25 The Conventional Side of the Station

25.1 Introduction

The basic similarity between typical electric generating stations is the conversion of shaft mechanical power to electrical power in a generator. The major difference comes from the method used to produce the shaft mechanical power. There are four principle methods of obtaining this shaft power in general use:

- hydraulic turbines,
- fossil fuel steam turbines,
- nuclear steam turbines, and
- gas turbines.

This module covers nuclear steam turbines and the different systems involved in the energy conversions. Electric power production requires the transfer and conversion of heat energy to mechanical energy. This is achieved by two basic energy transport systems: the heat transport system and the steam/feedwater system. These systems are sometimes called the primary heat transport system and the secondary heat transport system. The following sections discuss the steam/feedwater cycle, the equipment involved, energy transfers, control, and auxiliary equipment required. The values of pressure, temperature, etc., quoted in the text refer to full power operation and are approximate. Real values differ slightly from station to station.

25.2 The Boiler (Steam Generator)

During normal operation, the heat transport system transfers heat from the reactor to the secondary coolant by way of the boilers. The boilers thus act as the principal heat sink for the reactor. Reactor heat is transferred from the HTS to the boiler feedwater. As a result, the boiler produces steam to drive the turbine. To understand the production of steam in the boilers, it is useful to introduce some terminology.

Figure 25.1 shows the effect of adding heat to a kilogram of water. Adding more heat to the water will increase its temperature until it reaches the boiling point. At this point we say that the water has reached the saturation temperature. As we add more heat, latent heat of vapourization is added causing the water to boil. From this point, the water temperature does not change. The ratio of steam to water shifts to a higher steam percentage as more heat is added. The steam, being lighter than water, rises, leaving the water behind. This steam, which is free of moisture, is called saturated steam. Applying more heat to the saturated steam will increase the temperature above the boiling point.

When the steam temperature is above the boiling point, we have superheated steam.

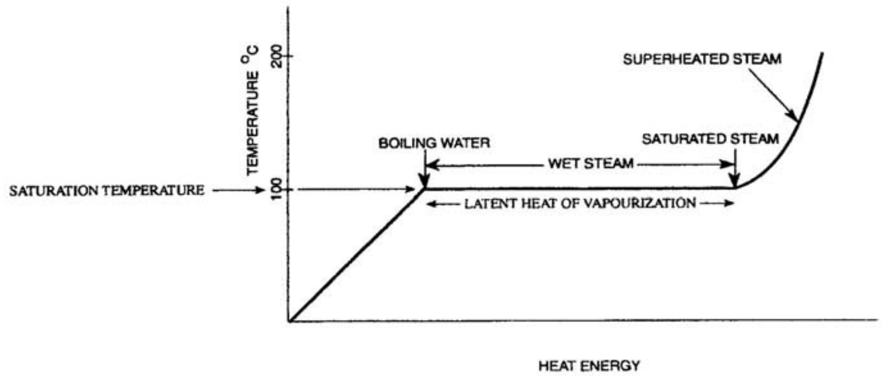

Figure 25.1

Figure 25.2 shows the effect of increasing the pressure in the boiler to 4000 kPa. Boiling does not occur until the temperature reaches 250°C. Saturated steam at about 250°C and 4000 kPa is typical in CANDU nuclear boilers. The temperature and pressure of the steam indicate its energy content. The higher the temperature and pressure the greater the heat energy will be. In boiler operations it is very important that steam pressure is maintained.

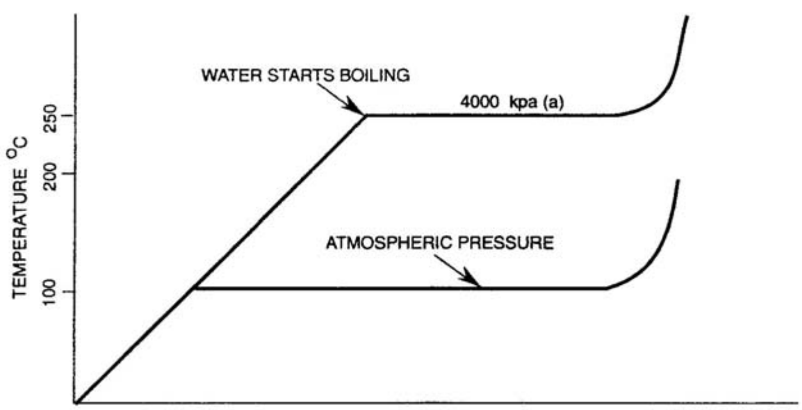

Figure 25.2

Figure 25.3 shows a nuclear power plant boiler typical of those used in large generating stations. Hot, pressurized heavy water enters the boiler and passes through the tube bundle. The heavy water inside the tube is hotter than the feedwater around the tubes. This allows heat transfer from the heavy water to the feedwater, causing the feedwater to boil.

