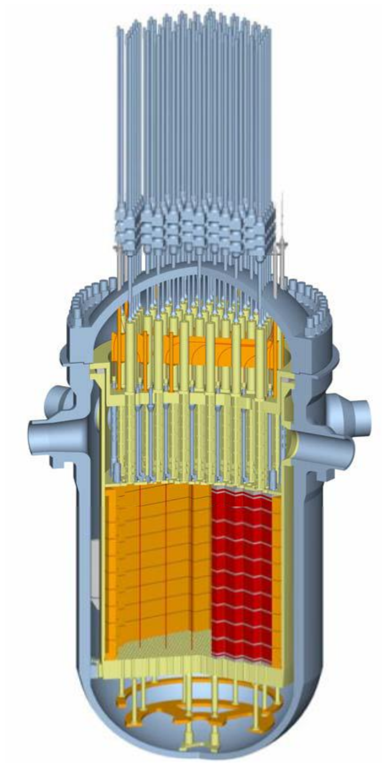
# iPOWER

- iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)
  - RCS and General arrangement
    - 2-loop PWR with pre-stressed concrete containment
    - **Top-mounted ICI**
    - **Elevated IRWST for gravity feed**

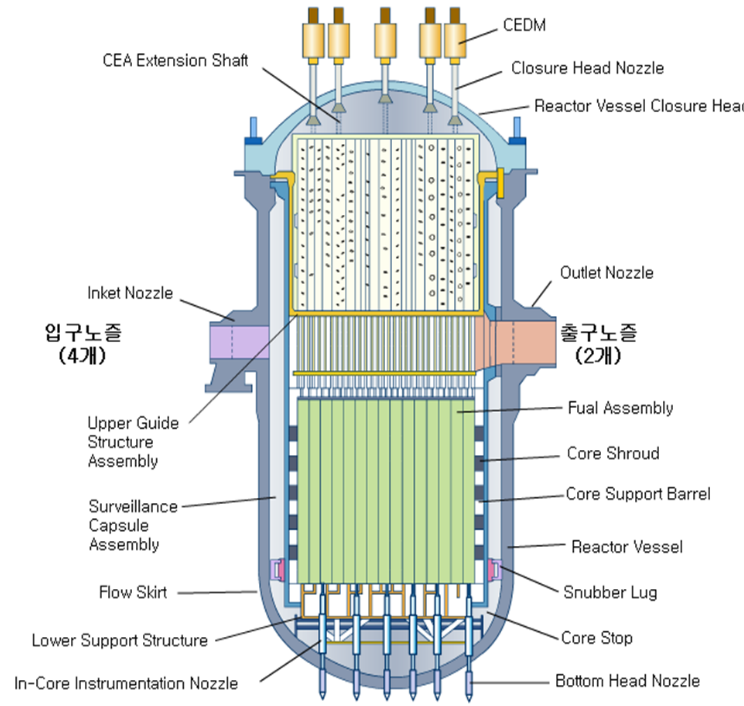


❖ iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)

- **Top-mounted ICI**



Top Mounted ICI
(AP1000, EPR, APWR)

