CHAPTER 1

OVERALL UNIT

CHAPTER OBJECTIVES:

At the end of this chapter, you will be able to describe the following for a CANDU nuclear generating station:

1.1 Energy conversions from fission to electricity;
1.2 The main functions and components of each major system;
1.3 How an energy balance is maintained between the reactor and the conventional side of the station;
1.4 How the unit as a whole is controlled;
1.5 The fundamentals of reactor safety;
1.6 The main systems and operating characteristics of a CANDU generating unit.

Nuclear generating stations exist for the purpose of converting the energy obtained from the fission of certain nuclei to electricity. This energy conversion takes place via a number of intermediate stages that require many pieces of equipment organized into several systems under the control and protection of both manual and automatic operations. This chapter presents the main features of a nuclear power plant, so that as each system is studied in greater detail in subsequent chapters and in other courses, the reader should always be able to place such detail into the overall context of an operating station.

1.1 ENERGY CONVERSION

The basic nuclear generating station energy cycle is shown in Figure 1.1. Fuel containing fissile material (Uranium) is fed to the reactor where fission takes place. The energy liberated appears in the form of heat, which is used to boil water. The steam produced from the boiling water spins a turbine-generator set, where the heat is converted first to kinetic energy in the turbine and to electricity by the generator; the electricity produced (denoted as megawatts) is supplied to the electric power system.

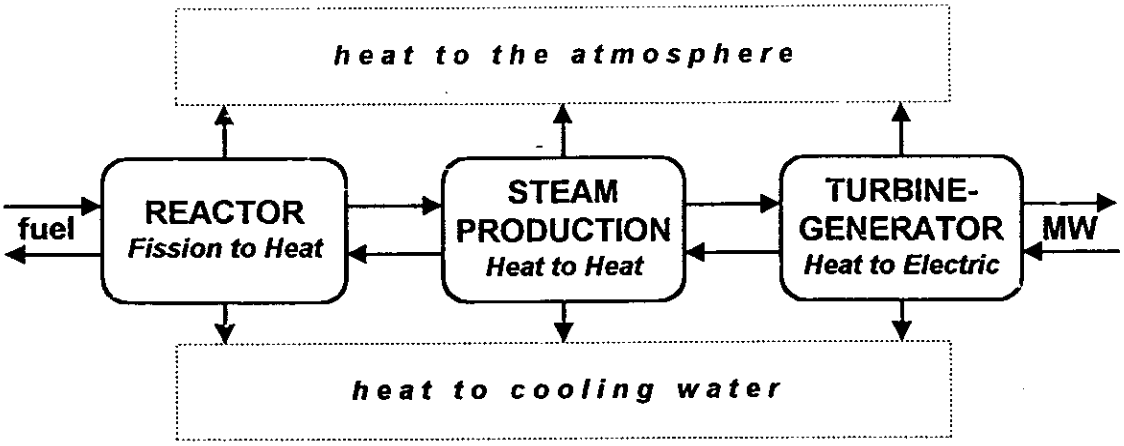


Figure 1.1. Basic flow of energy in a nuclear generating station.

It is important to recognize that while the transport of heat from the reactor to the turbine takes place in one or two closed loop systems that are highly efficient, the transformation of the heat energy of the steam to the kinetic energy of the turbine is accompanied by a large loss of energy as the steam is condensed to water prior to recirculating it back to the steam production system. Approximately 60% of the heat energy removed from the fuel is rejected to the condenser cooling water. As we will see, several other systems are also cooled by water. Under normal operations only a few % of the energy is lost directly to the atmosphere.

As indicated in Figure 1.1 spent fuel is periodically removed from the reactor. On the generator end the flow of electrical energy is shown to be in two directions to indicate the electrical energy consumption of the station itself.

This very much oversimplified representation of a nuclear generating station will become increasingly more complex as we study the details of the many systems involved directly or indirectly in the energy conversion processes, and in ensuring that these processes are always under control and are operated in a safe manner.

Energy Balance

Nuclear generating stations are designed to operate for extended periods at a constant power level, requiring that a steady state balance is maintained between the rate of energy released from the fuel in the reactor and the electrical output of the generator. This must be achieved despite inherent variations in the burn-up of fuel in the reactor, disturbances in the energy conversion processes, in the demands of the electrical power system and in the energy exchanges between the environment and the station.

As a minimum the plant control system must be able to adjust reactor power to produce the desired amount of electricity. Since under normal operating conditions the generator is synchronized to the electric power grid, the electrical energy produced by the generator is determined by the energy of the steam admitted to the turbine. A mis-match between the energy produced by the reactor and the steam energy required to produce the desired electrical output will result in a change of steam temperature and pressure. Because steam pressure measurements respond more quickly than temperature measurements, it is steam pressure that is used to indicate an imbalance of energy between reactor and generator, and is therefore the parameter chosen as an input to the control system to maintain the required balance.

A very much simplified plant control system is shown in Figure 1.2. The key inputs to the control system are:
- reactor power
- steam pressure
- generator output (MW).

The station control system is designed to keep steam pressure constant while matching the stations output to the desired setpoint. If the setpoint is the desired level of megawatts, then the control system adjusts reactor power by changing the position of the reactivity control devices, and the control system is said to be in 'reactor lagging' mode. If the setpoint is the desired reactor power output, then the control system adjusts the steam flow to the turbine by changing the opening of the governor valve, thereby altering the generator's output, and the control system is said to be in 'reactor leading' mode. The choice of which type of setpoint to specify depends on the operating status of the generating station and the requirements of the electrical power grid, and input to the control system by the authorized station operator.

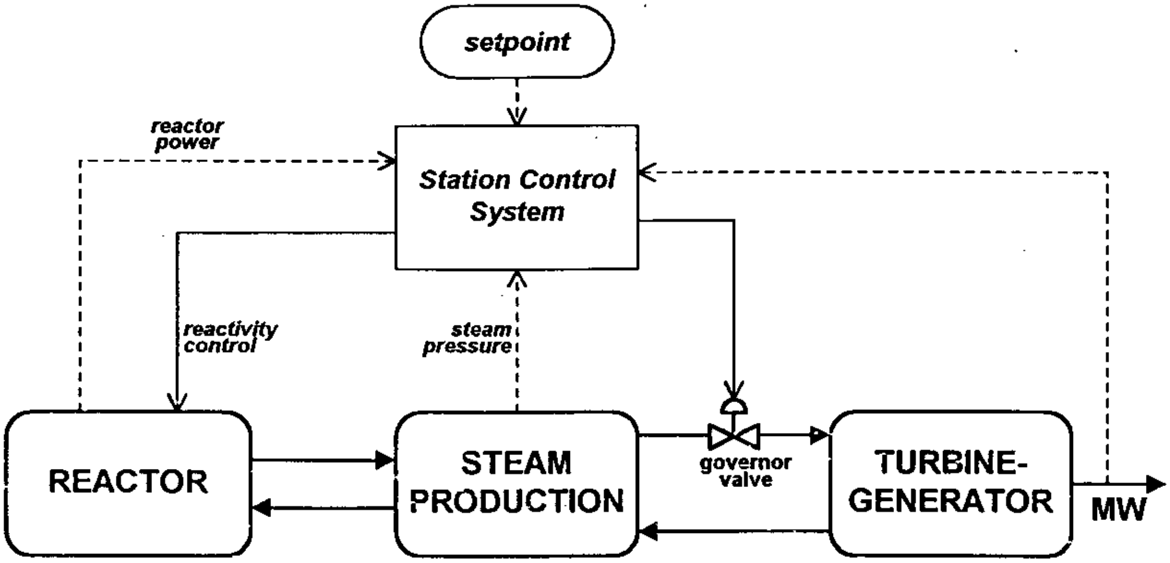
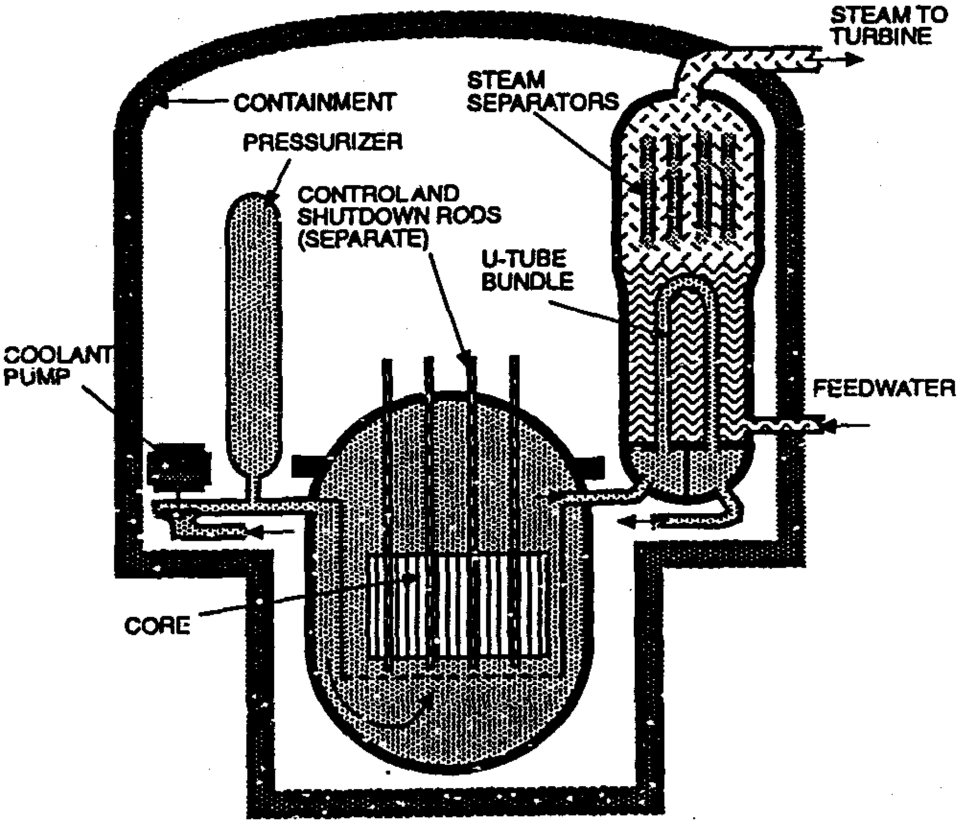


Figure 1.2. Simplified Nuclear Generating Station Control System.