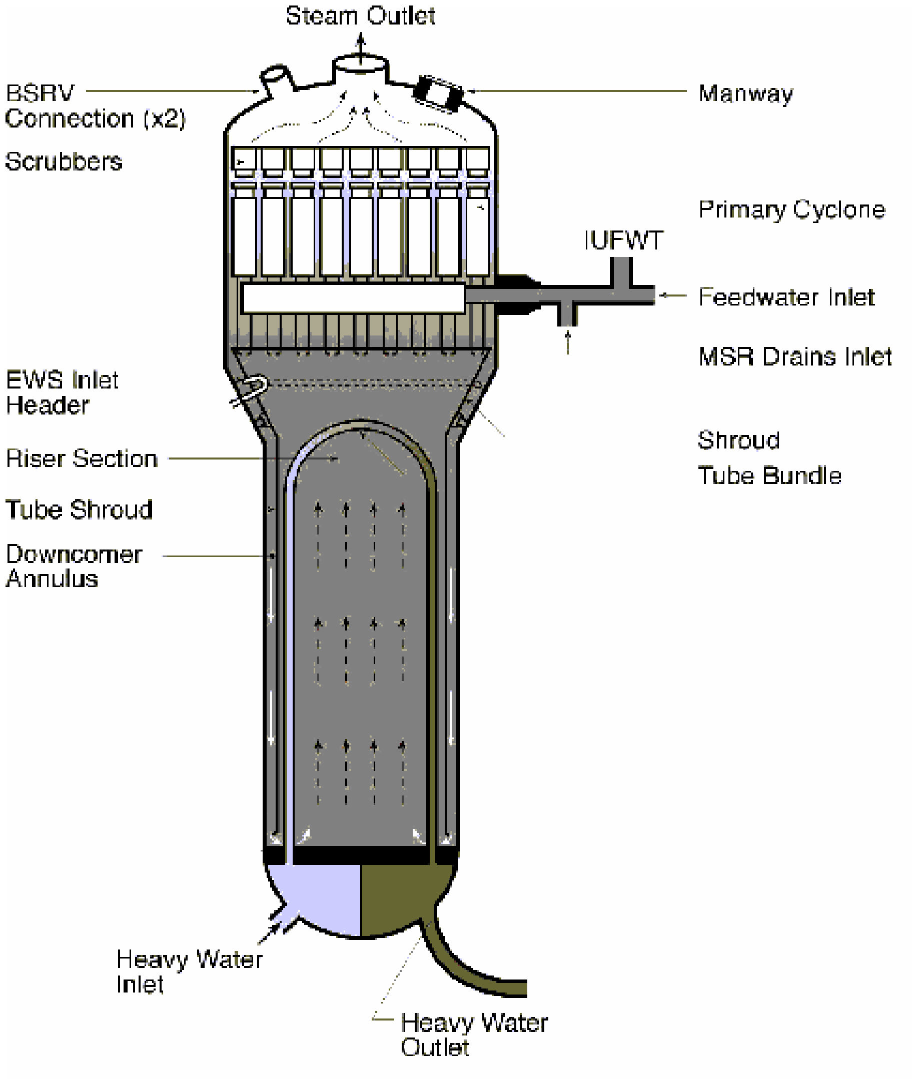

Figure 25.3
Typical Boiler

The steam leaving the top of the tube bundle is about 90% water. To prevent damage to the steam piping, valves and (most important) the turbine, only dry steam must leave the boiler. Cyclone separators, located above the tube bundle, dry the steam by giving the steam/water mixture a swirling centrifugal motion. The water, being denser than steam, moves to the outside area of the separator and is drained off. The steam that leaves the top of the cyclone separators has low moisture content but is still unacceptable for use in the turbine. The steam scrubbers, located above the cyclone separators, remove the last traces of moisture.

Water separated from the steam in the cyclone separator and steam scrubber drains to the outside of the boiler's tube shroud. The water flows down to the bottom of the boiler through the downcomer annulus and re-enters the tube bundle area enabling it to generate more steam. The amount of water cycling through the tube bundle, through the downcomer, is typically ten times as much as feedwater entering the boiler.

The water in the boiler moves through natural circulation without the use of pumps. The water and steam in the tube bundle move upward because of the decrease in density due to the addition of heat. The water that comes out from the cyclone separators is relatively dense, because it has no steam bubbles, and falls down the downcomer to begin the cycle again.

Simply, the feedwater flow in the boiler starts from the preheater. The preheater heats the feedwater to near saturation temperature. Inside the boiler, the feedwater circulates up around the tube bundle and down the downcomer many times while acquiring the latent heat of vapourization, and finally leaves the boiler as nearly saturated steam.

25.3 The Steam/Feedwater Cycle

The major functions of the steam/feedwater cycle are to provide cooling for the HTS and to convert heat into mechanical energy for the generator. This system operates as a continuous loop of demineralized light water. The major systems are the steam system and the boiler feedwater system.

25.3.1 The Steam System

Figure 25.4 shows a simplified schematic of the steam system and components typical of a large turbine unit. Safety valves protect the steam system components from over pressure. The pressure from the boilers drives the steam to the high-pressure (HP) turbine. On route to the turbine, the steam travels through several valves. Two, of interest, are the emergency stop valve and the governor valve. The governor valve varies the electrical output from no load to full load by controlling the quantity of steam flowing to the turbine. Before reaching the governor valve the steam passes through the emergency stop valve. The emergency stop valve quickly stops the steam flow to the turbine in the event of an emergency that could damage the turbine.

