# CANDU 6

## Technical Summary

# CANDU® 6 Technical Summary

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*The systems described in this brochure are those of a typical CANDU 6 generating station; however, they are essentially the same as those of other CANDU stations in most respects.*

# Introduction

CANDU nuclear power stations have consistently proven to be competitive with other types of nuclear power plants, while offering unique advantages to their operators. Some of the design features and unique characteristics of the CANDU reactor are:

- a reactor core comprising several hundred small diameter fuel channels rather than one huge pressure vessel
- heavy water ($D_2O$) for moderator and coolant
- separate low pressure moderator and high pressure fuel cooling systems
- on-power refuelling
- reactivity devices that are located in the cool low pressure moderator, and not subjected to high temperatures or pressures
- natural uranium fuel or other low fissile content fuel
- reduced consequences from accidental reactivity fluctuations — excess reactivity available from the fuel is small and the relatively long lifetime of prompt neutrons in the reactor precludes rapid changes in power levels
- two fully capable safety shutdown systems, independent from each other and the reactor regulating system.

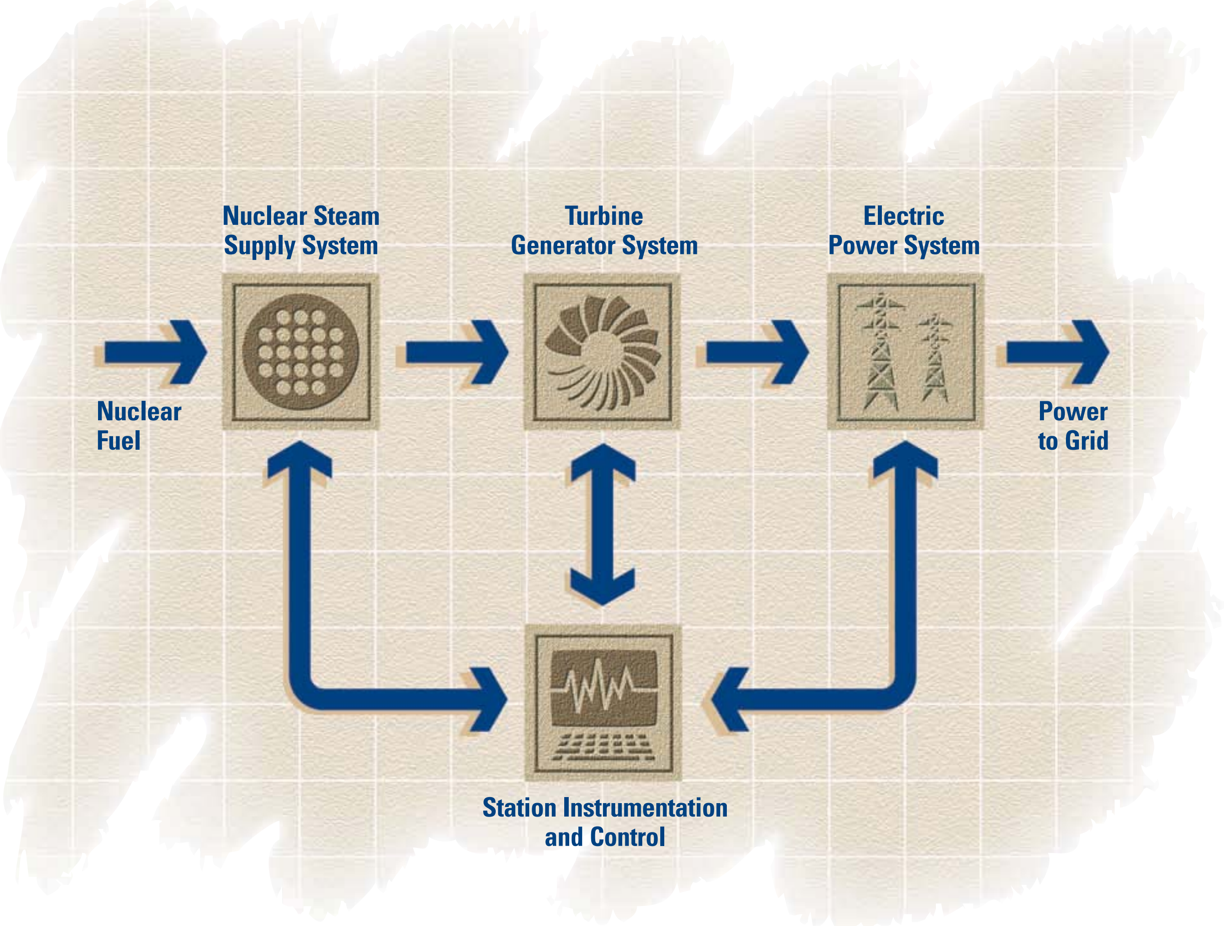
This Technical Summary provides an overview of the CANDU 6 nuclear power system. All CANDU 6 power plants are fundamentally the same, although there are differences in detail: these largely result from different site conditions, and from improvements made in the newer designs.

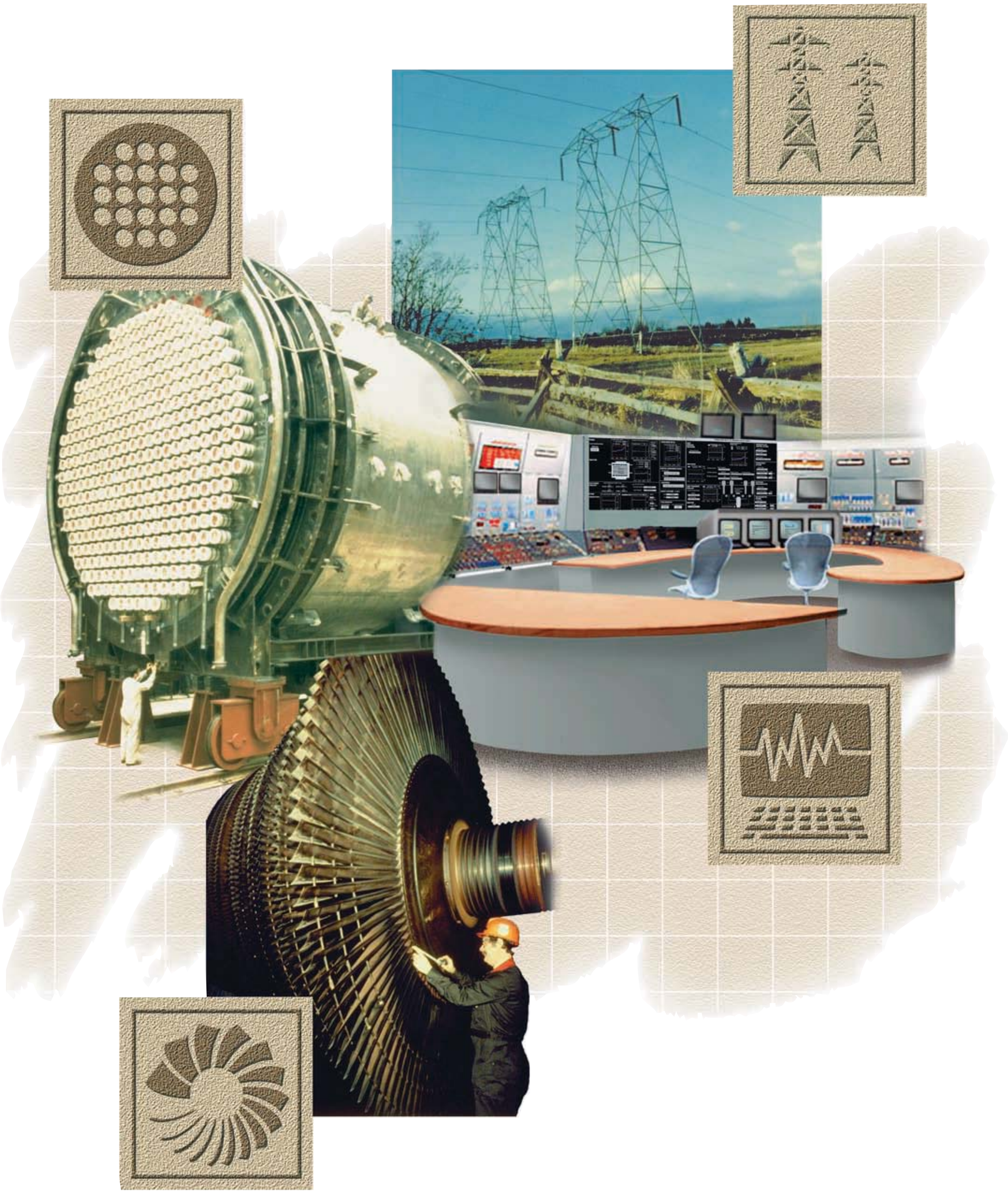
The evolution of CANDU 6 is illustrated in the inside back cover.