1.2 WATER MODERATED REACTORS

Most of the nuclear power plants in operation around the globe use reactors that are both moderated and cooled by water. Reactors that use enriched uranium use ordinary (or light) water as both moderator and coolant. The reactor core is contained in a pressure vessel with no separation between moderator and coolant. Two main types of light water reactors have been developed, the Pressurized Water Reactor (PWR) and the Boiling Water Reactor (BWR). In the former the reactor coolant forms a closed primary loop in which it is not permitted to boil under normal operating conditions, and the steam is produced in a secondary loop. In a BWR the coolant is allowed to boil and the steam is fed directly to the turbine. The main characteristics of PWR and BWR reactors are shown in Figure 1.3 and Figure 1.4. The next two sections outline some of the main design and operating features of these types of reactors.

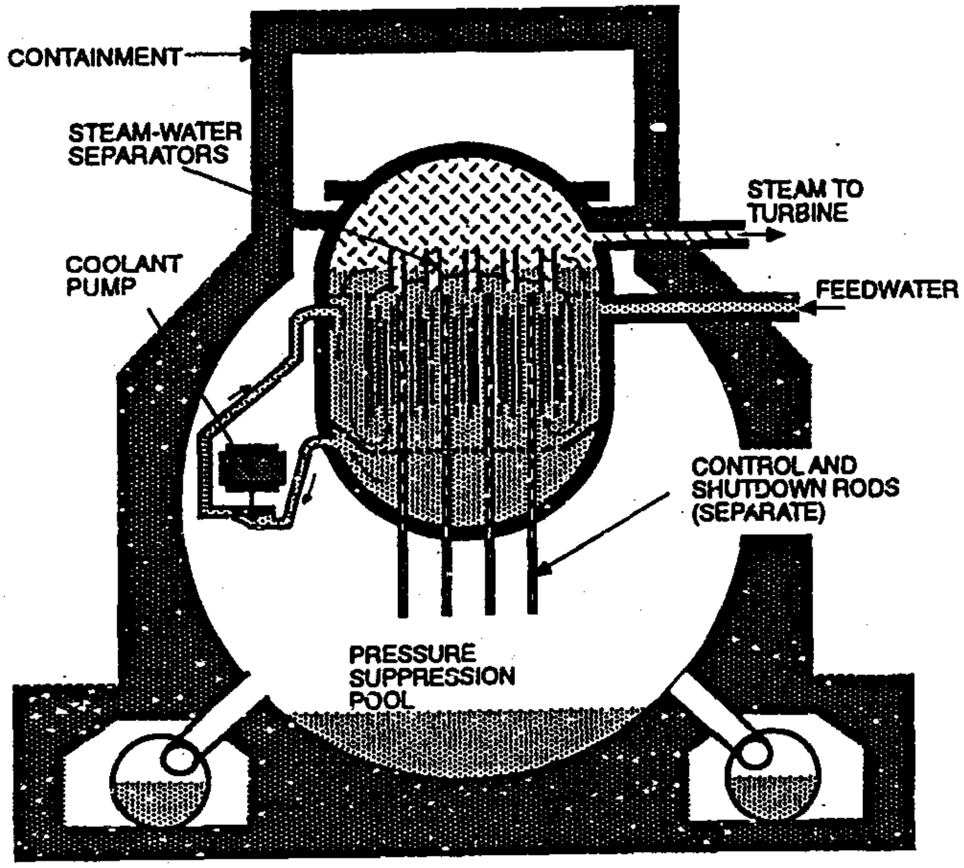
Reactors fueled with natural uranium must use heavy water instead of light water as the moderator, and in order to achieve maximum neutron economy, many heavy water moderated reactors also use heavy water as the coolant. The currently used designs are of the pressurized primary loop type similar to PWRs, but instead of a pressure vessel, pressure tubes contain the coolant and the fuel, while the moderator is in a low pressure, low temperature calandria vessel. Since this text deals extensively with the CANDU (CANadian Deuterium Uranium) type of pressurized heavy water reactors, the illustration of a CANDU in Figure 1.5 is provided only as a means of easy comparison with the PWR and BWR reactor types.



Moderator	H_2O at 15 MPa
Coolant	H_2O at 15 MPa
Fuel	U-235, enriched to 3-5%

Moderator and coolant are combined.
Refueled off load every 12-18 months.
Light water coolant transfers heat to boiler.

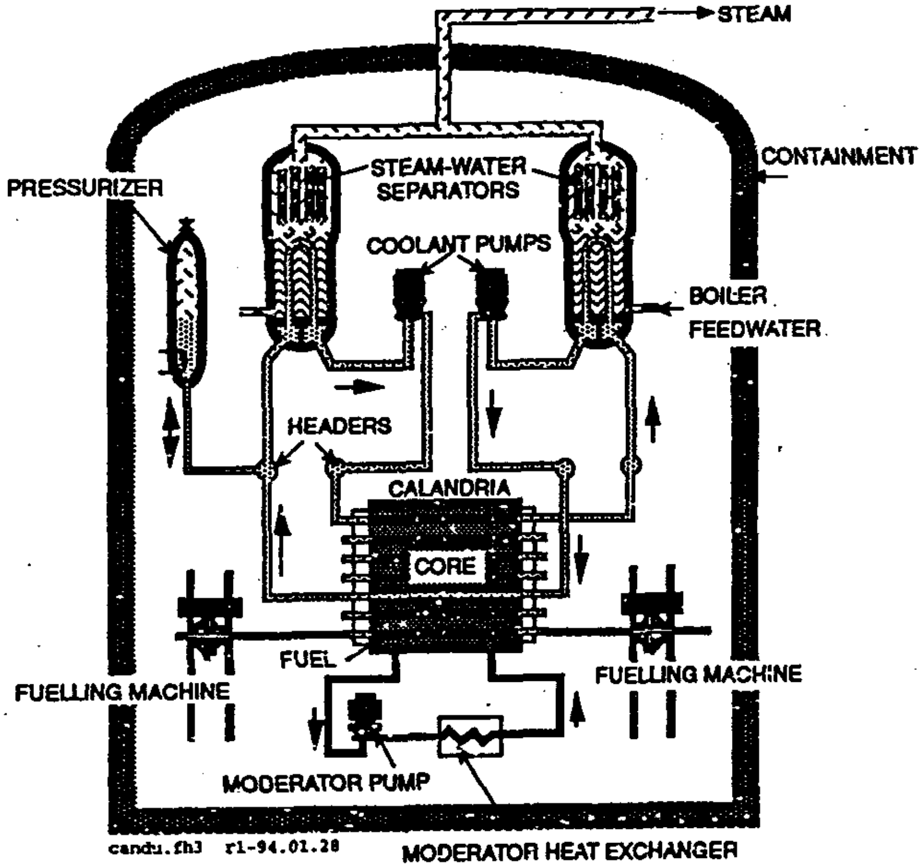
Figure 1.3. Pressurized Water Reactor.



Moderator	H_2O 6-7 MPa
Coolant	H_2O, Enriched to 2-3%

Moderator and coolant are combined.
Refueled off load every 12-18 months.
Steam flows directly to the turbine.

Figure 1.4. Boiling Water Reactor.



Moderator	D_2O at 1 atmosphere
Coolant	D_2O 9-10 MPa
Fuel	Natural Uranium Dioxide

Pressure tube reactor.
Refueled while at power.
Heavy water coolant transfers heat to boiler.

Figure 1.5. CANDU Reactor.

1.3 REACTOR SAFETY

In order to minimize the potential threat to the public from the radioactive materials contained within a nuclear station, a number principles have been developed and incorporated into the design and operation of nuclear generating stations. Collectively, these principles have been incorporated in the golden rule of Reactor Safety, which can be stated as:

There is a minimum risk to the public and the environment from reactor fuel, provided that at all times:

- The reactor power is controlled;
- The fuel is cooled;
- The radioactivity is contained.

This rule is often shortened to CONTROL, COOL, and CONTAIN.

1.4 DEFENSE IN DEPTH

There are different ways of achieving the golden rule (CONTROL, COOL and CONTAIN). Many of these have been incorporated into an important concept known as Defense in Depth. This underlies the whole process of design, construction, commissioning, and operation of a nuclear power plant. This concept is illustrated by the five part model shown in Figure 1.6.

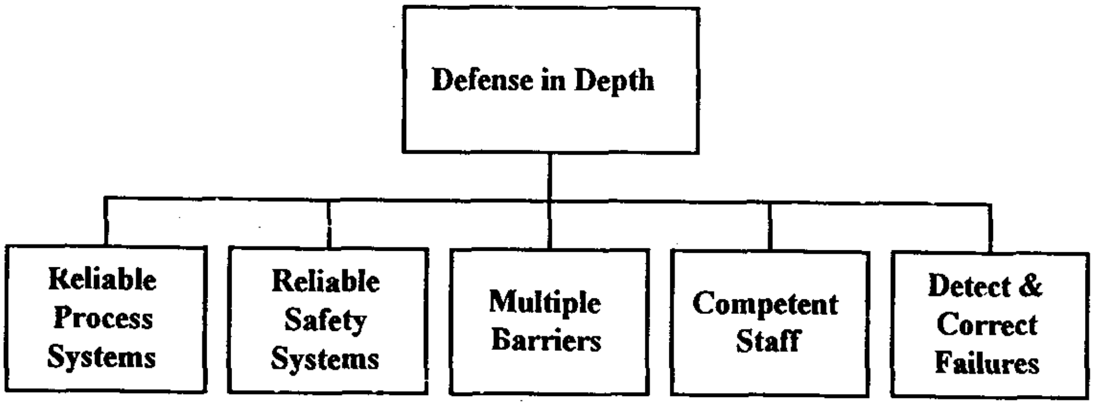


Figure 1.6. Defense in Depth Model.

