# PMT3533

## Reatores Nucleares: Geração II, III, III+ e IV

## Estruturas e sistemas que compõem os reatores nucleares

Marcelo S. Rocha

Pedro E. Umbehaun

# Reatores Nucleares de Potência

Duas formas de análise:

- Por característica de funcionamento (Todreas; Tong; El-Wakil)
- Por característica de projeto (Gerações) (Goldberg & Rosner)

I- Análise dos reatores de potência por característica de funcionamento:

- Reatores Nucleares Refrigerados e Moderados a Água:

- Reatores refrigerados e moderados a água leve (Light Water Reactors – LWR)

  - Pressurized Water Reactors (PWR)

  - Boiling Water Reactors (BWR)

# Reatores Nucleares de Potência

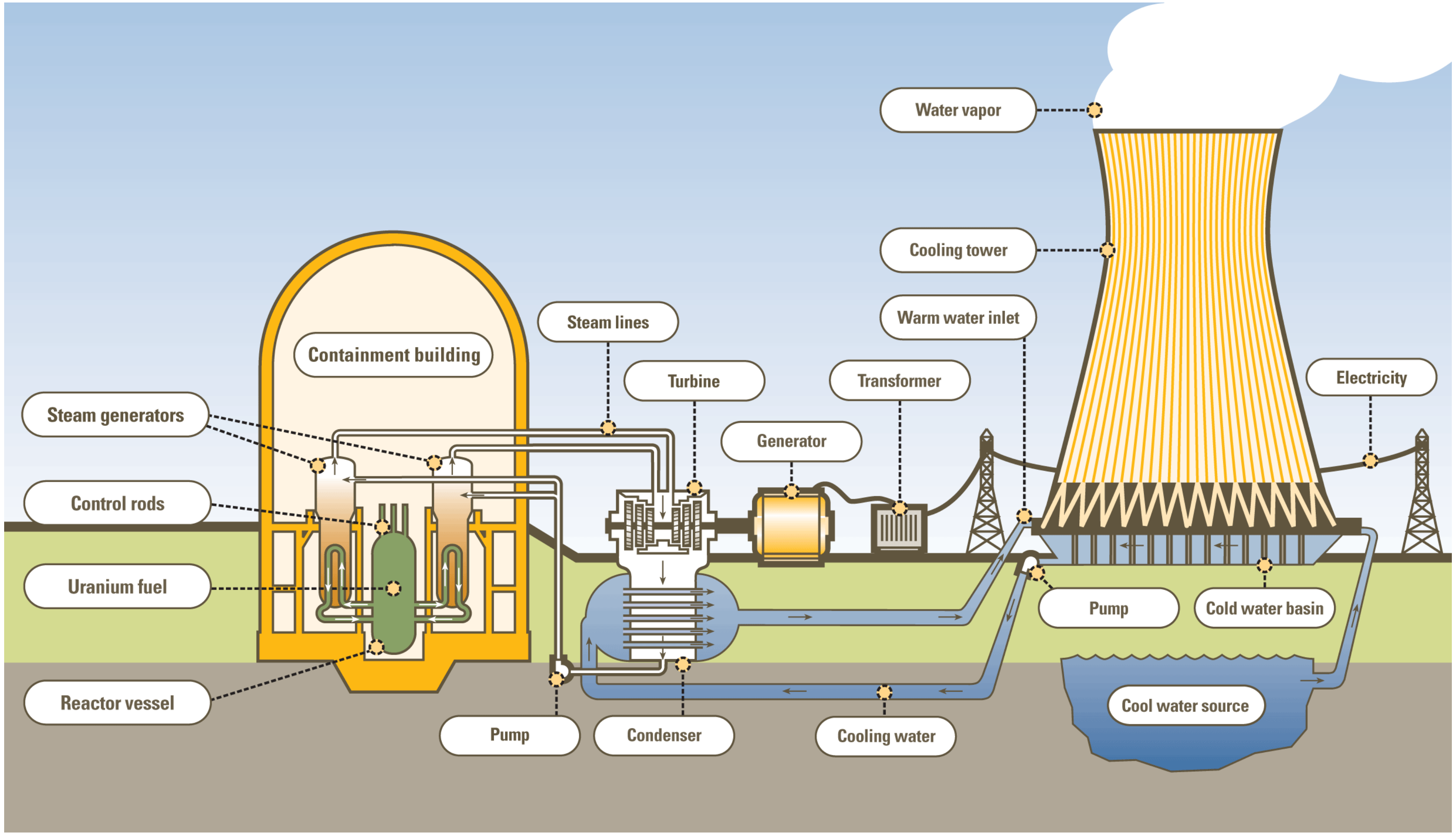
Função: Geração de eletricidade.

De forma geral, um reator nuclear de potência é uma usina termelétrica cujo combustível é o combustível nuclear (Urânio metálico enriquecido). Por suas peculiaridades possui sistemas específicos de controle e segurança que uma termelétrica convencional não possui.

# Reatores Nucleares de Potência

ATMEA

# Reatores Nucleares de Potência



# Reatores Nucleares de Potência

Os principais tipos de reatores nucleares de potência existentes são:

Reatores moderados e refrigerados a água

Reatores refrigerados a gás

Reatores refrigerados a metal líquido e sal fundido

# Reatores Nucleares de Potência

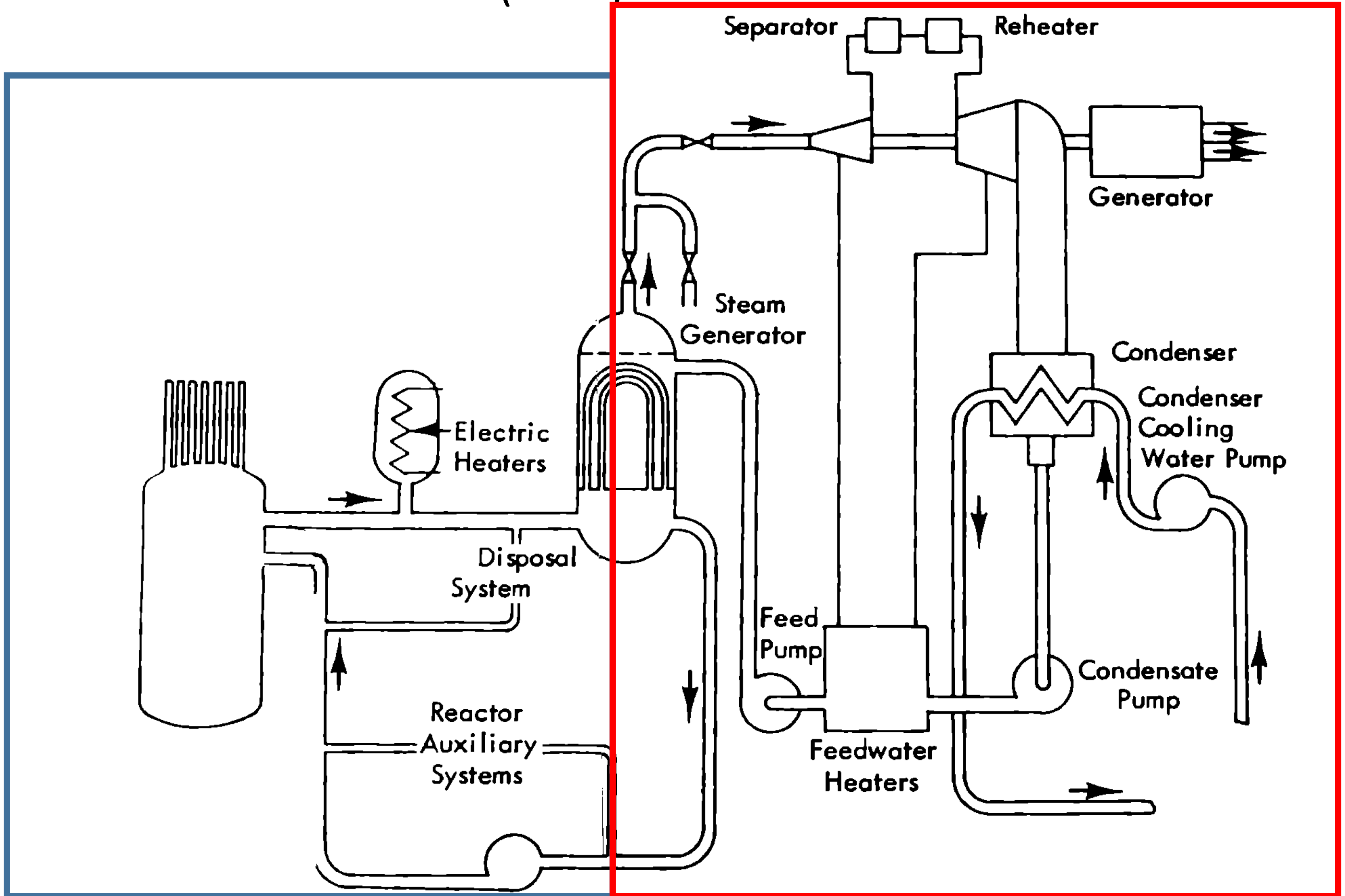
**Table 1-1 Basic features of major power reactor types**

| Reactor type | Neutron spectrum | Moderator | Coolant | Fuel: Chemical form | Fuel: Approximate fissile content (all $^{235}U$ except LMFBR) |
|---|---|---|---|---|---|
| Water-cooled | Thermal | | | | |
| PWR | | $H_2O$ | $H_2O$ | $UO_2$ | ≈ 3% Enrichment |
| BWR | | $H_2O$ | $H_2O$ | $UO_2$ | ≈ 3% Enrichment |
| PHWR (CANDU) | | $D_2O$ | $D_2O$ | $UO_2$ | Natural |
| SGHWR | | $D_2O$ | $H_2O$ | $UO_2$ | ≈ 3% Enrichment |
| Gas-cooled | Thermal | Graphite | | | |
| Magnox | | | $CO_2$ | U metal | Natural |
| AGR | | | $CO_2$ | $UO_2$ | ≈ 3% Enrichment |
| HTGR | | | Helium | UC, $ThO_2$ | ≈ 7–20% Enrichment[a] |
| Liquid-metal-cooled | Fast | None | Sodium | | |
| LMR | | | | U/Pu metal; $UO_2/PuO_2$ | ≈ 15–20% Pu |
| LMFBR | | | | $UO_2/PuO_2$ | ≈ 15–20% Pu |

[a]Older operating plants have enrichments of more than 90%.

# Reatores Nucleares de Potência

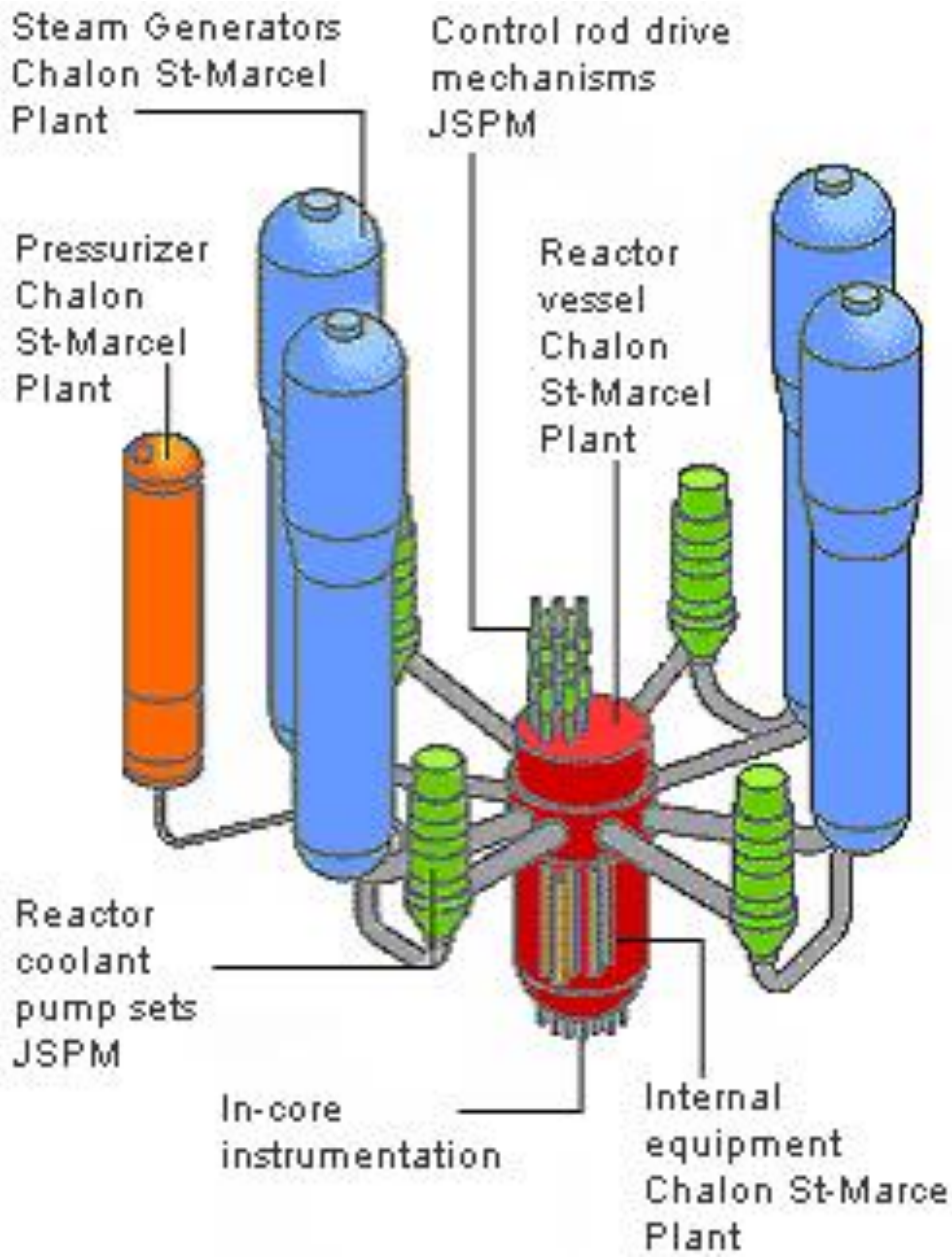
- Pressurized Water Reactors (PWR)



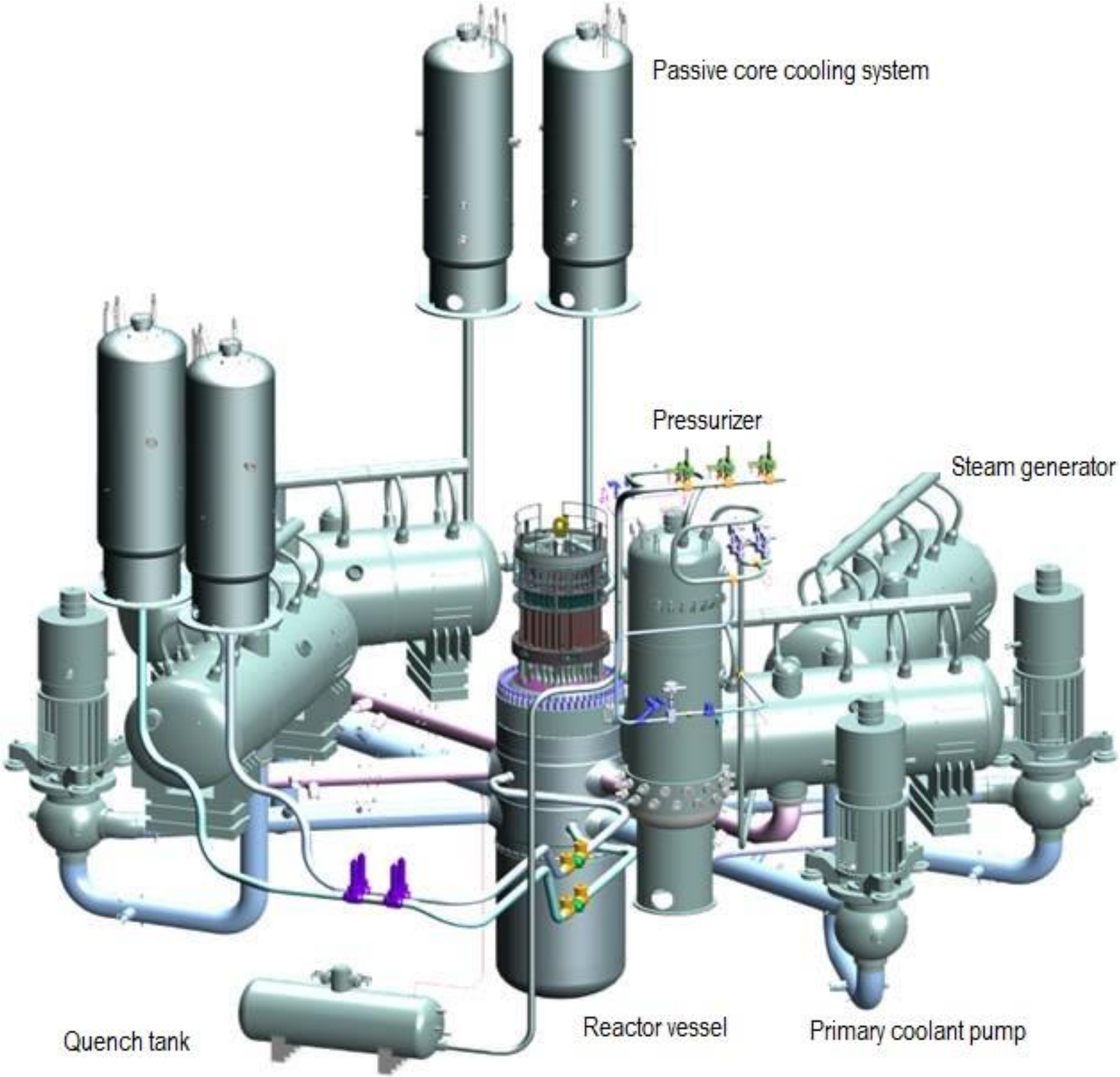
Reatores tipo PWR:

- Calor gerado dentro do núcleo sem geração de vapor;
- Calor é conduzido para fora do núcleo pela água pressurizada (~ 300 $^{o}$C/150 atm) (circuito primário) que é bombeada;
- Calor é transferido para o fluido (água leve) do circuito secundário no GV.
- Água é bombeada novamente para o núcleo (baixa temperatura)
- Fluido do circuito secundário é vaporizado (trabalha a uma pressão menor) e o vapor é conduzido para a turbina onde é expandido e move as pás transformando a energia cinética e de pressão em energia mecânica e posteriormente em energia elétrica (gerador elétrico);
- Vapor é condensado (condensador) e bombeado novamente para o GV.