## Major Systems

Pictorial symbols representing major systems are used throughout this publication to indicate relationships between major systems and their sub-systems.

Systems that are not featured on this page are described later in the document.





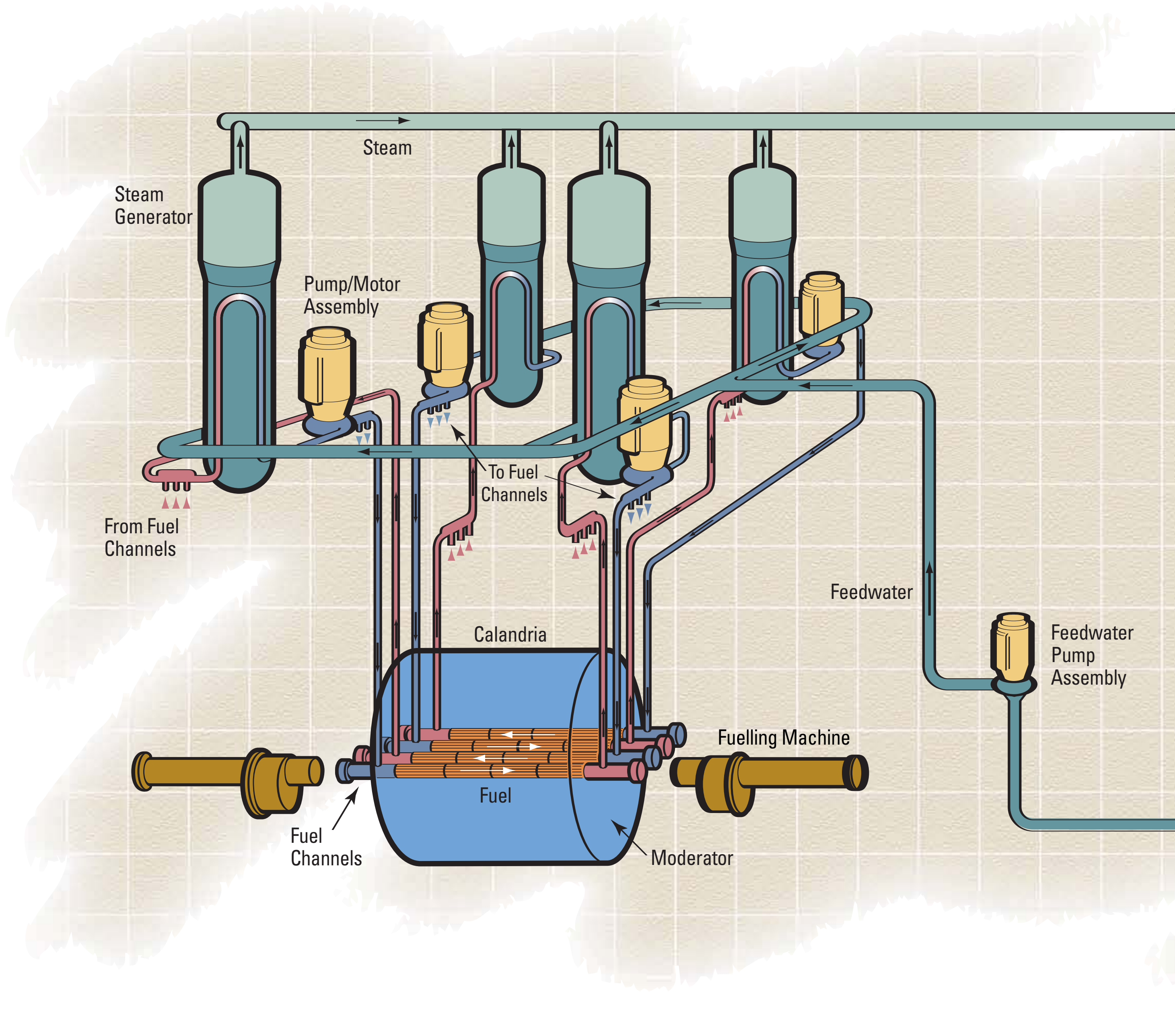
# Station Flow Diagram

## Nuclear Steam Supply System

A CANDU 6 nuclear steam supply system's power production process starts like that of any other nuclear steam supply system, with controlled fission in the reactor core. However, unlike other reactors, the CANDU 6 is fuelled with natural uranium fuel that is distributed among 380 fuel channels. Each six-meter-long fuel channel contains 12 fuel bundles. The fuel channels are housed in a horizontal cylindrical tank (called a calandria) that contains cool heavy water ($D_2O$) moderator at low pressure. Fuelling machines connect to each fuel channel as necessary to provide on-power refuelling; this eliminates the need for refuelling outages.

The on-power refuelling system can also be used to remove a defective fuel bundle in the unlikely event that a fuel defect develops. CANDU 6 reactors have systems to identify and locate defective fuel.

Pressurized heavy water ($D_2O$) coolant is circulated through the fuel channels and steam generators in a closed circuit. The fission heat produced in the fuel is transferred to heavy water coolant flowing through the fuel channels. The coolant carries the heat to steam generators, where it is transferred to light water to produce steam. The steam is used to drive the turbine generator to produce electricity.



## Turbine Generator System

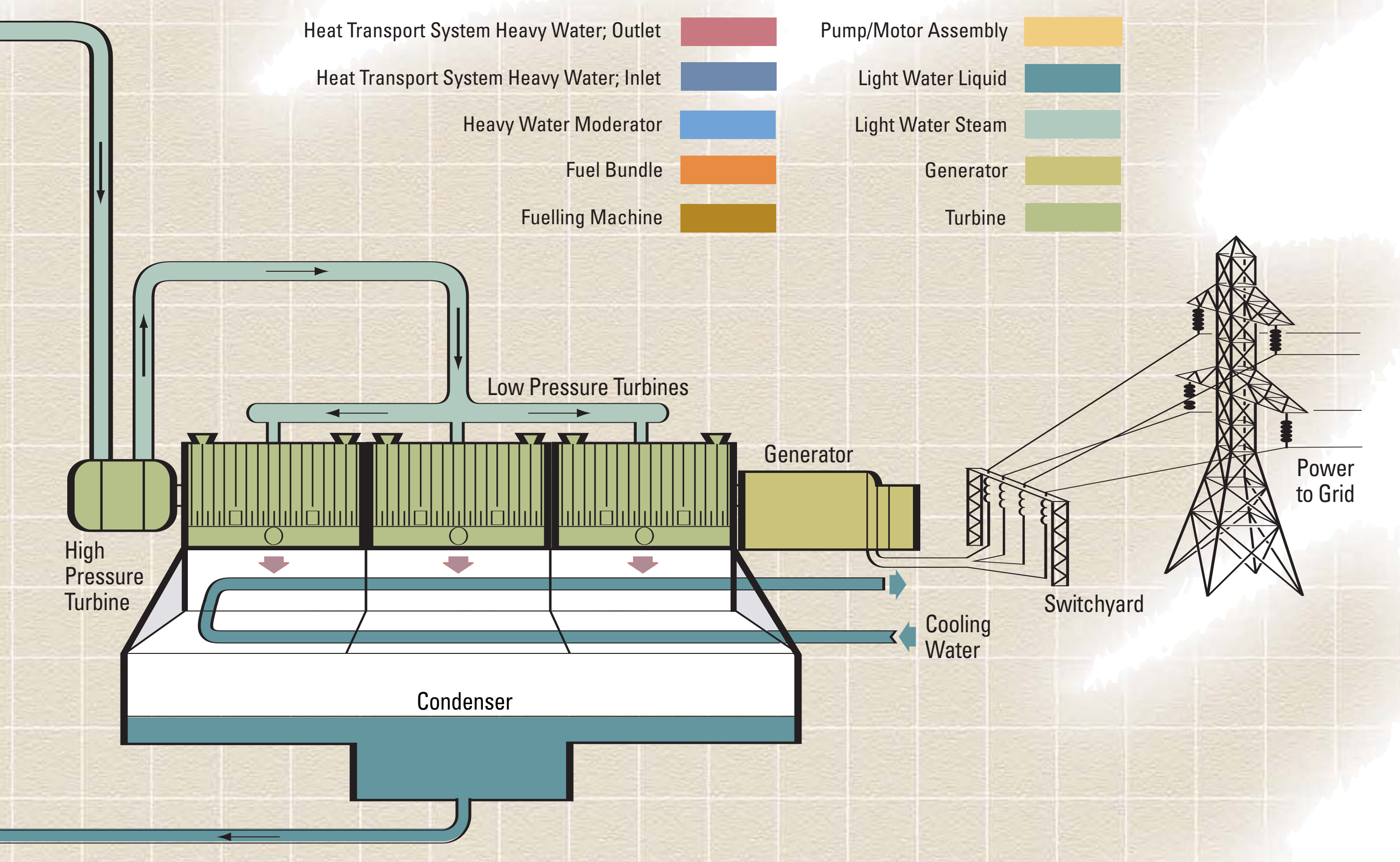
The turbine generator system comprises steam turbines directly coupled to an alternating current electrical generator operating at synchronous speed.

