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Joint ICTP-IAEA School of Nuclear Energy Management

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Current Reactor Technology and Advanced Reactor Development

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Current Reactor Technology and Advanced Reactor Development

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Nuclear Power Technology Development Section

Division of Nuclear Power, Department of Nuclear Energy

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Outline

- Introduction
- Summary of Commercially Available and Near Term Deployment Reactor Designs
- Global Trends in Advanced Reactor Development
- Light Water Cooled Reactors
- Boiling Water Reactors – fundamental
- Pressurized Water Reactors – fundamental
- Pressurized Heavy Water Reactors – fundamental
- Non Electric Applications
- Conclusions

Typical 4-unit PWR in a nuclear site

!!! Plant Layouts are similar even for different designs …

Commercially Available Reactors #1

A brief summary …

Reactor Design	Output in MWe	Designer	Country of Origin
VVERs	300, 600, 1000, and 1200	JSC OKB Gidropress	Russian Federation
US-APWR, EU-APWR	1700	Mitsubishi Heavy Indutries, Ltd.	Japan
EPR	1600	AREVA, NP	France
OPR-1000	1000	Korea Hydro and Nuclear Power (KHNP)	Republic of Korea
APR-1400	1400	KHNP	Republic of Korea
CNP-650	650	CNNC	China
CPR-1000	1000	CGNPC	China
AP1000	1000 – 1200	Toshiba – Westinghouse	Japan, USA

Commercially Available Reactors #2

A brief summary …

Reactor Design	Output in MWe	Designer	Country of Origin
ATMEA1	1100	ATMEA	France, Japan
US-ABWR, US-ABWR	1300 – 1600	Toshiba Corporation	Japan
ESBWR	1500	GE Hitachi Nuclear Energy	USA, Japan
Enhanced CANDU6	700	Atomic Energy of Canada Limited (AECL)	Canada
ACR 1000	1000	(AECL)	Canada
PHWRs	220, 540 and 700	Nuclear Power Corporation of India Limited (NPCIL)	India
KLT-40s	38	OKBM Afrikantov	Russian Federation

Reactors for Near Term Deployment

A brief summary …

Reactor Design	Output in MWe	Designer	Country of Origin
mPower	125 – 250	Babcock & Wilcox	USA
NuScale Power	45	NuScale	USA
Westinghouse SMR	200	Westinghouse	USA
CAREM-25	27	CNEA	Argentina
SMART	100	Korea Atomic Energy Research Institute (KAERI)	Republic of Korea
SVBR-100	100	JSC AKME Engineering	Russian Federation
PRISM	311	GE Nuclear Energy	USA
4S	10	Toshiba Corporation	Japan
and so forth …			

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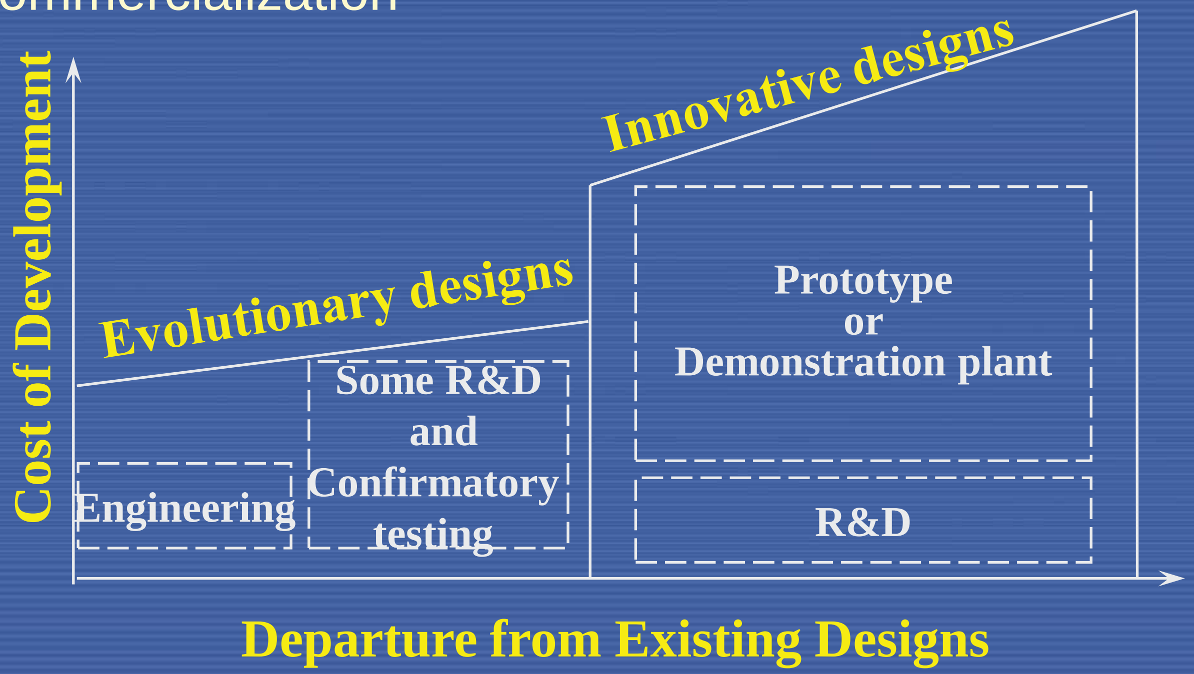
Global Trends in Advanced Reactor Design

- **Cost Reduction**
  - Standardization and series construction
  - Improving construction methods to shorten schedule
  - Modularization and factory fabrication
  - Design features for longer lifetime
  - Fuel cycle optimization
  - Economy of scale → larger reactors
  - Affordability → SMRs
- **Performance Improvement**
  - Establishment of user design requirements
  - Development of highly reliable components and systems, including “smart” components
  - Improving the technology base for reducing over-design
  - Further development of PSA methods and databases
  - Development of passive safety systems
  - Improved corrosion resistant materials
  - Development of Digital Instrumentation and Control
  - Development of computer based techniques
  - Development of systems with higher thermal efficiency and expanded applications (Non-electrical applications)

Advanced Reactor Designs

(As defined in IAEA-TECDOC-936)

- **Evolutionary Designs** - achieve improvements over existing designs through small to moderate modifications
- **Innovative Designs** - incorporate radical conceptual changes and may require a prototype or demonstration plant before commercialization



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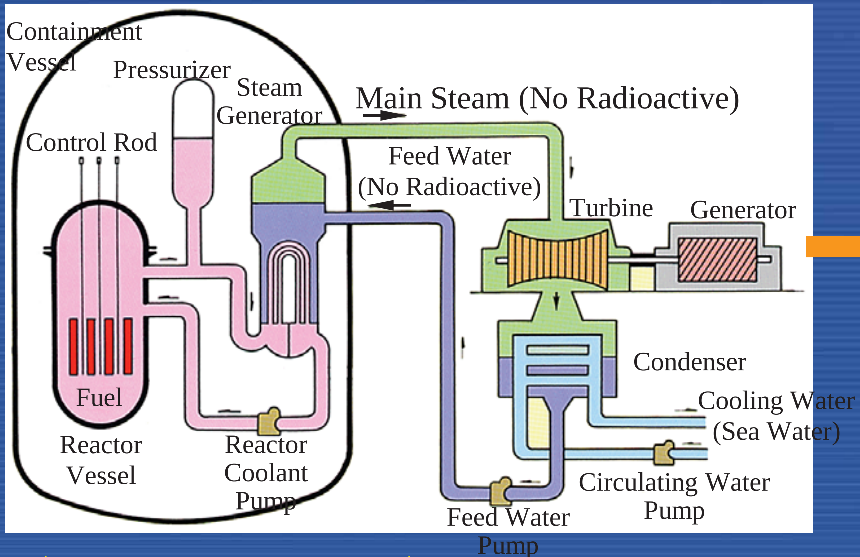
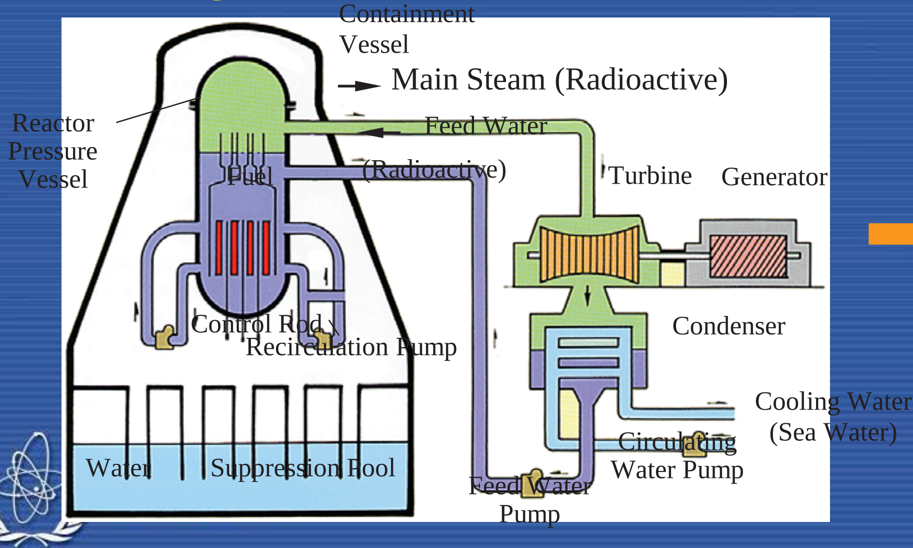
Light Water Reactor: PWR and BWR

PWR（Pressurized Water Reactor）

Courtesy of Mitsubishi Heavy Industries, LTD



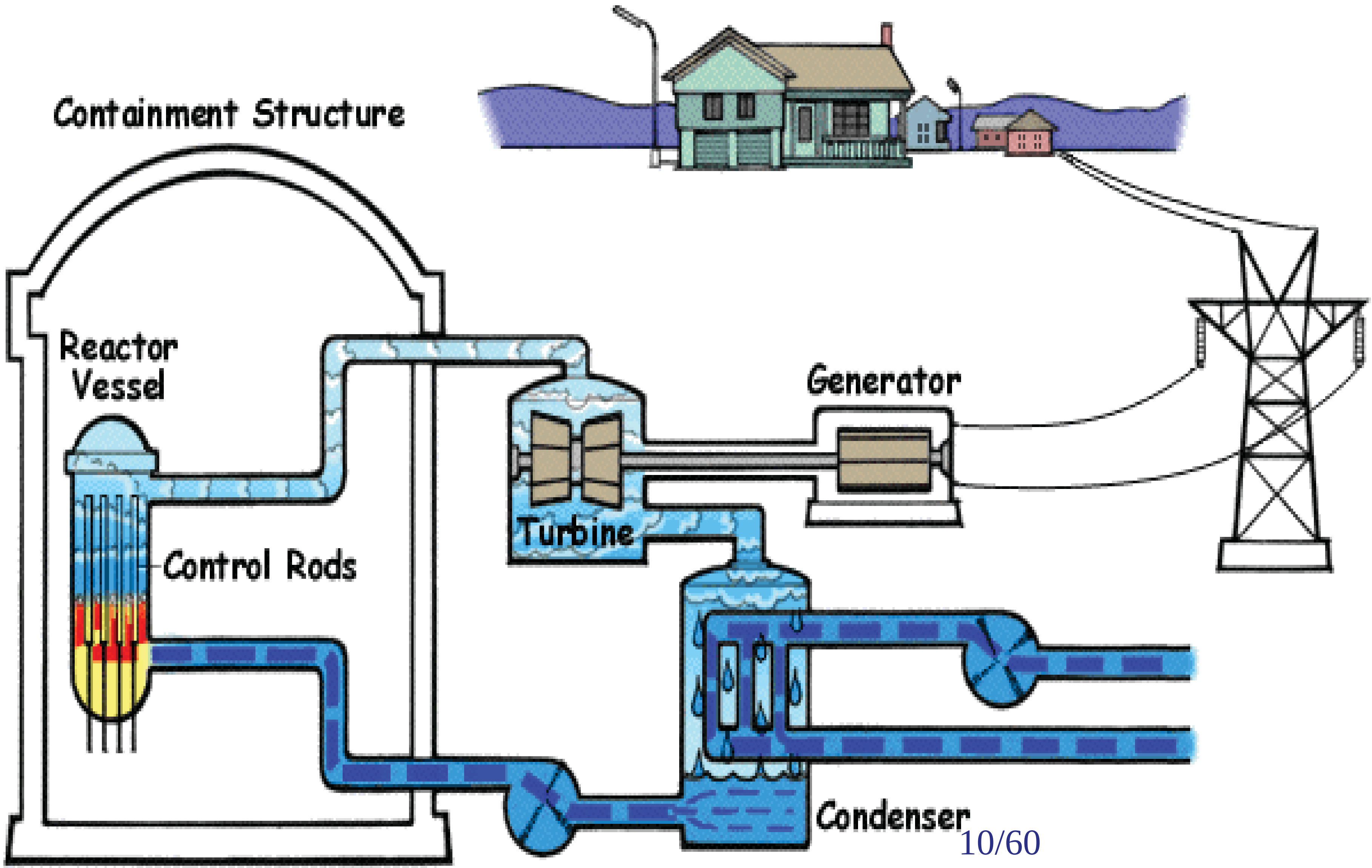
BWR（Boiling Water Reactor）



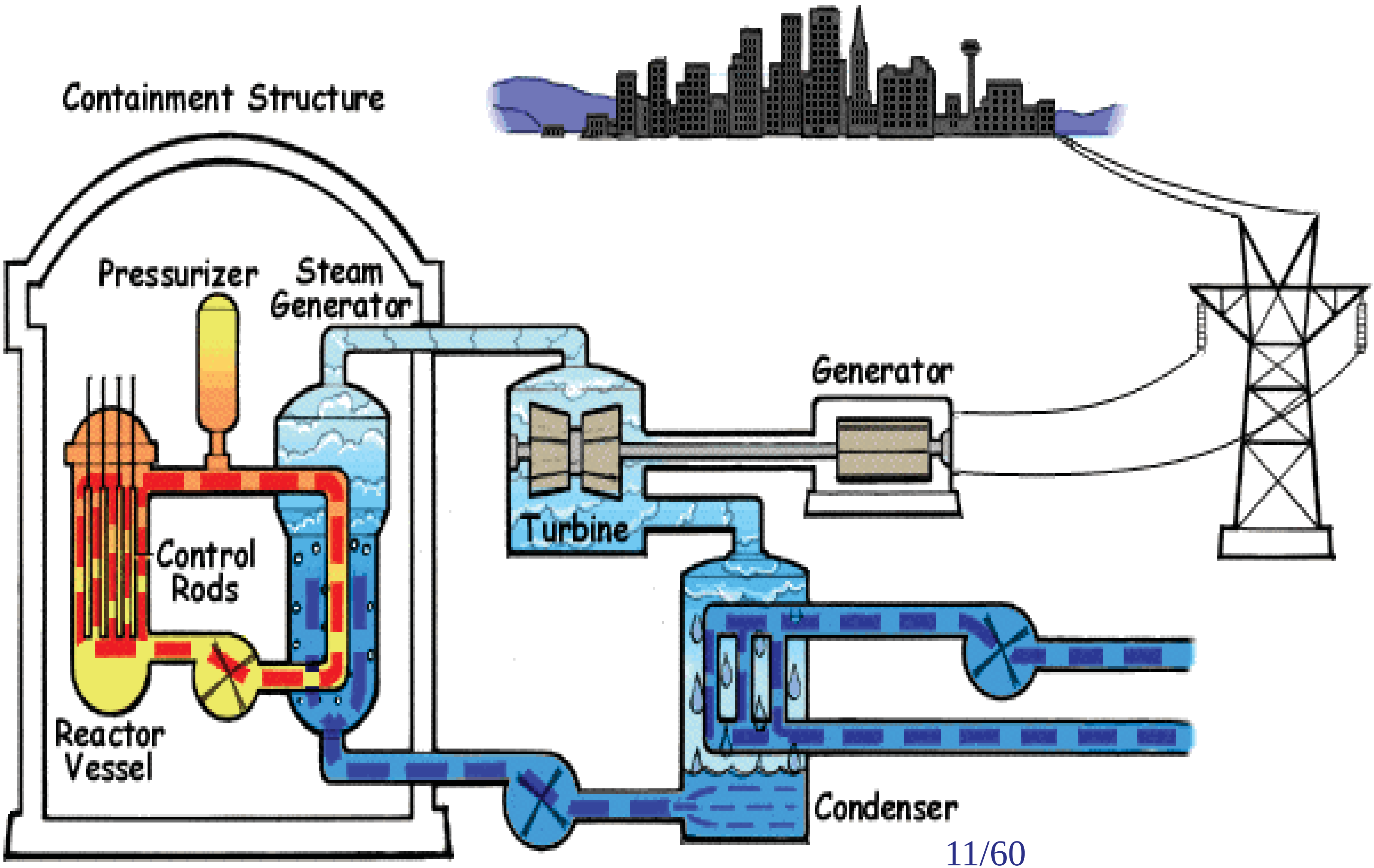
Transformer

Transmission Line

How does BWR work?

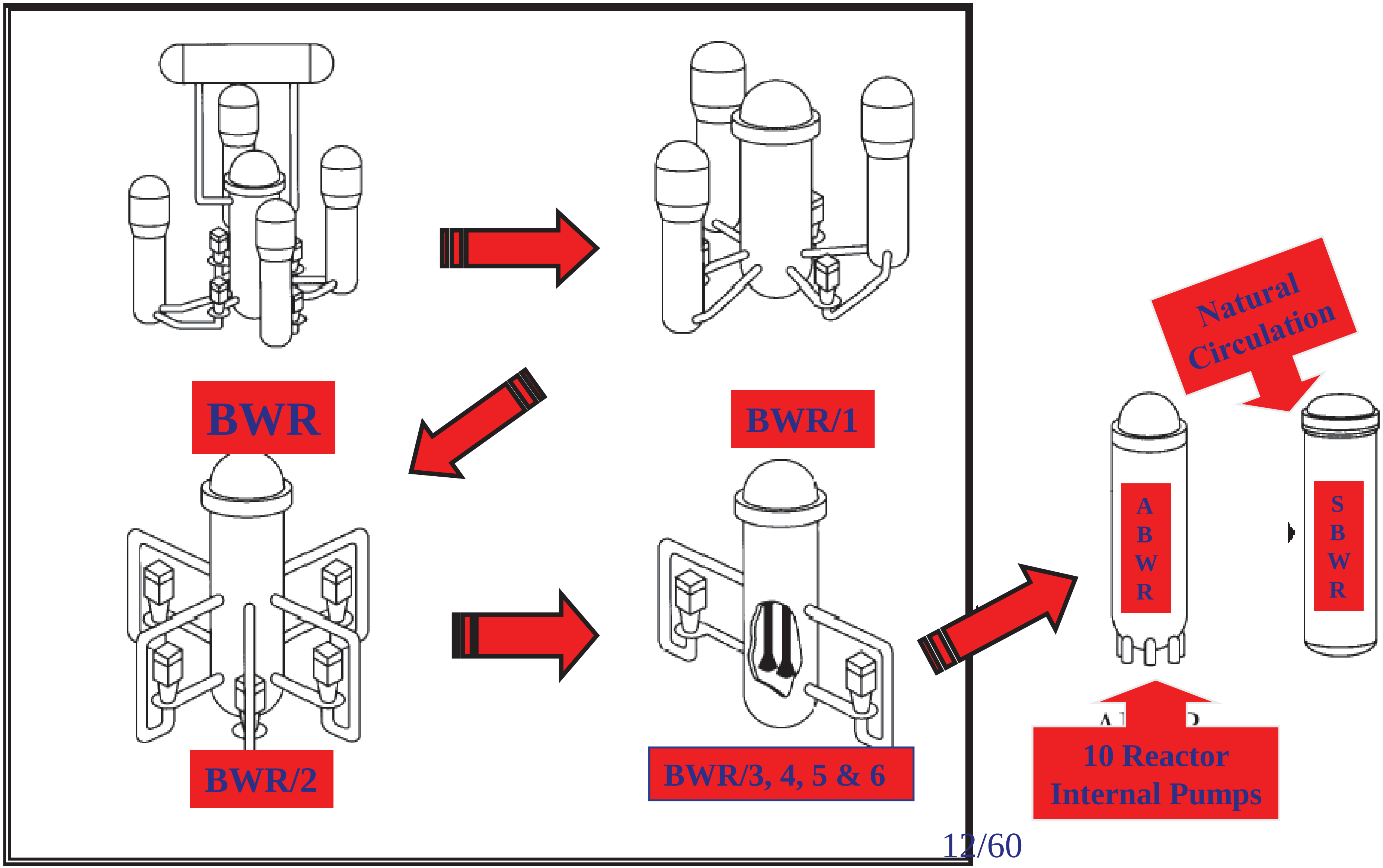


How does PWR work?



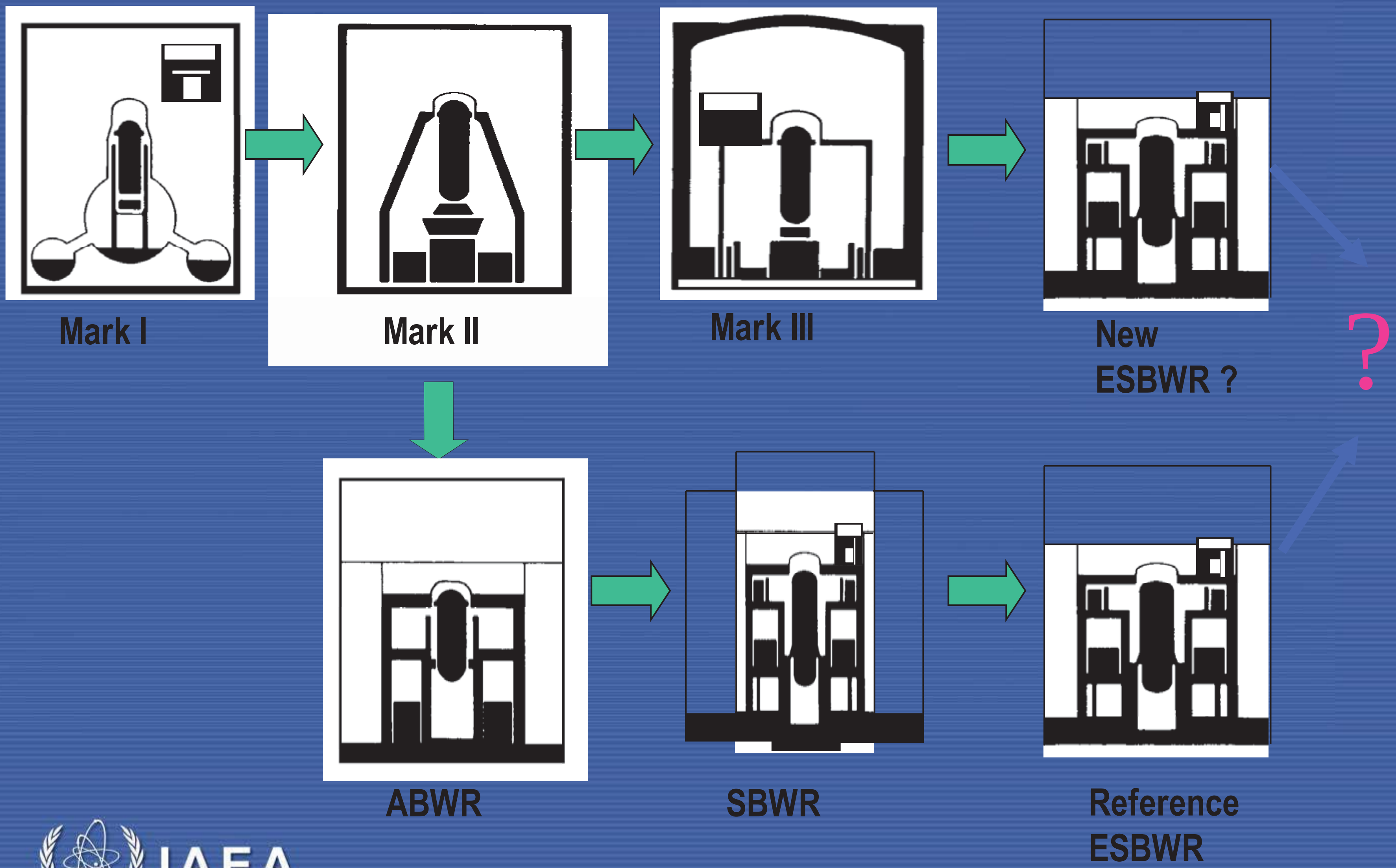
Evolution of BWR Design

Courtesy of GE Hitachi Nuclear Energy



Evolution of BWR Containment

Courtesy of GE Hitachi Nuclear Energy



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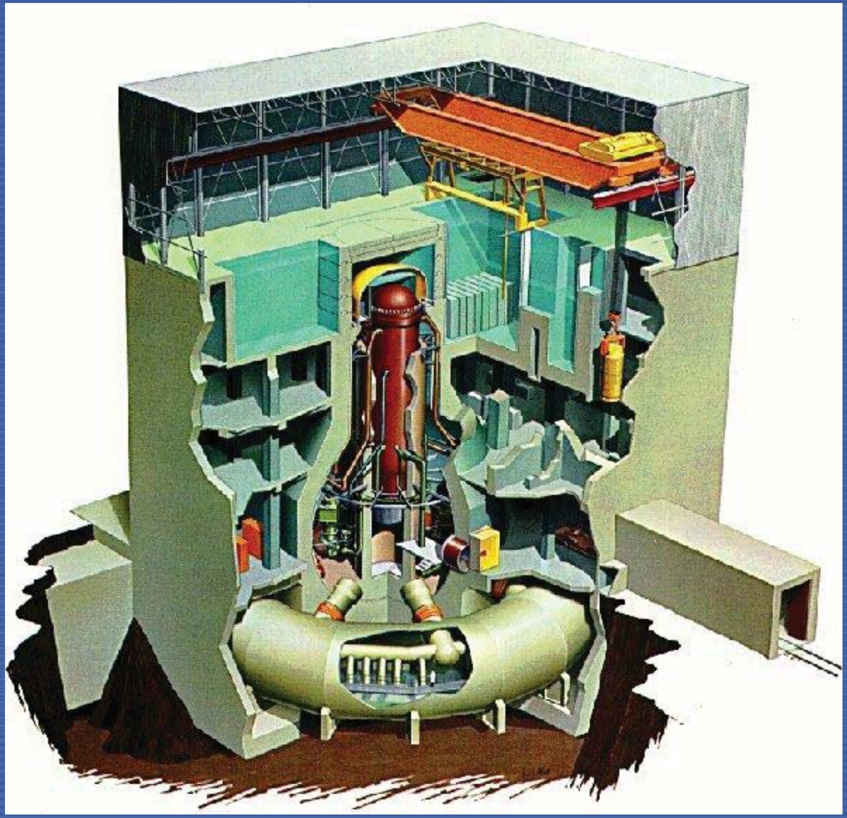
BWR/4 with Mark-I Containment

