MAAE 4903 A

Reactor Thermal Hydraulic Fundamentals

Lecture 1 : CANDU Reactor Design

Extracts from : "The Essential CANDU, A Textbook on the CANDU Nuclear Power Plant Technology", Editor-in-Chief Wm. J. Garland, Chapters 6 & 7, University Network of Excellence in Nuclear Engineering (UNENE), ISBN 0-9730040. Textbook retrieved from: www.nuceng.ca/candu

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Course Contents

- **Part 1: Thermal Hydraulic Design (Chapter 6 of textbook)**
- Part 2: Thermal Hydraulic Analysis
- Part 3: Safety Regulations

Part 1: Thermal Hydraulic Design
(Chapter 6 of textbook)
Contents

- **CANDU Reactor Design (Lecture 1)**
- Thermal Hydraulic Design Requirements
- Thermal Hydraulic Design Limits and Margins
- Thermal Hydraulic Design Fundamentals
- Heat Transfer and Fluid Flow Design

CANDU Reactor Design (Lecture 1)
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(Section numbers are kept as in the textbook)

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2.1.6 Primary heat transport piping

2.1.7 Secondary heat transport system design

2.1.8 Turbine

2.1.9 Condenser

2.1.10 Heat exchangers and pumps

2.2 Problems

Introduction

- In this section some generic background will be presented (that do not follow the material in the referenced textbook)
- After the introduction we will follow the sections in Chapter 6 more closely.

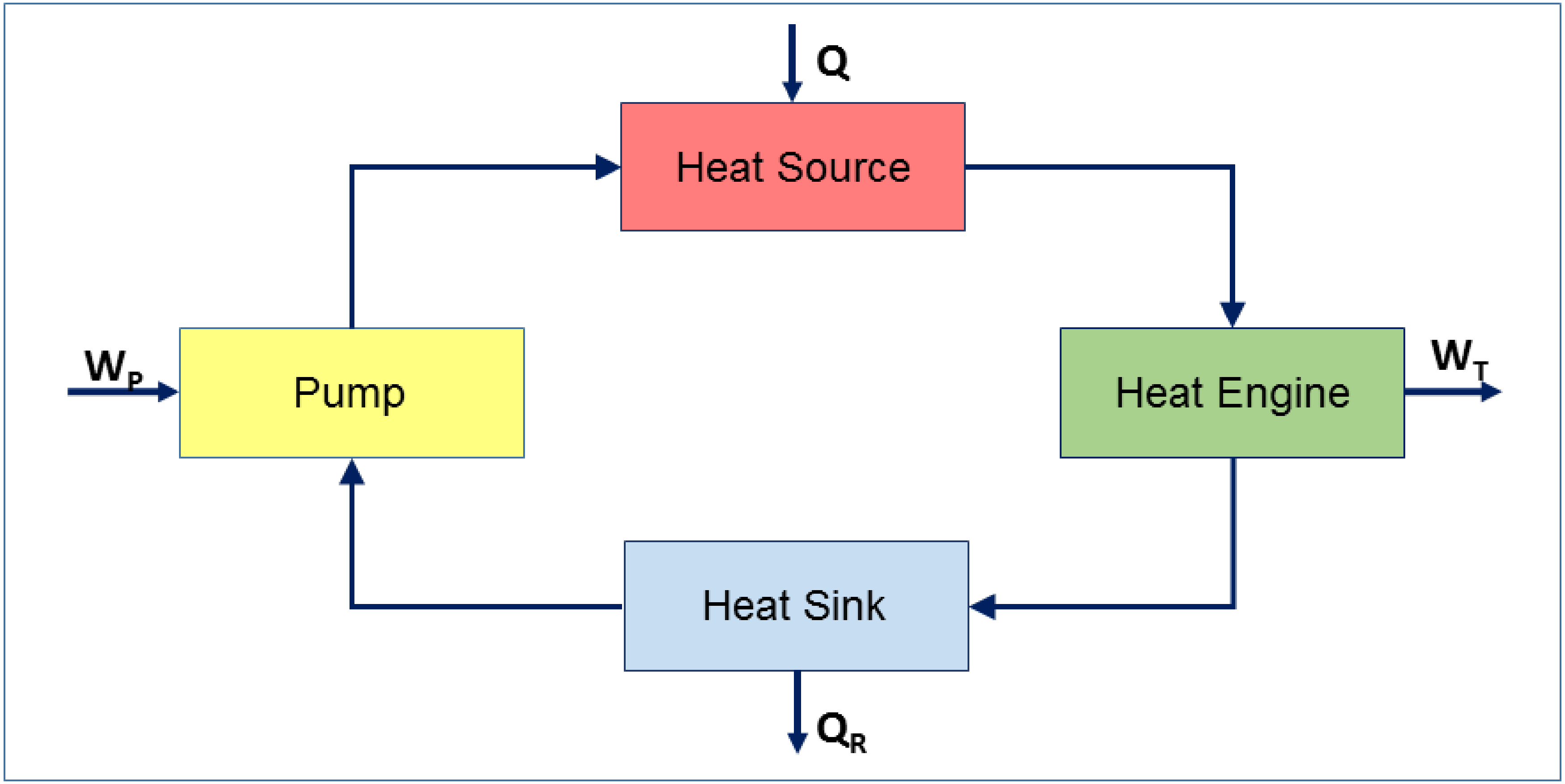


Figure 1 Heat engine concepts

- The heat source in a reactor is the energy generated from the fission process taken place within the uranium fuel

- The energy deposited in the fuel is transferred to the reactor coolant by conduction, convection and radiation

Stored energy in the coolant is then used to produce steam to drive the turbine

(... for the purpose of generating electricity, for example)

[PWR Video from Youtube]

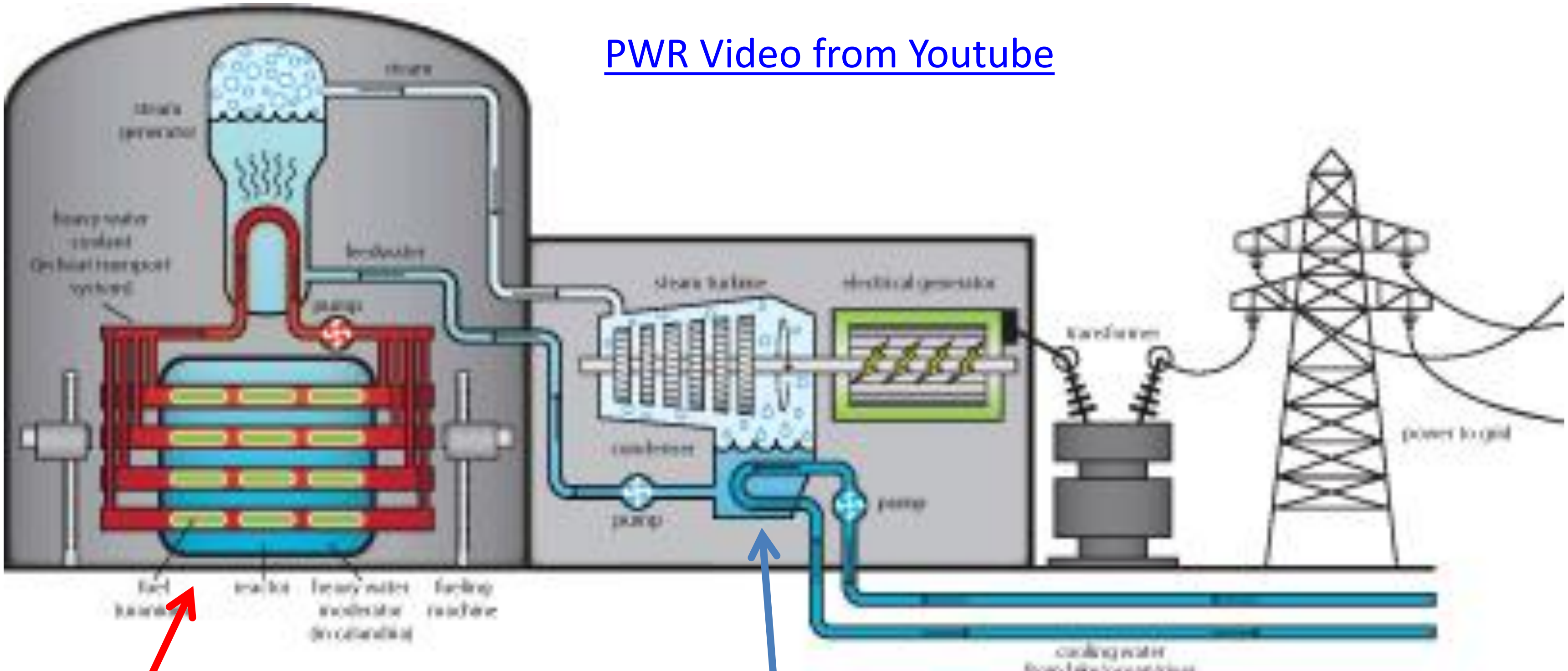


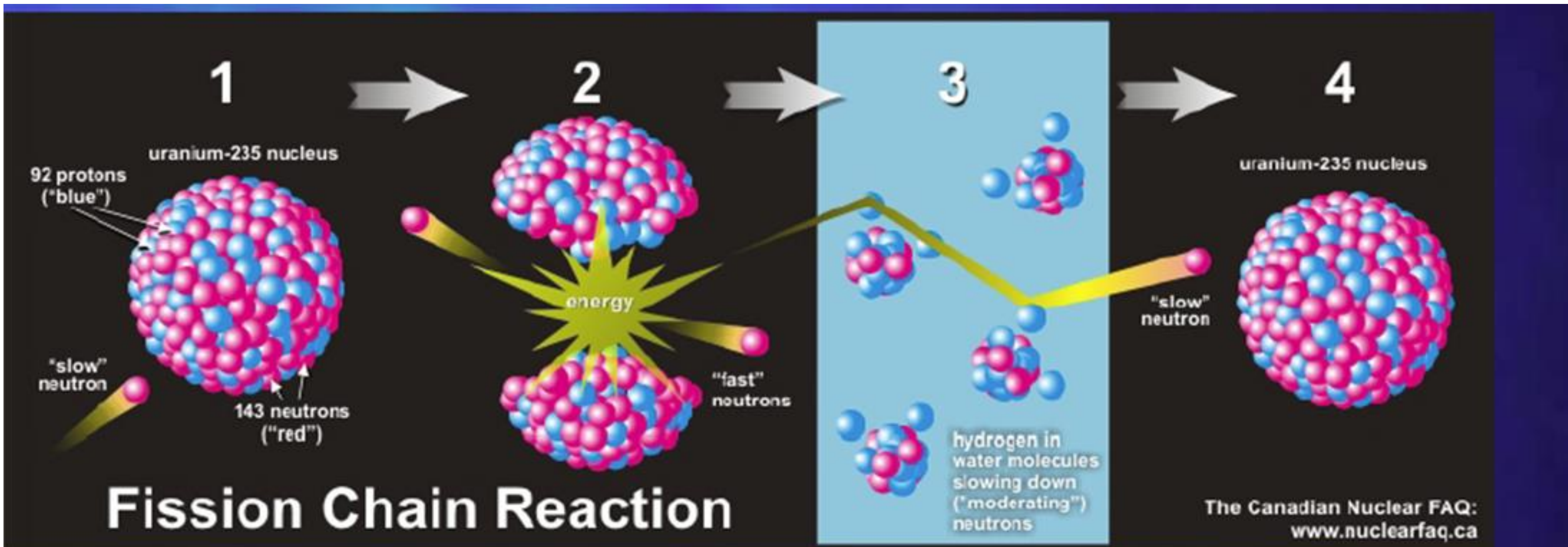
Image from CNSC website

Heat Source (see next slide)

Heat Sink

Heat Source

Figure obtained from CNSC website



Multiplication constant (factor) k:

k = number of neutrons in one generation/number of neutrons in previous generation

k = 1 , reactor critical, k<1 reactor subcritical, k> reactor supercritical

Uranium 235 Fission

$$^{235}_{92}U + ^{1}_{0}n \rightarrow \left(^{236}_{92}U\right) \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n$$

Plutonium 239 production

$$^{238}U + ^{1}n \rightarrow ^{239}U \qquad ^{239}U \xrightarrow[23.5\,\text{min}]{\beta-} ^{239}Np \xrightarrow[2.3d]{\beta-} + ^{239}Pu$$

Thorium – Uranium 233 production

$$^{232}Th + ^{1}n \rightarrow ^{233}Th \qquad ^{233}Th \xrightarrow[23\,.5\,mun]{\beta\,-} ^{233}Pa \xrightarrow[27\,.4\,.d]{\beta\,-} + ^{233}U$$