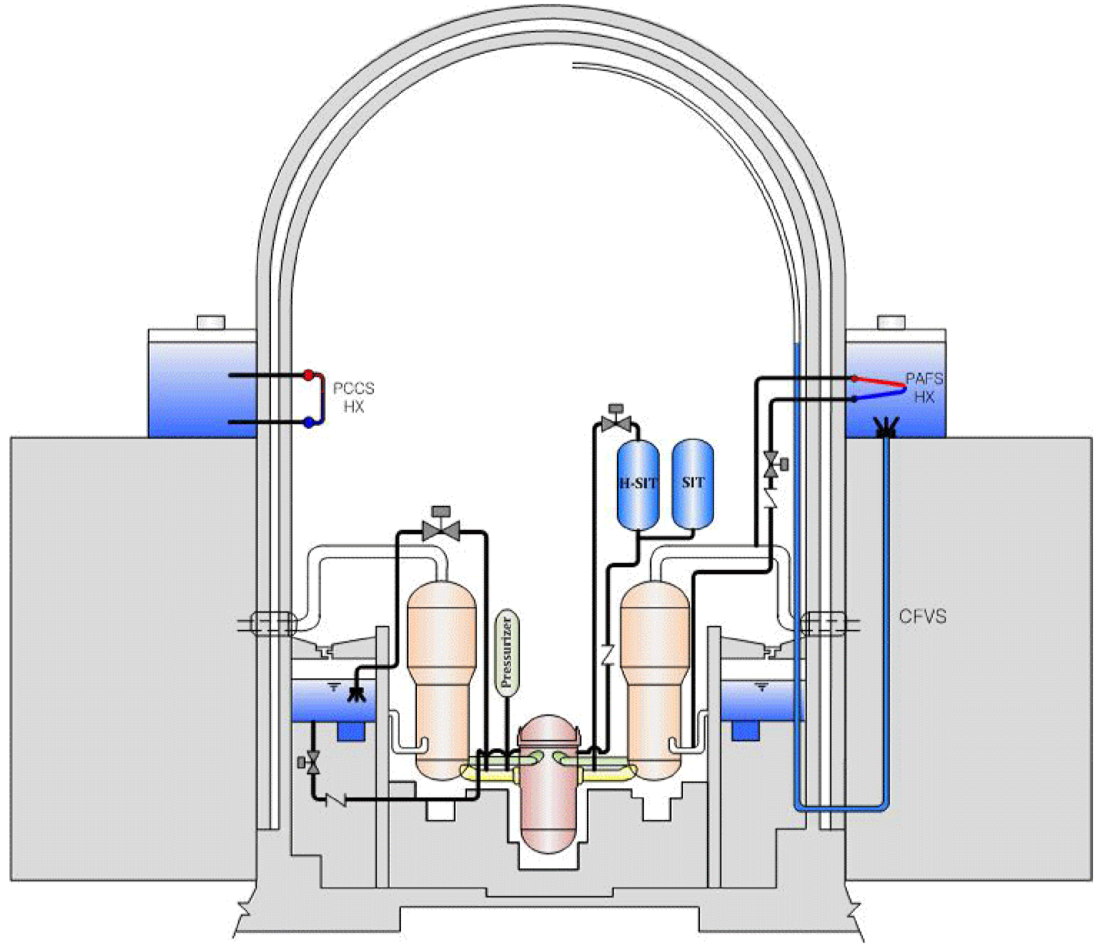



Bottom Mounted ICI
(APR1400, APR+)

## iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)

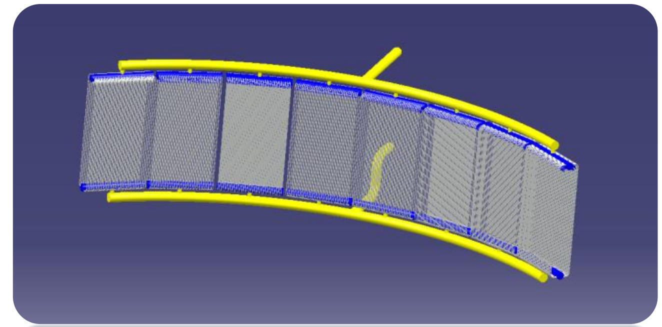
- Passive safety features
  - Passive containment cooling
  - Passive safety injection system
  - Passive residual heat removal system
  - Passive filtered ventilation system
  - Passive spent fuel pool cooling

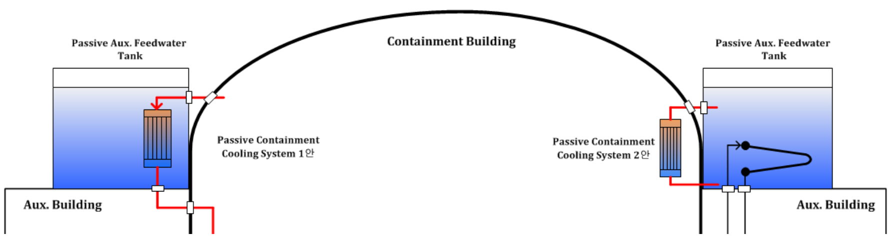
- No Pump
- No Electricity
- No Operator Action
- No Failure