Courtesy of GE Hitachi Nuclear Energy

- Building structure
  - Concrete Building
  - Steel-framed Service Floor



- Containment
  - Pear-shaped Dry-Well
  - Torus-shaped Wet-Well

en.wikipedia.org/wiki/Browns_Ferry_Nuclear_Power_Plant

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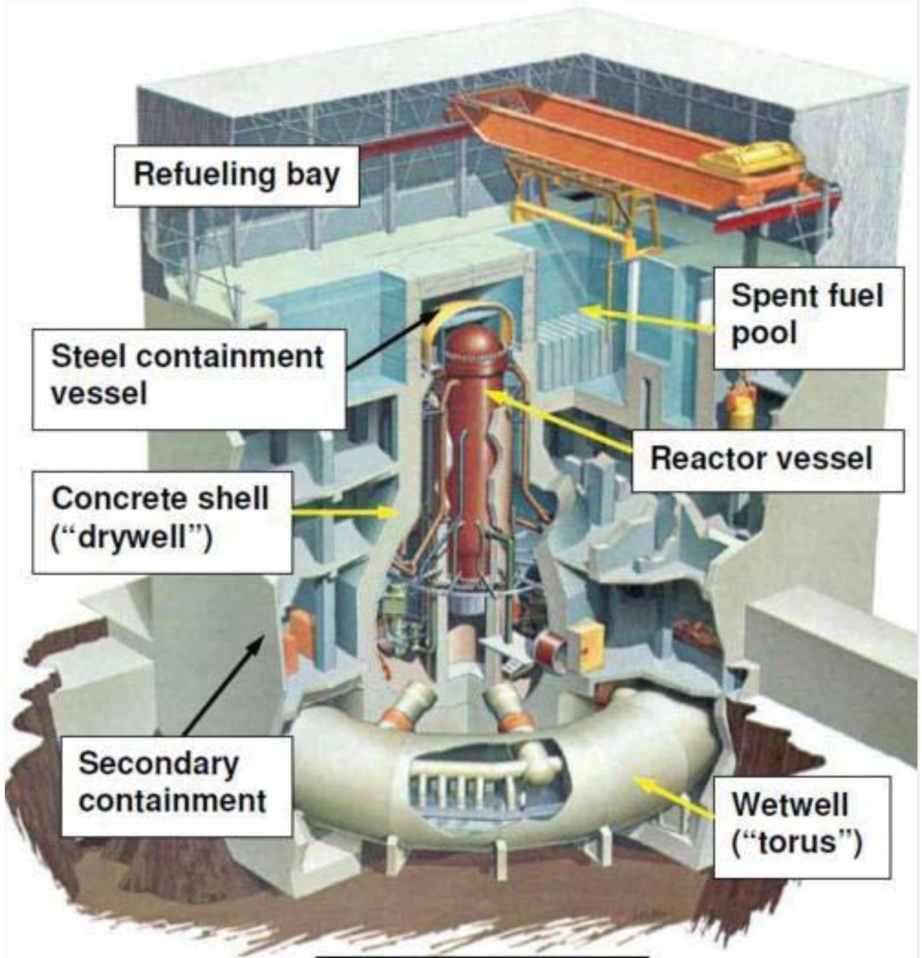
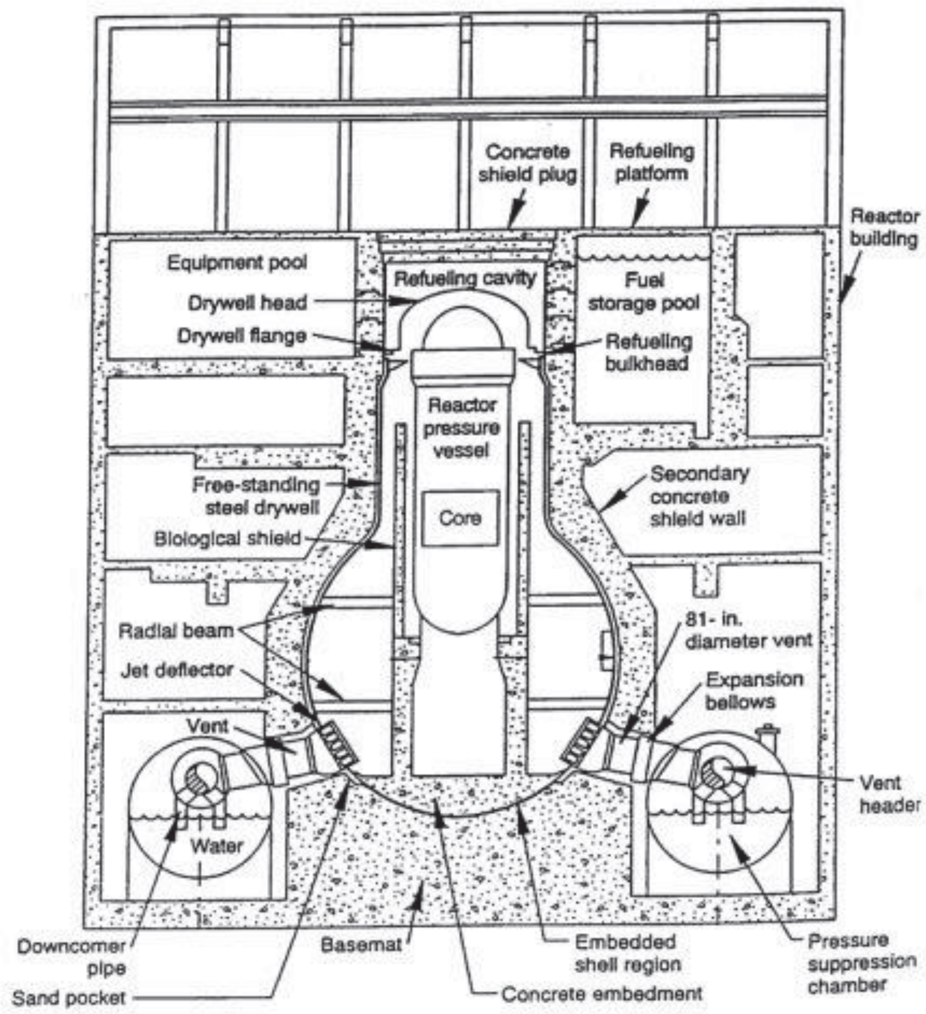
BWR/4 with Mark I Containment

