Operational Characteristics and Management of the Qinshan Phase III CANDU Nuclear Power Plant

by
Zhu Jizhou*, Shan Jianqiang* and Dennis McQuade**
*Xi'an Jiaotong University
** Atomic Energy of Canada Limited

1. CANDU Operational Characteristics

1.1 Introduction

Some of the design features and characteristics of the CANDU reactor are:

- Operating and control characteristics adapted to a variety of electrical grids
- A reactor core comprising several hundred small diameter fuel channels
- Heavy water (D_2O) for moderator and coolant
- Separate low pressure moderator and high pressure fuel cooling systems
- On-power fuelling
- Reactivity devices that are located in the cool low pressure moderator
- Natural uranium fuel or other low fissile content fuel
- Two fully capable safety shutdown systems, independent from each other

This summary of operational characteristics provides an overview for the CANDU 6 nuclear power system for Qinshan.

The evolution of CANDU design, as applied to operation, is described below. The design aspects summarized in this section are discussed in more detail in other papers of this publication.

1.2 Historical Background of CANDU 6

The specific features of the Qinshan CANDU 6 Nuclear Power Plant have evolved over a considerable period of time since the start-up of the first commercial CANDU at Pickering in 1971. Today's features are based on the successful installation of CANDUs in several countries, each with unique electrical grid characteristics.

The operational characteristics of the CANDU 6 are such that, with the wide diversity of application to grids of varying degrees of stability and size, each CANDU has performed very well. The following identifies some of the plants and the type of grids into which the power is fed.

1.2.1 CANDU Application Examples

Canada: Ontario Hydro: Pickering A, B, Base load operation into a developing grid
Ontario Hydro: Bruce Units 1-8, early life grid limitations leading to load cycling

	Ontario Hydro: Darlington, Base load operation into a large, stable grid Hydro Quebec: Gentilly-2 (CANDU 6), Early life grid limitations, very widely extended grid New Brunswick Power, Point Lepreau (CANDU 6), Small stable grid; Outage timing important
Argentina:	Embalse (CANDU 6), Early life grid limitations and instabilities
Romania:	Cernavoda-1 (CANDU 6), Extensive grid, lightly loaded; some instabilities and voltage fluctuations on plant in early life
Korea:	Wolsong-1 (CANDU 6), Base load operation from early life, into a developing grid; Prone to some fluctuation in early life Wolsong 2 and 3 (CANDU 6), Base loaded operation from early life into major stable grid

Main features of CANDU plants that enable them to operate with flexibility in this range of electrical grids are summarized below.

1.3 CANDU 6 Load Following Capability

1.3.1 Unit Operating Characteristics

CANDU stations operate extensively in the automatic, reactor-following-turbine mode, where the plant is subjected to continuous small perturbations in reactor power, with no adverse effects. The digital control systems provide 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. In addition, considerable operational data is available documenting successful experience with deep load changes (down to 60% and back to 100%) in the Bruce B and Embalse stations since 1984 and 1986 respectively. This provides substantial data to confirm the load following capabilities of CANDU reactors.

The CANDU 6 can operate continuously in the reactor-following-turbine mode and be capable of load following that typically involve rapid power reductions from 100% to 60%. The reactor will operate at steady-state at 60% power, and can return to full power in less than 4 hours.

The following is a summary of significant operating characteristics:

a) The unit is capable of sustained operation at any net electrical output up to 100 percent of rated full power output.
b) The normal operating mode is with reactor following turbine.

c) For reactor power increases, the nuclear steam plant is capable of manoeuvring at the following rates:

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

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

d) The unit is capable of reaching 100 percent net electrical output from a cold shutdown within 12 hours. If the pressurizer is at its normal operating temperature and pressure, the unit is capable of reaching 100 percent electrical output within seven hours (depending on xenon level).

e) Computers control the reactor and the turbine from 0 to 100 percent of full power.

1.3.2 Load Following

The only real constraint limiting the depth of a load cycle is the ability of the adjuster rods to compensate for the xenon reactivity transients resulting from the power reduction. There is no constraint on the rate of power reduction at the beginning of the cycle, nor on the length of time the reduced power is maintained before power is again raised. The rate at which power is raised again at the end of the cycle is constrained by the xenon transient and the flux shape variations associated with adjuster withdrawal; if the cycle was shallow or the time at reduced power was either very short or very long, then a very rapid return to full power is possible, but after deep cycles involving several hours of reduced power operation, the subsequent return to full power may take about 4 hours.

The Qinshan CANDU plant has a number of inherent features which makes it well suited to load cycling operation:

- There is no thick pressure vessel subject to large thermal stresses, thereby limiting fatigue life.
- The reactor is near neutral equilibrium, so only small changes in reactivity are needed to manoeuvre reactor power quickly.
- The secondary side operates at constant pressure over the entire power range, reducing thermal stresses on the secondary system.
- Totally automatic computer control over the reactor, steam generator and turbine-generator make load cycling as automatic as desired.
- The load cycling capability is constant throughout the life of the plant. Due to the use of on-power refuelling on CANDU, adjuster rod reactivity is not normally needed to compensate for reactivity loss due to fuel burn-up, and therefore remains fully available for load cycling.

1.4 Frequency Stabilization

1.4.1 Primary Frequency Stabilization

When the station is operated in the "normal" (reactor-follows-turbine) control mode, the station electrical output will automatically respond to grid frequency upsets, and reactor power is automatically adjusted to the new level of electrical output. Frequency increases will cause a reduction in electrical output, while frequency decreases will cause an increase in output, in both cases helping to correct the frequency deviation.

In the downward direction, the station's capability is effectively unlimited. The combination of steam bypass and reactor power reduction allows sudden electrical load reductions of any magnitude, including 100% load rejection, to be tolerated without incurring a turbine trip or a reactor trip. Reactor power reductions are usually limited to 60 % FP, the so-called poison prevent level, to prevent excessive xenon transients.

In the upward direction, the station's capability is naturally more limited. The station is capable of providing at least a 5% prompt and fully automatic increase in electrical output in response to a drop in grid frequency. More than half of this increase can occur immediately (1 or 2 seconds), and is sustained initially by energy stored in the steam generators. The full amount is available within 30 seconds, as the steam generated by the increased reactor power reaches the turbine. This type of power increase requires, of course, that the station was initially operating at least 5% below full power and that there were no other operational constraints preventing power increases.

In addition to sporadic load increases or decreases due to grid upset events, the station is also capable of performing more continual small load changes in response to small grid frequency variations. CANDU stations have been operated in this fashion for relatively short periods of time (weeks). It is not normal for nuclear plants to be used in this manner for continuous frequency control.

1.4.2 Secondary Frequency Stabilization

Secondary frequency control consists of deliberate station power manoeuvres initiated either by the operator or by a remote load control centre for the purpose of supporting grid requirements, i.e. to bring power production and power demand into balance.

The capability of the station to handle this type of transient is essentially the same as its ability to handle power manoeuvres. The time to respond cannot be characterised as a simple time constant. Manoeuvres take place at linear rates, which may be pre-configured in the control system or may be selected by the operator initiating the manoeuvre. Therefore a large power change takes proportionately longer than a small power change. CANDU power manoeuvring rates are quite fast, and are typically limited by the turbine rather than by the reactor.

1.4.3 Unscheduled Load Variation Limits and Capability to Cope with Major Grid Perturbation / Grid Failures

Operating experience has indicated that CANDU stations have a robust operating characteristic, and are tolerant of grid perturbations and failures. A combination of protective features limits the effects of such upsets on the plant process systems. These protective features include the following:

- A turbine load limiter, automatically adjusted to prevent sudden turbine load increases greater than 5 %.
- The turbine low pressure unloader, prevents excessive turbine load relative to available reactor power.
- Steam rejection to the condenser and to atmosphere allows the station to cope with sudden reductions of turbine load.
- Reactor power is automatically reduced in a controlled manner, either slowly or very quickly. These reductions are called setbacks and stepbacks.

The station is designed not to trip the turbine or the reactor on a full loss of line from 100% FP, and not to lift the boiler safety valves, but to continue operating, providing its own electrical power and bypassing any excess steam to the condenser. This capability is demonstrated by commissioning tests.

1.5 On-Power Fuelling

The on-power fuelling system fuels about 10 channels per week for full power operation. In the event of a fuel-handling problem, which prevents fuelling, the adjusters will be removed gradually to increase reactivity in compensation. This allows continued operation at a power somewhat less than 100% (depending on the adjusters removed), for a number of days. This feature allows significant flexibility for fuel handling repairs and assists in optimizing outages.