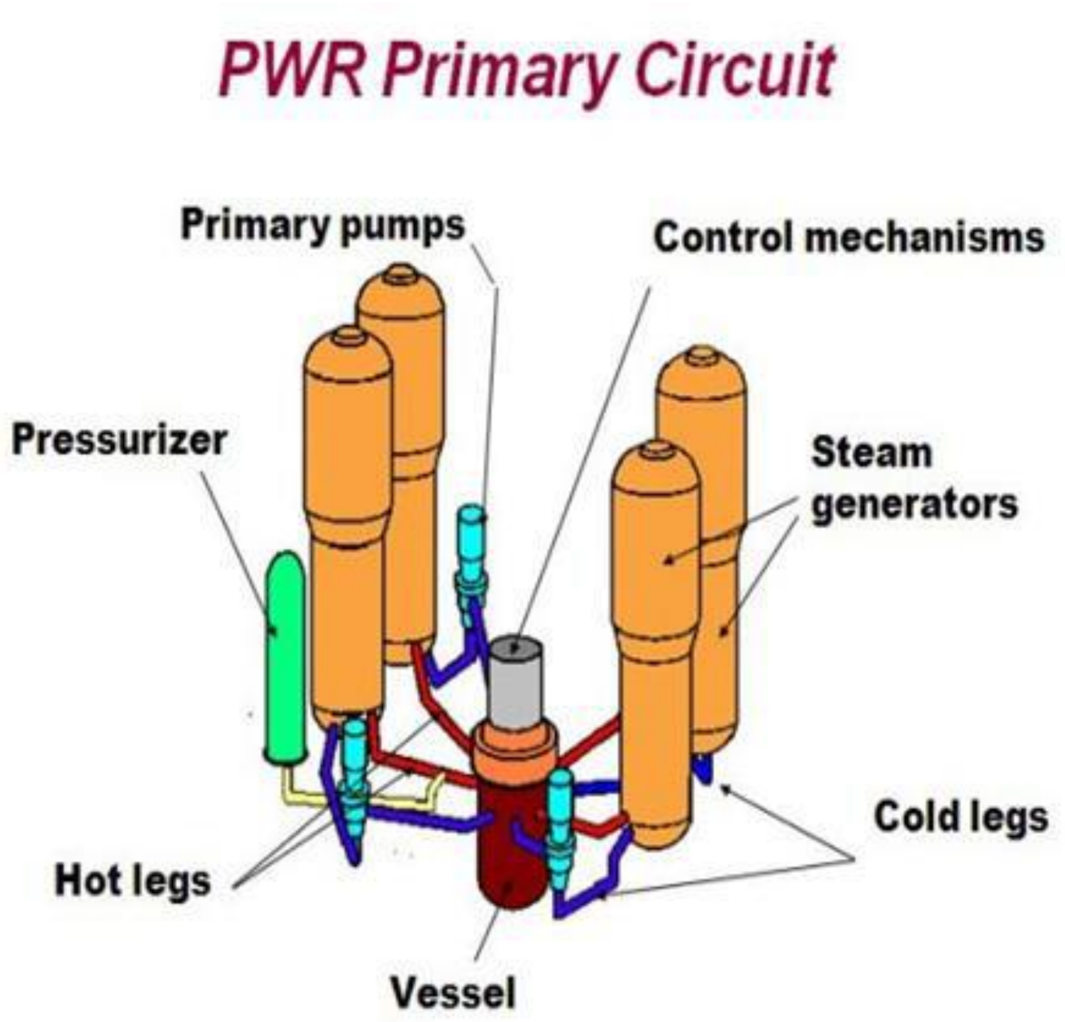
From CNSC website

2. Reactor Types

(Section numbers are kept as in the textbook)

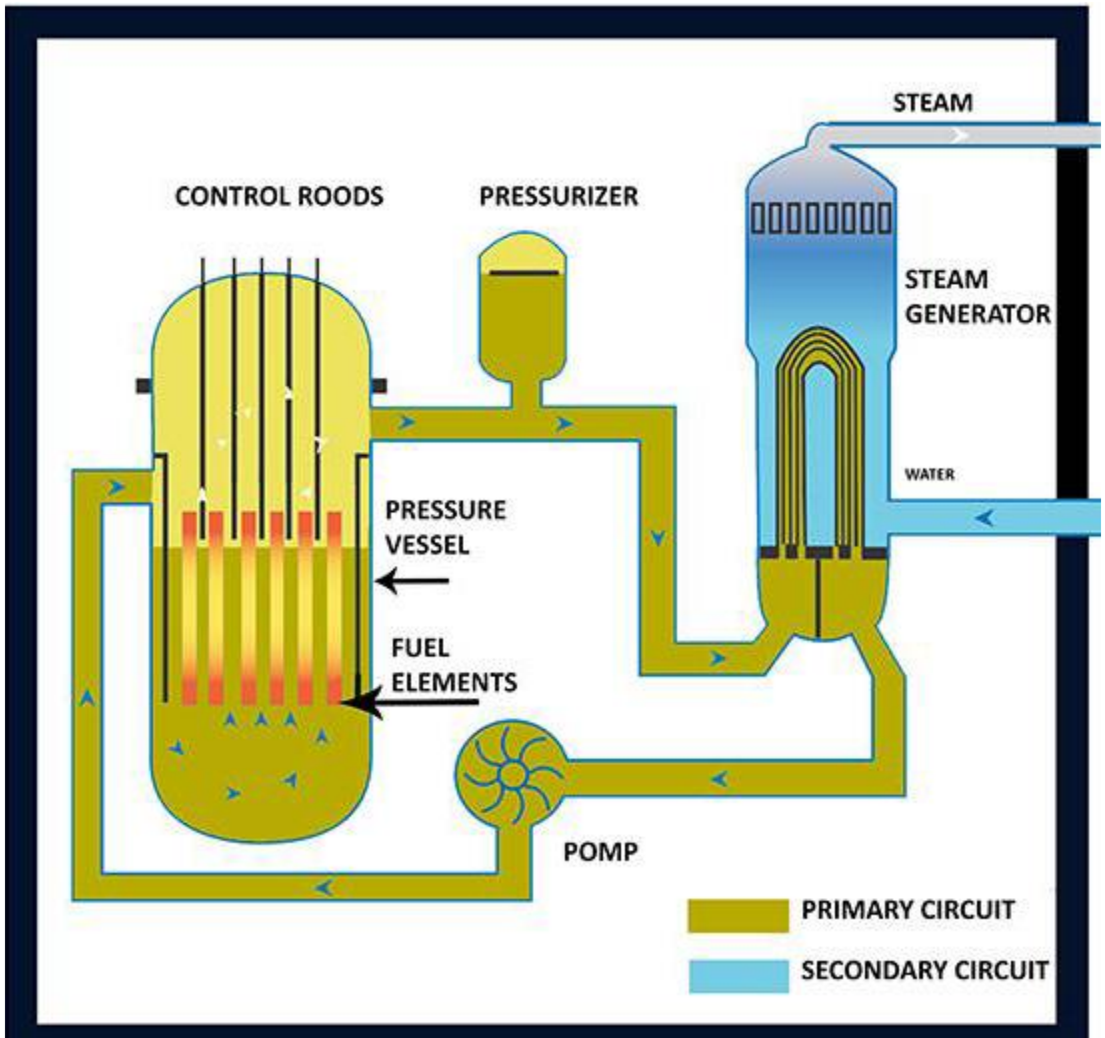
- **Pressurized Water Reactors**
- **Boiling Water Reactors**
- **Gas-cooled Reactors**
  - Magnox Reactors
  - Advanced Gas-cooled Reactor (AGR)
  - High Temperature Gas Cooled Reactor (HTGCR)
- **Channel-type Reactors**
  - Steam Generating Heavy Water Reactor (SGHWR)
  - **CANDU Reactor**
  - RBMK reactor (the acronym is for High Power Channel Type Reactor in Russian)
- **Fast Breeder Reactors**

Pressurized water reactors (1)



Pressurized water reactors (2)

PWR primary coolant loop cross section



Pressurized water reactors (3)
(typical data)

Reactor	Fuel	
Thermal output: 3800 MWth	Fuel pellet material :	UO_2
Electrical output: 1300 MWe	Pellet outer diameter:	8.19 mm
Thermal efficiency: 34 %	Rod outer diameter:	9.5 mm
Specific power: 33 kW/kg(U)	Zircaloy cladding thickness:	0.57 mm
Power density : 102 kW/L	Rods per bundle (17 x 17):	264
Ave. linear heat flux: 17.5 kW/m	Bundles in core:	193

Pressurized water reactors (4) (typical data)

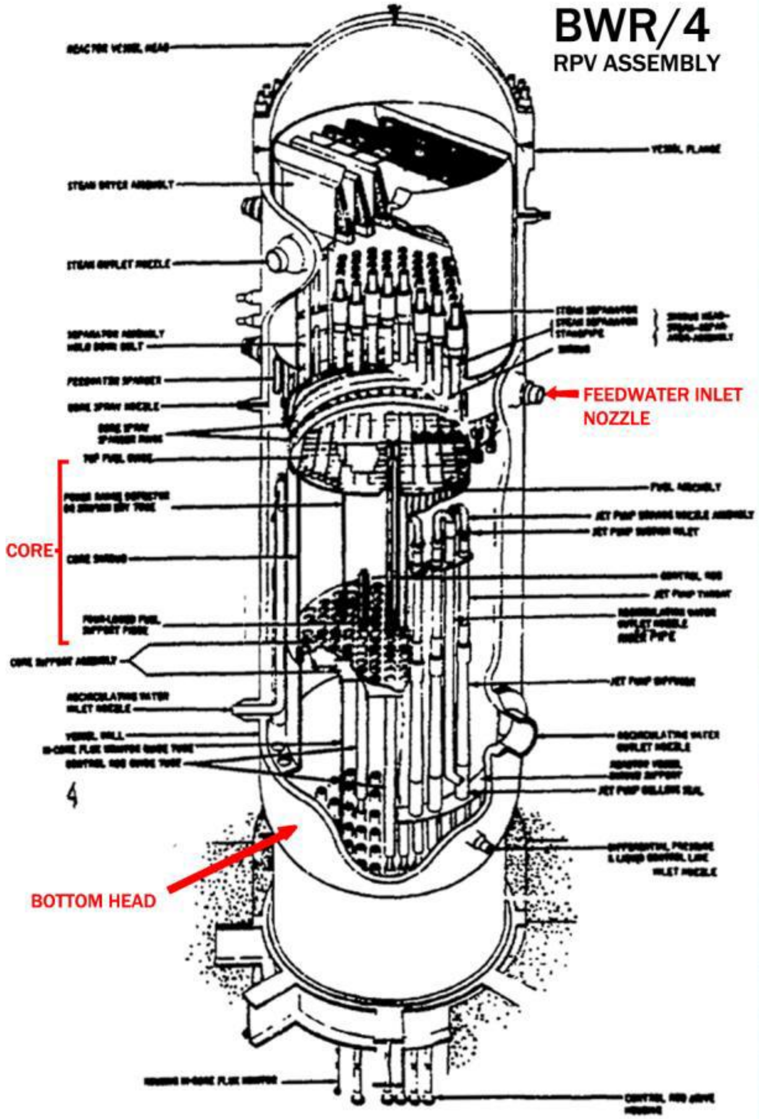
Vessel		Core	
Outer diameter:	4.4 m	Length:	4.17 m
Height:	13.6 m	Outer diameter:	3.37 m
Wall thickness:	0.22 m	Pressure:	15.5 MPa
		Inlet temperature:	292 °C
		Outlet temperature :	329 °C
		Mass flow rate:	531 kg/s

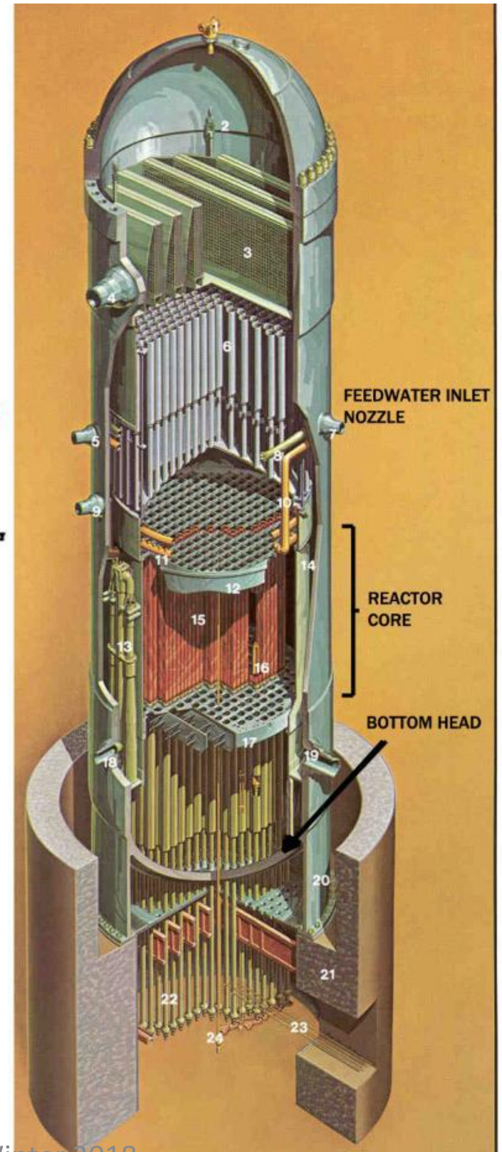
Pressurized water reactors (5) (typical data)

Steam Generator

No.	4
Outlet pressure:	6.9 MPa
Outlet temperature:	284 ^{o}C
Mass flow rate:	528 kg/s

Boiling water reactors (1)