Courtesy of GE Hitachi Nuclear Energy

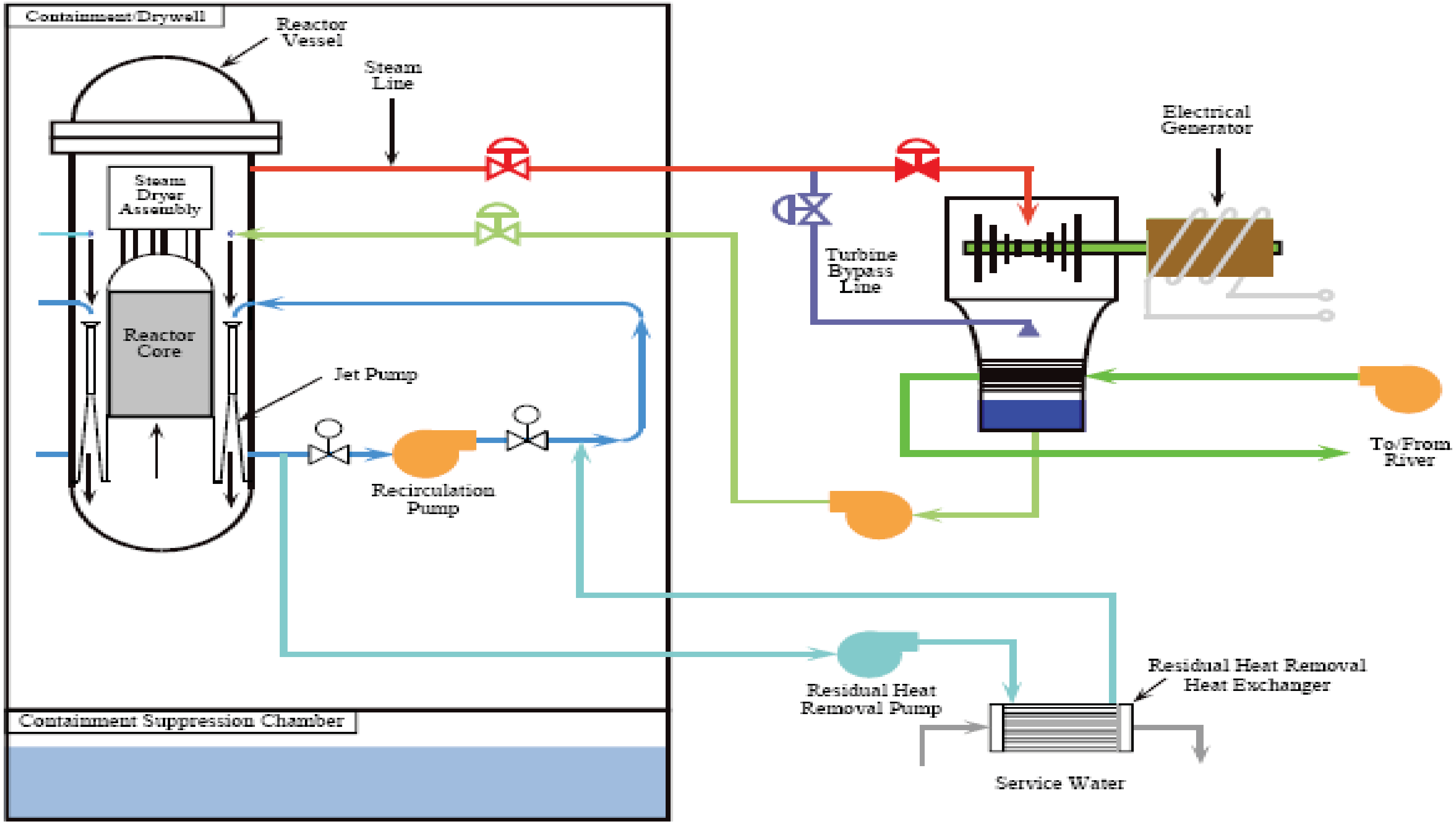


Mark I Containment



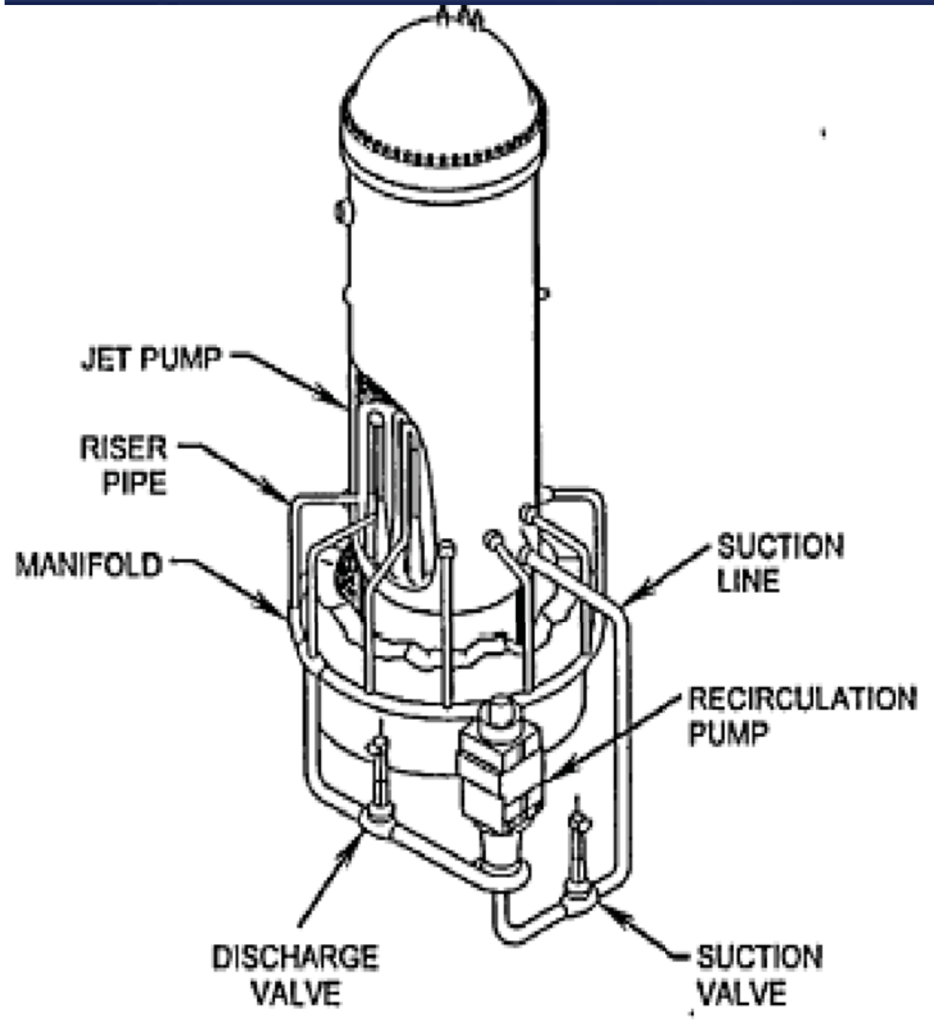
BWR/4 during Normal Operation

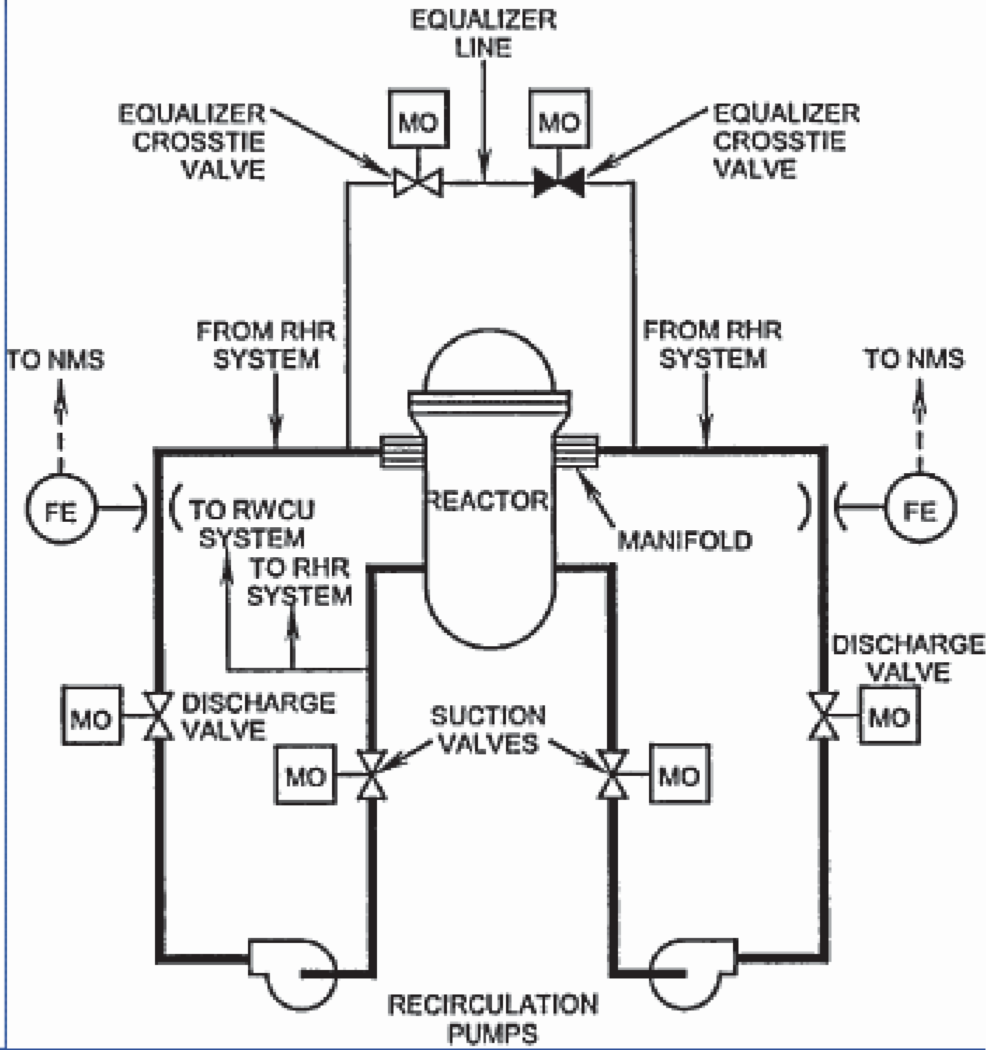
Courtesy of SFEN, France



BWR Recirculation System

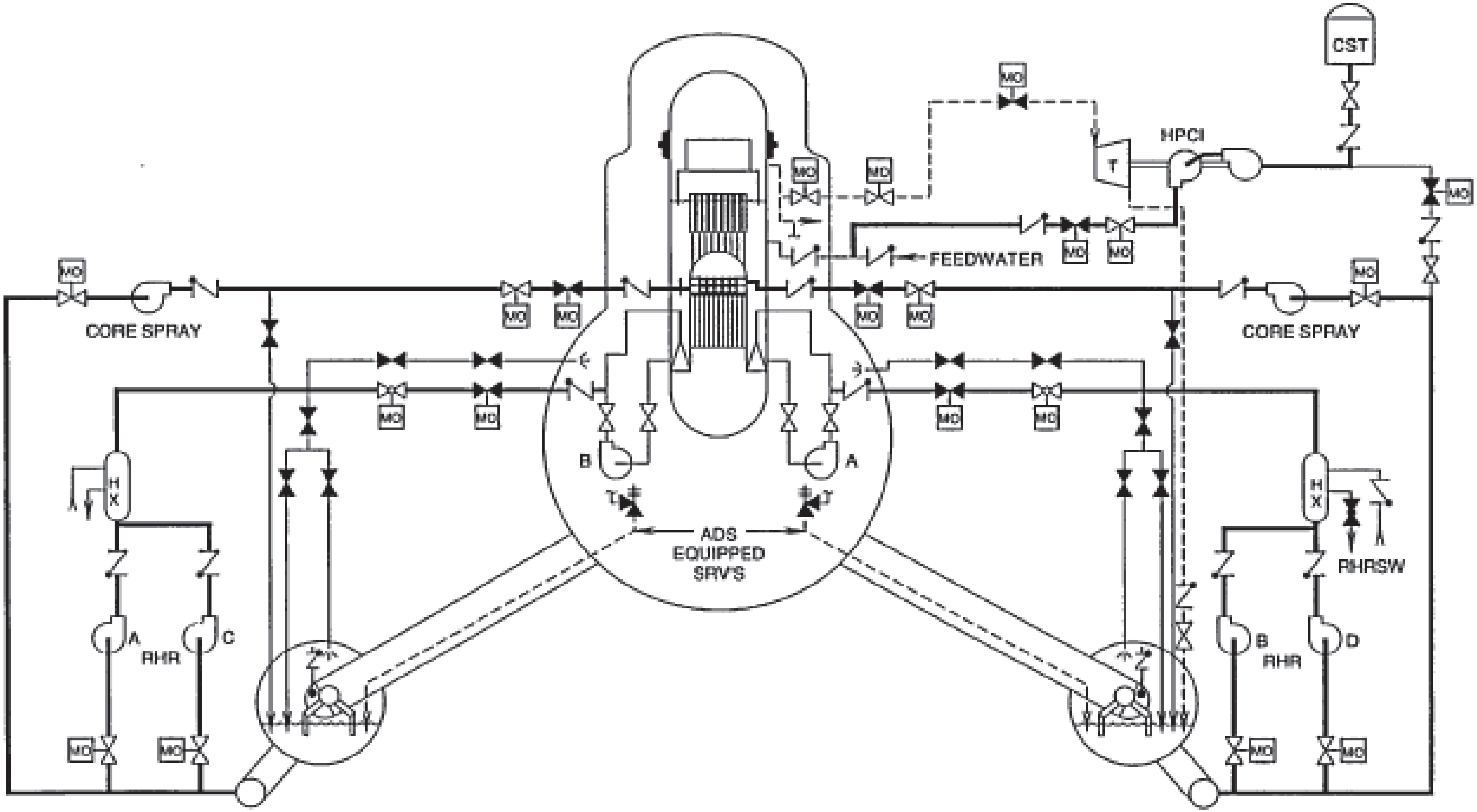
Courtesy of GE Hitachi Nuclear Energy





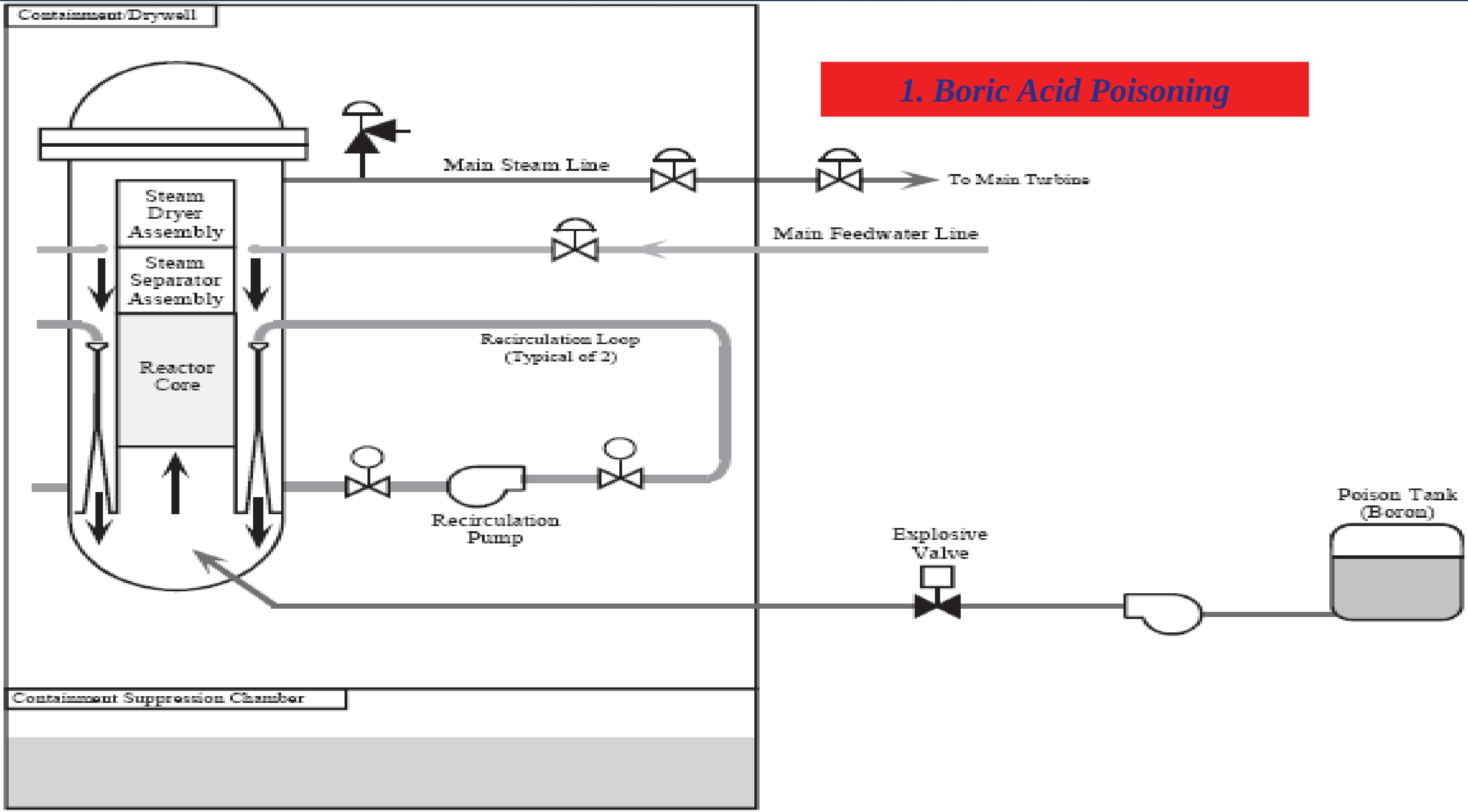
BWR Emergency Core Cooling System

Courtesy of GE Hitachi Nuclear Energy



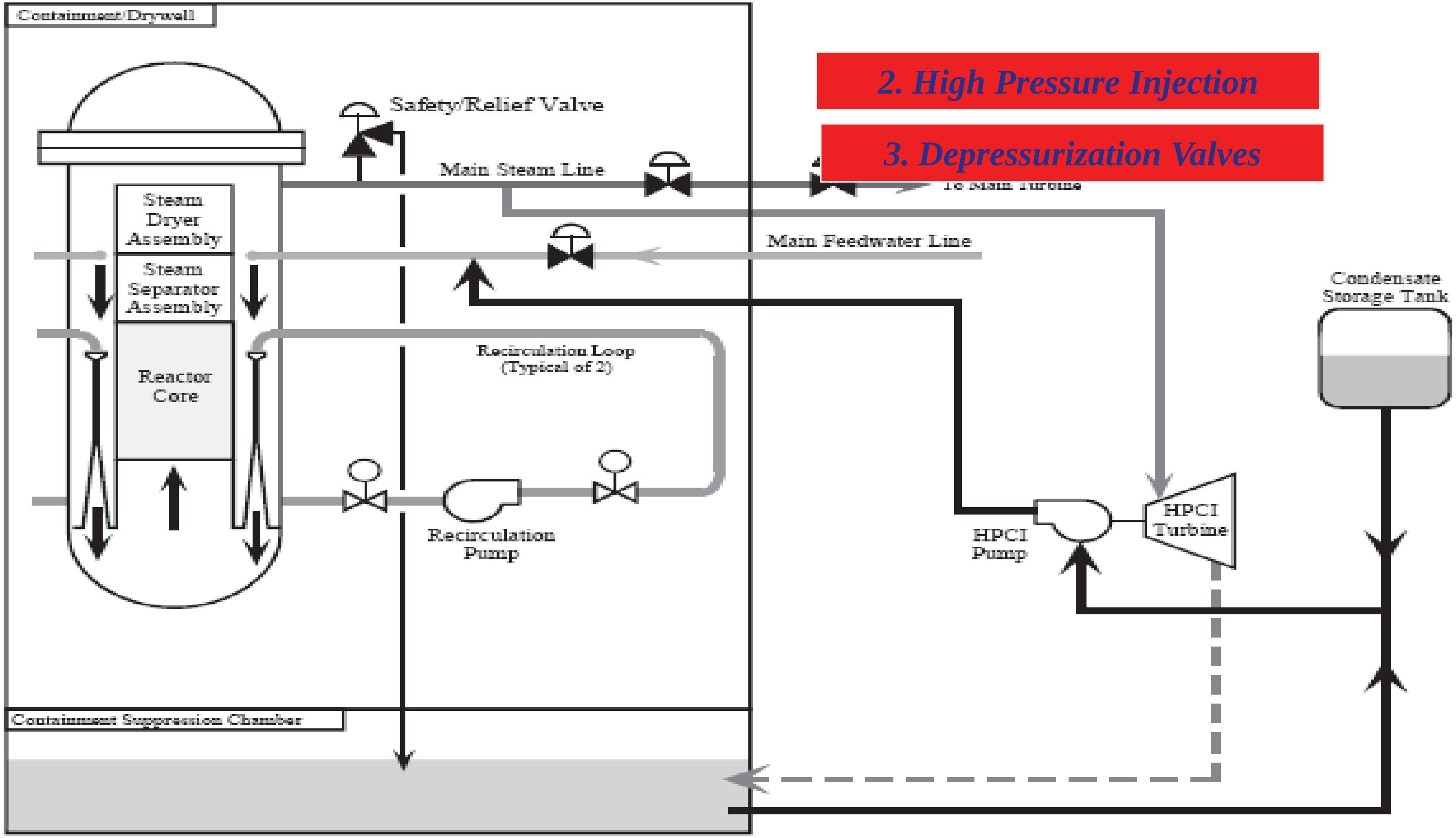
Engineered Safeguard System -1

Courtesy of SFEN, France



Engineered Safeguard System-2

Courtesy of SFEN, France

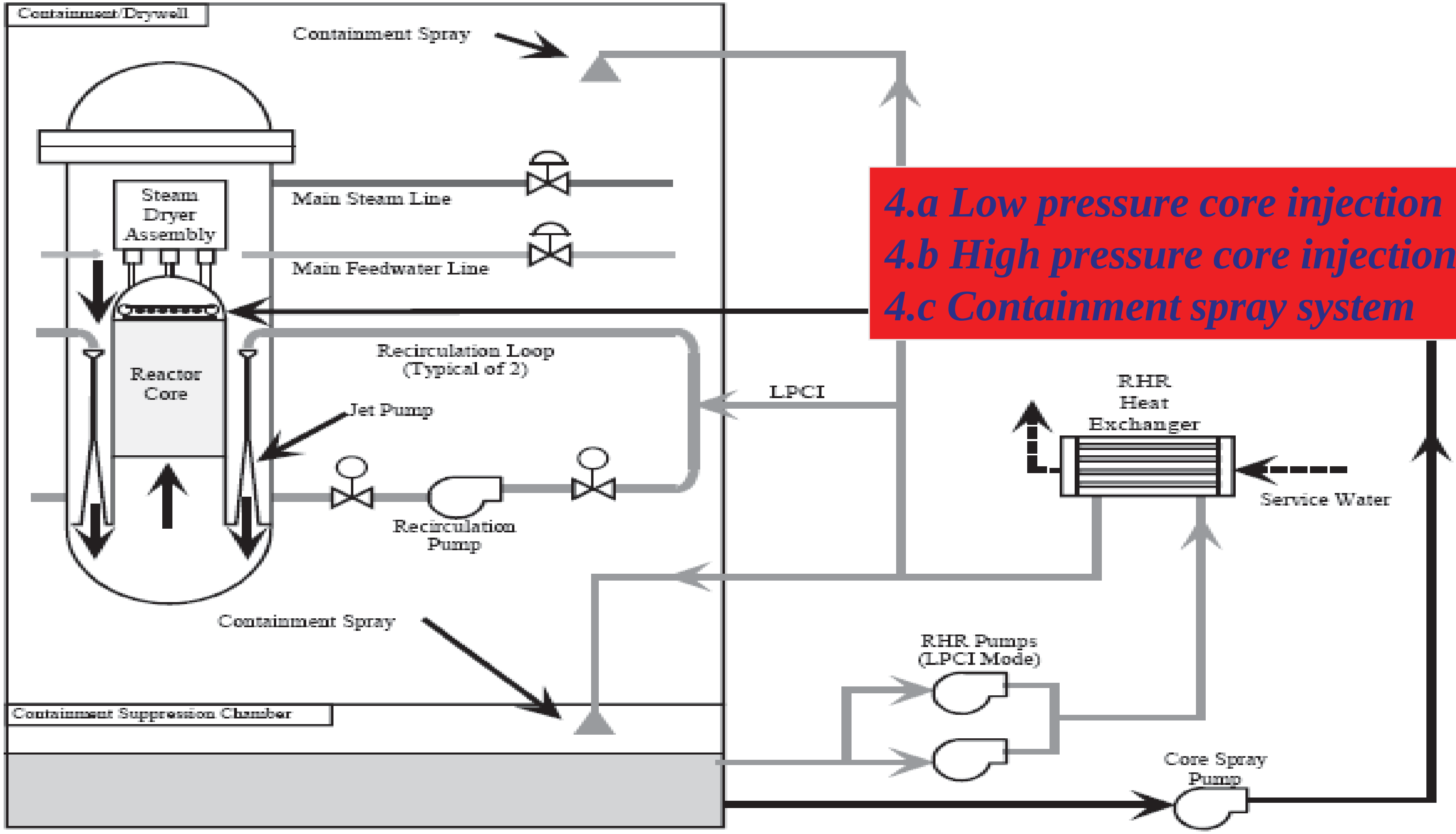


2. *High Pressure Injection*

3. *Depressurization Valves*

Engineered Safeguard System - 3

Courtesy of SFEN, France



4.a Low pressure core injection
4.b High pressure core injection
4.c Containment spray system

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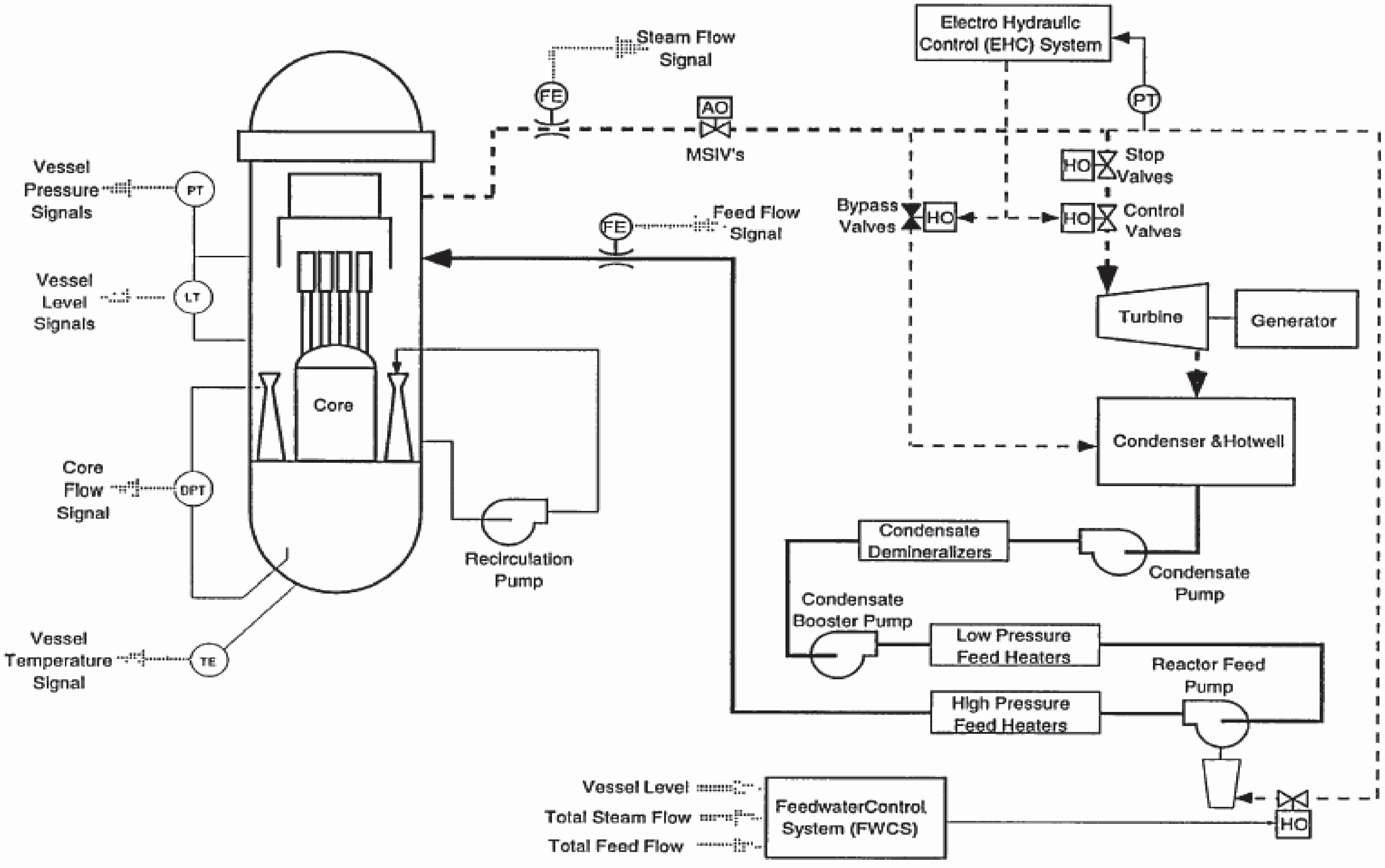
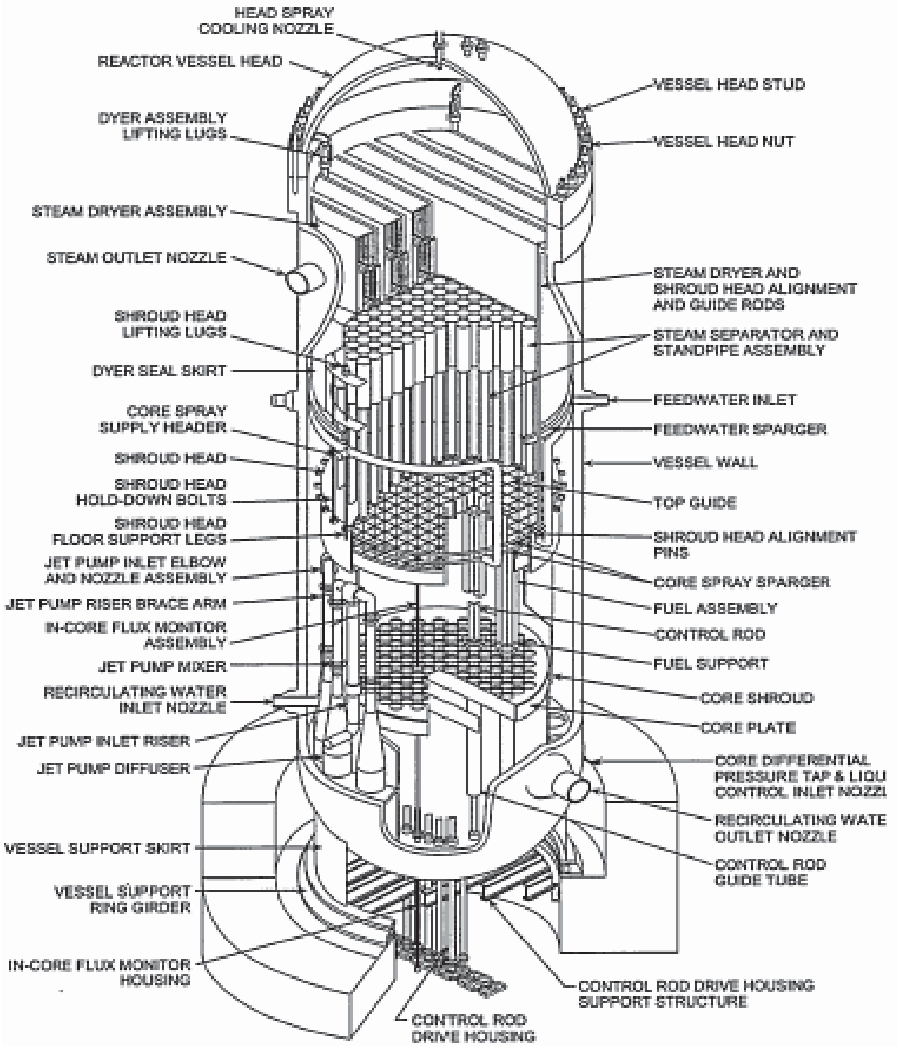
BWR Instrument and Control System

