Introduction to the Qinshan Phase III CANDU Nuclear Power Plant

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ABSTRACT

Qinshan Phase 3 is the latest in a series of 700 megawatt-class CANDU power plants designated as CANDU 6. Seven units of this class are operating and four more are under construction. The first of the CANDU 6 series entered commercial service in 1983.

The initial design of CANDU 6 was derived as a single-unit version of the successful Pickering A station in Ontario, an integrated four-unit plant operated by Ontario Hydro. Many evolutionary improvements have been made in the design since these first units entered service, based on improved technology and the feedback of operating experience. Many of these later improvements have been backfitted to the older plants.

Fuel channels are the primary high-technology element of the CANDU design. A closed loop containing pressurized heavy water transports reactor heat to conventional U-tube steam generators and then to the steam turbine. Power, power shape, steam generator level and pressure, and other control tasks are managed by the digital control system. A second digital system controls the operation of the on-power fuelling machines which transport fresh fuel from storage to the reactor and used fuel from the reactor to the used fuel storage pool.

This paper describes the configuration and operating characteristics of the CANDU 6 now being built at the Qinshan site in China.

1.0 INTRODUCTION

Qinshan Phase 3 is the latest in a series of 700 MWe class of CANDU power plants being built in China. The Qinshan site is located in Haiyan County, Zhejiang Province, on the shore of Hangzhou Bay off the East China Sea and approximately 126 km south west of Shanghai. The In-service dates of Units 1 and 2 are seventy-two months (February 2003) and eighty-one months (November 2003) respectively after the Contract Effective Date.

The reference plant for the Qinshan CANDU Project is the Wolsong 3 and 4 Units in South Korea that are the most recently built CANDU 6 plants off shore.

The major project participants and their roles are:

- The Third Qinshan Nuclear Power Company Ltd. (TQNPC) - Owner, BOP construction management, fuel and heavy water supply.
- China National Nuclear Corporation (CNNC) - Majority owner of TQNPC.
- China Nuclear Energy Industry Corporation (CNEIC).
- Atomic Energy Canada Limited (AECL) - Main contractor, NSP design.
- Hitachi-Bechtel Consortium - BOP design and equipment supply.
- Nuclear Project Managers Canada Inc. (NPM) - Site project management, NSP. construction management, commissioning management, and NSP equipment supply.
- Hitachi - NSP equipment supply.
- HANJUNG - NSP equipment supply.
- Canatom - BNSP design.
- Chinese construction contractors - Construction.

Figure 1 illustrates the progress (as of March 99) of the CANDU NPP construction at Qinshan site.

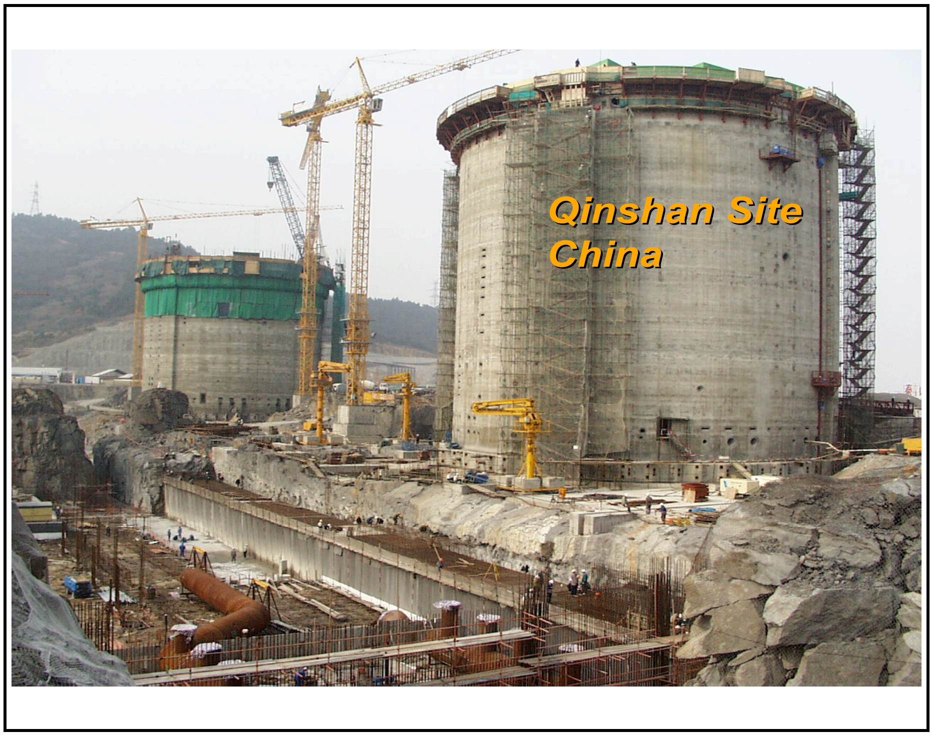

Figure 1: - Qinshan CANDU Units 1 & 2 Construction

The Qinshan 700 MWe class CANDU 6 NPP is based on a proven design evolving from the CANDU family of Pressurized Heavy Water Reactors (PHWRS) shown in Figure 2.