# PWR – Principais Sistemas



# PWR – Principais Sistemas



# PWR - Núcleo

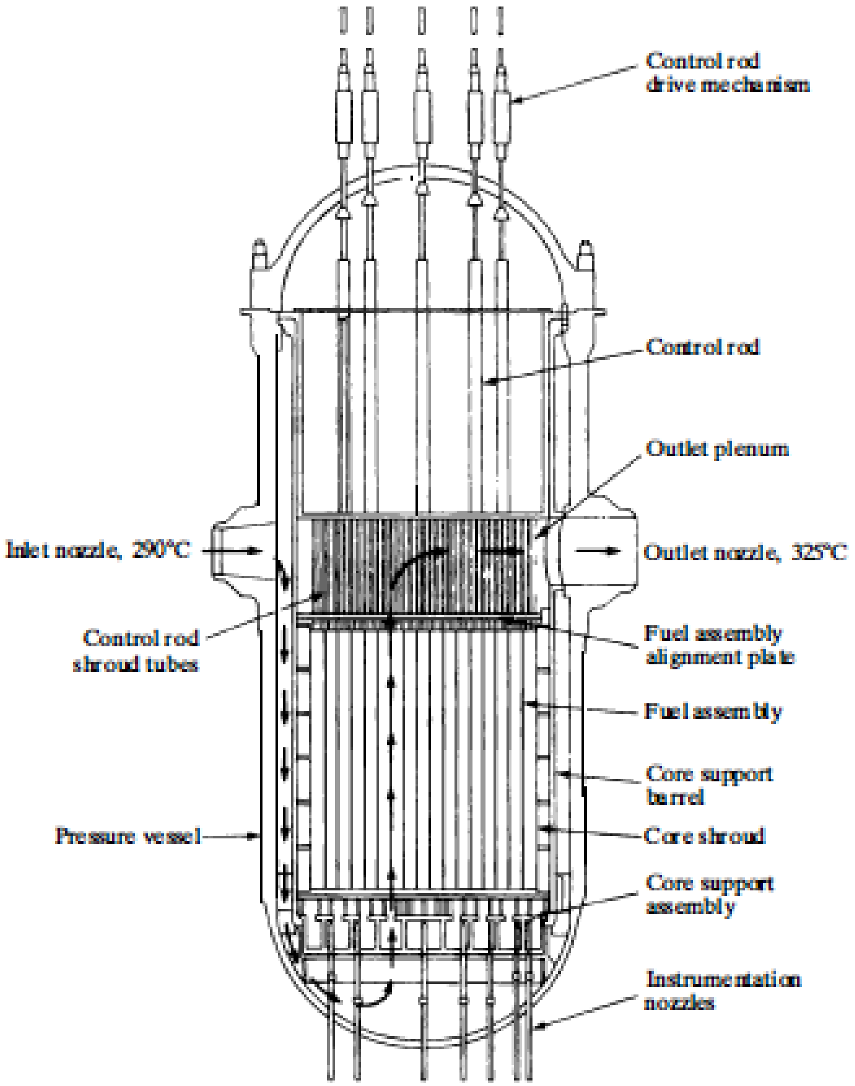



**Figure 4.6** Cross-sectional view of a PWR. (Courtesy of Combustion Engineering, Inc.)

# PWR - Núcleo

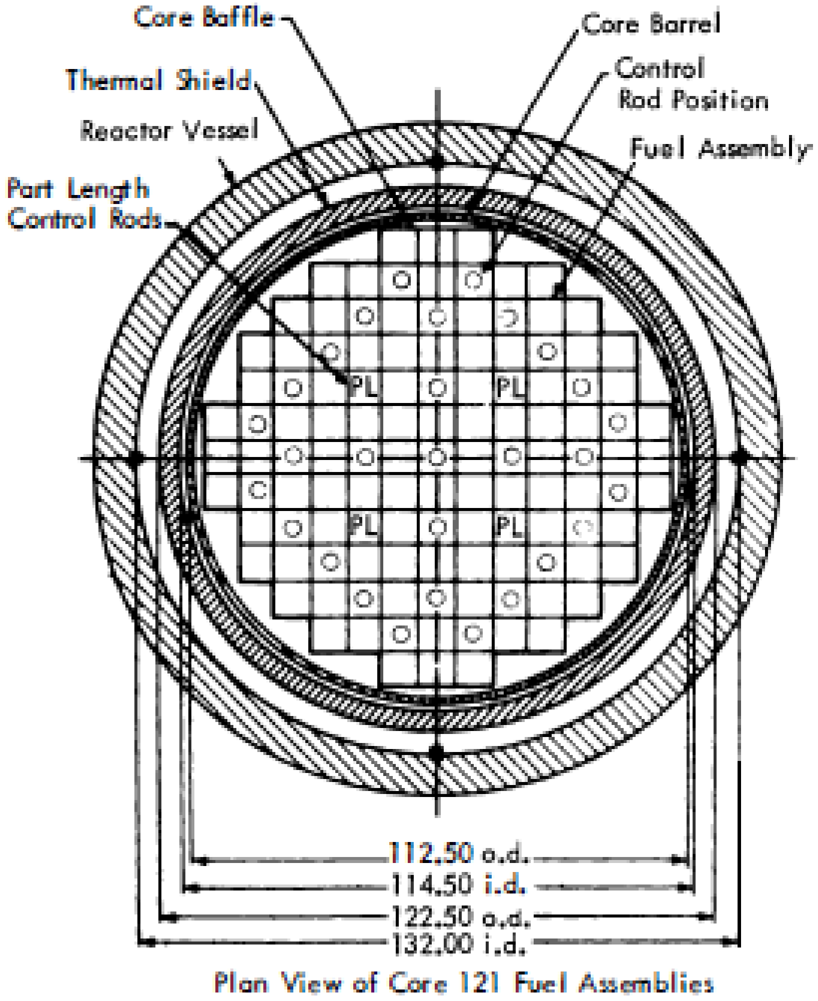
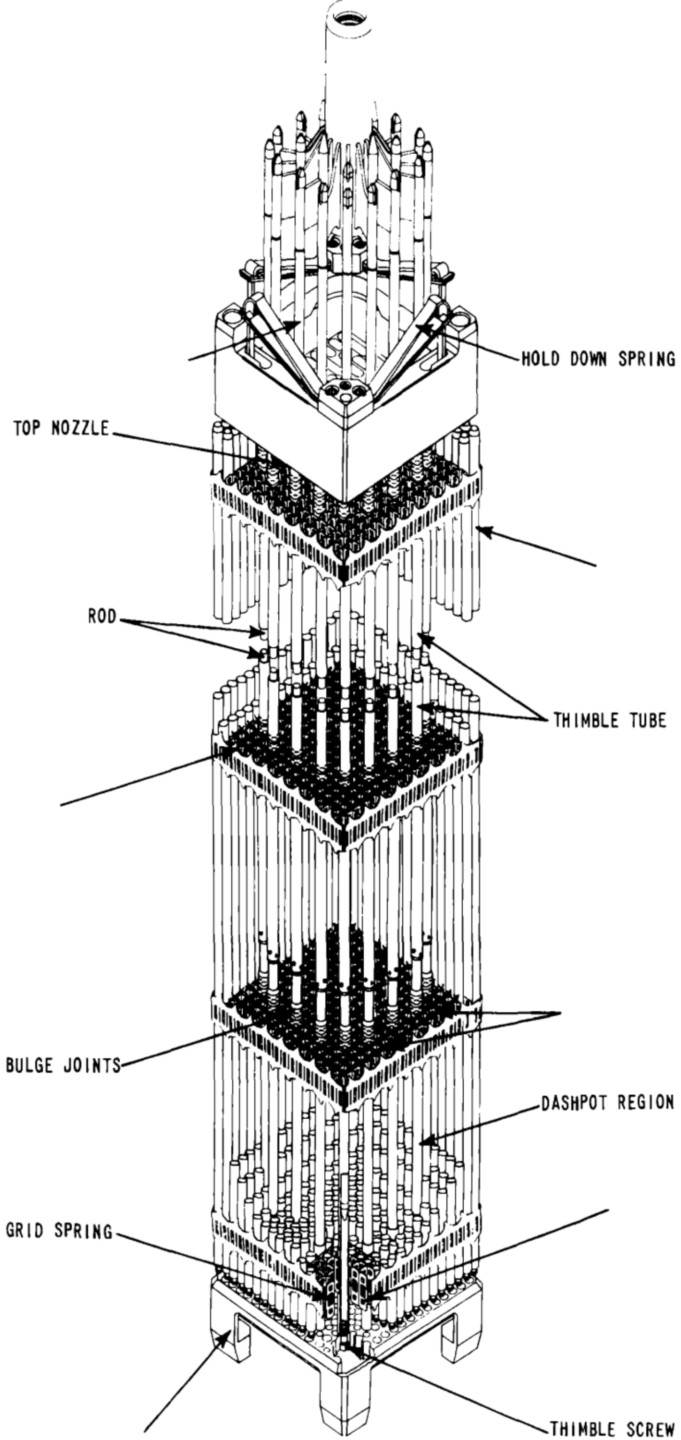



**Fig. 1.3** Cross section of PWR reactor vessel [from *Proc. Am. Power Conf.*, 30, 298 (1968)].

# PWR – Elemento Combustível

180 a 200 EC
200 a 250 Varetas



# PWR - Condições Térmicas

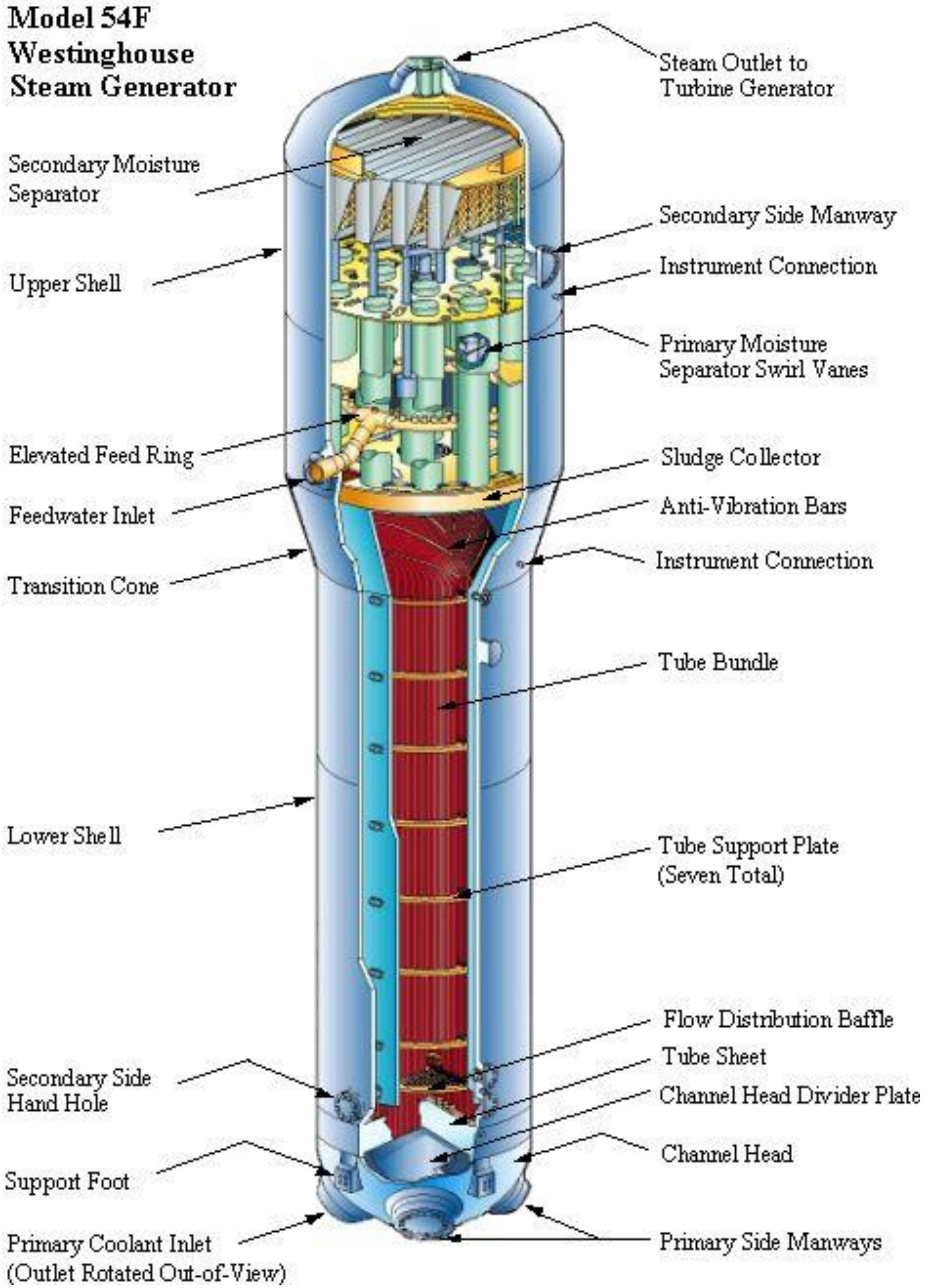
**Table 2-1 Light-water reactor thermal conditions**

| Condition | PWR (Sequoyah) | BWR/6 |
|---|---|---|
| Primary coolant outlet temperature | 324°C | 288°C |
| Primary coolant system pressure | 15.5 MPa | 7.17 MPa |
| Turbine steam saturation conditions | | |
| Pressure | 5.7 MPa | 7.17 MPa |
| Temperature | 272.3°C | 287.5°C |
| Plant thermal efficiency | 33.5% | 32.9% |

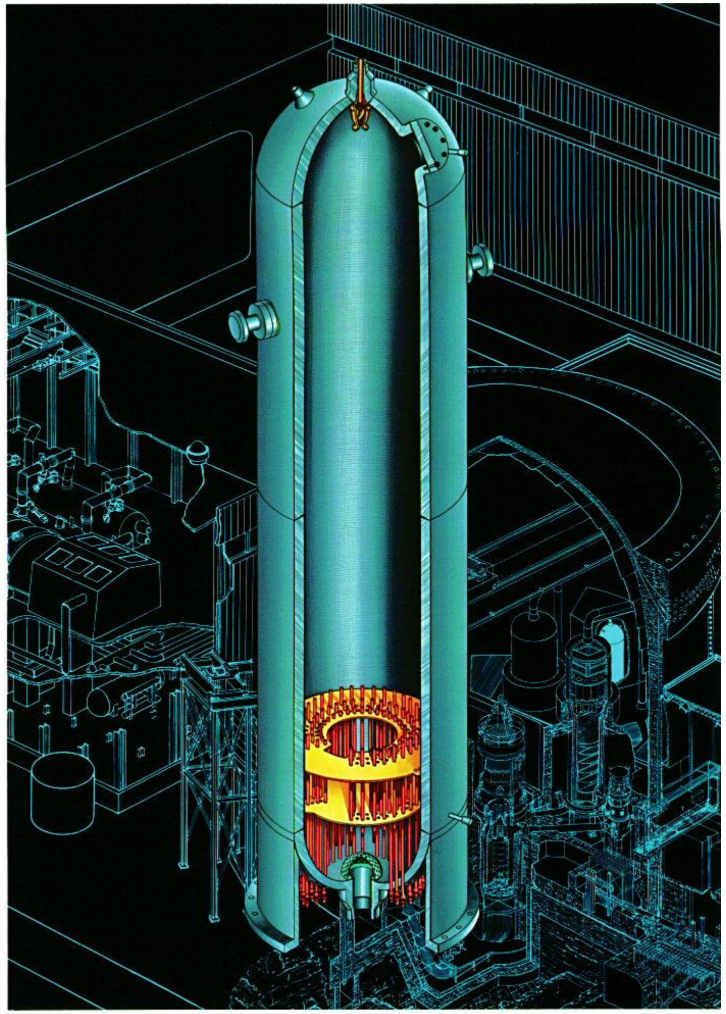
*Source:* Table 1-2.

Nuclear Systems I; Todreas

# Gerador de Vapor



# Pressurizador



Westinghouse PRESSURIZER

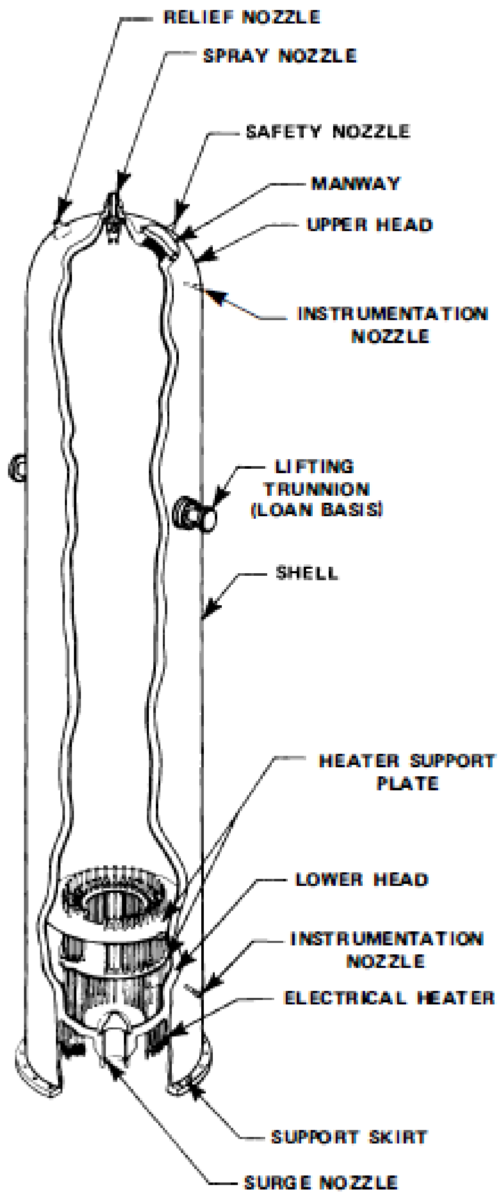



Fig. 1.12 Cutaway of typical pressurizer (courtesy Westinghouse Electric Corp.).