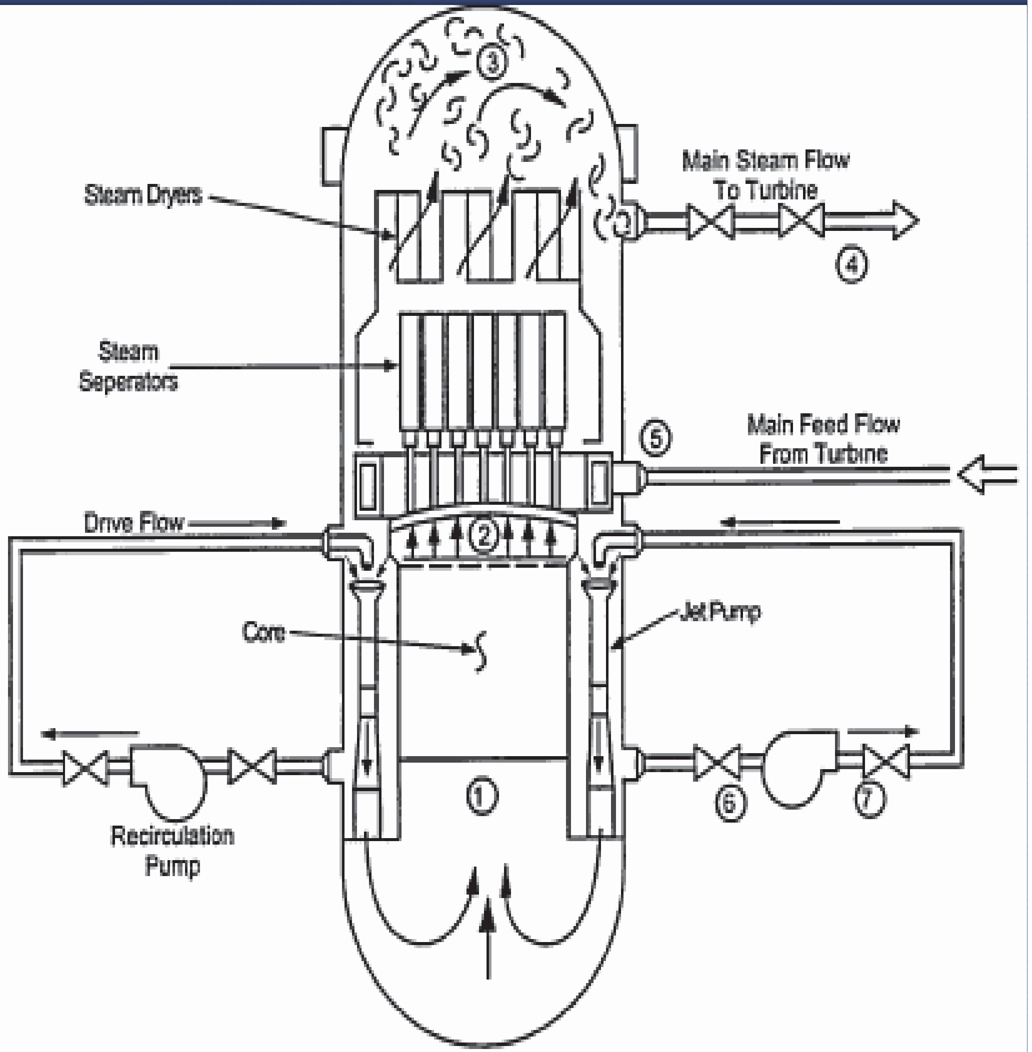
Courtesy of GE Hitachi Nuclear Energy



Reactor Vessel and Coolant Flowpath

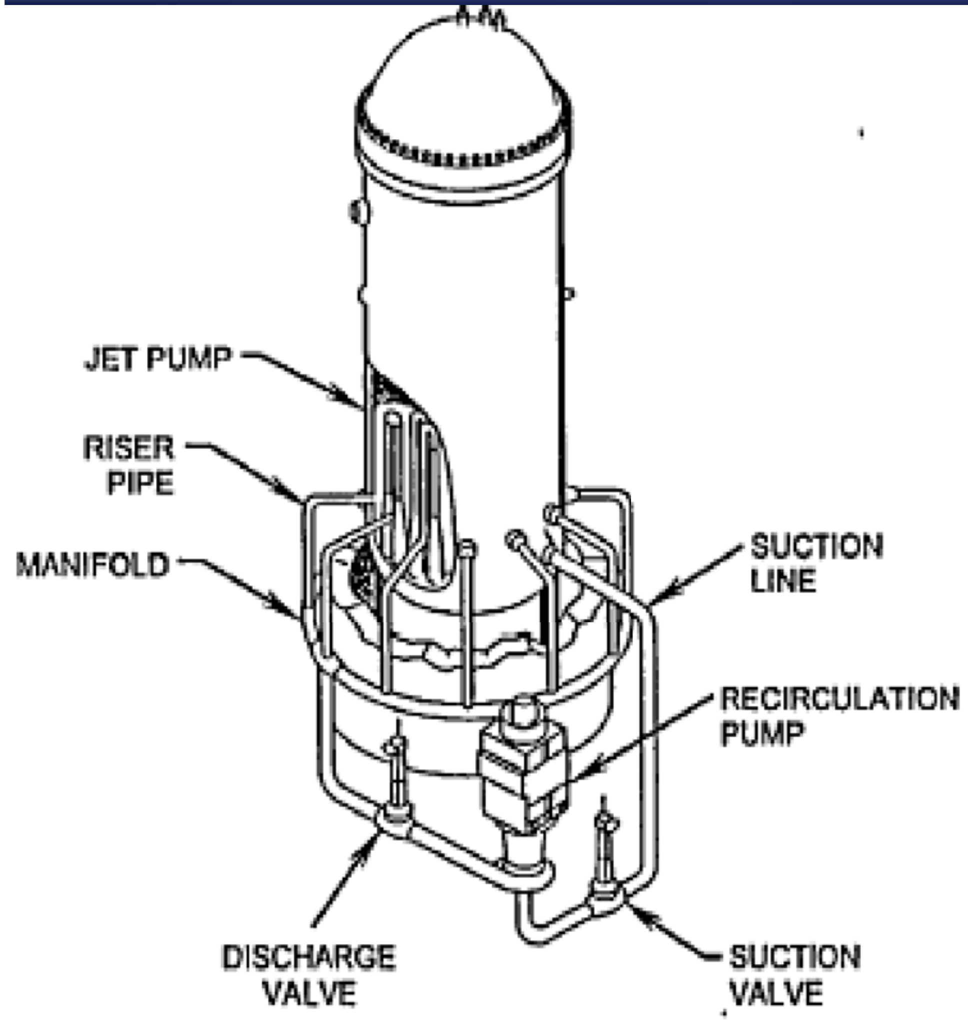
Courtesy of GE Hitachi Nuclear Energy

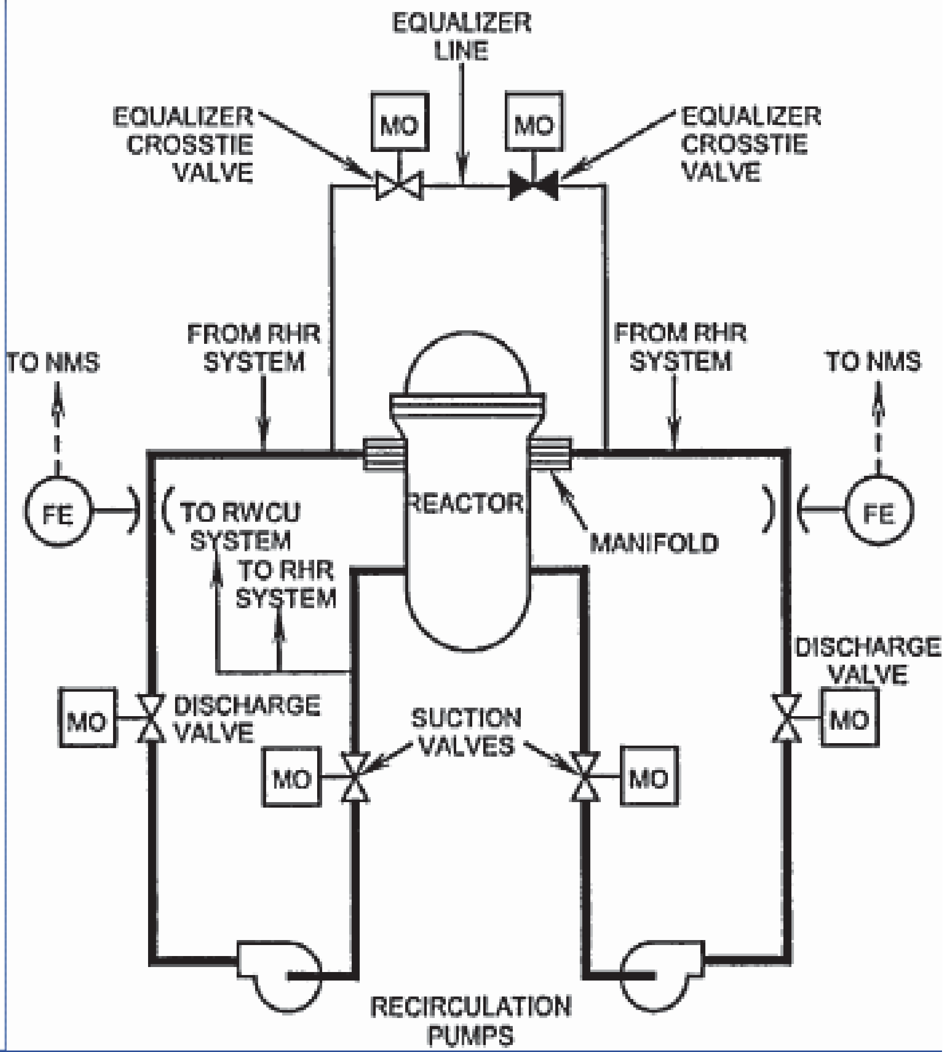




BWR Coolant Recirculation System

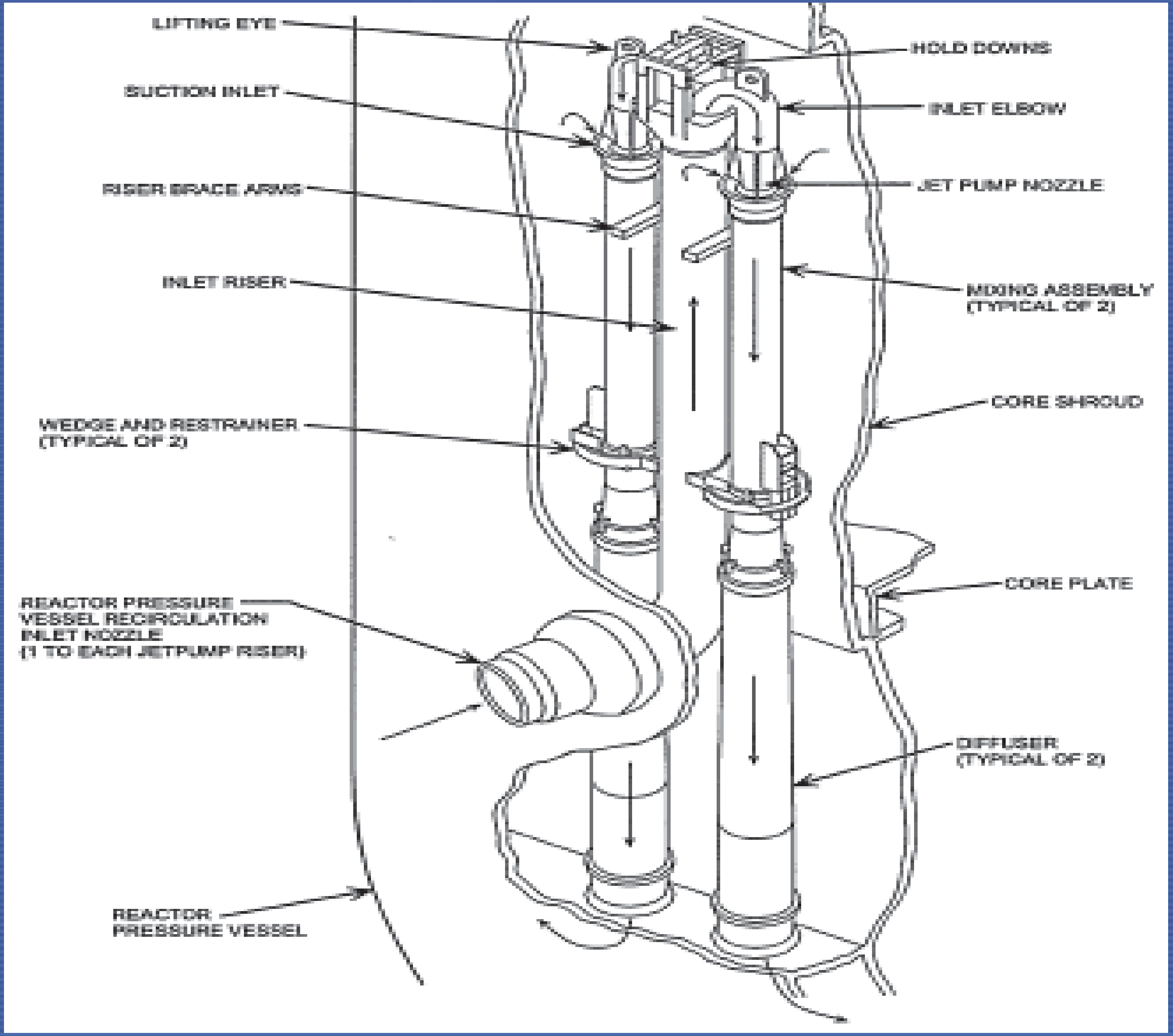
Courtesy of GE Hitachi Nuclear Energy





Internal Jet Pumps in earlier BWRs

Courtesy of GE Hitachi Nuclear Energy



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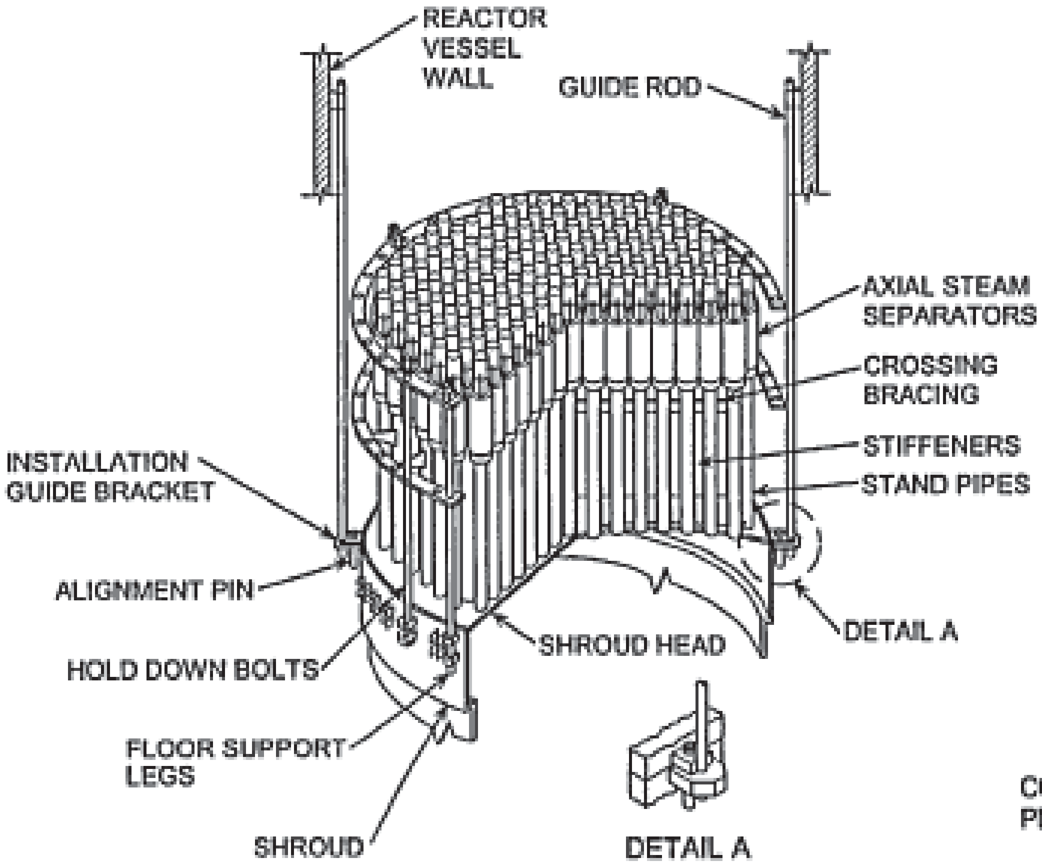
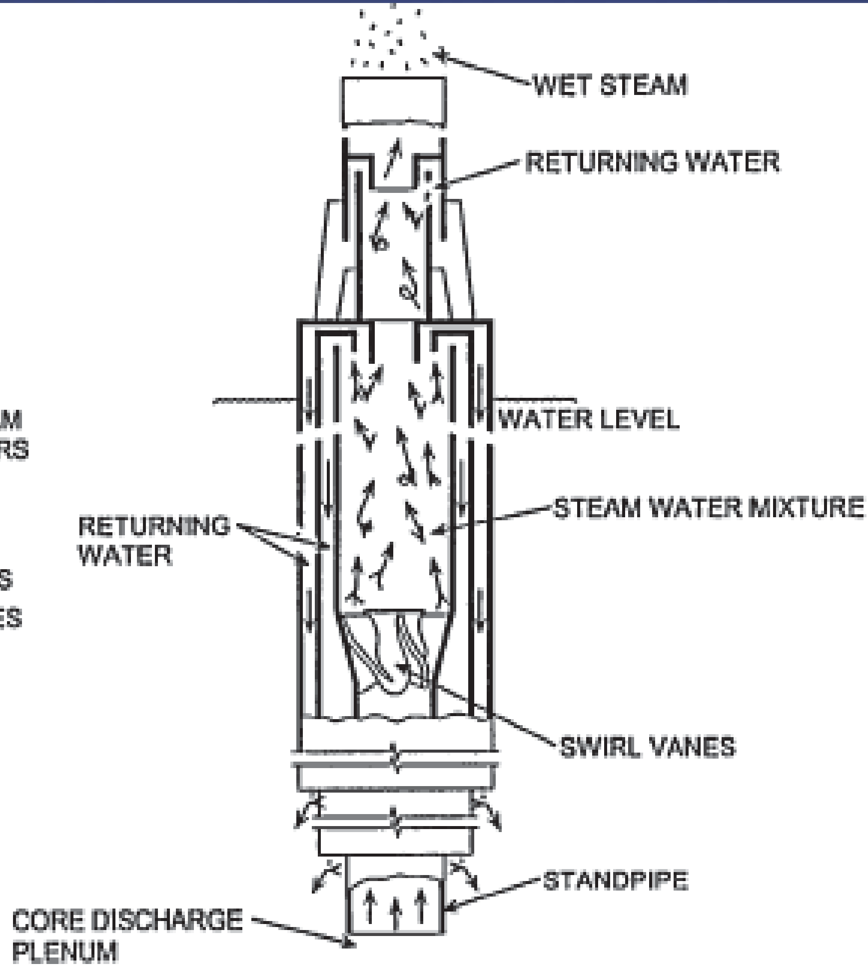
BWR Steam Separator Assembly

Courtesy of GE Hitachi Nuclear Energy

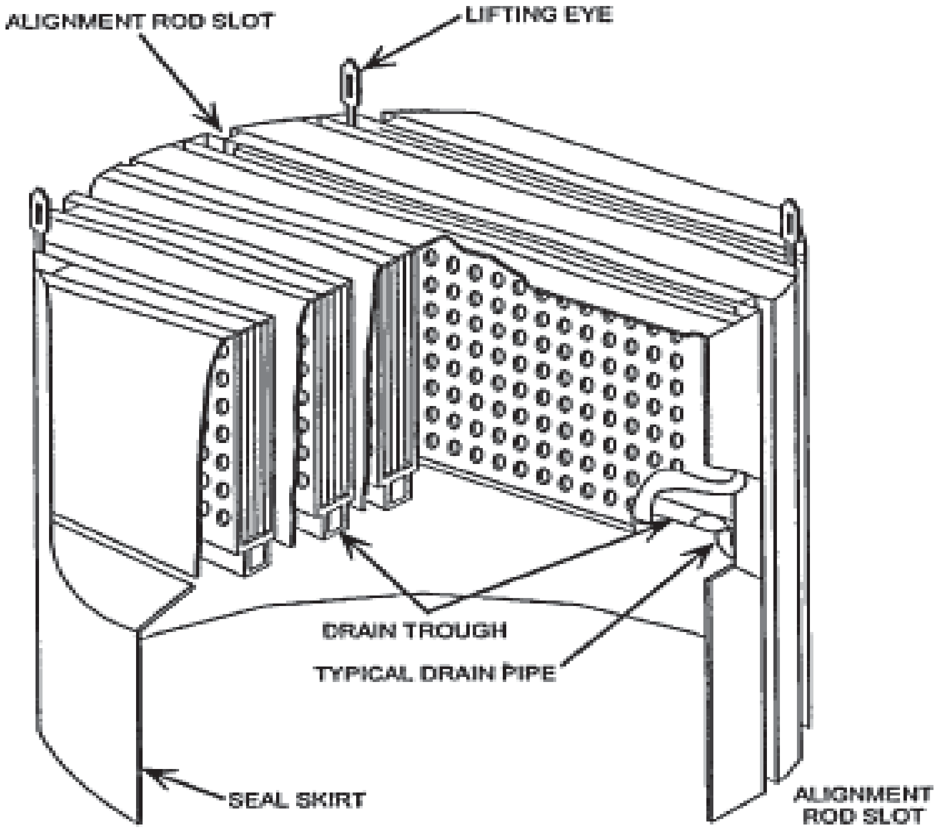


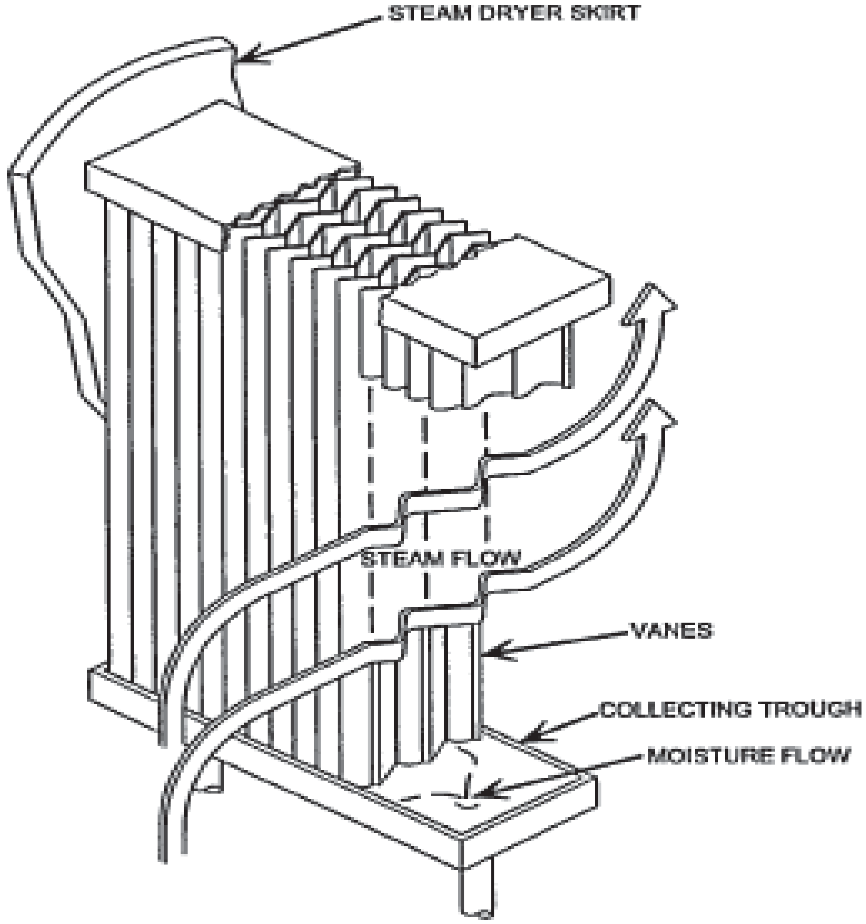


INDIVIDUAL STEAM
SEPARATOR

BWR Steam Dryer Assembly

Courtesy of GE Hitachi Nuclear Energy

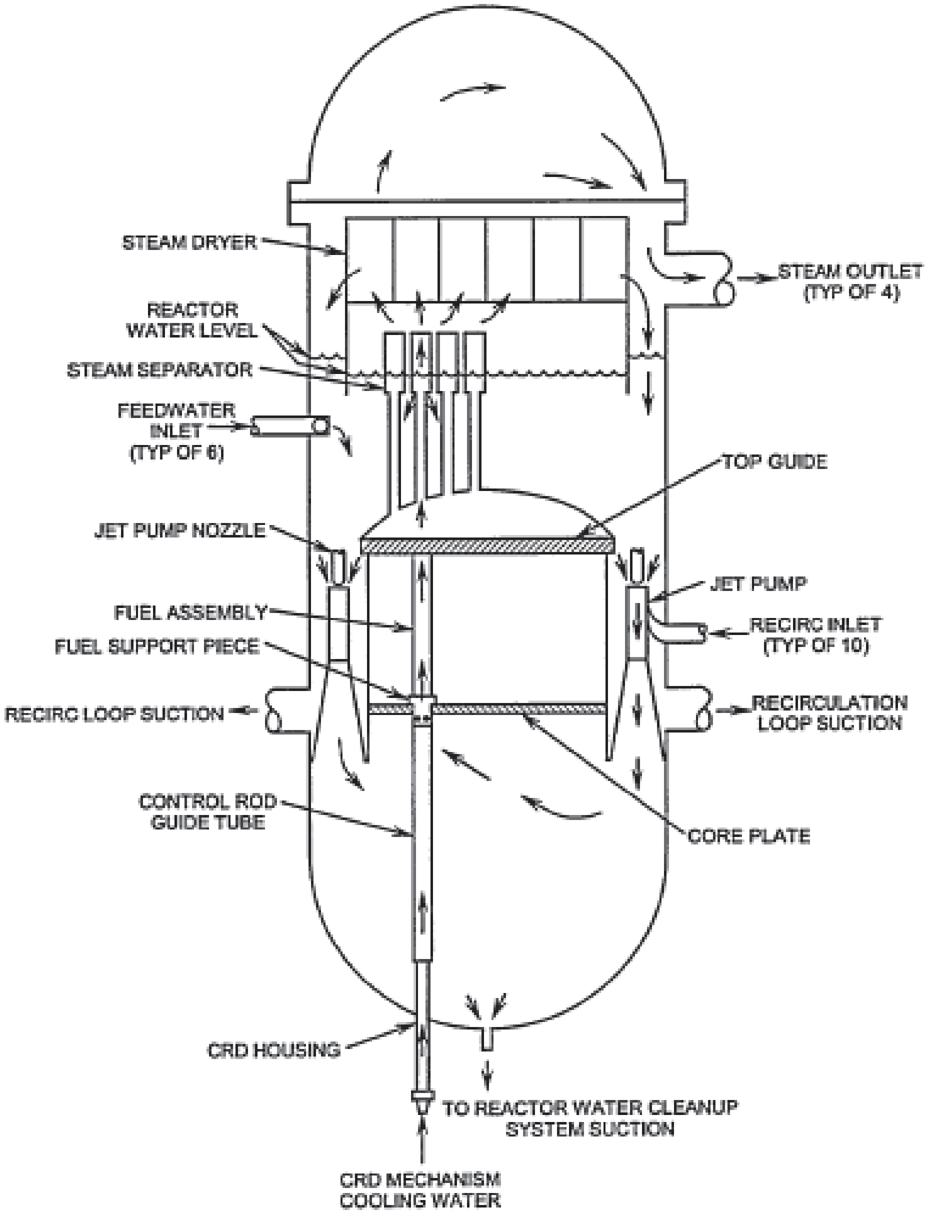


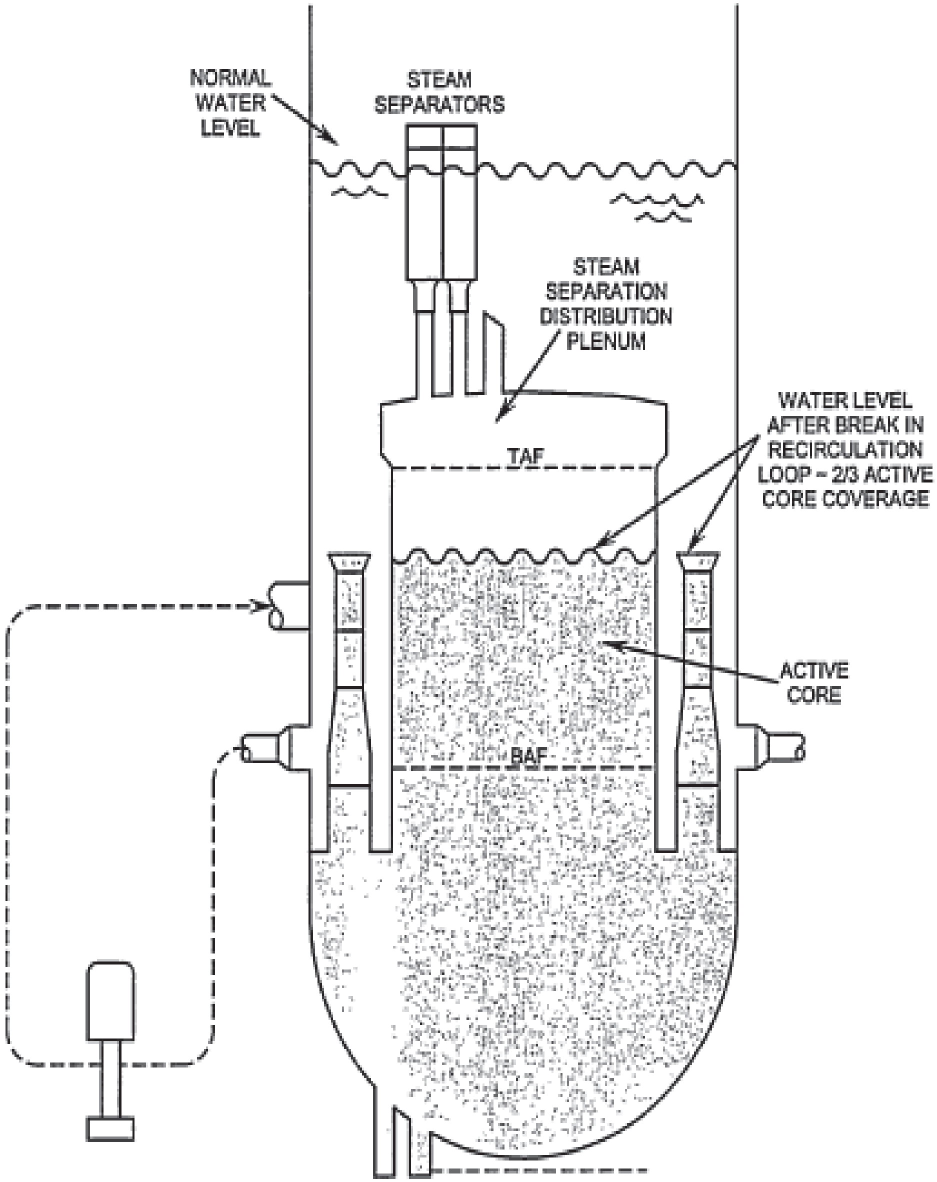


INDIVIDUAL DRYER PANEL

Flowpath inside BWR Reactor Vessel

Courtesy of GE Hitachi Nuclear Energy

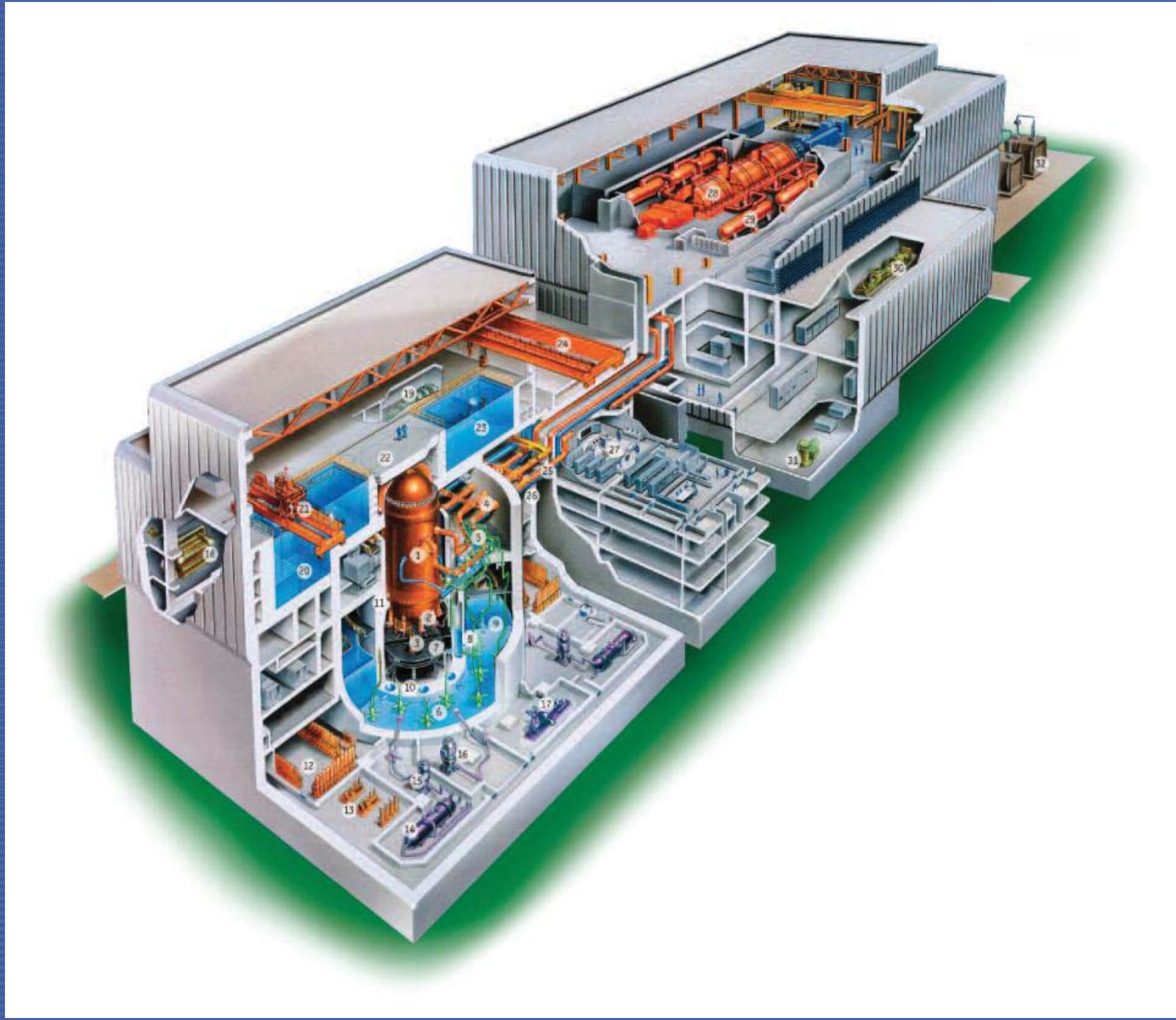




Advanced Boiling Water Reactor (ABWR)