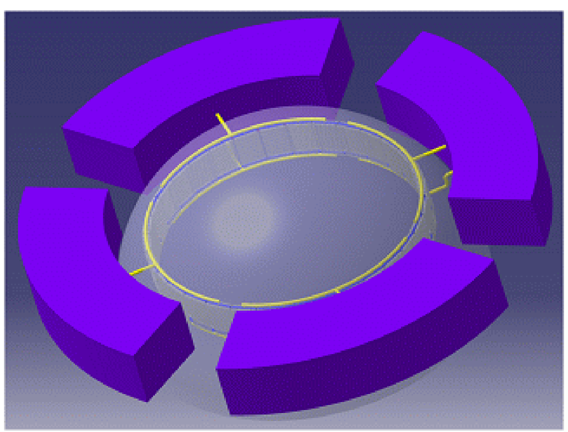


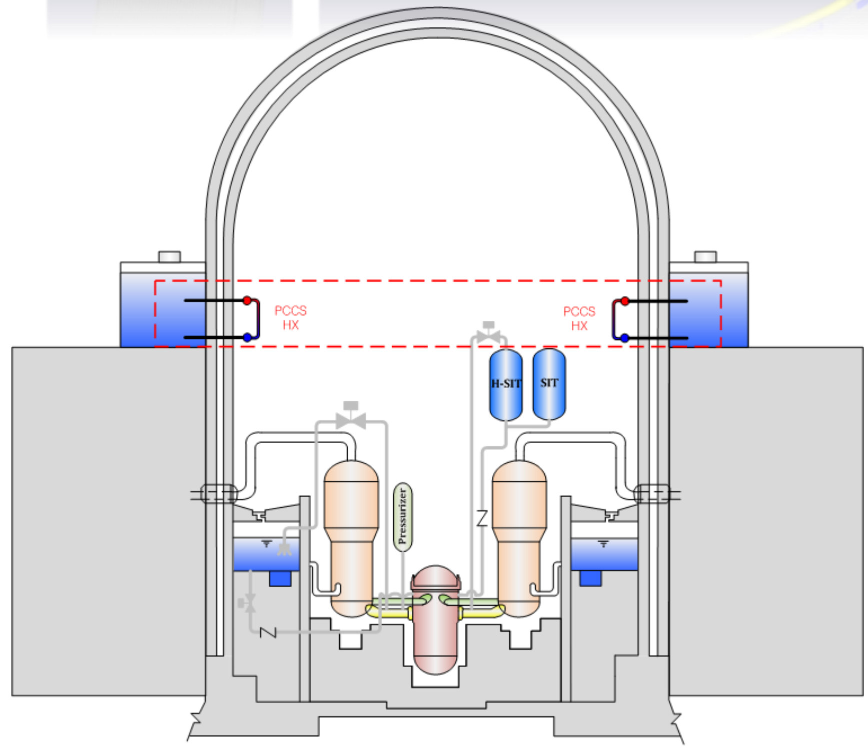
## iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)

- Passive safety features
  - Passive containment cooling
  - Mission time: > 72 hours (up to 1 week)
  - 4 independent trains (33% × 4)