# Bomba

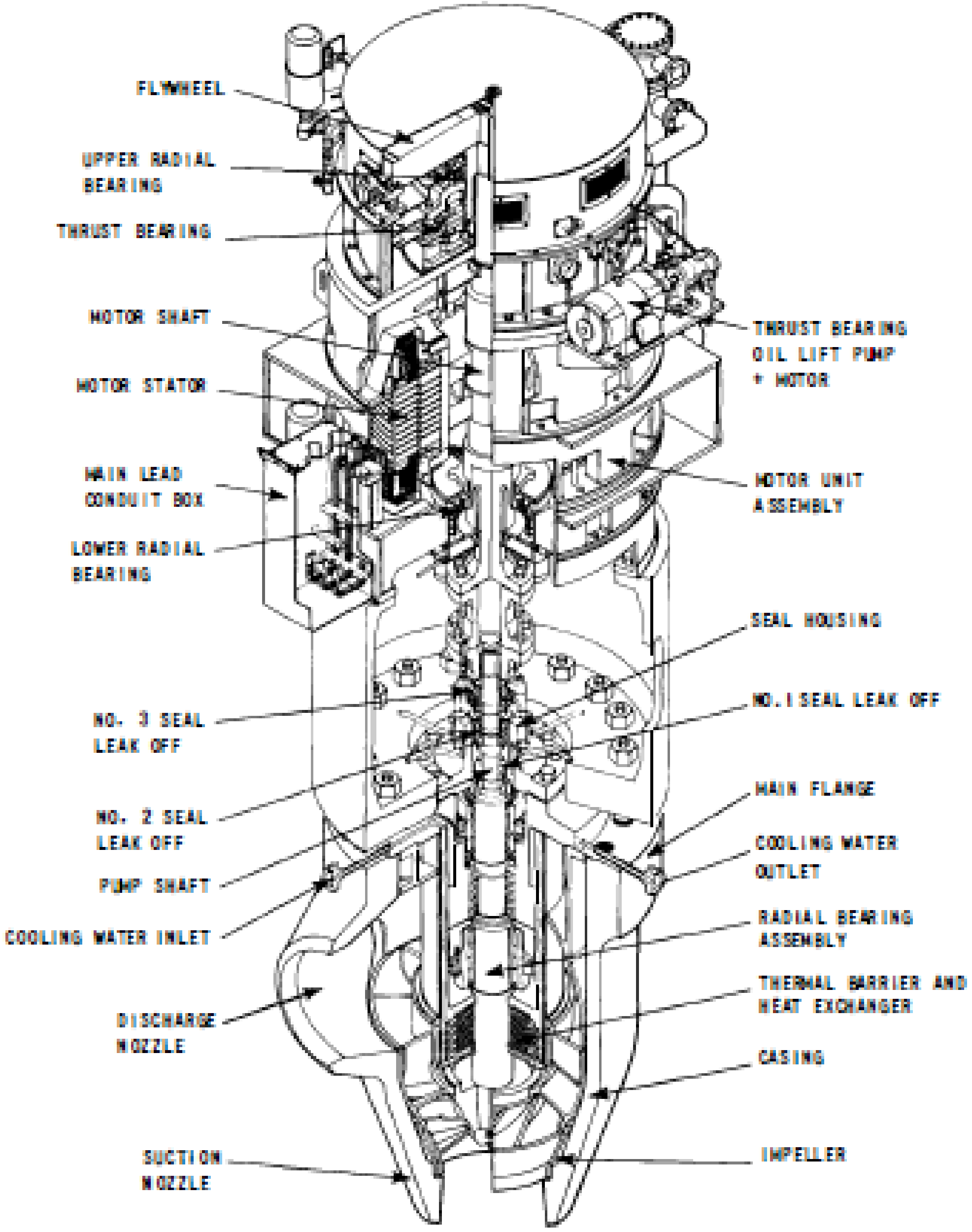



**Fig. 1.11** Cutaway of typical reactor coolant pump (courtesy Westinghouse Electric Corp.).

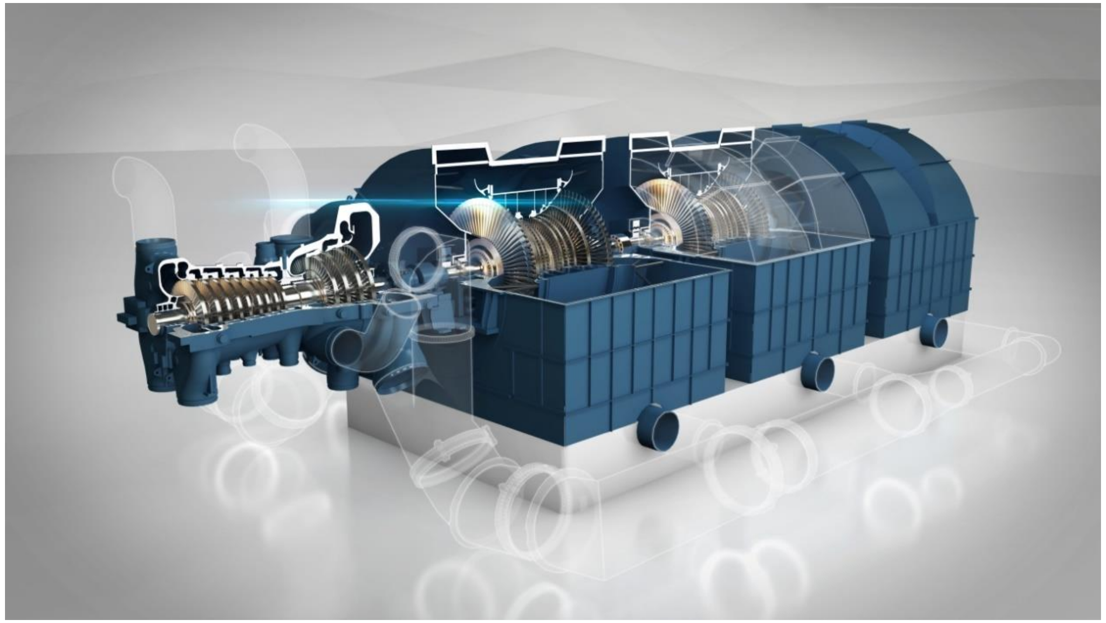
#### 1.1.1.5 *Auxiliary Systems*

In addition to the primary loop, several auxiliary systems are necessary for the proper functioning of the plant during normal operation and to provide adequate core cooling during shutdown and accident situations. The major systems and their functions are as follows:

1. *Chemical and volume control system:* Fills and pressurizes system, maintains water level, reduces concentration of contaminants, adjusts concentration of chemical poisons added to primary coolant.
2. *Residual heat removal system:* Transfers thermal energy from the reactor coolant during shutdown and refueling operations. System used in conjunction with safety systems during LOCA to remove heat from water being recirculated by injection system.
3. *Safety injection system:* Rapidly injects water from gas pressurized accumulators during early phase of large LOCA, adds borated water from high head pumps (needed during small LOCA where depressurization is slow), adds large volume of borated water from low head pumps during LOCA (needed during large LOCA with rapid depressurization).
4. *Fuel handling system:* Provides for fuel insertion and removal from the core, provides for fuel storage.
5. *Containment system:* Provides a vessel capable of containing the pressures and temperatures generated by a large LOCA, provides a spray of cold water to limit the containment pressure and to remove iodine from the containment system, provides heat removal from the containment during normal and accident conditions.

# PWR – Turbina a Vapor

# PWR – Turbina a Vapor

# PWR – Turbina a Vapor

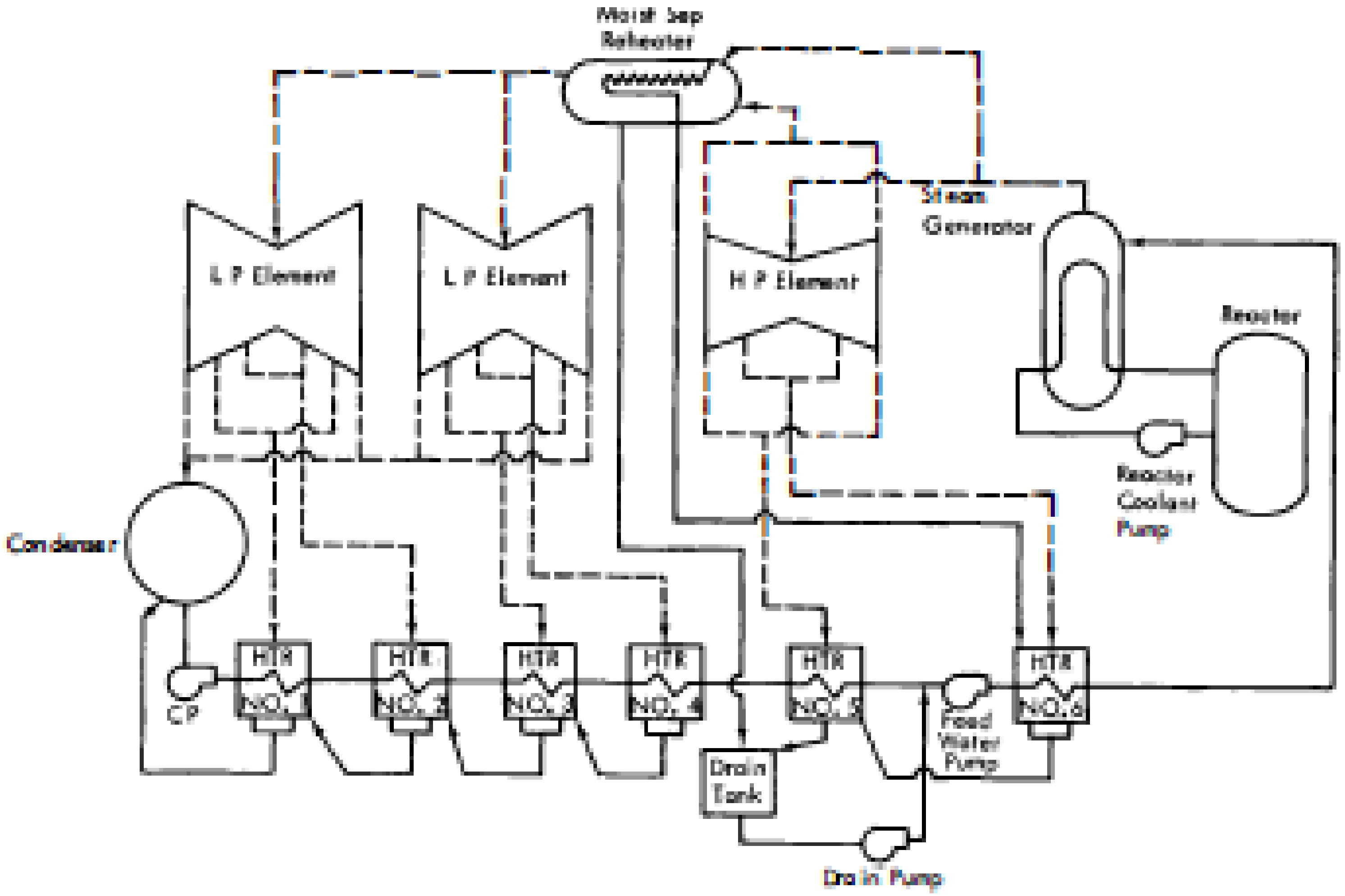
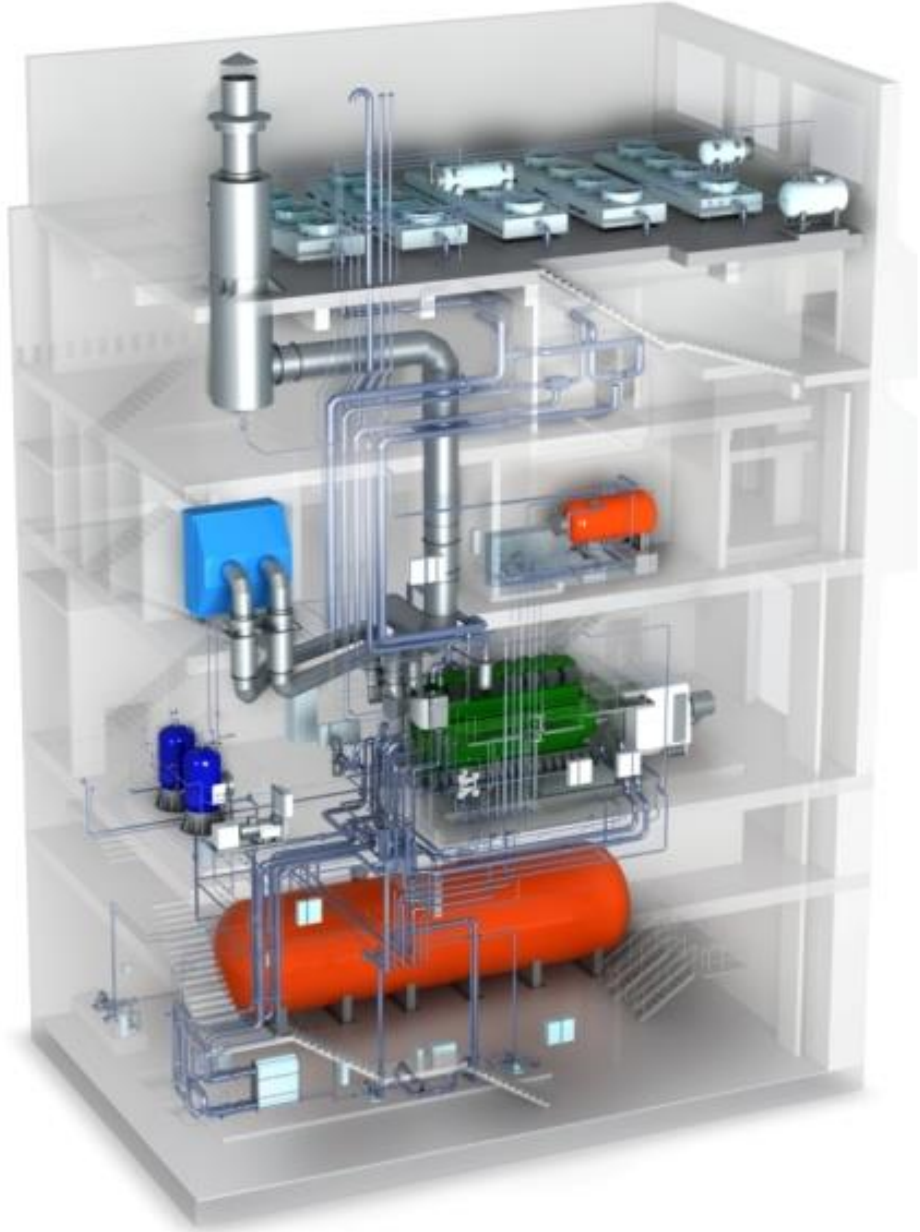