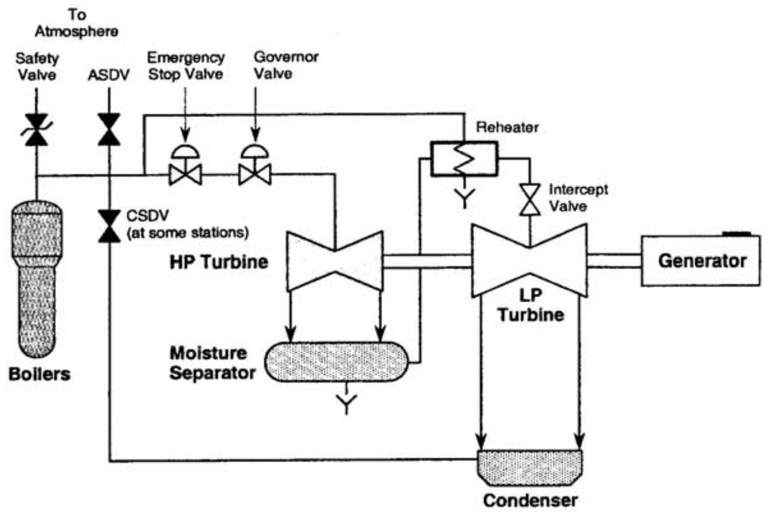

Figure 25.4
Steam Cycle

From the governor valve the steam passes through the HP turbine. The HP turbine converts the latent heat of the steam to mechanical energy. As the HP turbine uses the latent heat in the steam, the steam becomes wet (moist). Moisture content of more than 10% will cause excessive erosion on the turbine blades. Removing the moisture in the steam allows further conversion of the remaining available energy. The HP/LP arrangement of the turbine provides an opportunity at this stage to improve the quality of the steam to allow more energy to be converted without risk of damage to the turbine.

Steam leaves the high-pressure turbine at approximately 900 kPa and 170°C at 10% moisture. It passes to the moisture separator, which removes the moisture in the steam. Steam leaving the moisture separator has the same temperature and pressure as that at the turbine outlet but without moisture. It then passes through a reheater to heat the steam. This increases the work that the steam can do in the Low-pressure (LP) turbine. The reheater uses steam directly from the boiler to heat the steam from the moisture separator. The steam leaves the reheater in a superheated condition at about 230°C and 900 kPa. Before entering the LP turbine, the steam passes through intercept valves. In a fashion similar to the emergency stop valve, these valves shut off steam to the LP turbine in an emergency. Steam passes through the normally open intercept valve, passes through the low-pressure turbine, and is then exhausted to the condenser at approximately 5 kPaa (absolute pressure), 35°C and 10% moisture.

Stopping the flow of steam to the turbine results in increased boiler pressure. This can happen on a turbine trip, when the turbine is stopped due to mechanical failure. Reducing reactor power and getting rid of the steam prevents excessive boiler pressure build up. Adjusting the reactor power level too low can poison out the reactor. However, if the power level is kept above 60% full power, the reactor can keep operating. Providing an alternative heat sink, while operating at this power level, will prevent a boiler pressure increase. The alternate heat sink can be provided by blowing the steam to atmosphere or directly to the condenser. All CANDU units have large steam reject valves able to discharge steam either to the atmosphere or to the condenser with the reactor at 60% FP. They are also equipped with smaller steam reject valves that are able to discharge steam to the atmosphere at the decay heat power level, if the condenser is unavailable. The valves that direct steam to the condenser are called condenser steam discharge valves or CSDVs. The ones that send steam to atmosphere are ASDVs, an acronym for atmospheric steam discharge valves.

25.4 The Steam Turbine

The turbine uses steam from the boiler. It converts steam pressure to rotational energy. This conversion involves transformation of the heat energy (pressure) of steam into high velocity steam through fixed nozzles. A nozzle is a device that converts the heat energy of the steam to this high velocity kinetic energy. The fixed nozzles form the turbine fixed blades. The high velocity steam directs its kinetic energy on to the moving blades forcing them to move (rotate). Figure 25.5 shows how the high velocity steam leaves the fixed nozzles and drives the moving blades.

From the first set of fixed and moving blades, the steam then moves through succeeding sets to repeat the process of energy conversions. A set of fixed blade nozzles and moving blade constitutes a turbine stage. It is common to use a number of stages in a turbine to convert the useful heat energy in the steam into mechanical energy. The moving blades are attached to a blade wheel, as shown in Figure 25.6, and the blade wheel is mounted on the rotor shaft. The high velocity steam leaving the nozzle drives the wheel, which in turn rotates the shaft.