1.5.1 The Fuel Handling System

The fuel handling system:

- Provides facilities for the storage and handling of new fuel
- Refuels the reactor remotely while it is operating at any level of power
- Transfers the irradiated fuel remotely from the reactor to the storage bay

1.5.1.1 Fuel Changing

The fuel changing operation is based on the combined use of two remotely controlled fuelling machines, one operating on each end of a fuel channel. New fuel bundles, from one fuelling machine, are inserted into a fuel channel in the same direction as the coolant flow and the displaced irradiated fuel bundles are received into the second fuelling machine at the other end of the fuel channel. Typically, either four or eight of the 12 fuel bundles in a fuel channel are exchanged during a fuelling operation. The entire operation is directed from the control room through a pre-programmed computerized system.

1.5.1.2 Fuel Transfer

New fuel is received in the new fuel storage room in the service building. This room accommodates six months' fuel inventory and can store temporarily all the fuel required for the initial fuel loading.

When required, the new fuel bundles are transferred to the reactor building. Transfer of the new fuel bundles into the fuelling machines is remotely controlled.

Irradiated fuel received in the discharge port from the fuelling machine is transferred into an elevator that lowers it into a water filled discharge bay. The irradiated fuel is then conveyed under water through a transfer canal into a reception bay, where it is loaded onto storage trays or baskets and passed into the storage bay.

1.5.1.3 Removal of Defective Fuel

Fuel defects are rare; operating CANDU units have a record of less that 1 defect per 100,000 fuel pins, however, the on-power fuelling facilitates the removal of defective fuel in a timely manner, and minimizes the adverse radiological effect from such defects. Defected fuel is separately canned for storage. Because removal of defects is accomplished using the standard fuel handling system, the reactor can continue operating at full power during defect removal.

1.6 Capacity Factor

The CANDU 6 design for Qinshan incorporates lessons learned from design and operation of previous CANDU plants, resulting in demonstrated high capacity factor performance. CANDU 6 capacity factors have been consistently excellent for both the original and most recent units. A summary of CANDU 6 average lifetime capacity factors, as of December 31st, 1998 is, as follows:

Unit	Average Lifetime Capacity Factor (%)
Pt. Lepreau	85.2
Gentilly-2	79.2
Wolsong-1	85.4
Wolsong-2	87.5
Wolsong-3	98.5
Embalse	82.8
Cernavoda-1	87.2

Source: CANDU Owner's Group (COG)

- As of spring 1999, there are seven CANDU 6 reactors in service, two in Canada, three in Korea, one in Argentina, one in Romania, with in-service dates from 1983-1998

- The consistently high capacity factors achieved by different utilities (at different experience levels) in different countries, show the effectiveness of the common underlying technology, the CANDU 6 design.
- Current generation CANDU 6 plants newly entering service are starting out with equally good performance to the more established units. For example, Cernavoda 1 had a capacity factor of 88% in its first year of operation while Wolsong 2 had 97% in first six months.
- On-power refuelling is one distinctive feature contributing to high capacity factors. With used fuel being continuously replenished, there is a cost benefit because shutdowns for refuelling are not required. This makes maintenance outages shorter and planning for them more flexible in timing. For example, Point Lepreau's planned outage each year is required only for maintenance, modifications and inspections and lasts about 10 to 15 days on average. The outage is timed at the utility's convenience, to coincide with maximum output from alternate sources of power (hydro-electric).

1.6.1 Time Requirements of Planned and Unplanned Outages

The design target capacity factor of the CANDU 6 is 89%, as explained in the next section. An operational target capacity factor of 85% conservatively includes an additional 4% contingency. This is consistent with the lifetime average capacity factors for CANDU 6 units so far. Future CANDU units incorporate design features intended to further improve capacity factors. The time requirements for different types of outages in a CANDU 6 are summarized in the following table. The table below indicates designers' target for planned outages for future CANDU 6 units.

Table 0-1
CANDU 6 Design Target Incapacity Allowances During 40 Year Life

Activity	Full Power Days	Interval (years)	Total Days	%
1. Short Maintenance Outage	10	2	200	1.4
2. Longer Maintenance Outage	18	2	360	2.5
3. Major Conventional Outage	180	1 per 40 yrs	360	2.5
4. Major Nuclear Outage	460	1 per 40 yrs	460	3.1
5. Unplanned Outages	5	1	200	1.4
Subtotal (Design Target)				10.4
6. Contingency			609	4.2
Total (Design Target + Contingency)				15.1

Notes:

1) 40 years =40 x 365 days = 14600 days

2) Items 1& 2 are allowances for routine maintenance outages and occur in alternate years. They are based on CANDU 6 operating experience. Note that CANDU has **no** fuelling outages, so that these figures are significantly smaller than typical corresponding PWR figures.
3) Item 3 is an allowance for major maintenance outages e.g. activities such as turbine-generator overhaul
4) Item 4 allows sufficient time for pressure tube replacement, as well as for any other major nuclear equipment refurbishment. It is conservative in assuming pre-existing pressure tube replacement tools and methods, and takes no credit for improvements in these areas that are presently under development.
5) Item 5 is an allowance for unplanned outages based on operating CANDU plant experience

1.7 Distinctive CANDU Operating Features

1.7.1 Digital Control Computers (DCCs)

Digital computers are used for station control, alarm annunciation, graphic data display and data logging. The system consists of two independent digital computers (DCCX and DCCY), each capable of station control.

Both computers run continuously, with programs in both machines switched on, but only the controlling computer's outputs are connected to the station equipment. In the event that the controlling computer fails, the control of the station is automatically transferred to the "hot" standby computer.

Individual control programs use multiple inputs to ensure that erroneous inputs do not produce incorrect output signals. This is achieved by rejecting:

- analog input values that are outside the expected signal range
- individual readings that differ significantly from their median, average or other reference.

Alarm Annunciation

Alarm messages are presented on coloured display monitors (cathode ray tubes) which are centrally located above the station main control panels. Two line printers, one for each computer, provide chronological records of all alarm conditions.

Operator Communication Stations

These computerized stations replace much of the conventional panel instrumentation in the control room. A number of man-machine communication stations, each essentially comprising a keyboard and colour CRT monitor, are located on the main control room panels. The displays provided on the monitors include:

- graphic trends
- status displays
- historical trends
- bar charts
- pictorial displays

Copies can be obtained of any display monitor the operator wishes to record.

Automatic Transfer

A fault in any essential part of one computer results in automatic transfer of control to the other computer. If both computers fail, the station is automatically shut down.

1.7.2 Reactor Regulating System

The fundamental design requirement of the reactor regulating system (RRS) is to control the reactor power at a specified level and, when required, to manoeuvre the reactor power level between set limits at specific rates. The reactor regulating system combines the reactor's neutron flux and thermal power measurements, reactivity control devices, and a set of computer programs to perform three main functions:

- Monitor and control total reactor power to satisfy station load demands
- Monitor and control reactor flux shape
- Monitor important plant parameters and reduce reactor power at an appropriate rate if any parameter is outside specific limits

Computer Programs

The principal computer programs employed provide the following reactor control functions:

- Reactor power measurement and calibration
- The demand power routine
- Reactivity control and flux shaping
- Setback routine
  - Monitors a number of plant parameters and reduces reactor power gradually, in a ramp fashion, if any parameter exceeds specified operating limits. The rate at which reactor power is reduced and the level at which the setback is terminated are determined by the particular parameter.
- Stepback routine
  - A situation which could possibly result in damage is indicated when certain plant variables are outside their specified ranges. The stepback routine checks the values of these variables and if necessary, disengages the clutches of the mechanical control absorbers. This allows the absorbers to drop into the core, to produce a rapid decrease in power.
- flux mapping routines

Reactivity Control Devices

Short-term global and spatial reactivity control is provided by:

- Light water zone control absorbers
- Mechanical control absorbers
- Adjusters
- Soluble poison addition and removal to the moderator

The zone control system operates to maintain a specified amount of reactivity in the reactor, this amount being determined by the specified reactor power setpoint. If the reactivity range of the zone control system is insufficient to do this, the program in the reactor regulating system calls on other reactivity control devices. Adjusters are removed from the core for positive reactivity shim. Negative reactivity is provided by the mechanical control absorbers or by the automatic addition of poison to the moderator.

In addition, two separate safety grade reactor shutdown systems are provided. They are designed to be independent of each other, and of the reactor control system. Shutdown System No.1 consists of a set of spring-assisted, gravity-driven shutoff rods, while Shutdown System No.2 is rapid-acting liquid poison injection into the moderator.

Light Water Zone Control Absorbers

The liquid zone control system uses variable quantity of neutron absorbing light water in compartments within the reactor to provide short-term global and spatial reactivity control in the CANDU reactor core.

