CHAPTER 1

Introduction

1.1 Introduction to Types of Nuclear Power Plants

Nuclear Fission

One of Einstein's greatest discoveries is that the law of conservation of energy must be generalized to include mass as a form of energy

$$\mathcal{E} = mc^2, \tag{1.1.1}$$

where $\mathcal{E}$ is energy, m is mass, and c is the speed of light. Any change in mass in a reaction is accompanied by release or intake of energy. Nuclear energy comes from changes in the nuclei of atoms, which produces energy by mass conversion.

The purpose of a nuclear power plant (NPP) is to generate electricity safely, reliably, and economically. In nuclear reactors, nuclear fission releases heat energy by splitting atoms; it takes place when a large, somewhat unstable isotope, is bombarded by high-speed neutrons, causing it to undergo fission (break into smaller particles). In fission reaction, energy is released, and the process has potential of being self-perpetuating because neutrons that emerge from fission can induce more fissions. A reactor is a device to maintain and control nuclear fission chain reactions and convert the nuclear energy released by fission to heat energy.

Reactor Types

There are more than 400 nuclear power reactors, representing about 16% of the total electricity production of the world. The types of reactors could be categorized according to the purpose, coolant type, moderator type, and fuel.

The main design of a reactor for NPP is the pressurized water reactor (PWR), which has water at over 300°C under pressure in its primary cooling/heat transfer circuit and generates steam in a secondary circuit. The less numerous boiling water reactor (BWR) makes steam in the primary circuit above the reactor core, at similar temperatures and pressure. Both PWR and BWR use enriched uranium as fuel and water as both coolant and moderator to slow down neutrons. Because water normally boils at 100°C, they have robust steel pressure vessels or tubes to enable the higher operating temperature.

In Canada, CANDU (CANada Deuterium Uranium) reactors are employed, which is a pressurized heavy water reactor (PHWR) type. Heavy water is used as both moderator and coolant in CANDU reactors.

PWR

Figure 1.1 shows a schematic diagram depicting a typical working process of PWR NPP. Water carries heat from the fission heat generated from the reactor vessel and becomes high-temperature and high-pressure water. It then flows into U tubes of the steam generators (primary coolant loop) and exchanges heat with the feeder water outside the U tube (secondary loop), which becomes saturated steam. The main steam lines direct the steam, which powers the turbine generator. The cooled coolant is then pumped back to the reactor to be reheated; this circulation is iterated and forms a closed heat absorption and release loop called first loop, also known as a nuclear steam supply system.

BWR

In a BWR reactor, a steam–water mixture is produced when reactor coolant (pure water) moves upward through the core, absorbing heat. The steam–water mixture leaves the top of the core and enters the two stages of moisture separation, where water droplets are removed before the steam is allowed to enter the steam line, which directs the steam to power turbine generator.

The major difference between a PWR and a BWR is that a PWR has water at over 300°C under pressure in its primary cooling/heat transfer circuit and generates steam in a secondary circuit, while a BWR makes steam in the primary circuit above the reactor core.

PHWR (CANDU)

Figure 1.2 shows a schematic diagram illustrating the working process of a CANDU 6 reactor. A CANDU 6 nuclear steam supply system's power production process starts like that of any other PWR nuclear steam supply system, with controlled fission in the reactor core. However, unlike other reactors, the CANDU 6 is fuelled with natural uranium fuel that is distributed among 380 fuel channels. Each six-meter-long fuel channel contains 12 fuel bundles. The fuel channels are housed in a horizontal cylindrical tank (called a calandria) that contains cool heavy water (D_2O) moderator at low pressure. Fuelling machines connect to each fuel channel as necessary to provide on-power refuelling; this eliminates the need for refuelling outages.