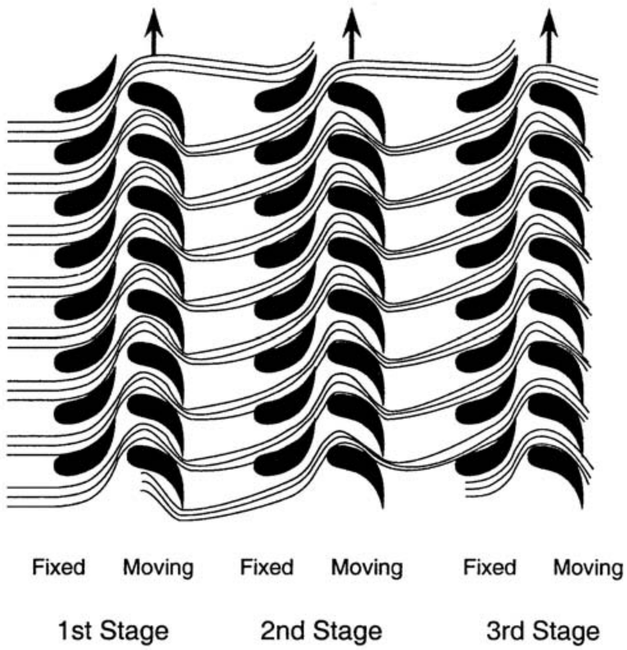

Figure 25.5
Fixed and Moving Blades Arrangement

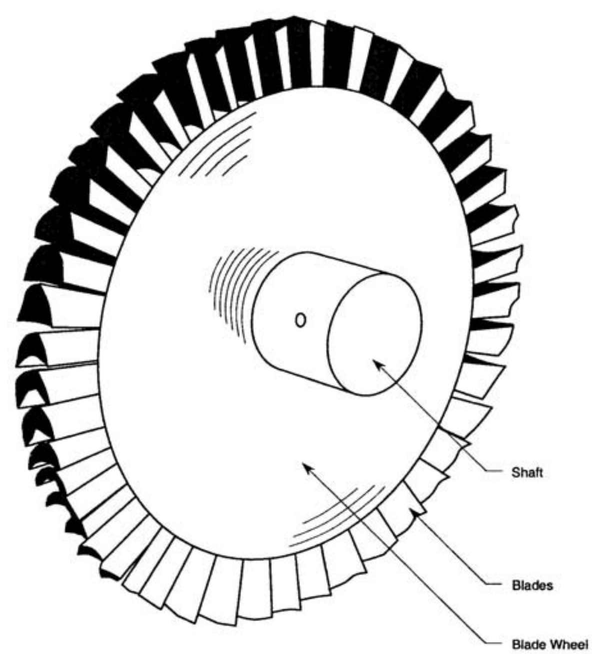

Figure 25.6
Moving Blade

Figure 25.7 is a simplified section view of a turbine. The steam turbine consists of a single rotating shaft that has a number of blade wheels attached to it. The steam passing through the turbine is contained within a casing. The casing is usually split into upper and lower halves that are bolted together. This allows the upper half to be raised for maintenance. Attached to the casing are diaphragms that support the fixed blade nozzles. Wherever the fixed and moving parts of the turbine come together, there is a need for sealing to prevent leakage from the high-pressure side to the low-pressure side. This leakage is prevented by gland seals installed on the turbine casing.

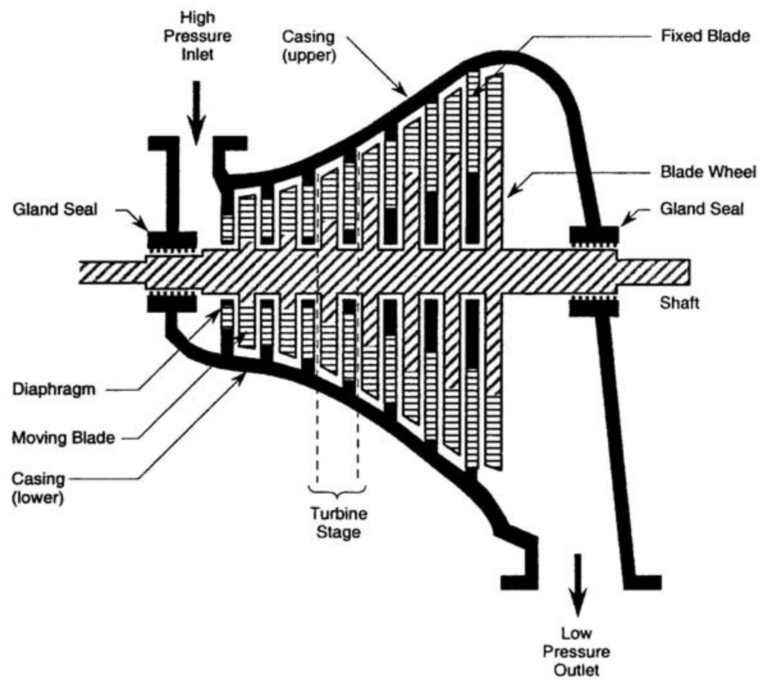

Figure 25.7
Turbine Section View

Figure 25.8 shows the construction of a typical diaphragm. The upper and lower halves of the diaphragm attach to the upper and lower casings respectively.

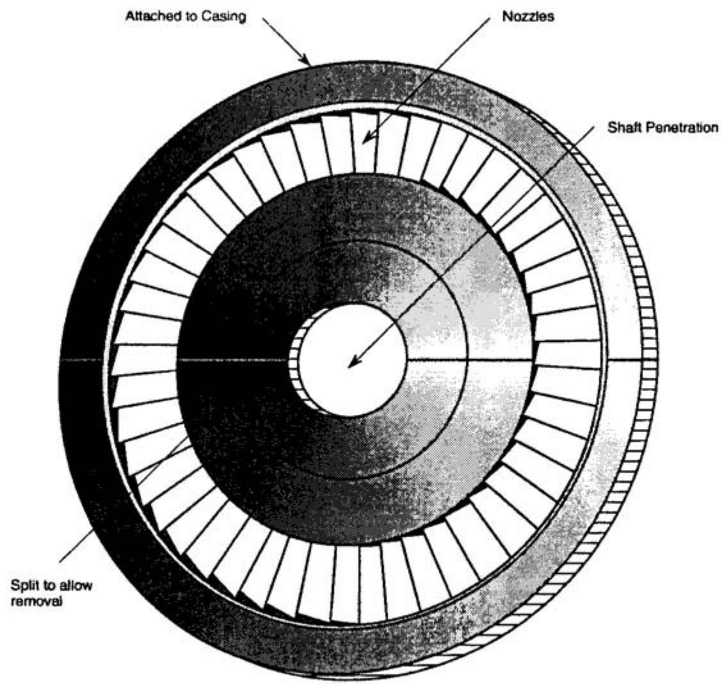

Figure 25.8
Turbine Diaphragm

Looking at Figure 25.7, you will note that the turbine casing gets progressively larger as the steam goes from the high-pressure end to the low-pressure end. This is necessary to accommodate the expansion of the steam as a direct result of pressure and temperature reduction. Steam entering the high-pressure end of a modern nuclear turbine set is typically around 250°C and 4000 kPa. At this temperature and pressure, one kilogram of steam occupies .05 m^3. The steam leaving the turbine unit and entering the condenser is typically around 35°C and 5 kPa(a). At this temperature and pressure one kilogram of steam occupies 25.2 m^3. The steam expands roughly five hundred times from the inlet to the exhaust. In a large turbine generator set it is usually not possible to accommodate the large volume of steam in one turbine unit. Normally one high-pressure turbine will exhaust to two or more low-pressure turbines in combination with the double flow design.