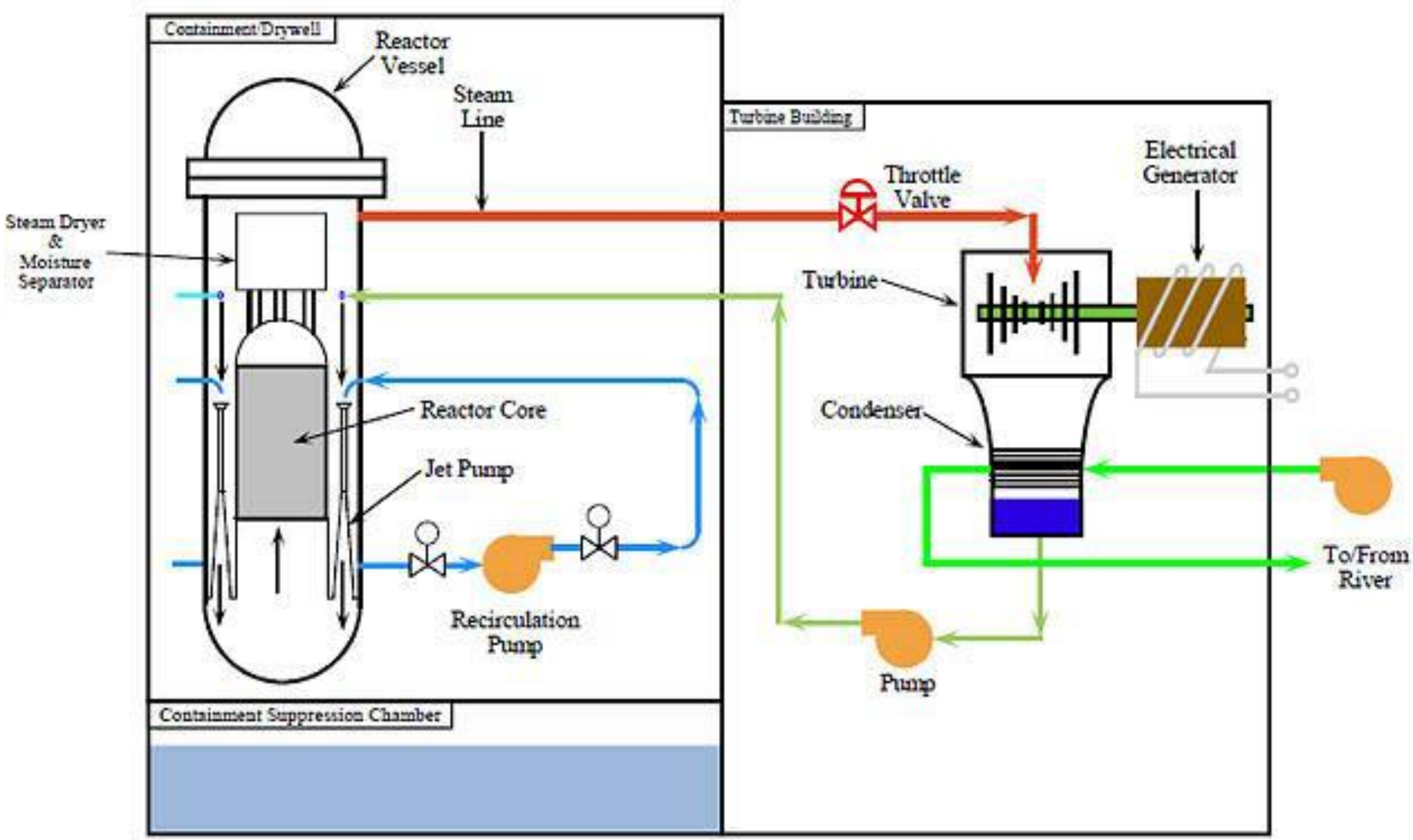


BWR/6
REACTOR ASSEMBLY

1. VENT AND HEAD SPRAY
2. STEAM DRYER LIFTING LUG
3. STEAM DRYER ASSEMBLY
4. STEAM OUTLET
5. CORE SPRAY INLET
6. STEAM SEPARATOR ASSEMBLY
7. FEEDWATER INLET
8. FEEDWATER SPARGER
9. LOW PRESSURE COOLANT INJECTION INLET
10. CORE SPRAY LINE
11. CORE SPRAY SPARGER
12. TOP GUIDE
13. JET PUMP ASSEMBLY
14. CORE SHROUD
15. FUEL ASSEMBLIES
16. CONTROL BLADE
17. CORE PLATE
18. JET PUMP / RECIRCULATION WATER INLET
19. RECIRCULATION WATER OUTLET
20. VESSEL SUPPORT SKIRT
21. SHIELD WALL
22. CONTROL ROD DRIVES
23. CONTROL ROD DRIVE HYDRAULIC LINES
24. IN-CORE FLUX MONITOR

GENERAL ELECTRIC

Boiling water reactors (2)



Typical BWR reactor vessel coolant circulation

2.1 CANDU Reactors Design

- Nuclear Power Demonstration (NPD) CANDU design
- Douglas Point
- Pickering A and B
- Bruce A and B
- CANDU 6
- Darlington
- And others:
  - Advanced CANDU designs
  - CANDU 3, CANDU 9, and ACR-700
  - ACR-1000
  - Enhanced CANDU 6