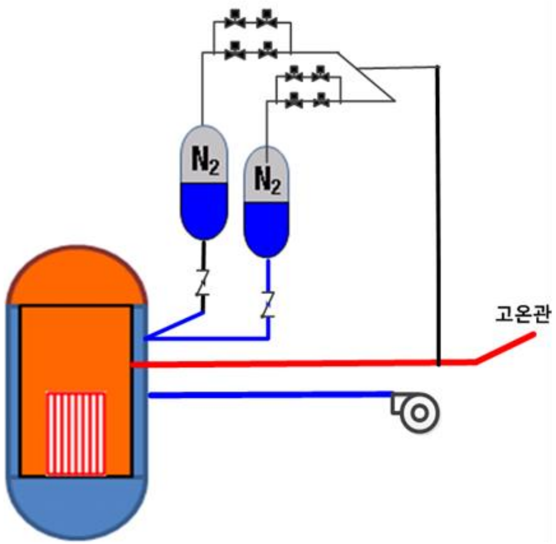


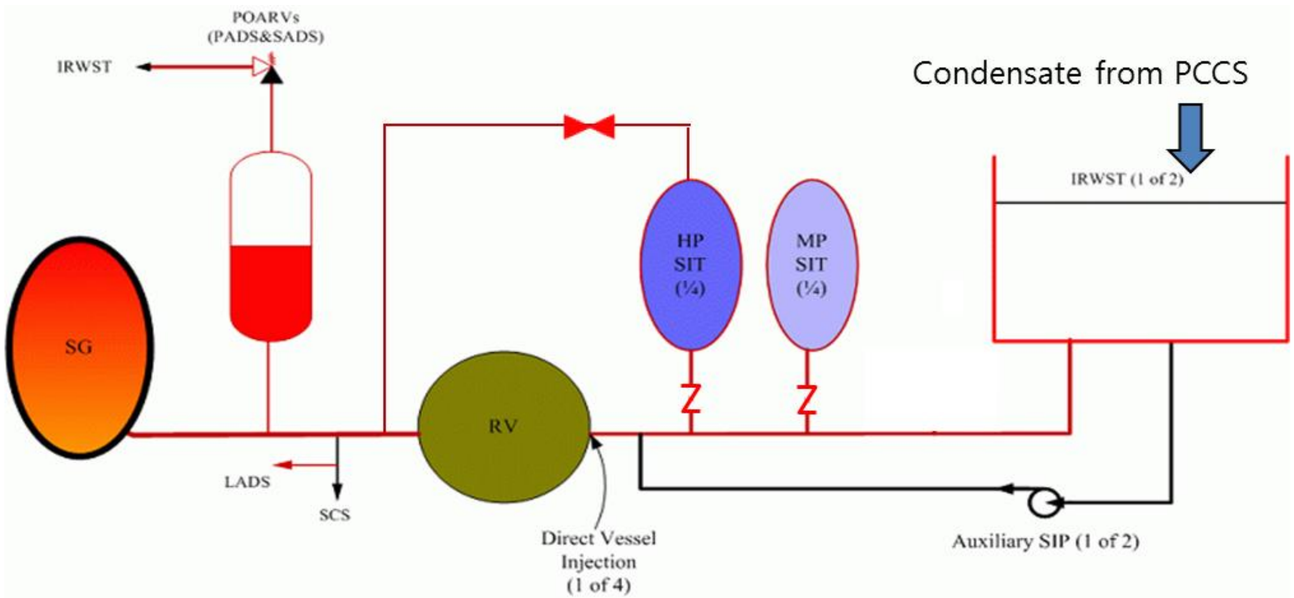


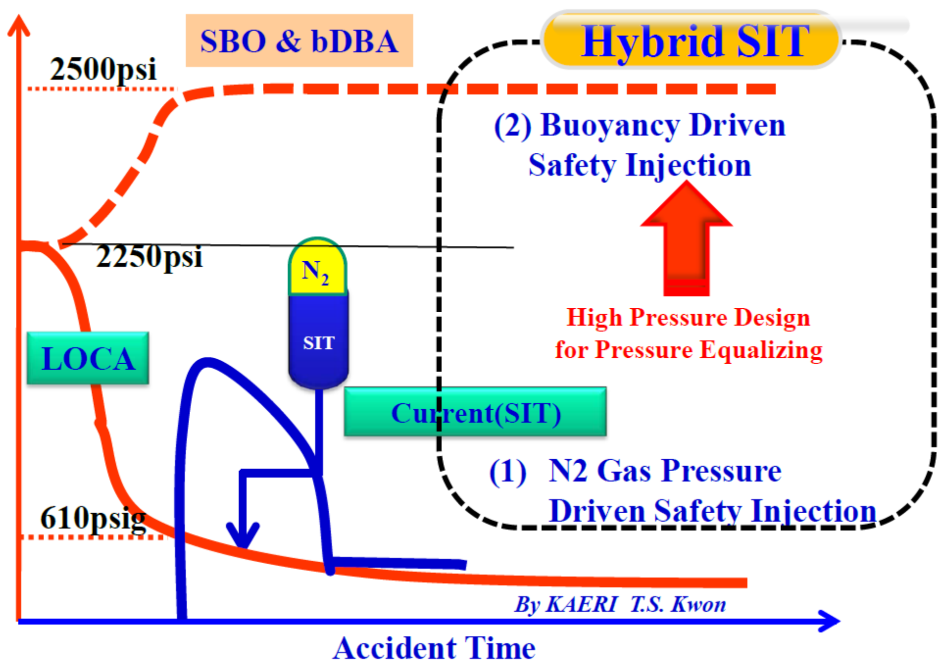


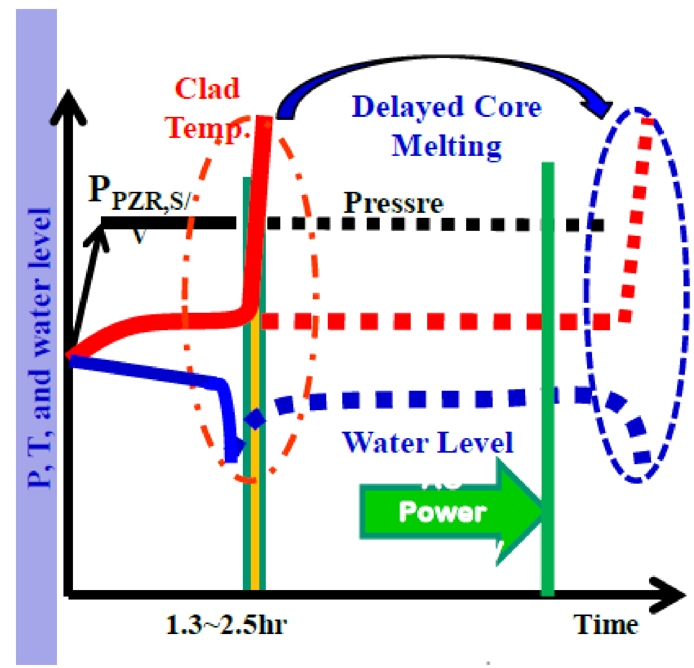
- iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)
  - Passive safety features
    - Passive safety injection system (PECCS: Passive Emergency core cooling system)
      - Hybrid SIT
        - Depressurization event (LOCA): conventional SIT