Figure 25.9 shows a turbine unit typical of those installed at a modern CANDU plant.

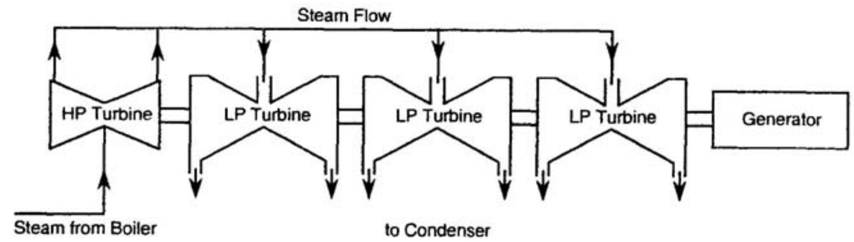

Figure 25.9
Typical Turbine Layout

Why use double flow steam turbines? The double flow turbine design not only provides double the expansion volume within a common casing, it also balances the large pressure drop between the turbine steam inlet and exhaust which tends to force the blade wheels from the high-pressure side towards the low-pressure side.

Figure 25.10 shows a double flow turbine. Steam enters the turbine in the middle of the casing and expands outward in both directions before exhausting at the ends of the turbine. In each half of the turbine, a very large thrust is generated. These thrusts oppose each other; the resultant force is significantly reduced. The resultant thrust is taken up by a thrust-bearing located between the high-pressure and first low-pressure turbine.

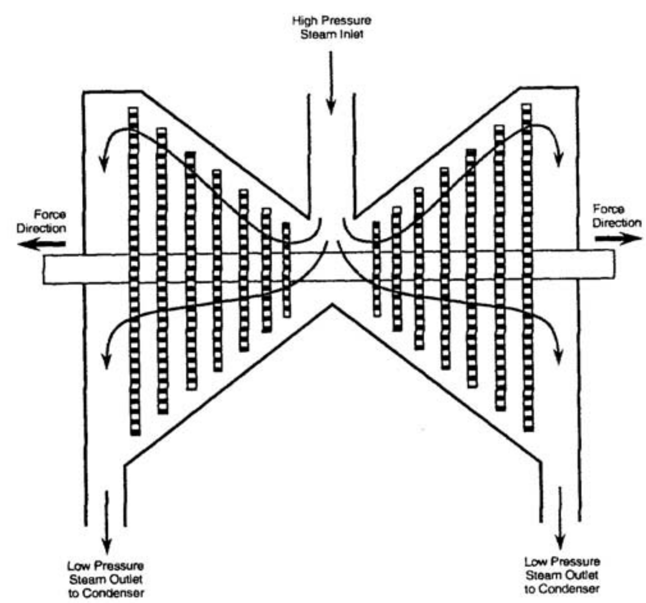

Figure 25.10
Double Flow Turbine

25.5 The Condenser

The condenser is the final destination for most of the steam produced in the boiler. The condenser removes latent heat, turning the steam back into water. The large decrease in volume creates a vacuum in the condenser. This permits steam flow from the high-pressure boiler to the low-pressure condenser so the turbine can extract mechanical energy efficiently.

Figure 25.11 shows a typical condenser used in most CANDU turbine units. The condenser cooling water (CCW) system supplies cooling water to the condenser. The water enters through the inlet water-box, passes through the condenser tubes and discharges to the lake through the outlet water-box. The turbine exhaust steam enters the condenser through the condenser exhaust trunk and reaches the outside surface of the condenser tubes. The steam condenses to a liquid by releasing its latent heat of vaporization through the tubes. The large volume of CCW absorbs the latent heat of vaporization from the steam. The condensate falls into the bottom of the condenser and collects in the hotwell.

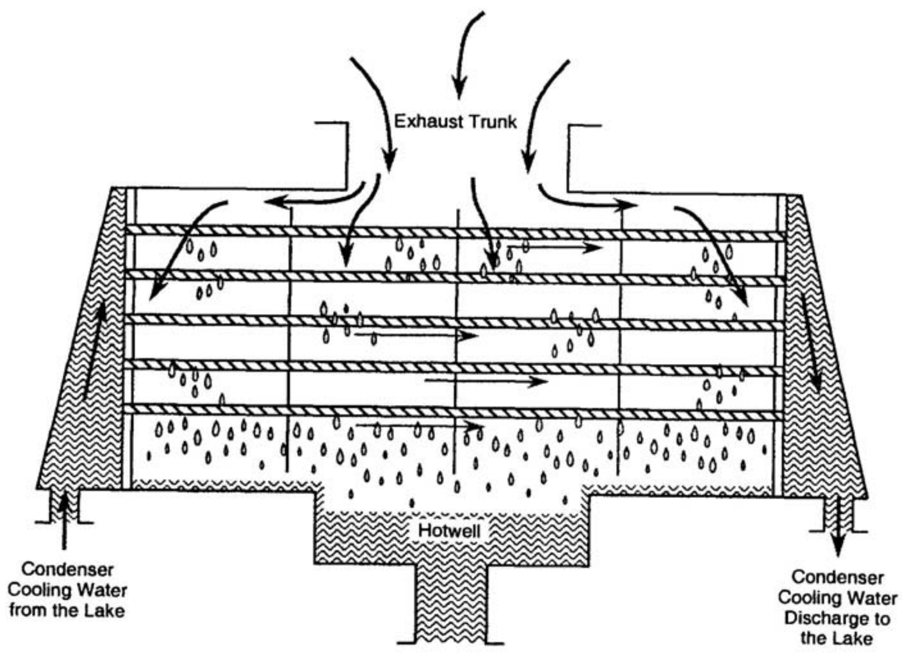

Figure 25.11
The Condenser

The CCW flow maintains the saturation temperature of the condensate. The exact condenser conditions (temperature and pressure) are dependent on the temperature of the lake water. Since the maximum power output of the unit depends on the pressure and temperature across the turbine, the output of the unit varies several percent with lake temperature.