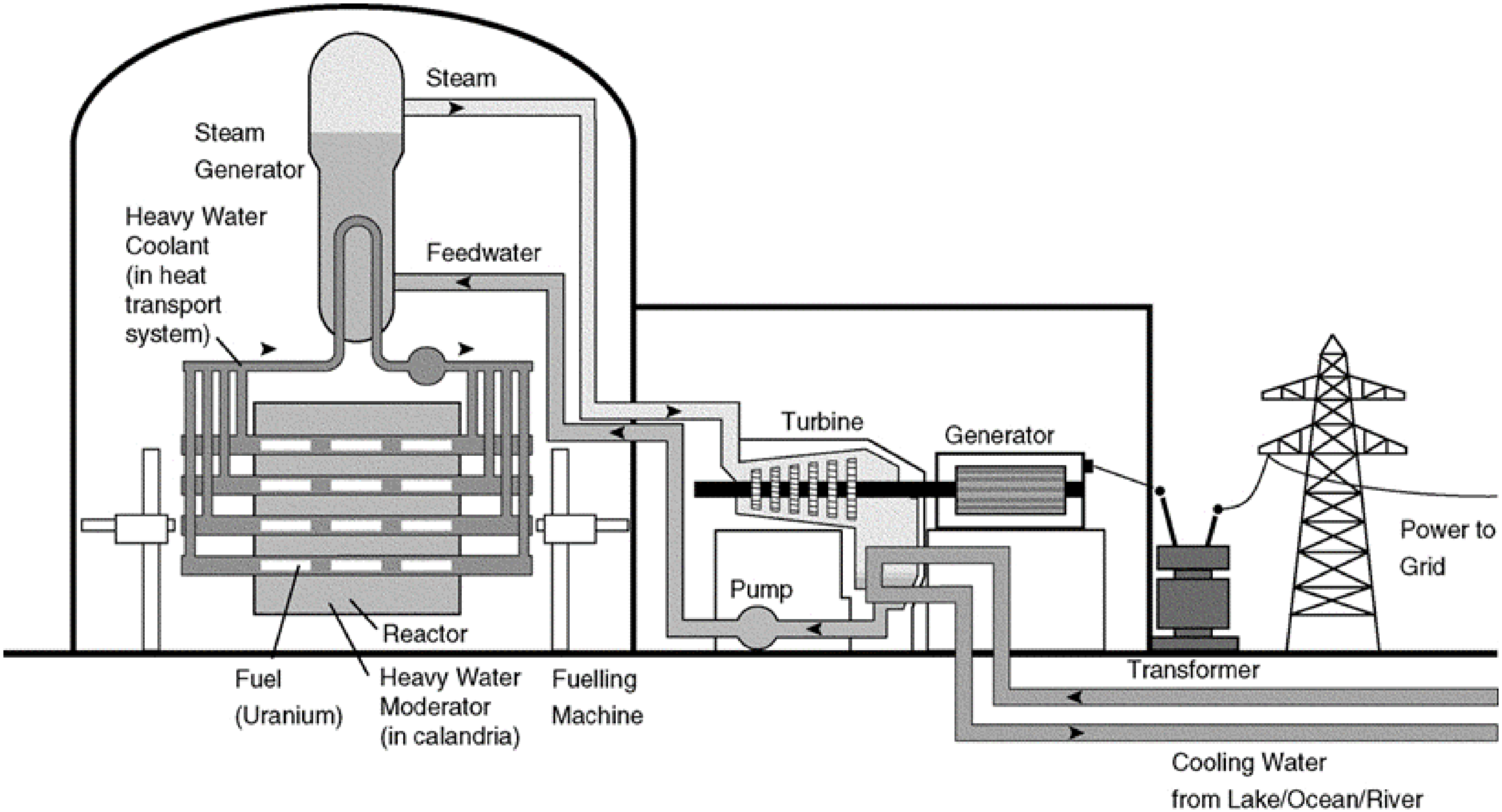


Figure 2 : Typical CANDU plant

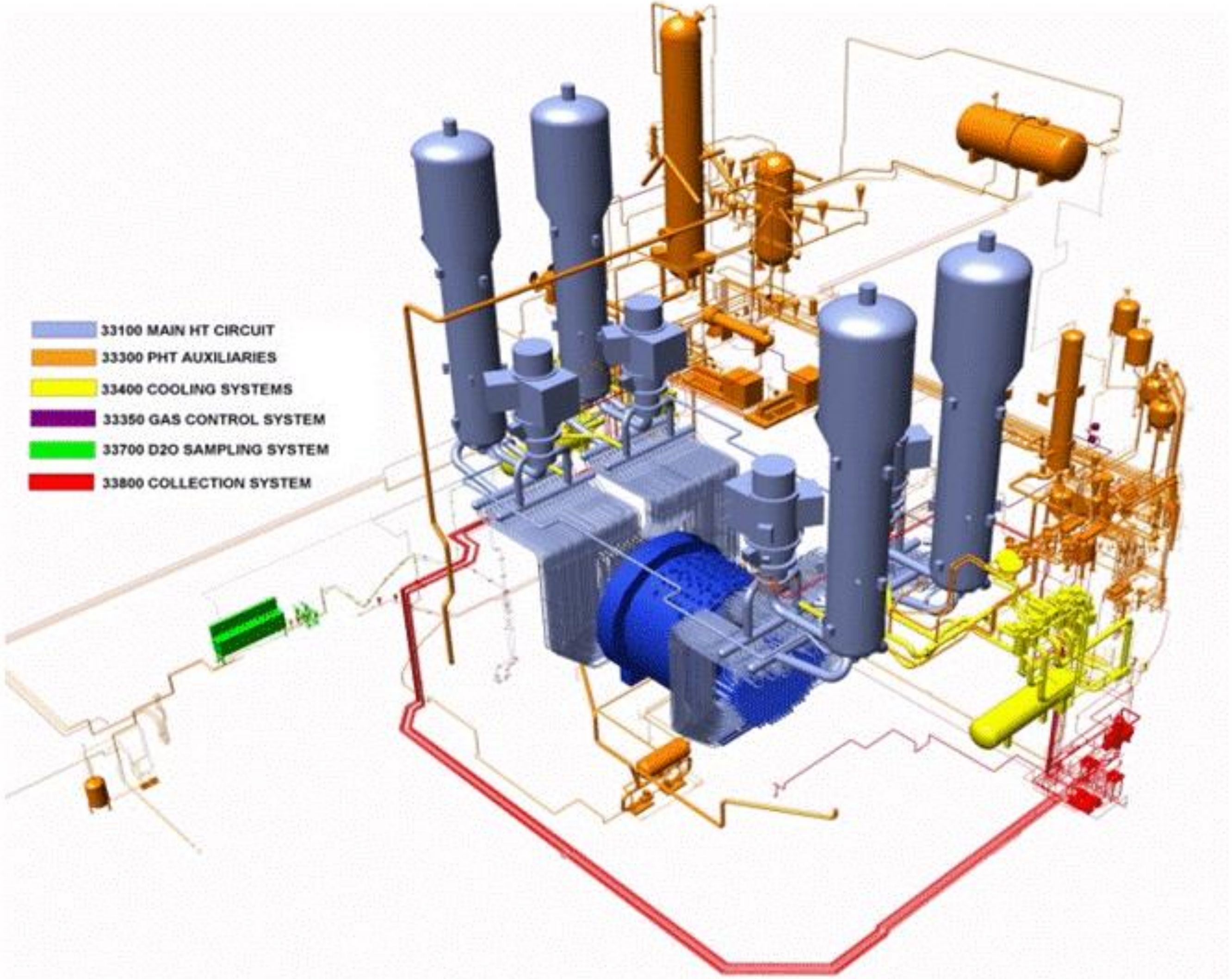


Figure 3 CANDU 6 reactor cooling loops

2.1.1 Reactor core and calandria vessel

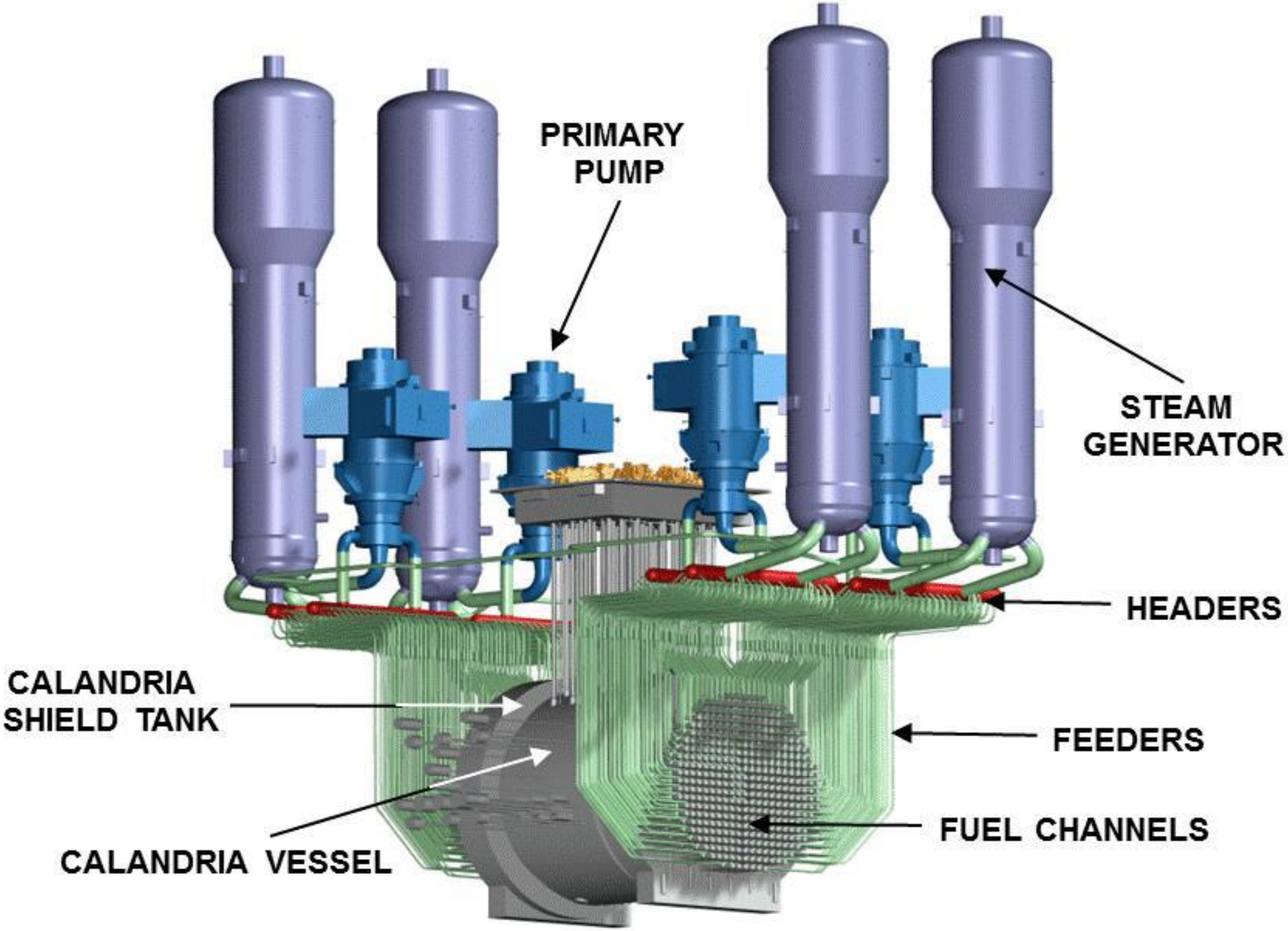


Figure 4a) : Typical CANDU reactor and heat transport system

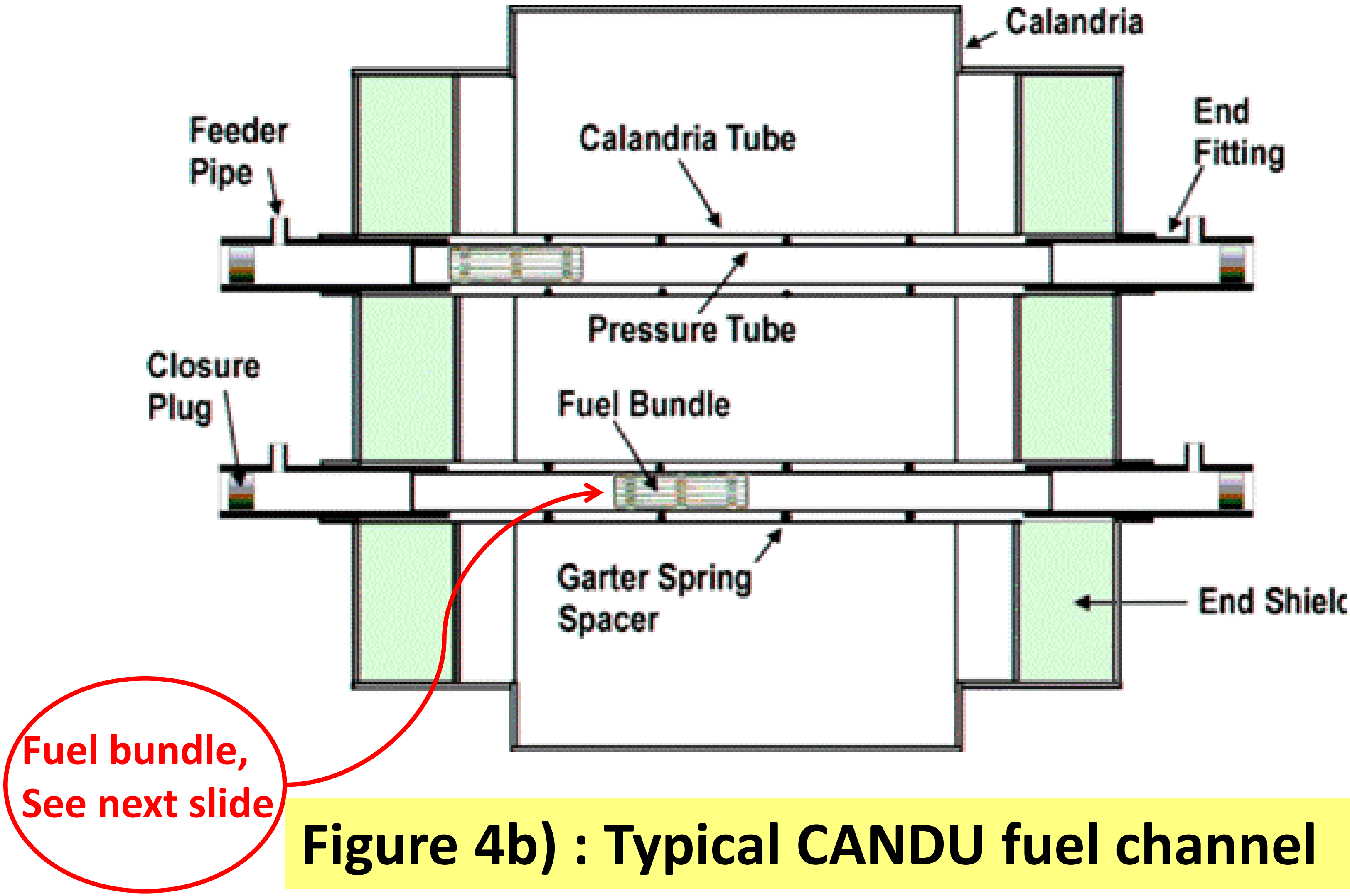


Figure 4b) : Typical CANDU fuel channel

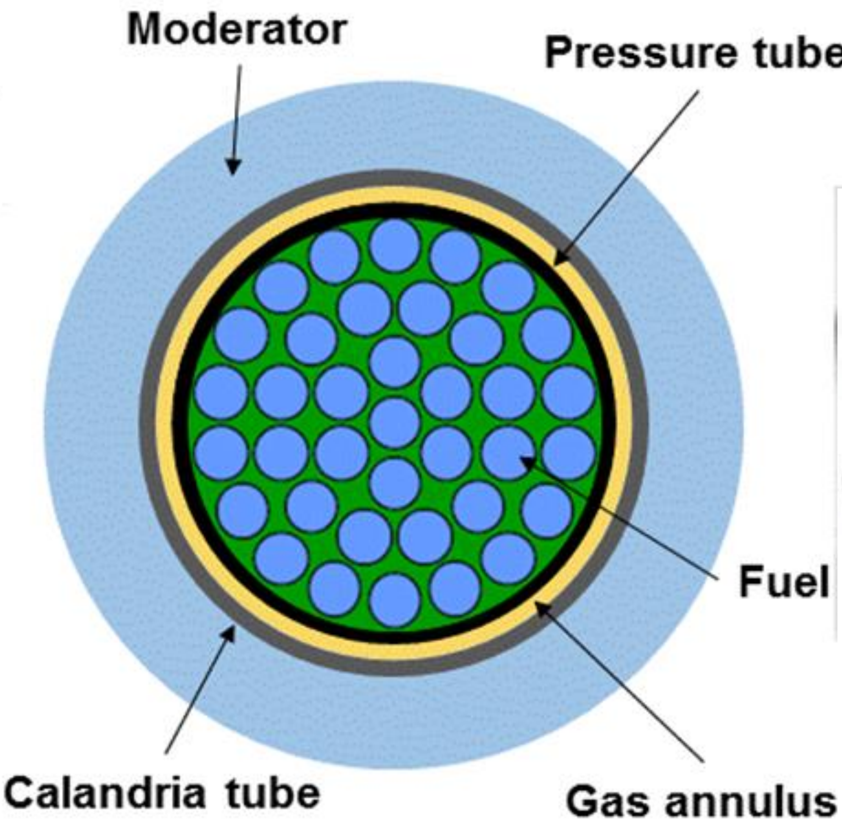
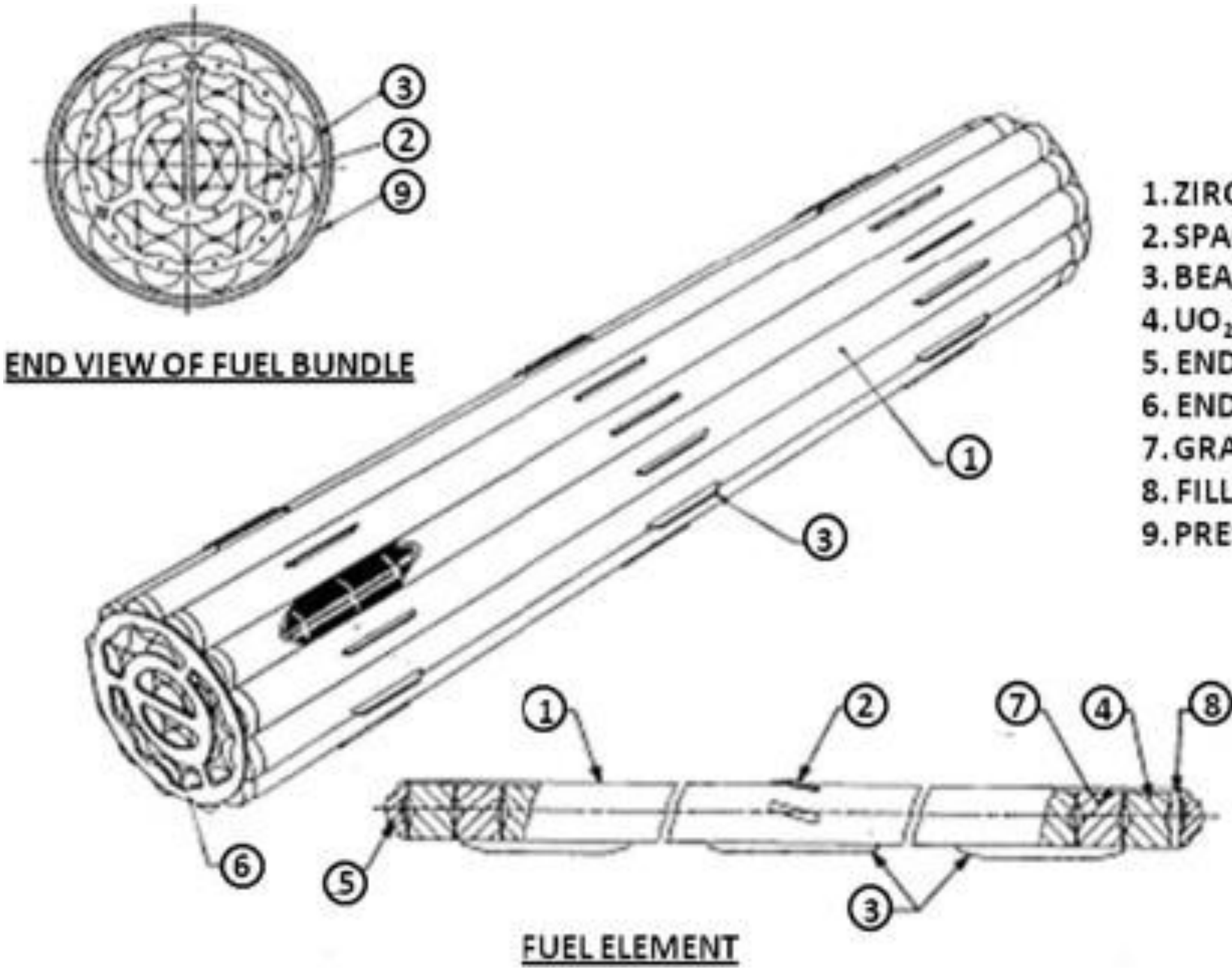


Figure 4c) : Typical CANDU fuel bundle



1. ZIRCALOY CLAD
2. SPACER PAD
3. BEARING PAD
4. UO_2 PELLET
5. END PLUG
6. END PLATE
7. GRAPHITE COATING
8. FILLER GAS
9. PRESSURE TUBE

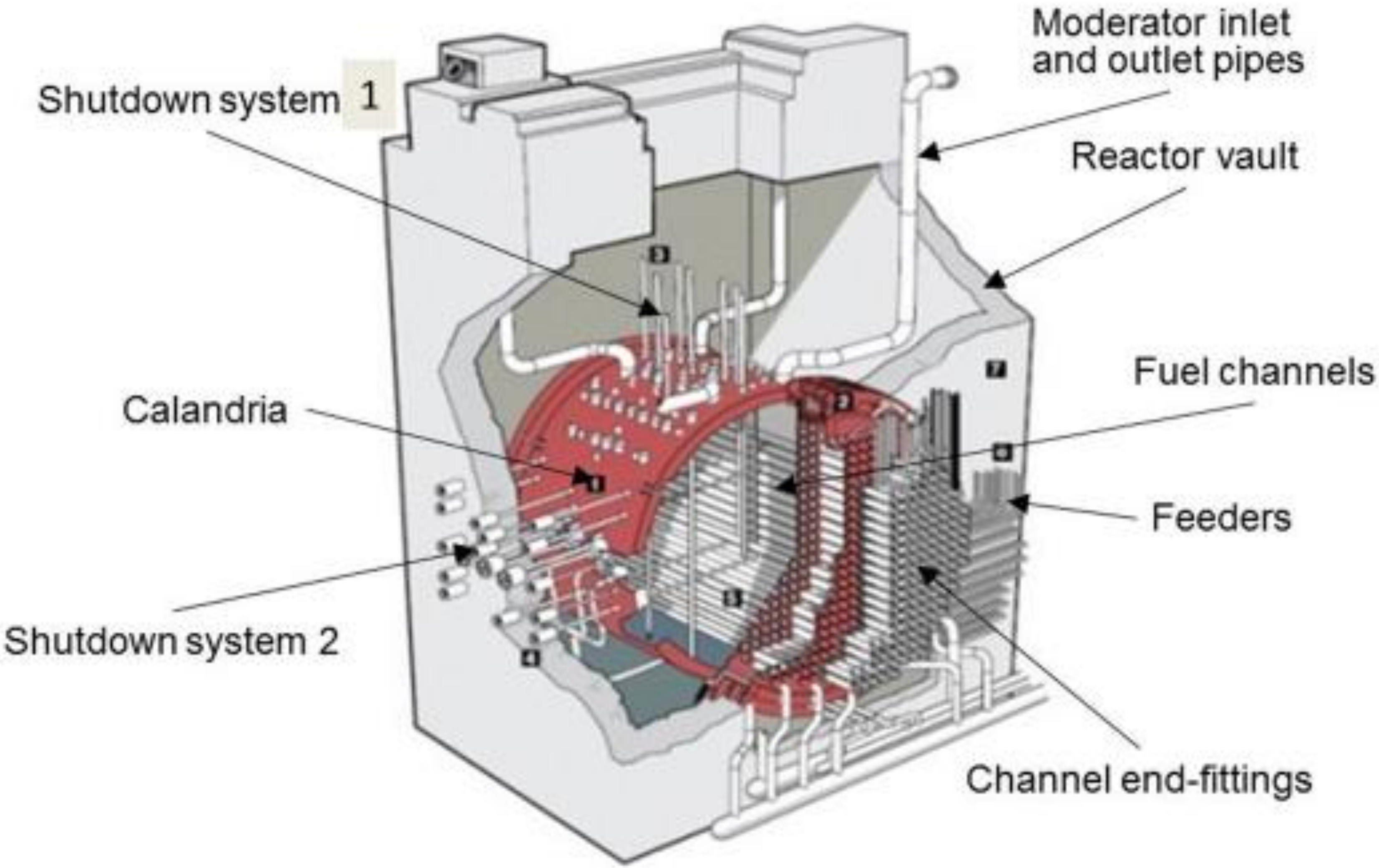


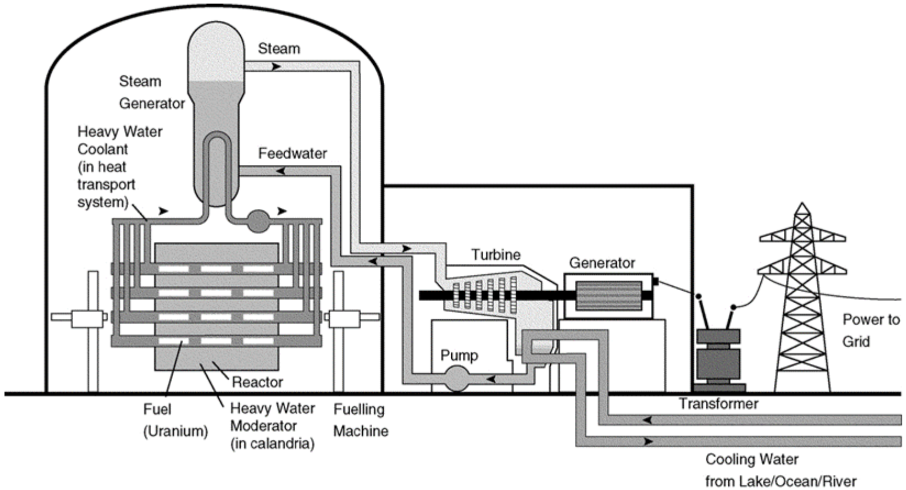
Figure 5 CANDU calandria vessel and reactor vault