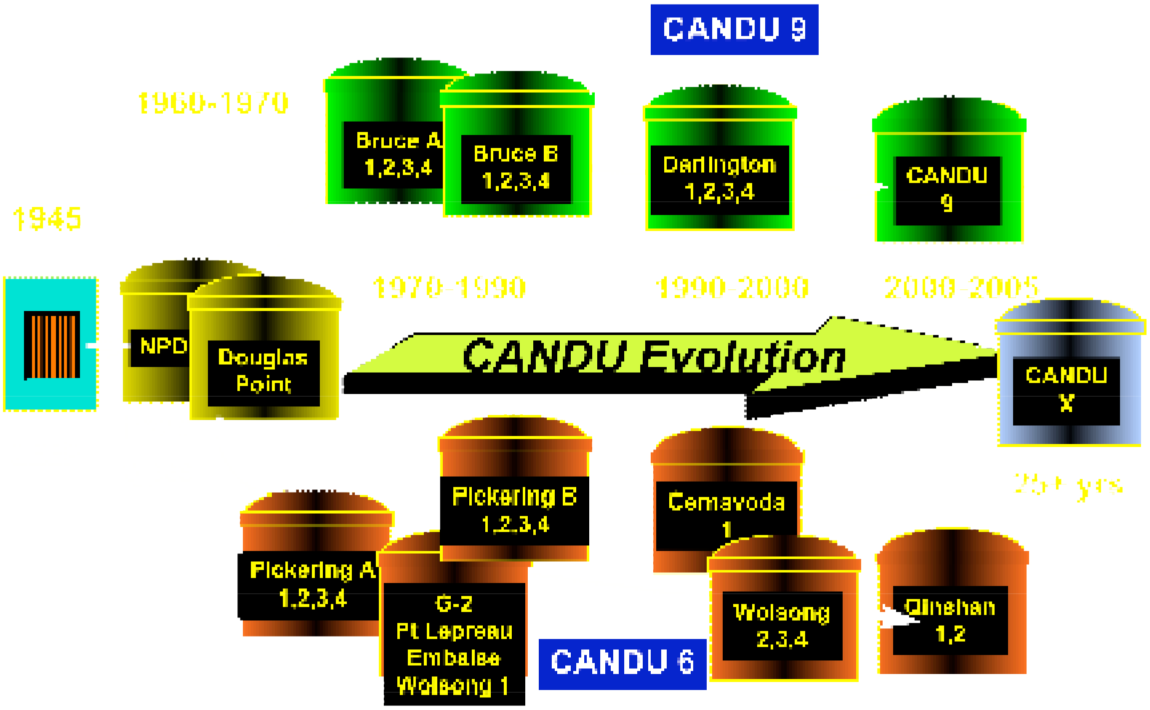

Figure - 2: Evolution of CANDU

Qinshan CANDU 6 meets Canadian licensing regulations and also complies with International Atomic Energy Agency (IAEA) design guides.

2.0 SCOPE

Changes to Qinshan from the reference plant at Wolsong have been incorporated both in plant design and product delivery to account for:

- Site-specific conditions
- Local Chinese regulations and
- Owner's requirements.

Other changes made to the Qinshan design were:

- To account for a 40 year design life;
- To meet local fire protection regulations;
- Improved surface finishes on the Calandria Tube for enhanced heat transfer characteristics;

- The implementation of a full scale 3-D CADDS application linked to project electronic database; and
- The adoption of an open top construction for work within the Reactor Building using a Very Heavy Lift (VHL) crane for major equipment installation.

The CANDU plant illustrated in Fig. 3 is divided into two major areas; Nuclear Steam Plant (NSP) and Balance of Plant (BOP). The NSP scope includes the Nuclear Steam Supply Systems (NSSS) in the reactor building, the service building and other auxiliary systems called the Balance of Nuclear Steam Plant (BNSP) systems. The BOP scope includes buildings, structures and systems within the turbine building (T/B), T/B annex, water treatment plant, pumphouse, firewater supply system and transformer area.