The lower the turbine exhaust temperature and pressure the greater the amount of steam energy that can be converted into mechanical energy in the turbine. As mentioned, steam leaves the turbine at about 35°C and 5 kPaa. This condition is near a perfect vacuum. This allows roughly 35% more energy extraction than if the steam is left at atmospheric pressure (101.3 kPa). The condenser provides the means of maintaining this low absolute pressure at the turbine exhaust through condensation of steam (the 25.2 m^3 of steam reduces to 0.001 m^3 of water or 25200 times volume reduction).

The steam/feedwater system is a closed loop because it would be wasteful and expensive to reject the clean, chemically treated, demineralized water after it has completed its work in the turbine. It would also be wasteful to throw away the heat held by the 35°C condensate, especially as the CCW flow is adjusted to keep the condensate at saturation temperature and not cool it more than necessary for condensation.

25.6 Boiler Feedwater System

Figure 25.12 shows a simplified steam system and boiler feedwater system. The feedwater system is generally divided into three parts:

- low-pressure feedheating system,
- deaerator and storage tank, and
- high-pressure feedheating system.

The water leaving the condenser is at relatively low temperature and pressure. A series of heat exchangers raises the condensate temperature to 170°C. The preheaters then increase the temperature to 240°C (almost saturation temperature in the boiler). A set of pumps, known as boiler feed pumps (BFP), force the feedwater into the boilers operating at 4000 kPa.

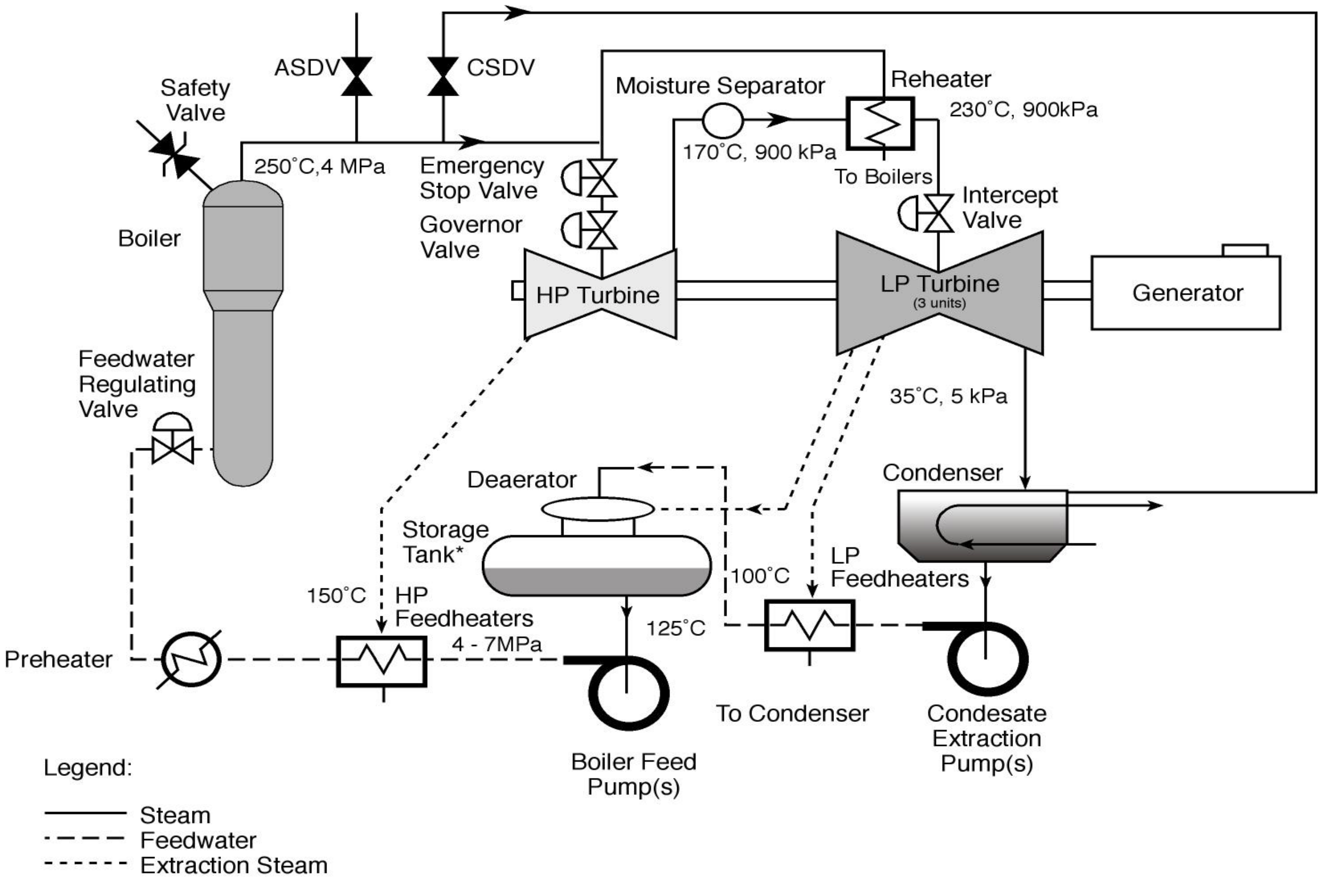

Figure 25.12
Simplified Feedheating System and Steam System

25.6.1 Low-pressure Feedheating System

The first stage in the boiler feedwater heating is through the LP feedheating system. The condensate extraction pump (CEP) delivers the condensate from the condenser hotwell to the LP feedheaters. The low-pressure feedheating system gets its name from the low-pressure condition of the feedwater, at about 1400 kPa, compared to the 4000 kPa in the boiler.