**Fig. 1.13** The PWR steam cycle.

# PWR – Condensador

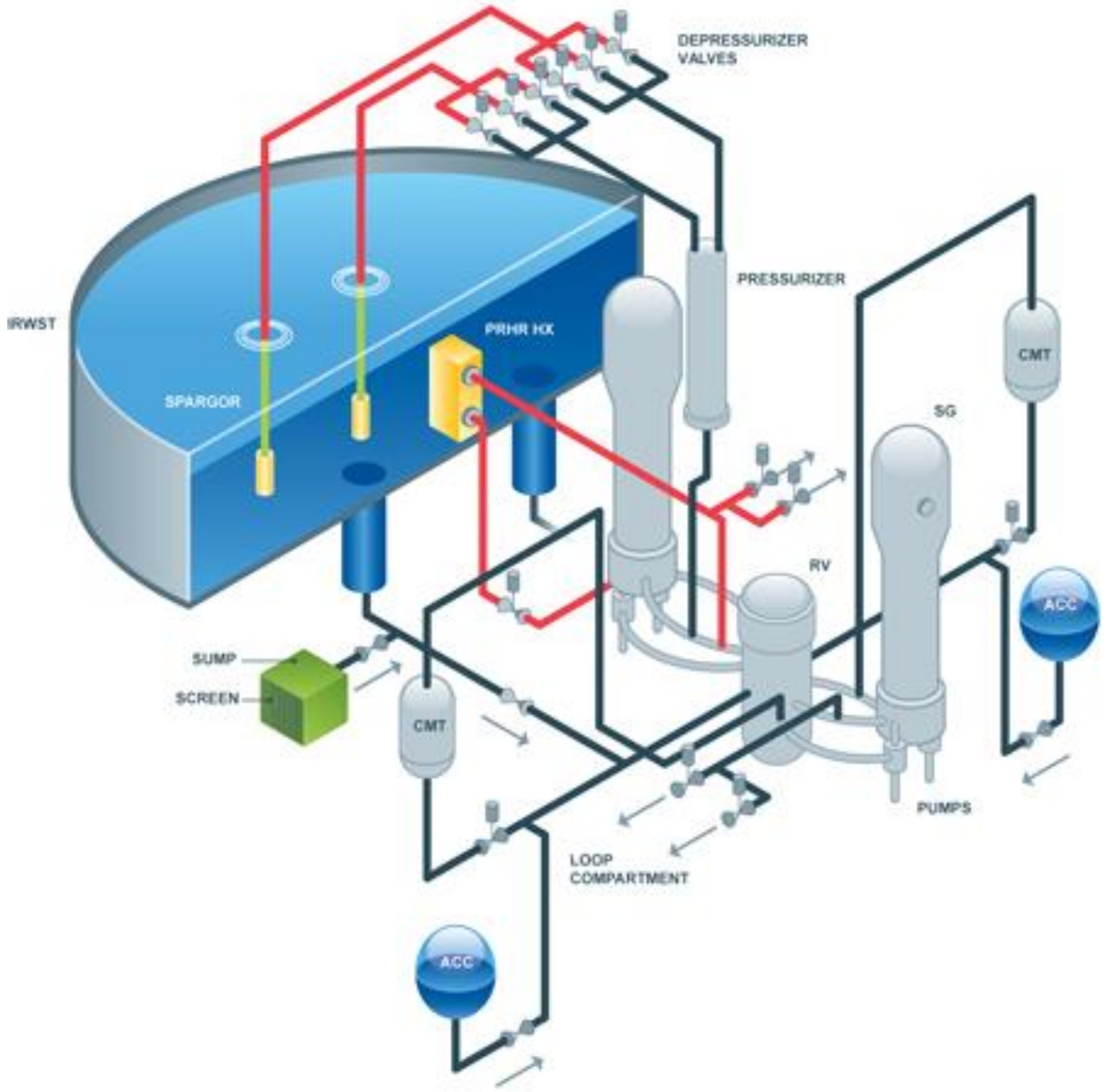
# PWR – Gerador

# PWR – Grupos Geradores Diesel

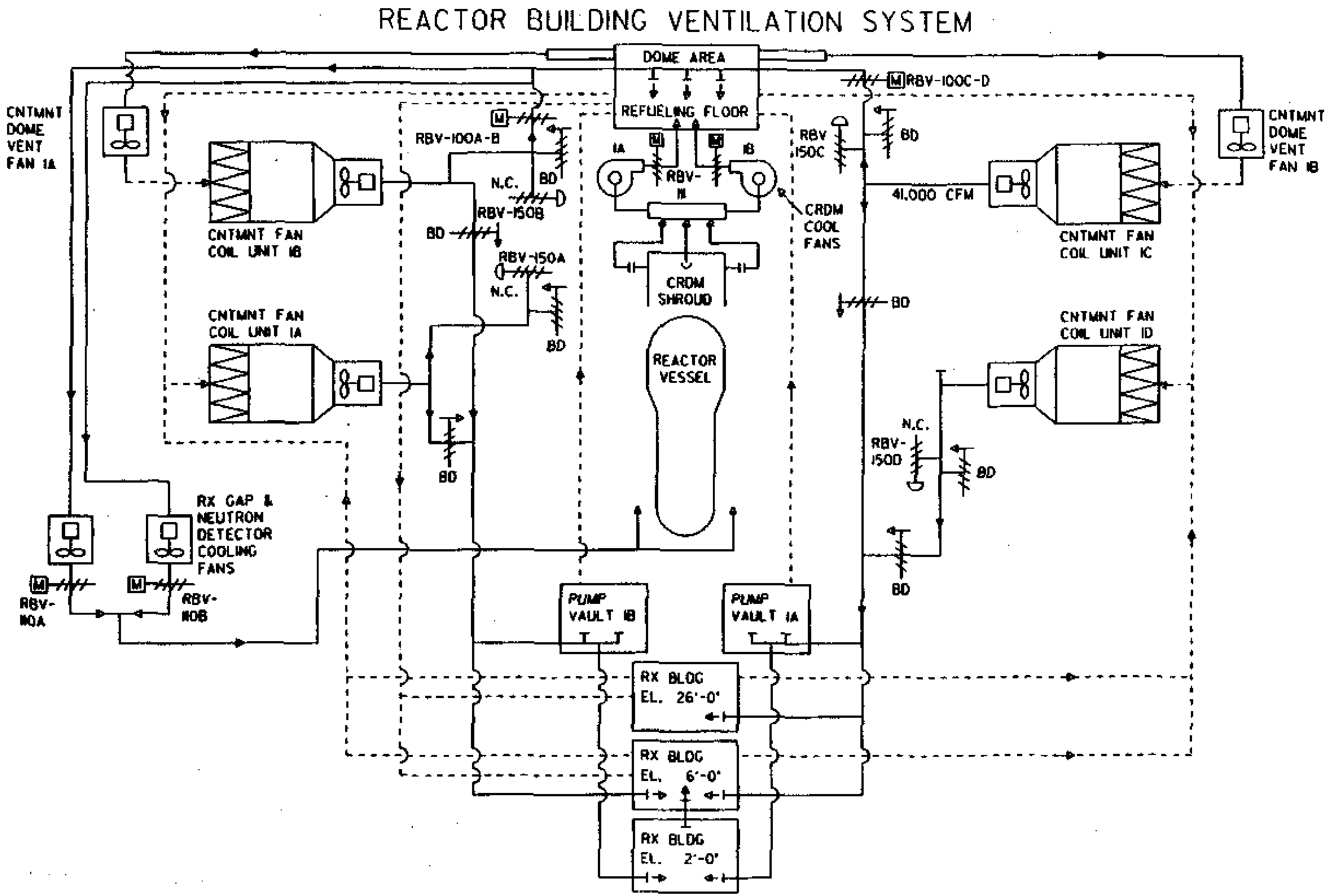


# PWR – Outros Sistemas Importantes

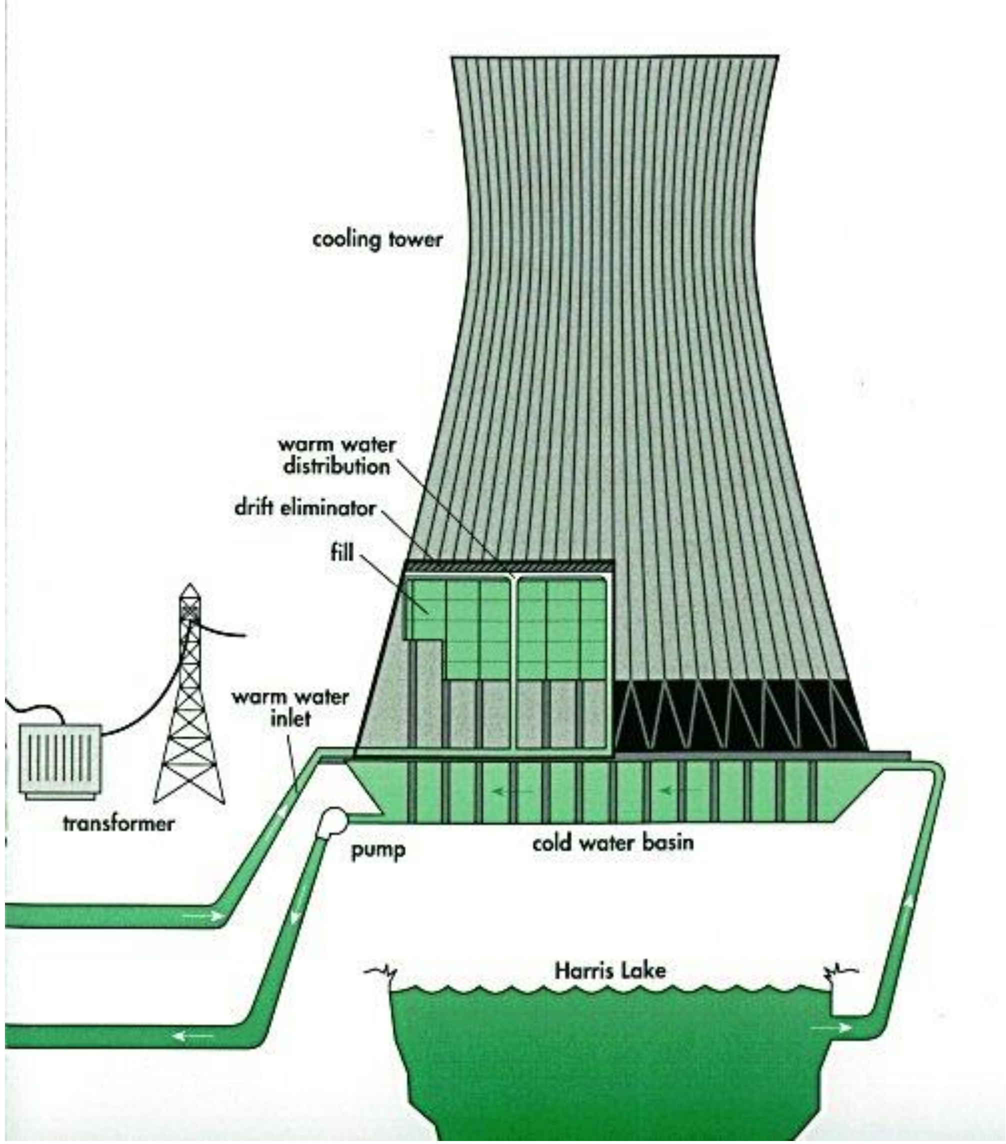
Emergency Cooling System



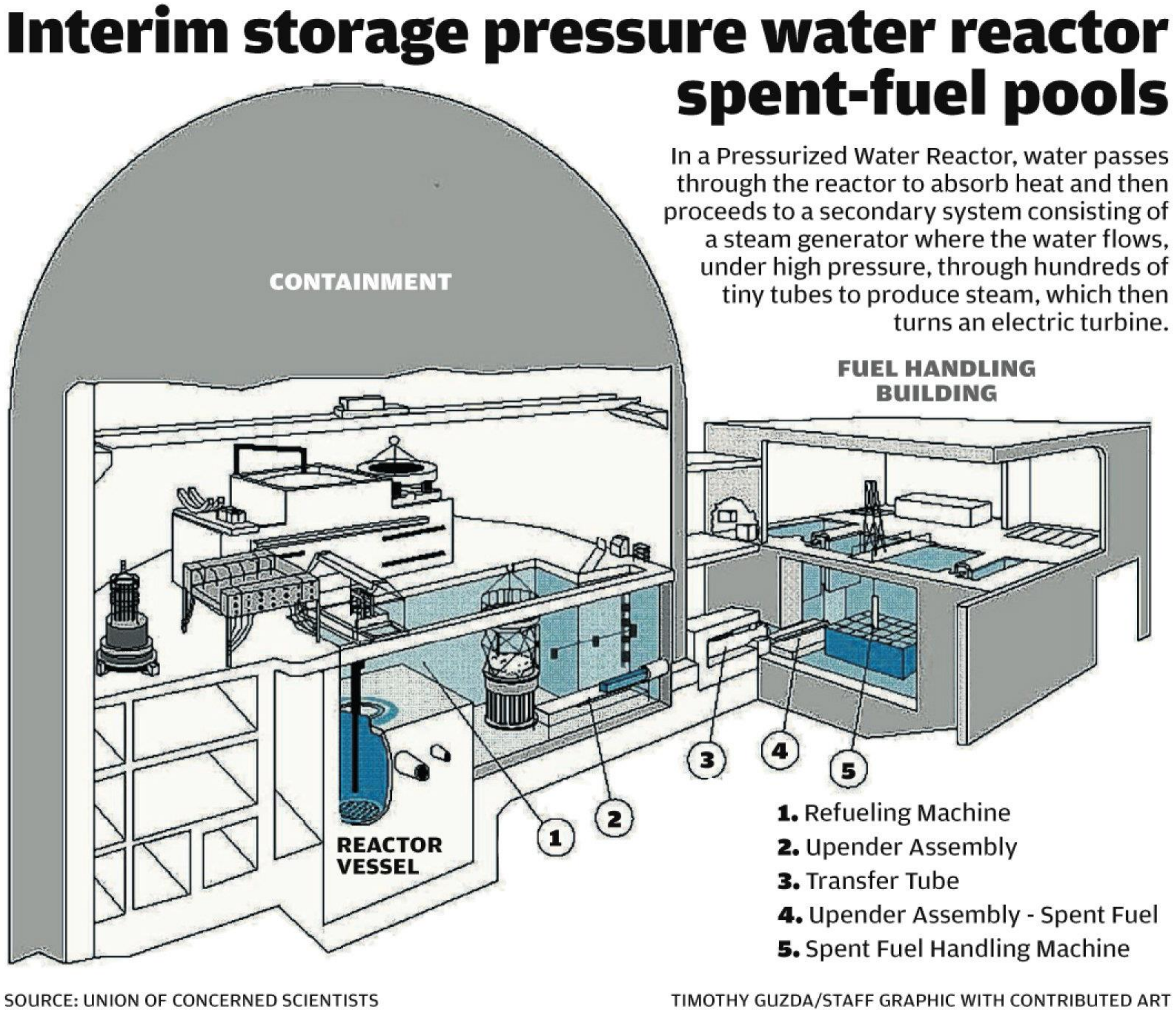
# PWR – Outros Sistemas Importantes

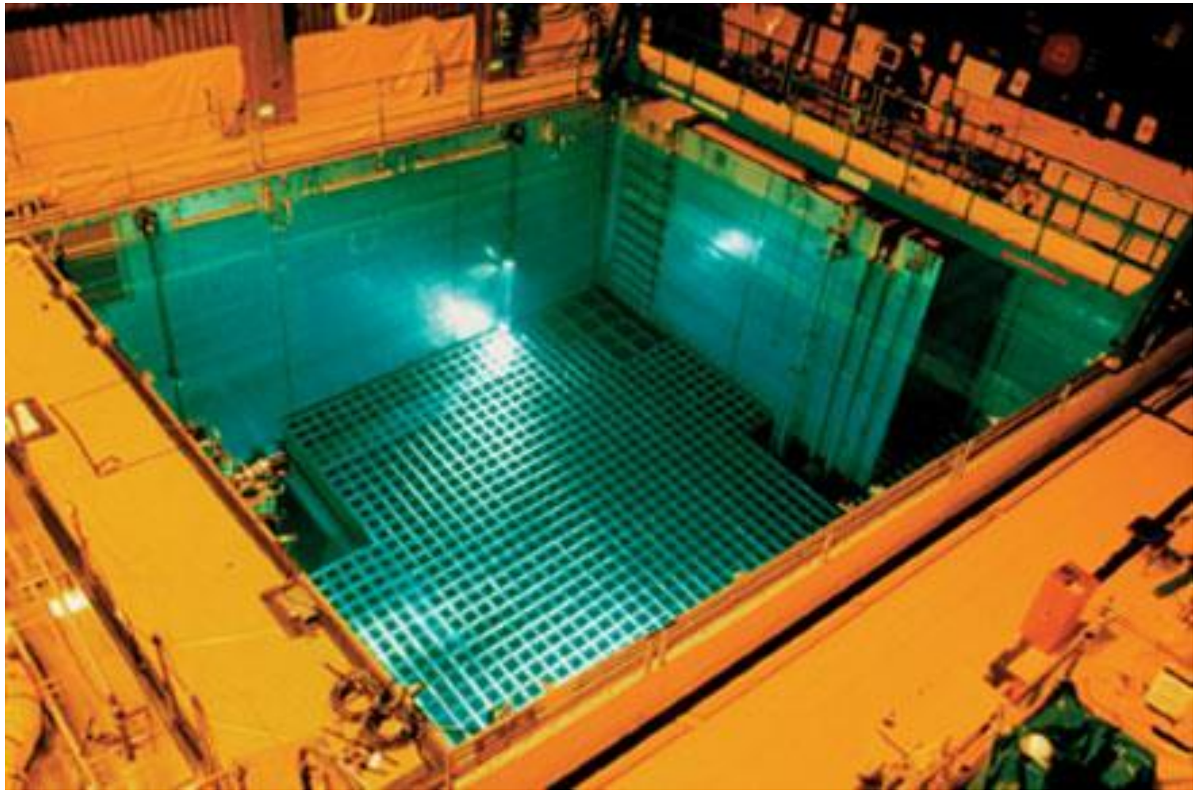


# PWR – Outros Sistemas Importantes



## Exemplo de PWR – Piscina de Estocagem de Combustíveis Queimados



# Exemplo de PWR – Central Termonuclear ANGRA

**ANGRA I**

**ANGRA II**
**1.280 MWe**
**3.771 MWt**

**POTÊNCIA DO REATOR / *OUTPUT PER REACTOR UNIT***

| | |
|---|---|
| TÉRMICA / *NUCLEAR THERMAL* | NOMINAL / *CURRENT*: 3.771 MWt |
| ELÉTRICA (BRUTA) / *GROSS ELECTRICAL* | NOMINAL / *CURRENT*: 1.350 MWe |
| ELÉTRICA (LÍQUIDA) / *NET ELECTRICAL* | NOMINAL / *CURRENT*: 1.280 MWe |
| FAIXA OPERACIONAL CONTÍNUA / *CONTINUOUS OPERATIONAL RANGE* | 80% -100% |
| RENDIMENTO TÉRMICO / *THERMAL YELD* | 35.8 % (Temp. água do mar 27˚C) |