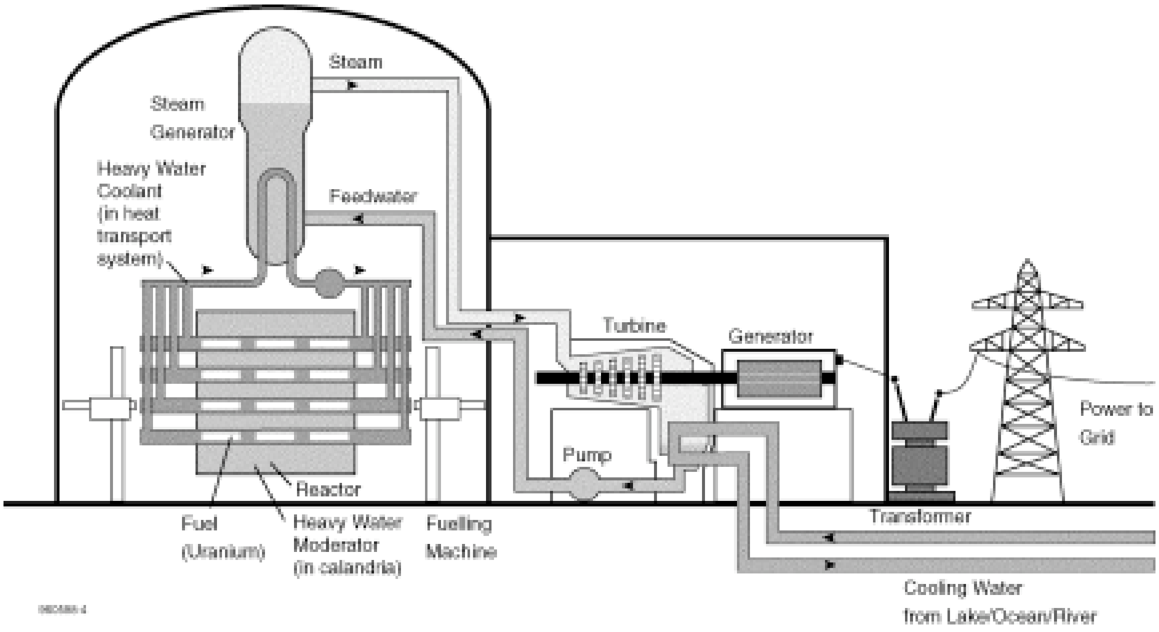

Figure - 3: Station Flow Diagram

3.0 NUCLEAR STEAM SUPPLY SYSTEM (NSSS)

3.1 General Arrangement:

The general arrangement of the Qinshan Nuclear Steam Supply System is illustrated in Figure 4. This figure shows the heat transport system components (steam generators, pumps, headers and feeders), the moderator system components (pumps and heat exchangers), the reactor assembly, and the fuelling machine bridge and fuelling machine.

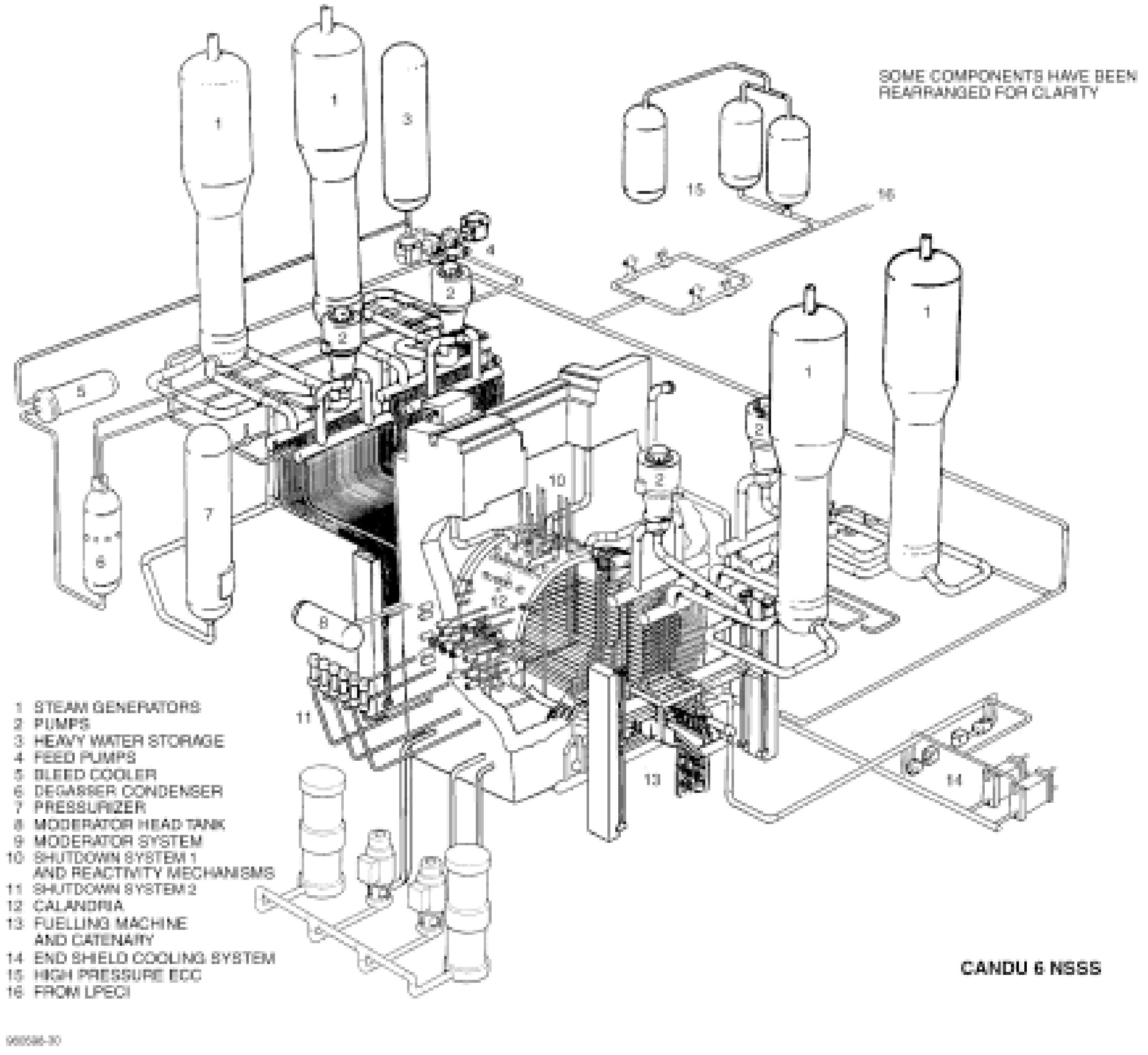

Figure - 4: Nuclear Steam Supply System

3.2 Core Configuration

The essential features of the CANDU reactor design arise from the use of natural uranium or other low fissile content fuel, pressure tubes that contain the fuel, high pressure heavy water coolant, efficient heavy water moderator, and low neutron absorbing zirconium alloys for the core structures and fuel cladding.

The use of pressure tubes to contain the fuel and heat transport system coolant allows the use of a moderator with a separate low pressure system, in which the reactivity control devices operate. The core does not contain a large amount of excess reactivity. Instead it uses on-power replacement of fuel to maintain sufficient positive and to achieve optimum burnup of the fuel.

This feature contributes to high availability factors and outage flexibility since fuelling outages are not required on CANDU reactors.

The CANDU 6 reactor core has 380 fuel channels contained in and supported by a horizontal cylindrical vessel known as the calandria Figure 5. The channels are located on a square lattice pitch of 286 mm. The calandria contains the heavy water moderator that slows the fast neutrons produced by fission to thermal energy levels to sustain the fission chain reaction. The fuel bundles in the pressure tubes generate heat that is removed by the pressurized heat transport system heavy water coolant circulating through the pressure tubes. This hot coolant is then used to generate steam from ordinary water in the steam generators. Horizontal and vertical reactivity control devices pass through the moderator in the calandria located between the fuel channels. The pressure tubes are thermally insulated from the moderator by a gas filled annulus between the pressure tube and the calandria tube. The gas annulus system is also used to detect any leak in either pressure tube or calandria tube.

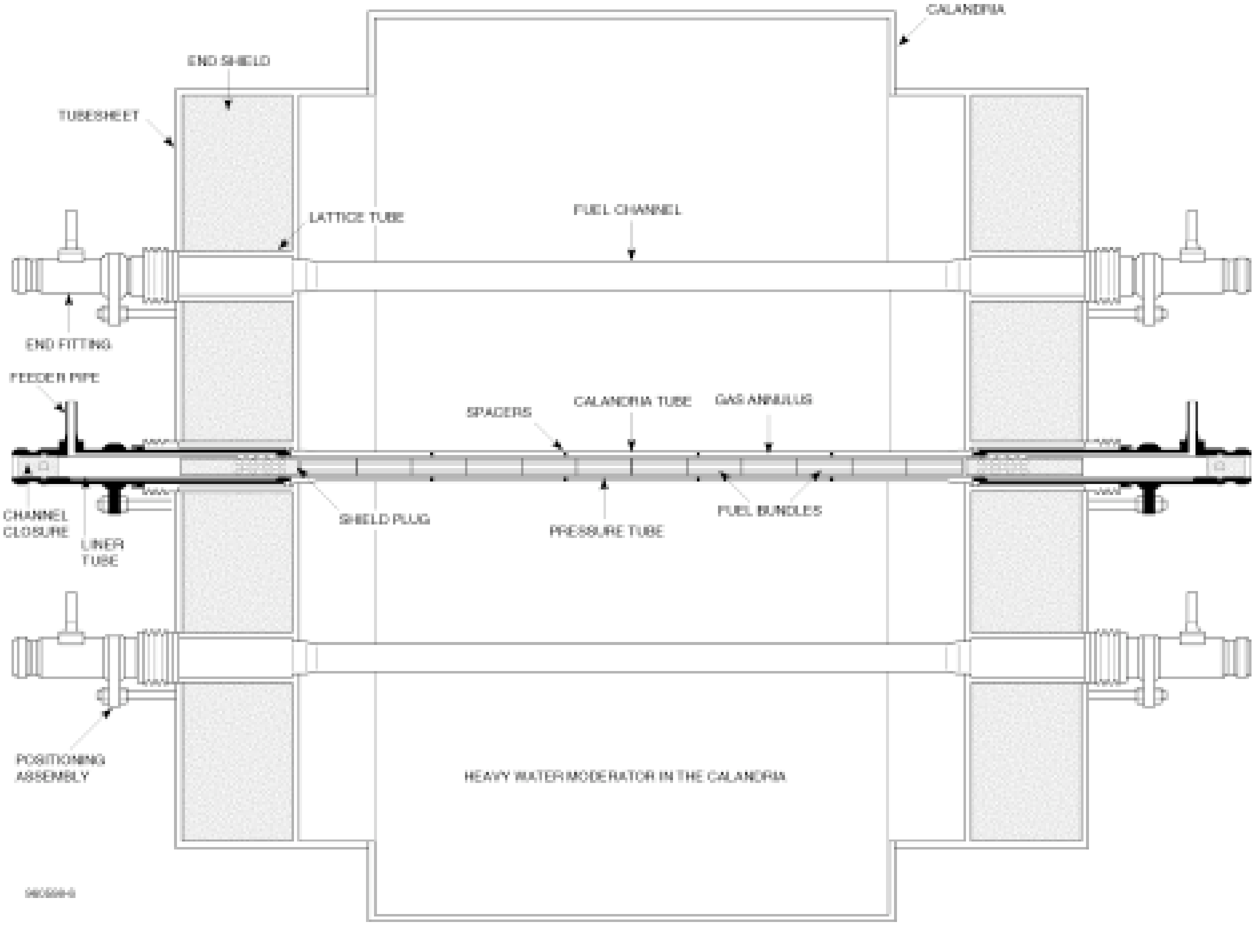

Figure - 5: Calandria Assembly Schematic

Key CANDU 6 plant data is presented in Table 1.

The calandria is a cylindrical vessel closed at each end by a flat shield. The end shields support the fuel channels and provide shielding of the reactor vault to limit activation during operation and to permit access for maintenance during a plant shutdown.

The basic design criteria for the design of the reactor structure are:

- To provide support to the whole reactor assembly via the embedments in the walls of the calandria vault.
- To provide support to the fuel channels by the end shields.
- To provide support to the reactivity control units and piping attached to the calandria.
- To provide shielding to the fuelling machine vault.

TABLE 1
CANDU 6 Unit Data

Reactor	
Type	Horizontal pressure tube
Coolant	Pressurized heavy water
Moderator	Heavy water
Number of fuel channels	380
Fuel	
Fuel	Compacted and sintered natural UO_2 pellets
Form	Fuel bundle assembly of 37 elements
Length of bundle	495 mm
Outside diameter	102.4 mm
Bundle weight	23.5 kg (includes 2.1 kg zirconium alloy)
Bundles per fuel channel	12
Heat Transport System	
Reactor outlet header pressure (gauge)	9.9 MPa
Reactor outlet temperature	310^0C
Reactor coolant flow	8.6 Mg/s
Number of steam generators	4
Steam generator type	Vertical U-tube with integral steam drum and preheater
Steam temperature (nominal)	268^0C

Steam quality (minimum)	99.75%
Steam pressure (gauge)	4.7 MPa
Number of heat transport pumps	4
Heat transport pump type	Vertical, centrifugal, single suction, double discharge
Net heat to turbine	2064 MW (th)
Electrical output (gross)	728 MWe

3.3 Fuel

CANDU 6 uses standard CANDU fuel. It consists of 37 elements of natural uranium dioxide sheathed in Zircaloy and held together as a bundle by end plates. There are 12 fuel bundles in each fuel channel. Fuel and heavy water (D_2O) coolant are enclosed in zirconium-niobium pressure tubes that in turn are surrounded by Zircaloy calandria tubes. High purity heavy water contained in the calandria vessel at low pressure and low temperature serves as the moderator. The heavy water moderator is a low pressure, low temperature and completely independent from the pressurized heavy water coolant of the heat transport system.

CANDU reactor core design using natural UO_2 fuel and D_2O moderator is dedicated to maximum neutron economy and fuel utilization. As the fuel burns and U-235 is depleted, the buildup of plutonium provides additional reactivity and contributes about half of the energy production. Fission products account for a very small fraction of the total neutron absorption. The heavy water moderator and high purity Zircaloy used for fuel sheath and structural components within the core also have very low absorption.

3.4 Fuelling

Continuous on-power fuelling eliminates the need to provide a large excess reactivity to compensate for reactivity depletion in the fuel, and permits continuous overall flux shaping to give an optimum power distribution, and thus eliminates the need for scheduling the plant for fuelling outages. The fuelling machines, located in the fuelling machine vaults at each end of the reactor, receive new fuel via the new fuel loading ports, move to the reactor and exchange the specified number of fuel bundles in fuel channels designated by the fuelling operator, and subsequently discharge irradiated fuel to the irradiated fuel storage bays via the irradiated fuel ports in the spent fuel discharge room and from there transferred through the containment wall. The number of fresh fuel bundles introduced into the channel can vary based on fuelling simulations.

It is the on power fuelling along with high neutron economy which provides CANDU with the unique capability to operate with wide variety of fuels including recovered uranium (Ru), Slightly Enriched Uranium (SEU) and Thorium.

Since there is no requirement for refuelling outages, maintenance and inspection outages (about every 2 years) can be scheduled to meet the utility’s system load requirements.

3.5 Reactor Control

The core power distribution is radially and axially flattened. Power flattening is achieved through the use of regional differential fuel burnup, in combination with a set of absorber devices called adjuster rods. Long-term control of the power distribution and reactivity is achieved through on-power refuelling. Short-term reactor control is by the reactor regulating system, which includes a set of in-core self-powered flux detectors, liquid zone control absorber and a dedicated direct digital control system. This system provides for global and spatial control of power. In addition, absorber rods provide power maneuvering capabilities for large power changes, reactor startup and reactor shutdown.

No chemicals are added to the heat transport system coolant for the purpose of reactivity control. Gadolinium and boron can be added to and removed from the heavy water moderator, for long term reactivity adjustment.