The Defense in Depth concept assumes the following:

- nuclear station design will have some flaws;
- equipment will occasionally fail;
- operating personnel will occasionally make mistakes.

The key is to ensure sufficient depth of defense that flaws, failures and mistakes can be accommodated without increasing the risk or consequences of an accident. If we look at each of the major blocks of the model in turn, we can see how this is accomplished.

Reliable Process Systems

Process systems are the systems that perform a continuous function in the normal operation of the plant. For example, the primary heat transport system is a process system that is continuously active in the removal of heat from the fuel. The reactor regulating system is a process system that is continuously active in the normal control of reactor power. Reliable process systems ensure that heat is produced and electricity generated while maintaining control, cooling and containment.

Reliable Safety Systems

Safety systems are poised systems that operate only to compensate for the failure of process systems. They can do this by shutting down the reactor to regain control (shutdown systems), by providing additional cooling to the fuel (emergency core cooling system), and by containing radioactivity which has escaped from the fuel (containment system). Reliability in this context means that in the rare event these systems are called upon to act, they will be available to perform their intended function. The remaining sections of this chapter deal with these four safety systems.

Multiple Barriers

The multiple barrier approach that has been built into station design is intended to prevent or impede the release of radioactivity from the fuel to the public. There are five passive barriers (refer to Figure 5.2) that are continuously available:

- the uranium fuel is molded into ceramic fuel pellets which have a high melting point and lock in most of the fission products;
- the fuel sheath which is made of high integrity welded metal (zircaloy) and contains the ceramic fuel;
- the heat transport system which is constructed of high strength pressure tubes, piping and vessels and contains the fuel bundles;
- the system which provides a relatively leak tight envelope maintained slightly below atmospheric pressure. This partial vacuum encourages air to leak in instead of out thereby helping to prevent release of radioactivity that escapes from the heat transport system;
- the exclusion zone of at least one kilometer radius around the reactor that ensures any radioactive releases from the station are well diluted by the time they reach the boundary.

For radioactivity to reach the public from the fuel, it would have to breach each of the five barriers in succession. This provides a significant degree of protection to the general public.

Competent Operating and Maintenance Staff

The safety systems are designed to operate automatically and the five passive barriers are always in place, but the Defense in Depth concept does not allow reliance on equipment and systems to prevent accidents. It is essential that the operating and maintenance staff are knowledgeable about system conditions, alert for any evidence that systems or equipment may be on the verge of failure, and act promptly to prevent or minimize the consequences of such failures.

Detect and Correct Failures

Adequate detection and correction of failures requires not just competent staff but also processes and procedures for the staff to carry out in a systematic fashion. For example, a routine testing program for safety systems helps us meet the availability targets. An operational surveillance program in conjunction with a planned preventive maintenance program helps us to ensure that equipment and systems are monitored, inspected and repaired before they fail. Failures, when they do occur, are thoroughly investigated and solutions applied through a rigorous change approval process.

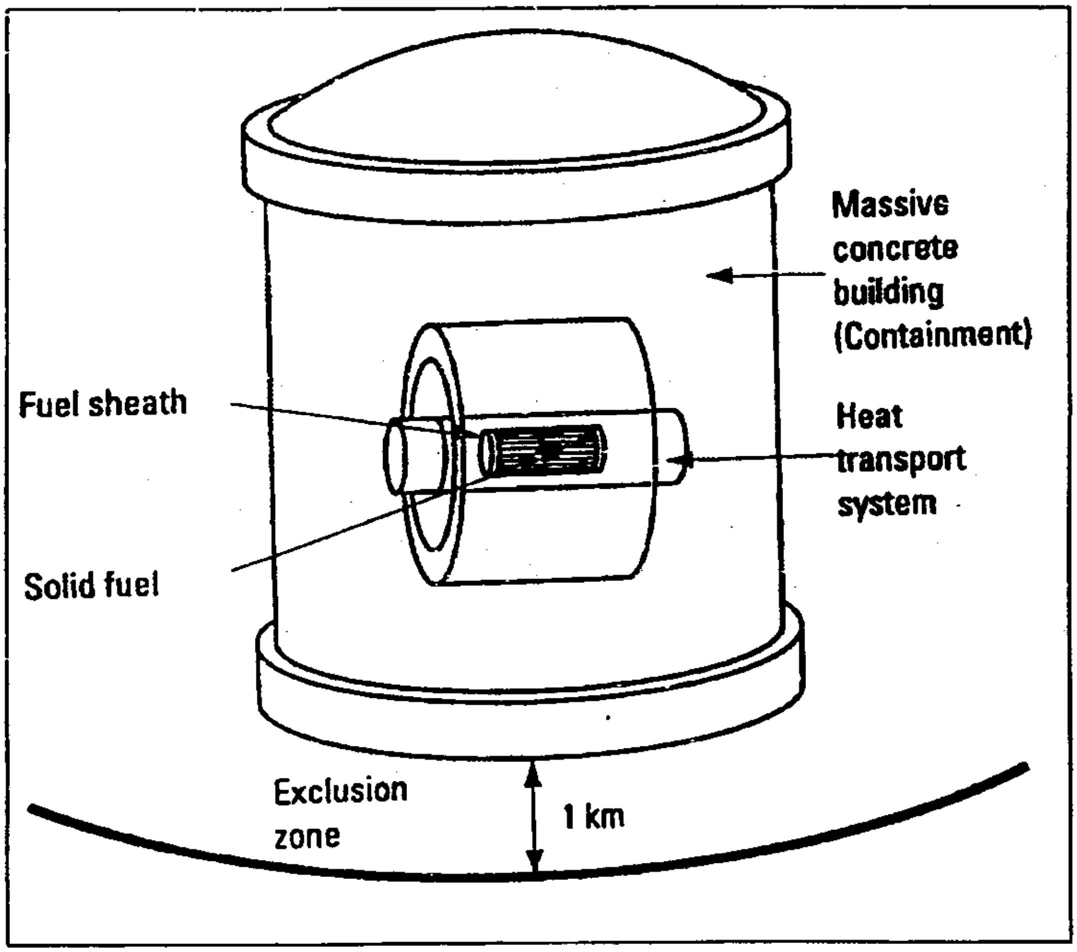


Figure 1.7. The Five Barriers to Radioactivity Release from the Fuel.

1.5 REACTOR SAFETY FUNDAMENTALS

There are special safety systems which are specifically incorporated in the plant to mitigate the consequences of a serious process failure requiring reactor shutdown, decay heat removal and/or retention of released radioactivity. Special safety systems perform no active functions in the normal operation of the plant, they are said to be 'poised' to prevent unsafe consequences of plant operation under abnormal or accident conditions. There are four special safety systems, as follows:

- shutdown system number 1,
- shutdown system number 2,
- emergency core cooling system,
- containment system.

The reactor may not be operated without all of the special safety systems being available. Systems which provide reliable services, such as electrical power, cooling water, and air supplies to the special safety systems are referred to as safety support systems.

The methods used to ensure that the safety requirements for the special safety systems are satisfied include redundancy, diversity, reliability and testability, separation, qualification, quality assurance and the use of appropriate design codes and standards. These are discussed below.

Redundancy

Redundancy is the use of two or more components or systems which are each capable of performing the necessary function. Redundancy provides protection against independent equipment failures.

Diversity

Diversity is the use of two physically or functionally different means of performing the same safety function. Diversity provides protection against certain types of common-mode failures, such as those arising from design or maintenance errors. The special safety systems use diversity where practicable in performing the same safety function. For example, the two shutdown systems use different principles of operation and are of a physically different design.

Reliability and Testability

A high reliability ensures that the chance of a serious accident is very low. The special safety systems must each meet an availability target of 1×10^{-3}. This target is used during system design and checked by a reliability calculation. It must also be demonstrated during plant operation. The design therefore provides for testing of components and systems during plant operation to confirm the calculated reliabilities.

Separation

Separation refers to the use of barriers or distance to separate components or systems performing similar safety functions, so that a failure or localized event affecting one does not affect the other. Separation provides protection against common cause effects, such as fires and missiles.

In the CANDU 9, plant systems are separated in accordance with the 'two-group separation philosophy'. This separation philosophy divides systems into two groups, each group capable of performing the essential safety functions of reactor shutdown, decay heat removal, and monitoring. The Group 1 systems include the normal power production systems as well as two of the special safety systems. The Group 2 systems are dedicated to safety. To guard against cross-linked and common-mode events and to facilitate the comprehensive seismic and environmental qualification of the Group 2 systems, the Group 1 and Group 2 systems are, to the greatest extent possible, located in separate areas.

Seismic and Environmental Qualification, and Tornado Protection

All systems, equipment and structures required to perform the functions of maintaining reactor coolant pressure boundary integrity, reactor shutdown, decay heat removal and containment following postulated accidents are seismically and environmentally qualified and protected against tornados. This includes all Group 2 systems, the special safety systems in Group 1, structures and components, the reactor building and Class 1 systems and certain safety-support systems within the Reactor Building. Qualification ensures that the system, component, or structure can withstand the effects of the design basis earthquake, environmental condition, or tornado. Qualification is achieved by testing and/or analysis.

Quality Assurance

A comprehensive quality assurance program is applied to all stages of design, manufacture, installation, construction and commissioning of safety-related systems and structures. A program of periodic inspection is provided to detect, on a sample basis, unexpected deterioration occurring during normal operation of the plant. This ensures that the integrity of safety-related systems is not degraded by an unanticipated mechanism.

Codes and Standards

In addition to meeting the safety design objectives of redundancy, diversity, reliability and testability, separation, qualification and quality assurance, the special safety systems design complies with the mandatory codes and standards.

1.6 CANDU STATION SYSTEMS

The distinguishing characteristics of Pressurized Heavy Water Reactors (PHWR) are the use of heavy water as both moderator and coolant, allowing for the use of natural uranium as fuel. The only PHWR type that has found wide commercial applications is the CANDU reactor, a Canadian design that uses high pressure tubes for the fuel and coolant, and a low pressure calandria to contain the moderator. The CANDU design will be used throughout this text to illustrate the design and operating characteristics of PHWRs.