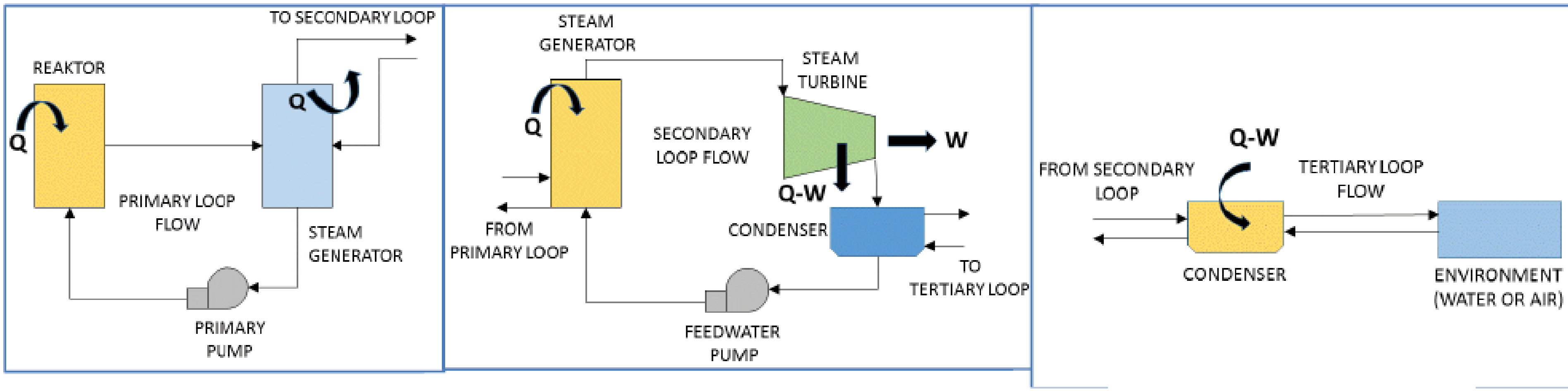
2.1.2 Primary heat transport system design

Recall that the CANDU heat transport system consists of

1. **Primary loop**
2. **Secondary loop, and**
3. **Tertiary loop**

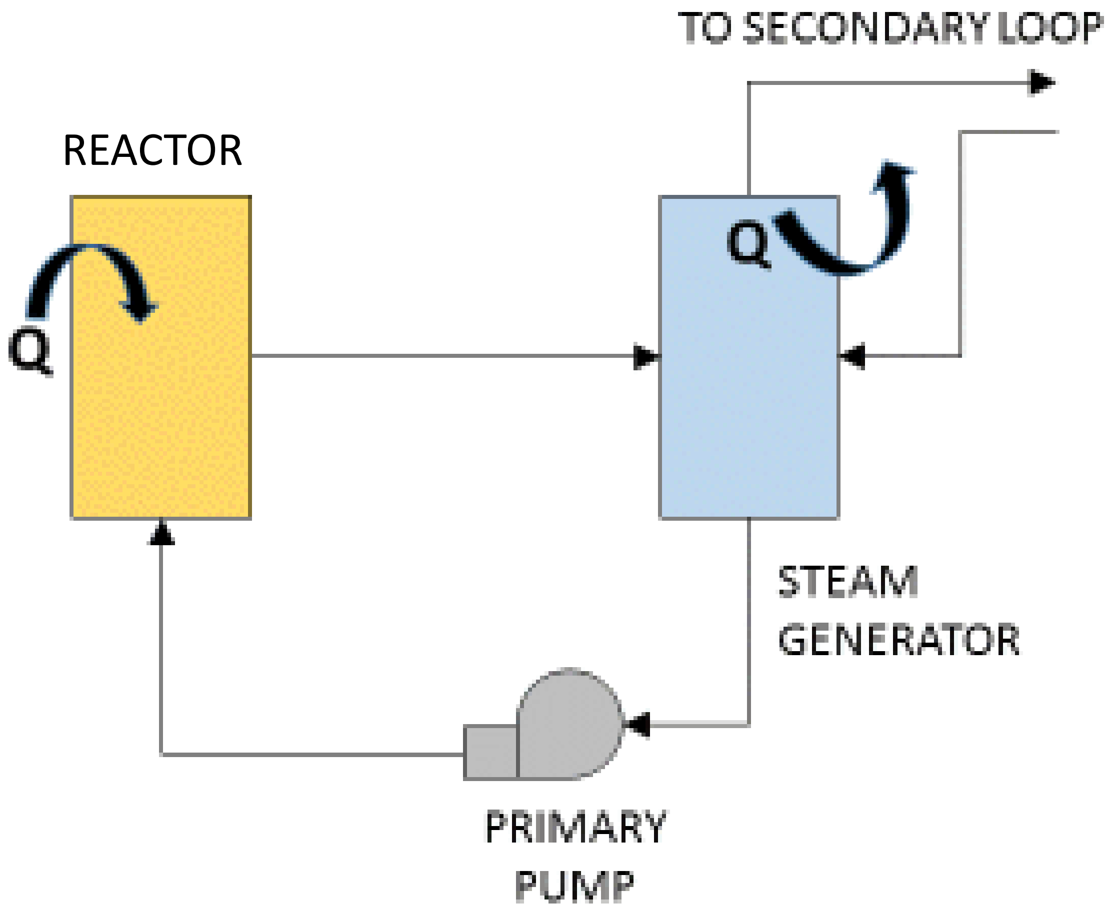
(Recall Figure 2)