Courtesy of GE Hitachi Nuclear Energy

- Originally by GE, then Hitachi & Toshiba
- Developed in response to URD
- First Gen III reactor to operate commercially
- Licensed in USA, Japan & Taiwan, China
- 1380 MWe - 1500 MWe
- Shorter construction time
- Standardized series
  - 4 in operation (Kashiwazaki-Kariwa -6 & 7, Hamaoka-5 and Shika-2)
  - 7 planned in Japan
  - 2 under construction in Taiwan, China
  - Proposed for South Texas Project (USA)



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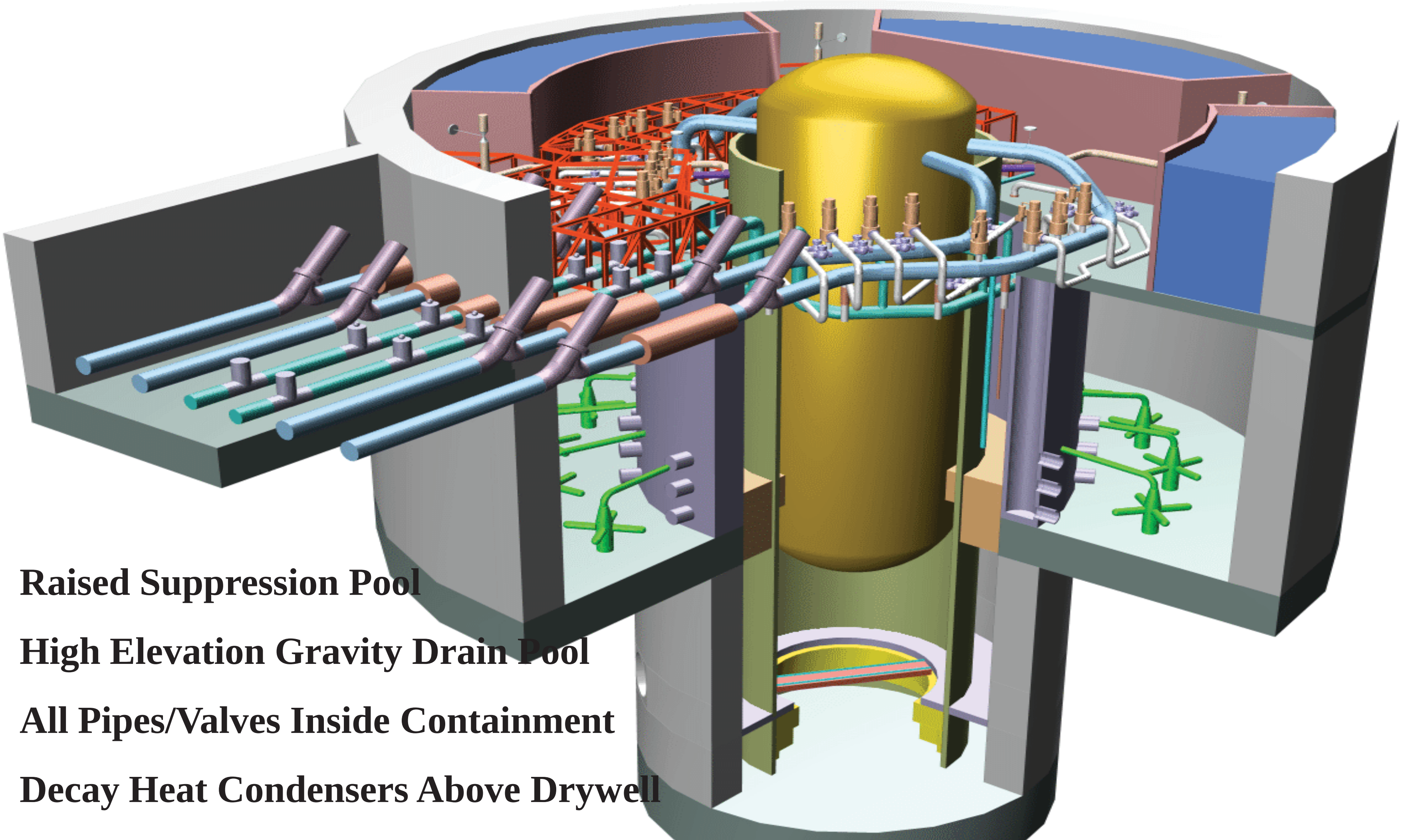
ESBWR Containment System

Courtesy of GE Hitachi Nuclear Energy



- Raised Suppression Pool
- High Elevation Gravity Drain Pool
- All Pipes/Valves Inside Containment
- Decay Heat Condensers Above Drywell

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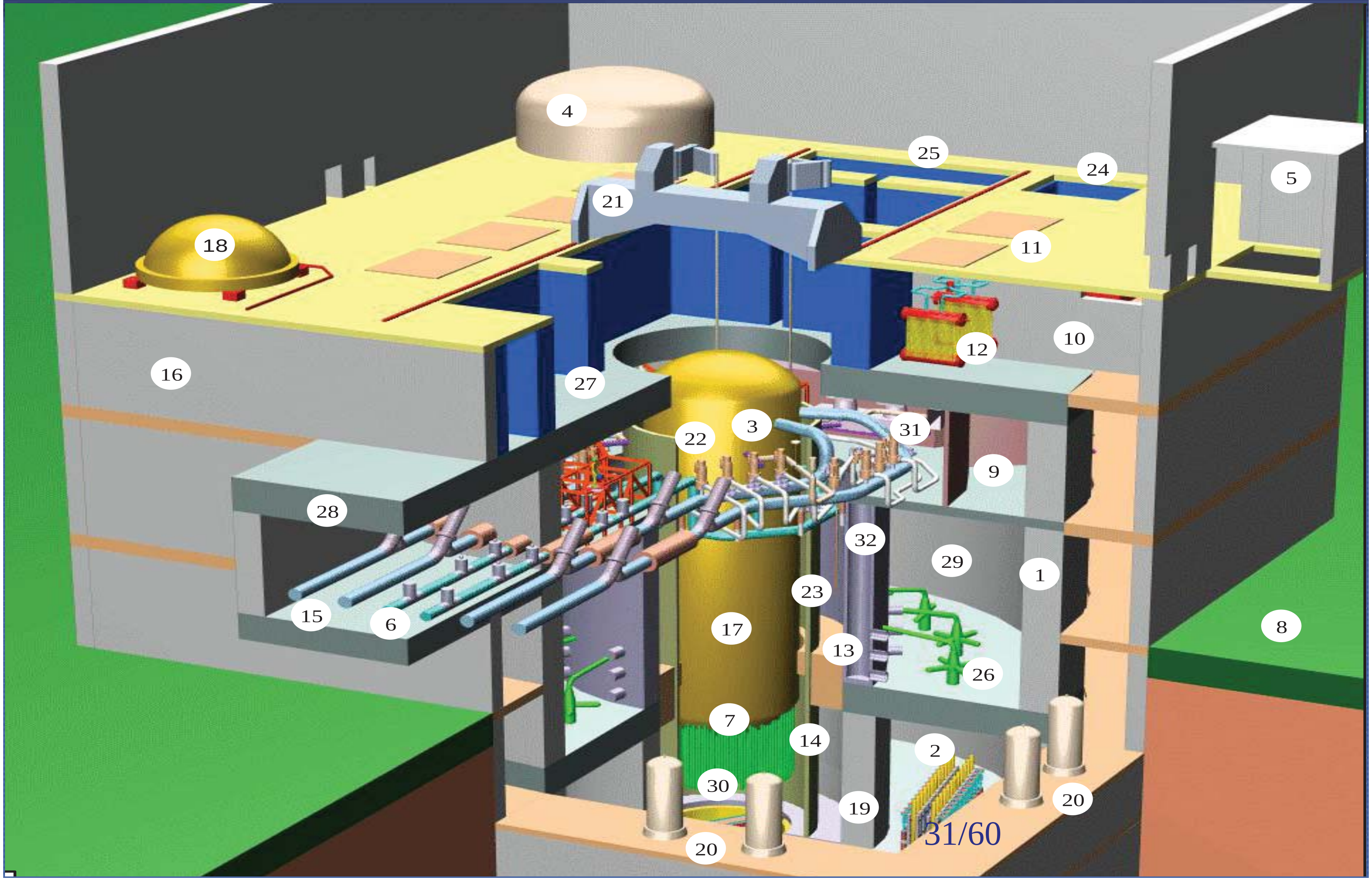
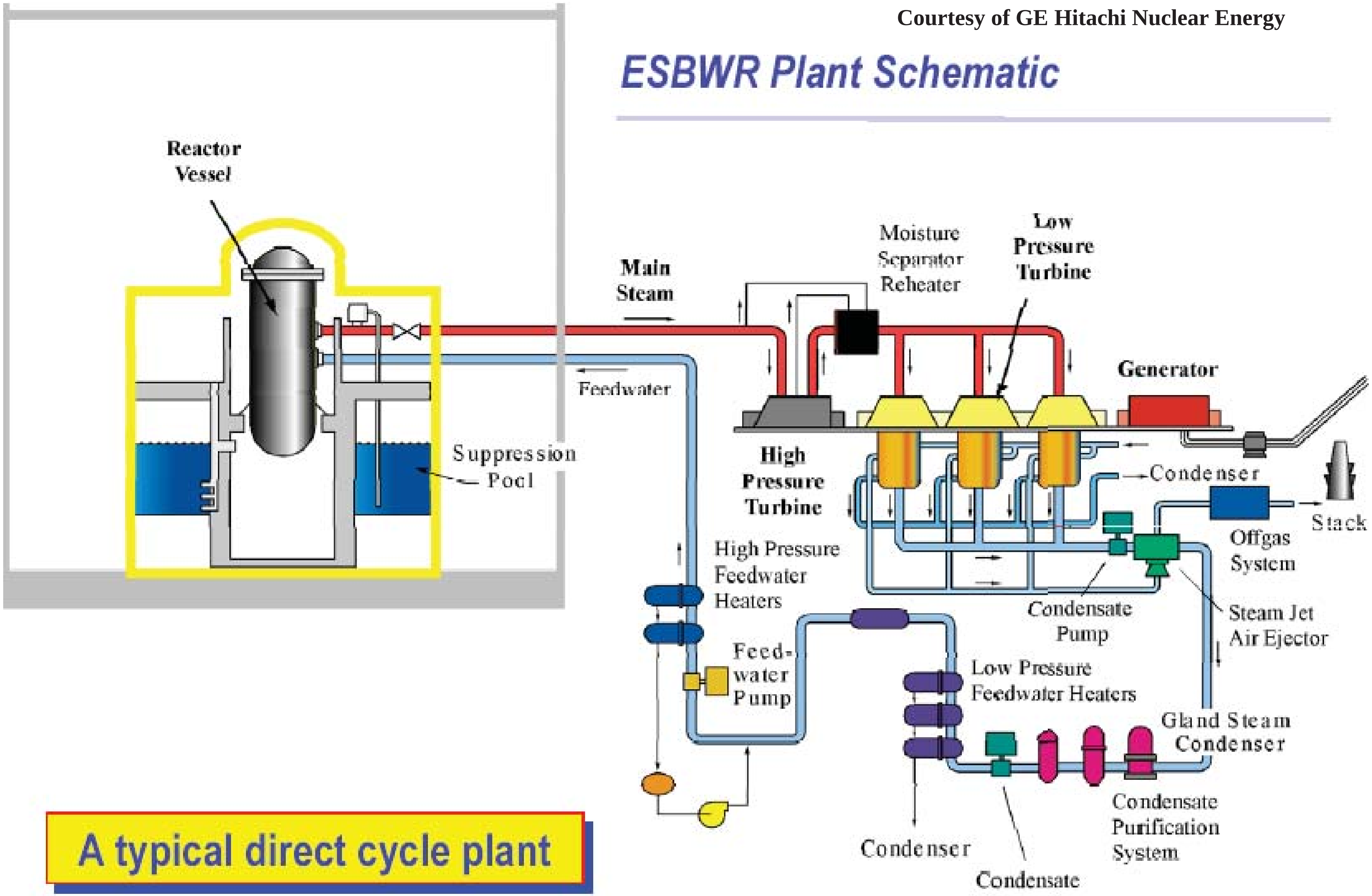
ESBWR Spent Fuel Storage Pool

Courtesy of GE Hitachi Nuclear Energy



Courtesy of GE Hitachi Nuclear Energy



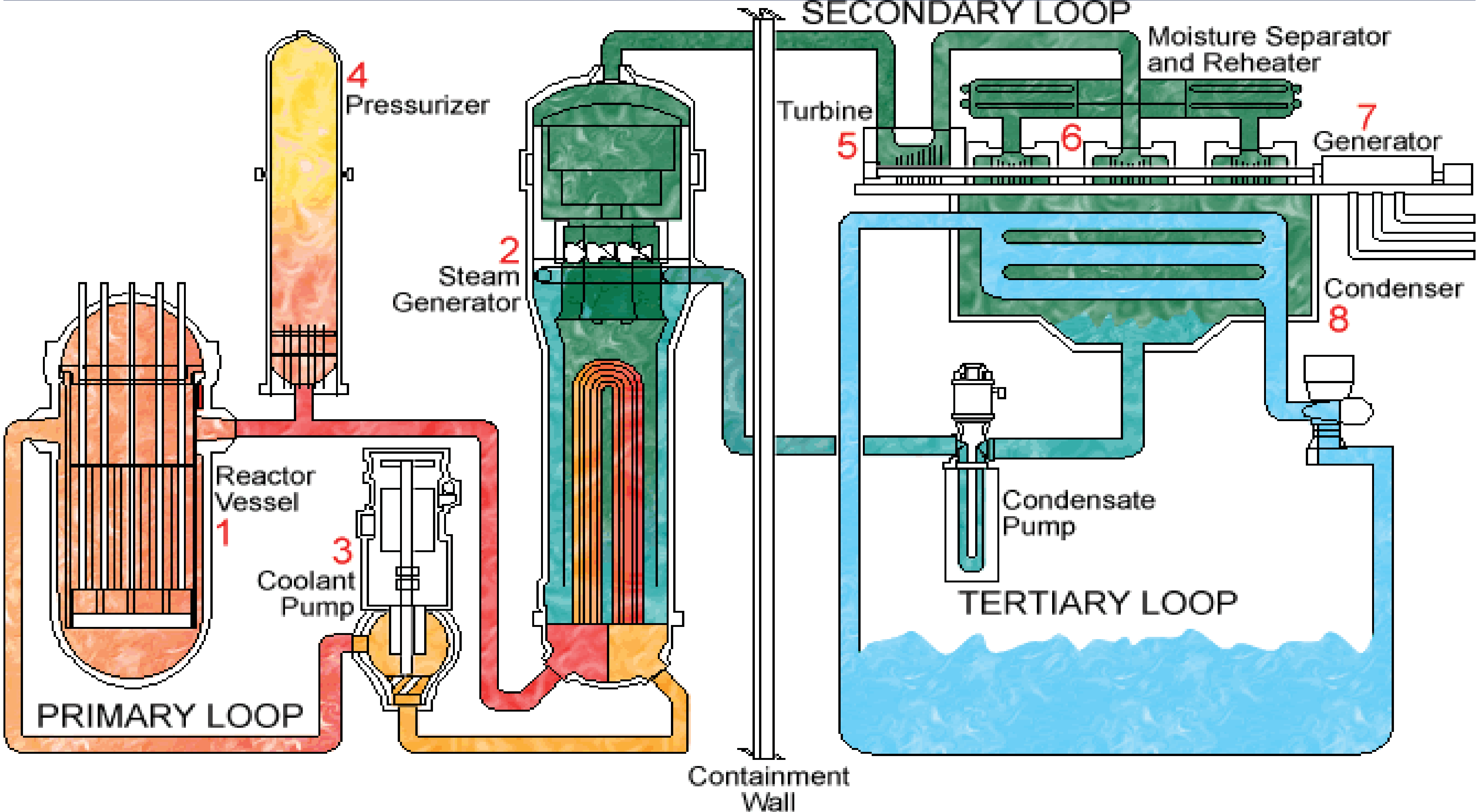
AR0103- 13

Courtesy of GE Hitachi Nuclear Energy

1. Containment
2. CRD HCU's
3. Depressurization Valve
4. Drywell Head (storage)
5. External Equipment Removal Hatch
6. Feedwater Lines
7. Fine-Motion Control Rod Drives (FMCRD)
8. Grade Level (variable elevation)
9. Gravity Driven Cooling System (GDCS) Pool
10. Isolation & Passive Cooling (IC/PCC) Pools
11. IC/PCC Pool Cover
12. Isolation Condenser
13. LOCA Vents
14. Lower Drywell
15. Main Steam Lines
16. Reactor Building
17. Reactor Pressure Vessel (RPV)
18. RPV Head (storage)
19. RPV Pedestal
20. Reactor Water & Shutdown Cooling System
21. Refueling Machine
22. Safety Relief Valves (SRV)
23. Shield Wall
24. Spent Fuel Cask Pit
25. Spent Fuel Storage Pool
26. SRV Quenchers
27. Steam Dryer/Separator Storage Pool
28. Steam Tunnel
29. Suppression Pool
30. Under vessel Servicing Platform
31. Upper Drywell
32. Vent Wall