The main CANDU process systems are shown in Figure 1.8. The pressurized heavy water of the Heat Transport System (HTS) removes the heat energy generated by the fissioning of the fuel in the reactor. Hot heavy water (300°C) enters the boilers where some of its heat is transferred to the feedwater circulated over the boiler tubes. Cooler heavy water (260°C) goes to the heat transport pumps from where it is circulated back to the reactor. The HTS is a closed loop system, pressurized at 10 MPa to get its saturation temperature about 40°C higher than the secondary side steam requirement, so that heat transfer can occur. Approximately 95% of the heat energy released in the reactor is transferred to light water in the boiler. The remaining 5% is lost, mainly to the moderator.

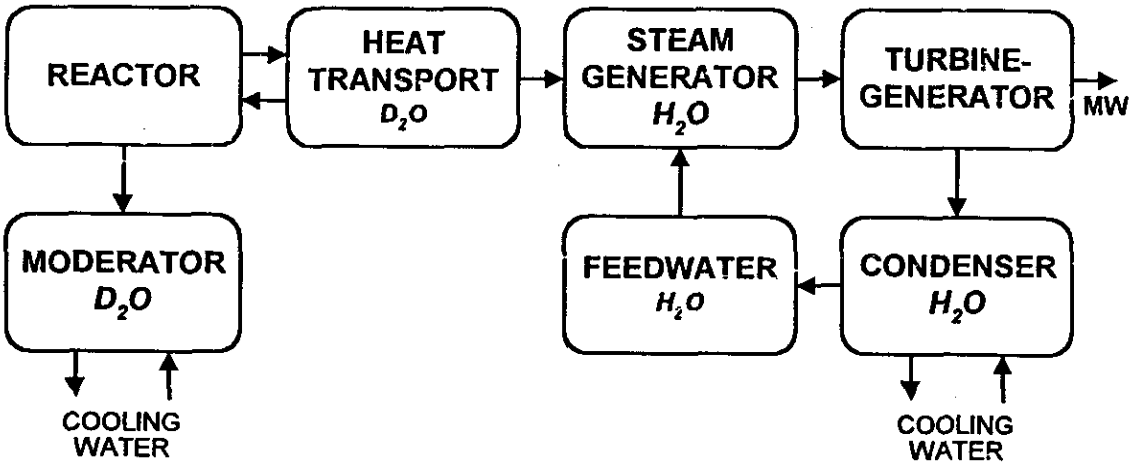


Figure 1.8. CANDU Station Main Process Systems.

In the Steam-Feedwater System the light water in the boilers is tuned to steam by the heat transferred from the Heat Transport System (HTS). The steam generated flows to the turbine where it exerts force on the turbine blades causing rotation of the turbine shaft. In the process, heat energy is converted to mechanical energy. The turbine drives the generator to produce electrical energy. The mechanical energy is converted to electrical energy and the chain of conversions is completed. The heat energy that cannot be used is given up in the process of condensing the exhaust steam to water in the condenser and the energy is transferred to the condenser cooling water. The condensate is pumped back to the boiler through different stages of feedheating as feedwater to complete the steam-feedwater cycle.

A simplified schematic of a typical CANDU unit is shown in Figure 1.9. It illustrates the location of the main process systems in the Reactor Building and the Powerhouse.

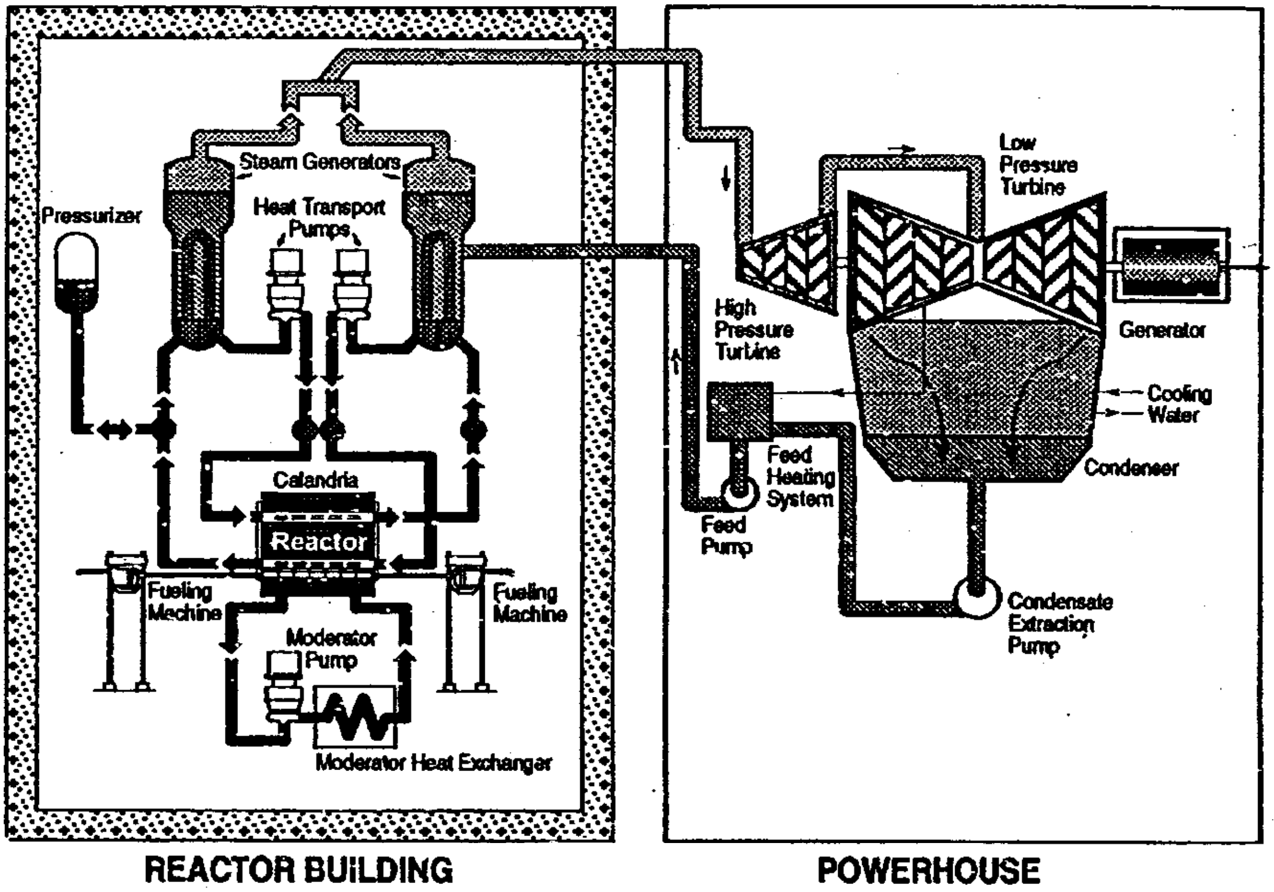


Figure 1.9. Simplified schematic and location of major systems of a typical CANDU unit.

1.7 CANDU 9 OPERATING CHARACTERISTICS

The main operating characteristics of a CANDU-9 unit are as follows:

a. The unit is capable of sustained operation at any net electrical output of up to 100 percent of rated full power output.
b. The overall plant control is normally of the reactor-following-turbine type.
c. For reactor power increases, the nuclear steam plant portion of the plant is capable of maneuvering at the following rates:

Power Range	Maximum Rate
0 - 25 percent of full power	4 percent of actual power per second
25 - 80 percent of full power	1 percent of full power per second
80 - 100 percent of full power	0.15 percent of full power per second

The overall plant power maneuvering rate is a function of turbine design, and is typically limited to 5 to 10 percent of full power per minute.

d. During normal plant operation, assuming an initial power of 100 percent, xenon load at a steady state level, and with a normal flux shape, the reactor power may be reduced to 60 percent of full power at rates of up to 10 percent of full power per minute. The power may be held at the new lower level, indefinitely. Return to high power (98 percent) can be accomplished within four hours, or less, depending on the degree and duration of the power reduction.
e. In the event of a temporary or extended loss of line(s) to the grid, the unit can continue to run and supply its own power requirements.

The turbine bypass system to the condenser is capable of accepting the entire steam flow during a reactor power setback following loss of line or turbine trip, thereby avoiding any steam discharge to the atmosphere. The steam flow is initially 100 percent, but decreases to a steady state value in the range of 60 percent after several minutes.

f. The unit is capable of reaching 100 percent net electrical output, from a cold shutdown within 12 hours. If the pressurizer is at its normal operating temperature and pressure, the unit is capable of reaching 100 percent electrical output within seven hours (depending on Xenon level).
g. The reactor and turbine are controlled by computer from zero to 100 percent of full power.
h. Following a shutdown from sustained full power operation with equilibrium fuel, the reactor can be restarted within 35 minutes (the poison override time) and returned to full power operation, otherwise, a 'poison-out' period of about 36 hours results, during which the reactor cannot be restarted.

The gross output of the generator is 925 MW and the station service power is 55 MW, yielding a net unit electrical output of 870 MW.

The orientation of the CANDU 9 on a given site is defined by the reference directions, designated A, B, C, and D, as shown on all layout drawings and illustrations (see Figure 1.10 for example).

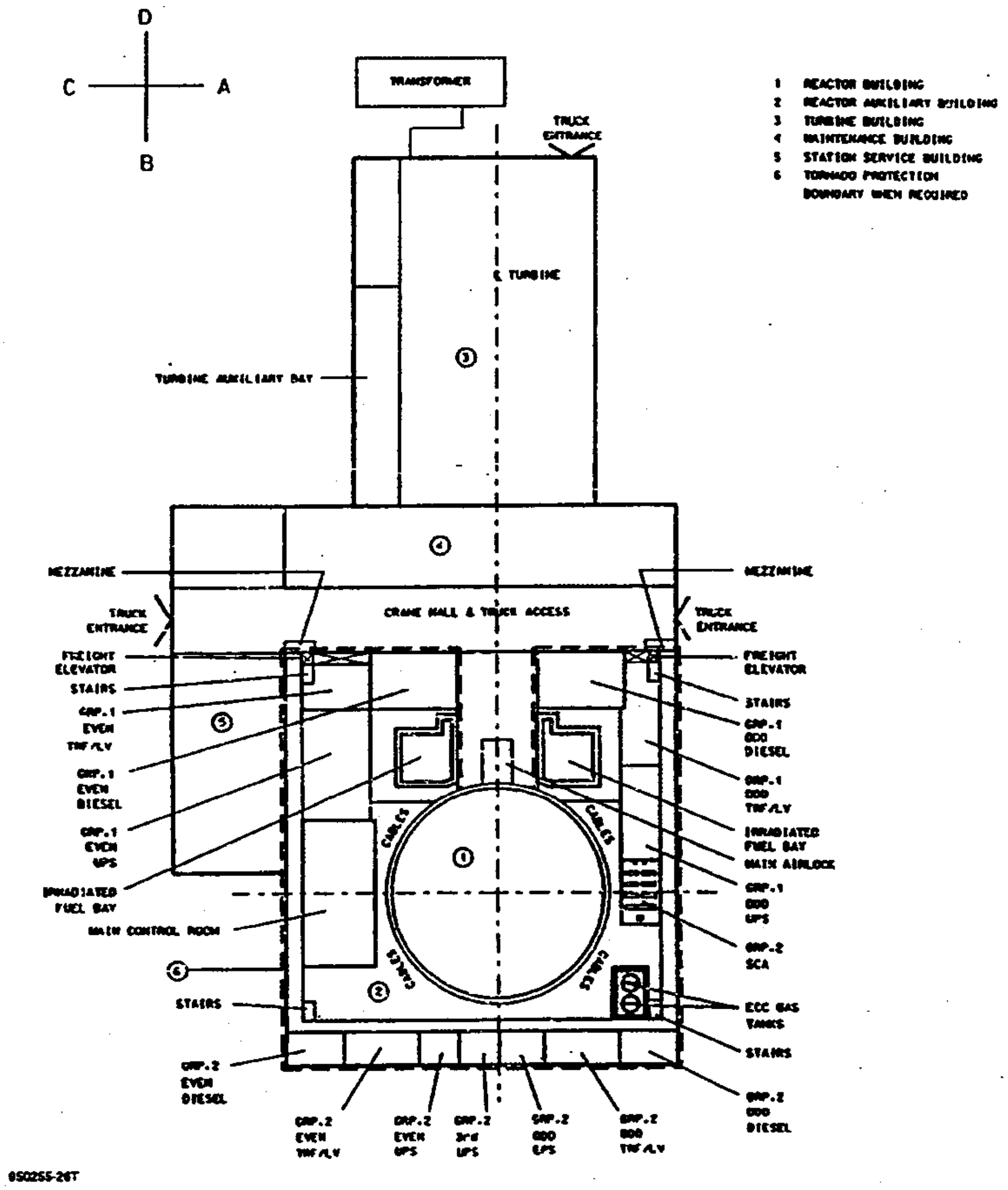


Figure 1.10. CANDU 9 Single Unit Station Layout.

Two Group Layout of Plant Systems

All plant systems are assigned to one of two groups (Group 1 or Group 2); each group is capable of shutting the reactor down, cooling the fuel, and of providing plant monitoring. In general, Group 1 systems sustain normal plant operation and power production and include two special safety systems while Group 2 systems have a safety or safety support function. Group 1 and Group 2 services are accommodated in physically separate areas of the station to the extent feasible. All Group 2 services, except for the Group 2 raw service water system, are totally accommodated within the Group 2 portion of the reactor auxiliary building and to the extent practical are physically separated from the Group 1 areas. Group 2 structures and all equipment within them are seismically qualified, and protected against severe external events such as tornado.

Group 1 services are housed in the Group 1 areas of the reactor auxiliary building and in a portion of the turbine building auxiliary bay. The Group 1 areas of the reactor auxiliary building are seismically and environmentally qualified. The Group 1 services portion of the turbine building auxiliary bay is environmentally sealed to prevent steam ingress in the event of a steam line break occurring in the turbine building. The main steam safety valves must be seismically qualified and protected from severe external events.

The main control room, located in the reactor auxiliary building, is seismically qualified and environmentally protected to protect the operator from all design basis events. A secure route is provided allowing the operator to move from the main control room to the secondary control area, located in the Group 2 area of the reactor auxiliary building, following an event which causes a loss of operability or habitability of the main control room.

Reactor

The position of the reactor in the reactor vault is shown in Figures 1.11 and 1.12. The arrangement of the reactor is shown in Figure 2.3. The cylindrical calandria and end shield assembly is enclosed and supported by the cylindrical shield tank and its end walls. The calandria contains heavy water moderator and reflector; the shield tank contains light water. The heavy water moderator system is independent from the pressurized heavy water heat transport coolant in the fuel channel pressure tubes.

The lattice sites, arranged parallel to the horizontal axis, pass through the calandria. Each of the lattice sites accommodates a fuel channel assembly. Each fuel channel assembly consists of a zirconium-niobium alloy pressure tube, centralized in a calandria tube, and expanded into stainless steel end fittings at both ends. The annulus between the pressure tube and the calandria tube is maintained by annular spacers and is gas-filled to provide thermal insulation. Each of the fuel channel assemblies contains 12 fuel bundles.

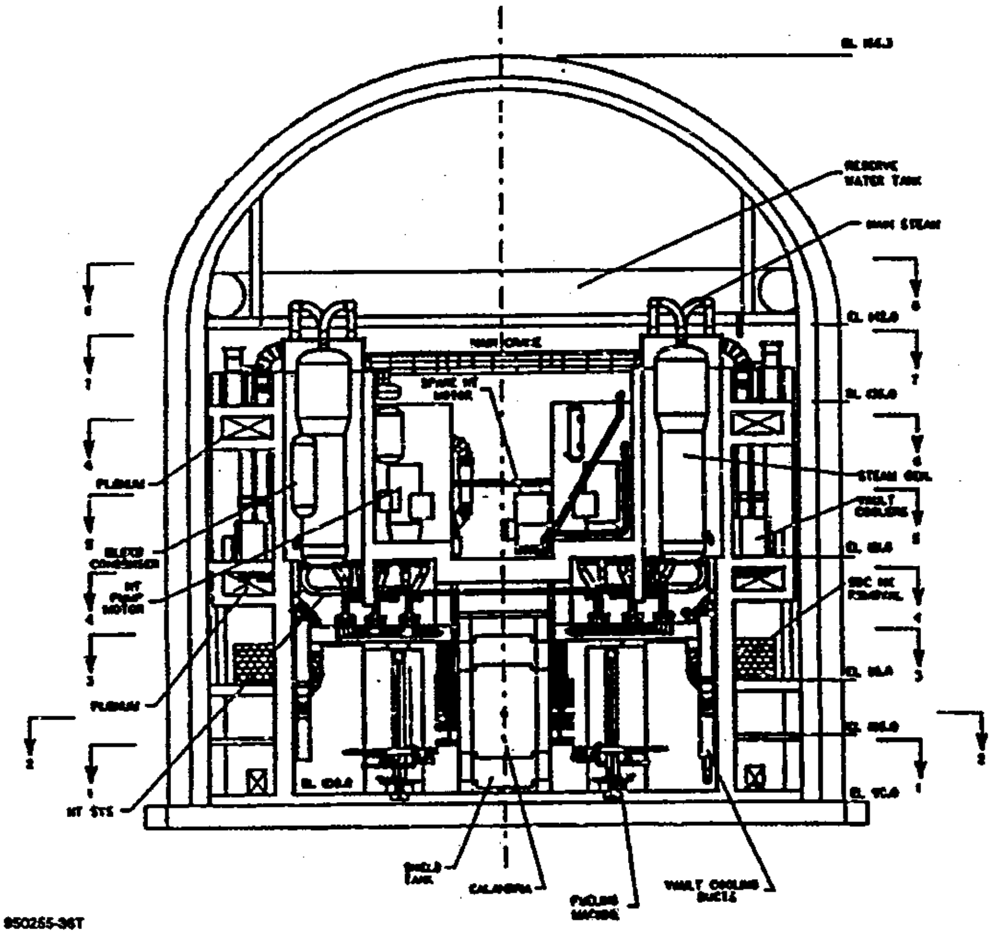


Figure 1.11. Reactor Building Section 7-7.

The calandria shell is closed and supported by the end shields at each end. Each end shield is comprised of an inner and outer tubesheet joined by lattice tubes and a peripheral shell. The spaces between the inner and outer tubesheets of both end shields are filled with steel balls and water, and are water-cooled. This shielding allows personnel access to the reactor face during reactor shutdown.

The end shields are connected to the end walls of the shield tank assembly which are, in turn, supported from the vault floor by the reactor vault walls The space between the calandria shell and the shield tank shell is filled with light water, which serves as a thermal and a biological shield. This shielding allows personnel access to the reactor vault during reactor shutdown.

The vertical and horizontal reactivity control units are installed from the top and from the sides of the calandria, respectively, between and perpendicular to the calandria tubes. The vertical and horizontal reactivity control units enter the calandria from the reactivity mechanisms deck and from the shield tank side walls, respectively.

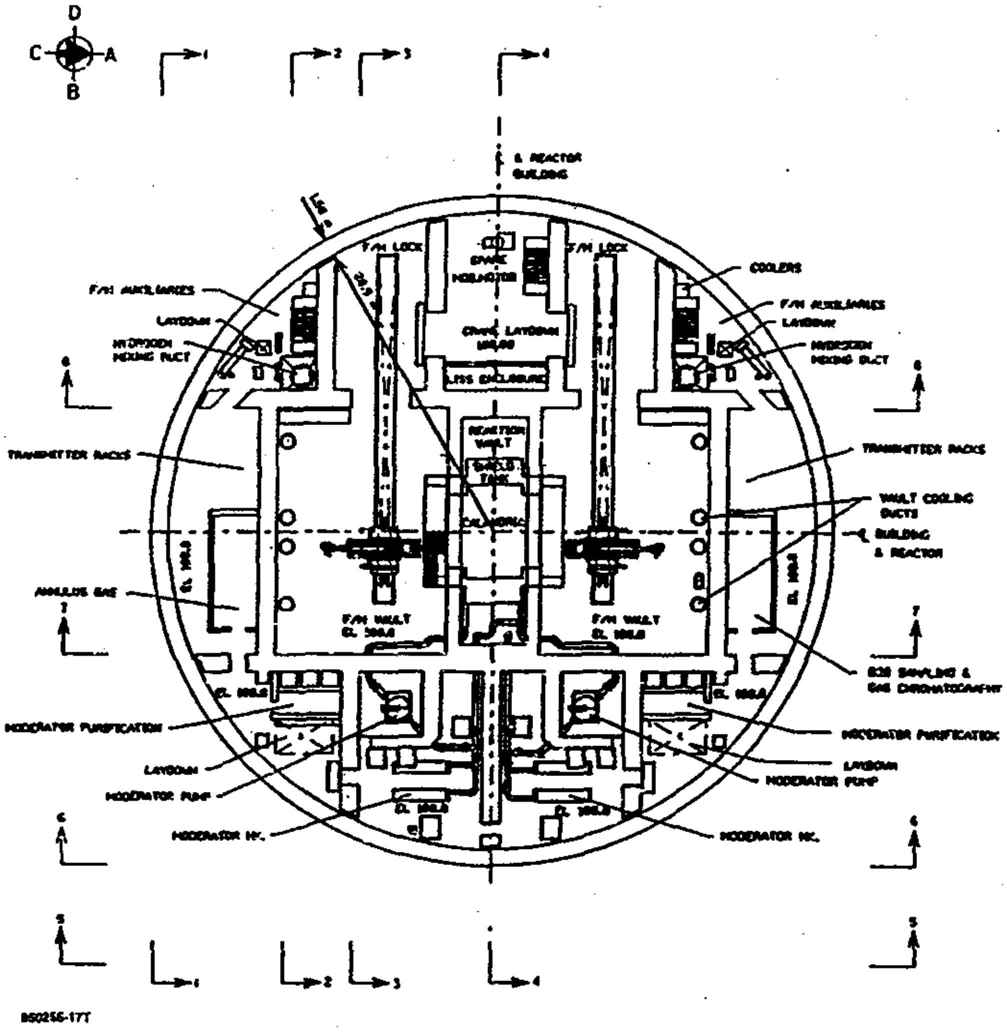


Figure 1.12. Reactor Building Plan El. 100.00.

Moderator Systems

The heavy water moderator in the calandria is used to moderate the fast neutrons produced by fission and is circulated through the calandria and moderator heat exchangers to remove the heat generated in the moderator during reactor operation. The location of the inlet and outlet nozzles high on the sides of the calandria ensures uniform moderator temperature distribution inside the calandria. The moderator free surface is near the top of the calandria. The operating pressure at the moderator free surface is the normal cover gas system pressure.

The moderator system consists of two interconnected circuits, each containing a heat exchanger and a circulation pump.

The moderator auxiliary systems include the moderator D_2O collection system, the moderator D_2O sampling system, the moderator liquid poison system, the moderator purification system, and the moderator cover gas system.

Heat Transport Systems

The heat transport system is a single loop with a figure of eight coolant flow pattern. The equipment arrangement with the steam generators and pumps 'in-line' at each end of the reactor results in bi-directional flow through the core (Figure 1.13). The four steam generators are of the vertical U-tube type with an integral preheating section. The four heat transport system pumps are vertical single discharge, electric motor driven, centrifugal pumps with multi-stage mechanical shaft seals.

No chemicals are added to the heat transport system for reactivity control. The heat transport auxiliary systems include the heat transport purification system, the pressure and inventory control system, the shutdown cooling system, the heat transport collection system and the heat transport sampling system.

Fuel

The CANDU 9 uses the same 37-element fuel bundle design as the other operating CANDU reactors. Each fuel element contains sintered pellets of uranium dioxide with a U235 content of 0.71 wt% in a Zircaloy-4 sheath. There is a graphite layer (CANLUB) on the inside surface of the sheath. End caps are resistance welded to the ends of the sheaths to seal the element. End plates are resistance welded to the end caps to hold the elements in a bundle assembly. Spacer pads are brazed to the elements at their midpoints, to provide inter-element spacing. Element contact with the pressure tube is prevented by bearing pads brazed near the ends and at the mid-point of each outer element. Beryllium metal is alloyed with the Zircaloy-4 to make the braze joints.

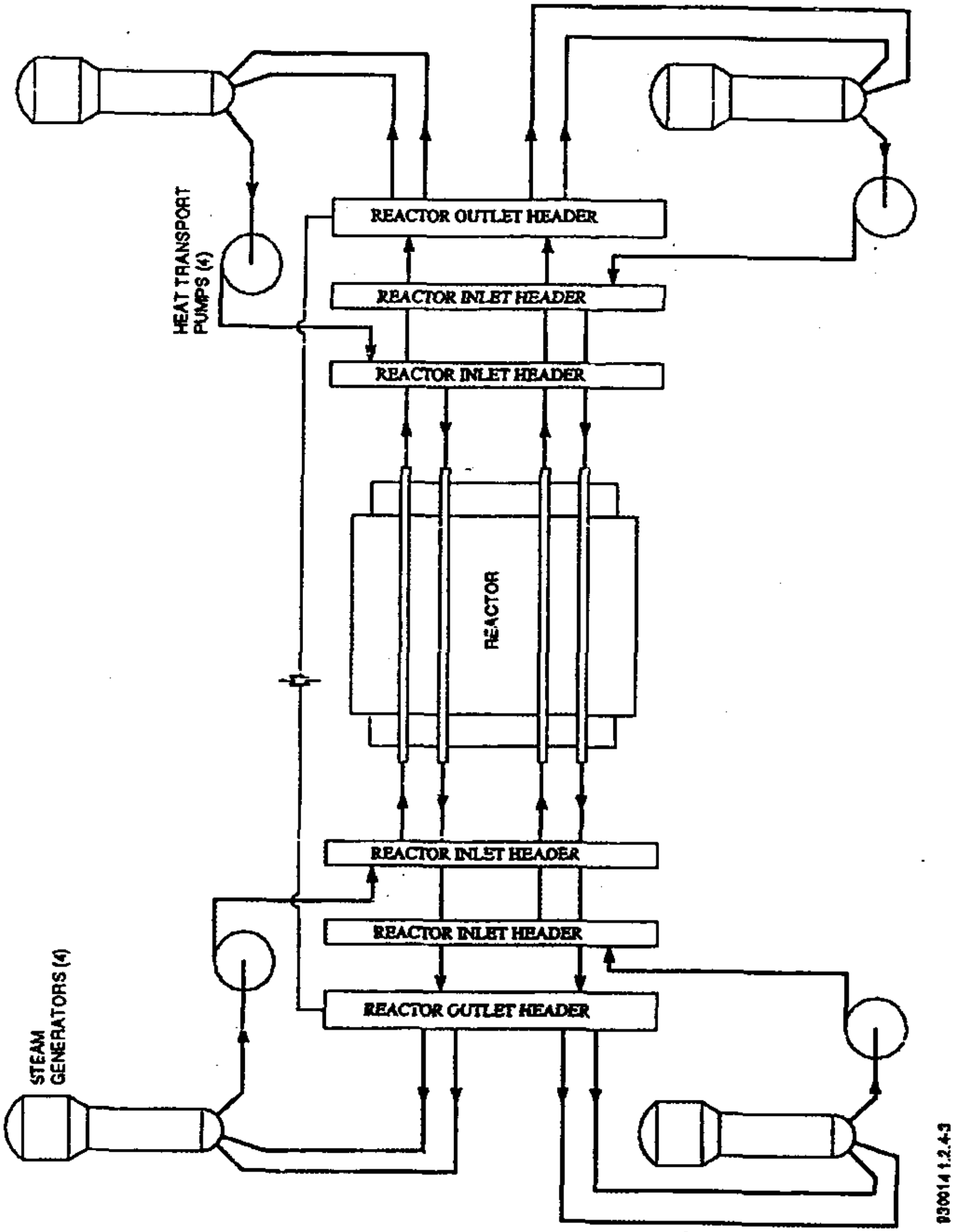


Figure 1.13. Heat Transport System Simplified Flow Diagram.

Fuel Handling

To use natural uranium fuel economically, it is necessary to introduce new fuel and remove irradiated fuel (spent fuel) in a continuous manner. The pressure tube design is convenient for on-power refueling. The fuel inside the individual pressure tubes can be changed using remotely controlled fuelling machines one channel at a time.

The CANDU 9 is refueled on-power using two fuelling machines located at opposite ends of the reactor. The fuelling machines are operated from the main control room. For refueling, the fuelling machines are positioned at opposite ends of the fuel channel to be refueled, and locked on to the end fittings to obtain leak-tight joints.

After the fuelling machines are aligned and clamped to the channel, the pressures in the machines and channel are equalized. The fuelling machines then remove the channel closures, guide sleeves are installed and injection flows are established from the fuelling machines. The shield plugs are then removed which allows the fuelling machine at the inlet end of the channel to move the fuel string towards the fuelling machine located at the outlet end. A ram adapter is added to the fuelling machine ram. The irradiated fuel bundles are supported with this ram adapter as they are pushed, separated into pairs and stored in the fuelling machine. During refueling, the irradiated fuel bundles are removed from the fuel channel outlet and new fuel bundles added at the inlet.

The fuel management scheme dictates which irradiated bundles are sent to the irradiated fuel storage bay, and the arrangement of the fuel bundles (including both irradiated bundles and new fuel bundles) in the fuel channel after refueling.

The reverse sequence of returning shield plugs, removal of guide sleeves and re-installation of the channel closures completes the refueling sequence on channel.

The fuelling machine unloads irradiated fuel bundles through the associated irradiated fuel port which leads to one of the irradiated fuel storage bays located outside the reactor building containment wall. The irradiated fuel storage bays have a storage capacity for six years of reactor operation, plus a reactor load of fuel. Lifting facilities are provided for the handling and shipping of the irradiated fuel.

The fuelling machines, the fuel transfer ports and the irradiated fuel discharge equipment are operated remotely and automatically from the main control room. Personnel access to the reactor building is required for in-situ maintenance of the fuel handling equipment. The fuelling machines are removed from the reactor building for all major maintenance.

Reactor Power Control

Total reactor power is controlled automatically by computer from zero power to full power. Liquid zone control compartments, distributed throughout the reactor core in vertical zone control units, provide the primary means to regulate reactivity during normal reactor operation. The zone control units adjust the flux level in any of the reactor zones by adding or removing light water to/from the zone control compartment to provide local control of neutron absorption.

The semi-continuous on-power refueling system provides the principal means of long term reactivity control. In addition to the zone control system, adjuster rods, mechanical control absorbers, and the addition of soluble poison to the low temperature moderator are other means available for reactivity control.

The reactor regulating system allows the reactor power to be reduced to about 60 percent of full power and operation continued indefinitely at that level or to be quickly reduced to zero power and then restarted within 35 minutes (which is the xenon override time). Steam discharge to the turbine condenser allows continued reactor operation at reduced power when the turbine or electrical grid connection is not available.

Instrumentation and Control

Most of the plant systems used for normal power production and fuel handling, i.e., the Group 1 systems, are monitored and controlled by a distributed digital computer control system. This system includes a Plant Display System to provide the primary operator interface in the main control room. Redundant channelized sensors and actuators are used for important functions.

Separate, independent, and diverse instrumentation and control systems are used for the special safety systems and Group 2 safety support systems. Separate independent operator interface equipment is provided in the secondary control area to perform all necessary safety functions in the event that the main control room becomes uninhabitable.

Reactor Safety

Safety related systems perform the safety functions necessary to maintain the plant in a safe condition during normal operation, and to mitigate events caused by the failure of the normally operating systems or by naturally occurring phenomena (e.g. earthquakes). The safety related systems used for mitigating events include four special safety systems and safety support systems which provide necessary services to the former. The four Special Safety Systems are: Shutdown System Number 1 (SDS1), Shutdown System Number 2 (SDS2), Emergency Core Cooling (ECC), and Containment.

Safety related systems are separated into two groups, Group 1 and Group 2, to provide protection against common cause events which impair a number of systems or damage a localized area of the plant (e.g. fires). Group 1 includes most of the systems required for normal operation of the plant as well as two special safety systems. Systems in each group are capable of performing the essential safety functions of reactor shutdown, decay heat removal, and control and monitoring. Each group contains safety support services (e.g. electrical power systems with diesel generators, cooling water systems, and steam generator feedwater systems), which can also provide backup support services to the other group, as required. During normal plant operation, the Group 1 systems generally provide the support services to the systems in both groups.

The systems in each group are designed to be as independent from each other as practicable, to prevent common cause events from affecting systems in both groups.

Interconnections between groups are kept to a practical minimum, and provided with suitable isolation devices. Inside the reactor building, components of each group are physically separated by distance or local barriers. Outside the reactor building, the physical interface between groups is designed as a fire barrier, and as a barrier against any flooding that can occur in either of the groups. Fire barriers, flood control, and physical separation of selected components are also provided where necessary within each group.

The special safety systems are assigned to groups to provide maximum independence between those that have similar or complementary safety functions. SDS1 and the containment system are assigned to Group 1, and SDS2 and ECC are assigned to Group 2. This grouping assignment minimizes physical and functional cross connections between groups.

Most design basis events are controlled and monitored from the main control room, in Group 1. Following an event which causes loss of the operability or habitability of the main control room. the operator can control and monitor the plant from the secondary control area in Group 2.

Shutdown Systems

Two shutdown systems, additional to the regulating system, are provided to shut the reactor down for safety reasons. One system (SDS1) consists of mechanical shutdown rods while the other (SDS2) injects a gadolinium nitrate solution into the moderator via liquid poison injection nozzles. These two safety systems are independent and diverse in concept and are separated both physically and in a control sense to the maximum practical degree from each other and from the reactor regulating system. The two shutdown systems respond automatically to both neutronic and process signals. Either shutdown system, acting on its own, is capable of shutting down the reactor and maintaining it shut down for all design basis events.

Emergency Core Cooling System

The purpose of the emergency core cooling system is to replenish the reactor coolant and to assure cooling of the reactor fuel in the unlikely event of a loss-of-coolant accident. Emergency core cooling is provided by injecting light water into the reactor headers.

During the initial injection phase, air from the emergency core cooling system gas tanks is utilized to pressurize the emergency core cooling system water tanks and deliver light water to the headers at high pressure. In the long term the emergency core cooling system recirculates water through the reactor and dedicated heat exchangers for decay heat removal. Make-up water is provided from the reserve water tank.

The emergency core cooling system, except for the gas tanks and recovery pumps, is housed within the reactor building.

Containment System

The containment system consists of the containment envelope and the containment isolation.

The containment envelope is a pressure-retaining boundary consisting of the reactor building and metal extensions such as airlocks, piping system penetrations and electrical penetration assemblies. The containment envelope is designed to withstand the maximum pressure which could occur following the largest postulated loss-of-coolant accident. Piping systems passing through the envelope are equipped with isolation valves.

The containment isolation system automatically closes all reactor building penetrations open to the containment atmosphere when an increase in containment pressure or radioactivity level is detected.

A long-term containment atmosphere heat sink is provided by the reactor building air coolers.

Main Steam and Feedwater Systems

Four identical steam generators with integral preheaters transfer heat from the heavy water reactor coolant of the primary heat transport system side to the light water on the secondary side. The temperature of the incoming feedwater is increased to the boiling point and subsequently evaporated. The steam generators consist of an inverted vertical U-tube bundle installed in a shell. Steam separating equipment is housed in the steam drum at the upper end of the shell. The steam from the boilers is fed by separate steam mains to the turbine steam chest via the turbine stop valves, and its flow is controlled by the governor valves.

The steam pressure is normally controlled at a constant value by varying reactor power to match the turbine-generator demand. The condenser steam discharge valves, in combination with the atmospheric steam discharge valves, are sufficient to avoid lifting of the main steam safety valves following a loss of line or a turbine trip and, hence, permit continuation of reactor operation.

Main steam safety valves are provided on each steam main to protect the steam system and the steam generators from overpressure.

The feedwater system supplies normal feedwater to the steam generators. The feedwater system comprises the main feedwater pumps on Class IV power and a diesel-driven auxiliary feedwater pump. The feedwater is demineralized and preheated light water. The feedwater lines run from the feedwater regulating valve station in the turbine building to the reactor building and hence, to each steam generator.

The Group 2 feedwater system supplies feedwater to the steam generators at full operating pressure in the event that the main (Group 1) feedwater system is unavailable. A further backup supply is available from the reserve water tank.

Steam Generator Pressure Control

The steam generator pressure control system enables the reactor power output to track the turbine power output, using the steam generator pressure as the controlled variable. The steam generator pressure controller is a part of the overall plant control system.

During normal operation, steam pressure is primarily controlled by adjusting reactor power. If for some reason the reactor regulating system does not allow the reactor to respond to pressure controller demands, or if a reactor power reduction occurs because of a trip, a stepback, or a setback, the reactor setpoint is controlled directly by the respective reduction signal, and the 'normal' mode of control of steam generator secondary side pressure is interrupted. Steam pressure control switches to the 'alternate' mode of adjusting the plant loads. Similarly, if the operator elects to control the reactor power set point manually, steam pressure control is via plant loads.

When the plant is in the 'normal' mode, the turbine governor valves are controlled through the unit power regulator program; i.e., the unit power regulator calculates what the valve setpoint should be and pulses to that position.

If the plant is in the 'alternate' mode, the steam generator pressure control system controls the turbine in response to the steam pressure error, steam pressure error rate of change, and the rate of change of reactor power.

The turbine has a low steam pressure unloader external to the control computers. This overrides directly the turbine governor action including the steam generator pressure control signal, and causes a fast runback of the turbine.

Atmospheric Steam Discharge Valves are low capacity valves that are used to control steam generator pressure via the steam pressure control program. They are opened in proportion to the pressure error, normally with an offset in the steam pressure setpoint. These valves may also be used to provide a heat sink during shutdown for decay heat removal when the main condenser is unavailable.

Condenser Steam Discharge Valves are capable of discharging up to 70% of full power live steam to the condenser on loss of turbine so that the reactor can continue to operate at the power required to prevent a 'poison-out'. They are also used to discharge steam on a loss of line, or on a turbine trip, so that the main steam safety valves do not lift. During normal operation these valves operate on the pressure control mode, with an offset to bias them closed. During 'poison-prevent', their steady state opening is proportional to the power mismatch between the poison-prevent reactor power level and actual turbine steam consumption. On a turbine trip, they are first opened fully and then returned to the pressure control mode. During reactor shutdown they provide a heat sink through the condenser for decay heat removal.

Steam Generator Level Control

The level in each of the steam generators is controlled individually, as a function of power.

Because of safety, range of control and maintenance considerations, each steam generator has a set of three control valves for feedwater control connected in parallel: one small valve to control feedwater during shutdown, startup, and low power operation, and two larger valves to control feedwater for on-power conditions. Each of the two large valves can handle the full power flow requirements. Isolating valves are provided for each control valve.

The steam generator level control system balances feedwater to steam flow for all operating conditions: fast reactor runup, reactor setback, turbine trip and 'poison-prevent' mode. The water level setpoint is automatically programmed over a set range as a function of load. Control is by the distributed computer control system.

Turbine-Generator and Auxiliaries

The CANDU 9 turbine assembly consists of one double flow high pressure cylinder and three double flow low pressure cylinders with reheaters between the high and low pressure cylinders.

The condenser consists of three separate shells, one for each low pressure turbine cylinder.

The extraction steam system supplies five stages of feedwater heating. The low pressure regenerative feedwater heating system consists of a single bank of low pressure closed feedwater heaters and a deaerator, whereas the high pressure system consists of a high pressure heater. The deaerator is heated with extraction steam or, if unavailable, with pegging steam from the steam mains.

The Group 1 feedwater system includes three 50 percent capacity electrically driven main feedwater pumps that take suction from the deaerator storage tank and an auxiliary feedwater pump, which is diesel driven.

Electric Power System

The electric power system generates and transmits electric power to the grid and to the unit loads. Unit service power (normal) is provided by one of the two 100 percent capacity transformers, the unit service transformer or the system service transformer, from either the turbine-generator or the grid respectively. This power is distributed and further stepped down in voltage as required. Auxiliary power to equipment is provided by the Group 1 standby diesel-electric generators to all station loads which must be re-energized within a short time after the loss of the normal supply, and by seismically qualified diesel-electric generators for the Group 2 loads.

Essential control, instrumentation and safety systems equipment are supplied with uninterruptible power, through inverters, fed from a bank of batteries, backed up by the standby power buses.

Heating, Ventilation and Air Conditioning Systems

The following systems are included under this heading:

a. The reactor building cooling system controls air temperatures in both the accessible and inaccessible areas of the building. The system consists of vault cooling units and local cooling units appropriately located within the building.
b. The reactor building ventilation system provides air exchange, maintains the reactor building at a pressure slightly below atmospheric and provides filtration of air before exhaust to the atmosphere.
c. The reactor auxiliary building heating, ventilation, air conditioning and clean air discharge systems.

Computerized Station Control Systems

Because of the complex interdependence of control systems in a CANDU unit, all major control functions are performed by Digital Control Computers (DCC). The main programs are:

- Reactor Regulating System (RRS)
- Boiler Pressure Control (BPC)
- Unit Power Regulator (UPR)
- Boiler Level Control (BLC)
- Heat Transport System Pressure and Inventory Control (HTSP)

Table 1.1 summarizes these programs with the parameters measured and the different variables controlled and manipulated. A simplified general layout of the station control system is illustrated in Figure 1.14.

Table 1.1

Program Name	Measured Parameter (s)	Variable(s) Controlled	Variable(s) Manipulated
RRS	• Reactor Bulk Power	• Neutron flux	• Zone water level • Rod Position
BPC	• Boiler pressure • Reactor power • Steam Flow	• Boiler pressure	• Reactor setpoint • Steam flow
UPR	• Electrical output	• Electrical Output • Steam Flow	• Steam flow
BLC	• Boiler level • Reactor power • Feedwater flow • Steam flow	• Level (Inventory)	• Feedwater flow
HTSP	• HTS Pressure	• D_2O Pressure • Pressurizer Level (where applicable)	• D_2O Feed & Bleed • pressurizer steam bleed & heaters

Reactor Regulating System (RRS)

This program adjusts the reactivity control devices to maintain reactor power at the desired setpoint and, when required, to maneuver the reactor power level between set limits at specific rates. It also monitors and controls power distribution within the reactor core. to optimize fuel bundle and fuel channel power within their design specification. The reactivity control devices include:

- liquid zones,
- control absorbers,
- adjusters.

Boiler Pressure Control (BPC)

This program controls boiler pressure to a constant setpoint, by changing reactor setpoint (reactor lagging mode), or adjusting the turbine load (reactor leading mode). BPC can open the steam reject valves if boiler pressure is higher than desired. If BPC cannot prevent high boiler pressure by adjusting either steam flow or by adjusting reactor power, the boiler pressure is reduced by steam reject valves.

Unit Power Regulation (UPR)

This program maneuvers the unit power in the reactor lagging mode, by adjusting the turbine load setpoint, to maintain the generator output at the level demanded by the local operator, or a remote control center. In reactor leading mode UPR has only a monitoring function and takes no active part in control.

Boiler Level Control (BLC)

BLC is used to control the water level in each boiler under all unit power conditions from 0% to 100% full power. This program controls the feedwater valves to maintain the water level in the boiler sufficient for the reactor power level setpoint.

Heat Transport System Pressure and Inventory Control (HTSP)

This program controls the heat transport pressure control system to maintain heat transport pressure at a fixed setpoint. In stations with a pressurizer, pressurizer level is also controlled.

There are many other control programs in a nuclear power plant, but the ones listed above are the programs required for overall unit control.

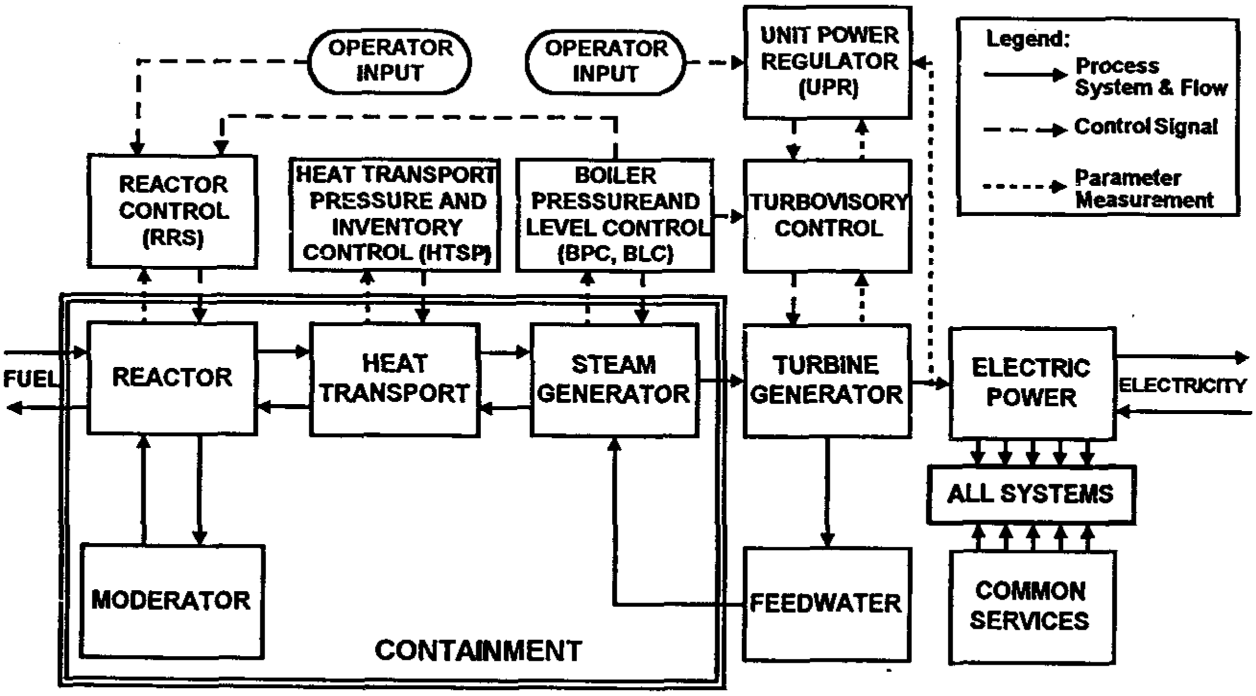


Figure 1.14. Simplified Overall Unit Control Block Diagram.

Operator/Computer Interface

As indicated earlier, digital computers are used to perform most of the control and monitoring functions of a CANDU station and replace much of the conventional panel instrumentation in the control room.

A number of man-machine communication stations, each essentially comprising a keyboard and color CRT monitors, are located on the main control room panels. The displays provided include graphic trends, bar charts, status displays, pictorial displays and historical trends.

The Unit Control Computer System was not designed to be a stand alone master brain that could handle all possible situations without intervention of an operator. Major set points, like the unit operating level, are input by the operator according to approved station procedures. Manual controls are also incorporated into the system to allow the operator to intervene under prescribed conditions, such as during major upsets, equipment failure or computer malfunction.

The operator interface was designed to provide two way communications between the operator and the computer system. The computer provides sufficient information in an appropriate form (easily understandable, meaningful, correct) to the operator to assist in decision making. The computer provides information about field processes, equipment operation, abnormal conditions, computer malfunctions, etc., in the form of displays on the monitor, alarms, or printed logs. The operator can enter information, requests, or instructions to the computer using keyboards and switches. Figure 1.15 shows a typical computer control process.

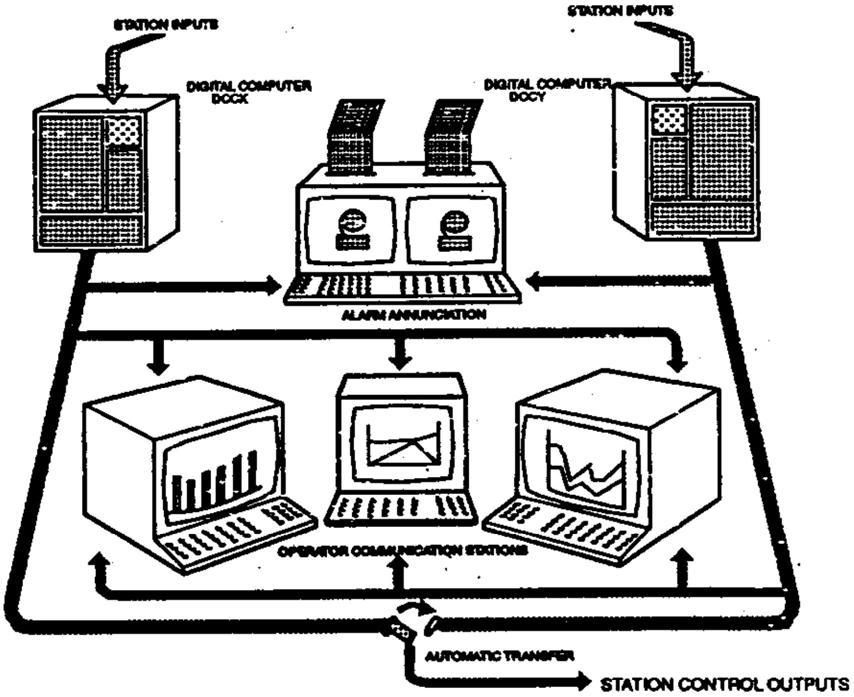


Figure 1.15. Man-machine interface and process computer control system.