        - High pressure event (SBO): pressure equalization between RCS and SIT
          - Gravity feed of safety injection water
      - Elevated IRWST
        - Gravity driven low pressure safety injection



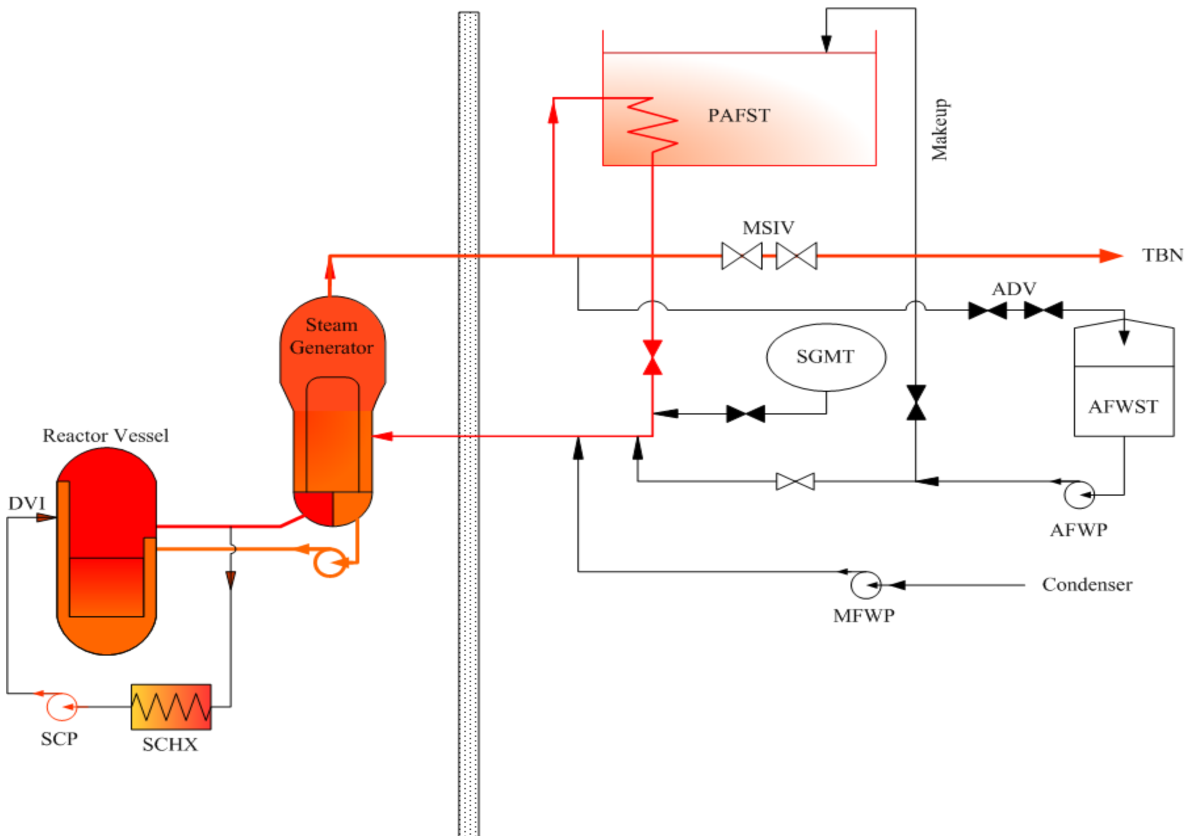



- iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)
  - Passive safety features
    - Passive safety injection system (PECCS: Passive Emergency core cooling system)
      - Hybrid SIT

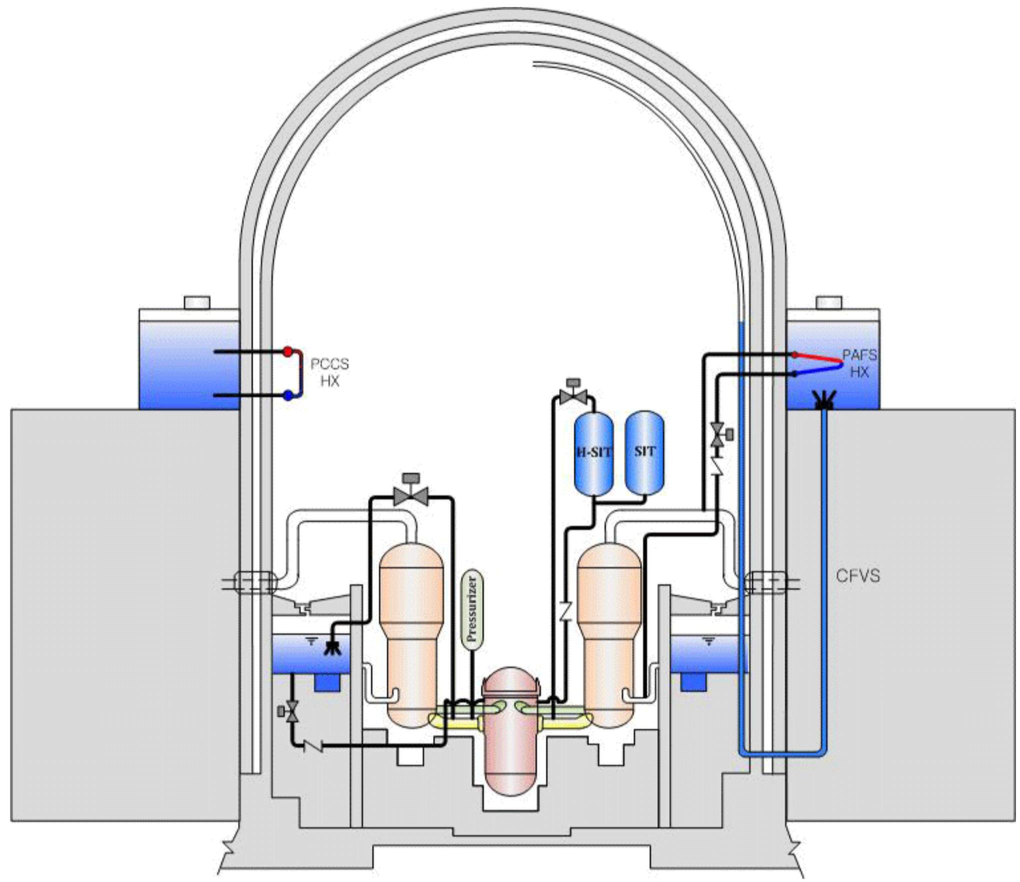


- iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)
  - Passive safety features
    - Passive residual heat removal system
      - PAFS + auxiliary feedwater pump (for backup)
      - Shutdown Cooling System