**CARACTERÍSTICAS DO NÚCLEO DO REATOR /*REACTOR CORE CHARACTERISTICS***

| | |
|---|---|
| MATERIAL COMBUSTÍVEL / *FUEL MATERIAL* | URÂNIO ENRIQUECIDO / *ENRICHED URANIUM* -$UO_2$ |
| No. DE ELEMENTOS COMBUSTÍVEIS / *Nr. OF FUEL ELEMENTS* | 193 |
| QUANTIDADE DE VARETAS COMBUSTÍVEIS POR ELEMENTO COMBUSTÍVEL / *Nr. OF FUEL RODS PER ASSEMBLY* | 236 |
| ENRIQUECIMENTO INICIAL DO COMBUSTÍVEL / *INITIAL FUEL ENRICHMENT* | Regiões: 1 (69EC-1.9%); 2 (68EC2.5%); 3 (60EC-3.2%) |
| ENRIQUECIMENTO DO COMBUSTÍVEL NOS CARREGAMENTOS / *AVERAGE RELOAD FUEL ENRICHMENT* | 3.6 % (INICIAL -2P1); 4.0 % (ATUAL -2P6) |
| MATERIAL DO REVESTIMENTO / *CLADDING MATERIAL* | ZIRCALOY 4 (Zr) |
| ESPESSURA / *THICKNESS* | 0.72 mm |
| INVENTÁRIO DE URÂNIO / *FUEL LOADING* | 103 t U |
| DENSIDADE MÉDIA DE POTÊNCIA DO COMBUSTÍVEL/ *MEAN POWER DENSITY IN FUEL* | 36.4 (kW/kg U) |
| DENSIDADE MÉDIA DE POTÊNCIA DO NÚCLEODO REATOR / *MEAN POWER DENSITY IN CORE* | 93.2 (kW/l) |
| POTÊNCIA LINEAR MÉDIA NOMINAL DAS VARETAS / *MEAN LINEAR POWER DENSITY* | 20.7 (kW/m) |
| IRRADIAÇÃO FINAL / *DISCHARGE BURN-UP* | 50.000 (MWd/t) (MÁXIMA) |

**SISTEMAS DA USINA / *PLANT SYSTEMS***

| | |
|---|---|
| VASO DO REATOR (MATERIAL BÁSICO) / *REACTOR VESSEL (BASIC MATERIAL)* | 20 Mn Mo Ni 55 |
| MATERIAL DO REVESTIMENTO / *CLADDING MATERIAL* | DIN 1.4550 (AISI 316L) |
| DESCRIÇÃO DO SISTEMA PRIMÁRIO / *PRIMARY SYSTEM DESCRIPTION* | 4 “LOOPS” (4 *LOOPS*) |
| No. DE BOMBAS DO PRIMÁRIO (BRR) / *Nr. OF PUMPS OF THE PRIMARY SYSTEM* | 4 |
| PRESSÃO DO PRIMÁRIO / *PRIM. SYS. PRESSURE* | 157.0 ($kg/cm_2$) |
| REFRIGERANTE / *COOLANT* | H2O |
| VAZÃO ATRAVÉS DO NÚCLEO / *MASS FLOW THROUGH CORE* | 67.680 (t/h) |
| TEMPERATURA MÉDIA / *AVERAGE TEMP.* | 308,6 ($_oC$) |

| | |
|---|---|
| **GERADOR DE VAPOR / *STEAM GENERATOR*** | 4 |
| TIPO / *TYPE* | VERTICAL, TUBOS EM “U” COM REAQUECEDOR E SEPARADOR DE UMIDADE / *vertical u -tubes w/ integral moisture separator reheater* |
| FABRICANTE / *MANUFACTURER* | SIEMENS |
| MATERIAL / *MATERIAL* | 20 Mn Mo Ni 55 |
| TUBOS / *TUBES* | INCOLOY 800 |

| | |
|---|---|
| **TURBINAS: / *TURBINES*** | 1 |
| FABRICANTE / *MANUFACTURER* | SIEMENS |
| ESTÁGIOS / *RATING* | 1AP, 3BP / *1 HP, 3 LP* |
| RPM | 1.800 |

| | |
|---|---|
| **CONDIÇÕES DO VAPOR NA ENTRADA DA TURBINA / *STEAM CONDITIONS AT TURBINE INLET*** | |
| TEMPERATURA / *TEMPERATURE* | 280 (°C) |
| PRESSÃO / *PRESSURE* | 64.2 ($kg/cm^2$) |
| UMIDADE / *MOISTURE CONTENT* | 0.25 (%) |
| VAZÃO / *FLOW* | 7.398 (t/h) |

| | |
|---|---|
| **TIPO DE REFRIGERAÇÃO DO CONDENSADOR / *TYPE OF CONDENSER COOLING*** | ÁGUA DO MAR / *SEAWATER COOLING* |
| VAZÃO NA CAPTAÇÃO / *SEAWATER FLOW* | 74.4 ($m^3/s$) |
| MATERIAL /*MATERIAL* | ASTM A-36 |
| TUBOS / *TUBES* | TITANIO / *TITANIUM* – (TIPO II) |

| | |
|---|---|
| **GERADOR DIESEL DE EMERGÊNCIA / *EMERGENCY DIESEL GENERATOR*** | |
| **SISTEMA 1 / *SYSTEM 1*: 1 -4XKA** | 4 UNIDADES / 4 *UNITS* |
| FABRICANTE / *MANUFACTURER* | KHD / SIEMENS |
| POTÊNCIA NOMINAL / *NOMINAL POWER* | 5.400 kW -6.600 kVA |
| FATOR DE POTÊNCIA / *POWER FACTOR* | 1 – 0.8 |
| FREQUÊNCIA / *FREQUENCY* | 60 Hz |
| RPM | 900 |

| | |
|---|---|
| **SISTEMA 2 / *SYSTEM 2*: 5 -8XKA** | 4 UNIDADES / 4 *UNITS* |
| FABRICANTE / *MANUFACTURER* | KHD / SIEMENS |
| POTÊNCIA NOMINAL / *NOMINAL POWER* | 860 kW -1.050 kVA |
| FATOR DE POTÊNCIA / *POWER FACTOR* | 1 -0.8 |
| FREQUÊNCIA / *FREQUENCY* | 60 Hz |
| RPM | 1.800 |

| | |
|---|---|
| **CONTENÇÃO DO SISTEMA DO REATOR:/ *REACTOR SYSTEM CONTAINMENT*** | VASO DE CONTENÇÃO DE AÇO C/ ENVOLTÓRIO ADICIONAL DE CONCRETO / *steel containment vessel with reinforced concrete shield* |
| MATERIAL / *MATERIAL* | WSTE 51 |

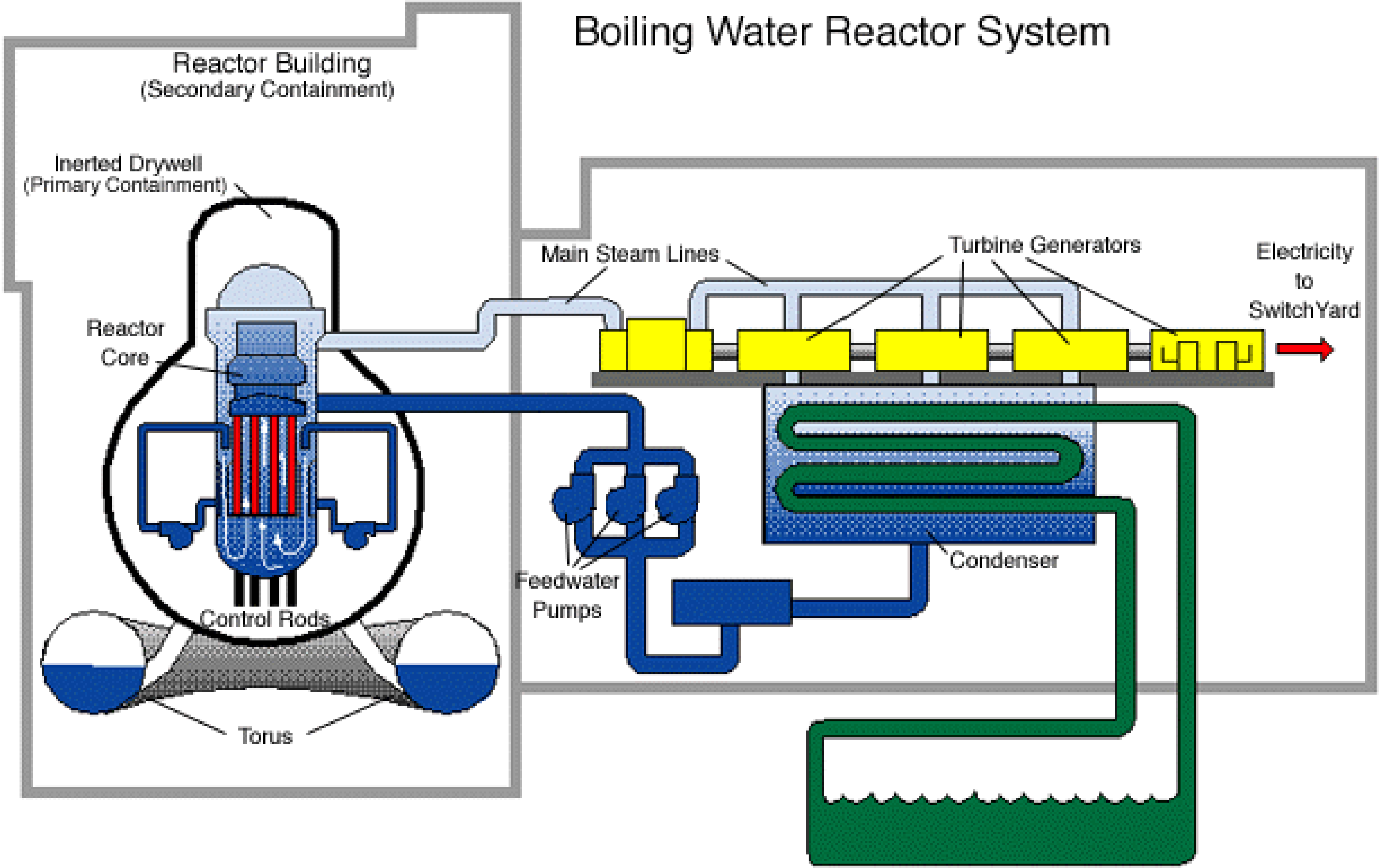
| | |
|---|---|
| **GERADOR ELÉTRICO / *ELECTRIC GENERATOR*** | 1 |
| FABRICANTE / *MANUFACTURER* | SIEMENS |
| TIPO / *TYPE*: THFF 180/64-18 | HORIZONTAL, RESFRIADO A $H_2$ /*horizontal,* $H_2$ *cooled* |
| POTÊNCIA (A 75 psig H2) / *POWER (AT* 75 psig H2) | 1.458 MVA |
| TENSÃO DE SAÍDA / *OUTLET TENSION* | 25 (+ 7.5; -10) kv |
| NÚMERO DE FASES / *NUMBER OF PHASES* | 3 |
| FREQUÊNCIA / *FREQUENCY* | 60 Hz |
| FATOR DE POTÊNCIA / *POWER FACTOR* | COS φ= 0.9 |
| CLASSE DE ISOLAMENTO / *INSULATION CLASS* | B |
| RPM | 1.800 |

# Reatores de Potência tipo Água Fervente (Boiling Water Reactor – BWR)

Características:

- Possui somente 1 circuito fechado (Ciclo Rankine – Turbina a Vapor)
- Fluido refrigerante e moderador: água (H2O)
- Não possui gerador de vapor
- O vapor é gerado no núcleo
- Controle de fissão e potência mais complexos
- Necessidade de bombas de recirculação da água dentro do núcleo

# Reatores de Potência tipo Água Fervente (Boiling Water Reactor – BWR)



# PWR - Condições Térmicas

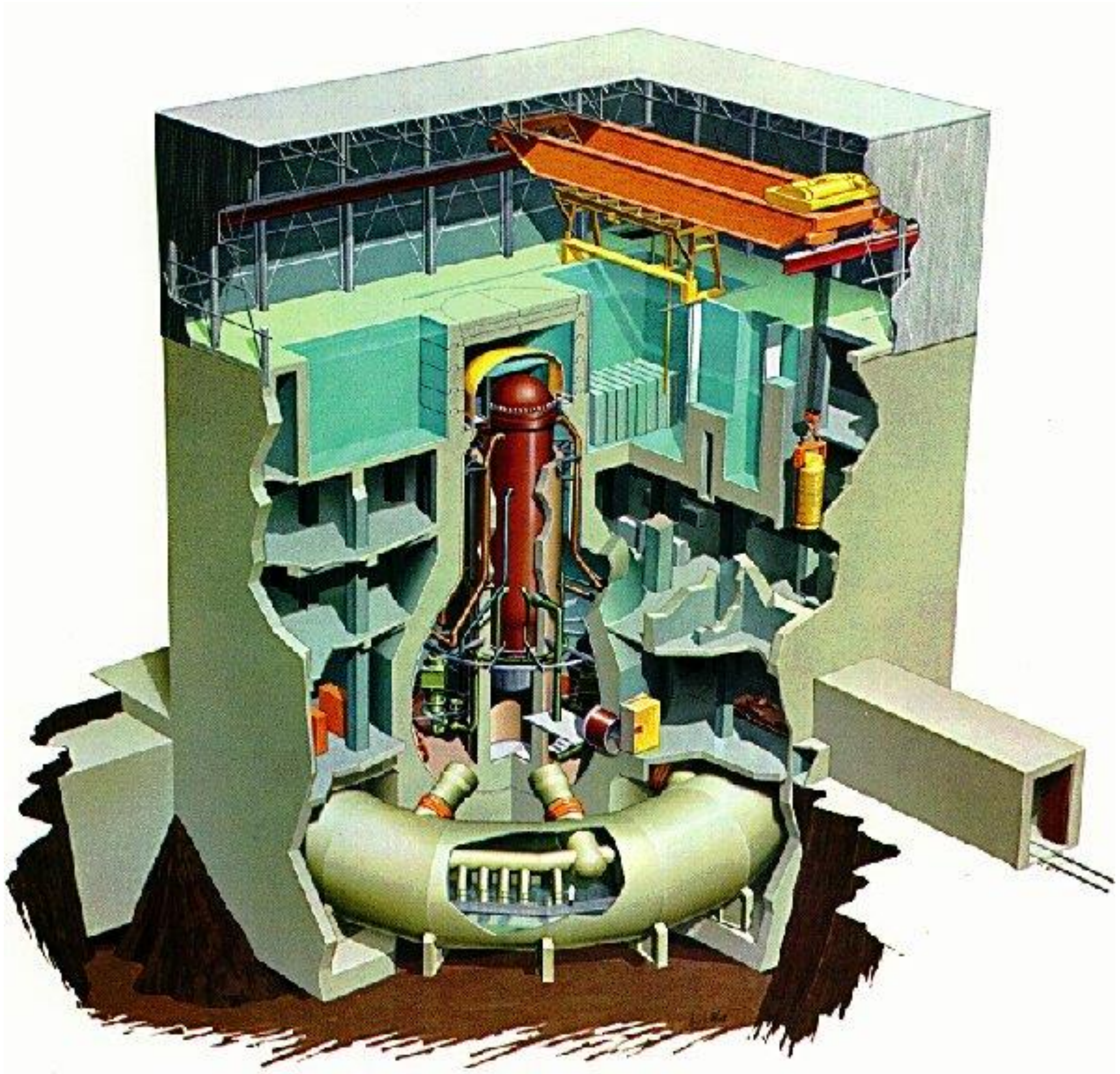
**Table 2-1 Light-water reactor thermal conditions**

| Condition | PWR (Sequoyah) | BWR/6 |
|---|---|---|
| Primary coolant outlet temperature | 324°C | 288°C |
| Primary coolant system pressure | 15.5 MPa | 7.17 MPa |
| Turbine steam saturation conditions | | |
| Pressure | 5.7 MPa | 7.17 MPa |
| Temperature | 272.3°C | 287.5°C |
| Plant thermal efficiency | 33.5% | 32.9% |

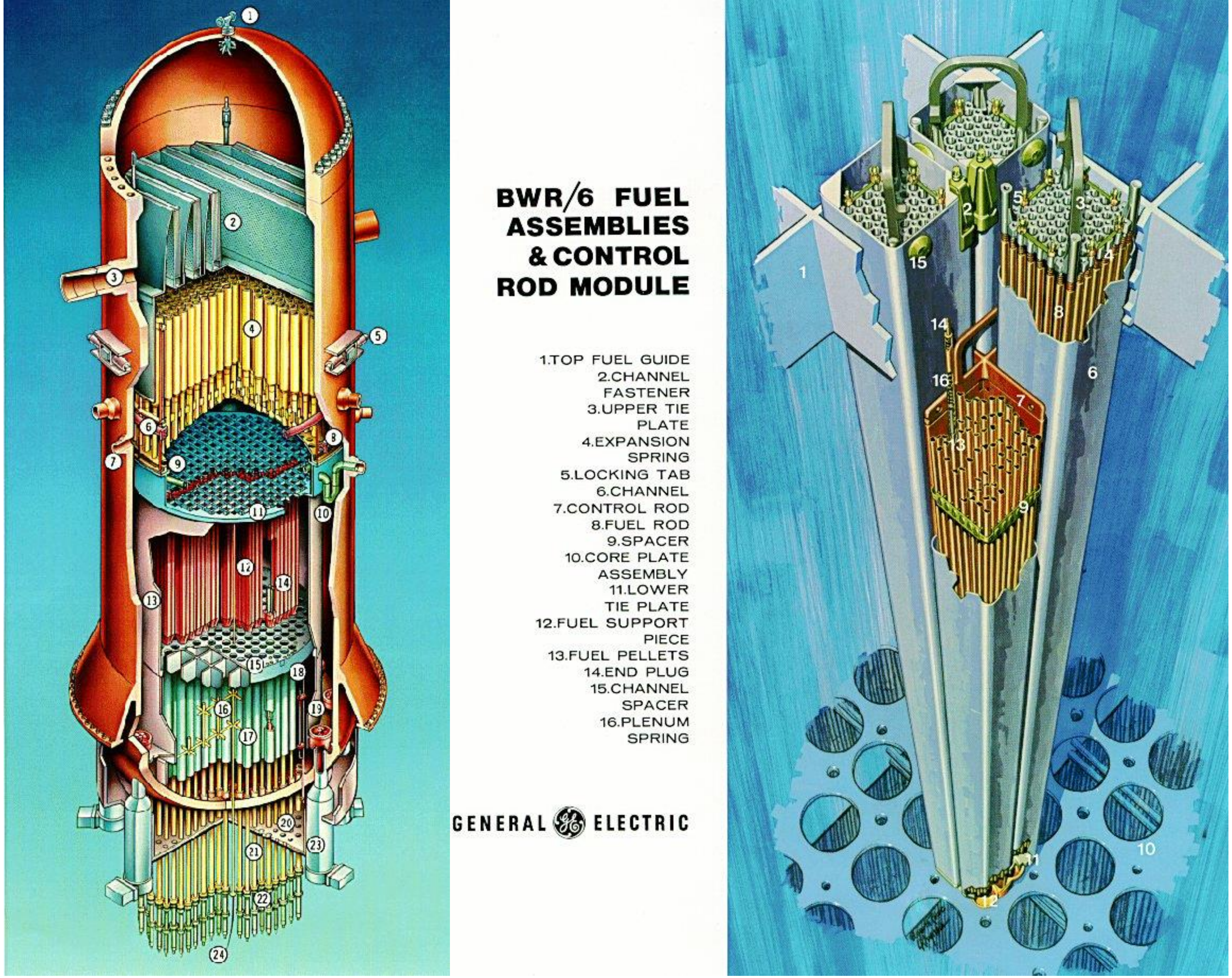
*Source:* Table 1-2.