3.6 Heat Transport System

CANDU 6 heat transport system comprises two loops, each loop serving 190 of the 380 fuel channels. Each loop contains two steam generators, two pumps, two inlet headers, and two outlet headers. Feeders connect the inlet and outlet ends of the fuel channels to inlet and outlet headers respectively. The equipment arrangement shown in Figure 4 is such that the flow through the fuel channel is bi-directional (in opposite directions in adjacent channels) and that the total flow is a “figure-of-eight”, with the heat transport pumps of each loop in series.

3.7 Moderator System

Heat is generated in the heavy water moderator contained in the calandria during reactor operation by gamma radiation, and by the thermalization of the fast neutrons produced by fission. In addition, a small amount of heat is transferred to the moderator from the fuel channels. This heat is removed by the moderator system, which circulates the moderator heavy water through heat exchangers, and rejects heat to the recirculating cooling water system.

3.8 Safety Systems

CANDU 6 has four special safety systems: two independent fully capable and passively initiated shutdown systems, the containment system, and the emergency core cooling system.

- Shutdown System No. 1 (SDS1)
- Shutdown System No. 2 (SDS2)
- Emergency Core Cooling System (ECCS) and
- Containment System (containment structures, and containment heat removal and isolation systems)

The two safety shutdown systems (Shutdown System No. 1 and Shutdown System No. 2) are physically and functionally separate from each other and from the reactor regulating system. Each of the two shutdown systems is independently capable of shutting down the reactor and maintaining the reactor shutdown for all design basis events. The relatively long prompt neutron generating time inherent in CANDU reactors retards power excursions and reduces the speed required for shutdown system action, even for large hypothetical reactivity increases.

The containment system, which includes the reactor building and the containment isolation system, provides a post-accident environmental barrier.

The emergency core cooling system provides fuel cooling in the event that the normal reactor coolant (D_2O) is lost from the heat transport system via a loss of coolant accident.

The reactor may not be operated without all of the special safety systems being available.

Systems that provide reliable services, such as electrical power, cooling water, and air supplies to the special safety systems are referred to as safety support systems.

To guard against cross-linked and common mode events, all plant systems, including the safety system are assigned to one of two Groups (Group 1 and Group 2).

Group 1 and Group 2:

To mitigate the effects of common cause events, which could affect multiple systems within a limited area of the plant, and cross linked failures, which could affect multiple interfacing systems in different areas of the plant, safety related systems are assigned to one of the two groups (Group 1 and Group 2). The systems in each group are physically separated by either spatial separation (distance) or barriers. Interconnections between the groups are designed to minimize the propagation of failures from one group to the other. Certain redundant components that may be particularly susceptible to common cause events (e.g. cabling for the trip channels of Special Safety Systems) are also physically separated within each group. Where components associated with each group must be located in close proximity to each other, an assessment is done to show that common cause events would not result in failure of the essential safety function on both groups.

Group 1 includes Shutdown System No. 1 and the Emergency Core Cooling System, as well as other safety related systems that also perform functions during normal plant operation. Group 2 includes Shutdown No. 2 and the containment system, and other safety related system which are in a standby mode during normal plant operation. In the absence of accident conditions (e.g. LOCA), either group can perform the necessary safety functions to maintain the plant in a safe state despite loss of the other group.

The special safety systems must each meet an availability of 0.999. This target is used during system design and checked by a reliability calculation. It must also be demonstrated during plant operation. The design therefore provides for testing of components and systems during plant operation to confirm the calculated reliabilities. A high reliability ensures that a serious accident is mitigated and consequences are very low.

The design ensures that special safety systems and safety support systems perform their safety functions which a high degree of reliability, including the use of redundancy, diversity, reliability and testability separation, the application of appropriate quality assurance standards, and the use of stringent technical specifications including environmental qualification for accident conditions.

Further safety characteristics include:

- As noted above CANDU 6 uses natural uranium fuel in a core lattice arrangement that provides maximum reactivity. On-power fuelling assures that very little reactivity needs to be held up in movable control devices or in chemically treated moderator (no chemicals are added to the reactor coolant for reactivity control). Thus malfunctions in the control system produce only modest reactivity changes. Further, in a severe accident, a damaged core would tend to shut down inherently. The injection of ordinary water (e.g. through the emergency core cooling system) inserts negative reactivity.

- The control and shutdown devices are in the low-pressure moderator and are not subject to large hydraulic forces. There are no control or shutdown devices in the high pressure coolant. This inherently reduces the hazard of uncontrolled reactivity insertion.

- Natural coolant circulation removes decay heat from the fuel if pumping power is lost. This is effective even if the heat transport system coolant inventory is somewhat depleted.

- The shutdown cooling system can remove decay heat from the fuel at full HTS coolant temperature and pressure conditions, and is therefore a backup to the steam generators for emergencies as well as for normal low-power heat removal. CANDU 6 has a further method of emergency heat removal, through the Emergency Water Supply (EWS) system supplying the steam generators.

- Separate, seismically qualified water and power systems assure heat removal after an earthquake. For a loss of main feed water and/or main electrical power, the auxiliary feed water and Class III power systems are effective; these are backed up by the emergency water and emergency power systems.