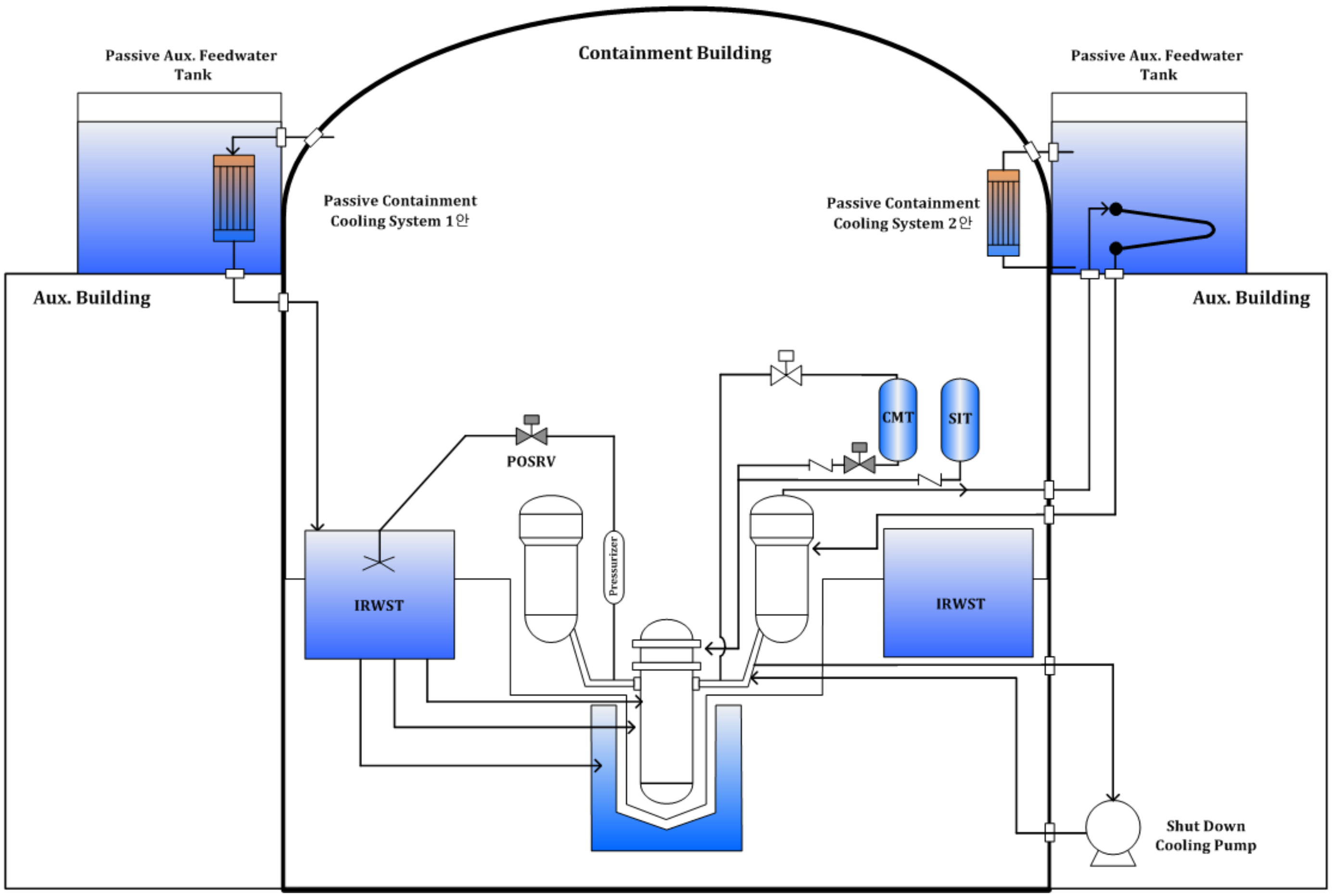


- iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)
  - Passive safety features
    - Passive filtered ventilation system
      - Containment filtered ventilation system
      - Water valve: zero failure probability
    - Passive spent fuel pool cooling
      - Water supply using PAFS water tank