Nuclear Systems I; Todreas

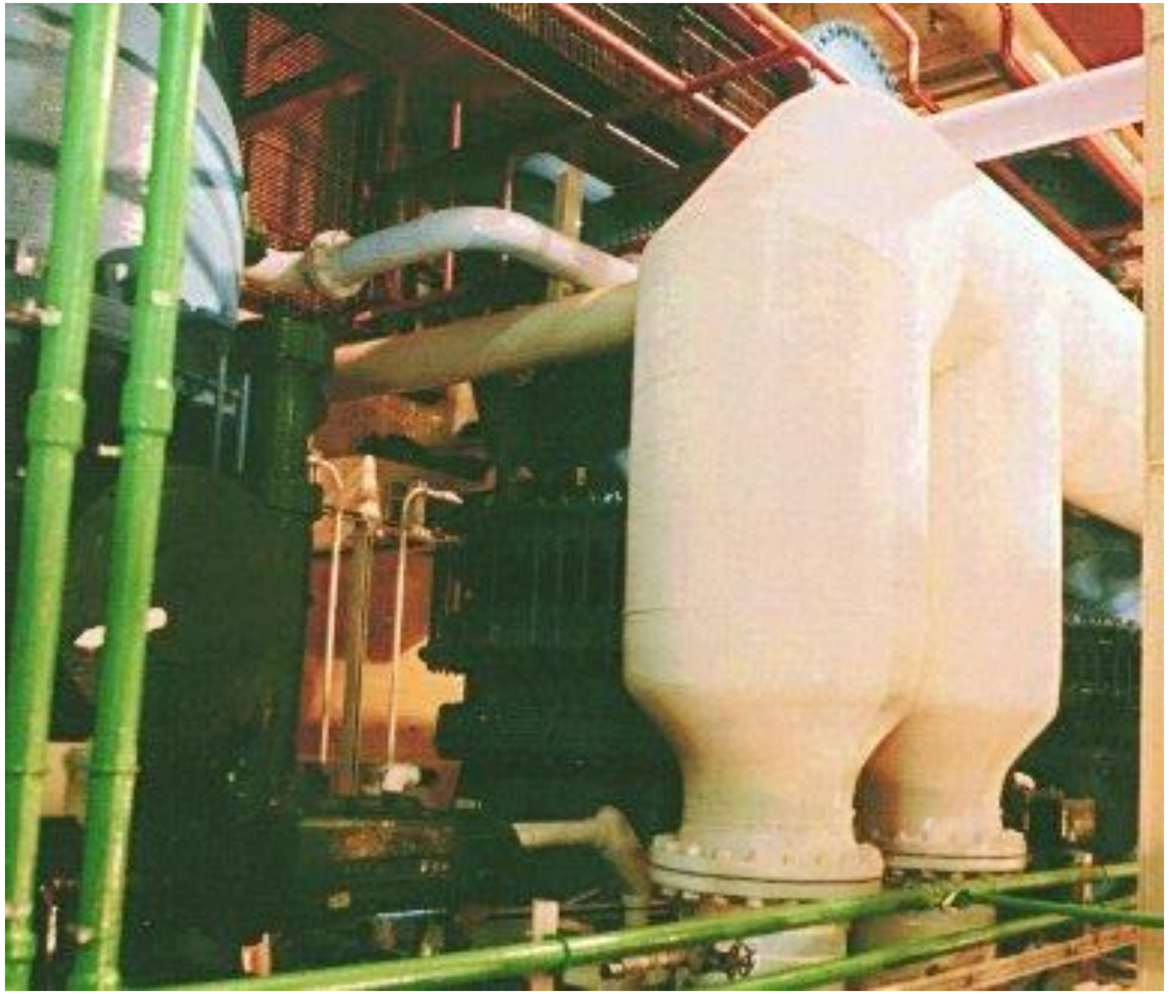
# Reatores de Potência tipo Água Fervente (Boiling Water Reactor – BWR)



# BWR - Núcleo

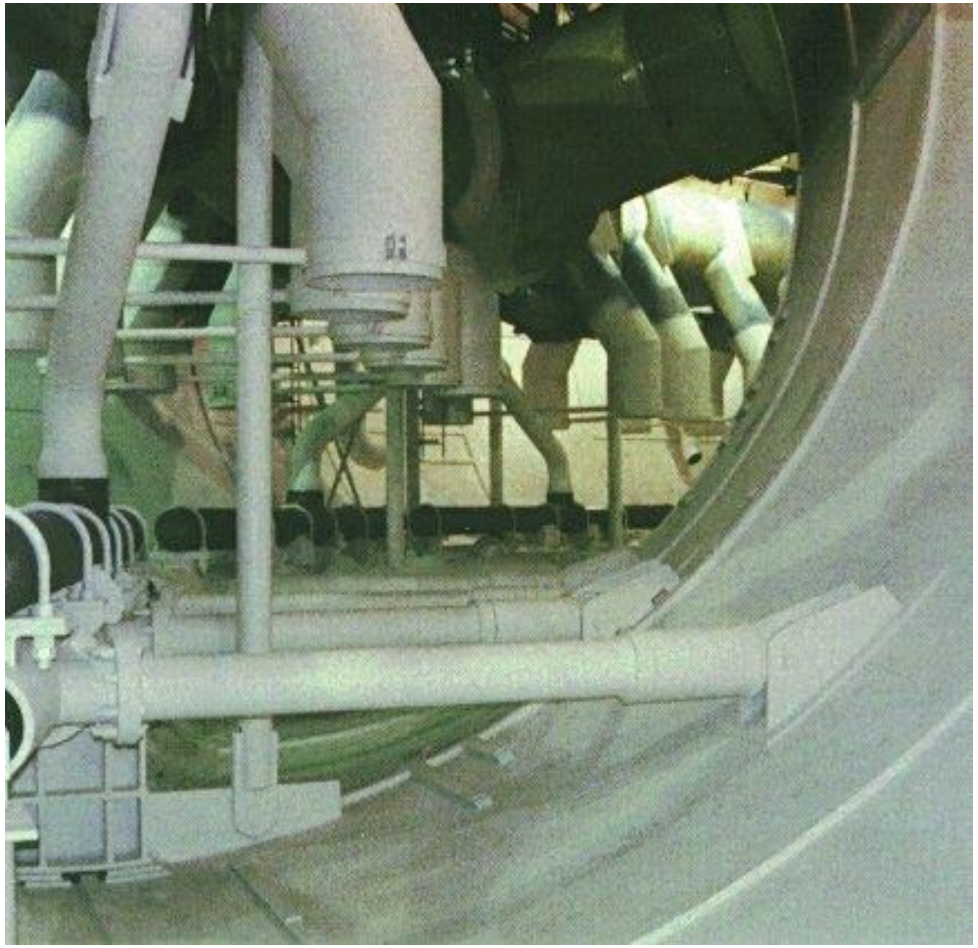

BWR/6 FUEL ASSEMBLIES & CONTROL ROD MODULE
1.TOP FUEL GUIDE
2.CHANNEL FASTENER
3.UPPER TIE PLATE
4.EXPANSION SPRING
5.LOCKING TAB
6.CHANNEL
7.CONTROL ROD
8.FUEL ROD
9.SPACER
10.CORE PLATE ASSEMBLY
11.LOWER TIE PLATE
12.FUEL SUPPORT PIECE
13.FUEL PELLETS
14.END PLUG
15.CHANNEL SPACER
16.PLENUM SPRING
GENERAL ELECTRIC

# BWR – Bombas de Recirculação



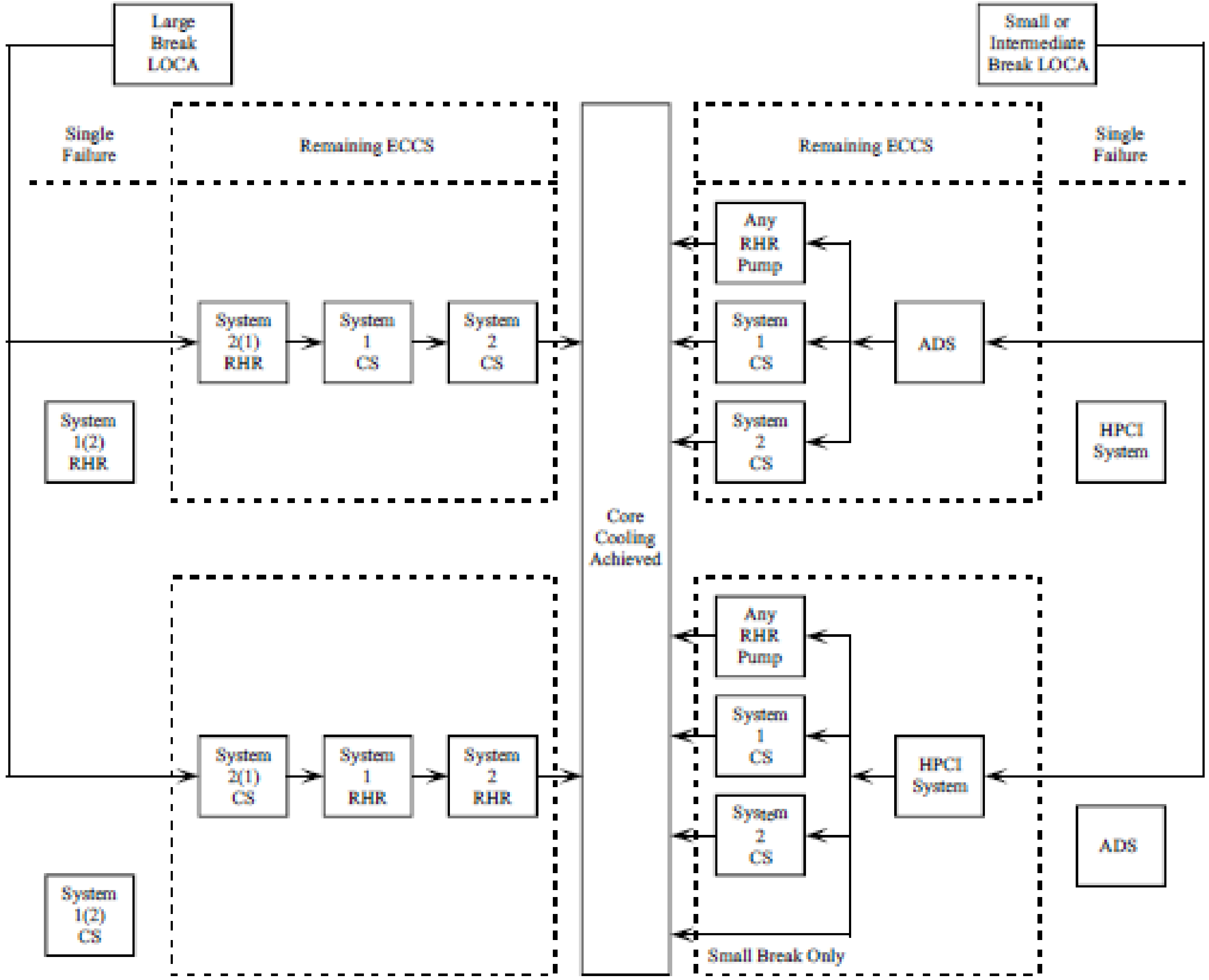
# BWR – Bombas de reposição de água

# BWR – Sistema de supressão de pressão

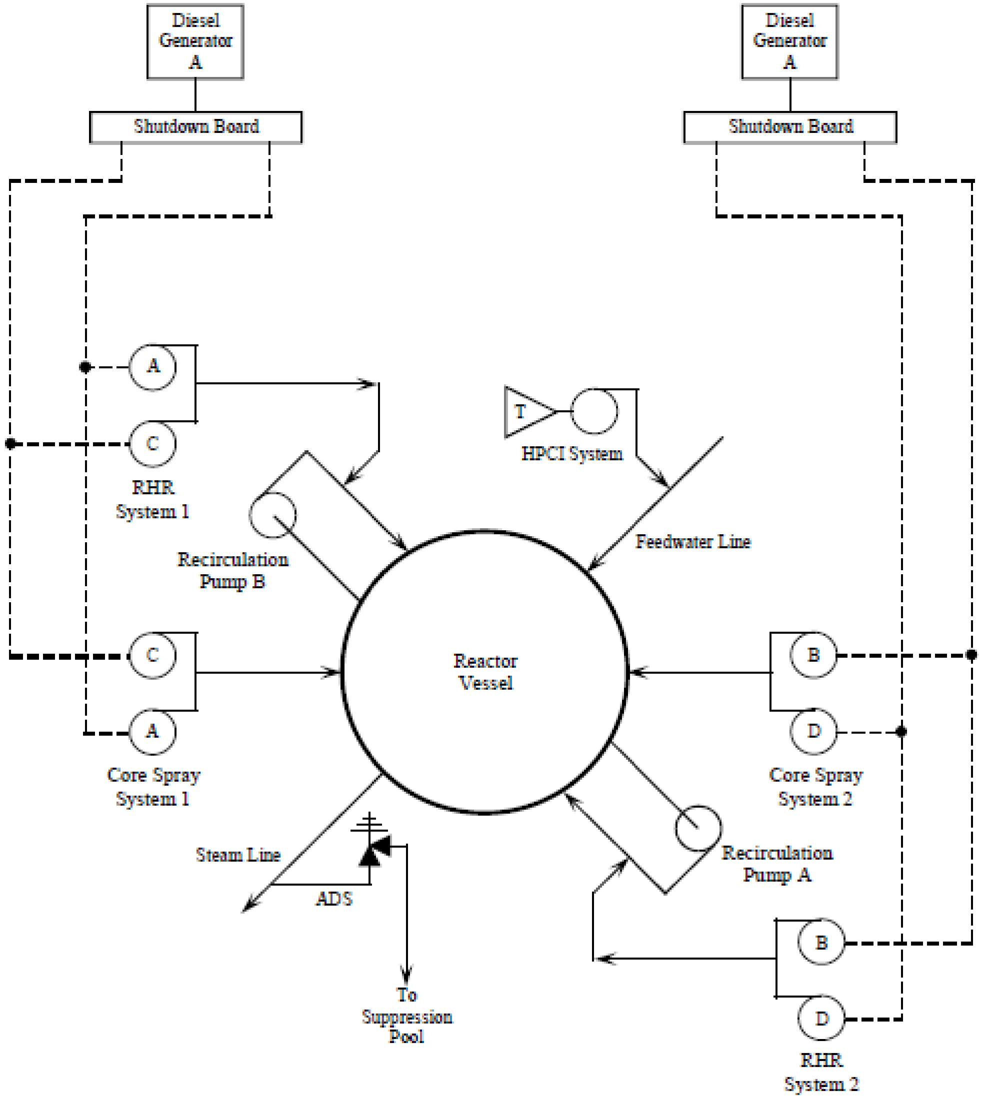
# BWR – Sistema de Emergência de Resfriamento do Núcleo - ECCS

ADS – Automatic Depressurization System
CS – Core Spray
HPCI – High Pressure Coolant Injection
LPCI – Low Pressure Coolant Injection
RHR – Residual Heat Removal
RWCS – Reactor Water Cleanup System