- The steam turbine is a tandem compound unit, generally consisting of a double flow, high pressure turbine and three double flow, low pressure turbines, which exhaust to a high vacuum condenser for maximum thermal efficiency. The condenser may be cooled by sea, lake or river water, or by atmospheric cooling towers.
- The generator is a high efficiency hydrogen-cooled machine arranged to supply alternating current at medium voltage to the electric power system.

## Electric Power System

The electric power system comprises a main power output transformer, unit and service transformers, and a switchyard. This system steps up (increases) the generator output voltage to match the electric utility's grid requirements for transmission to the load centres and also supplies the power needed to operate all of the station services.

The main switchyard portion of the electric power system permits switching of outputs between transmission lines and comprises automatic switching mechanisms, and lightning and grounding protection to shield the equipment against electrical surges and faults.



# Nuclear Steam Supply System – Overview

## Reactor

The reactor comprises a stainless steel horizontal cylinder (called the calandria), closed at each end by end shields, which support the horizontal fuel channels that span the calandria, and provide personnel shielding. The calandria is housed in and supported by a light water-filled, steel lined concrete structure (the reactor vault) which provides thermal shielding. The calandria contains heavy water ($D_2O$) moderator at low temperature and pressure, reactivity control mechanisms and several hundred fuel channels.

## Fuel Handling System

The fuel handling system refuels the reactor with new fuel bundles without interruption of normal reactor operation; it is designed to operate at all reactor power levels. The system also provides for the secure handling and temporary storage of new and irradiated fuel.

## Heat Transport System

The heat transport system circulates pressurized heavy water coolant ($D_2O$) through the reactor fuel channels to remove heat produced by fission in the uranium fuel. The heat is carried by the reactor coolant to the steam generators, where
it is transferred to light water to produce steam. The coolant leaving the steam generators is returned to the inlet of the fuel channels.

## Moderator System

Neutrons produced by nuclear fission are moderated (slowed) by the $D_2O$ in the calandria. The moderator $D_2O$ is circulated through systems that cool and purify it, and control the concentrations of soluble neutron absorbers used for adjusting the reactivity.

## Feedwater and Steam Generator System

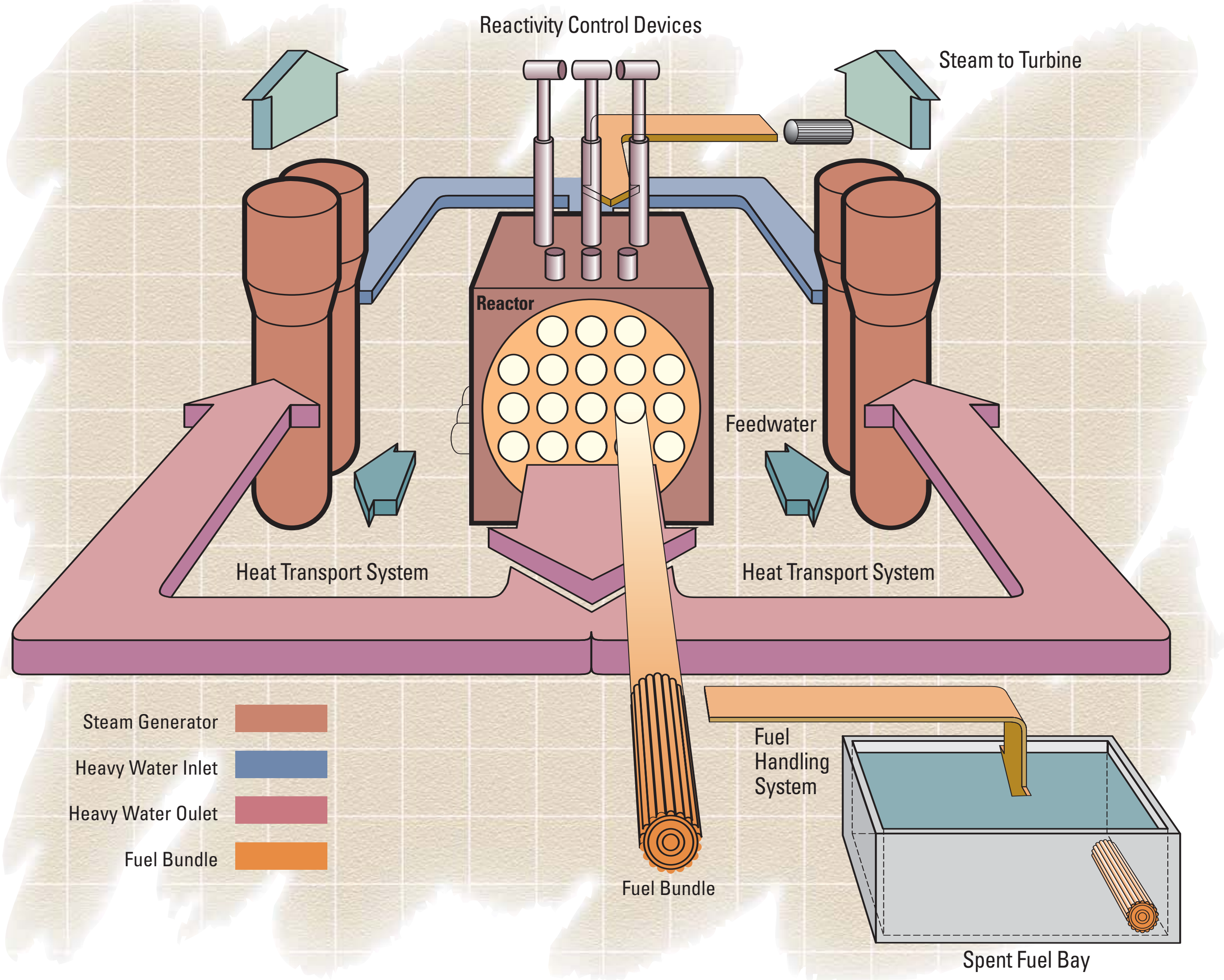
The steam generators transfer heat from the heavy water reactor coolant to light water ($H_2O$) to form steam, which drives the turbine generator. The low pressure steam exhausted by the low pressure turbine is condensed in the condensers by a flow of condenser cooling water. The feedwater system processes condensed steam from the condensers and returns it to the steam generators via pumps and a series of heaters.

## Reactor Regulating System

This system controls reactor power within specific limits and ensures that station load demands are met. It also monitors and controls power distribution within the reactor core, to optimize fuel bundle and fuel channel power within their design specifications.