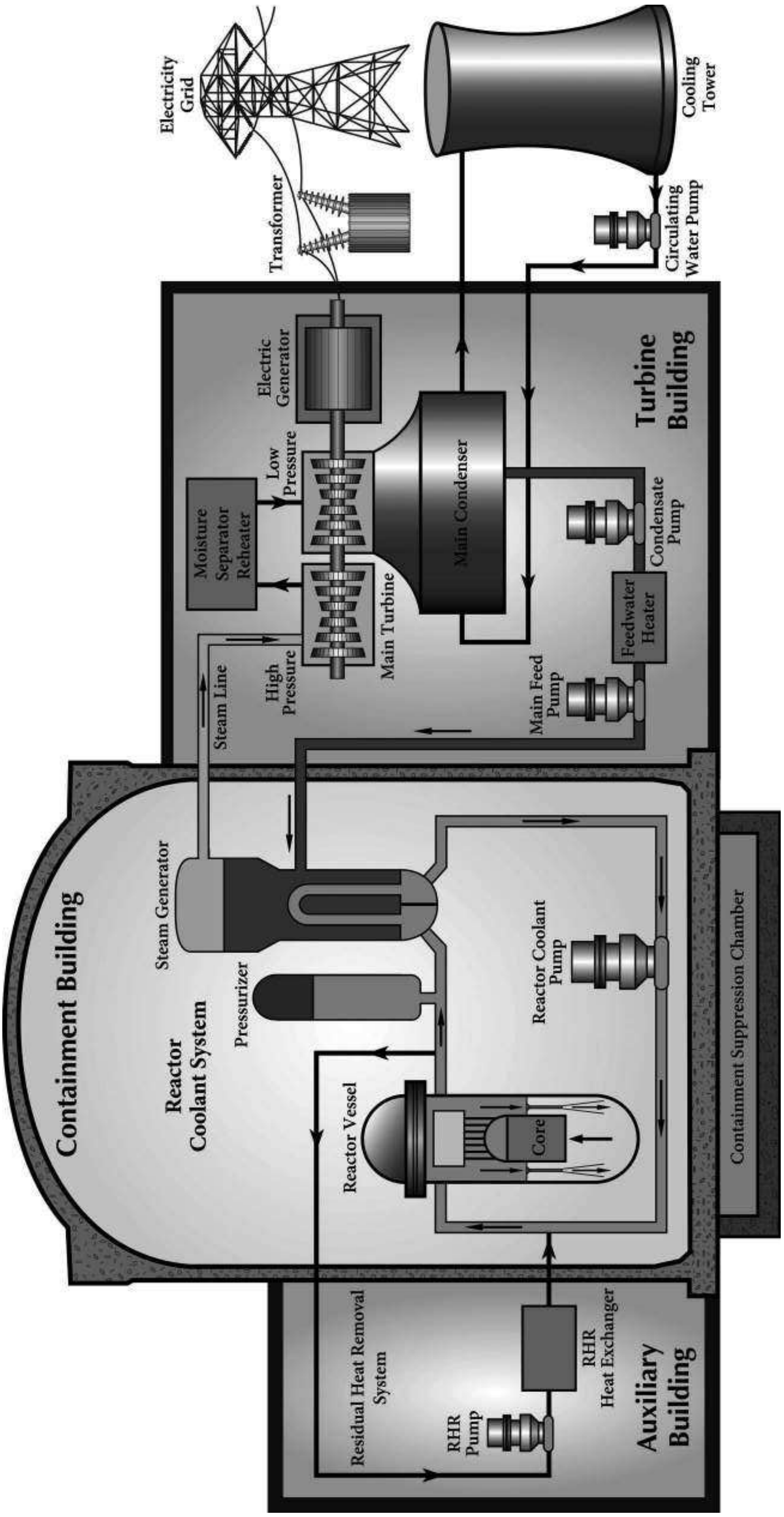

Figure 1.1 Pressurized water reactor (PWR).

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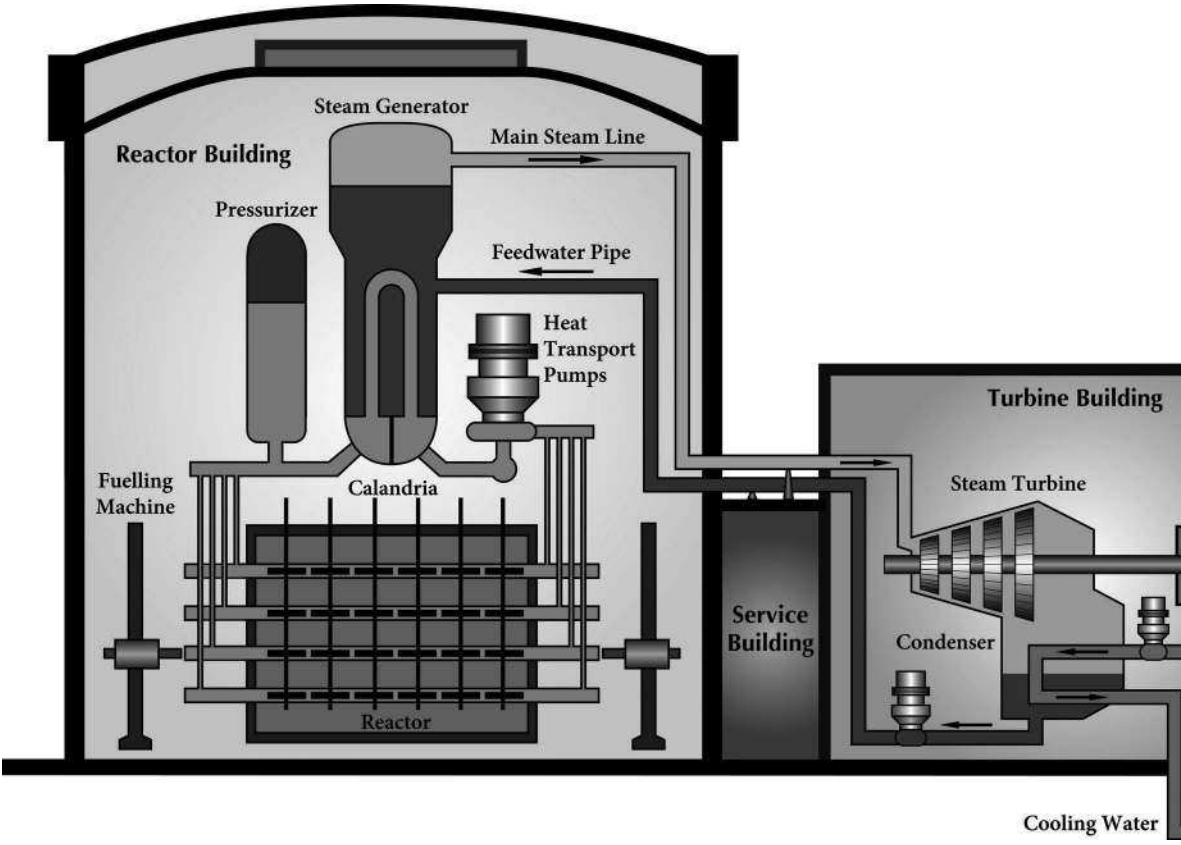

Figure 1.2 CANDU reactor.

1.2 Important Structures, Systems, and Components in Nuclear Power Plants

In this section, only the structures, systems, and components (SSCs) of PWR and PHWR are described.

General Description

According to functions of the building structures, PWR NPP could be grouped into

- Nuclear island (NI) or nuclear steam plant (NSP),
- Conventional island (CI) or turbine island,
- Balance of plant (BOP).

PHWR NPP consists of

- Nuclear steam plant (NSP), including the balance of nuclear steam plant (BNSP),
- Balance of plant (BOP).

Per definitions of NI, CI, and BOP for PWR and NSP, BNSP, and BOP for PHWR

- NI of PWR = NSP (including BNSP) of PHWR,
- (CI + BOP) of PWR = BOP of PHWR.

The NI/NSP part of the NPP is defined as all equipment required for the production of steam, including the nuclear reactor, relevant safety systems, and their auxiliaries. The main functionality of NI is to utilize the energy from nuclear fission to generate steam.

- In PWR NPP, NI includes five main building structures:
  - reactor building,
  - fuel building,
  - electrical building,
  - connecting building,
  - nuclear auxiliary building,

  as well as other building structures, such as an emergency diesel generator building.
- In PHWR CANDU 6 NPP, NSP (including BNSP) includes
  - reactor building,
  - service building,
  - secondary control area,
  - emergency water supply pump house,
  - emergency power supply building,
  - high-pressure emergency core cooling building,
  - D_2O upgrading tower.

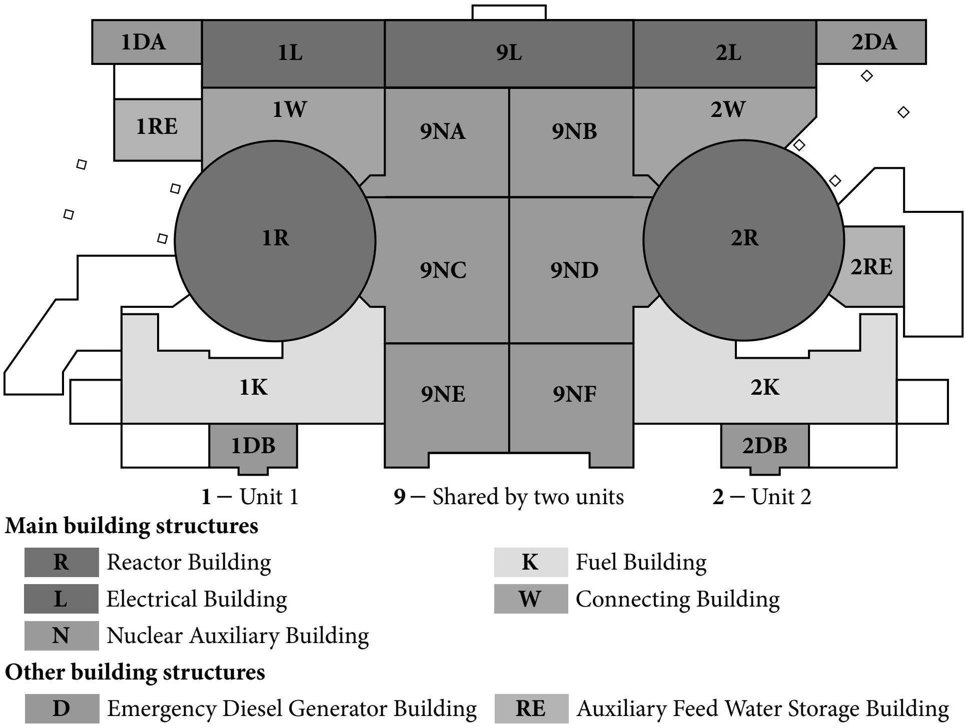

Figure 1.3 PWR NPP layout.