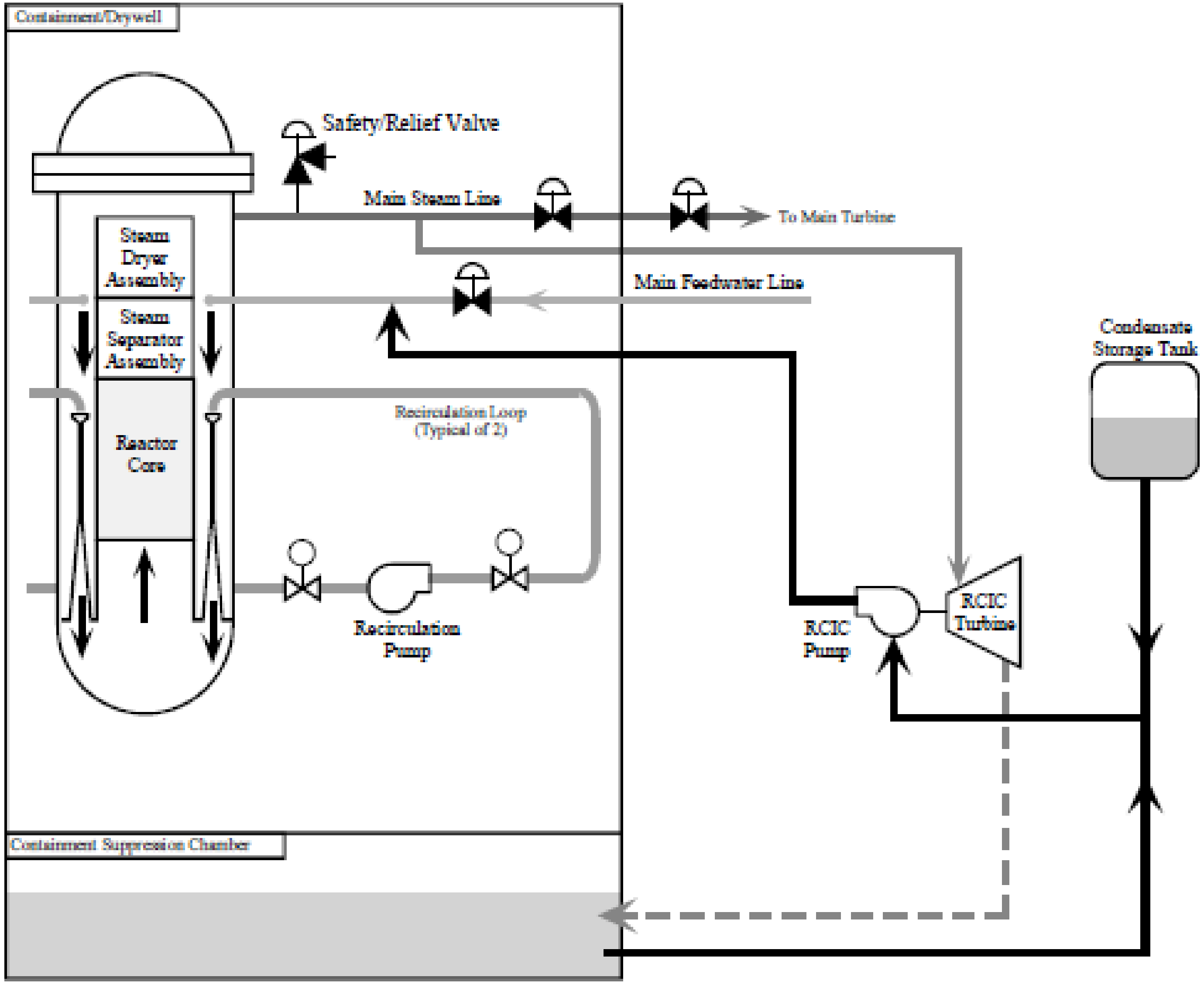

ECCS Integrated Performance

# BWR – RCCS



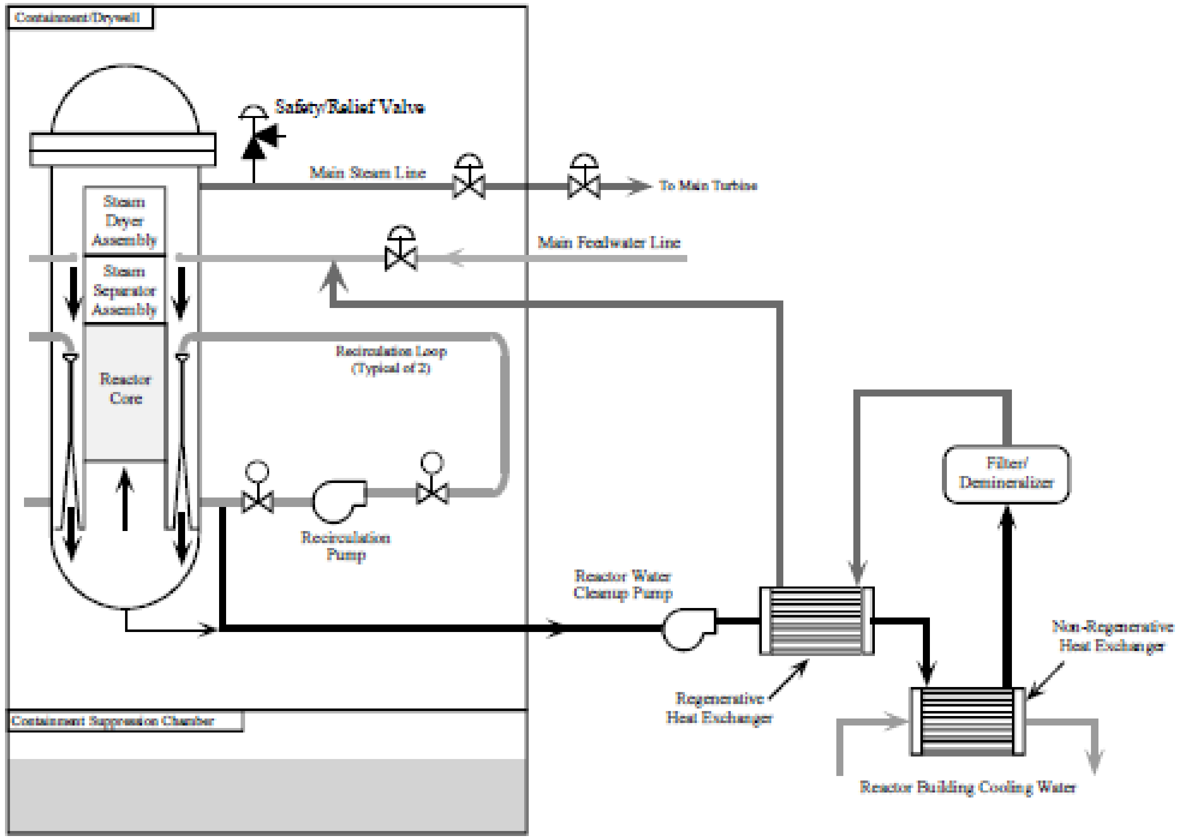

Emergency Core Cooling System Network

# BWR – RCR



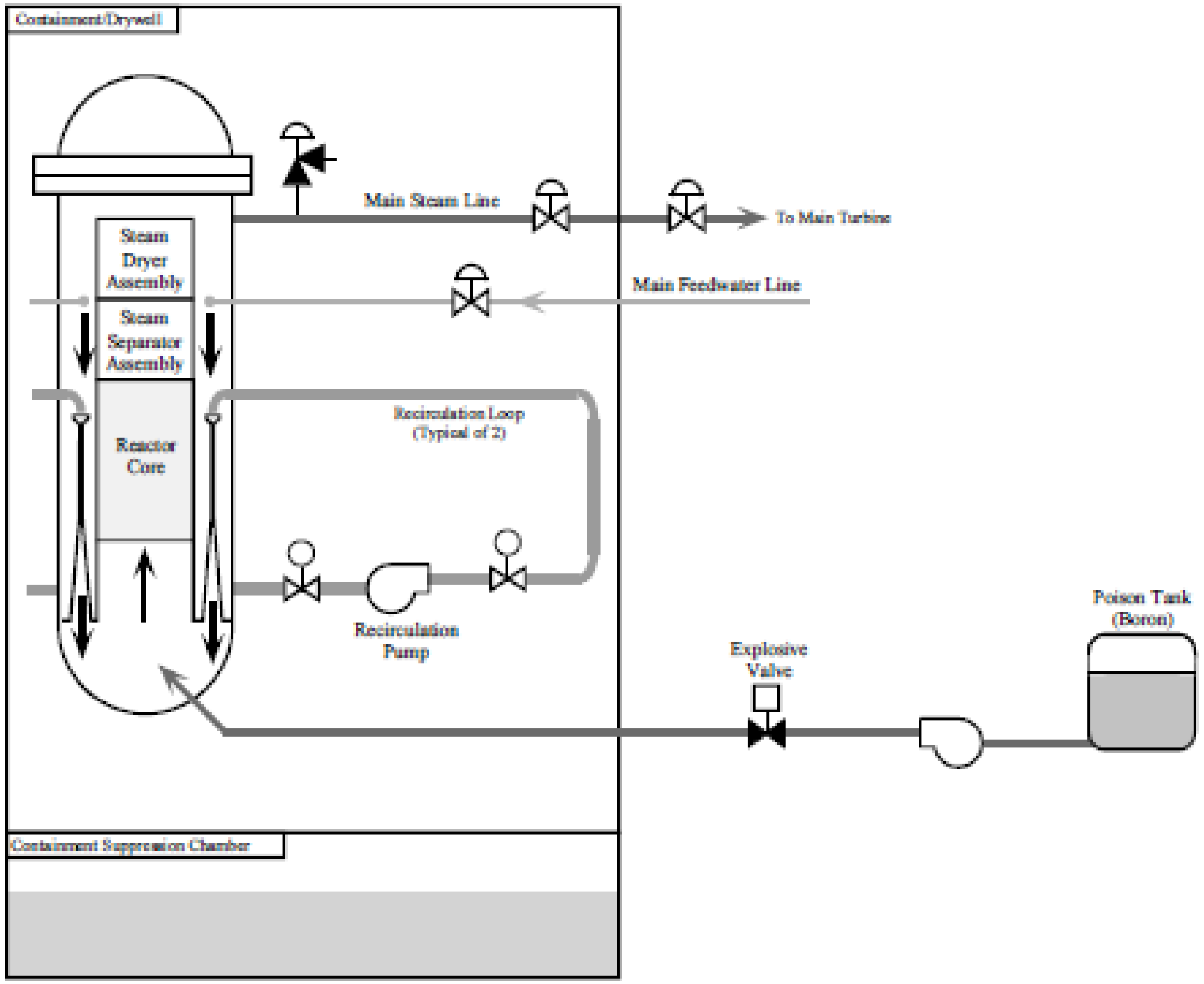
Containment/Drywell
Safety/Relief Valve
Main Steam Line
To Main Turbine
Steam Dryer Assembly
Main Feedwater Line
Steam Separator Assembly
Condensate Storage Tank
Reactor Core
Recirculation Loop (Typical of 2)
Recirculation Pump
RCIC Turbine
RCIC Pump
Containment Suppression Chamber