## Safety Systems

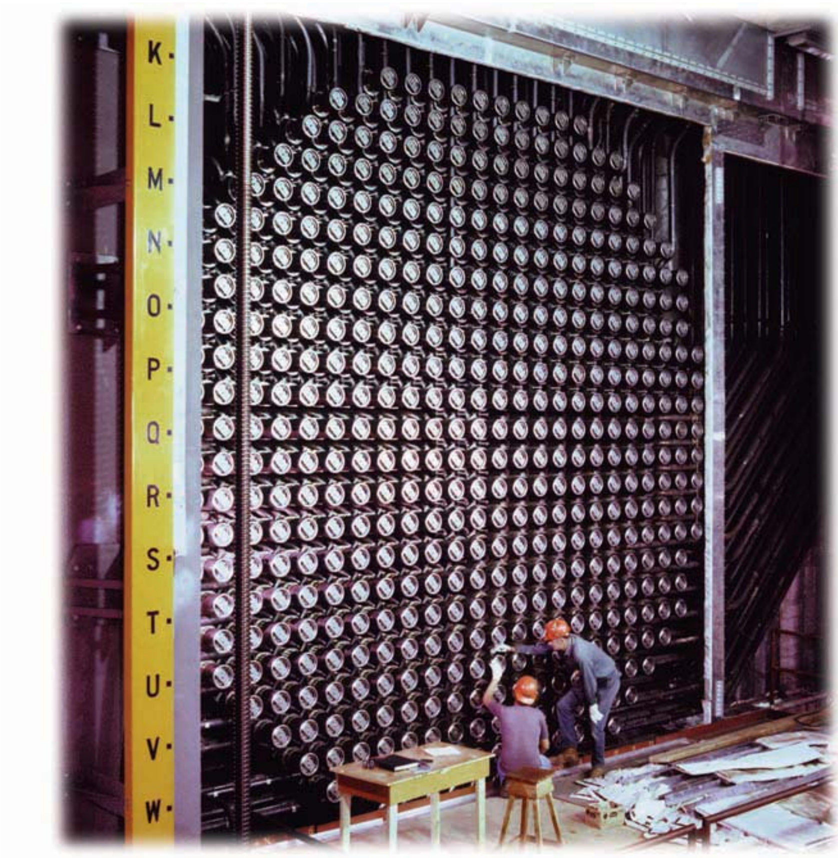
Four special safety systems (shutdown system number 1, shutdown system number 2, the emergency core cooling system and containment system) are provided to minimize and mitigate the impact of any postulated failure in the principal nuclear steam plant systems. Safety support systems provide services as required (electric power, cooling water and compressed air) to the special safety systems. (See Safety Systems on page 46.)


Reactivity Control Devices
Steam to Turbine
Reactor
Feedwater
Heat Transport System
Heat Transport System
Steam Generator
Heavy Water Inlet
Heavy Water Oulet
Fuel Bundle
Fuel
Handling
System
Fuel Bundle
Spent Fuel Bay

# Reactor Assembly and Fuel

## Reactor Assembly

The CANDU 6 reactor assembly, shown in the figure opposite, includes the fuel channels contained in and supported by a horizontal cylindrical tank known as the calandria. The calandria is closed and supported by end shields at each end. Each end shield comprises an inner and an outer tubesheet joined by lattice tubes at each fuel channel location and a peripheral shell. The inner space of the end shields are filled with steel balls and water, and are water cooled. The fuel channels, supported by the end shields, are located on a square lattice pitch. The calandria is filled with heavy water moderator at low temperature and pressure. The calandria is located in a steel lined, water filled concrete vault.




*Reactor face (during construction)*

Horizontal and vertical reactivity measurement and control devices are located between rows and columns of fuel channels, and are perpendicular to the fuel channels.

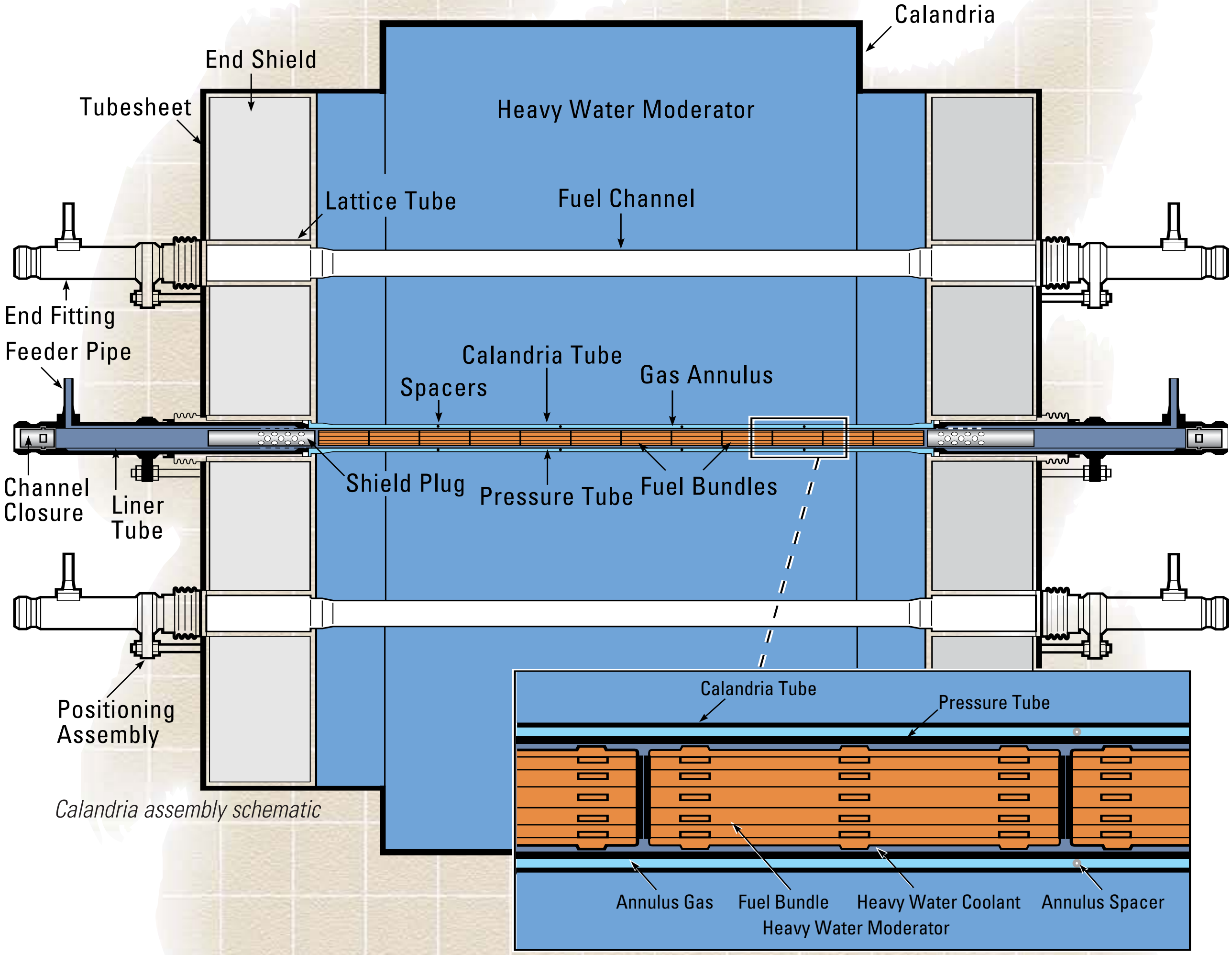
The fuel channels are also shown in the figure opposite, with additional detail provided in the accompanying figure. Each fuel channel locates and supports 12 fuel bundles in the reactor core. The fuel channel assembly includes a zirconium-niobium alloy pressure tube, a zirconium calandria tube, stainless steel endfittings at each end, and four spacers which maintain separation of the pressure tube and the calandria tube. Each pressure tube is thermally insulated from the cool, low pressure moderator, by the $CO_2$ filled gas annulus formed 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 flow through adjacent channels in the reactor is in opposite directions.

During on-power refuelling, the fuelling machines gain access to the fuel channel by removing the closure plug and shield plug from both end fittings of the channel to be refuelled.

## Fuel

The CANDU 6 fuel bundle consists of 37 elements, arranged in circular rings as shown in the photo opposite. Each element consists of natural uranium in the form of cylindrical pellets of sintered uranium dioxide contained in a zircaloy 4 sheath closed at each end by an end cap. The 37 elements are held together by end plates at each end to form the fuel bundle. The required separation of the fuel elements is maintained by spacers brazed to the fuel elements at the transverse mid-plane. The outer fuel elements have bearing pads brazed to the outer surface to support the fuel bundle in the pressure tube.