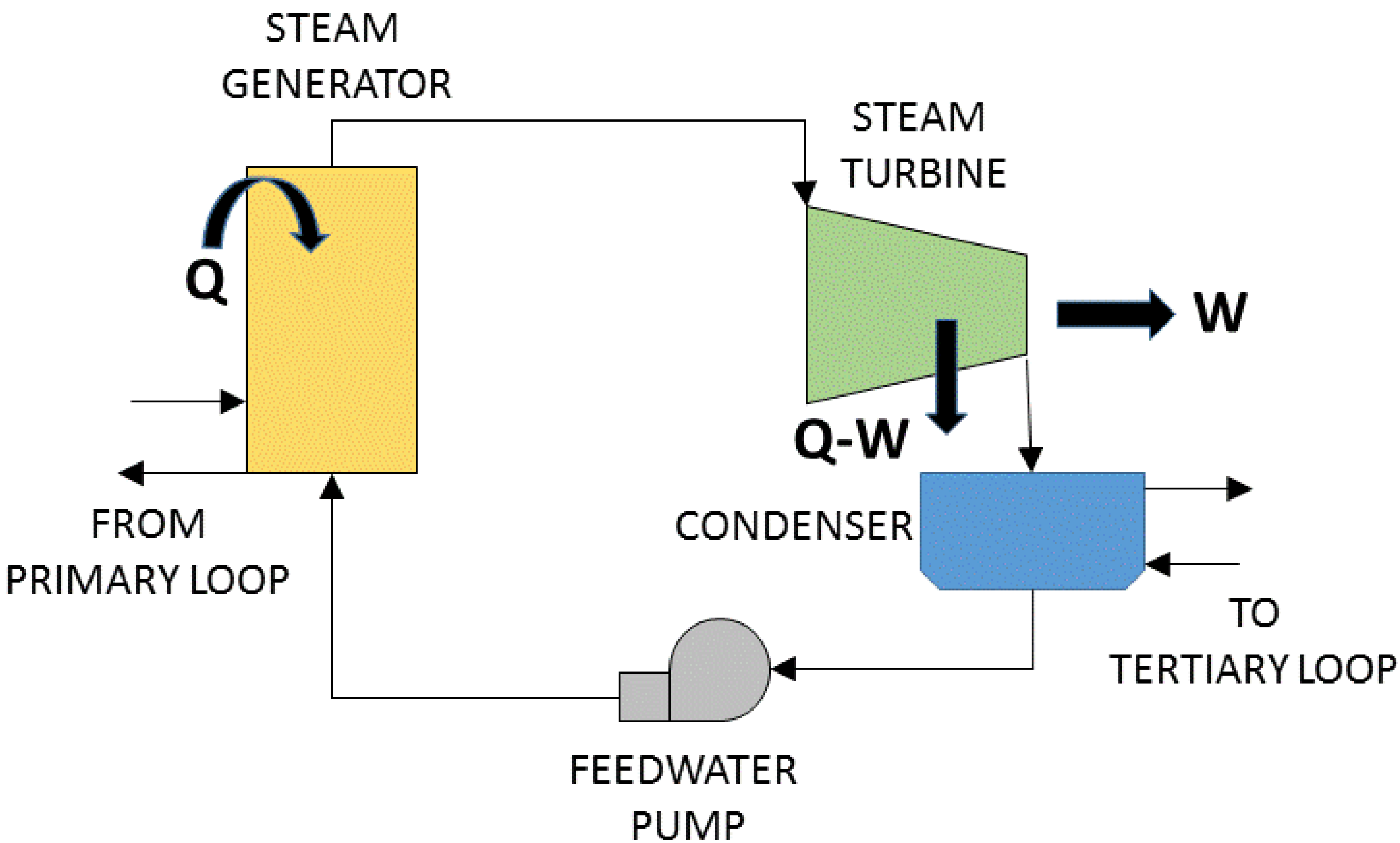


a) Primary Loop b) Secondary Loop c) Tertiary Loop

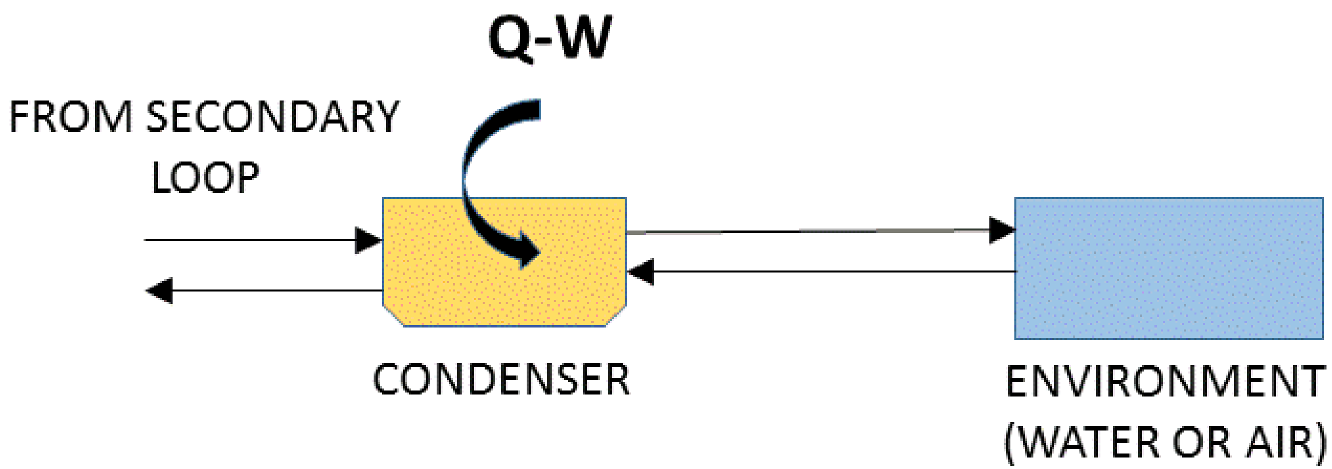
Figure 56: Reactor cooling systems



a) Primary Loop Flow



b) Secondary Loop Flow



c) Tertiary Loop Flow

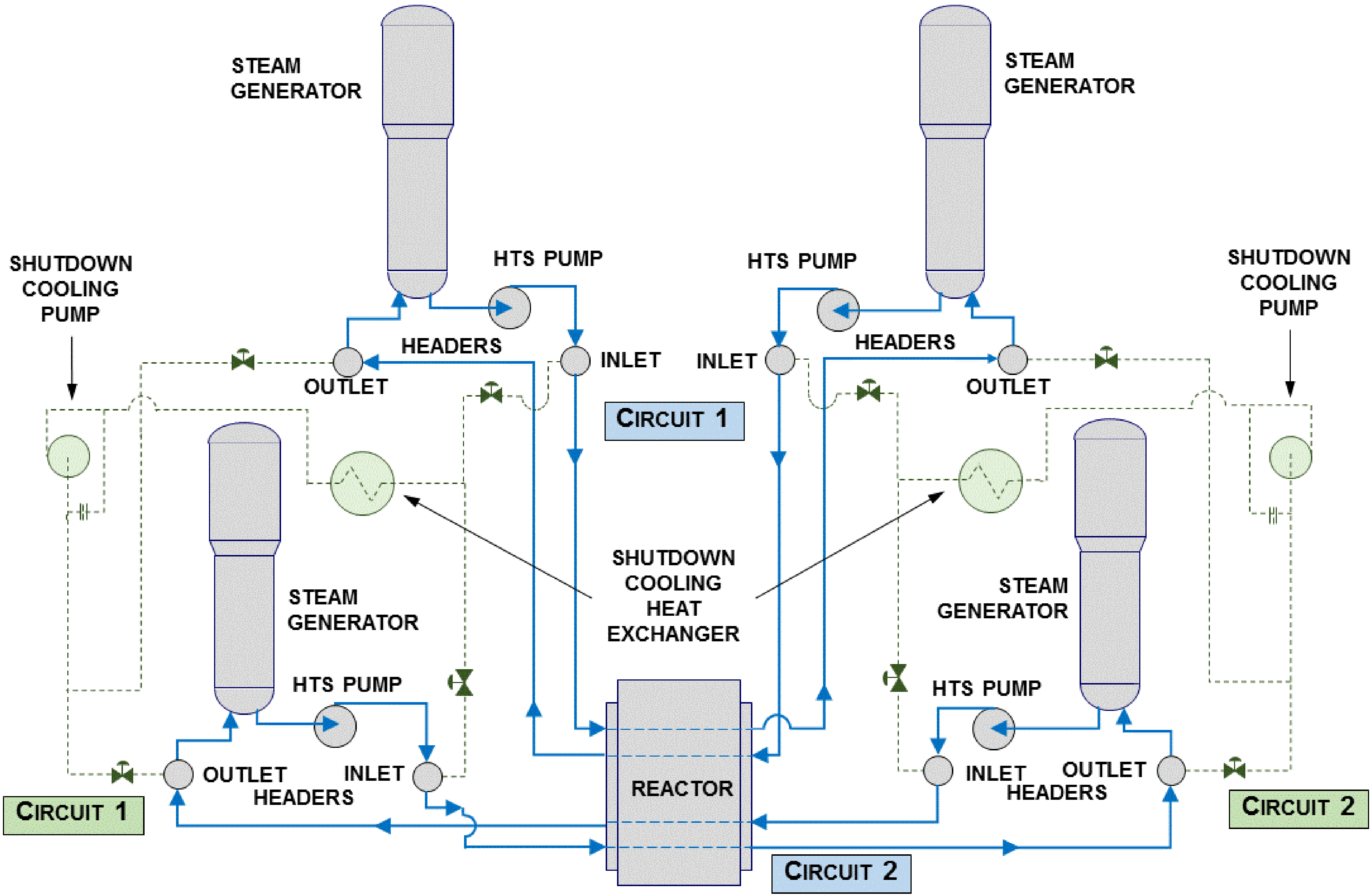
This section addresses the ``Primary loop`` or ``Primary heat transport system``

- There are several variations of the CANDU heat transport system design.

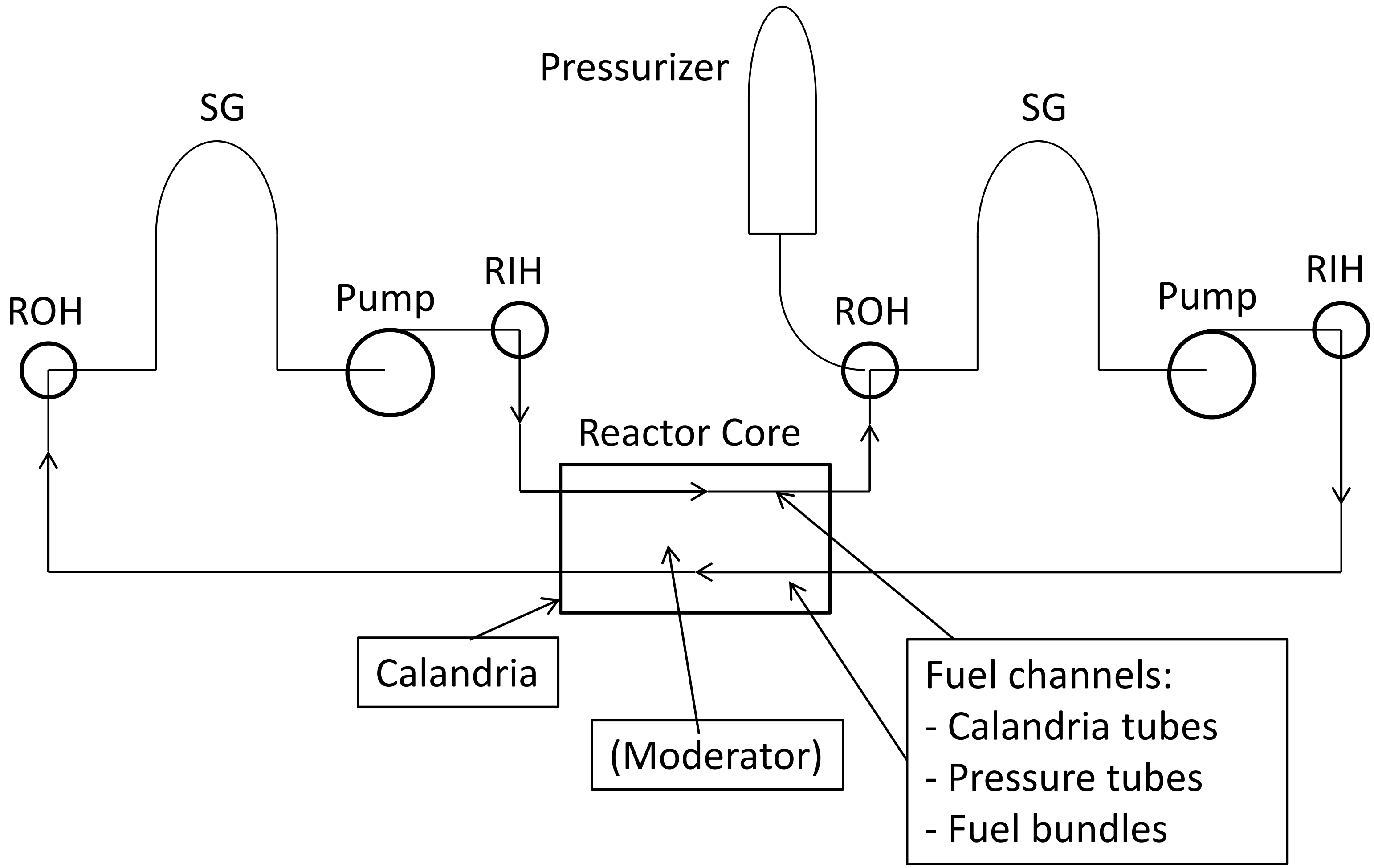
- The CANDU 6 heat transport system design is described in the following sections.

- The **primary heat transport system (PHTS)** circulates pressurized D_2O coolant through the fuel channels to remove the heat produced by fission in the nuclear fuel.

- The coolant transports the heat to steam generators, where heat energy is transferred to light water to produce steam to drive the turbine.



CANDU 6 Primary and Shutdown Cooling Loops



Simple Sketch of Primary Cooling Loop

(referred to as Figure-of-Eight)

Major components in PHTS

Examples

- Steam generators
- Pressurizer
- Primary Pumps
- Primary heat transport piping

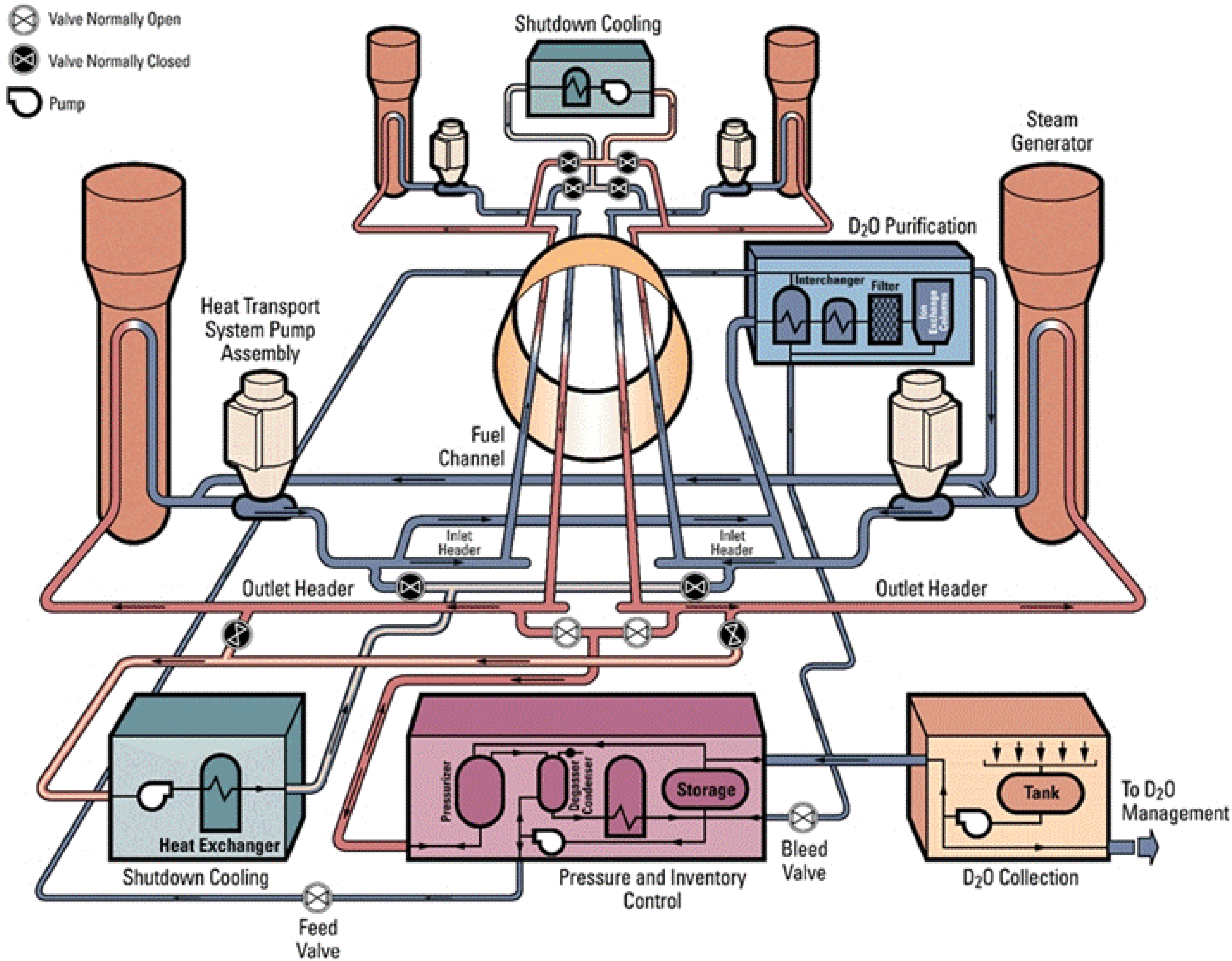


Figure 6 : CANDU primary heat transport system

2.1.3 Steam generators

- The steam generator has a very important role in energy transport from the reactor core to the turbine because it connects the primary and secondary loops.
- The CANDU steam generators consist of an inverted **U-tube** bundle within a cylindrical shell.
- Heavy water coolant passes through the U-tubes.