The LP feedheaters use extraction steam from the LP turbines as their heating medium. Extraction steam is wet steam removed from the turbine before it reaches the exhaust end because it could cause damage to turbine blades. The extraction steam transfers its latent heat of vapourization to the feedwater through a process similar to that in the condenser. A series of low-pressure feedheaters heat the feedwater. The extraction steam condenses in the shell of the heater. A separate pump recovers this condensate by pumping it to the condenser hotwell. The feedwater leaves the last LP feedheater at approximately 80°C to

100°C. The heated feedwater then goes to the next stage of the feedheating process.

25.6.2 The Deaerator and Storage Tank

The deaerator is the next stage in the feedwater heating process. This is the highest vessel in the system. The deaerator adds heat to and removes non-condensable gases from the feedwater. Some of these gases can increase the corrosion rate of the metals in the high-pressure feedheating system and boiler. All non-condensable gases will take-up space in the steam system. This reduces the amount of steam in the system and hence energy flows in the plant.

Figure 25.13 shows a typical deaerator and its associated storage tank. The incoming feedwater enters the deaerator near the top and sprays downward over cascade trays. Extraction steam from the LP turbine enters the deaerator near the bottom and passes upward. As a result the feedwater heats up to about 125°C. The steam passing over the water droplets scrubs the non-condensable gases off their surface. As the extraction steam condenses, the water droplets release the non-condensable gases, which are vented to the atmosphere. The deaerated feedwater and condensed steam drain from the deaerator into a storage tank. The storage tank supplies water for boiler operation.

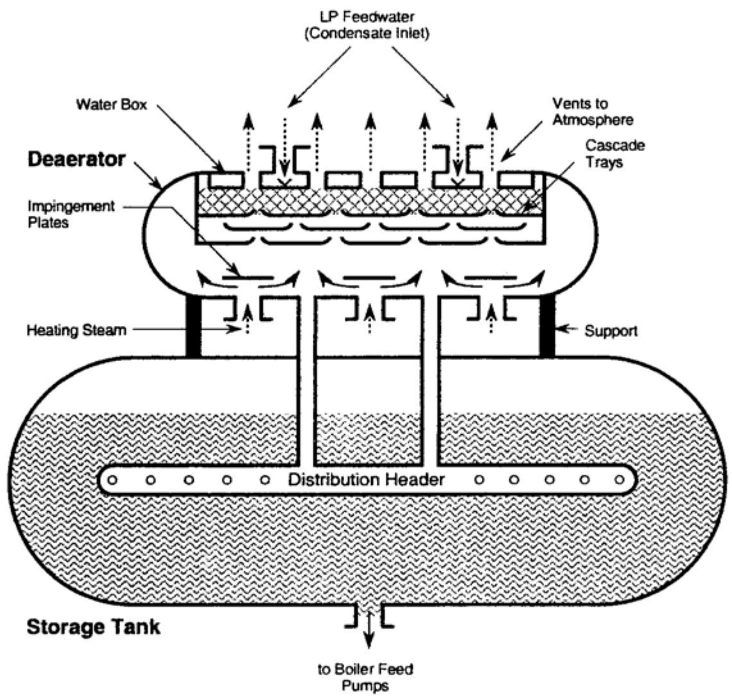

Figure 25.13
Simplified Deaerator and Storage Tank Assembly

25.6.3 High-pressure Feedheating System

From the deaerator storage tank, the feedwater undergoes the final preparation. The boiler feed pumps (BFP) take suction from the deaerator storage tank and raise the feedwater pressure to between 4 and 7 MPa. The pump discharges the high-pressure feedwater to the high-pressure (HP) feedheaters. The HP feedheaters heat the feedwater to about 170°C. HP feedheater operation and construction are similar to that of the LP feedheaters. Extraction steam from the HP turbine normally supplies the heating medium.

The feedwater regulating valve controls the flow of feedwater into the boiler. This valve allows sufficient feedwater to enter the boiler to match the steam flow out hence, maintaining a constant water mass in the boiler. To do this, the controller for the valve compares steam flow out of the boiler with feedwater flow into the boiler and positions the valve to make the two equal. It also compares the actual boiler water level with a predetermined programmed level and positions the valve to make these two equal.

It is critical to maintain a proper boiler level. If the boiler water level is too high, the cyclone separators and scrubbers will not operate properly. This results in wet steam being delivered to the turbine, which could lead to damage to the turbine blades. If water level were too low, there would not be enough inventory to cool the HTS coolant.

25.7 Lubrication System

Each unit of the turbine and the generator has its own rotor/shaft that is supported at each end by journal bearings. Journal bearings get hot due to friction and heat conduction along the shaft from hot parts of the turbine. The journal bearings are normally lined with white metal known as anti-friction metal or Babbitt, a lead-tin alloy with a melting point that can be as low as 182.2°C. A centralized lubricating system is employed to protect the bearings from damage due to metal-to-metal contact and high temperature. This extends the life of the bearings and reduces the chance of failure. A bearing failure is a very serious incident, as far as the turbine-generator is concerned and would cause extensive damage. For this reason it is always important to have sufficient oil flow through the bearings for lubrication and cooling purposes.

25.8 The Turning Gear

When a turbine comes to rest, after operating, the cooler denser steam tends to collect in the lower half of the cylinder and makes the lower half of the rotor cool quicker than the upper half. This causes the shaft to hog (bend upwards). When at rest and cool, the shaft will begin to sag under its own weight. If the turbine shaft is not rotated, hogging, especially above a critical temperature, can become permanent and the shaft would have to be sent to the manufacturer for heat treatment and straightening. Sagging does not usually become permanent but it takes time to recover the sag. To prevent a bent shaft due to sag or hog the shaft is rotated by a turning gear, which is a motor-driven gear-train mechanism on the turbine-generator shaft.

25.9 Chemical Control

Boiler steam and feedwater system construction in almost all CANDU stations uses carbon steel, copper alloys and nickel alloys. Each metal is susceptible to corrosion at a different pH level. A compromise pH of 8.8 to 9.3 is relatively safe for all metals involved. Chemical addition of morpholine and/or hydrazine into the feedwater maintains the appropriate pH level.

Other methods used to prevent corrosion are:

- oxygen removal from the system, and
- chemical addition to react with oxygen.

All stations use a common approach in removing oxygen from the system. Most oxygen is removed from the system by the condenser air extraction system and the scrubbing action of the deaerator. Hydrazine addition to the feedwater, after the deaerator, removes the remaining oxygen. Its reaction with oxygen produces non-corrosive nitrogen gas and water. Unfortunately, hydrazine also produces ammonia, which attacks copper alloys. Stations with boiler tubes that are a copper alloy have lower hydrazine levels than stations with stainless steel alloy tubes.

High quality feedwater and makeup water is vital, as low quality will produce deposits in the boiler and turbine causing:

- Reduced heat transfer because of an insulating scale layer on the boiler tube surface.

- An increased risk of stress corrosion cracking. This is a form of metal failure from low stresses in a corrosive environment.

- Corrosion of tubes and other components.

All will shorten the life of the boilers and turbines. Demineralization, deaeration, oxygen removal and pH control ensures high quality boiler water. A blowdown system in each boiler allows removal of any impurities that collect in the boilers. This system minimizes accumulation of impurities by draining the contaminated water out of the boiler. Blowdown can be intermittent or continuous, depending on the water condition.

25.10 Conventional and Radiological Hazards

25.10.1 .Chemical Energy

In the feedwater system, chemicals treat the boiler feedwater. These chemicals include hydrazine, ammonia and morpholine. Proper protection and careful handling of these chemicals will prevent injury.

Hydrogen used for generator cooling is potentially explosive in the range of 4% to 76% in air. Hydrogen can leak out of the generator or air can leak into the generator. This requires very good seals on the generator to minimize the explosion hazard.

25.10.2 Thermal Energy

Steam and hot feedwater leaks are thermal hazards. Steam leaks are often invisible. Therefore, once found a leak location should be roped off immediately. In most cases, it is necessary to shut down a unit before the steam leak can be repaired. Equipment that handles hot feedwater or steam will have high temperatures. Insulation and/or physical barriers are installed to prevent personnel from being exposed to the heat.

25.10.3 Electrical Energy

Most equipment and controls associated with the conventional side of the station will require electrical energy to operate. This includes numerous DC and AC electrical hazards. This energy is either produced by the generator or supplied by different sources. If not controlled and handled properly, it can cause shock, burns or even cardiac arrest.

25.10.4 Mechanical Energy

This hazard is found in anything that moves or is capable of moving. Generator and turbine rotating parts and other major components in pumps and motors are hazards that can cause cuts, abrasions, and crushing injuries.

25.10.5 Noise Energy

The main hazard here is excessive noise from unexpected opening of boiler safety valves, which could cause temporary loss of concentration and risk of injury. Personal hearing protection will reduce this risk somewhat.

25.10.6 Pressurized Fluid Energy

This hazard is found in most of the conventional systems. Uncontrolled release of pressurized fluid can cause punctures, fractures, abrasions and crushing injuries. Excessive pressure can cause equipment to fail. This could lead to broken components flying around causing injury to personnel and damage to other equipment.

Oil supplied to the hydraulic valves and bearings is pressurized. Any rupture in the oil lines can result in fire, if ignition sources are present. Fire Retardant Fluid (FRF) is used for operating the valves that control the turbine, making a fire around the valves unlikely.

25.10.7 Radiation Energy

There is a large pressure difference across the boiler tubes. The HTS is at 10 MPa and the boiler at 4 MPa, hence a leak will always occur into the feedwater. Failure of boiler tubes during operation will result in loss of D_2O to the boiler feedwater system, along with radioactive tritium, activated corrosion products and, possibly, fission products. In this case steam leaks from the main steam system could result in radiological hazards. Units are shutdown and the tube leaks repaired if a significant leak occurs.

25.11 Assignment

1. What is the function of the steam cycle and the feedwater cycle?

2. In the table, indicate the quality of steam at each location.

Location	Moisture Content	Temperature	Pressure
Outlet of HP Turbine			
Outlet of Moisture Separator			
Outlet of Reheater			
Outlet of LP Turbine			

3. Why is the turbine set divided into high and low-pressure units?

4. How does condenser vacuum improve the efficiency of turbine operation?

5. What is the purpose of each of the following components?

    a) Boiler
    b) Emergency Stop Valve
    c) Governor Valve
    d) HP and LP Turbines
    e) Boiler Feed Pumps
    f) Lubricating System
    g) Turning Gear

6. What is an alternative heat sink for the boiler if the turbine is tripped?

7. What are the three stages of heating for condensate water, and from where does each stage draw its heating source?

8. What are the major chemistry problems in the steam/feedwater cycle and how are they minimized?

9. What are the major hazards associated with the conventional side of the station?