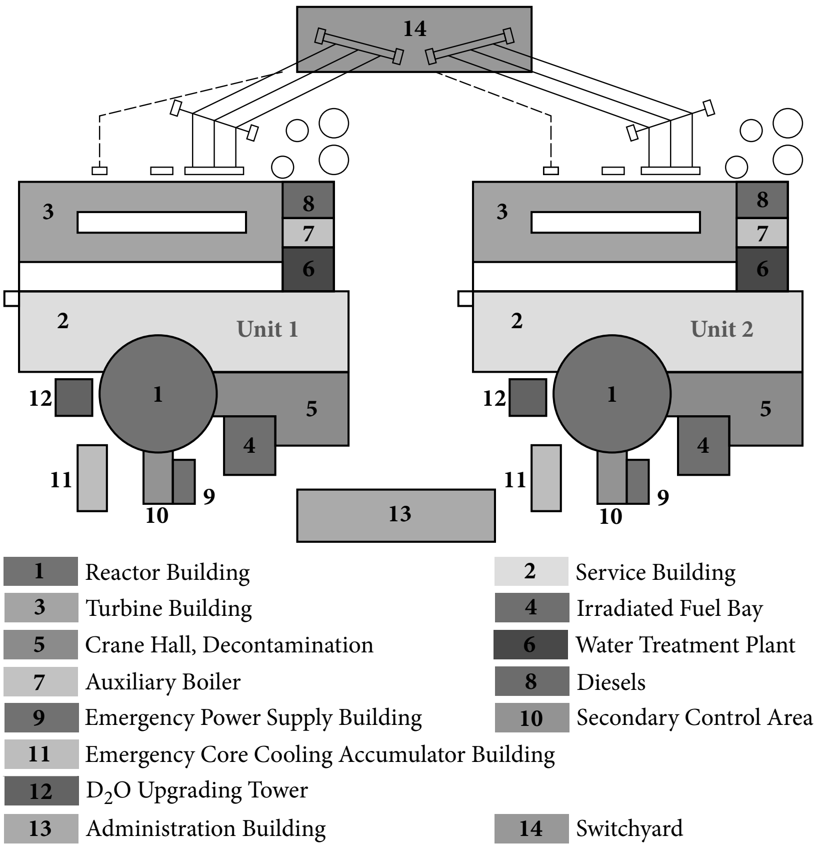

Figure 1.4 Candu PHWR NPP layout.

Conventional island (CI), also called turbine island, is the general term for the turbine-generator set and its supporting facilities in an NPP. The main function of the conventional island is to convert the thermal energy of the steam produced at the nuclear island into mechanical energy of the steam turbine and then into electrical energy through the generator. For all NPPs, CI are similar.

Schematic layouts of a PWR plant and a CANDU 6 PHWR plant are shown in Figures 1.3 and 1.4, respectively. In this book, the main focus is on the NI/NSP, where safety-related SSCs are located.

Reactor Building

The reactor building (RB) houses the primary coolant loop together with its associated auxiliary and safety systems. For PHWR, unique moderator systems and fuel-handling systems are also housed inside the reactor building. To minimize the seismic response, the heavy equipment is located close to low elevations of the reactor building, and the structural and equipment layouts are designed to be as symmetrical as possible. To optimize the seismic response of the reactor building, the containment structure of the reactor building is designed as ellipsoid. The reactor building is divided into three major structural components:

- ❧ prestressed concrete containment structure,
- ❧ internal reinforced concrete structure,
- ❧ reinforced concrete reactor vault (PHWR only).

The containment structure is the main component of the containment system. This system is provided to ensure that public exposure to radiation is prevented beyond the station's exclusion area in the event of the accidents postulated for the reactor. The containment structure is typically a prestressed concrete building comprising three structural components:

- ❧ a base slab,
- ❧ a cylindrical perimeter,
- ❧ a spherical segmental dome.

The internal structure supports reactor process systems and is therefore a major nuclear support structure.

1.3 Seismic Design Philosophy and Requirements

In this section, seismic design philosophy and high-level seismic requirements for NPPs are briefly introduced. The philosophy is general and applicable to all types of nuclear reactors, but it is presented here in the terminology for CANDU NPPs.

Seismic Levels

For CANDU plants, two levels of earthquake are defined as design envelopes for achieving the safety objectives (CSA N 289.3, CSA, 2010a):

❧ **Design Basis Earthquake (DBE)** – an engineering representation of potentially severe effects at the site due to earthquake ground motions having a selected probability of exceedance of 1×10^{-4} per year.

❧ **Site Design Earthquake (SDE)** – an engineering representation of the effects at the site of a set of possible earthquakes with an occurrence rate, based on historical records, not greater than 1×10^{-2} per year.

☞ DBE or SDE ground motion is usually referred to as an "earthquake" and can take the form of a response spectrum or time-history.

Seismic Categories

Two categories, "A" and "B", are used in design to establish the extent to which components must remain operational during and/or after an earthquake:

❧ **Category "A" Components** – Those that must retain their pressure boundary integrity or structural integrity or passive function (e.g., cables) and are not required to change state during and/or following an earthquake.

❧ **Category "B" Components** – Those that must retain their pressure boundary integrity and remain operable during and/or following an earthquake.

Site Considerations

When selecting an NPP site, the following seismic-related aspects must be considered:

- ❧ Seismicity is a major item for site selection.
- ❧ Seismic requirements generally refer to the ability of the facility to withstand movement in three orthogonal directions (two horizontal and one vertical).
- ❧ The seismic requirement for a generic NPP design is typically $0.2g$ peak ground acceleration (PGA) for GEN II and $0.3g$ PGA for GEN III reactors.
- ❧ For seismic considerations, an NPP is selected to be founded in a geologically stable zone and should not be near fault lines.
- ❧ The space requirements between the structures will be determined by seismic movements of the structures.