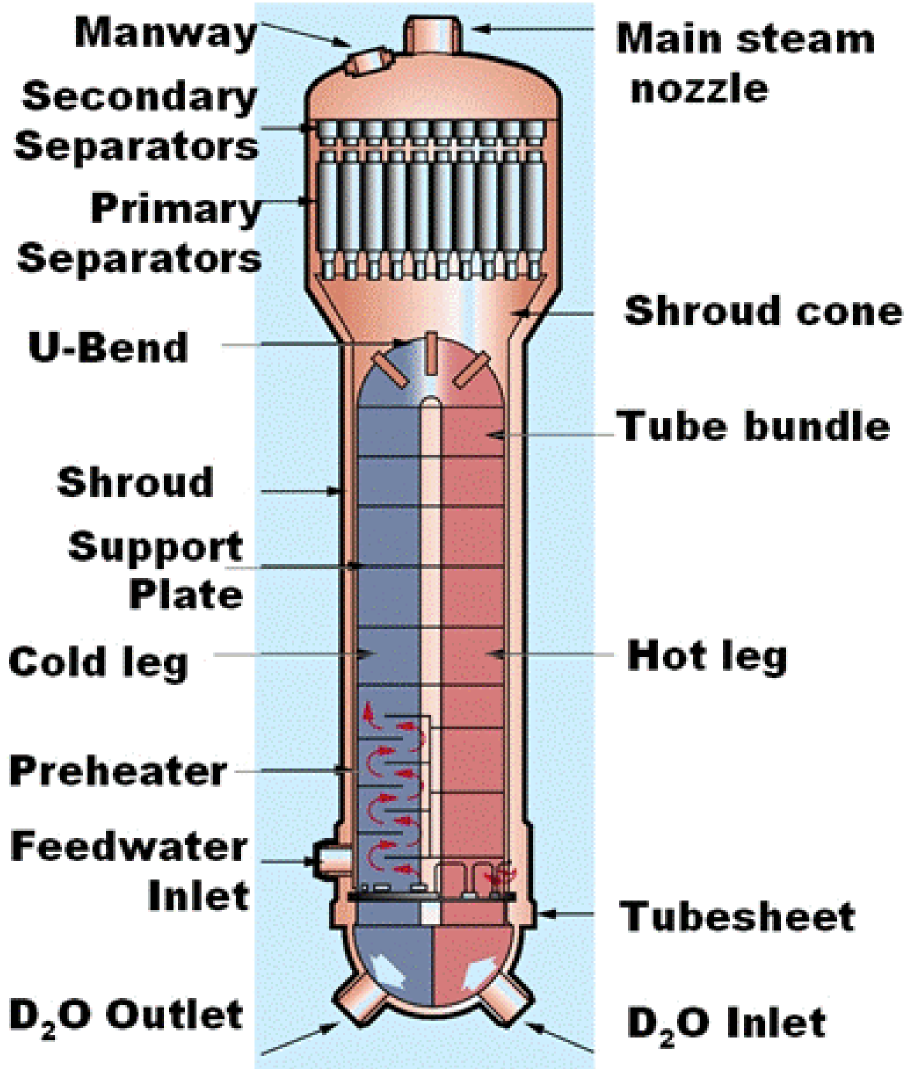
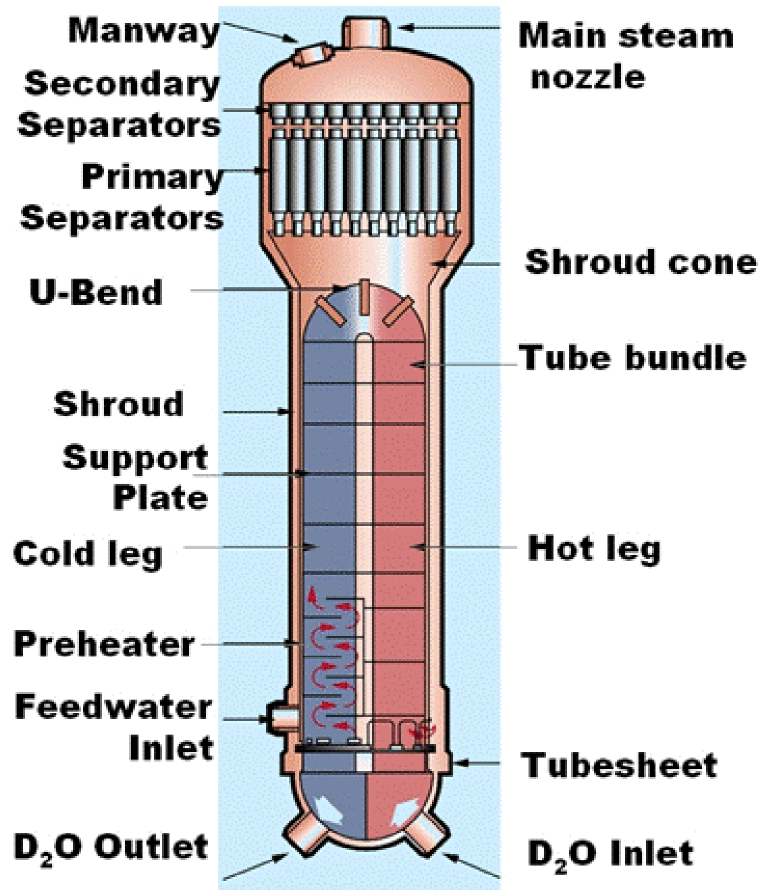


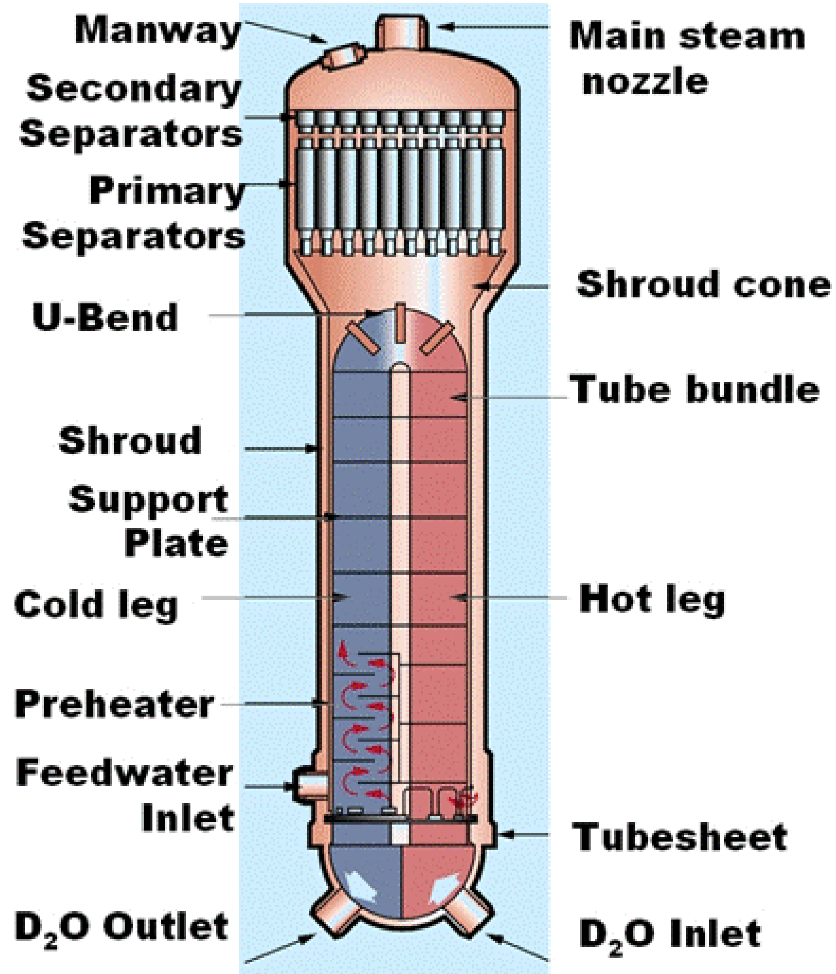
Figure 7 : Typical steam generator design

The primary coolant moves through the U-tubes from right to left in the diagram, starting as saturated with a certain percentage of quality and becoming sub-cooled as it transfers the heat to the secondary side.



The secondary coolant (feedwater) enters sub-cooled and, as it receives heat from the primary side, heats up to saturation.

Thereafter, the secondary coolant boils off as it receives more heat through the steam generator.



2.1.4 Pressurizer

- The pressure in the reactor primary coolant system is maintained at a controlled level by a pressurizer.

- The pressurizer contains steam in the upper section of its cylinder and water in the lower section.

(See figure)

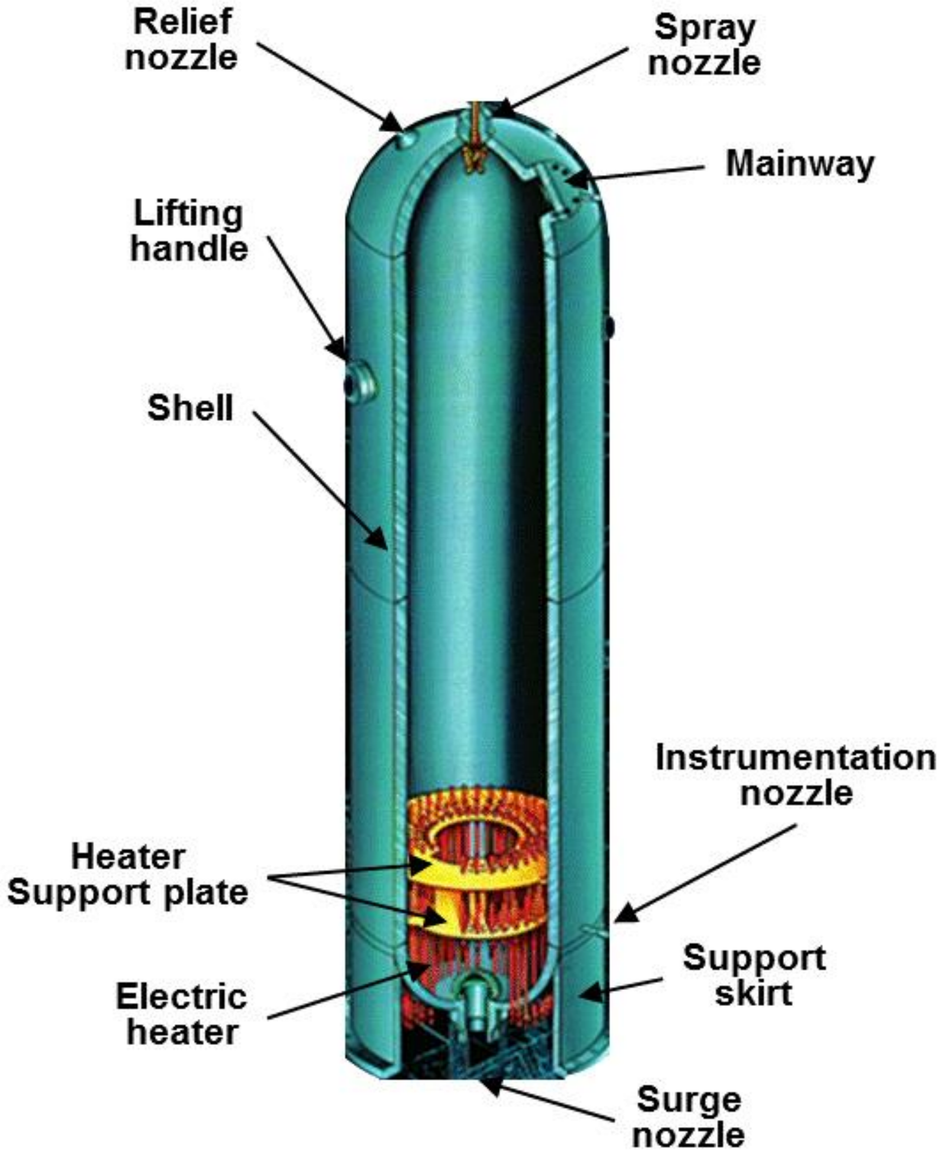


Figure 8 : Typical pressurizer design

- The pressurizer is connected to the primary loop through a surge nozzle at the bottom.

- Heaters are provided at the bottom of the pressurizer internals, and
- a spray nozzle, relief nozzle, and safety nozzle are installed at the top of the pressurizer head.

- A "**positive surge**" of water from the primary loop due to increasing loop pressure is compensated for by injecting cold water from the top of the pressurizer to condense steam

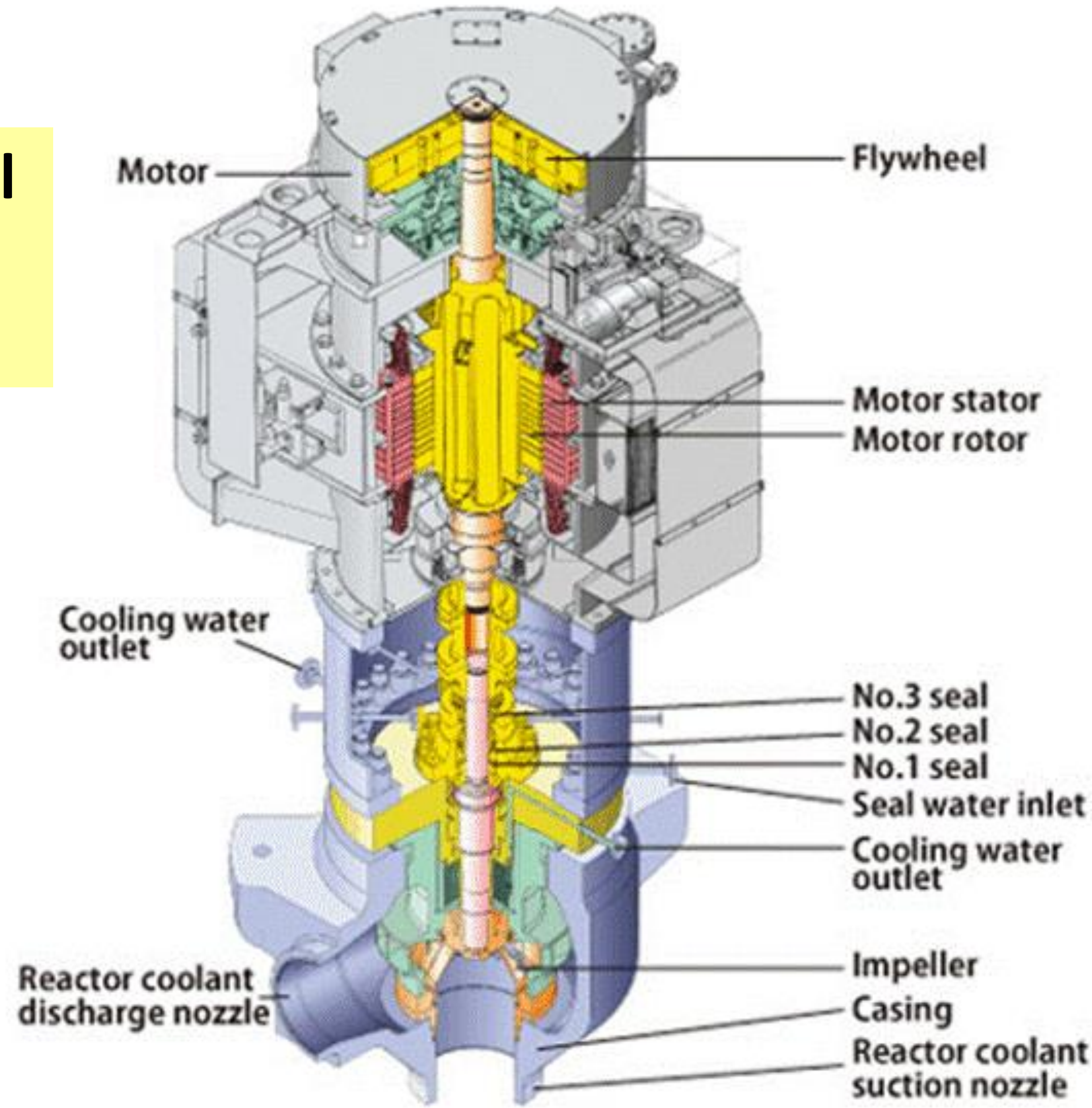
A "**negative surge**" of water empties the pressurizer, reducing steam pressure at the top of the pressurizer and thus loop pressure.

In this situation, the electrical heaters at the bottom of the pressurizer are automatically activated, converting a portion of the water into steam, resulting in a loop pressure increase

2.1.5 Primary pumps

- The primary pumps used in the CANDU heat transport system are vertical, centrifugal motor-driven pumps with a single suction and a double discharge.