- For hazards such as earthquake, fires, floods, etc., the plant is protected through implementation of the two-group approach. This entails a combination of redundancy of systems which protect the plant against frequent events, protection of essential systems so they can withstand the event; and separation of redundant systems so the same event cannot disable more than one.

- Digital controllers control the plant routinely, freeing the operator of mundane tasks and reducing the likelihood of operator error. The safety system responses are automated to the extent that no operator action is needed for a minimum of eight hours following most design basis accidents. Even for dual failure events (one safety system assumed failed) the plant is designed so that no operator action is required for 15 minutes.

Radiation doses to the public and to operators of existing CANDUs during normal operation have been low. This is partly due to the economic need to minimize and collect heavy water leakage, and to the ability to remove defected fuel during operation.

4.0 CANDU 6 OPERATING CHARACTERISTICS

Although CANDU stations provide for a base electricity load to utilities grids, they are operated extensively in the automatic, reactor following-turbine mode, subjecting the plant to continuous small perturbations in reactor power with no adverse effects.

All CANDU reactors are capable of continuous operation in the reactor-following-turbine mode of operation, the digital control systems providing the capability to respond to a megawatt demand signal generated from a remote dispatch facility. CANDU reactors operating in the reactor-following-turbine mode can continuously compensate for grid frequency fluctuations requiring a plus or minus variation of 2.5% full power while operating between 90% power and 100% power.

The CANDU 6 can operate continuously in the reactor-following-turbine mode and be capable of load cycling that typically involve a rapid reduction of power from 100% to 60%, steady-state operation at 60% power for 6 hours, and a return to full power over the following three hour period.

The following is a summary of significant operating characteristics:

- The unit is capable of sustained operation at any net electrical output up to 100 percent of rated full power output.
- The normal operating mode is with reactor following turbine.
- For reactor power increases, the nuclear steam plant is capable of maneuvering at the following rates:

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

The plant power-maneuvering rate is limited by the turbine design, and is typically 5 to 10 percent of full power per minute.

- During normal plant operation, assuming an initial power of 100 percent, xenon load at a steady state level, and with a normal flux shape, the reactor power may be reduced to 60 percent of full power at rates up to 10 percent of full power per minute. The power may be held at the lower level, indefinitely. Return to full power can be accomplished within three hours, or less, depending on the degree and duration of the power reduction.

5.0 SEVERE ACCIDENT MITIGATION

Probabilistic safety assessments are performed for CANDU 6. The redundant heat removal paths in CANDU, and redundant shutdown systems, lead to a predicted severe core damage frequency of 6.1×10^{-6} events/year. (PSA results depend on site-specific and station-specific application).

The moderator can act as an emergency heat sink even with no water in the fuel channels. Should the moderator heat removal system subsequently fail, the shield tank surrounding the calandria vessel provides an additional line of defence. This tank is a large water-filled low-pressure vessel, surrounding the calandria. Its primary purpose is to provide shielding of the concrete reactor vault from neutrons and gamma rays. However, it can also act as a passive emergency water reservoir in case of a severe core damage accident; that is should be primary coolant system (HTS), the emergency core cooling system, and the moderator heat removal system all fail, the shield tank will retain the debris inside the calandria, by keeping the outside of the calandria shell cool for a minimum period of 24 hours. This allows time for fission products to decay further and for decay heat to reduce, and for emergency planning.

Overall, the characteristics of the multiple heat sinks ensure that the challenges to containment from severe accidents are relatively simple and well understood. The likelihood of large radioactivity release, resulting from a severe accident with consequent containment impairment, is therefore very small.

6.0 SAFEGUARDS

Provision is made in the design of the plant for the installation of safeguards systems. The provision of the safeguards instrumentation is the responsibility of the International Atomic Energy Agency (IAEA) through its agreements with the client. The provision made for this equipment is based on the installation of systems with the client. The provision made for this equipment is based on the installation of systems similar to ones which have been acceptable to the IAEA in the past for this type of reactor. The instrumentation is used to assist the IAEA in its inspection function. The instrumentation for safeguards purposes in a CANDU 6 station includes irradiated fuel bundle counters, television and film cameras and may include other devices.

7.0 CANDU 6 PERFORMANCE

7.1 Capacity Factors

The first four generating CANDU 6 units, have over 60 years of cumulative operating experience, and have established an excellent safety and performance record. The CANDU 6 at Point Lepreau, operated by New Brunswick Power has frequently led the world in terms of lifetime capacity factor (Figure 6), while the Wolsong 1 CANDU 6, operated by the Korean Electric Power Corporation, has been the best performing plant in the world for three out of its twelve years of operation, including 1993 when it achieved a capacity factor of 100.8%. CANDU 6 operating records vary from year to year, but overall demonstrate sustained successful performance.

The CANDU 6 design has been continuously improved to meet current licensing requirements, codes and standards, and to reflect both operating experience and technical advances achieved through research and development by AECL. Hence the performance of new CANDU 6 plants is expected to be even better than that of the operating units.