*Calandria assembly schematic*

*Fuel channel arrangement*

*37 Element Fuel Bundle*

# Fuel Handling System

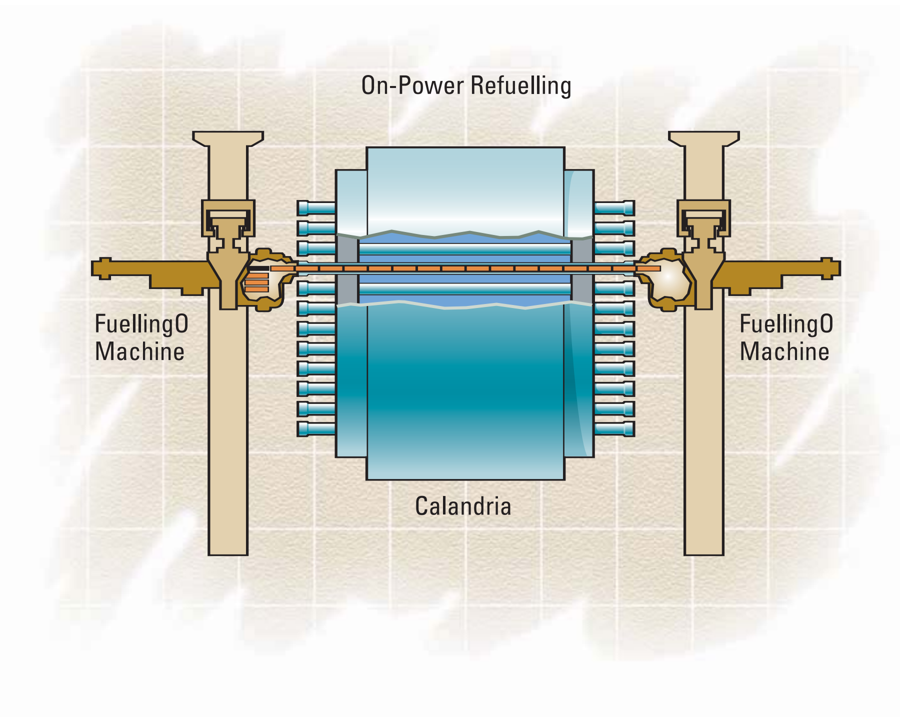
The fuel handling system:

- 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.

## 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 replaced during a refuelling operation. For a CANDU 6 reactor, about 10 fuel channels per week are refuelled.

Either machine can load or receive fuel. The direction of loading depends upon the direction of coolant flow in the fuel channel being fuelled, which alternates from channel to channel.




The fuelling machines receive new fuel while connected to the new fuel port and discharge irradiated fuel while connected to the discharge port.

The entire operation is directed from the control room through a pre-programmed computerized system. The control system provides a printed log of all operations and permits manual intervention by the operator, if required.

*Fuelling machine in operating position at face of reactor.*

## 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.

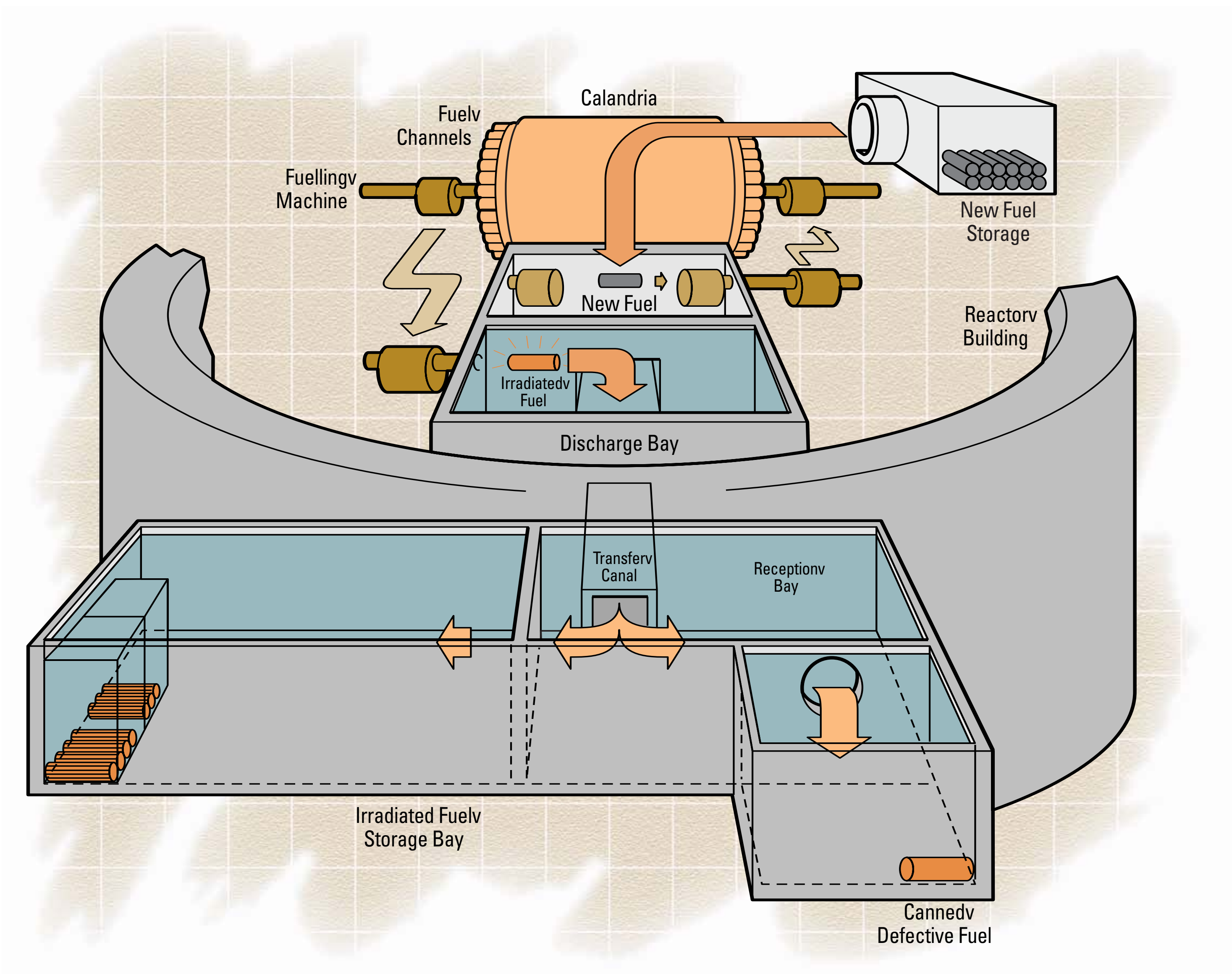
When required, the fuel bundles are transferred to the new fuel transfer room in the reactor building. The fuel bundles are identified and loaded manually into the magazines of the two new fuel ports. Transfer of the new fuel bundles into the fuelling machines is remotely controlled.

Irradiated fuel received in the discharge port from the fuelling machine is transferred into an elevator which 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.

The discharge and transfer operations are remotely controlled by station staff. Operations in the storage bays are carried out under water, using special tools aided by cranes and hoists. Defective fuel is inserted into cans under water to limit the spread of contamination before transfer to the defective fuel bay.

The storage volume of the bays has sufficient capacity for a minimum of 7 years' accumulation of irradiated fuel.

Neither new or nor irradiated CANDU fuel can achieve criticality in air or light water, regardless of the storage configuration.



# Moderator and Auxiliary Systems

## Moderator System

About four per cent of reactor thermal power appears in the moderator. The largest portion of this heat is from gamma radiation; additional heat is generated by moderation (slowing down) of the fast neutrons produced by fission in the fuel, and a small amount of heat is transferred to the moderator from the hot pressure tubes.

The system includes two 100 per cent capacity pumps, two 50 per cent flow capacity heat exchangers cooled by recirculated cooling water and a number of control and check valves. Connections are provided for the purification, liquid poison addition, heavy water ($D_2O$) collection, supply and sampling systems.

The moderator pump motors are connected to the medium voltage Class III power supply. In addition, each pump has a pony motor, capable of driving the pump at 25 per cent speed, connected to the Class II power supply. In the event of a loss of Class IV power (see page 34), the power to the main motors is lost until the diesel generators can supply Class III power. The cooling water supply to the heat exchangers is also re-established after three minutes at a reduced flow rate following a total failure of Class IV power. The rate of heat removal is sufficient to limit the increase of moderator temperature in the calandria to an acceptable value during a failure of Class IV power and subsequent reactor shutdown.

The heavy water in the calandria functions as a heat sink in the unlikely event of a loss of coolant accident in the heat transport system coincident with a failure of emergency core cooling.

## Cover Gas System

Helium is used as the cover gas for the moderator system because it is chemically inert and is not activated by neutron irradiation. Radiolysis of the heavy water moderator in the calandria results in production of deuterium and oxygen gases. The cover gas system prevents accumulation of these gases by catalytically recombining them to form heavy water. The deuterium and oxygen concentrations are maintained well below levels at which an explosion hazard would exist.

The system includes two compressors and two recombination units which form a circuit for the circulation of cover gas through the calandria relief ducts. Normally one compressor and both recombination units operate, with the other compressor on standby.

## Purification System

The moderator purification system:

- maintains the purity of $D_2O$, thereby minimizing radiolysis which can cause excessive production of deuterium in the cover gas.
- minimizes corrosion of components, by removing impurities present in the $D_2O$ and by controlling the pD.
- under operator command reduces the concentration of the soluble poisons, boron and gadolinium, in response to reactivity demands.
- removes the soluble poison, gadolinium, after shutdown system number 2 has operated.

## $D_2O$ Sampling System

This system allows samples to be taken from the:

- main moderator system
- moderator $D_2O$ collection system
- moderator purification system
- $D_2O$ cleanup system.

Laboratory tests may be performed on the samples to determine:

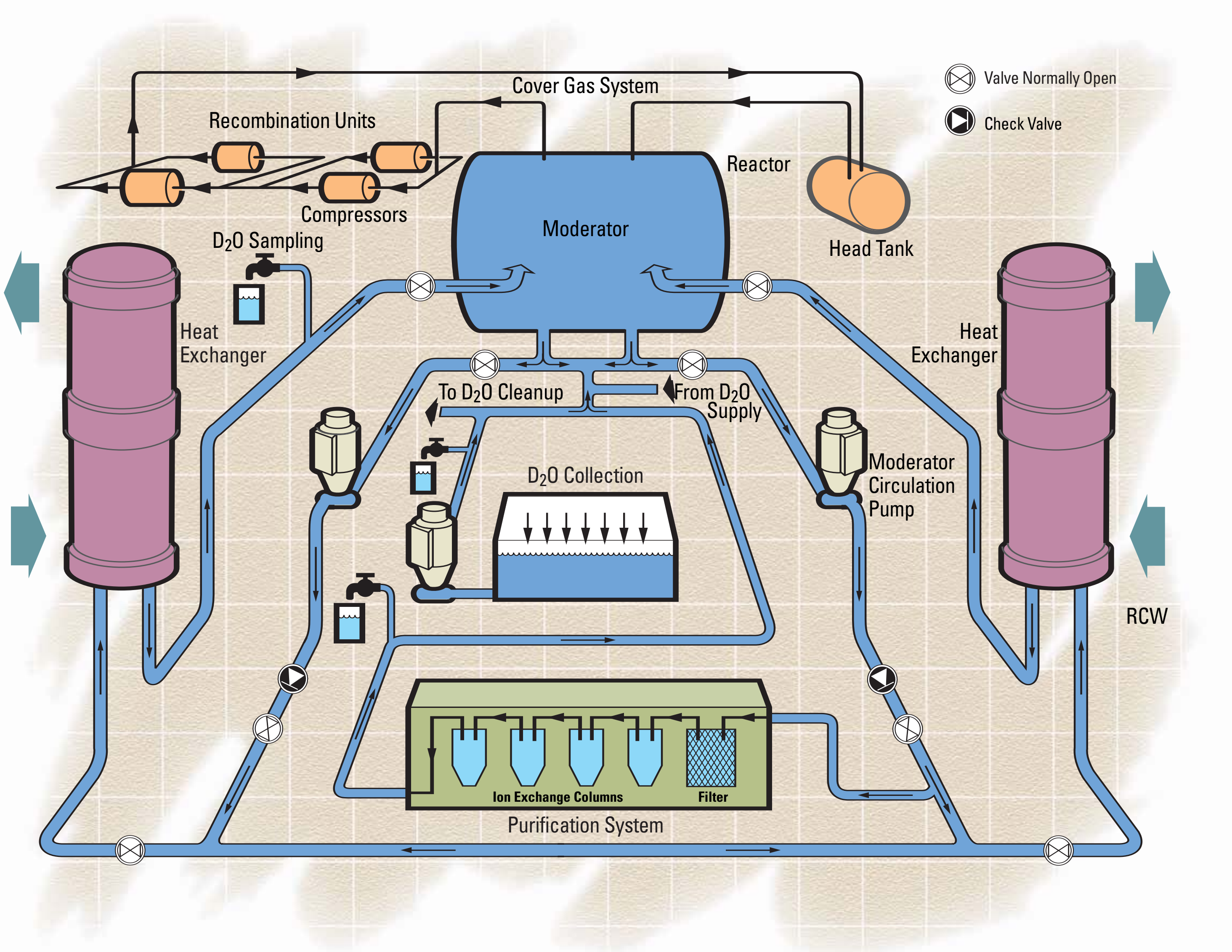
- pD (pH)
- conductivity
- chlorides concentration
- isotopic purity
- boron and gadolinium concentration
- tritium content
- fluorides content
- organics content.

## Operation of the Moderator System

The series/parallel arrangement of the system lines and valves permits the output from either pump to be cooled by both of the heat exchangers and assures an acceptable level of moderator cooling when either of the two pumps is isolated for maintenance. Reactor power must be reduced to about 60 per cent if one moderator heat exchanger is isolated.

The primary functions of the system are to:

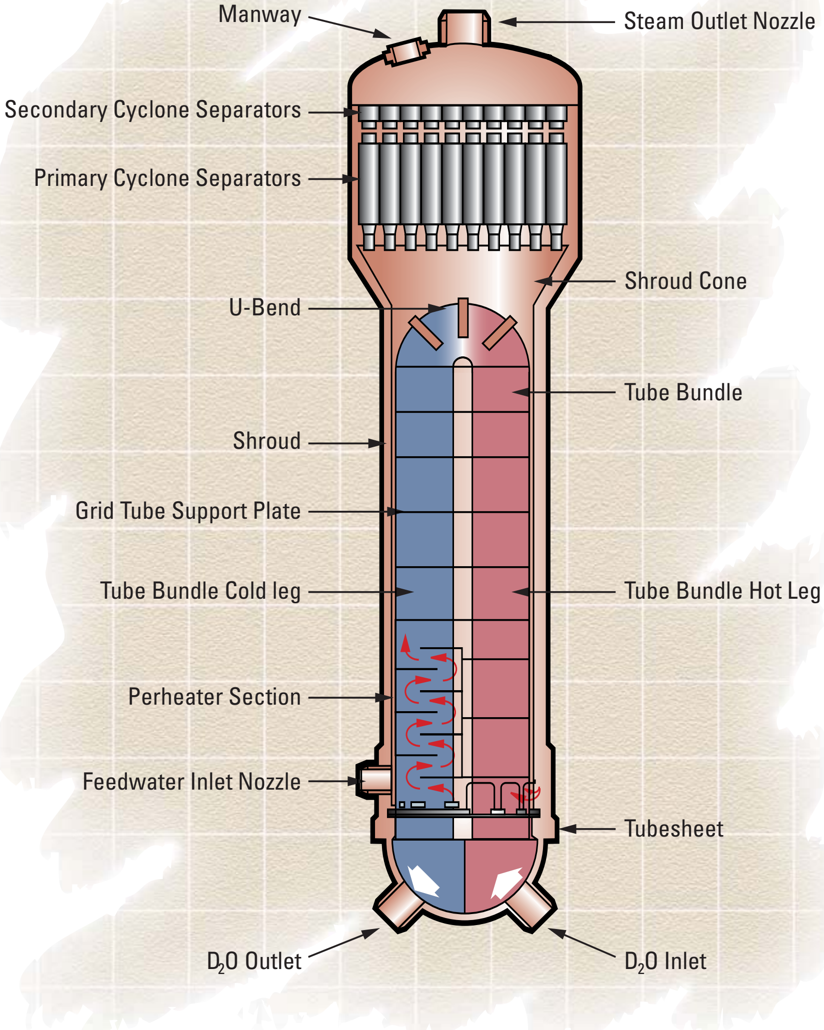
- provide moderator cooling
- control the level of heavy water in the calandria
- maintain the calandria inlet temperature at approximately 70°C.



## System Operation

The heat transport system (HTS) circulates pressurized $D_2O$ coolant through the fuel channels to remove the heat produced by fission in the nuclear fuel. The coolant transports the heat to steam generators, where it is transferred to light water to produce steam to drive the turbine. Two parallel HTS coolant loops are provided in CANDU 6. The heat from half of the 380 fuel channels in the reactor core is removed by each loop. Each loop has one inlet and one outlet header at each end of the reactor core. $D_2O$ is fed to each of the fuel channels through individual feeder pipes from the inlet headers and is returned from each channel through individual feeder pipes to the outlet headers. Each heat transport system loop is arranged in a 'Figure of 8', with the coolant making two passes, in opposite directions, through the core during each complete circuit, and the pumps in each loop operating in series. The coolant flow in adjacent fuel channels is in opposite directions. The HTS piping is fabricated from corrosion resistant carbon steel.

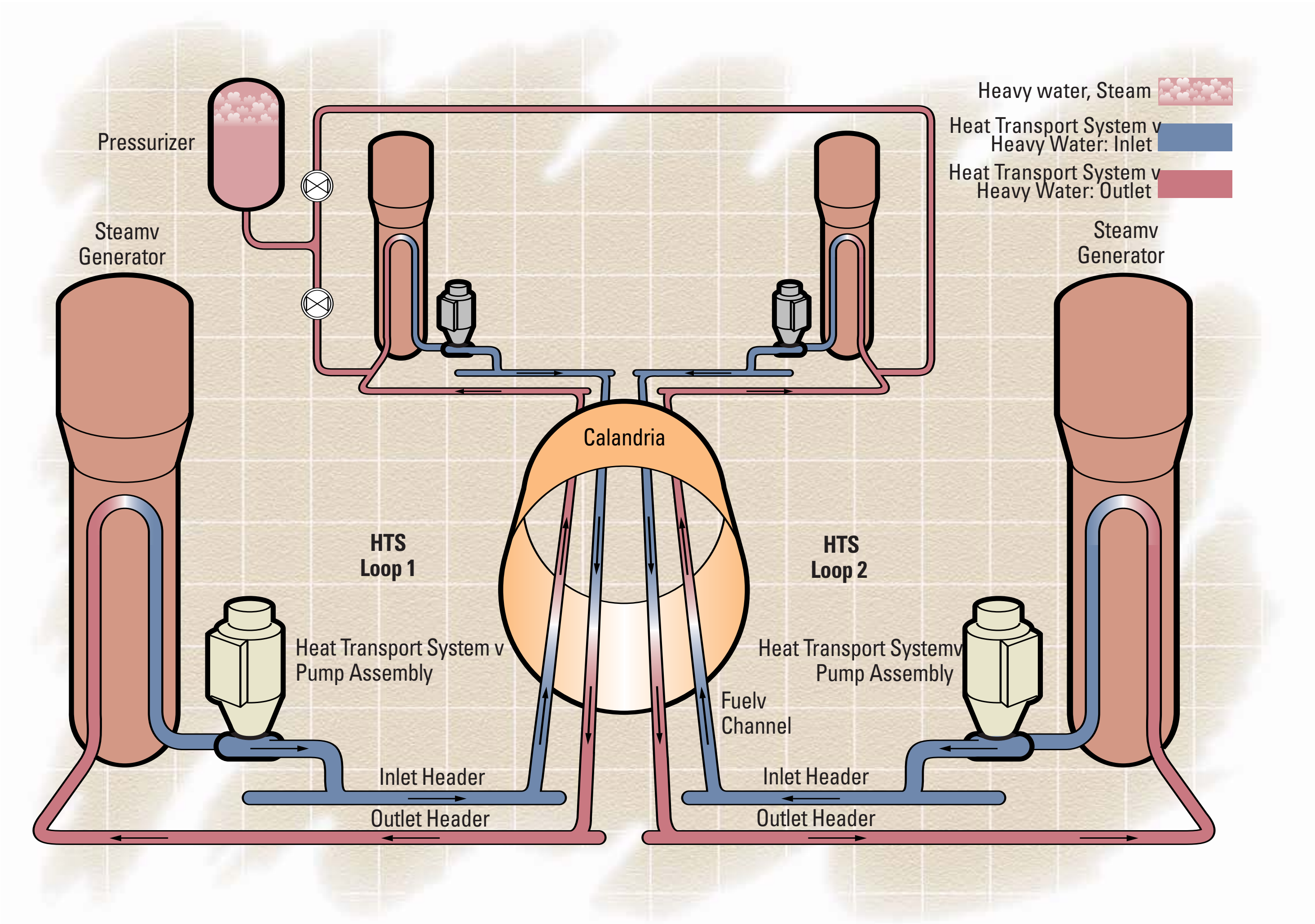
The pressure in the heat transport system is controlled by a pressurizer connected to the outlet headers at one end of the reactor. Valves provide isolation between the two loops and the pressurizer in the event of a loss-of-coolant accident.




*Steam Generator*

## Key Features

- The steam generators consist of an inverted U-tube bundle within a cylindrical shell. Heavy water coolant passes through the U-tubes. The steam generators include an integral preheater on the secondary side of the U-tube outlet section, and integral steam separating equipment in the steam drum above the U-tube bundle.
- The heat transport pumps are vertical, centrifugal motor driven pumps with a single suction and double discharge.
- Cooling of the reactor fuel, in the event of electrical power supply interruption, is maintained by the rotational momentum of the heat transport pumps during reactor power rundown, and by natural convection flow after the pumps have stopped.
- No chemicals are added to the heat transport system for the purpose of reactivity control.
- Carbon steel piping, which is ductile and relatively easy to fabricate and to inspect is used in the heat transport system.
- Radiation exposure to personnel is low because of the low fuel defect rate, and is minimized by designing for maintenance, application of stringent material specifications, controlling the reactor coolant chemistry and by providing radiation shielding.




*A comparison of principal CANDU Heat Transport System Parameters*

| ***CANDU 6 Operating stations or under construction*** | Electrical Output (MW) Gross/Net | Number of Fuel Channels | **Heat Transport System Conditions** Elements in Fuel Bundle | Number of Loops | Outlet header Pressure (MPa) | Maximum Channel Flow (kg/s) | Outlet Header Quality (%) | **Heat Transport Pumps** Total | Operating | Motor Rating (kW) | **Steam Generators** Area ($m^2$) per Steam Generator | Integral Preheater | Steam Pressure (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Point Lepreau,** | 680/633 | 380 | 37 | 2 | 10.0 | 24 | 4 | 4 | 4 | 6700 | 3200 | Yes | 4.7 |
| **Gentilly 2** | 675/638 | 380 | 37 | 2 | 10.0 | 24 | 4 | 4 | 4 | 6700 | 3200 | Yes | 4.7 |
| **Wolsong 1** | 678/638 | 380 | 37 | 2 | 10.0 | 24 | 4 | 4 | 4 | 6700 | 3200 | Yes | 4.7 |
| **Embalse** | 648/600 | 380 | 37 | 2 | 10.0 | 24 | 4 | 4 | 4 | 6700 | 2800 | Yes | 4.7 |
| **Cernavoda 1, 2** | 710/665 | 380 | 37 | 2 | 10.0 | 24 | 4 | 4 | 4 | 6700 | 3200 | Yes | 4.7 |
| **Wolsong 2, 3, 4** | 715/668 | 380 | 37 | 2 | 10.0 | 24 | 4 | 4 | 4 | 6700 | 3200 | Yes | 4.7 |
| **Qinshan 1, 2** | 728/668 | 380 | 37 | 2 | 10.0 | 24 | 4 | 4 | 4 | 6700 | 3200 | Yes | 4.7 |
| ***Other CANDU operating stations*** | | | | | | | | | | | | | |
| **Pickering A** 4 Units | 542/515 | 390 | 28 | 2 | 8.7 | 23 | - | 16 | 12 | 1420 | 1850 | Yes | 4.1 |
| **Bruce A** 4 Units | 904/840 | 480 | 37 | 1 | 9.1 | 24 | <1 | 4 | 4 | 8200 | 2400 | No | 4.4 |
| **Pickering B** 4 Units | 540/516 | 380 | 28 | 2 | 8.7 | 23 | - | 16 | 12 | 1420 | 1850 | Yes | 4.1 |
| **Bruce B** 4 Units | 915/860 | 480 | 37 | 1 | 9.1 | 24 | <1 | 4 | 4 | 8200 | 2400 | No | 4.7 |
| **Darlington** 4 Units | 936/881 | 480 | 37 | 2 | 10.0 | 25 | 2 | 4 | 4 | 9600 | 4900 | Yes | 5.1 |

# Heat Transport Auxiliary Systems

## Pressure and Inventory Control System

The heat transport pressure and inventory control system consists of a pressurizer, $D_2O$ feed-pumps, feed and bleed valves and a $D_2O$ storage tank. This system provides:

- pressure and inventory control for each heat transport system loop
- overpressure protection
- a controlled degassing flow.