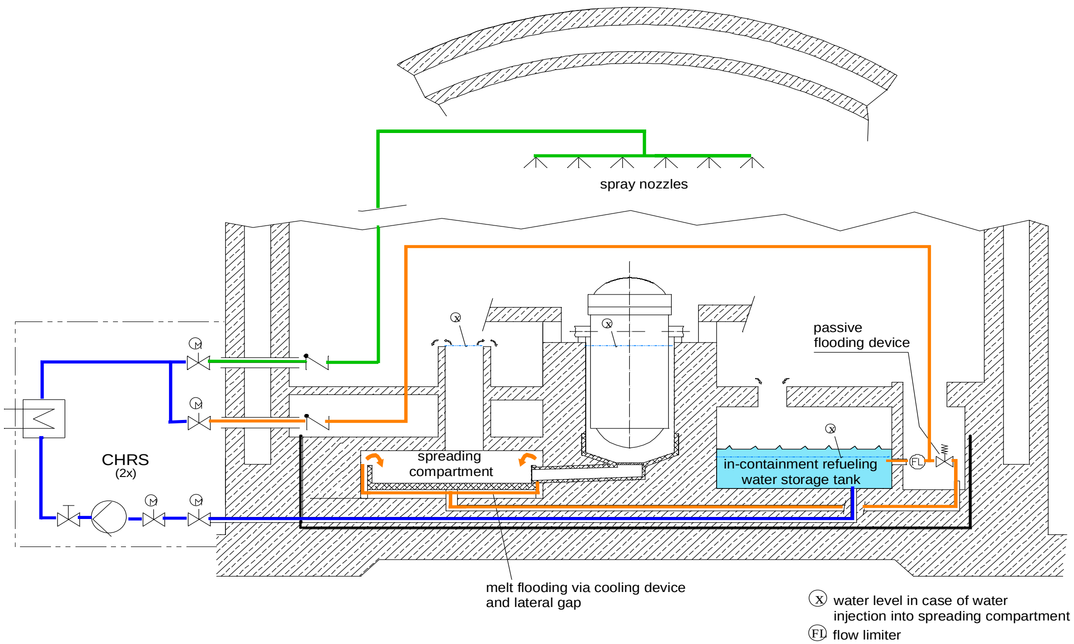


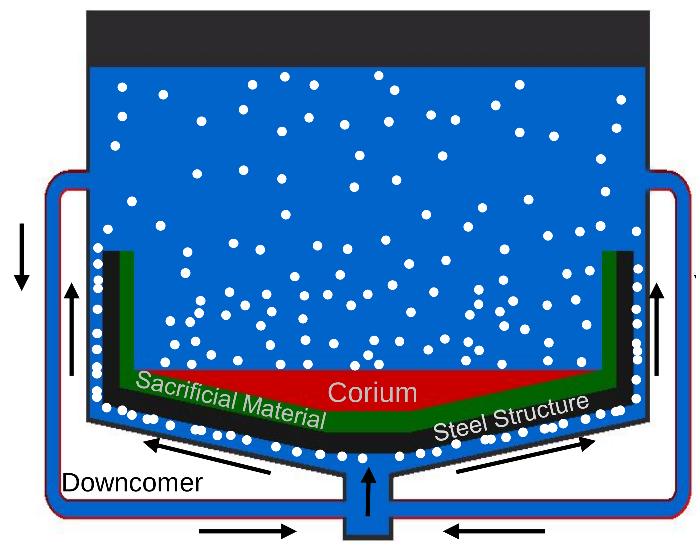
❖ iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)

- Passive safety features
  - Passive IVR/ERVC

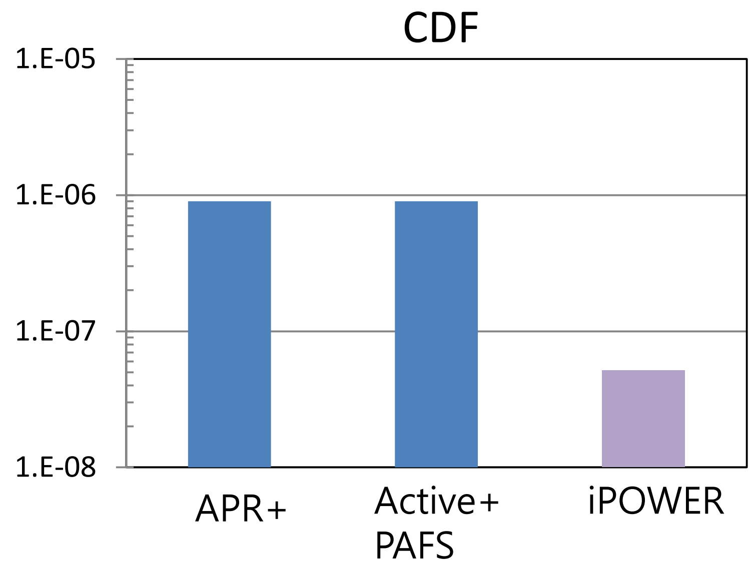


- iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)
  - Passive safety features
    - Core catcher
      - A core catcher is a device provided to catch the molten core material (Corium) of a nuclear reactor in case of a nuclear meltdown and prevent it from escaping the containment building.
      - Passive water supply using IRWST



- iPOWER (Innovative Passive Optimized Worldwide Economical Reactor)
  - PSA
    - CDF < 1 X $10^{-7}$ /RY
    - LRF < 1 X $10^{-8}$ /RY
  - Plan
    - Conceptual design: 2014~
    - Basic design: ~ 2022




From KHNP presentation material

**추진 전략**

- 핵심기술 개발 후 원자로 설계 착수
  - 혁신적 설계 개념의 구현성 입증 필요
- 기초연구 추진을 통한 인력양성 병행
  - APR1400 개발시의 학계의 CARR 역할 필요