Figure 9 : Typical primary pump design



- As shown in Figure 9, the pump impeller is at the bottom of the pump,
- and the pump shaft extends upward to the pump motor, passing through a number of pump seals and holding the pump flywheel.

- In the event of electrical power supply interruption, cooling of the reactor fuel is maintained by
  - the rotational momentum of the heat transport pumps during reactor power rundown and
  - by natural convection flow after the pumps have stopped.

2.1.6 Primary heat transport piping

- The CANDU reactor contains a relatively large number of pipes, called **feeders**, and
- manifolds, called **headers**, in the primary heat transport system,
- which are used to distribute coolant to the **fuel channels** in the core.

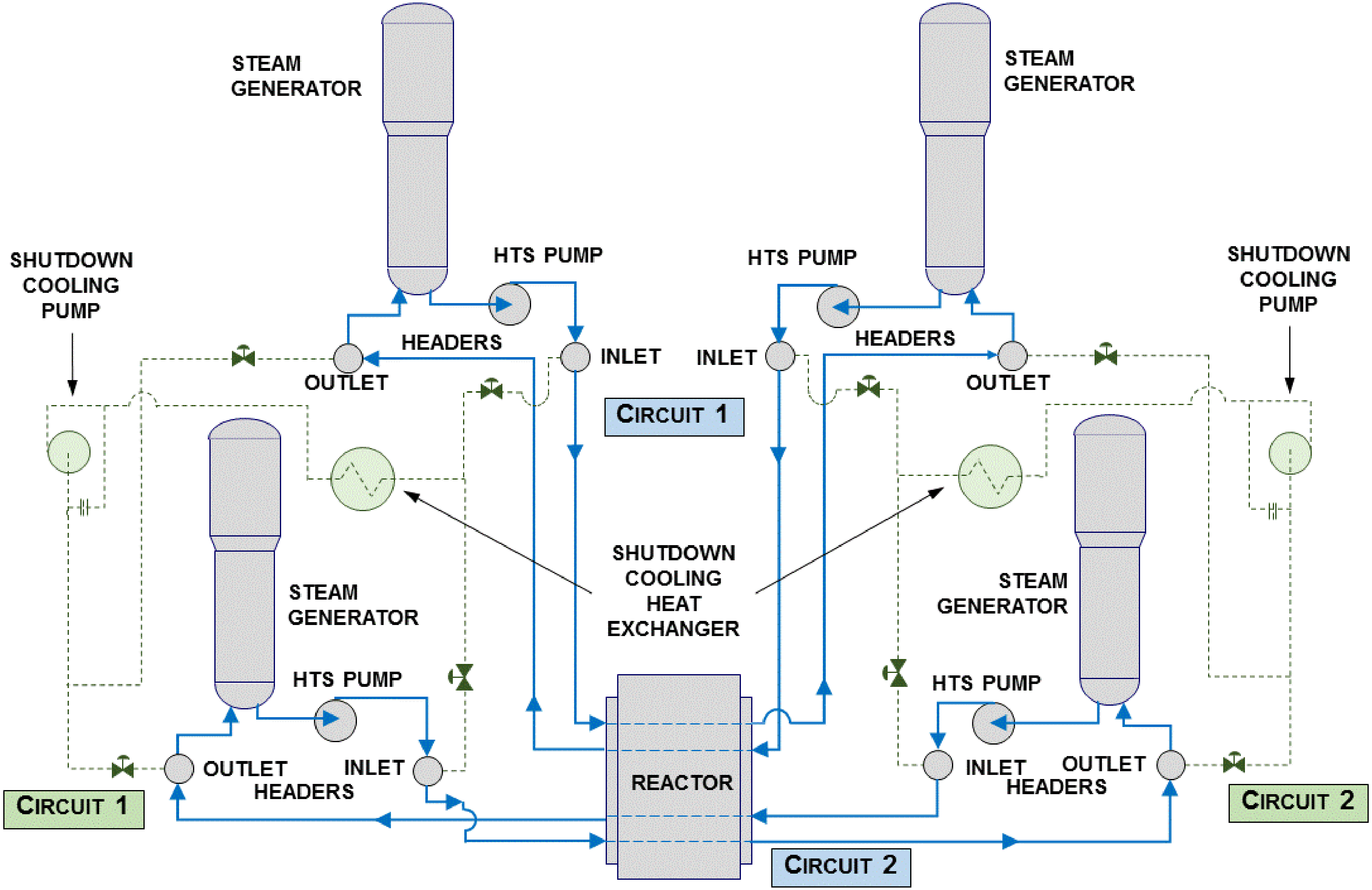
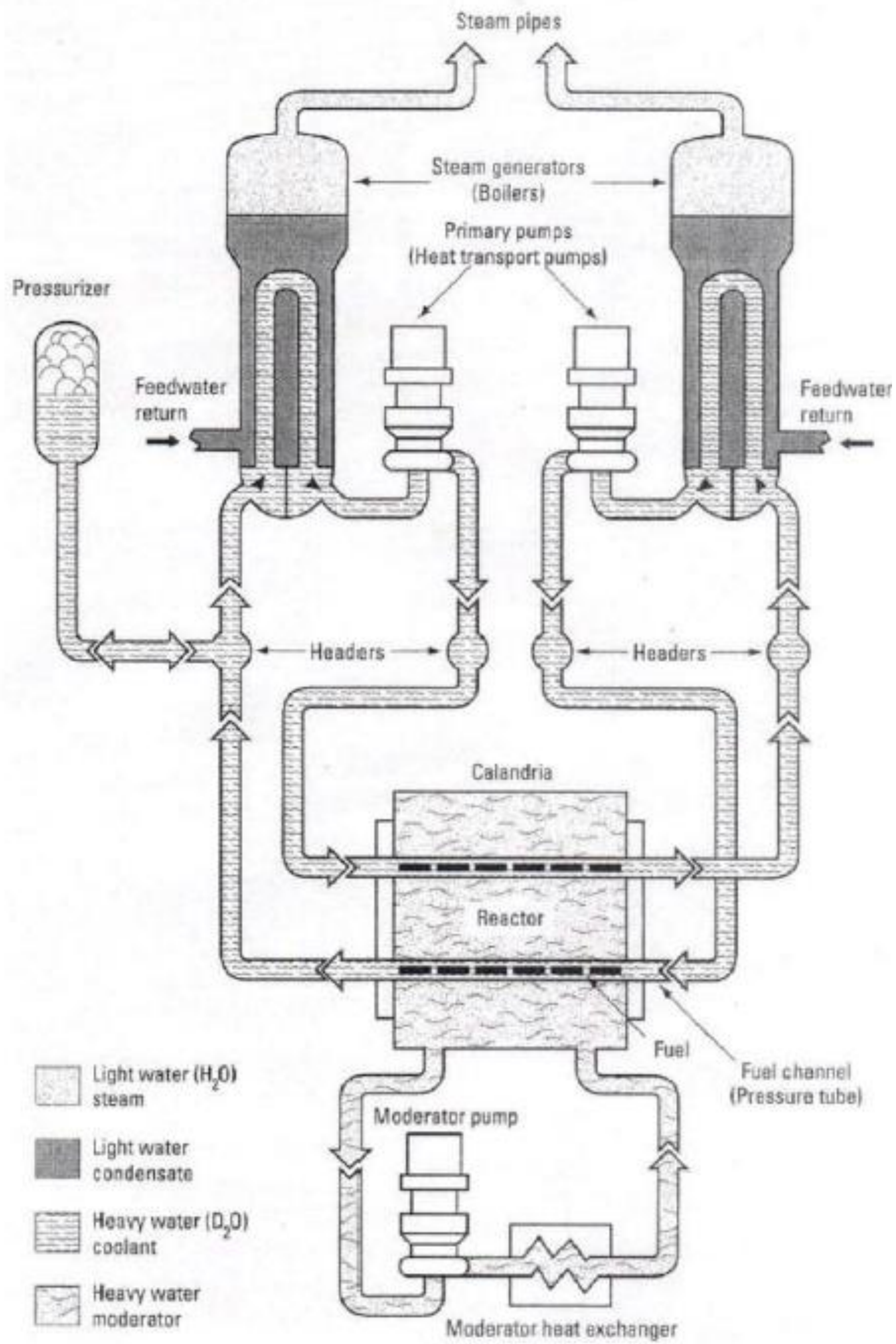


Figure 3a : CANDU 6 reactor cooling loops (HTS & shutdown cooling loops)



Primary heat transport system

Moderator circuit

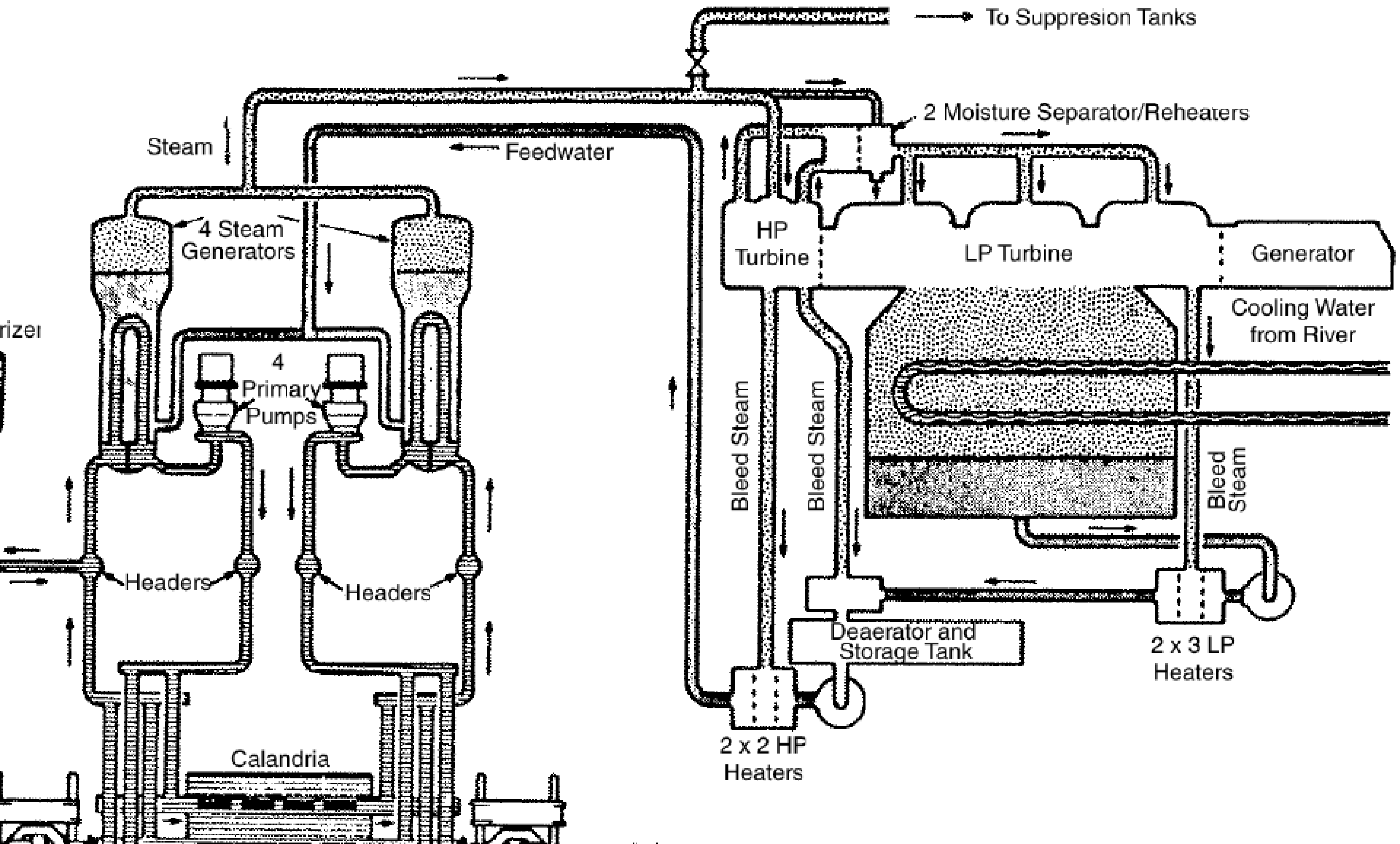
2.1.7 Secondary heat transport system design

- The nuclear power plant's (NPP's) secondary heat transport system transfers the generated energy from the primary closed circuit to the secondary,
  - where the heat energy is transformed into mechanical energy of rotation in the turbine and then into electrical energy by the electric generator.

The main components of the secondary heat transport system are

- –**the steam turbine,**
- –**condenser,**
- –**heat exchangers,**
- –**feedwater pumps**,
- –valves and piping;

Secondary heat transport system



2.1.8 Turbine

- The CANDU steam turbine is typically a tandem compound unit, directly coupled to an electrical generator by a single shaft.
- It consists of one double-flow high-pressure cylinder followed by external moisture separators, five steam reheaters, and three double-flow low-pressure cylinders.
- The turbine is designed to operate with saturated inlet steam

2.1.9 Condenser

- The turbine condenser consists of three separate shells. Each shell is connected to one of the three low-pressure turbine exhausts.
- Steam from the turbine flows into the shell, where it is condensed by flowing over a tube bundle assembly through which cooling water is pumped.

- The condenser cooling water typically consists of a once-through circuit that uses water from an ocean, lake, or river or is connected to cooling towers.
- The condensed steam collects in a tank at the bottom of the condenser called the “hot well”.
- A vacuum system is provided to remove air and other non-condensable gases from the condenser shell

2.1.10 Heat exchangers and pumps

- The condensate from the condenser is pumped through the feedwater heating system before returning to the steam generators

- Typically, it first passes through three low-pressure feedwater heater units.

- Next, the feedwater enters a deaerator, where dissolved oxygen is removed.

- From the deaerator, the feedwater is pumped to the steam generators through two high-pressure feedwater heaters

Problems (Lecture 1)

1.1 Name and describe the function of the main components of the CANDU primary heat transport system.

1.2 Describe the main components of the pressurizer in a CANDU reactor, with a detailed explanation of the method it uses to control the primary heat transport system pressure.

1.3 Provide a description of the steam generator function, with specific reference to its role in the relationship between the primary and secondary heat transport systems. Discuss the relationship of these systems with the overall size of a steam generator.