# BWR – Reactor water cleanup system

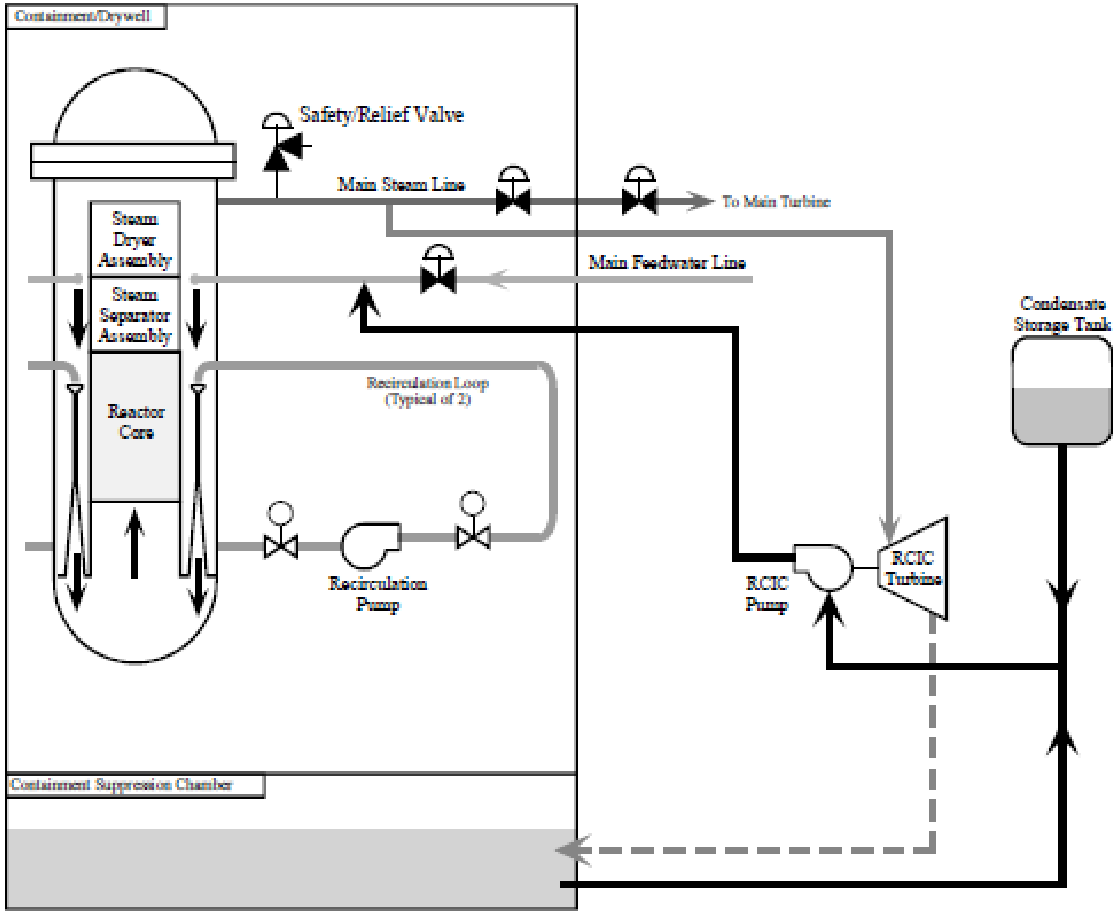



Reactor Water Cleanup System

# BWR – Sistema de Injeção de Boro



# BWR – Reactor Core Isolation System - RCIC

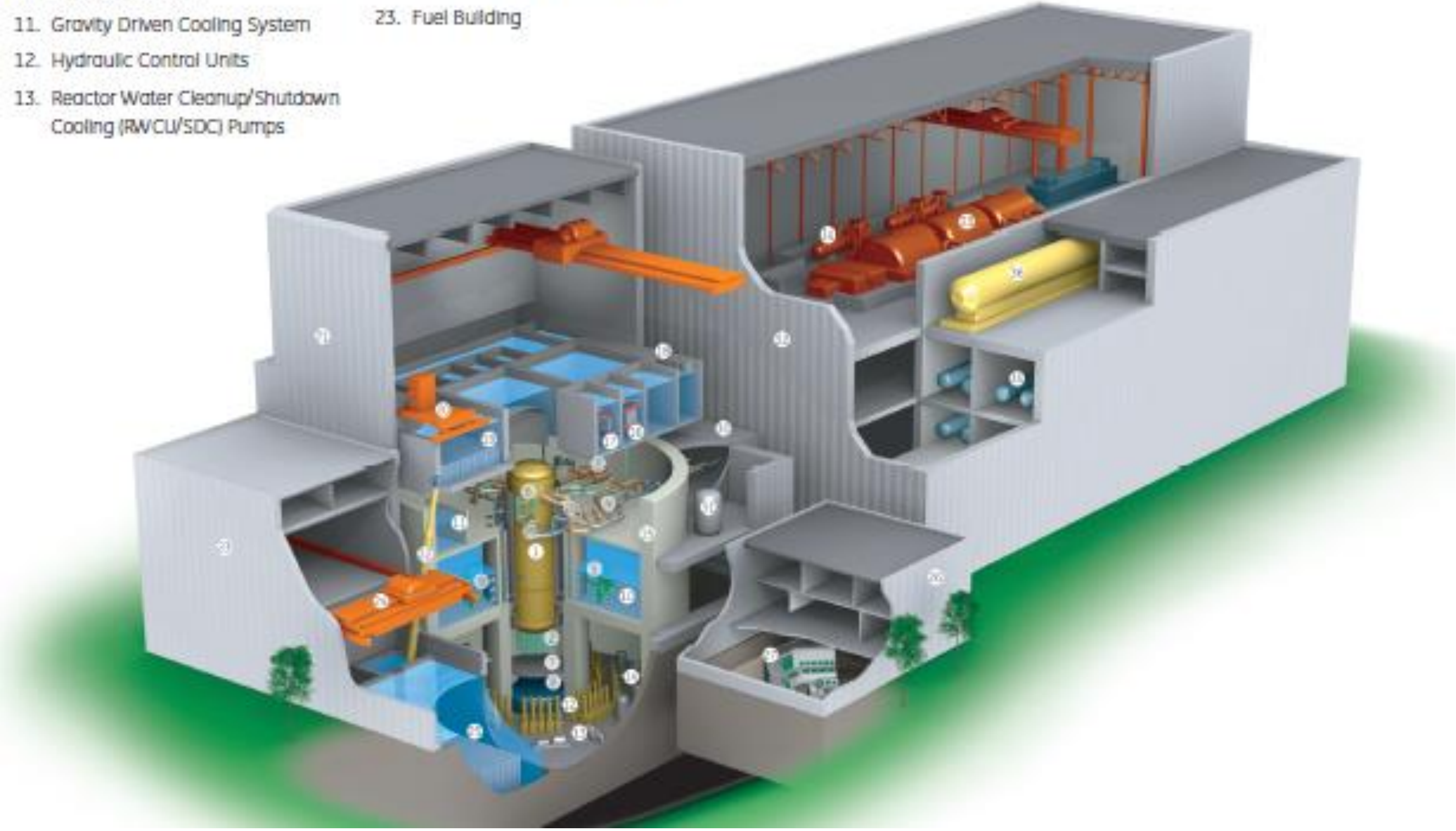



Reactor Core Isolation Cooling

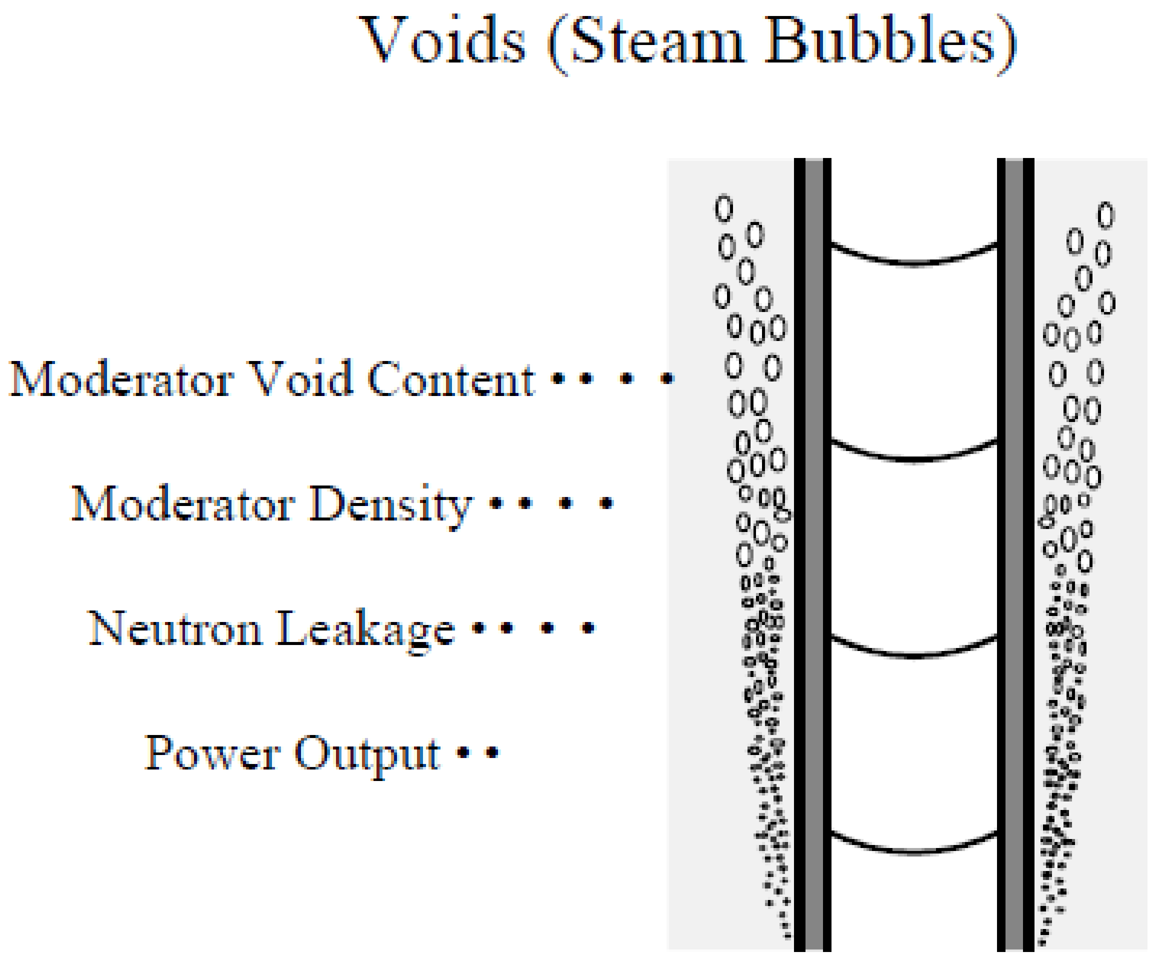
# ESBWR – GE & Hitachi

## ESBWR

1. Reactor Pressure Vessel
2. Fine Motion Control Rod Drives
3. Main Steam Isolation Valves
4. Safety/Relief Valves (SRV)
5. SRV Quenchers
6. Depressurization Valves
7. Lower Drywell Equipment Platform
8. BiMAC Core Catcher
9. Horizontal Vents
10. Suppression Pool
11. Gravity Driven Cooling System
12. Hydraulic Control Units
13. Reactor Water Cleanup/Shutdown Cooling (RWCU/SDC) Pumps
14. RWCU/SDC Heat Exchangers
15. Containment Vessel
16. Isolation Condensers
17. Passive Containment Cooling System
18. Moisture Separators
19. Buffer Fuel Storage Pool
20. Refueling Machine
21. Reactor Building
22. Inclined Fuel Transfer Machine
23. Fuel Building
24. Fuel Transfer Machine
25. Spent Fuel Storage Pool
26. Control Building
27. Main Control Room
28. Main Steam Lines
29. Feedwater Lines
30. Steam Tunnel
31. Standby Liquid Control System Accumulator
32. Turbine Building
33. Turbine-Generator
34. Moisture Separator Reheater
35. Feedwater Heaters
36. Direct Contact Feedwater Heater and Tank

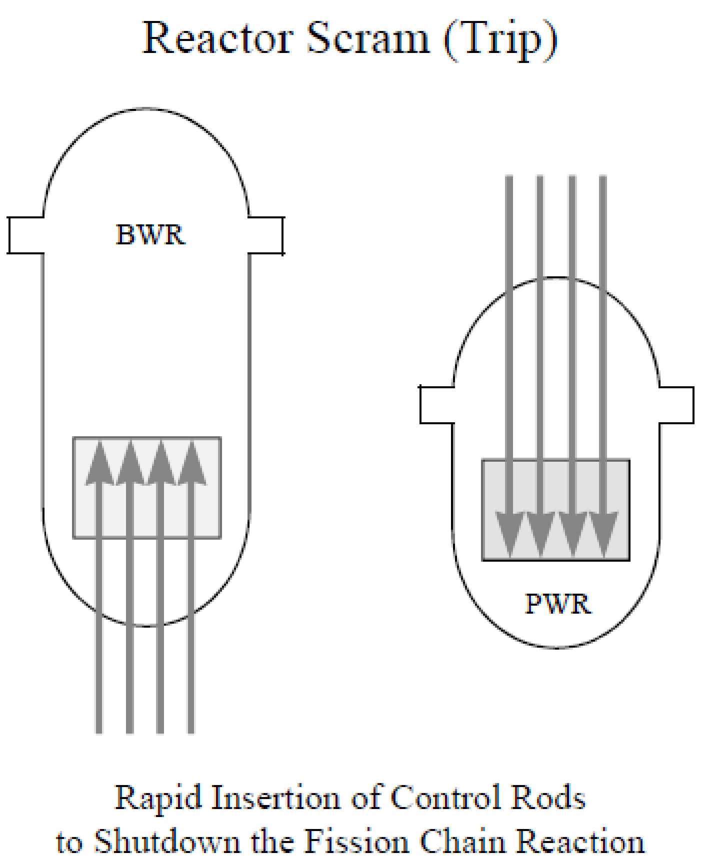


# Reatores de Potência tipo Água Fervente (Boiling Water Reactor – BWR)



# Reatores de Potência tipo Água Fervente (Boiling Water Reactor – BWR)

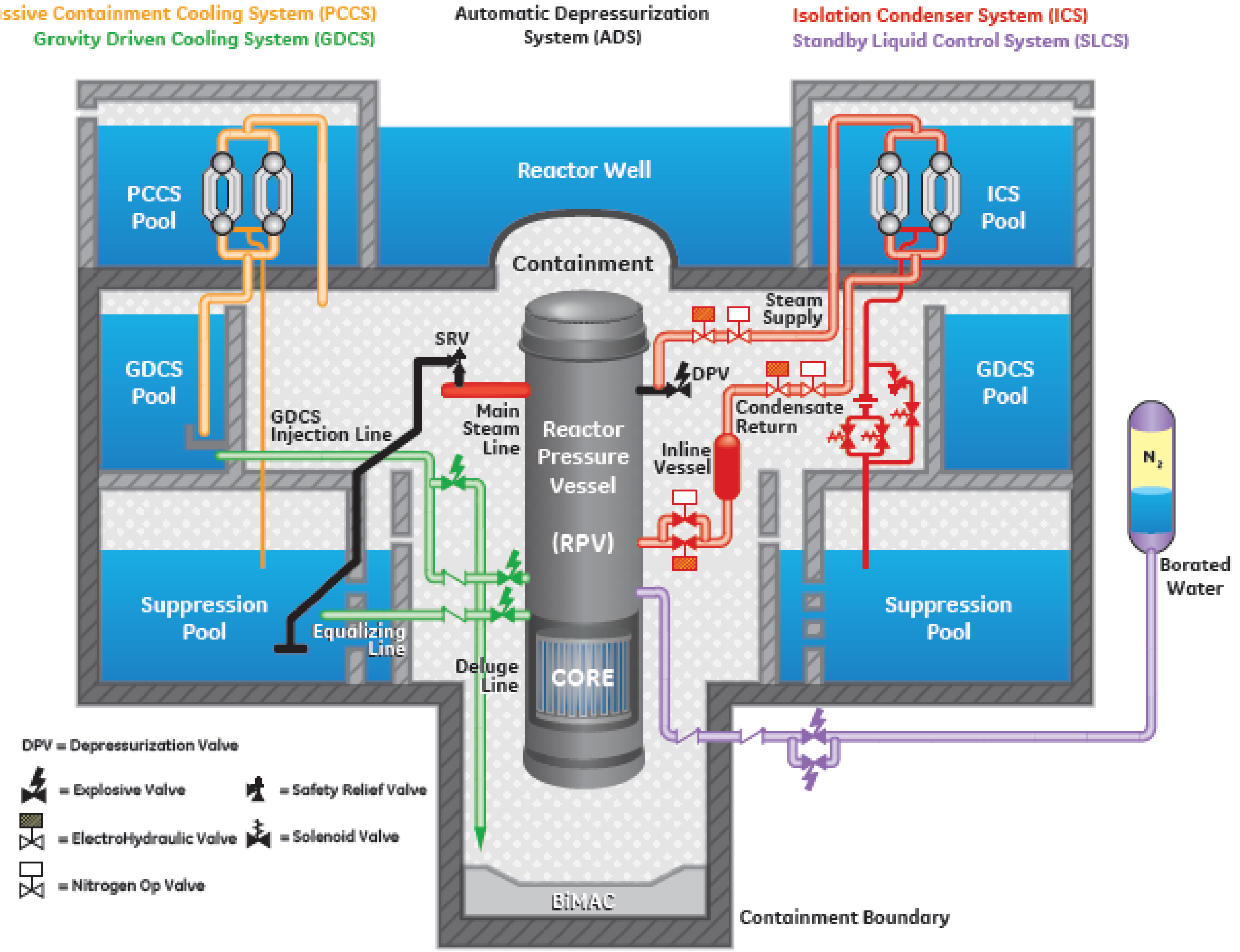
Barras de Controle e Segurança



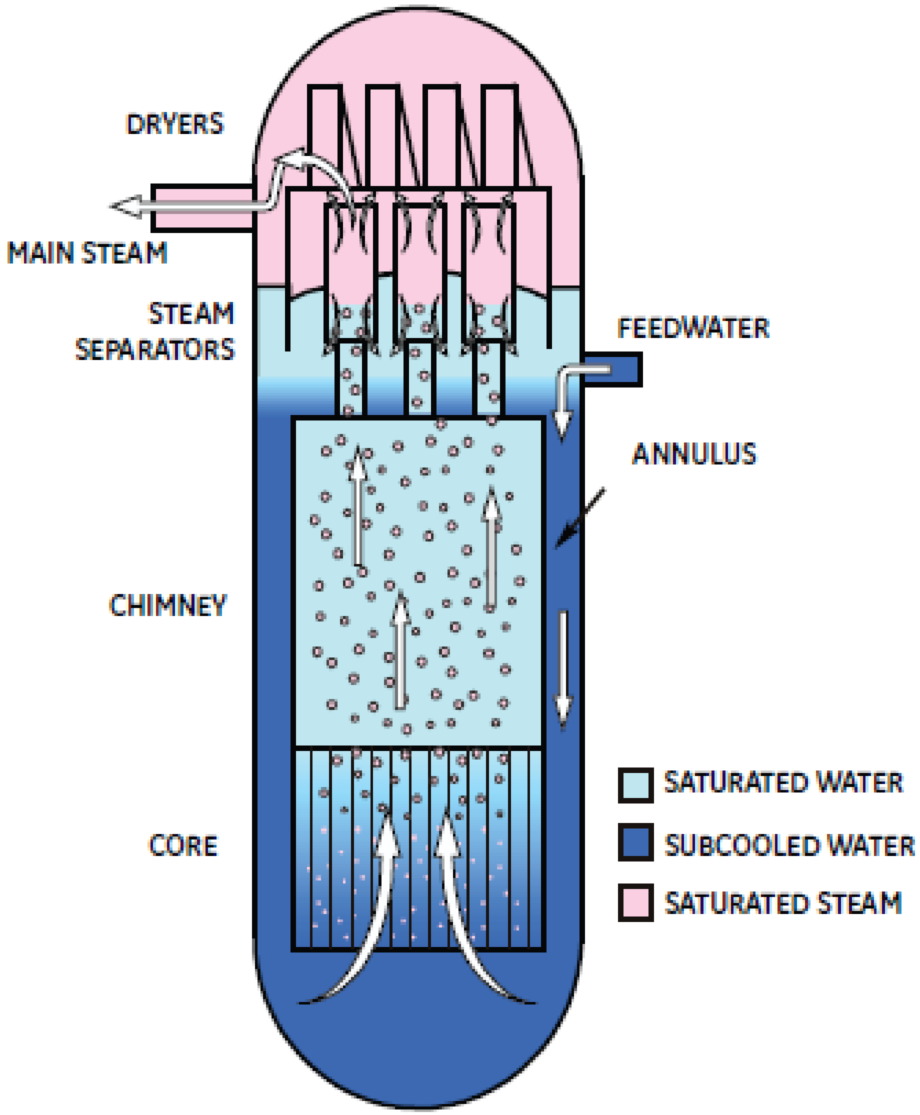

Sistema de separação de vapor

## ESBWR – GE & Hitachi

# ESBWR passive safety systems



# ESBWR – GE & Hitachi

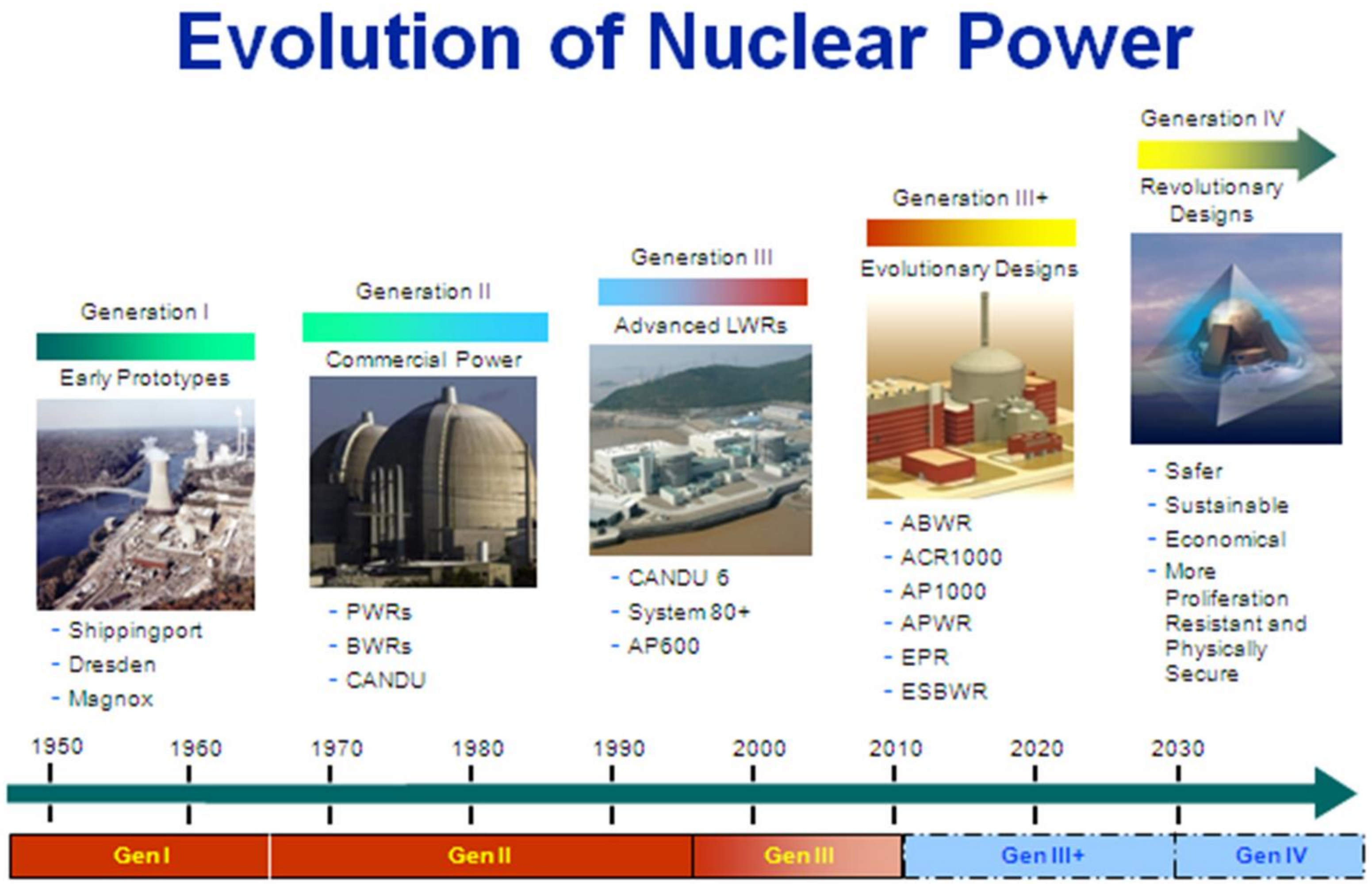



Natural Circulation

Because hot water is less dense, it rises through the core while the cool water flows down to the bottom of the core. These natural differences in density create circulation.

# Reatores Nucleares

Projetos do reator nuclear são categorizados geralmente pela "geração"; ou seja, a geração I, II, III, III + e IV.



Os principais atributos que caracterizam o desenvolvimento e implantação de reatores nucleares são as diferenças essenciais entre as várias gerações de reatores.

Faremos uma análise dos conceitos dos reatores existentes enfocando seis atributos chave dos reatores: