Status report 68 - Enhanced CANDU 6 (EC6)

Overview

Full name	Enhanced CANDU 6
Acronym	EC6
Reactor type	Pressure Tube Type Reactor
Coolant	Heavy Water
Moderator	Heavy water
Neutron spectrum	Thermal Neutrons
Thermal capacity	2084.00 MWth
Electrical capacity	740.00 MWe
Design status	Basic Design
Designers	AECL
Last update	01-04-2011

Description

Introduction

The Enhanced CANDU 6 (EC6) is a 740 MWe pressure tube reactor designed by Atomic Energy of Canada Limited(AECL) to provide safe and reliable nuclear power. It is an evolution of the CANDU® 6 reactor, and is designed to be licensable internationally by ensuring its compliance with the latest Canadian nuclear regulations and the fundamental safety principles of the International Atomic Energy Agency (IAEA) Safety Standards.

CANDU is a pressurized heavy water reactor (PHWR) that uses heavy water (deuterium oxide – D_2O) as a moderator and coolant, and natural uranium as its fuel.

Figure 1-1 illustrates how CANDU reactors produce electricity. The heat transport system (HTS) circulates the coolant through the reactor to remove the heat of fission from the fuel. The coolant then passes through the tubes of the steam generator where demineralized water is evaporated to produce steam. The steam flows through the turbine, is condensed in the condenser, and is subsequently returned as feed water to the steam generator. The condenser operates at vacuum conditions to condense the exhausted steam from the turbine using a supply of cooling water from a nearby river, lake or ocean.

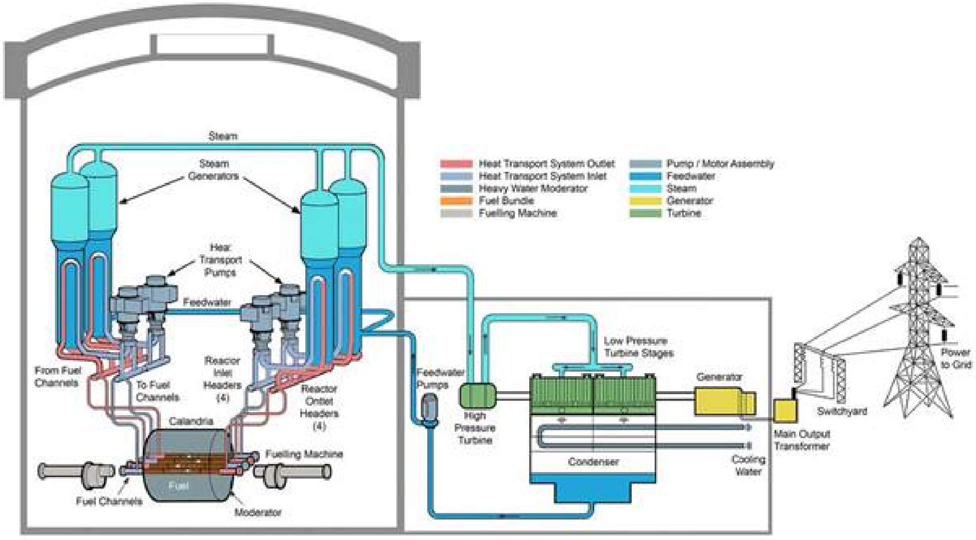

Figure 1-1 Overall Plant Flow Diagram

Pressurized water reactors (PWRs) and PHWRs have a two-circuit cooling system that operates at very high pressure (in the reactor and in the steam generator, where steam is generated to drive the turbine). The CANDU reactor, however, has pressure tubes rather than a pressure vessel enclosing the reactor core, which makes refuelling under load possible by disconnecting individual pressure tubes (on-power refuelling).

In the CANDU design, the heavy water moderator circulates through a large tank called the calandria and through the moderator heat exchangers to remove the heat generated during reactor operation. The calandria is penetrated by several horizontal pressure tubes that form channels for the fuel to be cooled by a flow of coolant under high pressure. The heavy water coolant carries the heat to the steam generators where the heat is transferred to the water to produce steam. The moderator system is completely independent of the HTS.

1.1. Historical Basis

AECL is the designer and builder of CANDU reactors, including the CANDUÒ 6, the EC6Ô, and the Advanced CANDU Reactor^{Ô} (ACR-1000^{Ô}). Established in 1952, AECL has been continually building nuclear reactors for over 50 years, delivering a wide variety of nuclear services that include:

- Research and development
- Design and engineering
- Procurement services
- Construction management
- Commissioning and decommissioning
- Specialized technology
- Life extension and plant life management programs
- Waste management, handling and storage technologies

AECL has built 34 CANDU reactors in North and South America, Asia, and Europe. An additional 15 heavy water reactors around the world are based on the CANDU. Since 1996, AECL has completed seven new CANDU 6 power plants, keeping design, manufacturing, and construction capabilities current.

1.2. Design Features

The EC6 design benefits from the proven principles and characteristics of the CANDU 6 design and the extensive knowledge base of CANDU technology gained over decades of operation. The key characteristics of the CANDU 6 reactor design include:

- Natural uranium fuel.
- Two independent safety shutdown systems.
- A separate low-temperature, low-pressure moderator that provides an inherently passive heat sink by permitting heat to be removed from the reactor core under abnormal conditions.
- A reactor vault that is filled with cool light water that surrounds the reactor core providing another passive heat sink.
- On-power refuelling.
- A modular, horizontal fuel channel core that facilitates installation.
- Reactor building access for on-power maintenance.
- Highly automated control systems with plant control computers that adjust and maintain the reactor power for plant stability. This is particularly beneficial in less-developed-power grids where fluctuations occur regularly and capacities are limited.

Major improvements incorporated into the EC6 design include:

- Improved plant power output of 740 MWe (target).
- More robust containment and increased passive safety features (e.g., thicker walls, steel liner).
- Enhanced severe accident management
- Addition of emergency heat removal system (EHRS) as a safety system.
- Improved shutdown performance for larger loss of coolant accident (LOCA) margins.
- Upgraded fire protection systems to meet current Canadian and international standards.
- Additional design features to improve environmental protection for workers and public following as low as reasonably achievable (ALARA) principle.
- Automated and unitized back-up standby power and water systems.
- Other improvements to meet higher safety goals consistent with Canadian and international standards based on probabilistic safety assessment (PSA) studies.
- Additional reactor trips to improve the trip coverage and effectiveness
- A plant life of 60 years with one life extension of critical equipment such as fuel channels and feeders at mid-life.
- Capacity factor of 90% (lifetime)

Table 1-1 CANDU Reactors Built

Name	**Location**	**Capacity MWe (Gross)**	**In-Service-Date**
Pickering-1	Canada	542	1971
Pickering-2	Canada	542	1971
Pickering-3	Canada	542	1972
Pickering-4	Canada	542	1973

Name	Location	Capacity MWe (Gross)	In-Service-Date
Kannup-1	Pakistan	125	1972
Rapp-1	India	90	1973
Rapp-2	India	187	1981
Bruce-1	Canada	825	1977
Bruce-2	Canada	825	1977
Bruce-3	Canada	805	1978
Bruce-4	Canada	805	1979
Wolsong-1	Rep. of Korea	679	1983
Point Lepreau	Canada	680	1983
Gentilly-2	Canada	675	1983
Pickering-5	Canada	540	1983
Pickering-6	Canada	540	1984
Pickering-7	Canada	540	1984
Pickering-8	Canada	540	1986
Embalse	Argentina	648	1984
Bruce-5	Canada	840	1985
Bruce-6	Canada	870	1984
Bruce-7	Canada	840	1984

Name	Location	Capacity MWe (Gross)	In-Service-Date
Bruce-8	Canada	840	1987
Darlington-1	Canada	935	1990
Darlington-2	Canada	935	1989
Darlington-3	Canada	935	1991
Darlington-4	Canada	935	1992
Cernavoda-1	Romania	706	1996
Wolsong-2	Rep. of Korea	715	1997
Wolsong-3	Rep. of Korea	715	1998
Wolsong-4	Rep. of Korea	715	1999
Qinshan 3-1	China	728	2002
Qinshan 3-2	China	728	2003
Cernavoda-2	Romania	650	2007

1.3. Safety Philosophy

The EC6 incorporates design enhancements to ensure that it meets the latest regulatory requirements in Canada for a new reactor design. These requirements are defined in Canadian Nuclear Safety Commission (CNSC) document RD-337 [1], which is in accordance with high-level international safety design requirements defined in IAEA report NS-R-1 [2].

Nuclear safety requires that the radioactive products from the nuclear fission process are 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 EC6 achieves this at all times by means of the following:

- Reactivity Control: Controlling the reactor power and, if necessary, shutting down the reactor.
- Heat Removal: Removing heat from the reactor core, including decay heat following shutdown, to prevent fuel overheating.
- Containment of Radioactive Materials: Containing radioactive products that are normally produced and contained in the fuel.
- Monitoring: Monitoring the plant to ensure that the above functions are being carried out and, if not, ensuring that mitigating actions are being taken.

These nuclear safety functions are carried out to a high degree of reliability in the EC6 by applying the following principles:

- The use of high-quality components and installations.
- Maximizing the use of inherent safety features.
- Implementing multiple defense-in-depth barriers for prevention of radioactive release.
- Providing enhanced features to mitigate and reduce consequences of design basis events and severe accidents.

The EC6 design maintains the following traditional CANDU inherent safety characteristics:

- The low-pressure and low-temperature heavy water moderator slows down neutrons, resulting in a fission process that is more than an order of magnitude slower than that of light water reactors (LWRs) and therefore inherently easier to control.
- Refuelling during on-power operation reduces the excess reactivity level needed for reactor control. Reactor characteristics are constant and no additional measures, such as the addition of boron to the reactor coolant (and its radioactive removal), are required.
- Natural circulation capability in the reactor cooling system copes with temperature transients due to loss of forced flow.
- Reactivity control devices cannot be ejected by high pressure because they are in the low-pressure moderator and do not penetrate the EC6 reactor coolant pressure boundary.
- Moderator back-up heat sink maintains core coolability for LOCAs even when combined with the unavailability of emergency core cooling (ECC) – for example, a severe accident.

Safety is delivered by design through safety systems, safety support systems, and robust buildings and structures that meet high standards for diversity, reliability and protection against common-mode events (i.e. seismic occurrences, tornados, fires, floods and malevolent acts).

Enhanced passive safety features incorporated into the EC6 design are:

- An elevated reserve water tank located in the upper level of the reactor building, designed to deliver passive make-up cooling water to the moderator vessel and the calandria vault to remove heat. This delays the progression of severe accidents and provides additional time for mitigating actions to be taken.
- A robust, seismically-qualified reactor building that includes a:

- Thicker pre-stressed concrete structure designed to withstand the impact of aircraft crashes.
- Leak-tight inner steel liner to reduce potential leakages following accidents.
- Passive slow flow spray system from the elevated water reserve tank to reduce pressure in the reactor building in the event of a severe accident.
- Passive autocatalytic hydrogen recombiners to limit the hydrogen content in the air in the event of a LOCA

1.4. Applications

The primary application of EC6 is electricity production. Studies are underway for possible application to district heating, desalination, industrial cogeneration, hydrogen production, and generation of process steam. For further details on non-electrical applications see Section 11.

Description of the nuclear systems

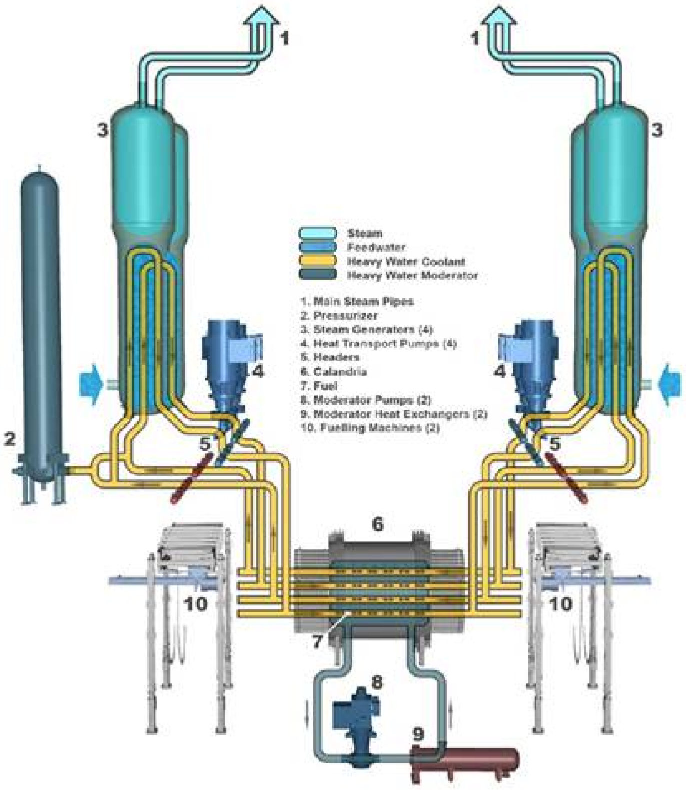

Figure 2-1 Nuclear Systems Schematic

The nuclear systems (Figure 2-1) comprise:

- A reactor assembly that consists of a calandria vessel complete with fuel channels installed in a concrete vault.
- A heavy-water moderator system.
- An HTS with reactor coolant, four steam generators, four heat transport pumps, four reactor outlet headers, four reactor inlet headers and feeders. This configuration is standard on all CANDU 6 reactors.
- A fuel handling system that consists of two fuelling machines, each mounted on a fuelling machine bridge that is supported by columns, which are located at each end of the reactor.
- Two independent shutdown systems (SDS1 and SDS2), ECC system, containment system, EHRS, and associated safety support systems.

Each of the above is explained in the following sections.

2.1. Reactor Assembly

The reactor assembly provides the facility in which uranium fuel undergoes fission to generate thermal power. Heavy water is pumped through the reactor assembly fuel channels to cool the fuel and carry the heat to the steam generators. Fuel bundles are inserted and removed, on power, by the fuelling machine. Reactivity control units, under direction of the reactor regulating system (RRS) and the two reactor shutdown systems, control the fission rate.

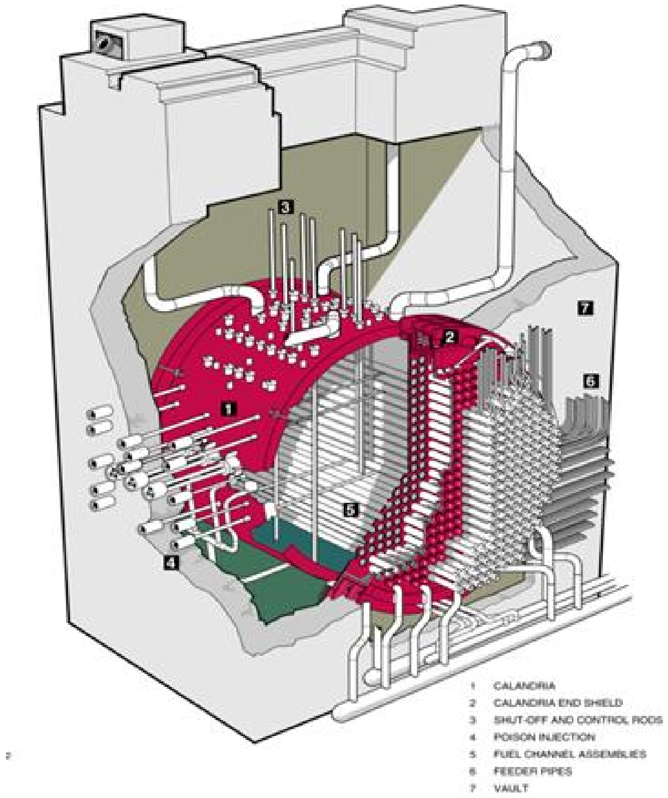

Figure 2-2 Reactor Assembly

The EC6 reactor assembly comprises the calandria vessel and end shields, 380 fuel channel assemblies, the reactivity control units, and the calandria vault (Figure 2-2).

The calandria shell, the two end shields, and the calandria tubes form a horizontal cylindrical vessel called the calandria vessel through which pressurized heavy water is circulated by the moderator system. This fluid is used to moderate the fast neutrons in the fission process and is independent of the HTS. The end shields support the axially - oriented horizontal fuel channel assemblies and the calandria shell, which supports the vertical and horizontal in-core reactivity control unit (RCU) components. This entire assembly is supported at the end shields by the end walls of the calandria vault.

The calandria vault comprises a rectangular, steel lined concrete structure, closed at the top by the reactivity mechanism deck (RMD). The RMD supports the upper ends of the reactivity control units, their mechanisms and connecting pipes and cables.

The fuel channel assemblies (Figure 2-3) contain the bundles of uranium fuel, through which the heat transport system heavy water is pumped via feeder pipes at each end. End fittings with removable closures and shield plugs permit removal and insertion of the fuel on load by the fuelling machines.

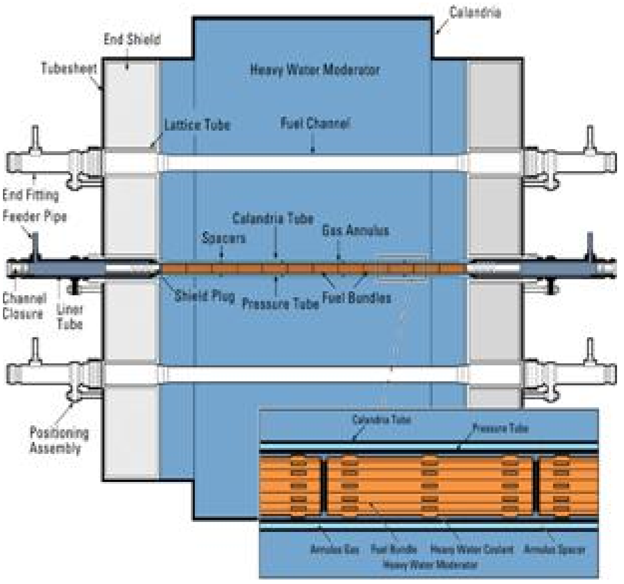

Figure 2-3 Calandria Assembly & Fuel Channels

Each fuel channel locates and supports 12 fuel bundles in the reactor core. The fuel channel assembly includes a zirconium-niobium alloy pressure tube, a zirconium calandria tube, stainless steel end fittings at each end, and four spacers that maintain separation of the pressure tube and the calandria tube.

Each pressure tube is thermally insulated from the cool, low-pressure moderator by the carbon dioxide annulus gas present between the pressure tube and the concentric calandria tube.

Each end fitting incorporates a feeder connection through which heavy water coolant enters/leaves the fuel channel. Pressurized heavy water coolant flows around and through the fuel bundles in the fuel channel, and removes the heat generated in the fuel by nuclear fission. Coolant flows through adjacent channels in the reactor in opposite directions.

The RCUs comprise tubes spanning the calandria, which contain devices to measure, regulate and shutdown the fission reaction. Measurement is made by ion chambers and self-powered in-core flux detectors; regulation is achieved by insertion of liquid and solid neutron absorbers; and shutdown is carried out by insertion of solid absorbers or injection of liquid absorbers into the moderator. The in-core tubes are extended upwards through the RMD, and laterally through the vault wall where actuator mechanisms or electrical and process connections are mounted (See information on the reactor regulating system in Section 7.2.4).

Six liquid zone control units do primary control of the nuclear reaction. Each liquid zone control assembly consists of zircaloy tubes that contain independently adjustable levels of light water absorber. By varying the quantity of water, they can independently regulate power levels.

2.2. Fuel

2.2.1. Fuel Design Features

The EC6 fuel bundle consists of 37 elements (Figure 2-4). Each element is approximately 0.5 metres long and contains three basic component parts: the uranium oxide (UO_2) pellets, the sheath with Canlub[1] (graphite) coating in the inside surface, and the end caps.

Figure 2-4 EC6 Fuel Bundle

The sheath contains the UO_2 pellets and is made of zircaloy-4, which has low neutron absorption, good corrosion resistance, and low hydrogen pick up. The end caps, resistance welded to the sheaths, seal the fuel elements at each end. Two end plates, also resistance welded to the end caps, hold together the 37 elements of the fuel bundle. Spacer pads are brazed to the elements at their mid points to provide the desired inter-element spacing. The bundle is spaced from the pressure tube by bearing pads brazed near the end and at the mid-point of each outer element. Beryllium metal is alloyed with the zircaloy to make the braze joints.

2.2.2. Fuel Cycle Options

The natural uranium fuel cycle offers simplicity of fuel design and ease of availability and fabrication of natural uranium. However, for those clients who want to take advantage of alternative fuel cycles, the EC6 offers a number of options:

- Slightly Enriched Uranium (SEU): Relatively low enrichment (up to 1.2%) results in a reduction in fuel-cycle costs and greater flexibility in plant operations. The use of SEU is the easiest first step in CANDU fuel-cycle evolution.
- Thorium Fuel Cycles: As early as the 1950s, the use of thorium was identified as a promising fuel cycle in the CANDU development program. This was due to thorium's anticipated improved fuel performance (e.g. reduced fission gas release due to thorium's enhanced thermal and chemical properties) in addition to the relative abundance of thorium. Thorium is three to four times more abundant than uranium in the earth's crust and is commercially exploitable. On-power refuelling, a simple fuel bundle, and the fundamental fuel channel design give the EC6 flexibility in accommodating thorium-based fuel. Furthermore, it is important to note that the existing CANDU reactors can be converted to use thorium-based fuel with small changes to the design, and the majority of the reactor systems would not need any modification. Long-term energy security can be assured through the thorium fuel cycle. Possible CANDU thorium cycles include open cycles, such as Once-Through Thorium (OTT) fuel cycles, and closed cycles, which involve unloading the used thorium fuel and separating the ^{233}U for further use in another reactor.
- Natural Uranium Equivalent (NUE) Fuel: NUE can be produced by mixing in predetermined proportions of recycled uranium from commercial nuclear power plants (^{235}U content ranging from 0.8 to 1%) with depleted uranium, which is available with different contents of ^{235}U, to obtain a blend that is neutronically equivalent to CANDU natural uranium fuel and which can be used in CANDU reactors. This is the easiest first step towards utilization of recycled uranium in a CANDU.
- Plutonium: A high burn-up CANDU MOX fuel design could utilize plutonium from conventional reprocessing or more advanced reprocessing options (such as co-processing).

Further information on fuel cycle options can be found in Reference [3]

2.3. Moderator System

The moderator system of the EC6 reactor (Figure 2-5) is a low-pressure and low-temperature recirculating system. It is independent of the HTS and consists of pumps and heat exchangers that circulate the heavy water moderator through the calandria and remove the heat that is generated during reactor operation. It also serves as a backup heat sink.

The heavy water acts as both a moderator and reflector for the neutron flux in the reactor core. The moderator slows down neutrons emitted from the fission chain reaction to increase the chances of the neutrons hitting another atom and causing further fission reactions. The reflector is the material layer around the reactor core that scatters neutrons and reflects them back into the reactor core to cause further fission chain reactions.

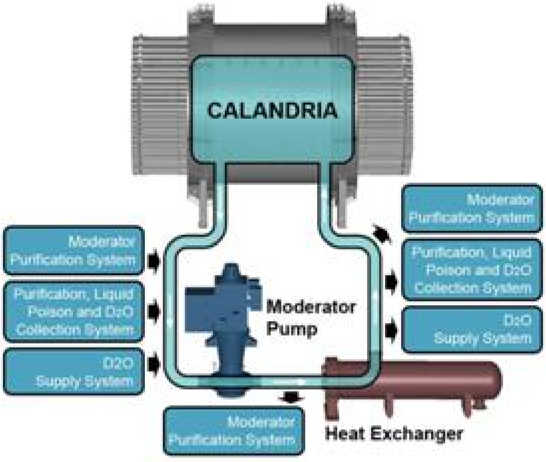

Figure 2-5 Moderator System Flow Diagram

The moderator system fulfills a safety function that is unique to CANDU. It serves as a backup heat sink for absorbing the heat from the reactor core in the event of loss of fuel cooling, i.e. failure of the HTS coincident with loss of the ECC system, to mitigate core damage. It also acts as a heat sink following a LOCA, both in-core and out-of-core, a LOCA with loss of the main power supply (Class IV), and a LOCA with loss of ECC.

The main moderator system consists of two 100% capacity centrifugal pumps, two 50% capacity tube in-shell heat exchangers, a head tank, valves, and associated instrumentation. Its primary purpose is to keep moderator temperature within acceptable limits. It also serves as a means for dispersion of chemicals for moderator purification and control of reactivity.

An added safety improvement in the EC6 reactor is a connection to an elevated reserve water tank that provides additional passive gravity-fed cooling water inventory to the calandria in case of a severe accident. This connection extends core cooling and delays severe accident event progression. This gravity-fed water cooling provision is supplemented by a pump-driven recovery recirculating circuit. See section 3.3 for details on the Severe Accident Recovery System (SARS).

Auxiliary systems to the main moderator system include the following:

- Purification system that removes particulates, ionic and soluble boron and gadolinium impurities from the moderator as needed to achieve the required reactivity
- Deuteration and dedeuteration system that replaces the light water in the resin used in the purification system and recovers the heavy water from the resin after use
- Cover gas system, above the moderator liquid surfaces in the calandria relief ducts and in the moderator head tank, to prevent corrosion and reduce radioactivity.
- Liquid poison system that can be used to add neutron-absorbing boron and gadolinium to the moderator to control and adjust the reactivity
- D_2O collection system that collects heavy water leakages from various parts of the system

2.4. Heat Transport System (HTS) and Auxiliary Systems

2.4.1. Primary Heat Transport System

The primary heat transport system (Figure 2-6) circulates pressurized heavy water coolant through the reactor fuel channels to remove heat produced by the nuclear fission chain reaction in the reactor core. The heat is carried by the reactor coolant to the steam generators where it is transferred to ordinary water to produce steam, which subsequently drives the turbine generator.

The major components of the HTS are the 380 reactor fuel channels with associated corrosion-resistant feeders, four vertical steam generators, four motor driven pumps, four reactor inlet headers (RIH), four reactor outlet headers (ROH), one electrically heated pressurizer, and all necessary interconnecting piping and valves.

The system is arranged in a two-loop, figure-of-eight configuration. The headers, steam generators and pumps are all located above the reactor.

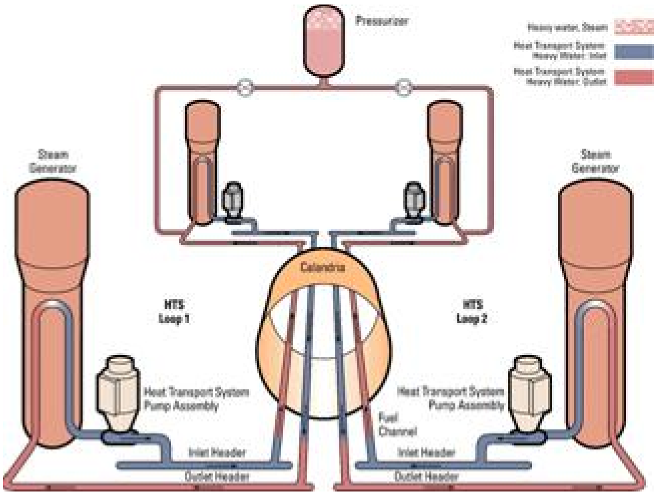

Figure 2-6 Heat Transport System

2.4.1.1. Steam Generators

There are four identical steam generators, with integral pre-heaters to transfer heat from the D_2O reactor coolant on the steam generator primary side to the H_2O on the secondary side. The steam generators consist of an inverted vertical U-tube bundle installed in a shell, made of Incoloy-800.

The primary side of the steam generators consists of the head or channel cover, the primary side of the tubesheet and the tube bundle. A partition plate separates the inlet half of the head from the outlet half. The secondary side of the steam generators consists of the shell, the steam separating equipment, the tube bundle shroud, the secondary side of the tube sheet, the secondary side of the tube bundle, the pre-heater baffles and the tube support plates. The shell is provided with a manway, an inspection opening above the tubesheet, and connections for emergency water supply, and steam generator blowdown.

2.4.1.2. Heat Transport Pumps

There are four heat transport pumps. They circulate reactor coolant through the fuel bundles in the reactor's fuel channels and through the steam generators. Electric motors drive the heat transport pumps.

The EC6 reactor heat transport pumps retain the CANDU 6 mechanical multi-seal design, which allows for their easy replacement. The cooling of the pump seals lengthens pump service life and the time that the pump will operate under accident conditions.

2.4.1.3. Feeders

The 380 feeders at each end of the reactor run vertically from the fuel channels up the face of the reactor and then horizontally across and above the fuelling machine area to the reactor headers.

2.4.1.4. Headers and Piping

There are four reactor outlet headers, two at each end of the reactor. Each of the reactor outlet headers receives the flow from 95 outlet feeders and conducts the flow to two steam generator inlet lines, which lead to a single steam generator. Similarly, there are four reactor inlet headers, two at each end of the reactor. Each of the reactor inlet headers receives the flow from two pump discharge lines, which lead from a single heat transport pump and conduct the flow to 95 inlet feeders.

2.4.2. Heat Transport Pressure and Inventory Control System

The heat transport pressure and inventory control system is designed to provide a means of pressure and inventory control as well as to provide adequate overpressure protection for the primary heat transport system. It also provides a controlled degassing flow. It consists of several subsystems, including the pressurizer and pressure control system, the feed and bleed circuit, the degasser condenser circuit, and a spray flow supply circuit.

2.4.2.1. Pressurizer

The pressurizer is the main component responsible for pressure control in the HTS. It is a cylindrical pressure vessel filled with liquid D_2O and saturated vapour in equilibrium with the liquid.

During the normal operating condition, the pressurizer is connected to the HTS. This is called normal mode. The pressure in reactor outlet headers is maintained at a desired value by controlling the pressure of the pressurizer steam space either by heat addition via headers or by bleeding steam via bleed valves.

When the reactor power is less than 5%, the pressurizer may be isolated from the HTS by closing the motorized, pressurizer isolation valves. This is called "solid mode" operation of the HT pressure control system. In this case the pressure control of the HTS is achieved by feed and bleed. Swell and shrink in HTS, during warm-up from cold to zero power hot or cool-down from zero power hot to cold, are compensated by bleeding from the system via the bleed circuit or feeding into the circuit via the feed circuit.

2.4.2.2. Feed and Bleed Circuit

The feed and bleed circuit is responsible for the inventory control of the HTS. The circuit is designed to handle the shrink and swell which take place during warm-up and cool-down. The feed flow is taken from the D_2O storage tank through two high-pressure, multi-stage D_2O feed pumps. The bleed flow is taken from the heat transport purification system return line.

2.4.3. Auxiliary Systems

They include but are not limited to the annulus gas system and the shield cooling system. The annulus gas system is classified as a safety related system (Section 3), which has the safety function of monitoring the integrity of the heat transport system pressure boundary (i.e. pressure tubes). It contains commercial grade dry carbon dioxide, which is continuously re-circulated through the system. The shield cooling system removes heat from the shield assemblies by circulating demineralized water through them and then by transferring this heat to the low pressure recirculated cooling water system by mean of heat exchangers.

2.5. Fuel Handling Systems

The fuel handling system comprises equipment for storage of new fuel, for fuel changing and for temporary storage of spent fuel. From the loading of fuel in the new-fuel mechanism to the discharge of spent fuel in the receiving bay, the fuelling process is automated and remotely controlled from the station control room.

2.5.1. New Fuel Storage and Handling System

The function of the new fuel handling and storage system is to receive, store, inspect and transfer new fuel. It is designed with sufficient storage for nine months supply, with provision for the temporary storage of the initial load of fuel. Two remote controlled fuelling machines are located on opposite sides of the reactor and mounted on bridges that are supported by columns. Refuelling is based on an eight-fuel bundle shift in the direction of the reactor coolant flow. Fresh fuel bundles are inserted at the inlet end of the fuel channel by one of the fuelling machines. The other fuelling machine removes spent fuel bundles from the outlet end of the same fuel channel.

2.5.2. Fuel Changing

The function of the fuelling machine head is to pick up new fuel from the new fuel port, load it into the reactor, receive spent fuel from the reactor, and discharge it into the spent fuel port.

2.5.3. Spent Fuel Handling and Storage System

The spent fuel handling system consists of discharge and transfer equipment in the reactor building, and spent fuel reception and storage equipment in the service building. Fuel is initially discharged into the discharge bay, through the transfer canal to the reception bay, and then to the storage bay. A storage bay man-bridge and handling tools permit safe access and manipulation of the spent fuel and containers.

[1] Canlub reduces the effect of pellet-clad interaction.

3.1. Overall Safety Concept and Licensing Approach

The objectives of safety design are to:

- Take all reasonably practicable measures to prevent accidents in the nuclear power plant and to mitigate their consequences should they occur
- Ensure with a high level of confidence that, for all postulated accidents considered in the design, including those of very low probability, radiological consequences would be below prescribed limits;
- Ensure that the likelihood of accidents with serious radiological consequences is extremely low

To ensure that the EC6 design is licensable in Canada and to facilitate its licensability in other countries, the following licensing requirements have been applied during the design process:

- The relevant Canadian nuclear safety requirements
- The IAEA requirements as specified in the IAEA Safety Standard Series No. NS-R-1 [2]
- The environmental requirements for siting in Canada

In addition, the EC6 design has taken into consideration requirements from other jurisdictions and can accommodate them with limited changes to the reference design.

3.1.1. Defence-in-Depth

The EC6 reactor is based on the CANDU principle of defence-in-depth by providing the following multiple diverse barriers for accident prevention and mitigation of consequences to the workers, public and environment.

- High-quality process systems to accommodate plant transients and to minimize the likelihood of accidents
- Reliable safety systems for reactor shutdown, ECC and containment
- Reliable safety support systems to provide services to the safety systems and other mitigating systems
- Back-up systems for heat sinks and essential controls
- Passive heat sinks to increase resistance against design basis and severe accidents
- Complementary design features to prevent accident progression and to mitigate the consequences of selected severe accidents.

The EC6 reactor has the following barriers for prevention of releases:

- Fuel sheath that contains the radioactive material
- HTS, including pressure tubes
- Calandria tubes
- Cool low-pressure moderator
- Cool low pressure reactor vault
- Steel-lined concrete containment structure

3.1.2. Safety Design and Philosophy

The design of the safety systems follows the design principles of separation, diversity and reliability. High degrees of redundancy within systems are provided to ensure the safety functions can be carried out, even when systems or components are impaired. Protection against seismic events, tornados, floods and fire is also provided to ensure highly reliable and effective mitigation of postulated events, including severe accidents.

The following safety features contribute to the overall safety of the EC6 design:

- The EC6 design continues to utilize the passive safety features of the traditional CANDU. The traditional CANDU 6 design includes two independent and fully capable shutdown systems. These systems are upgraded by adding new-engineered features to increase safety margins following postulated accidents including LOCA.
- For EC6, the large LOCA power transient has been reduced by almost a factor of two relative to CANDU 6, by a combination of changes to operating parameters and speeding up the slower of the two shutdown systems. Redundancy and other shutdown system improvements mitigate any positive reactivity insertion following a LOCA [4, 5].
- The containment has been made thicker and more reinforcing steel has been added to achieve a higher design pressure and lower test acceptance leakage rate. These features provide additional margin in design and the thicker containment wall results in an increased protection against external threats, such as deliberate aircraft strike.
- The EC6 design incorporates an EHRS, to provide heat sink capability, including automated emergency power supply (EPS) start-up.
- The addition of a low-flow spray system for operation in case of severe accidents.
- In the event of hydrogen release into containment following a postulated accident, hydrogen mitigation is accomplished through the use of igniters and Passive Autocatalytic Recombiners (PARs).
- In the moderator cooling system, increase of the number of outlet nozzles, modifications to nozzle orientation, and relocation of outlet flow taps to the top half of the calandria are made to improve moderator circulation and to give significant increase in subcooling margin. In the event of a loss of the ECC system, the moderator system's ability to maintain fuel cooling and fuel channel structural integrity has been considerably enhanced through this feature.
- EC6 feeder design, including choice of material, has been changed to improve its fitness for service
- Changes to the instrumentation and control functions of the EC6 include the addition of an emergency support centre (ESC) and an expanded safety parameter display system (SPDS) so that it is also available in the secondary control area (SCA) and the Emergency Support Centre (ESC).

3.1.3. Provisions for Simplicity and Robustness of the Design

The EC6 design maintains the simplicity of the CANDU 6 design, derived partly from its passive safety features (i.e. two independent passive safety systems; cool, low-pressure moderator that serves as heat sink; reactor vault filled with light water providing a second core heat sink, etc.). The CANDU 6 design basis does not require any operator intervention for at least 15 minutes following an abnormal condition. The CANDU 6 system relies on computer control through two redundant on-line computers that, in addition to control function, also manages information and alarms.

The EC6 offers improvements to the security of the plant by including increased protection against aircraft strikes and external events. The containment civil structure has been thickened and more reinforcing steel has been added to meet such objectives. Group 2 safety systems, which offer a redundant path to shutdown the plant safely, have been rearranged to be protected from the impact of an aircraft strike. Additionally, further hardening of the safety systems and improvements to the spatial separation of essential safety systems have been built into the design.

3.2. Safety and Safety Support Systems

3.2.1. Safety Systems

EC6 has five safety systems that mitigate the consequences of accidents:

- Shutdown system 1 (SDS1)
- Shutdown system 2 (SDS2)
- ECC system
- Containment system
- EHRS

All safety systems in EC6 are classified as being in one of two groups to provide defense against events that can affect more than one system in the plant, such as fire or malevolent acts. Either group, on its own, can shut down the plant, remove heat decay, prevent release of radioactive material to the public, and provide information on plant status. The groups are spatially separated, functionally independent, and diverse to the extent practical.

Group 1 comprises the normal process and control systems, SDS1 and ECC, with plant control and monitoring from the main control room. Group 2 comprises SDS2, the EHRS and containment system, with plant monitoring and control of essential safety functions from the Secondary Control Area (SCA). Group 2 also comprises the seismically qualified systems required to mitigate a design basis earthquake (DBE) and the water injection/recovery systems for mitigation of severe accidents

3.2.2.1. Shutdown Systems SDS1 and SDS2

The two fast-acting, diverse, redundant and independent shutdown systems (SDS1 & SDS2) are capable of handling all design basis accidents (DBAs) and serve as a back up to the reactor control systems for anticipated operational occurrences (AOOs). SDS1 consists of spring-assisted, gravity-driven rods that fall vertically into the moderator. SDS2 consists of horizontal perforated tubes in the calandria through which liquid neutron absorber (gadolinium nitrate) is injected at high pressure into the moderator by a passive hydraulic system.

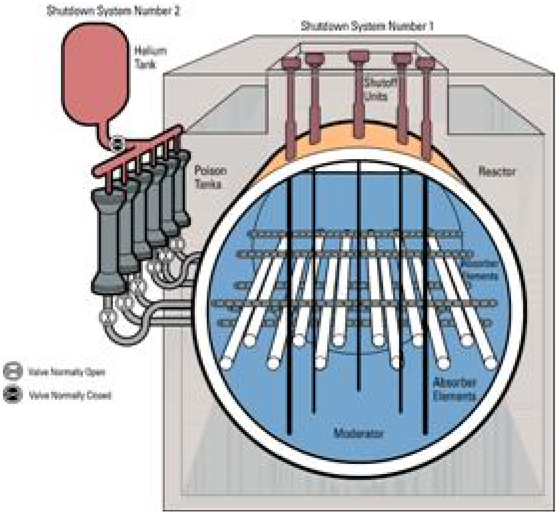

Figure 3-1 Shutdown Systems

A number of improvements are introduced to the EC6 shutdown systems and to the operational limits and alarms, which result in a reduced peak transient over-power following a large Loss of Coolant Accident (LOCA). These changes include additional SDS1 and SDS2 trip parameters and improvements in the shutoff rods design.

3.2.2.2. Emergency Core Cooling (ECC) System

The ECC system provides core refill and cooling following a small or large LOCA. It consists of: a passive high-pressure emergency core cooling (HPECC) system, a medium-pressure emergency core cooling (MPECC) system, and a low-pressure emergency core cooling (LPECC) system.

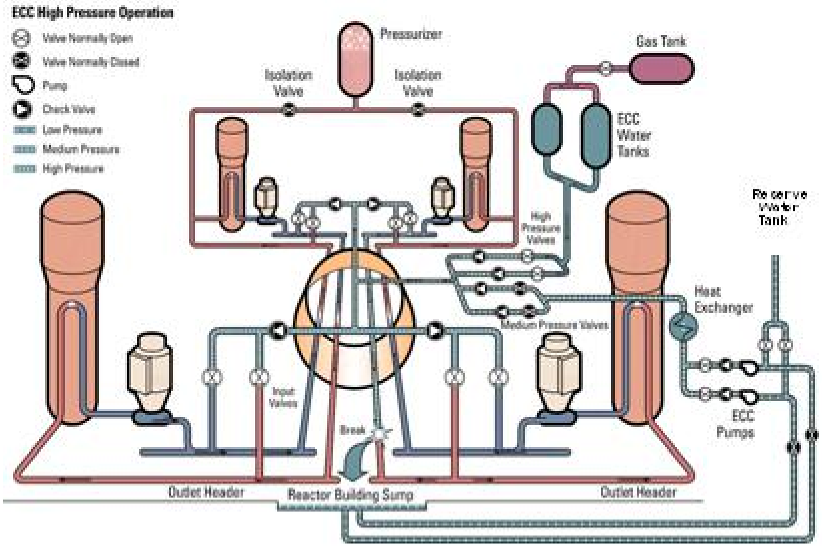

Figure 3-2 ECC System

The HPECC system has accumulator tanks that supply high-pressure water to the Heat Transport System (HTS) and refill the fuel channels in the short-term after a LOCA. During normal operation, the system is poised to detect any LOCA that results in a depletion of HTS inventory (i.e. reactor coolant) to such an extent that make-up by normal means is not assured. When the pressure in the HTS drops below the pressure of the HPECC accumulator tanks, make-up water is injected into the HTS. Valves on the interconnect lines between the reactor outlet headers open upon detection of a LOCA to establish a path for the water flow.

The MPECC system suctions water from the reserve water tank through two 100% ECC pumps and injects it into the HTS when the coolant pressure has decreased to sufficient levels

The LPECC system provides long-term recirculation and recovery. It is used for cooling the reactor following a LOCA in the longer term. The LPECC system is initiated automatically when the HTS is depressurized below a specific pressure, at which time the LPECC system begins operation in a long-term recovery mode.

3.2.2.3. Emergency Heat Removal System (EHRS)

The EHRS is a seismically qualified safety system that supplies cooling water to the secondary side of the steam generators, the ECC heat exchangers and the HTS via the ECC system piping in case of DBA. Also, the EHRS can supply cooling water to the SARS designed to mitigate severe accidents (see Section 3.3).

The EHRS design ensures that there is an adequate long-term heat sink available for decay heat removal following a loss of the normal heat removal systems for the reactor unit. The EHRS and its supporting structures, systems and components (SSCs) are designed to operate under the following postulated initiating events (PIEs) considered as DBAs and resulting in the loss of normal heat removal systems:

- LOCA plus loss of Class IV power; or
- DBE, design basis tornado (DBT); or
- LOCA followed by site design earthquake after 24 hours; or
- Total loss of electrical power (both Class IV and Class III)

The EHRS is a unitized system. Each unit has two 100% pumps taking suction from a source of on-site fresh water that is separate from the main plant service water system. A supply piping from the pump house serves users in the service building and the reactor building.

3.2.2.4. Containment System

The containment system is comprised of the following components and subsystems:

- A pre-stressed, post-tensioned concrete containment structure with a steel liner, which incorporates a reinforced concrete reserve water tank.
- A reinforced concrete steel lined irradiated fuel discharge chamber and its access passage.
- Steel piping and ductwork, which form a part of the containment boundary
- A containment isolation system consisting of valves and dampers in the system lines penetrating the containment. It also includes three radiation monitors and three differential pressure measurement loops with independent power supplies to actuate the system.
- Access airlocks.
- A hydrogen control system.
- Containment supporting systems, including building air coolers, a vapour recovery system, and a ventilation system train.

The robust concrete, steel-lined, low leakage (0.2%/day at design pressure) containment building surrounds the reactor core and the HTS and provides a barrier to the escape of radioactive materials released from those systems in an accident, and to external events such as tornadoes and malevolent acts, including deliberate crash of a large commercial aircraft. The containment design envelops the pressures reached in all DBAs, including main steam line breaks (MSLB). Heat removal for DBAs is achieved through local air coolers.

For long-term severe accident control (see also Section 3.3), a Severe Accident Recovery System (SARS) collects, cools and recirculates the water using dedicated pumps and heat exchangers. Containment maintains its role as a leak-tight barrier for a period that allows sufficient time for the implementation of off-site emergency procedures following the onset of core damage. Containment also prevents uncontrolled releases of radioactivity after this period.

PARs prevent hydrogen build-up in the containment during either DBAs or severe accidents. These recombiners are supplemented by igniters for DBAs in areas of potential high local hydrogen concentration and for some beyond-DBAs such as LOCA and loss of ECC.

3.2.3. Safety Support Systems

3.2.3.1. Emergency Power Supply (EPS) System

The EPS system is designed to provide a Group 2 seismically qualified alternative source of electrical power supply to systems important to safety in the event that normal power supplies (Class IV, Class III) are lost. The

Each EC6 unit has its dedicated EPS to supply the necessary safety-related loads. The EPS system for each unit is comprised of two duplicated, odd and even, automatically started, seismically qualified and functionally independent trains. For a two-unit station, an additional common diesel generator set serves as a backup power supply to either unit.

Each EPS generating set consists of a diesel generator with battery starting system, brushless excitation system, governor and controls.

The events specifically supported by the EPS system are:

- A DBE
- Loss of Class III/IV power
- LOCA followed 24 hours later by a SDE

3.2.3.2. Secondary Control Area (SCA)

The SCA is required following an event that could result in unavailability of the main control room. It contains the necessary controls and indications to:

- Shutdown the reactor by terminating the nuclear chain reaction and keeping the reactor in the shutdown state.
- Remove the decay heat from the reactor core.
- Assist the operator in assessing the state of the plant post-accident conditions.

3.2.3.3. Safety Related Instrumentation

The SPDS provides safety system monitoring during normal plant operation and post-accident monitoring functions following an event.

Under normal plant operating conditions, the SPDS provides sufficient information on the critical safety functions necessary for ensuring the proper operation of the reactor, including detection and diagnosis of malfunctions to allow mitigation of these conditions. When an accident occurs, the initial protecting and mitigating actions are to be performed automatically. As the accident progresses, the operator will tend to have an increasing role in managing the outcome of the event.

The SPDS and post accident monitoring instrumentation are provided to convey post-accident information, which enables the operator to:

- Assess the post-accident conditions of the plant and determine the nature and the course of the accident.
- Determine whether or not the safety-related systems have performed or are performing the required protective actions.
- Monitor the plant characteristics required to follow the effects of the accident.
- Determine the appropriate actions that need to be performed and monitor the results of those actions, including the need to execute the off-site emergency procedures.

The SPDS consists of a computer-based system for safety system monitoring and post-accident monitoring. Post-accident monitoring is carried out using a set of existing hardwired panel meters and status indicators that supplement the SPDS in providing post-accident indications.

3.3. Design Features to cope with Severe Accidents

A severe accident occurs when the fuel is not cooled within the HTS. The CANDU design principle is to prevent severe accidents and to mitigate them when they occur, minimizing their consequences. As discussed in previous sections, this is achieved in the EC6 reactor by providing a number of design measures, including the following:

- Normal heat removal systems
- Passive thermal capacity of moderator.
- Passive thermal capacity of reactor vault water.
- Passive emergency make-up to reactor vault heat sink from the Reserve Water System.
- Passive containment cooling via low-flow spray.
- Heat removal systems, using the EHRS.
- Emergency core cooling injection.
- Heat removal using the moderator system.
- Hydrogen recombiners (passive) and igniters to limit the hydrogen content to below the deflagration limit.
- Severe accident management monitoring capabilities.

The SARS in the EC6 is provided to prevent and mitigate severe accident progression that may lead to significant core degradation and challenge the containment integrity following beyond-DBA. The conceptual SARS is schematically shown in Figure 3-3. This system is designed and constructed to deliver the cooling water to the calandria vessel, the calandria vault, and the containment low-flow spray system following beyond-DBA, and can be divided into two major portions: (a) make-up water supply system to either moderator or calandria vault to establish controlled core state, and (b) containment low-flow spray system for containment cooling and pressure suppression.

This system includes gravity-driven, passive water supply lines and pump-driven, recovery circuit. The major active components and main water supply lines are duplicated to increase the system reliability and enhance the operational flexibility under conditions unpredictable in a beyond-DBA.

The reserve water tank provides gravity-driven water in the short-term, and the reactor building sump water is pumped to supply the water in the long term.

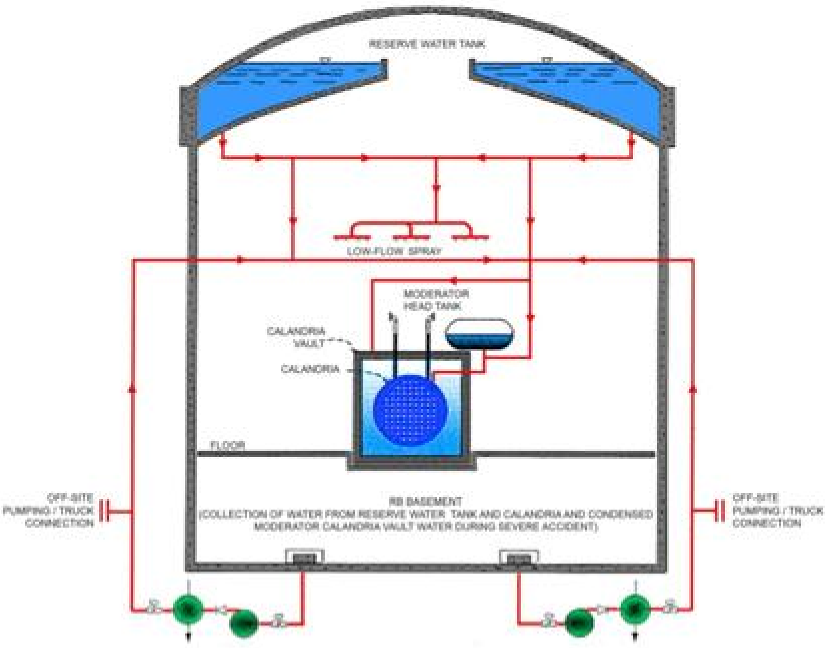

Figure 3-3 Severe Accident Recovery System (SARS)

3.4. Provisions for safety under seismic conditions

3.4.1. Seismic Safety Features

The safety objective of the seismic design for structures, systems and components is to have sufficient capability to perform the following essential safety functions:

a)In the event of an earthquake:

- The reactor is capable of being safely shutdown and of being maintained in that state indefinitely. This is achieved by seismic qualification of containment structures and buildings and safety systems (Group 2) that are used to perform this function.
- Decay heat is capable of being removed from the fuel during this shutdown period. As one requirement for this function, the primary coolant system pressure boundary will not fail.
- The containment structures and associated systems, as well as other critical structures and systems outside the containment area, are designed so that any radioactivity releases are within the reference dose limits.
- Performance of the above functions is monitored.

b)In the unlikely event of a LOCA, necessary portions of the emergency coolant injection system, the shutdown systems, containment system, monitoring equipment and supporting systems must remain functional following the most likely earthquake that might occur (SDE as applicable) during the recovery period after the LOCA

c)Neither seismically induced failure nor operability of non-seismically qualified systems such as instrument air, offsite power supply, etc, will impair the safety functions listed above.

3.4.2. EC6 Design Enhancements Related to Seismic Events

Based on the review of the most up-to-date PSA-based seismic margin assessment for a CANDU 6 (Section 3.6), the design improvements listed below have been incorporated into the EC6 design to ensure that the seismic risk is not a significant contributor to the overall risk.

- The seismically qualified buildings including service building, SCA/EPS building, EHRS structures, and ECC building have been upgraded to have seismic capacity of 0.3g.

- The service building is designed to resist malevolent acts.
- The seismic capacity of primary circuit components such as HTS and the calandria is 0.3g.
- The turbine building is designed to prevent its collapse onto neighboring buildings during a seismic event.
- The new SARS (Section 3.3) has been provided with a seismic capacity of 0.3g. The system uses electrical power and cooling water supplied from EPS diesel generators and the EHRS. In addition to these resources, the design has provisions for on-site portable electrical power and cooling water with seismic capacity of 0.3g.
- The calandria and calandria vault makeup system draw water from the reserve water tank. The system has a seismic capacity of 0.3g. Electrical power for the calandria vault makeup isolation valves is supplied from the seismically qualified batteries with backup EPS power.
- There are two automatically actuated 100% EPS diesel generators. A two-unit plant has a total of five EPS diesel generators, two per unit, and a manually actuated backup EPS diesel generator common between the two units. The generators and their auxiliaries are designed to have a seismic capacity of 0.3g.
- A seismically qualified circuit for auto-depressurization of the steam generator secondary side using EPS power (opening main steam safety valves and initiating EHRS to supply water to the steam generators).
- The seismically qualified ECC system has the capacity to mitigate the seismic-induced small LOCA.
- A high containment design pressure to give sufficient time to operators to actuate the SARS.

3.5. Safety Goals

The safety goals for the EC6 design are based on those defined in the CNSC regulatory document RD-337 [1] for Nuclear Plants in Canada. These safety goals are used to derive limits on the summed frequency and consequences of severe accidents, namely:

- Core damage frequency (CDF): The sum of frequencies of all event sequences that can lead to significant core degradation is less than 10^{-5} per reactor year.
- Small release frequency: The sum of frequencies of all event sequences that can lead to a release to the environment of more than 10^{3} T Bq. of iodine-131 is less than 10^{-5} per reactor year. A greater release may require temporary evacuation of the local population.
- Large release frequency (LRF): The sum of frequencies of all event sequences that can lead to a release to the environment of more than 10^{2} T Bq. of cesium-137 is less than 10^{-6} per reactor year. A greater release may require long-term relocation of the local population.

3.6. Safety Analysis

Safety analysis involves deterministic and probabilistic analysis in support of the siting, design, commissioning, operation or decommissioning of a nuclear power plant. The safety analysis of the plant is iterative with the design process. It assesses the behavior of the plant under an applicable set of postulated initiating events.

3.6.1. Deterministic Safety Analysis

The first step in the deterministic safety analysis program is the identification of the events to be analyzed, including initiating events, event combinations and event sequences. The EC6 safety analysis program includes the four following types of events, also referred to as plant states:

- All planned normal operation
- Planned performance in anticipated operational occurrences
- DBAs
- Beyond-DBAs

3.6.2. Probabilistic Safety Analysis

As part of the EC6 design process, a preliminary PSA was performed to assist in identification of the design changes needed to reduce the CDF and LRF from CANDU 6 values. The PSA was based on an existing PSA for CANDU 6 and on feedback from the refurbishment of a domestic CANDU 6. The scope included internal and external events, full power and shutdown states, and sensitivity, uncertainty and importance measure analysis. The seismic contribution was assessed using seismic margin assessment. The changes resulting from the PSA for EC6 aim at meeting the RD-337 safety goals with a sufficient margin. The EC6 CDF and LRF targets are given in Appendix 1.

Analysis has shown that the small release frequency is expected to satisfy the safety goals as long as the safety goals for large releases are met.

Some of the most important changes identified by the PSA are in the area of severe accident prevention and mitigation. The seismic margin assessment indicated that the DBE seismic capacity of 0.3g is sufficient to ensure the plant safety.

3.7. Emergency Planning Measures

The inherent and severe accident mitigation aspects of the EC6 described in this section mean that a severe core damage accident is very rare and, if it occurs, there are long time periods between the start of the accident sequence and the severe core damage (many hours to days). This allows ample time for both on-site and off-site emergency planning. On-site planning is generally done by the utility. AECL, as the designer, provides severe accident management procedures based on the PSA. The responsible government in consultation with the utility generally does off-site planning. In the design of the EC6, the frequency and consequences of large releases will be analyzed in detail to inform the off-site planning, and to determine if, when, and under what circumstances evacuation is technically necessary.

Proliferation resistance

CANDU reactors are required to meet all terms and conditions of Canada's nuclear non-proliferation and export policies. In accordance with Canadian bilateral nuclear cooperation agreements, all operating CANDU reactors are subject to safeguards by the IAEA through INFCIRC/153 [6], INFCIRC/66 [7] or voluntary offer agreements between the IAEA and the owner state.

The CANDU safeguards system consists of installed IAEA safeguards equipment backed up by regular inspections and reporting to provide verification of state's commitments. AECL is committed to making design provisions in the EC6 that facilitate efficient and effective safeguards and to work with the CNSC and the IAEA to integrate safeguards into the EC6. Ultimately, safeguard requirements for the EC6 will be included in the CNSC regulatory documents.

The application of required safeguards to EC6 is expected to be generally similar to that of the CANDU 6 but with further improvements. In regards to integrated safeguards, the EC6 must be designed to facilitate anticipated increased use of remote monitoring and near real time accounting, and can expect some reduction in the frequency of safeguards inspection of spent fuel.

The following sections provide a brief summary of the guidelines to facilitate implementation of safeguards in CANDU reactors as well as intrinsic and extrinsic CANDU features contributing to proliferation resistance. For further information on proliferation resistance in CANDU reactors, please see Reference [8].

4.1. Guidelines to Facilitate Implementation of Safeguards

The following guidelines have been established in order to facilitate the implementation of safeguards for the EC6 design:

- General: The EC6 shall support the installation of existing traditional CANDU safeguards equipment, e.g. spent fuel bundle counter (SFBC), core discharge monitor, radiation detectors on fuel loads, etc. It also shall support anticipated new technologies such as increased use of remote monitoring and near real time accounting and include design features to support safeguards that are found in existing CANDU plants such as the IAEA Safeguards Room, lighting in areas monitored by surveillance cameras, etc. Safeguards equipment provided by the IAEA for installation in the EC6 shall meet all applicable safety requirements (electrical, fire, seismic, and environmental qualification, etc.).
- Layout: Plant layout can help IAEA safeguards monitoring, specifically those safeguards concerned with diversion of fuel from the fuel path. Examples are the monitoring of fuel movements at reactor vault access points through spent fuel ports and airlocks.
- Space Allocation: For IAEA equipment room, installation of IAEA equipment in the spent fuel bay, discharge

monitor detectors in the reactor vault, locked storage cabinet and desk near the area in which transfer to dry storage occurs, etc.
- Discipline Related: Control and instrumentation systems, electrical systems, fuel handling systems, radiation physics, core physics, and fuel are designed to permit installation, connection and proper operation of the safeguard equipment.
- Safety: The IAEA supplied instrumentation that connects to the plant electrical system should follow the Canadian Electrical Code Part 1, as well as AECL and local electrical requirements.
- Inspection, Testing and Commissioning: Cables that are part of the IAEA safeguards equipment installation should be routed so that IAEA inspectors can visually inspect the entire cable length at any time for signs of tampering.
- Decommissioning: The IAEA is responsible for reclamation of its equipment at the point of cessation of safeguards, or as equipment is replaced.
- Materials and Chemistry: All applicable safety guidelines shall be implemented with respect to IAEA equipment as it is decommissioned.
- Human Factors
- Reliability and Maintainability

4.2. Intrinsic CANDU Features Contributing to Proliferation Resistance

The intrinsic proliferation resistance features of CANDU technology can be separated into those related directly to the fuel cycle, and those related to specific operational characteristics:

- Fuel Cycle Features: A significant feature of the CANDU 6 natural uranium fuel cycle is the lack of enrichment, and the consequent simplification of fuel cycle safeguards. A CANDU reactor is a relatively sparse generator of plutonium (which is reactor-grade in fissile purity) as a weight percentage of its used fuel. In order to obtain enough plutonium for a nuclear explosive device, over 100 irradiated CANDU fuel bundles with a total mass of over two tons would be required. The relatively high mass and item count necessary for successful diversion of significant quantities of CANDU fuel constitutes an inherent proliferation resistance benefit. Additionally, CANDU spent fuel has a high degree of uniformity in burn-up from bundle to bundle, which means that the fissile plutonium isotopic ratio does not vary appreciably among spent fuel bundles. This feature leads to simple characterization of the fissile content of the spent fuel, which is a positive feature from a proliferation resistance standpoint and is achieved through both axial shuffling of CANDU fuel during residence in core, and a high degree of axial flux flattening in the core achieved though on-line refuelling.
- Operational Features: CANDU 6 features of a reactor core with low excess reactivity and on-load refuelling through fully automated fuelling machines represent a constraint for high-purity fissile plutonium production. The fuelling machines are not capable of the sustained duty cycle this would require and hence the reactor would not be able to maintain safety margins nor remain critical. A CANDU reactor can hardly be operated for significant durations at low core burn-up. The reactor cannot be refuelled manually. The CANDU core as a whole is sensitive to fuel management decisions, and regional reactivity must be monitored and balanced as an integral part of steady-state operation. The flux throughout the core is measured with an array of in-core flux detectors and this information, available to the IAEA for verification of declared operation parameters, clearly indicates any deviations in fuel management from nominal operation.

In summary, the highly complex and mission-oriented nature of the fuelling machines, designed to maintain steady core power under low-excess reactivity conditions, and the requirement to fully characterize the core flux distribution on a continuous basis, combine to discourage misuse of the core for the purposes of weapons-grade material production. Moreover the automated nature of the entire refuelling process means that a continuous digital record is maintained that could be used by the IAEA to track trends and flag discrepancies in fuel management. It is possible to track every CANDU fuel bundle throughout its life cycle, as well as detecting with high probability any undeclared irradiation and movement of fuel bundles.

Finally, CANDU fuel has historically achieved an exceptionally low defect rate (<0.1%) due primarily to its relatively low burn-up. This combined with a series of fuel engineering improvements constitutes an inherent barrier to attempted diversion of fuel by disguising it as defective fuel.

4.3. Extrinsic CANDU Features Contributing to Proliferation

Resistance

The extrinsic proliferation resistance measures applicable to CANDU technology include the supply requirement for having a bilateral treaty with Canada that specifies the necessity for nuclear material used and produced by CANDU technology to be subject to IAEA comprehensive (or facility-specific) safeguards, as a measure to verify peaceful purposes only. All CANDU reactors are subject to IAEA safeguards and there has never been a diversion of CANDU spent fuel. CANDU safeguards equipment is constantly upgraded as new and improved technologies are introduced.

Safety and security (physical protection)

As explained in previous sections, the EC6 offers improvements to the plant's security by increased protection against aircraft strikes and external events. The containment structure has been thickened and more reinforcing steel has been added to meet such objectives. Other structures have been further protected / reinforced and the layout has been improved.

The protection of the plant against sabotage and malevolent acts or threats is provided by the engineered nuclear safety measures and the physical protection system. This system includes the following:

- An exclusion zone around the station.
- Robust physical barriers with intrusion detection for protected areas.
- Clear areas on both sides of the perimeter of a protected area with sufficient illumination for assessment.
- Nuclear materials, systems, and equipment that are important to safety or the sabotage of which could lead to unacceptable radiological consequences, are located within vital areas.
- Access and the number of access points to the protected areas and the vital areas are kept to a minimum. All emergency exits are fitted with intrusion detection sensors. Other points of potential access are secured and alarmed.
- Vital areas have access control and penetration delay. They are secured and alarmed when unattended.
- A continuously staffed and hardened security monitoring room located within the vital area(s) is provided.
- All intrusion detection sensors annunciate in the security monitoring room.
- All staff at an EC6 station undergoes security clearance and security and safety training.

Description of turbine-generator systems

The turbine generator, feedwater and condensate plant are completely located within the turbine building and are part of the balance of plant (BOP). They are based on conventional designs and meet the design requirements specified by the nuclear steam plant designer to assure the performance and integrity of the nuclear steam plant. These include requirements for materials (i.e. titanium condenser tubes and absence of copper alloys in the feed train), chemistry control, feed train reliability, feedwater inventory, and turbine bypass capability.

Site differences affect condenser cooling water design temperatures, which in turn affects turbine exhaust conditions and the amount of energy it is possible to extract from the steam. In the event of loss of off-site power to the plant, EC6 reactors are designed to stay at power for the duration of the event using turbine-generators that are disconnected from the grid. In this mode of operation, power is only supplied to internal auxiliaries as needed for the safe operation of the plant.

6.1. Turbine-Generators

Steam is conveyed from the steam generators' outlets inside the reactor building to the turbine generator located in the turbine building by four 26-inch diameter pipelines, one per steam generator. A main steam balance header is provided to receive the steam from each of the four steam generators and to equalize the pressures prior to entry to the turbine generator.

The CANDU 6 turbine assembly normally consists of one single-flow high-pressure turbine, three double-flow low-pressure turbines, and two moisture separator reheaters with two stages of reheating. The turbine generator is a single-shaft machine operating at 1,500 rpm (1,800 rpm for 60Hz machines).

The thermal regeneration cycle consists of two stages of steam reheating and six stages of feedwater heating (three low-pressure, one de-aerator and two high-pressure). The six stages of feedwater heating are accomplished by extracting steam from the appropriate stages of the high and low-pressure turbines.

The main steam supplied to the high-pressure turbine inlet is saturated and, as it expands through the turbine, its quality decreases. To minimize erosion damage of the last stage blades in the low-pressure turbine and to increase the efficiency of the turbine, water is removed from the system after it has passed through the high-pressure turbine. The steam is also reheated prior to its admission to the low-pressure turbine.

Water separation is achieved in the moisture separators mounted inside a set of combined moisture separator/reheater (MSR) vessels. There are two MSR vessels, each located on either side of the turbine axis. The moisture thus separated in each MSR vessel flows by gravity and is collected in the corresponding separator drain tanks.

Reheating is achieved in steam reheaters in the shell of the two MSRs. Each reheater has two stages of reheating. The first stage utilizes steam extracted from the high-pressure turbine, whereas the second stage of reheating utilizes live steam from the main steam header. This steam condenses within the reheater tubes while reheating the high-pressure turbine exhaust steam. The reheater drain system collects the condensed steam from the above two stages.

6.2. Condensing System

After expansion in the low-pressure turbines, the steam is condensed in the main condenser by heat transferred to the condenser cooling water system. The condensate from the main condenser is de-aerated and returned to the steam generators via regenerative feedwater heating.

The condenser consists of three separate shells, one per low-pressure tubing casing. It is made of titanium tube sheets and tubes with welded tube-to tube sheet joints and is equipped with on-line tube cleaning system.

The condenser cooling water system supplies once-through cooling water to the main condensers. The system pumps supply cooling water through the main condensers to condense the turbine exhaust steam and to maintain rated backpressure conditions at the turbine exhaust. The system components and materials minimize deterioration of the condenser heat transfer capability under normal operating conditions and ensure a high degree of availability.

6.3. Feedwater System

The feedwater system supplies water to the secondary side of the steam generators to maintain their required levels during various modes of operation, taking hot pressurized feedwater from the feedwater train in the turbine building and discharging the feedwater into the preheater section of the steam generators. It comprises the main feedwater and auxiliary feedwater pumps. The main feedwater circuit extends beyond the turbine building.

Main steam safety valves provide the safety functions of overpressure protection and cooling of the secondary side of the steam generators. The main steam isolation valves can be used to prevent releases in the event of steam generator tube leaks to the secondary side of the steam generator.

The EHRS provides an independent water supply to the steam generators following total loss of the main feedwater supply.

6.4. Auxiliary Systems

The turbine generator system is equipped with other necessary auxiliary systems, including the following:

- Sampling System: The sampling system in conjunction with the chemical injection system maintains the unit’s water quality via chemical control. It draws small process samples from strategic locations in the condensate and feedwater system and processes them in a common sampling and analysis facility located in the turbine building.
- Steam Drain System: Completely located in the turbine building, this system covers the facilities required for draining, collecting and disposing of the condensed steam in the main steam piping in the turbine and its associated equipment, and in the extraction steam piping.

- Chemical Injection System: Completely within the Turbine Building, this system continuously monitors the feedwater condensate loop at various points and adds the chemicals required to maintain optimum chemistry parameters.

7.1. Electrical Power System

The electrical power distribution system provides safe and reliable electrical power to the process, control and instrumentation, heating, ventilation and air conditioning, and lighting loads throughout the plant. Electrical power is distributed by networks of transformers, circuit breakers, motor starters, distribution panels, cables, etc., in a manner that maintains the redundancy and separation requirements as imposed by the process, control and safety systems.

To meet nuclear safety requirements for reliability of operation, two 100% redundant power distribution systems are provided for nuclear safety related loads. These are known as odd and even groups. In addition, three 100% redundant power systems are provided for control and instrumentation purposes. The distribution equipment associated with the odd load group is electrically separated from equipment associated with the even load group.

The electrical power distribution system is divided into four classes of power based on availability:

- Class IV. AC power available from the grid/turbine generator which serves as primary power source to the station. Long-term interruption of Class IV power can be tolerated without endangering equipment, personnel or safety. The Class IV power distribution system is powered directly from the unit and/or system transformer.
- Class III. AC power available from either Class IV or on-site standby diesel generators. Upon loss of Class IV power, the standby generators are automatically started and connected to loads required under reactor shutdown condition. It is sufficiently reliable to ensure safe plant shutdown and decay heat removal, and to prevent equipment damage, even though the plant may be disconnected from off-site power sources.
- Class I. DC power available from rectifiers supplied from Class III power system with backup from batteries.
- Class II. AC power available from inverters supplied from Class I batteries with backup from Class III. Class II power is uninterruptible.

In case of total loss of electrical power (i.e. Class IV and Class III), two seismically qualified diesel generators in each unit along with duplicated (odd and even) distribution systems provide the electrical power supply to the Group 2 essential loads.

7.2. Instrumentation and Control

The instrumentation and control systems are designed to give the operators in the main control room all information and control capability to operate the unit safely during normal operation and all anticipated operational occurrences. The systems are also designed to handle certain upset conditions to return the plant to normal conditions or to safely shutdown the reactor in a controlled manner if required. Separated, independent control and instrumentation systems are designed for shutting down the unit and maintaining it in a shutdown state under accident conditions. Shutdown of the reactor and monitoring of its major safety parameters is also possible from the SCA in case that the main control room is unavailable.

The process and reactor controls and safety functions are highly automated and provide information (i.e. plant parameters) to the operators using a combination of state of the art instrumentation and monitoring equipment. Human factors engineering is rigorously applied at all stages of the design process to maximize operator responses to the different plant conditions.

Various radiation-monitoring systems are used in the station. Fixed contamination monitors, such as portal whole-body counters and fixed area monitors between zones, are installed to ensure workers radiation protection and control contamination. Local area radiation monitors are also located in areas of higher radiation protection with local as well as control room annunciations. A “tritium in air “monitoring system continuously monitors tritium concentration in areas with higher potential of tritium leakage.

Plant surveillance is also centralized in the main control room. Instrumentation for closed-circuit television, meteorological sensing, fire detection and alarm, vibration monitoring, and access control are all indicated and controlled from the main control room. Communication networks such as telephone, public address, maintenance, and plastic suit are also centralized there.

7.2.1. Control Centres

The main control centre is a clean, air-conditioned area comprised of:

- Main Control Room: It contains the unit main control panels and operator's desk, the unit on-power fuel handling panels and console, the shift interrogation console, and the shift supervisor's desk. The main control room also contains one group of panels for the station's common systems, all safety systems and electrical services.
- Control Equipment Rooms: These rooms contain the bulk of the instrumentation & control equipment for the unit and the instrumentation & control equipment for the ECC, SDS1 and SDS2, fuel handling and common systems.
- Computer Rooms: They contain the unit's computer systems, including the PDS, the contact alarm scanner and other related computer equipment.
- Work Control Room: It is used for the issuance of work permits and associated records and drawings.
- Emergency Support Centre (ESC): It is used in the management of incidents affecting the safety of the plant.

The main control room features extensive use of computer-driven colour-graphic displays, which offer selective presentation of information in diagrammatic formats. The use of computer-based displays, designed using modern human factors engineering, simplifies the cluster of typical control room panels, and provides a uniform plant-machine interface for all plant systems.

The seismically qualified SCA houses safety system panels and Group 2 control panels with required instrumentation and controls to safely shutdown the reactor if needed and provide the needed displays to the operators if the main control room becomes unavailable.

7.2.2. Station Computer Control and Display System

Control computers implement the bulk of the control functions for the plant process control systems and perform data acquisition functions for them. Processing of this data for presentation to the operator is performed by the PDS.

The control computers are redundant (i.e. on failure of one computer, the functions of the failed computer are taken over seamlessly by its redundant partner to ensure bumpless control).

The computers/PDS hardware and software are qualified in compliance with current standards applicable to safety-related programmable electronic systems in nuclear plants.

The SPDS provides safety system monitoring during normal plant operation and post-accident monitoring functions following an event by providing sufficient information on the critical safety functions for supporting the proper operation of the reactor including detection and diagnosis of malfunctions to allow mitigation of these conditions. When an accident occurs, the SPDS conveys post-accident information to enable the operator to assess the post-accident condition of the plant, determine whether the safety systems have performed their function, and monitor the plant characteristics to follow the effects of the accident. SPDS equipment is located in the main control room, the SCA and the ESC.

The EC6 design uses an updated plant display system (PDS) to manage operator interactions. The PDS has the functionality required to manage plant annunciation. Features associated with the PDS are:

- Post-accident monitoring displays and information provided in the ESC.
- Displays for SPDS and plant overview monitoring.

7.2.3. Reactor Control Instrumentation

Three instrumentation systems are provided to measure reactor thermal neutron flux over the full operating range of the reactor. Start-up instrumentation covers the eight-decade range from 10^{-14} to 10^{-6} % of full power; the ion chamber system extends from 10^{-7} to 1.5 (150%) of full power, and the in-core flux detector system is used for accurate, spatial measurement in the uppermost decade of power (above 5% to 120% of full power). These instruments are installed in the reactivity control units (see section 2.1).

7.2.4. Reactor Regulating System (RRS)

The reactor regulating system (RRS) is part of the plant control system that controls and manoeuvres reactor power in accordance with specified set points. During normal operation, the set point is calculated by the steam generator pressure control system to maintain constant steam pressure in the steam generator. During serious plant upsets, RRS provides controlled or fast power reduction automatically. RRS also responds to operator manual request for reactor power reduction or shutdown.

The RRS uses the neutron flux measurements described in section 7.2.3 and process measurements to control reactivity control devices (adjusters, liquid zone control units, and mechanical control absorbers) via hardware interlocks and display devices. RRS action is generally initiated by control programs in the control computers that process the inputs and drive the appropriate reactivity control and display devices.

In CANDU reactors, emergency shutdown devices and systems are entirely independent of those used for reactor power regulation.

7.2.5. Reactor Safety Instrumentation

The EC6 safety systems are described in Section 3.2. The instrumentation and control of each safety system consists of independent and triplicated measurements of each variable and initiation of protective action when any two of the three channels are tripped by any process variable or combination of variables. The measurements and actuation circuits use hard-wired devices to ensure reliability.

SDS1 and SDS2 use digital process controllers called programmable digital comparators for those set points requiring conditioning or set points that are function of reactor power. SDS1 and SDS2 each have at least two trip parameters for each postulated event. The safety systems are provided with full test facilities to allow testing while the reactor is on power.

7.2.6. Other safety related systems

Other safety support systems include process system instrumentation; different regulating systems for overall plant control, steam pressure control, steam generator level control, heat transport pressure control, and pressurizer level control; defective fuel detection and location system; improved fire protection system; vibration monitoring and alarm system. These systems are controlled and monitored via the control computers.

Spent fuel and waste management

8.1. Fuel Utilization

The EC6 design maintains the traditional CANDU core design focus on neutron economy which stems from a number of design features dictated by the use of natural uranium fuel and ultimately means reduced electricity cost. Neutron absorption is minimized by the choice and strategic use of reactor structural materials, as well as by the heavy water moderator and coolant. In addition, on-power refuelling minimizes the excess reactivity required to maintain criticality. This eliminates the need for any neutron absorbing materials, which are used to suppress the initial excess reactivity associated with fuelling an LWR core.

A consequence of the high neutron economy of the PHWR is high uranium utilization[1]. CANDU uses about 28% less uranium than a typical PWR for each megawatt of electricity produced. The PHWR, therefore, makes efficient use of natural uranium resources. Additionally, CANDU fuel is relatively easy to manufacture - all countries having CANDU reactors manufacture their own fuel. The use of natural uranium fuel also avoids the production of enrichment tails. The PHWR's efficient use of neutrons also contributes to its fuel cycle flexibility.

The defect rate of CANDU fuel is very low, with many stations observing no failures for extended periods of time. With on-line failed fuel detection and location system, and the ability to remove failed fuel on power during refuelling, the economic impact of failed fuel is minimized.

Excellent uranium utilization and a simple fuel bundle design help to minimize the CANDU fuel cycle unit energy cost, in absolute terms, and relative to other reactor types. The bundle, with its limited number of components, is easy to manufacture and there are no criticality concerns associated with the handling or transporting of natural uranium.

At the station, on-power refuelling contributes to high capacity factors. Upon discharge from the reactor, criticality is again of no concern, and the lower average burn-up results in lower decay powers and shorter cooling periods. This translates into higher packing densities for ultimate disposal, which offset the greater amount of spent fuel produced.

8.2. Waste Management

The waste management systems of the EC6 reactor will minimize the radiological exposure to operating staff and to the public. Radiological exposure for workers from the plant is monitored and controlled to ensure that the exposure is within the limits recommended by the International Commission on Radiological Protection. There are systems in the plant that provide for the collection, transfer and storage of all radioactive gases, liquids and solids, including spent fuel and wastes generated within the plant.

For the CANDU design, the origins of the waste activity can be classified into the following groups:

- Fuel fission products
- System material activation products
- System fluid activation products

The majority of radionuclides in the categories above are contained at their place of origin. Otherwise, they are treated in the waste management system. The majority of the fission products that escape from fuel defects while in the core or in the fuel handling equipment, are filtered, trapped or removed in the HTS and its auxiliary systems. This leads to disposal of the majority of the fission products in either spent resin or filter elements as solid wastes.

Radionuclides that escape by leakage or from the HTS boundary reach the building atmosphere. Most of these are collected by the active ventilation system, and if not retained in the D_2O dryers, they are released under control. The radionuclides retained are deposited and washed down and then sent to the liquid radioactive waste management system through the active drainage system.

The tritium produced by activation of the heavy water in the HTS and moderator D_2O circuits may escape as Deuterium-Tritium Oxide (DTO) or a similar form. Most of it is retained in the D_2O liquid and vapor collection systems or otherwise end up in the active liquid or gaseous radioactive waste systems.

Components being serviced are subjected to decontamination procedures either "in-situ" or in special decontamination facilities for the removal of fission products or activation products. The residues from these procedures are sent to the appropriate radioactive waste systems.

8.2.1. Solid Radioactive Waste Management System

A separate solid waste management system is provided for each unit. This system includes the facilities to handle the following:

- Spent fuel. Spent fuel is stored in the spent fuel storage bay at site. The spent fuel storage bay has a capacity to store spent fuel discharged for approximately ten years. However, after about six years of cooling in the Spent Fuel Storage Bay, the spent fuel can be stored in concrete storage canisters or MACSTOR^{TM} modules at site (dry interim storage facility). The storage period in the dry interim storage facility is expected to be

about 50 years.
- Spent resins. Spent resin apart from de-deuteration is handled by the resin transfer system and stored in the spent resin storage system.
- Spent charcoal from the activated charcoal systems.
- Spent filter cartridges.
- Low activity solid wastes (e.g. metal, glass, paper, rags, etc.).
- Organic fluids, oil, and chemicals, etc.

Each type of waste is processed and moved using specially designed transporting devices if necessary. After processing, the wastes are collected and prepared for on-site storage by the utility or for transport to an offsite storage location.

AECL provides the conceptual design for a solid radioactive waste storage structure to store medium and all low solid radioactive wastes generated by two EC6 units during five years of operation. After five years, these wastes shall be removed from this storage structure and relocated to an off-site permanent facility. Types of wastes to be stored in the solid radioactive waste storage tanks include spent filter cartridges (medium and low level), other medium level radioactive wastes such as contaminated tools, piping, reactor components, etc., and low level wastes generated in the plant.

8.2.2. Liquid Radioactive Waste Management

The liquid radioactive waste management system collects and processes liquid radioactive wastes before discharge to the environment. Liquid radioactive wastes are stored in concrete tanks that are located in the service building. Any liquid, including spills that require removal of radioactivity are treated using cartridge filters and ion exchange resins. Liquid waste is monitored for radioactivity before being discharged to the environment.

8.2.3. Gaseous Radioactive Effluent Management

Gaseous radioactive effluents (gases, vapours or airborne particulates) are monitored and filtered before being released to the environment. The off-gas management system treats radioactive noble gases. D_2O leaks are collected and recovered by a vapour recovery system.

8.3. Provisions for Acceptable or Reduced Dose Limits

The limitation of internal and external radiation exposure to persons at the site boundary and to plant personnel is accomplished by a combination of facilities incorporated into the station design and by adherence to a set of approved operating procedures and regulations. In general, the measures employed in EC6 follow the principles used at previous CANDU plants.

Exposure by members of the population is limited by exclusion of all unauthorized persons from the station area and by preventing any habitation within the exclusion boundary. The release of all effluents, liquid and gaseous, which might conceivably carry significant radioactivity is monitored and controlled. Active solids are contained in a manner, which prevents the release of activity.

The exposure of station personnel to radiation is limited by control of access to areas of high activity or possible contamination, and by plant layout and structural shielding arrangements. In addition, protective clothing, air masks and decontamination facilities are available for use when required. Personnel monitoring and dosimetry facilities are provided. The ALARA principle is applied to the design stage to ensure radiation exposures are as low as reasonable achievable, economic and social factors being taken into account.

For all CANDU 6 stations, radiation worker doses are comfortably below the limit allowed for a single year (50 mSv). Several improvements are being incorporated to the EC6 design to reduce internal/external radiation exposures.

The radiation protection design features ensure that inadvertent exposure of plant personnel or members of the public is avoided. The design features consists of:

- System of access control to prevent any acute exposure for internal or external hazards.
- System of contamination control to limit any chronic exposure from internal hazards.

- Radiation shield system to limit any chronic exposure from external hazards.
- HVAC system designed such that the flow of air goes from areas of zero or low probability of activity to areas with higher probability of activity and to maintain the reactor building at slightly lower than atmospheric pressure.
- Radiation waste management system.
- System of radiation monitoring.
- The EC6 design includes several improvements over the CANDU 6 to reduce airborne tritium emissions; reduction in liquid emissions; reduction of airborne carbon-14 emissions and argon-41 emissions.

8.4. Waste Management Costs

Provisions incorporated in the EC6 design to reduce waste management costs include:

- CANDU fuel bundles are small (~50 cm long by ~ 10 cm in diameter), light weight (~24 kg) which allows them to be easily handled and stored thereby reducing operating costs.
- On-power refuelling is one of the unique features of the CANDU system. This maximizes the burn-up resulting in lower fuel throughput rate and therefore lower spent fuel generation.
- Dry storage – The MACSTOR$^{\hat{O}}$ (Modular air-cooled storage) dry storage facility is a concrete structure, which uses passive air circulation to cool the spent fuel bundles. This facility is maintenance free, which reduces costs associated with ongoing maintenance of the spent fuel.
- Segregation of the spent resin storage tanks to ensure that the moderator resins holding large quantities of carbon-14 are separated from other resins. Segregation of the resins containing high levels of carbon-14 from other resins in the CANDU 6 plants will reduce the overall waste management cost

Plant layout

The EC6 plant is designed for more efficient operation and increased safety. The plant layout provides improved separation by distance, elevations (different heights), and the use of barriers for safety-related structures, systems, and components that contribute to protection and safety. Security and physical protection have been enhanced to meet the latest criteria required in response to potential common mode events, i.e. fires, aircraft crashes and malevolent acts. The plant is tornado protected.

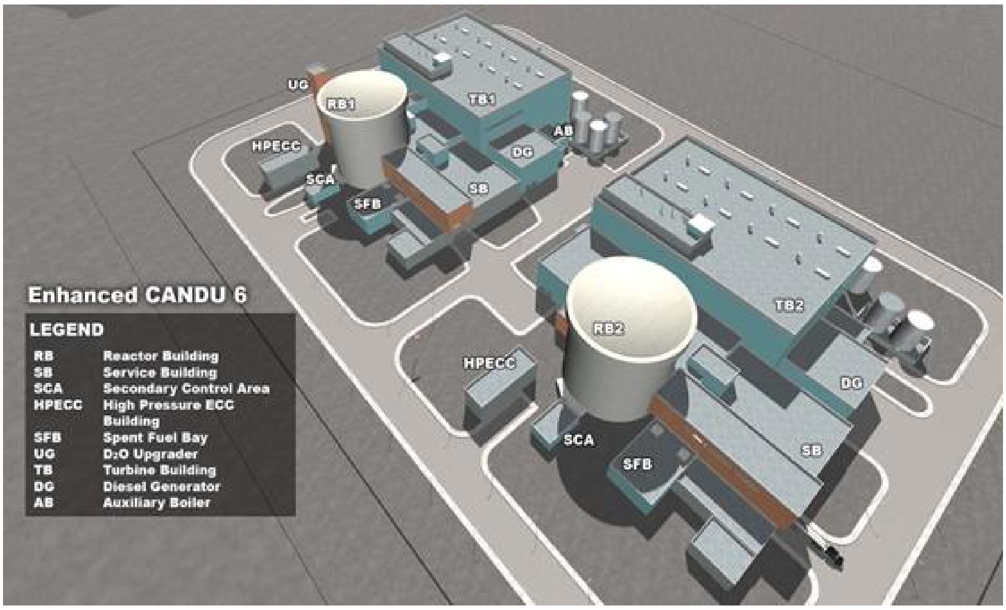

Figure 9-1 Two-Unit Plant Layout of Major Structures

The plant layout for a two-unit plant is designed to achieve the shortest practical construction schedule while supporting shorter maintenance durations with longer intervals between maintenance outages. The buildings are arranged to minimize interferences during construction, with allowance for on-site fabrication of module assemblies. Open-top construction (before placing the roof of the reactor building in place), allows for the flexible sequence of installation of equipment and reduces the overall project schedule risk

The size of the power block for a two-unit integrated EC6 plant is 32,700 square meters. The power block consists of two reactor buildings, two service buildings, two turbine buildings, two high pressure ECC buildings, two secondary control areas and one heavy water upgrader building.

A single-unit plant can be easily adapted from the two-unit layout with no significant changes to the basic design.

9.1. Layout Philosophy and Principles

The principal structures of the EC6 nuclear generation station are the reactor, service, and turbine buildings

The reactor building internals are divided into three areas: accessible, restricted to limited access and inaccessible. This division allows for the placement of systems and equipment that require on power maintenance or access locations that are safe for personnel.

The service building is arranged such that the main control room and equipment areas are separated from the SCA and its related support services by 180 degree with the reactor building between them. This arrangement makes it virtually impossible for both control areas to be lost to a common cause event.

Within the service building the irradiated fuel transfer and storage bays are located immediately adjacent to the reactor building. This keeps the length of the irradiated fuel transfer duct and mechanism as short as practical while locating the storage bay in an area remote from the rest of the service building.

The turbine building adjoins the service building with the turbine auxiliary bay. This arrangement provides for the shortest length of inter-phasing piping and cables.

Auxiliary structures include the administration building, pumphouse, water intake and discharge, high pressure ECC building, EHRS pump house, among others.

9.2. Buildings and Structures

9.2.1. Reactor Building

The reactor building houses the reactor, fuel-handling systems, the HTS, including the steam generators, and the moderator system, together with their auxiliary and special safety systems.

The reactor building can be divided into three major, structural components as follows:

- Pre-stressed, steel lined, concrete containment structure
- Internal reinforced containment structure
- Reinforced concrete calandria vault

The pre-stressed, seismically qualified, concrete reactor building has been strengthened compared to previous CANDU 6 designs. Pre-stressed concrete is reinforced with cables that are tightened to keep the structure under compression even when the forces it is designed to withstand would normally result in tension. The concrete containment structure has an inner steel liner that significantly reduces leakage rates in the event of an accident.

The entire structure, including concrete internal structures, is supported by a reinforced concrete base slab that ensures a fully enclosed boundary for environmental protection and biological shielding, which in turn reduces the level of radiation emitted outside the reactor building to values that are insignificant to human health.

Internal shielding allows personnel access during operation to specific areas for inspection and routine maintenance. These areas are designed to maintain temperatures that are suitable for personnel activities. Airlocks are designed as routine entry/exit doors.

Containment structure perimeter walls are separate from internal structures, eliminate any interdependence and provide flexibility in construction.

9.2.2. Service Building

The service building is a multi-level, reinforced concrete and steel structure that is seismically qualified and tornado protected. It accommodates the ‘umbilicals’ that run between the principal structures, the electrical systems and the spent fuel bay and associated fuel-handling facilities. It houses the ECC pumps and heat exchangers and the main control room.

The service building also houses the spent fuel bay cooling and purification system pumps and heat exchangers. The spent fuel bay is a water-filled pool for storing spent fuel.

Safety and isolation valves of the main steam lines are housed in a seismically qualified concrete structure that is located on top of the service building.

9.2.3. Turbine Building

The EC6 turbine building is located on the side of the service building. This is an optimal location for access to the main control room; the piping and cable trays run to and from the service building and the condenser cooling water ducts run to and from the main pumphouse. Access routes are provided between the turbine building and the service building.

The turbine building houses the turbine generator. It also houses the auxiliary systems, the condenser, the condensate and feedwater systems, the building heating plant, and any compressed gas required for the BOP. The BOP consists of the remaining systems, components and structures that comprise the complete power plant but are not included in the nuclear steam plant.

Blowout panels in the walls and roof of the turbine building will relieve the internal pressure in the turbine building in the event of a steam line break.

9.2.4. Miscellaneous Structures

The EPS – secondary control area is a single-story structure situated on one side of the reactor building, adjacent to the electrical cable gallery. It is designed for protection against tornado and malevolent acts and is seismically qualified to be fully operational following an earthquake.

The D_2O upgrading tower houses the heavy water upgrading columns and the associated mechanical and electrical equipment. The upgrading facility is required for the on-line processing of moderator D_2O. The process continuously removes traces of unwanted H_2O to maintain the heavy water at a high isotopic content.

The high-pressure ECC accumulator building, located separately from the reactor building, houses two vertical water tanks, one horizontal gas tank, and associated mechanical piping and electrical equipment.

The EHRS structure mainly consists of an EHRS reservoir, only for seawater sites, and a pumphouse and supply and return piping from the EHRS pumphouse.

Plant performance

The design of the plant follows the following key principles:

- Enhanced safety which has been achieved through the use of the proven passive safety features of the traditional CANDU plants, improved severe accident response, more robust structures, improved design margins, and more modern computers and control systems.
- Enhanced economics, which has been obtained through the use of state-of-the-art construction techniques, and simplification and standardization of components and systems that result in reduced capital and maintenance

costs.

- Enhanced sustainability, which has been accomplished by the selective use and conservation of resources and the reduction of waste, both radioactive, and non-radioactive.
- Enhanced performance resulting from design features that provide for ease of operation and maintenance, and facilitation of repair and replacement of equipment.

10.1. Power Generation Objectives

The EC6 has set new objectives to further improve upon the CANDU 6 by raising its power output and simplifying operations and maintenance. This has resulted in a reduction of the operator's workload and the need to deal with obsolescence issues and streamlining the design. Advancements made by AECL to improve the plant output up to 740 MWe include:

- Installation of an ultrasonic flow meter (UFM) to improve the accuracy of feedwater flow measurement.
- Use of two-stage reheater in the turbine cycle.
- Improvements to the moisture separator reheater in the turbine high pressure and low pressure cycle.
- Reduction of steam losses across the steam discharge valves.
- Improved turbine and generator efficiency.

10.2. Reliability and Availability Objectives

10.2.1. Capacity Factor

The EC6 reactor is designed for a target lifetime capacity factor of 90%. Since the number and duration of maintenance outages impact plant capacity factors, periodic short duration maintenance outages of less than a month once every 24 months is a key target of the EC6 reactor. This objective is achieved by automating a number of tasks such as shutdown systems testing. The majority of these activities can be undertaken with the reactor at power.

An array of health monitoring equipment are also installed to foretell impending equipment problems, which can be acted upon, avoiding complications that could result in forced shutdowns.

Enhancements incorporated into the EC6 design to improve performance and facilitate maintenance include:

- Use of improved material and plant chemistry specifications based on operating experience from CANDU plants, e.g. life-limiting components such as HTS feeders and headers have been enhanced with higher chromium content to limit the effect of feeder corrosion.
- Implementation of advanced computer control systems for monitoring, display, diagnostics and annunciation and improvement of configuration management capability.
- Utilization of SMART CANDUÔ modules for monitoring plant chemistry of systems and components, equipment status monitoring, and providing predictive maintenance capability.
- Ensuring capability for return to full power on restoration of the electrical grid. The EC6 reactor has the capability to continue operating and delivering house load without connection to the grid, therefore enabling a rapid return to production of power upon reconnection.
- A maintenance-based design strategy. This program incorporates lessons learned and ensures maintainability of systems and components. It defines an improved maintenance program to ensure plant conditions are diagnosed and maintained within their design performance limits. This results in improved preventive maintenance and reduced forced outages at a rate of less than five days/year.
- Improved plant maintenance with provisions for electrical, water and air supplies that are built-in for on-power and normal shutdown maintenance.
- Shielding in radiologically controlled areas is provided to minimize worker exposure and occupational dose.
- Improved equipment selection and system design based on probabilistic safety evaluations using two-year outage intervals.

10.2.2. Design Life

The EC6 design offers a target life of 60 years with one mid-life refurbishment of certain critical equipment, such as the fuel channels and feeders. This objective is achieved by elongating the fuel channel bearings, thickening the pressure tube slightly, increasing the feeder wall thickness, using improved equipment and materials, better plant chemistry, and more active monitoring of critical plant parameters. All life-limiting factors have been evaluated and addressed, supported by extensive studies. By essentially doubling the useful life of the reactor, the plant owners are assured of a long-term supply of their electricity needs with an improved return of assets.

10.3. Construction

The EC6 construction is based on the proven construction methodology used at Qinshan, which resulted in a very successful project that was ahead of schedule and under budget. The main elements of the EC6 construction strategy are:

- Open-top construction method using a very-heavy-lift crane.
- Parallel construction.
- Modularization and prefabrication; and use of advanced technologies to minimize interferences.
- Extensive use of computer aided design scheduling and material management tools.
- Integrated approach to project management.
- Optimization of equipment procurement

The EC6 is targeted to achieve a construction schedule of 55 months from first concrete to in-service, with a second unit to follow six months later.

Throughout the CANDU 6 design process, standardization of systems and components has continuously been taking place to reduce the number of types of components, thus simplifying spares and maintenance. In addition, following the Qinshan design a major review has been underway to further reduce the number of different components - for example standardizing on a few sizes for valves. This leads to further reduction in maintenance efforts.

In line with this approach, critical equipment such as piping, valves, pipe hangers, cables, cable trays, fasteners, nuts and bolts, etc, continue to be standardized. This will result in significant reduction of maintenance effort.

10.4. Provision for Low Fuel Reload Cost

The EC6 reactor uses CANDU natural uranium fuel management to determine fuel loading and fuel replacement strategies to operate the reactor in a safe and reliable fashion while keeping the total energy cost low. The specific objectives of CANDU natural uranium fuel management are to:

- Adjust the refuelling rate to maintain the reactor.
- Control the core power to satisfy safety and operational limits on fuel power, thus ensuring that the reactor can be operated at full rating.
- Maximize burn-up within operational constraints to minimize fuelling cost.
- Avoid fuel defects to minimize replacement fuel costs and radiological occupational hazards.
- Optimize the fuel-handling capability to minimize capital, operating and maintenance cost.

On-power refuelling is one of the unique features of the CANDU system. Due to the low excess reactivity of a natural-uranium fuel cycle, the core is designed to be continuously "stocked" with new fuel, rather than changed in a batch process (as in PWRs and BWRs). This reduces core excess reactivity, and the requirement for utilizable poisons.

Other advantages of on-power refuelling include increased capacity factors (availability of the reactor), the ability to "fine-tune" the power distribution: the ability to detect defective fuel by means of gaseous fission products and failed fuel detection systems: and the ability to remove the defective fuel on-power, and the minimization of power perturbations due to refuelling.

The use of natural uranium as fuel in CANDU reactors widens the source of supply and avoids a requirement for uranium-enrichment capability, decoupling owners from the narrowly controlled uranium-enrichment market.

10.5. Manoeuvrability

Like most nuclear power plants, CANDU plants have been operated in continuous full power, base-load mode. The EC6, like other CANDU plants, has the capability of operating with the reactor directly responding to fluctuations in grid demand while running at or near full power.

The EC6 can operate in the automatic, reactor-following-turbine mode that enhances grid stability, even when the plant is subjected continuously to overall perturbations in reactor power (about 2.5% of full power) with no adverse effect. The EC6 is also capable of operating with deep planned load cycle, although the typical utility option has been to run the plants as base load plants. Deeper power manoeuvres from 100% to 60% full power are possible.

Load following can be carried out automatically with total automatic computer control over the reactor, steam generator, and turbine-generator between 0% to 100% full power.

Development status of technologies relevant to the NPP

AECL has undertaken studies to look into the feasibility of using CANDU energy in applications other than electricity generation, such as seawater desalination, oil sands extraction and hydrogen production. The following sections provide a brief summary of the work done in these areas.

11.1. Reverse Osmosis (RO) Desalination

A study conducted by AECL and CANDESAL Water Systems to combine a CANDU 6 electric generation plant with a desalination plant concluded that reverse osmosis was the appropriate seawater desalination technology.

For this option, the nuclear power plant is a standard electricity generation design, but it is co-located with a reverse osmosis desalination plant by the sea. Part of the condenser cooling water is used as the feedwater of the desalination plant, and the rest of the cooling water returns to the sea through outfall. The CANDU power plant provides the electrical power used to pressurize the feedwater in the desalination plant. Bypass capability is provided in the system to ensure isolation of one facility from the other when required.

Further information will be found in Reference [9].

11.2. Oil Sands Extraction

From 2004 to 2007, AECL performed site specific studies with several oil sand producers on deployment of EC6 units in northern Alberta in steam/electricity configuration. The many studies concluded that CANDU energy output is technically feasible and economically competitive for oil sands applications, the design can be adapted for minimal water consumption, the plant structures can be adapted to climate and geology, nuclear licensing could be effectively managed, and that modular assembly minimizes construction challenges due to labour costs and skills. Steam can be economically transported up to 15 km without undue thermal losses or cost. Further information can be found in Reference [10].

11.3. Hydrogen Production

Hydrogen is considered a clean fuel and the demand for it is increasing. The only available emission free technology for hydrogen production is water electrolysis powered by nuclear electricity or renewable energy. With its reliable and steady supply of electricity, the CANDU reactor is well suited for this application.

11.4. Thorium Cycle

See Section 2.2.2 for details on the thorium cycle application.

Deployment status and planned schedule

12.1. Research and Technology Development Status

Since the EC6 is based on the proven CANDU 6 design, there is no major R&D program attached to it. The EC6 originates in the CANDU 6 reference plant plus upgrades in safety, performance, operability and cost reduction. The following are the general design principles for EC6:

- The EC6 design complies with all current applicable regulatory policies and standards as per the code effective date for the new plant construction.
- The EC6 design fully complies with the suite of codes and standards for design, construction, commissioning and operation of the plant as per the code effective date for the new plant construction.
- The EC6 design incorporates appropriate design features to resolve issues arising from Generic Action Items identified by the CNSC for operating plants.
- The EC6 design shall take into account past operating and design experience.

12.2. Companies/Institutions Involved in R&D and Design

The EC6 reactor is the beneficiary of many years of R&D of the CANDU 6 product to address new codes and standards, feedback items, and security issues as they have arisen over more than 150-reactor years of operation. This R&D is ongoing under the direction and control of AECL and the cooperation of numerous Canadian and international companies.

12.3. Planned Schedule

The EC6 design is based on the reference CANDU 6 plant, which is the Qinshan plant in China, and includes changes driven by safety, licensing, operability, and client requirements. The reference design already meets most of the current CNSC requirements. The EC6 design also takes into consideration safety-related changes made during CANDU 6 life extension projects. Additionally, the EC6 design is intended to meet the top-level international requirements for a nuclear plant, in particular IAEA NS-R-1 safety standards [2].

The CNSC is currently conducting the pre-project design review of the EC6. This review identifies and mitigates any project risks due to licensing before project commitment. The CNSC's review includes two phases. Phase 1 involves a high-level review of the safety design as a whole. Phase 2 deals with a complete review of design details and analysis.

The Phase 1 EC6 pre-licensing review is now completed. Based on the Phase 1 pre-project review of the documentation submitted, the CNSC has concluded that to an overall level, the EC6 design intent is compliant with the CNS requirements and meets the expectations for new nuclear plant designs in Canada.

Phase 2 is expected to take approximately 18 months, after which the conceptual design of the EC6 will be completed and project ready. During Phase 2, the generic PSAR for the EC6 design will be prepared. The PSAR will contain the design details, the safety and design methodology and the safety analysis that demonstrate the EC6 safety case and compliance with Canadian and international regulatory requirements and expectations.

The generic design is suitable for a large range of site conditions and will be the basis for new-build construction projects. Necessary R&D programs to support the design is planned primarily in the laboratories of AECL in Chalk River.

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Technical data

General plant data

Reactor thermal output	2084 MWth
Power plant output, gross	740 MWe
Power plant output, net	690 MWe
Power plant efficiency, net	35.5 %
Mode of operation	Baseload
Plant design life	60 Years
Plant availability target >	90 %
Primary coolant material	Heavy Water
Secondary coolant material	Light Water
Moderator material	Heavy water
Thermodynamic cycle	Rankine
Type of cycle	Indirect
Non-electric applications	Desalination, District heat, Industrial, Cogeneration, H2 production

Safety goals

Core damage frequency <	1E-06 /Reactor-Year
Large early release frequency <	1E-07 /Reactor-Year
Operator Action Time	0.25 Hours

Nuclear steam supply system

Steam flow rate at nominal conditions	1043 Kg/s
Steam pressure	4.7 MPa(a)
Steam temperature	260 °C
Feedwater flow rate at nominal conditions	1044 Kg/s
Feedwater temperature	186.7 °C

Reactor coolant system

Primary coolant flow rate	9200 Kg/s
Reactor operating pressure	10.09 MPa(a)
Core coolant inlet temperature	266.3 °C
Core coolant outlet temperature	310.0 °C
Mean temperature rise across core	45 °C

Reactor core

Fuel column height	6.28 m
Average linear heat rate	25.2 KW/m
Average fuel power density	33 KW/KgU
Average core power density	11.3 MW/m^3
Fuel material	UO2
Fuel element type	Fuel rod
Cladding material	Zircaloy-4
Outer diameter of fuel rods	13.08 mm
Rod array of a fuel assembly	37-fuel element bundles in 380 fuel channels
Number of fuel assemblies	4560
Number of fuel Elements in fuel assemblies	37
Enrichment of reload fuel at equilibrium core	0.7 Weight %
Average discharge burnup of fuel	7.5 MWd/Kg
Control rod absorber material	Stainless steel-clad cadmium mixture
Soluble neutron absorber	Boron and gadolinium mixture

Reactor pressure vessel

Inner diameter of cylindrical shell	7595 mm
Wall thickness of cylindrical shell	28.6 mm
Design pressure	0.0269 MPa(a)
Design temperature	149 °C
Base material	SS304L
Transport weight	265 t

Fuel channel

Number	380
Pressure Tube inside diameter	103.38 mm
Core length	5.94 m
Pressure Tube material	Zr 2.5wt% Nb alloy

Steam generator or Heat Exchanger

Type	Vertical, recirculating, U-tube with integral preheater and steam drum
Number	4
Mode of operation	Primary coolant inside /Steam generated outside the tube.
Total tube outside surface area	3195 m^2
Number of heat exchanger tubes	3500
Tube outside diameter	16 mm
Tube material	Incoloy 800
Transport weight	220 t

Reactor coolant pump (Primary circulation System)

Circulation Type	Forced
Pump Type	Centrifugal
Number of pumps	4
Pump speed	1800 rpm
Head at rated conditions	237 m
Flow at rated conditions	2.34 m^3/s

Pressurizer

Type	External, steam

Total volume	45.3 m^3
Heating power of heater rods	200 kW

Moderator system

Moderator volume, core	220 m^3
Inlet temperature	46 °C

Primary containment

Type	Sealed envelope of prestressed reinforced concrete with lining
Overall form (spherical/cylindrical)	Cylindrical
Dimensions - diameter	41.45 m
Dimensions - height	51.21 m
Design pressure	0.5 MPa
Design temperature	150 °C
Design leakage rate	0.2 Volume % /day

Residual heat removal systems

Active/passive systems	Active and passive systems

Safety injection systems

Active/passive systems	Active and Passive

Turbine

Number of turbine sections per unit (e.g. HP/MP/LP)	1 HP , 2 LP
Turbine speed	1800 rpm
HP turbine inlet pressure	4.51 MPa(a)
HP turbine inlet temperature	258 °C

Generator

Type	Directly-coupled synchronous
Rated power	850 MVA
Active power	740 MW

Voltage	24 kV
Frequency	60 Hz
Total generator mass including exciter	540 t

Condenser

Type	Single pass, shell and tube
Condenser pressure	3.74 kPa

Plant configuration and layout

Plant configuration options	Ground-based

Feedwater pumps

Type	Horizontal, centrifugal
Number	3
Pump speed	3600 rpm
Head at rated conditions	680 m
Flow at rated conditions	0.56 m^3/s