The liquid zone control system in the CANDU 6 reactor consists of a total of 14 compartments distributed throughout the reactor core, thereby dividing the core into 14 zones for the purposes of flux control. Flux (power) in each zone is controlled by the addition or removal of light water to/from the liquid zone control compartment in that zone, by controlling the level of light water in the liquid zone control compartment.

1.7.3 Adjusters

Adjusters are cylindrical neutron absorbing rods. A CANDU reactor typically has 21 vertically mounted adjuster rods, normally fully inserted between columns of fuel channels for flux shaping purposes.

Removal of adjusters from the core provides positive reactivity to compensate for xenon buildup following large power reductions, or in the event that the on-power refuelling system is unavailable. The adjusters are capable of being driven in and out of the reactor core at variable speed to provide reactivity control. The adjusters are normally driven in banks, the largest bank containing five rods.

1.7.4 Poison Addition

A reactivity balance can be maintained by the addition of soluble poison to the moderator. Boron is used to compensate for an excess of reactivity when fresh fuel is introduced into the reactor. Gadolinium is added when the xenon load is significantly less than equilibrium (as happens after prolonged shutdowns).

An ion exchange system removes the poisons from the moderator. The operator normally controls addition and removal of poison. However, the reactor regulating system can also add gadolinium in special circumstances.

1.7.5 Main Control Room

The control room features an array of panels at the perimeter with two large central display screens, and the operations console. Information is provided on the panels and at the operations console to allow the station to be safely controlled and monitored.

The instrumentation and controls on the panels are grouped on a system basis, with a separate panel allocated to each major system. Coloured cathode ray tube (CRT) displays and advanced annunciation systems provide uncluttered control room panel layouts and excellent monitoring capabilities. The operator can call up information displays on the panel CRTs, the operating control console CRTs, and central display screens in a variety of alphanumeric and graphic formats via keyboards. All display annunciation messages are colour coded to facilitate system identification and the priority of the alarm.

Conventional display and annunciation instrumentation is provided for all safety related systems and to permit the station to be safely monitored in the event of dual computer failure, which automatically shuts down the reactor.

If for any reason the control room has to be evacuated, the station can be shut down and monitored from a remotely located secondary control area.

1.7.6 Heavy Water Management

The station is designed to prevent the loss of D_2O from the reactor systems. Operating experience with modern CANDUs demonstrates that only a small fraction of the D_2O escapes during operation. Special measures are taken to recover and upgrade the small quantity of D_2O that does escape, since it is a valuable resource. Provisions ensuring optimum D_2O management are:

- Extensive use of welded joints, with the number of mechanical joints in heavy water systems kept to a minimum
- Heavy water and light water systems are segregated as much as possible
- A D_2O liquid recovery system is provided
- Air entering and leaving the reactor building is dried to minimize D_2O downgrading and loss respectively
- Air within the building is maintained dry by closed circulation drying systems. Heavy water vapour removed by the dryers is recovered and upgraded.

Deuteration and De-deuteration System

The spent resins from the ion exchange columns of the heat transport system and the moderator system contain D_2O. To recover the D_2O the resins are processed (de-deuteration - a downward flow of H_2O through the resin beds) in the deuteration and de-deuteration system.

Similarly when ion exchange resins are received from the suppliers they are also processed (deuteration - an upward flow of D_2O through the resin bed) to remove H_2O.
The ion exchange resins from the heat transport and moderator systems are processed separately and in both of the processes some D_2O is downgraded, collected and transferred to the D_2O cleanup system.

Vapour Recovery System

A D_2O vapour recovery system is provided in the reactor building to maintain a dry atmosphere in areas that may be subject to leakage. The areas are segregated into three groups, each group serviced by one portion of the system.

Areas where access is required only during reactor shutdown

- Fuelling machine operating areas
- Boiler room, including shutdown cooler areas
- Moderator room (exclusive of enclosure around equipment)

Areas designed for access during reactor operation

- Fuelling machine maintenance locks
- Fuelling machine auxiliary equipment room
- Monitoring rooms

D_2O Collection System

This system is designed to collect D_2O leakage from mechanical components that may occur in any area of the reactor building and to receive D_2O drained from equipment prior to maintenance.

D_2O Upgrading System

The D_2O upgrading system separates a mixture of H_2O and D_2O into:

- An overhead distillate, richer in light water than the feed
- A bottom product, richer in heavy water than the feed.

The upgrading system accepts mixtures varying from 2 percent to 99 percent D_2O and upgrades them to reactor grade 99.8 percent D_2O. The overhead distillate has a concentration of less than 2 percent D_2O.