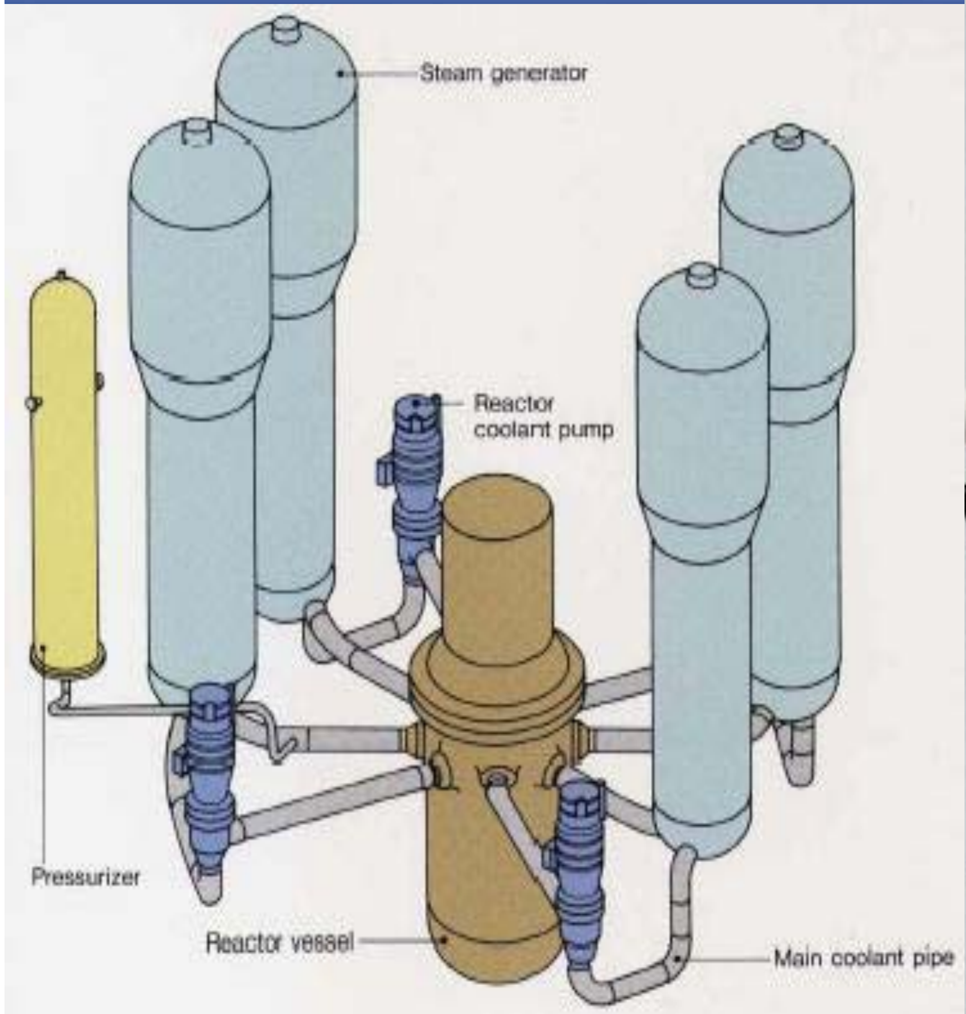
A Simplified 1380 MWe BWR

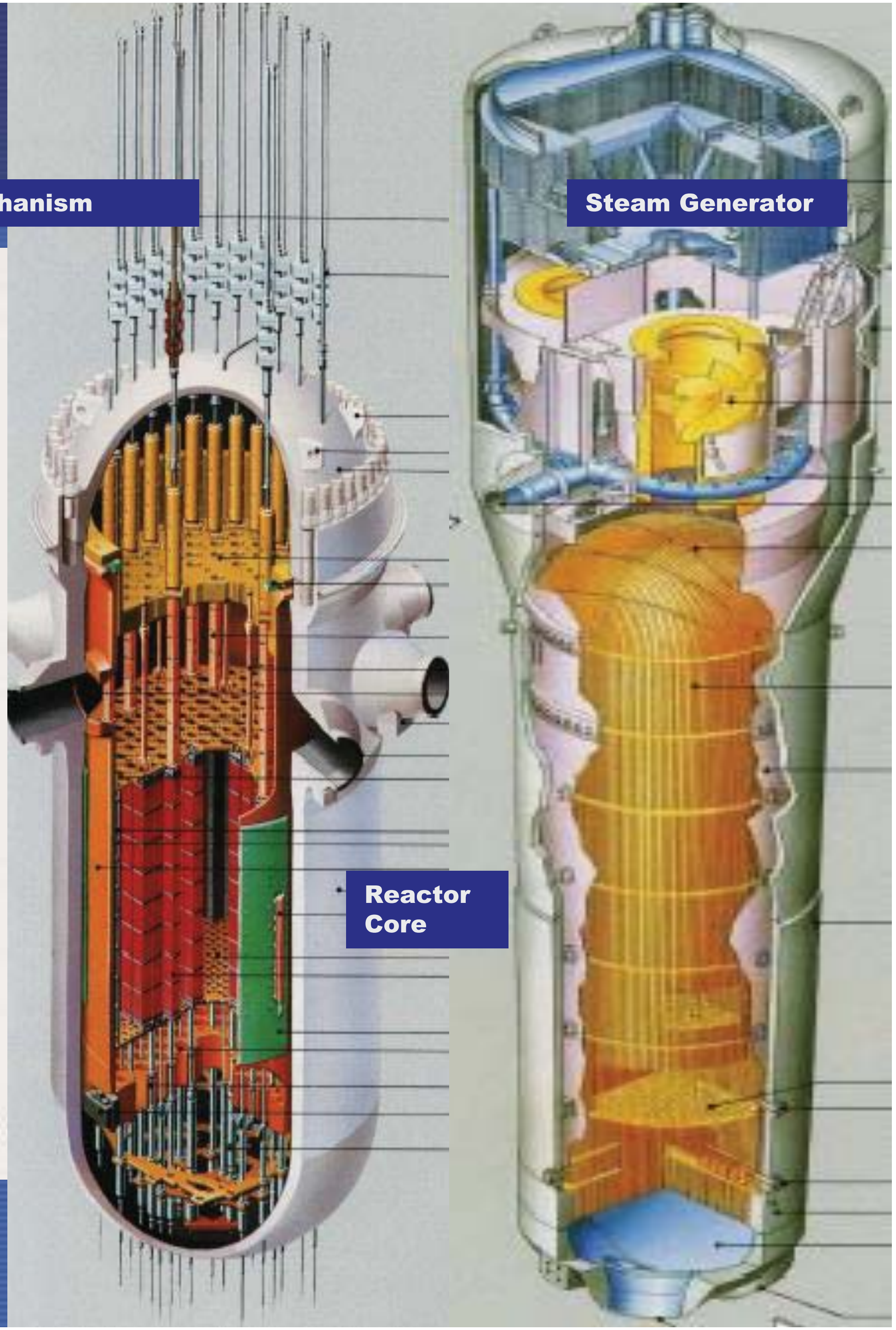
Typical PWR Plant Schematic



PWR Coolant System

Courtesy of Mitsubishi Heavy Industries

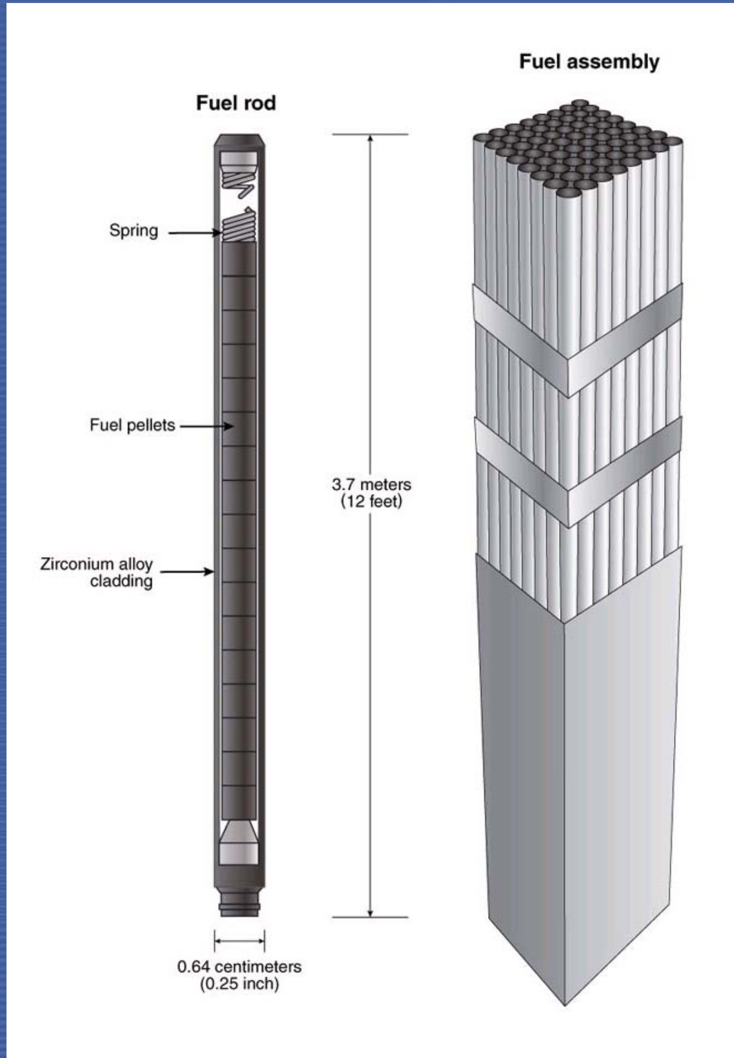




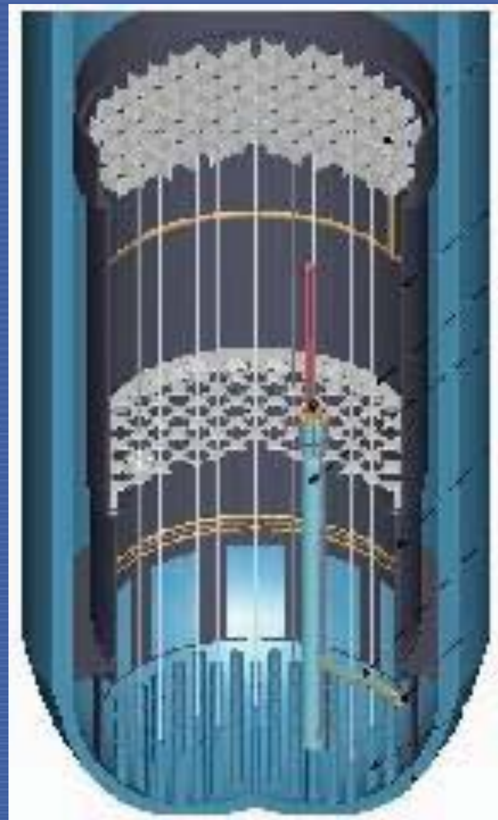
Typical Reactor Core

Fuel Pellet

Fuel Rod



Fuel Assembly



Reactor Core / Reactor Vessel

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The Westinghouse AP600

Description of PWR Reactor Coolant System

- **REACTOR VESSEL**

  The RV contains the core, fuel assembly and internal structure designed and fabricated in compliance with a high standard to endure high operational pressure and temperature, also various stresses during plant life time of 60 years.
- **STEAM GENERATOR**

  High-quality steam is generated in the shell side of secondary circuit. The steam is used to rotate the turbine that in turns rotate the electric generator. The SG also is used to remove the residual heat after reactor shutdown.
- **REACTOR COOLANT PUMP**

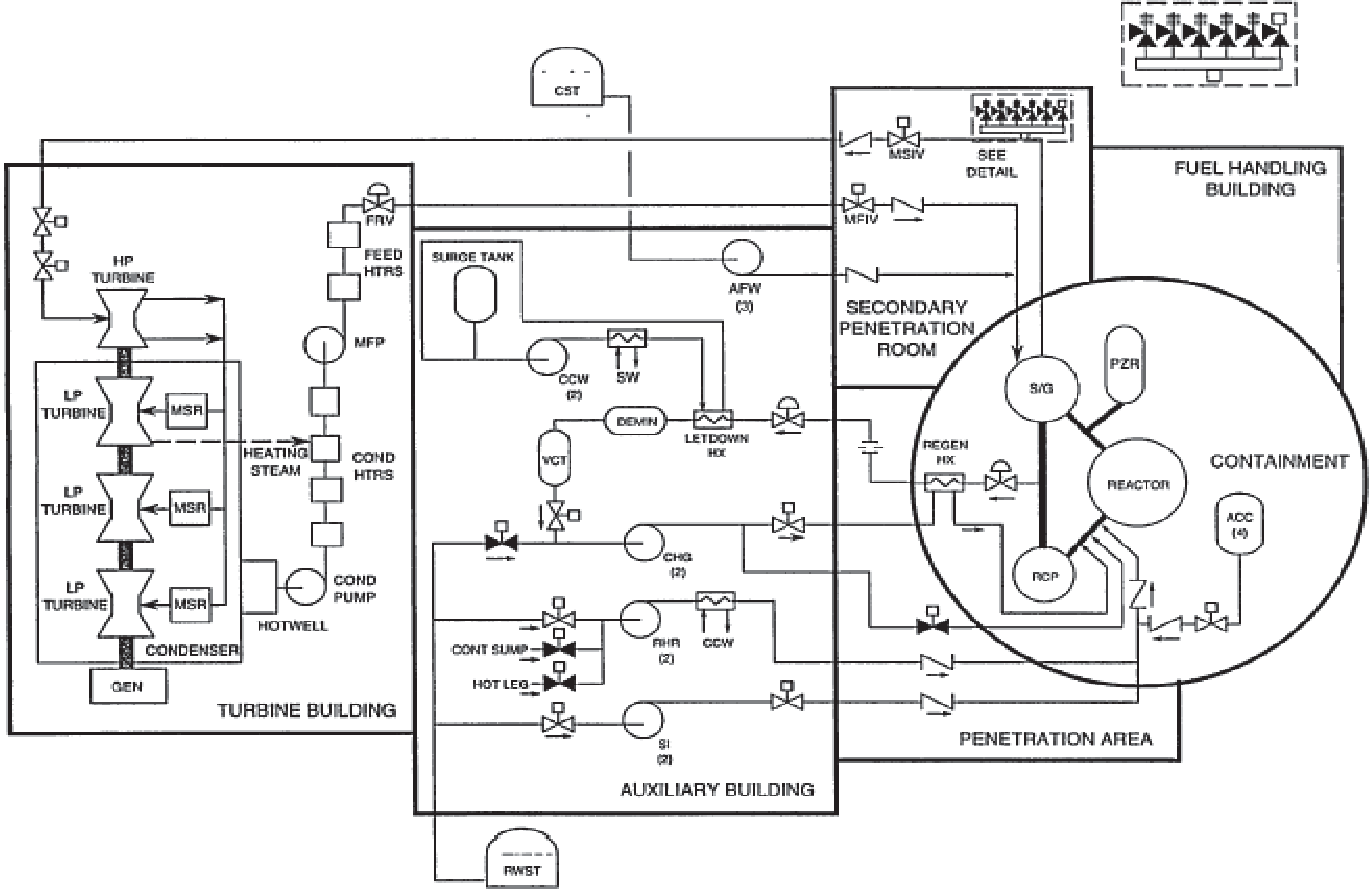
  The RCP circulates the coolant to remove heat from the fuels in the core.
- **PRESSURIZER**

  The pressurizer is connected to one of the loops in the primary circuit. Its main function is to control and maintain system pressure using electrical heater and water spray.
- **MAIN COOLANT PIPE**

  The main coolant pipe is connected with the primary circuit to enable the closed-loop connection for the coolant recirculation.

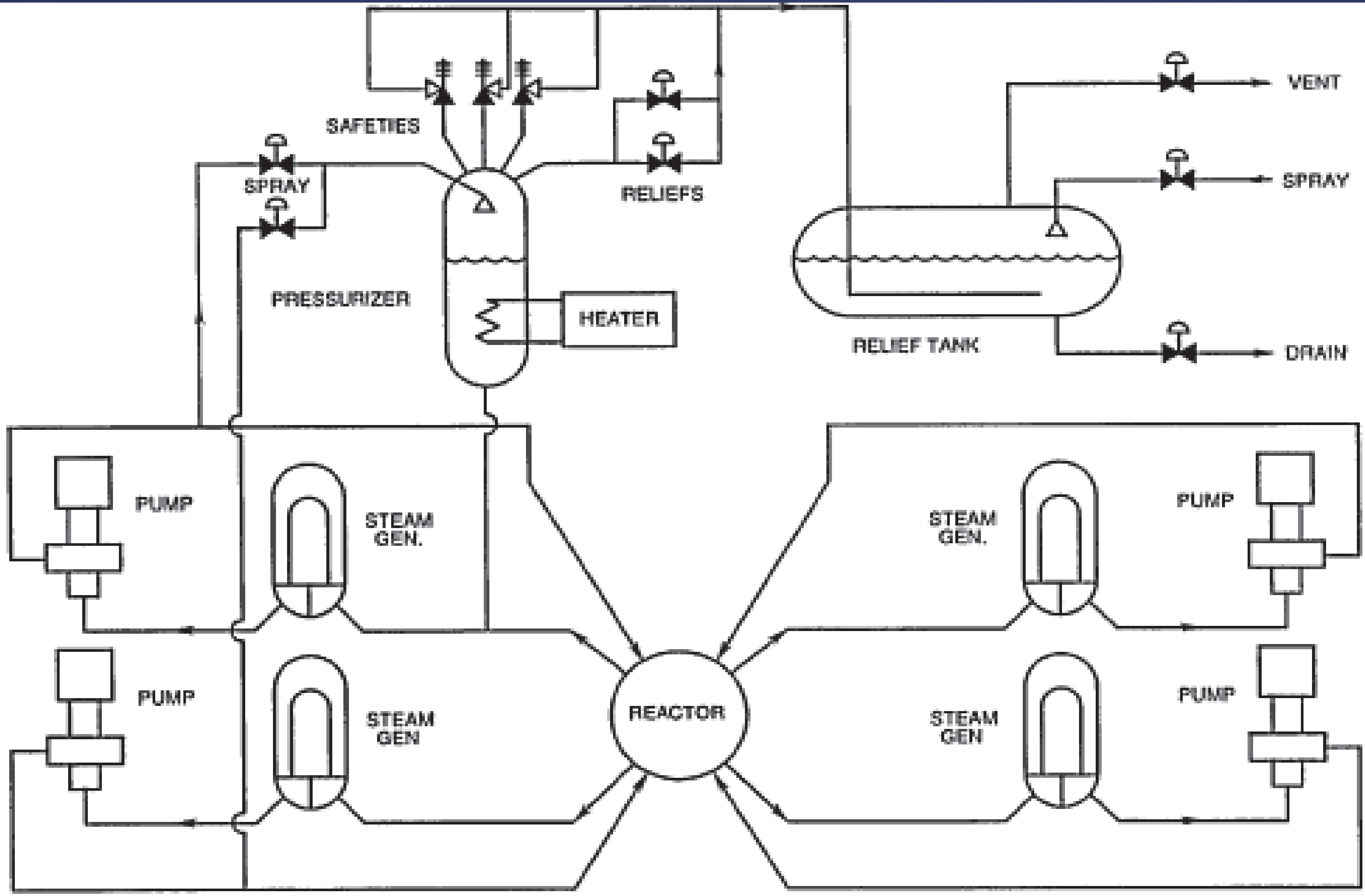
Typical 2-Loop PWR Schematic

Courtesy of Westinghouse



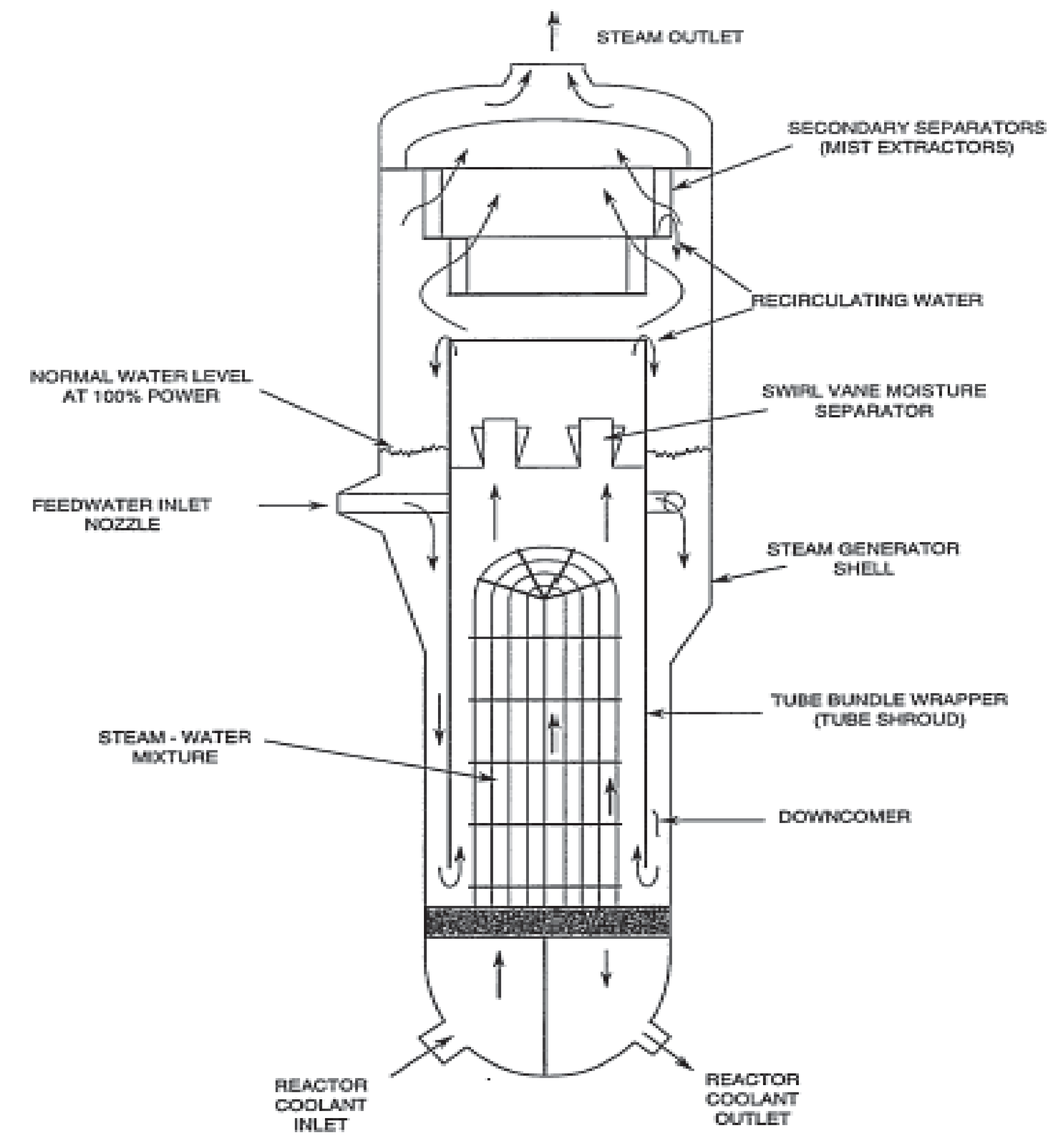
PWR Reactor Coolant System Diagram

Courtesy of Westinghouse



Coolant Flowpath inside the Steam Generator

Courtesy of Westinghouse



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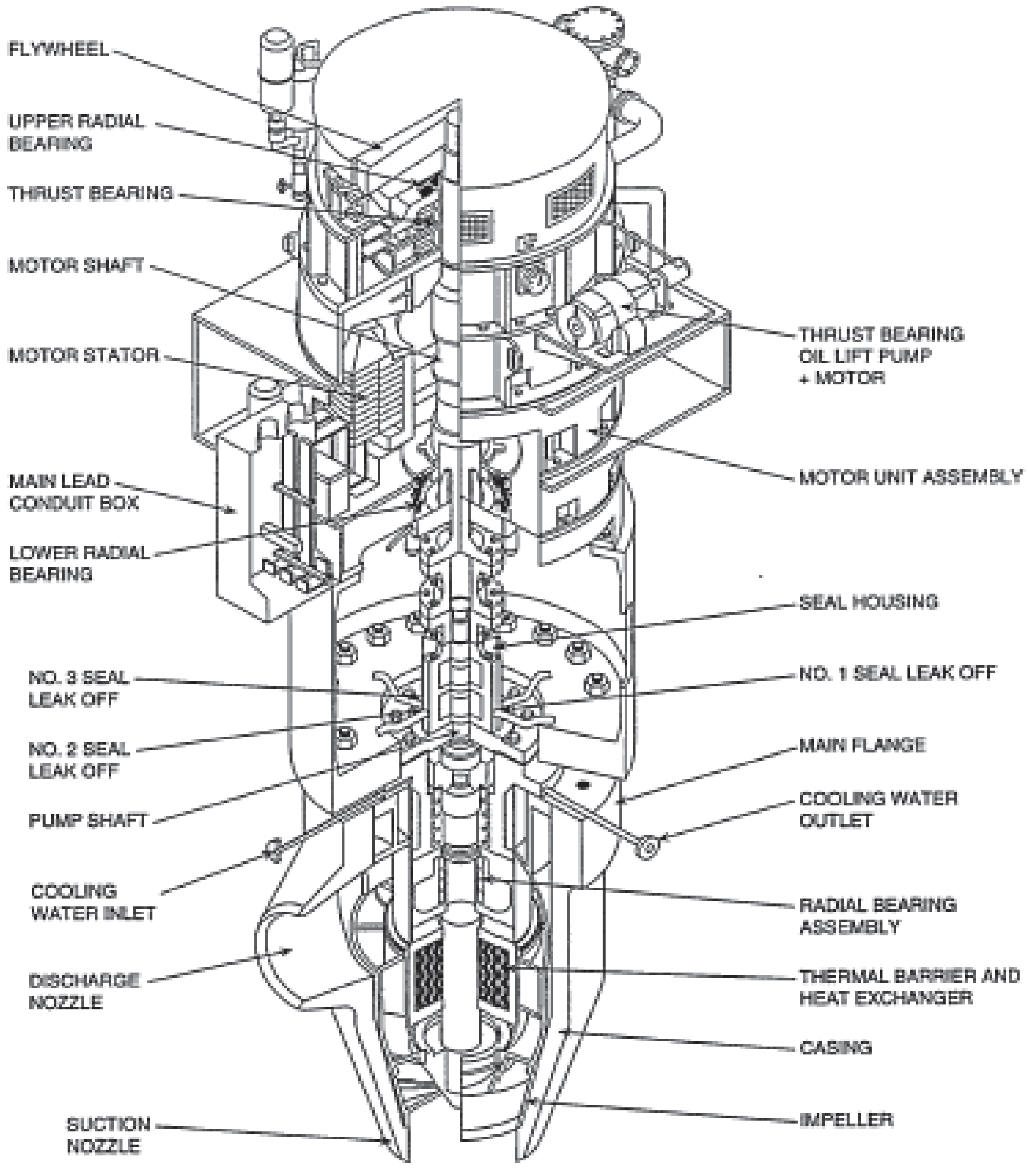
Reactor Coolant Pump