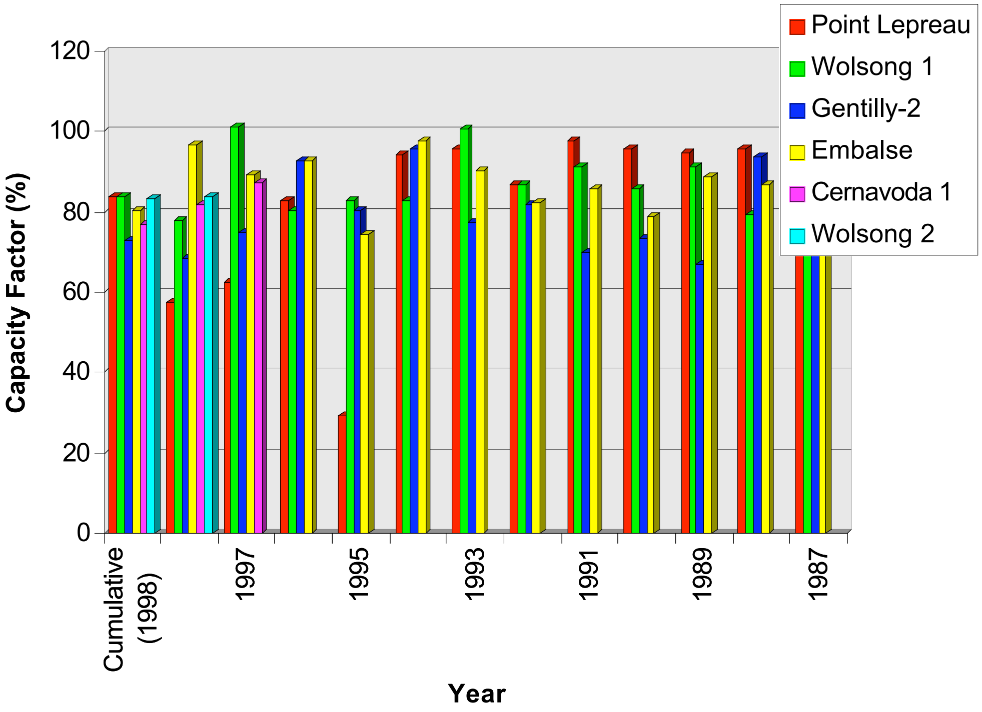

Figure - 6: CANDU 6 Capacity Factor

7.2 Operational Safety

The CANDU plants have been designed to reduce the consequences of human errors in operation and maintenance.

The systematic application of human factors design techniques and the automation and information access features of the design will ensure substantial risk reduction. Some specific features are:

- Emergency operating procedures are integrated with the control room alarm annunciation and display systems.
- The control room information system provides the operators with a clear “mental model” of the operational state of the plant.
- Operational complexity is reduced through use of automation and selective replacement of physical panel devices by graphical, interactive CRT interfaces to the plant.
- Equipment complexity is reduced through the use of computer automation to replace analog and relay control systems.

In over 300 reactors years of operation, the fault tolerant, self-checking computer systems utilized in the CANDU plant control systems have demonstrated that failures requiring shutdown system action can be reduced to near zero and spurious trips to about 1.5 per year.

7.3 Plant Life

The design life for current CANDU 6 plants is 40 years. However, the high degree of conservatism in the design (assumed frequency for various transients etc.) and the high quality of station operation and maintenance, have combined to assure substantially longer station life. Recent review of the operating CANDU 6 plants, including an assessment of actual transients, equipment condition, and degradation mechanisms, indicate that an operating life in excess of 50 years is probable.

The 50 or more year plant operating life for the CANDU 6 is possible in part due to the unique CANDU pressure tube reactor concept, which provides for pressure tube replacement and avoids life limiting pressure vessel embrittlement problems. Other factors include:

- Design practices and operational requirements ensure that non-replaceable components will operate in the design environment for 50 years or more.
- Design, backed by research and development, that ensures replaceable components last for their intended life and that replacement is made in a cost effective manner.

- Utilization of a life assurance and monitoring program for critical components that predicts the behavior of such components and requirements for rehabilitation/refurbishment/replacement.

The 50-year operating life can be achieved with a single plant shutdown with a duration of 18 months or less to perform mid-life refurbishment and modernization and retrofits. The refurbishing could include the replacement of the pressure tubes and a limited number of other reactor components, replacement of the steam generators, replacement of trunk cabling and obsolete instrumentation and control equipment as required, and reblading the turbine, if necessary.

8.0 SUMMARY

The two CANDU 6 units being built in Qinshan are based on a mature design currently operated by many utilities in Canada and offshore countries (South Korea, Argentina, Romania). The six currently operating CANDU 6 plants have over 60 years of cumulative operating experience and have established an excellent record. The performance of new CANDU 6 plants in Wolsong 4 and Qinshan are expected to excel beyond the current operating units given the continuous design and operations feedback from operating experience and technical advances through R&D.

CANDU features of natural uranium fuel and on power fuelling provides for independence in fuel supply and high capacity factors respectively. Digital controllers control the plant routinely freeing the operator from manual control actions and reducing the likelihood of operator error.

Safety system responses are automated to the extent that no operator action is required for a minimum of eight hours following most design basis events.