1.3.1 Safety Functions

Nuclear safety requires that the radioactive products from the nuclear fission process of the reactor be contained, both within the plant systems for the protection of the plant workforce and outside the plant structure for the protection of the public. The safety-related SSCs, which are necessary to ensure the four basic safety functions that have to be performed both during and after a severe earthquake, are seismically qualified to perform these safety functions. These four safety functions are essentially the same for all NPPs, but for different types of reactors the descriptions are somewhat different because the systems and components are different. For a CANDU NPP, the four major safety functions are as follows:

1. **Shut down the reactor and maintain it in a safe shutdown condition**

   ❧ Shutdown system #2 is qualified to shut down the reactor but is not qualified to be recocked. Shutdown system #1 is qualified to drop the rods into the core if electrical power to the clutch assemblies is lost.

   ❧ Even though the shutdown systems can shut down the reactor under any circumstances, the reactor regulating system is qualified to ensure that a seismically induced failure in this system will not cause an increase in positive reactivity exceeding the capability of the shutdown systems and heat removal systems.

2. **Remove decay heat**

   ❧ The primary heat transport system (HTS), including the fuel channels, headers, pumps, steam generators, and connected subsystems, are qualified to ensure that a loss of coolant accident (LOCA) does not occur as a result of the earthquake.

   ❧ The pumps may not remain operable, in which case the fuel is cooled by natural circulation – "thermosyphoning". The pumps remain freewheeling immediately after the earthquake to enable pump rundown to assist thermosyphoning.

   ❧ Because a reduction in coolant inventory may be caused by shrinkage due to cooling, minor leaks, or transfer of coolant to the bleed condenser, the emergency water supply (EWS) system is qualified to provide a light water makeup after a period of about thirty minutes.

   ❧ If the normal unqualified feedwater system fails, an alternative qualified source of emergency water is available, either from the dousing tank, or from the EWS.

   ❧ A portion of the main steam piping and the main steam safety valves is qualified to ensure that the residual heat is discharged to the atmosphere.

   ❧ The recovery portion of the emergency core cooling (ECC) system is qualified to cater for the occurrence of an SDE following a LOCA. Cooling water to the ECC heat exchanger is supplied by the EWS.

   ❧ Electrical power is supplied by the emergency power supply system.

- ❧ The high- and intermediate-pressure portions of the ECC system need not be qualified because the earthquake is not postulated to occur immediately after a LOCA.

3. **Maintain a barrier to limit the release of radioactive material**

   - ❧ Structures or components outside the reactor building whose failures could result in the release limits being exceeded are seismically qualified. This includes the spent fuel storage bay. The reactor building containment system is qualified to remain available after an earthquake.
   - ❧ Releases of radiation within containment may be caused by minor leaks in the HTS (possibly existing prior to the earthquake) or by interruption of the cooling to spent fuel being transferred in the fuelling machine. The containment system must also remain functional for the occurrence of an SDE following a LOCA.
   - ❧ The containment needs not be qualified to withstand peak building pressure coincident with an earthquake. However, the containment structure is qualified to withstand a "reduced accident pressure" (due to the failure of piping or components that are not qualified and that may contain high energy) combined with the DBE.

4. **Perform essential safety-related control and monitoring functions**
   The secondary control area (SCA) and the control and monitoring systems associated with it are qualified.

   - ❧ Electrical power is supplied from the qualified emergency power system.
   - ❧ A qualified source of instrument air is supplied, in the form of qualified local air tanks, where required for essential control functions.
   - ❧ A sufficient number of control and monitoring functions are provided in the SCA, or in areas accessible after a seismic event, to shut down the reactor and maintain it in a safe shutdown condition.
   - ❧ Structures and components that may pose a hazard to seismically qualified systems are also qualified.

In addition to the systems and components noted earlier, structures that house and support them also have a safety function to maintain their structural integrity during and following the earthquake. These structures include

- the reactor building,
- the service building,
- the secondary control area building,
- the structure housing the main steam safety valves.