Courtesy of Westinghouse



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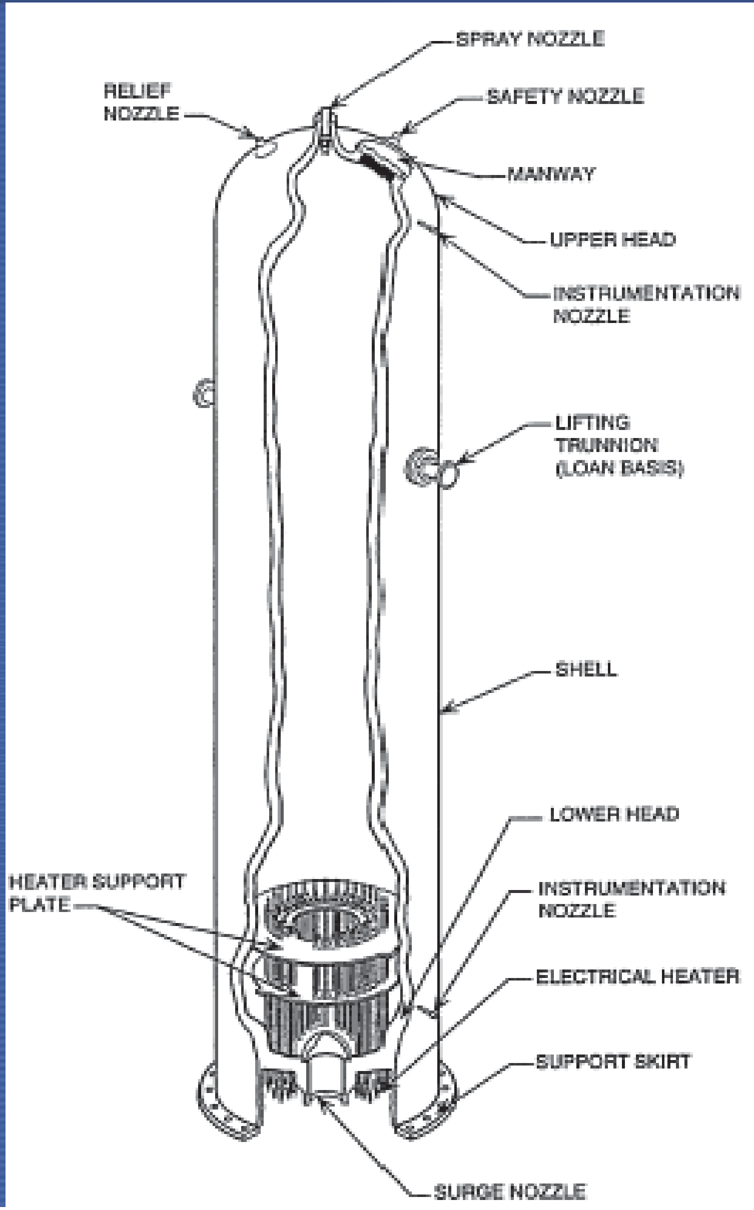
Pressurizer

Courtesy of Westinghouse



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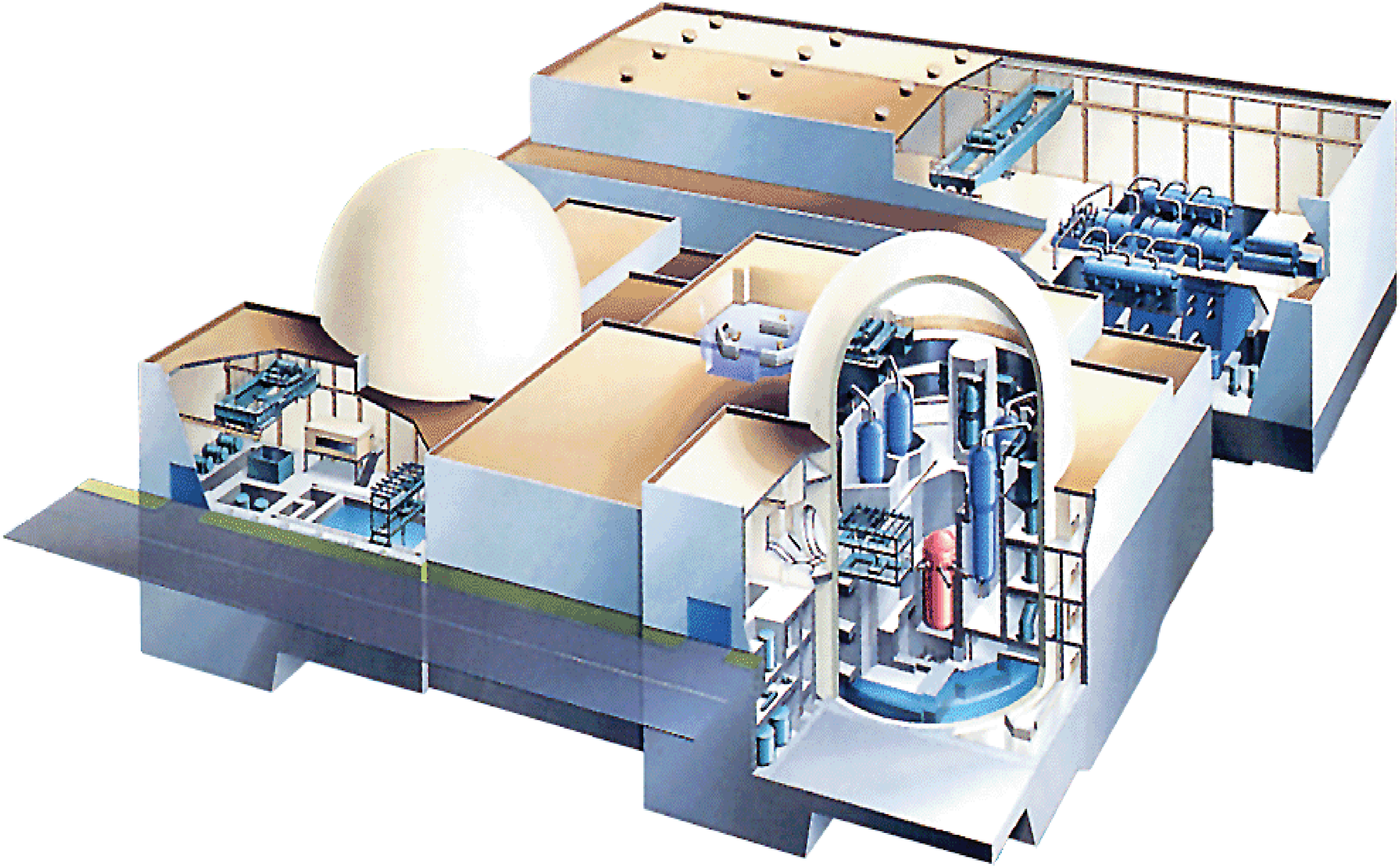
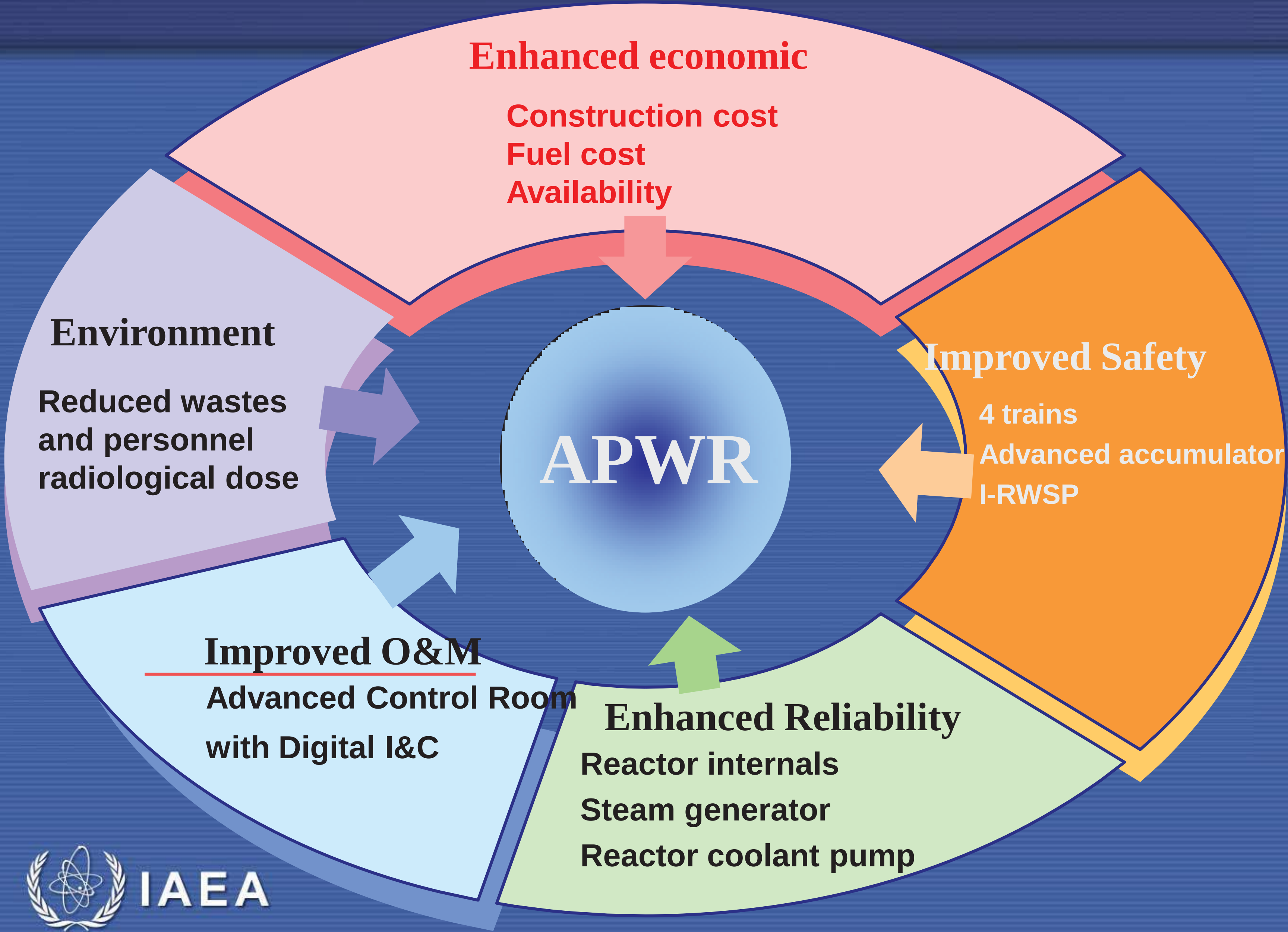
Advanced Pressurized Water Reactor

Courtesy of Mitsubishi Heavy Industries



APWR Design Characteristics



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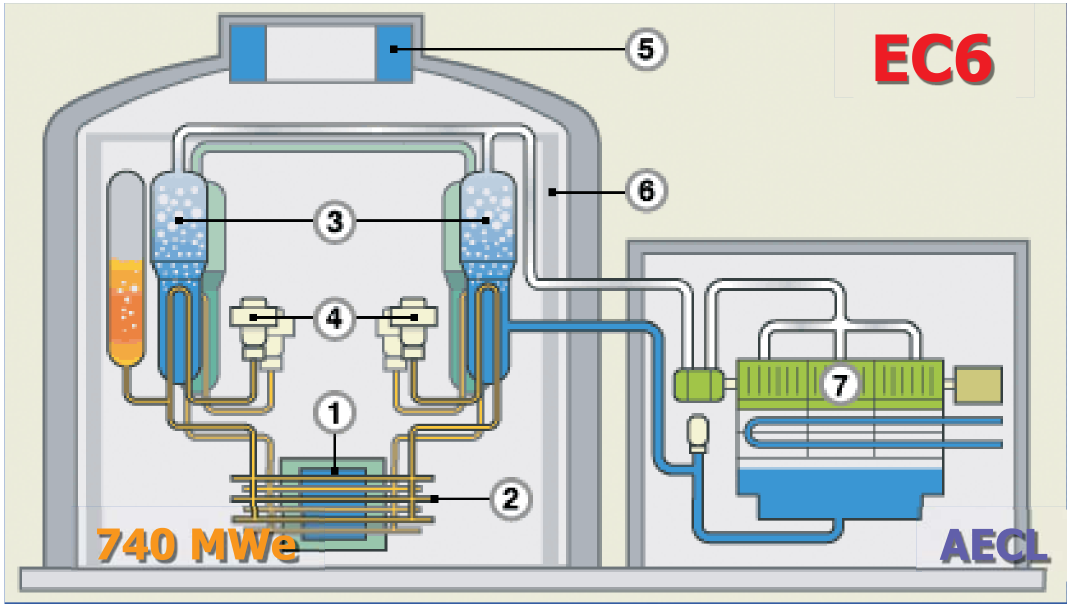
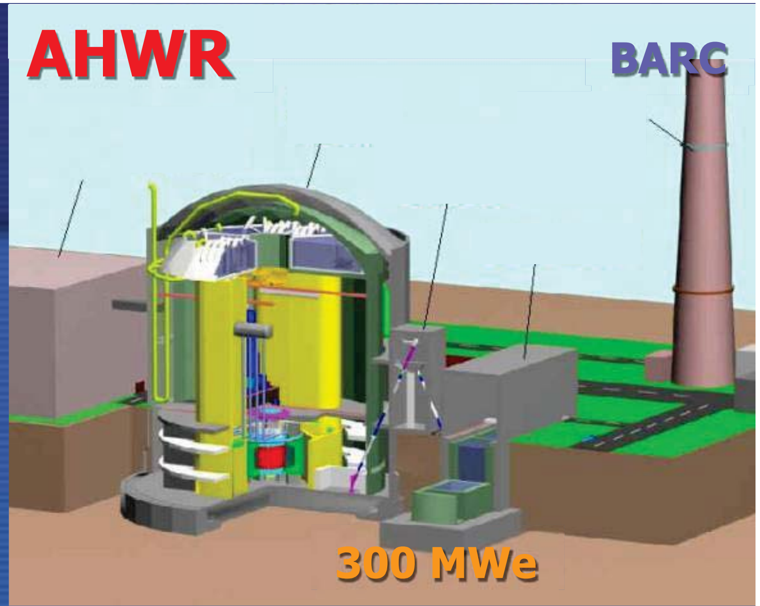
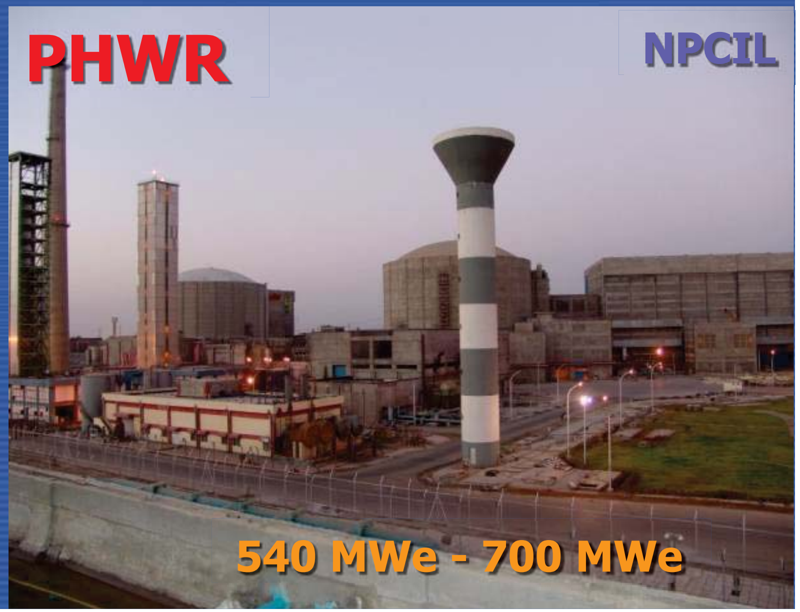
APWR Technical Specification

ITEM		APWR	Current 4 Loop
Main Specifications	Electric Output	1,538 MWe	1,180 MWe
	Core Thermal Output	4,451 MWt	3,411 MWt
	Fuel Assembly Type, Number	17×17, 257	17×17, 193
	Radial Core Support	Neutron Reflector	Baffle/Former
	SG heat transfer area	6,500 m^2	4,879 m^2
	Coolant Flow	25,800 m^3 /h/loop	20,100 m^3 /h/loop
	Engineered Safety Features	4 Divisions	2 Divisions
	Steam Turbine	TC6F54	TC6F44
	I & C	Full-Digital	Digital (Partially)
Reliability / Safety	Design Life Time	60 years	40 years
	Core Damage Frequency	approx.1/10	Base
Operation / Maintenance	Occupational Dose	0.2 man SV/y	0.4 – 5 man SV/y
	Radioactive Waste	60 Drums/y	140 Drums/y
	Min. Operators in MCR	1	2
Uranium Saving	MOX Loading	1 / 3 – 1 / 1 Core	1 / 4 – 1 / 3 Core
Economy	Primary build.volume /KWe	20 %less	Base

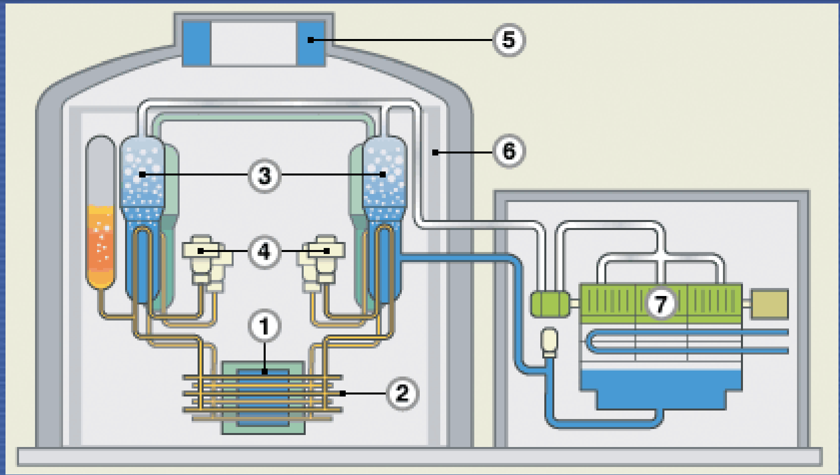




Heavy Water Reactors (HWR)



ACR-700 & ACR-1000



- AECL
- 740 MWe Enhanced CANDU-6
- 1000 MWe Advanced CANDU reactor
- 284 / 520 horizontal channels
- Low enriched uranium– 2.1%,
- 60 yr design life
- Continuous refueling
- Combination of active and passive safety systems
- CNSC has started “pre-project” design review
- Energy Alberta has filed *an Application for a License to Prepare Site* with the CNSC -- for siting up to two twin-unit ACR-1000s --- commissioning by ~2017
- 30 CANDU operating in the world
  - 18 Canada (+2 refurbishing, +5 decommissioned)
  - 4 South Korea
  - 2 China
  - 2 India (+13 Indian-HWR in use, +3 Indian-HWR under construction)
  - 1 Argentina
  - 2 Romania (+3 under construction)
  - 1 Pakistan

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India's HWR

- 540 MWe PHWR [evolution from current 220 MWe HWRs]
  - Nuclear Power Corporation of India, Ltd.
  - First units: Tarapur-3 & -4 connected to grid (2005 & 6)
- 700 MWe PHWR [further evolution – economy of scale]
  - NPCIL
  - Regulatory review in progress
  - Use of Passive Decay Heat Removal System; reduced CDF from PSA insights
  - Better hydrogen management during postulated core damage scenario
  - First units planned at Kakrapar & Rawatbhata

- 300 MWe Advanced HWR
  - BARC
  - for conversion of Th232 or U238 (addressing sustainability goals)
  - vertical pressure tube design with natural circulation

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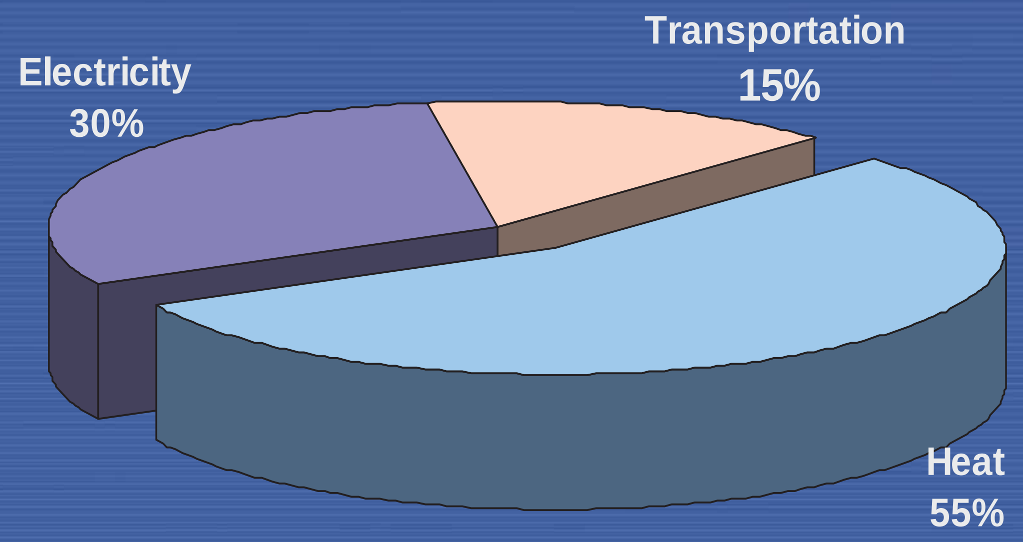
The potential for non-electric applications of nuclear energy is large



Energy consumption by application

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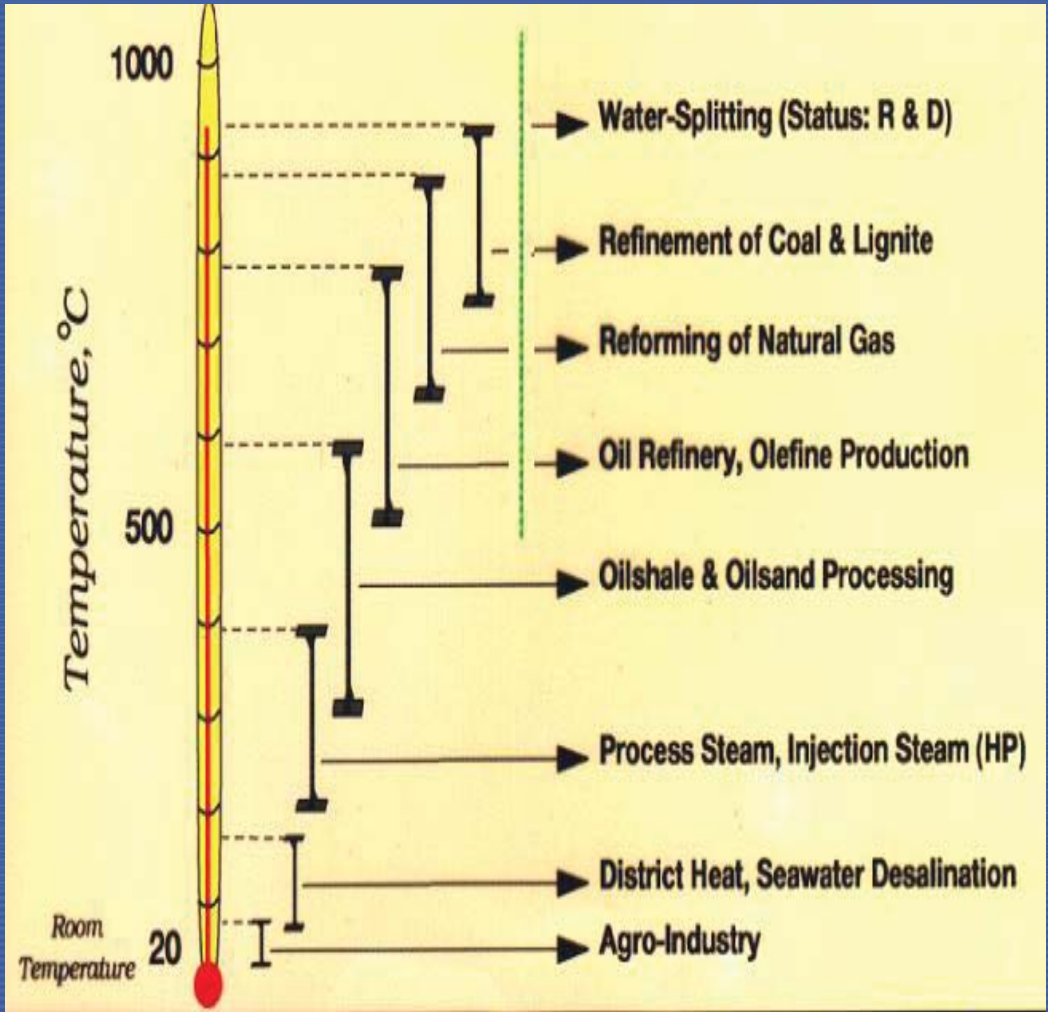
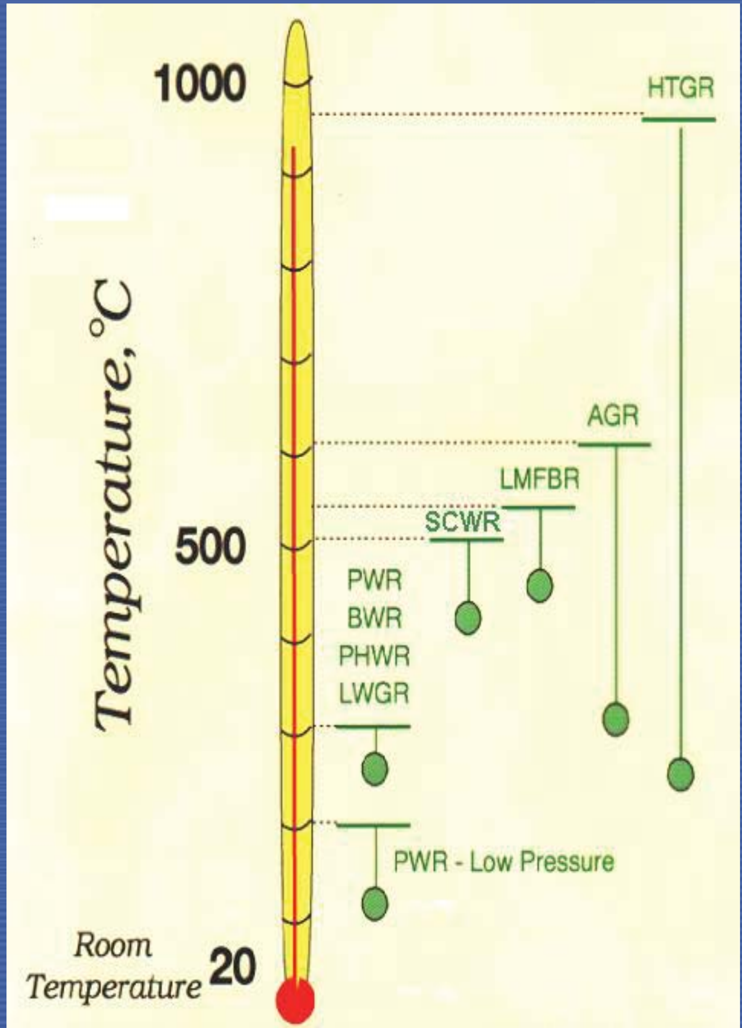
Advanced Applications of Nuclear Energy

- Sea-water desalination
- District heating
- Heat for industrial processes
- Hydrogen production
  - At "fuelling stations" by water electrolysis
  - At central nuclear stations by
    - high temperature electrolysis
    - thermo-chemical processes
    - hybrid processes
- Coal gasification
- Enhanced oil recovery (e.g. from oil shale and tar sands)
- Electricity for Plug-in Hybrid Vehicles

Nuclear Plants Can Provide the Heat Required for Many Processes





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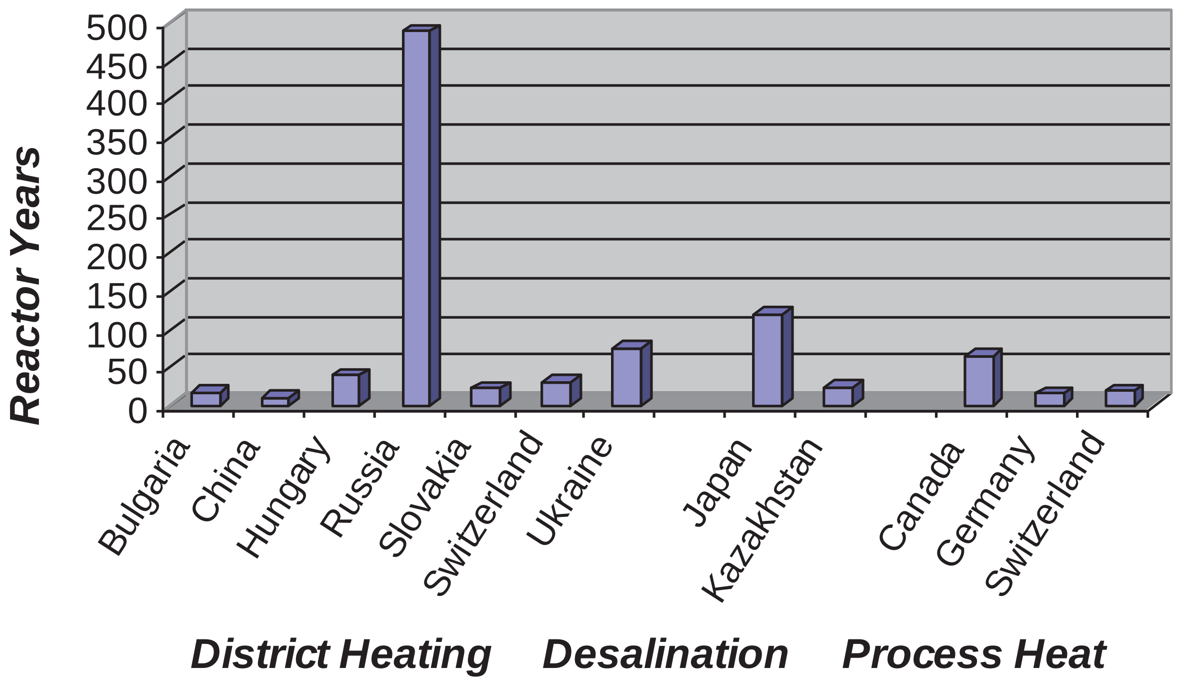
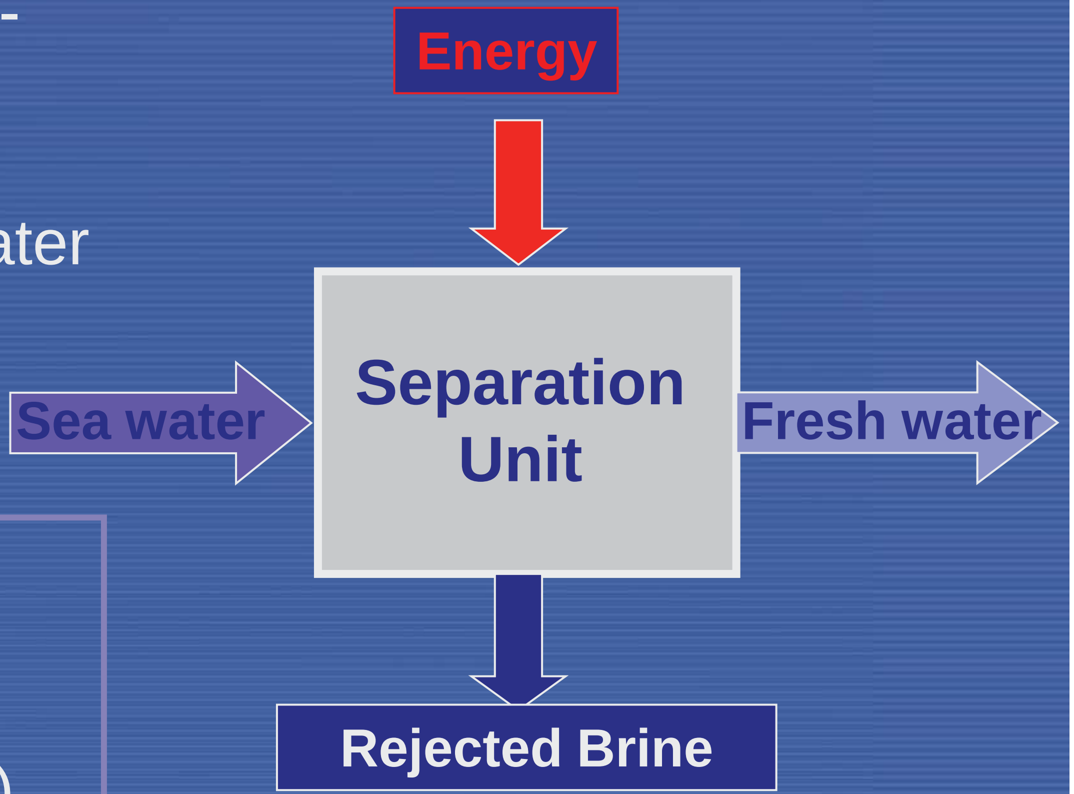
Non-Electrical Applications

- As of December 2010 443 NPPs in operation worldwide
- 30 are being used for cogeneration (about 5 GW(th))
- About 700 reactor-years of experience



Desalination

Fully developed to a large-scale commercial process providing 38 Million m^3/d of fresh water in 120 countries



Distillation

Multi-stage flash (MSF)

Multi effect (MED)

Vapor compression (TVC)

Membrane separation

Reverse osmosis (RO)

Reactor Types and Desalination Processes

Reactor type	Location	Capacities (cu.m./d)	Status
LMFR	Kazakhstan (Aktau)	80,000	in service till 1999
PWRs	Japan (Ohi, Takahama, Ikata, Genkai) Rep. of Korea Argentina Russia	1,000 – 2,000 40,000 12,000	in service with operating experience of over 125 reactor-years under design under design (floating unit)
BWR	Japan (Kashiwazaki)		never in service following testing in 1980s, due to alternative freshwater sources; dismantled in 1999
PHWR	India (Kalpakkam) Canada Pakistan (KANUPP)	6,300 4,800	under commissioning under design under design
NHR	China		under design
HTGR	South Africa, France, The Netherlands		under consideration

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Hydrogen production using nuclear power

- High Temperature Electrolysis (up to ~ 1000ºC).
- Sulfur-based thermo-chemical cycles for water splitting:
  - Using Sulfur- Iodine cycle (needs about 900ºC)
  - Hybrid Sulfur cycle (i.e. Electrolysis and Thermo-Ch)
  - Lower temperature processes are under consideration
- Steam reforming of methane (600-800ºC)

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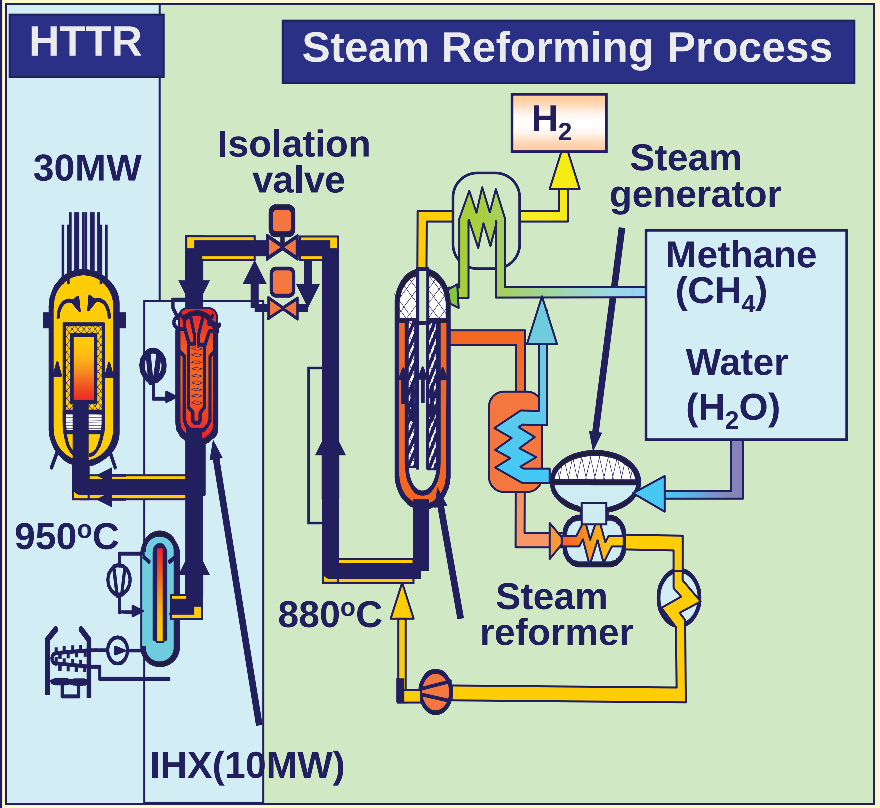
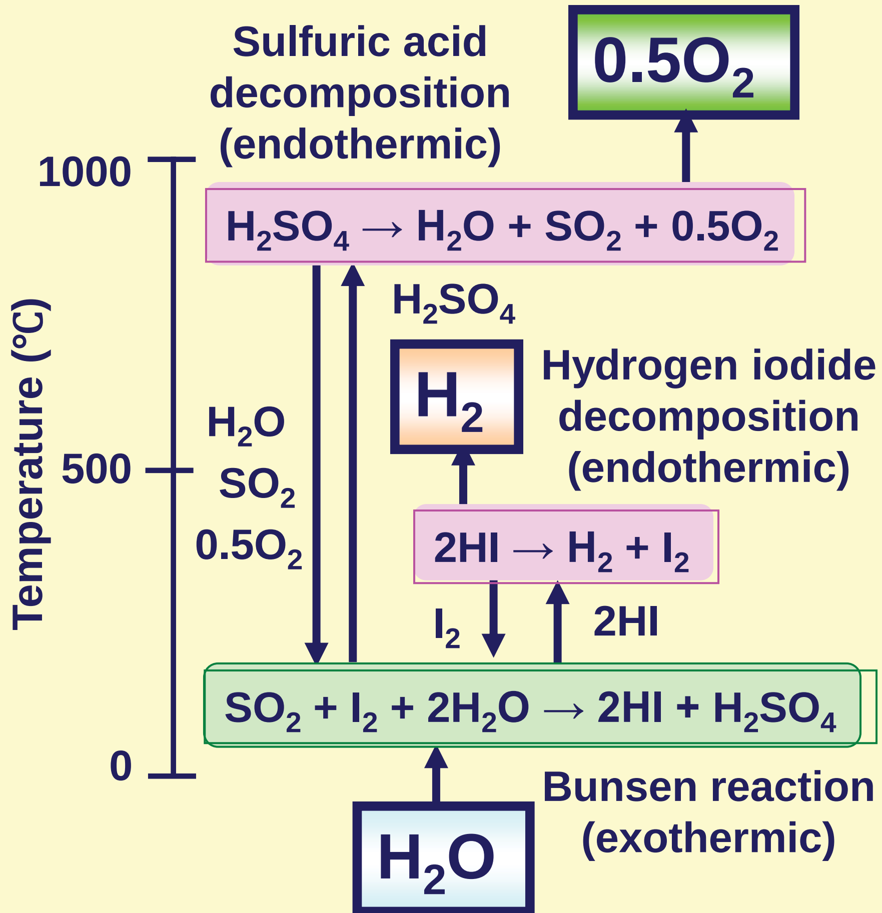
Hydrogen Production Systems

Steam Reforming Process



$$CH_4 + H_2O \rightarrow 3H_2 + CO$$

IS Process



ENERGY FOR TRANSPORTATION

- Transportation
  - 15 - 20% of the world's energy consumption
  - fastest growing energy sector
- If nuclear would power part of this sector, it could significantly impact global environmental sustainability
- Two examples:
  - Electricity
    - for plug-in hybrid electric vehicles (very near term)
    - For electric transportation systems (Trains; subways,…)
  - Hydrogen fuelled vehicles

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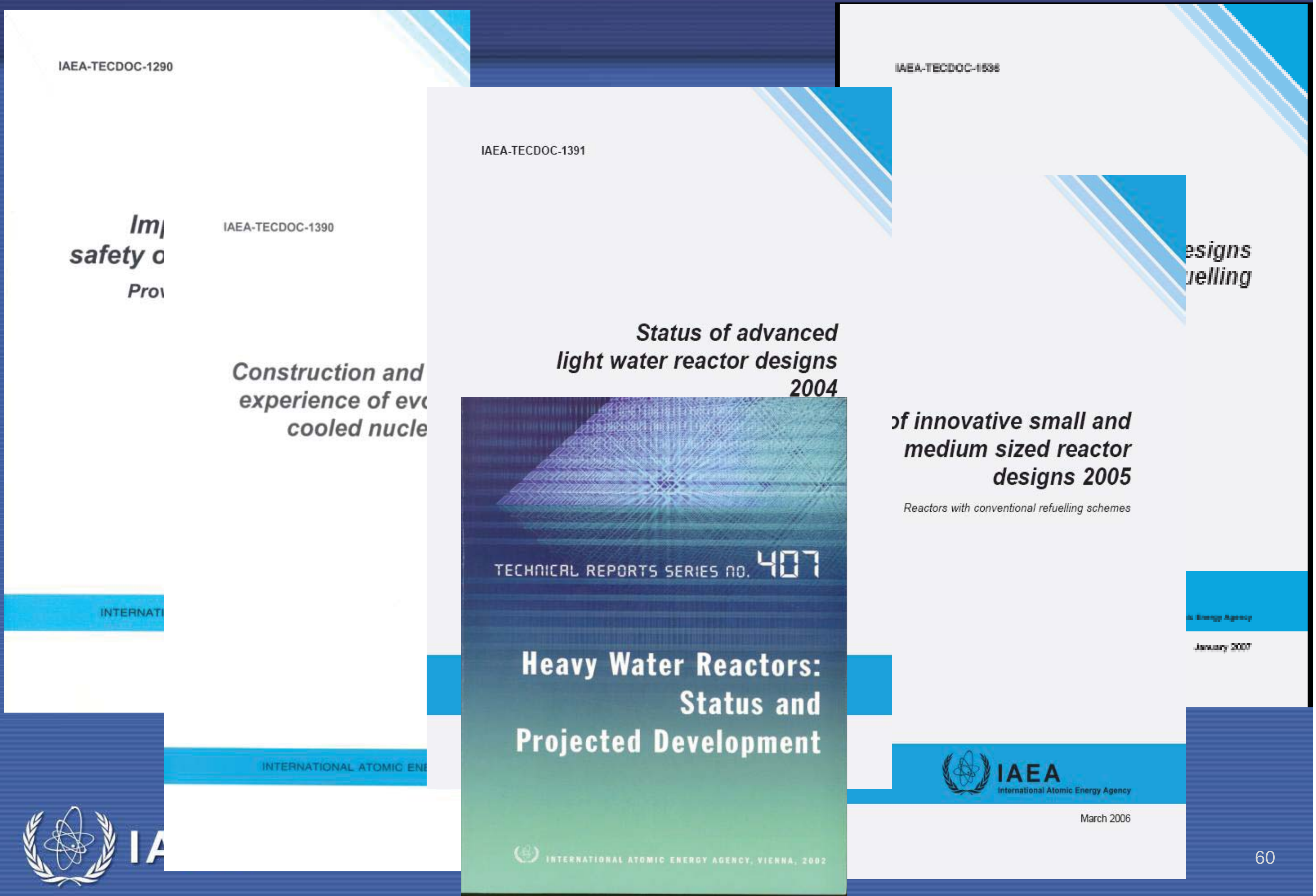
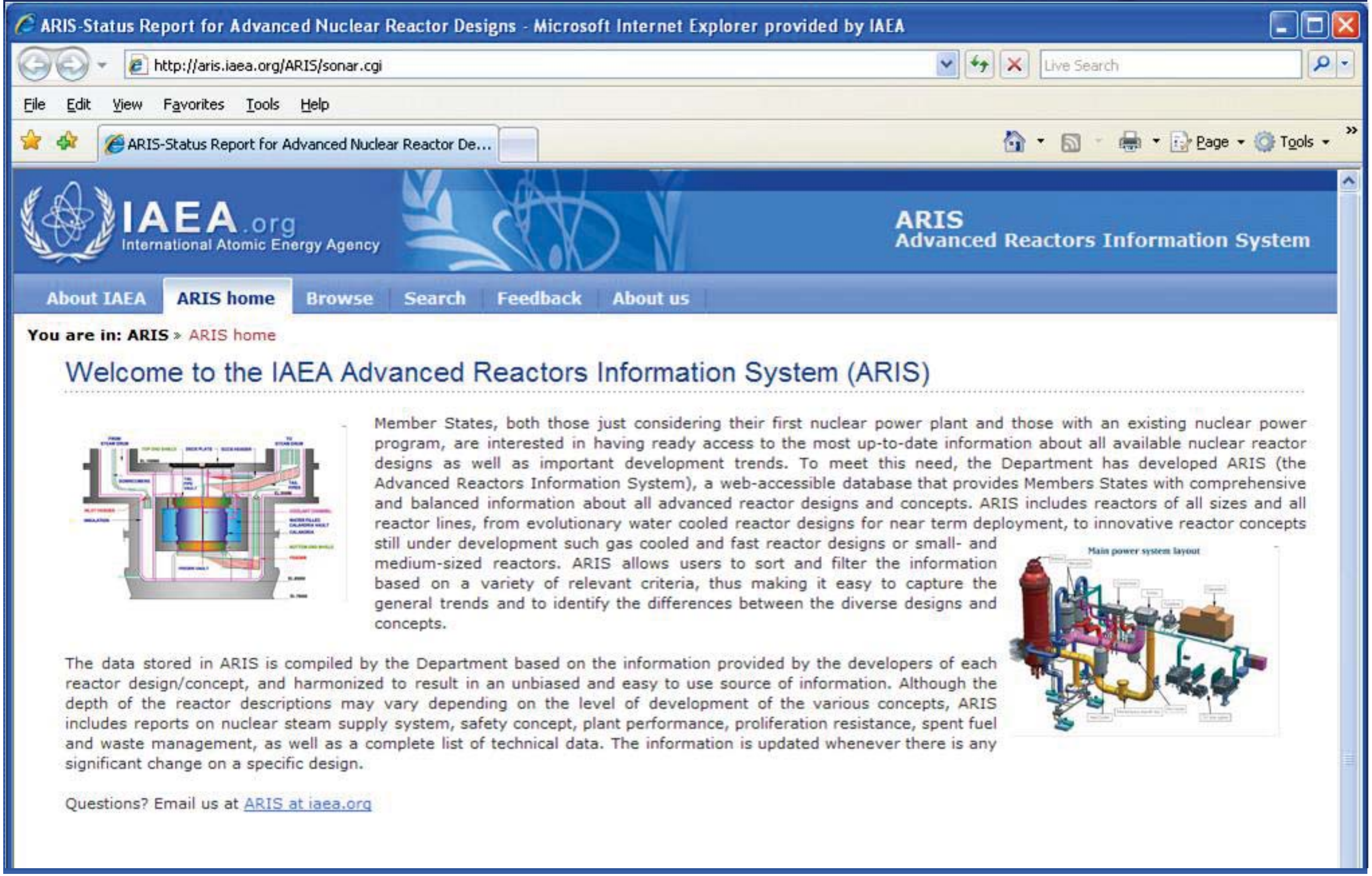
Lessons Learned from the recent accident

- **Issues to be addressed for all lines of reactor design:**
  - Multiple external initiating events and common cause failures
  - Wider scenario of Beyond Design Basis Accident (DBA)
  - Station Black-Out - reliability of emergency power supply
  - Containment seismic/hydrodynamics strength
  - Hybrid passive and active engineered safety features
  - Safety viability of multi-modules – first of a kind engineering
  - Accident management and emergency preparedness
  - Spent fuel pool seismic and cooling provision
  - Hydrogen generation
  - Environmental impact assessment
  - Waste management
  - Severe accident management guideline improvement

IAEA Publications on Advanced Reactors



http://aris.iaea.org/


ARIS-Status Report for Advanced Nuclear Reactor Designs - Microsoft Internet Explorer provided by IAEA

http://aris.iaea.org/ARIS/sonar.cgi

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ARIS
Advanced Reactors Information System

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Welcome to the IAEA Advanced Reactors Information System (ARIS)

Member States, both those just considering their first nuclear power plant and those with an existing nuclear power program, are interested in having ready access to the most up-to-date information about all available nuclear reactor designs as well as important development trends. To meet this need, the Department has developed ARIS (the Advanced Reactors Information System), a web-accessible database that provides Members States with comprehensive and balanced information about all advanced reactor designs and concepts. ARIS includes reactors of all sizes and all reactor lines, from evolutionary water cooled reactor designs for near term deployment, to innovative reactor concepts still under development such gas cooled and fast reactor designs or small- and medium-sized reactors. ARIS allows users to sort and filter the information based on a variety of relevant criteria, thus making it easy to capture the general trends and to identify the differences between the diverse designs and concepts.

Main power system layout

The data stored in ARIS is compiled by the Department based on the information provided by the developers of each reactor design/concept, and harmonized to result in an unbiased and easy to use source of information. Although the depth of the reactor descriptions may vary depending on the level of development of the various concepts, ARIS includes reports on nuclear steam supply system, safety concept, plant performance, proliferation resistance, spent fuel and waste management, as well as a complete list of technical data. The information is updated whenever there is any significant change on a specific design.

Questions? Email us at ARIS at iaea.org

Conclusions

- There are many designs to choose from
  - Not all are commercially available today
  - All have advantages and disadvantages
- Many of them have been:
  - Endorsed by User Requirements (EUR, URD, etc)
  - Certified by licensing authorities in several countries
  - Built and operated for many years in various countries… or
  - … In the process of being built

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Conclusions

- Considerations when choosing a design
  - Balance between technology maturity and innovation
  - Balance between constructability and operability
  - Advantages of “Owner Groups”
    - Operating Experience
    - Market for spare parts
    - Assurance of supplier support
  - Development of national capabilities
  - Electrical and non-electrical applications

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Thank you for your attention …

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