Heavy water in the pressurizer is heated electrically to pressurize the vapour space above the liquid. The volume of the vapour space is designed to cushion pressure transients, without allowing excessively high or low pressures in the heat transport system.

The pressurizer also accommodates the change in volume of the reactor coolant in the heat transport system from zero power to full power. This permits the reactor power to be increased or decreased rapidly, without imposing a severe demand on the $D_2O$ feed and bleed components of the system.

When the reactor is at power, pressure is controlled by the pressurizer; heat is added to the pressurizer via the electric heaters to increase pressure, and heat is removed from the pressurizer via $D_2O$ steam bleed to reduce pressure. The coolant inventory is adjusted by the feed and bleed circuit. Pressure can also be controlled by the feed and bleed circuit with the pressurizer isolated at low reactor power and when the reactor is shut down. This feed and bleed circuit is designed to accommodate the changes in coolant volume that take place during heat-up and cool-down.

## $D_2O$ Collection System

- collects leakage from mechanical components
- receives $D_2O$ sampling flow
- receives $D_2O$ drained from equipment prior to maintenance.

The collected $D_2O$ is pumped from the collection tank to the storage tanks of the pressure and inventory control system for re-use in the heat transport system. However, if the isotopic purity of the collection tank contents is low, the $D_2O$ can be pumped to drums for upgrading.

## Shutdown Cooling System

The shutdown cooling system is capable of:

- cooling the heat transport system from 177°C down to 54°C, and holding the system at that temperature indefinitely
- providing core cooling during maintenance work on the steam generators and heat transport pumps when the heat transport system is drained down to the level of the headers
- of being put into operation with the heat transport system at full temperature and pressure.

The shutdown cooling system consists of two independent circuits, one located at each end of the reactor. Each circuit consists of a pump and a heat exchanger, connected between the inlet and outlet headers of both heat transport system loops. The system is normally full of $D_2O$ and isolated from the heat transport system by power operated valves.

The shutdown cooling pumps are sized so that no boiling can occur in any of the fuel channels. For normal cool-down, steam from the steam generators bypasses the turbine and flows into the turbine condenser to reduce the heat transport system temperature to 177°C in approximately 30 minutes.

For cool-down from 177°C to 77°C, the isolating valves at the reactor headers are opened and all heat transport pumps are kept running. The heat transport pumps force a portion of the total core flow through the shutdown cooling heat exchangers, where it is cooled by recirculated cooling water flowing around the heat exchanger coils.

At 77°C, the heat transport pumps are shut down and the shutdown cooling system pumps are started. The system is then cooled to 54°C. $D_2O$ can be drained down to the level just above the reactor headers, if required for maintenance of the steam generators or pumps.

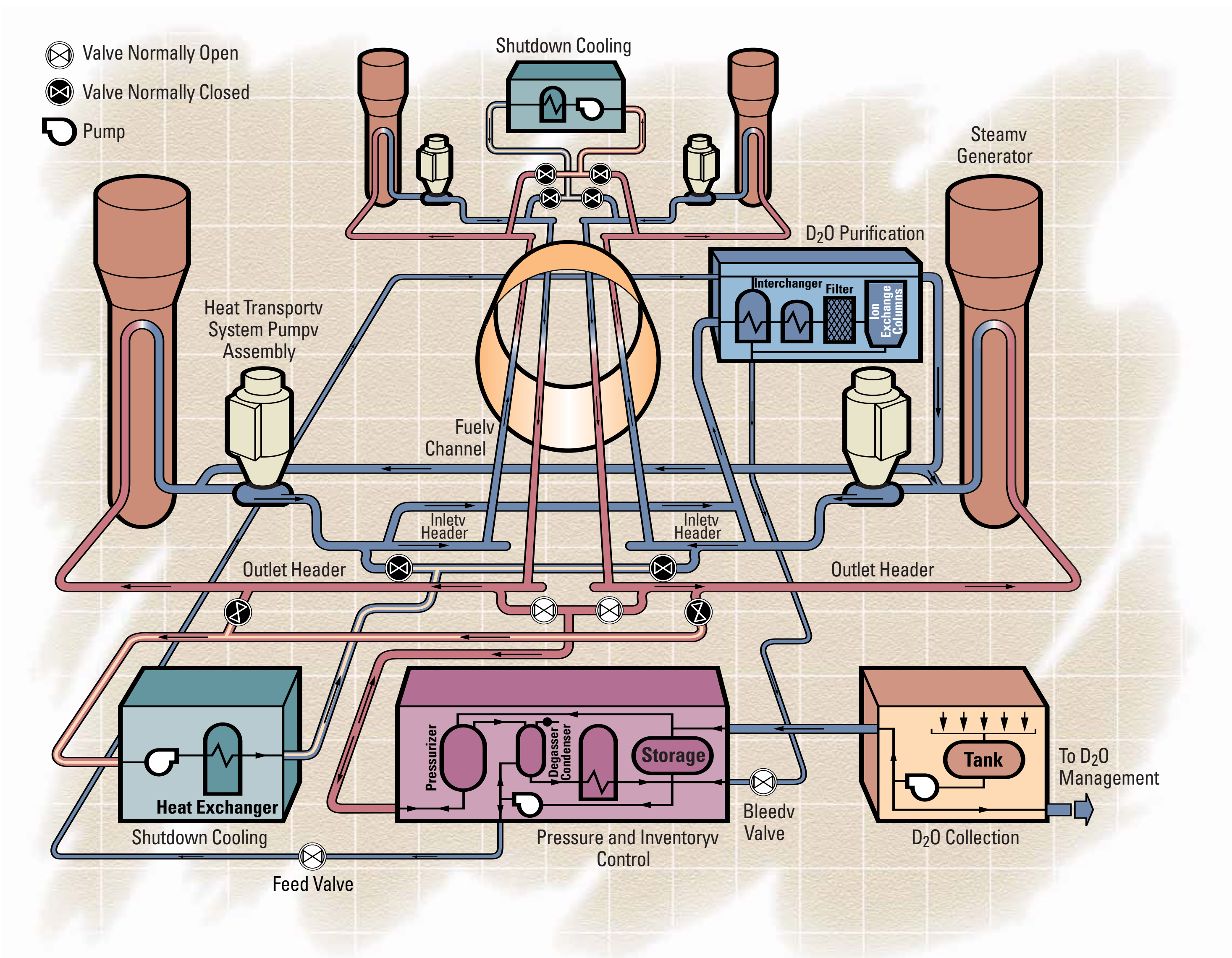
## Purification System

The heat transport purification system:

- limits the accumulation of corrosion products in the coolant by removing soluble and insoluble impurities
- removes accumulations of fine solids following their sudden release due to chemical, hydraulic or temperature transients
- maintains the pD(pH) of $D_2O$ at the required value.

Flow is taken from one reactor inlet header of each heat transport loop, passed through an interchanger, cooler, filter and ion exchange column before being returned through the interchanger to a pump inlet in each circuit. The heat transport pump provides the flow through the purification system. The interchanger-cooler combination minimizes the heat loss in the $D_2O$ purification cycle.

Isolating valves in the purification system inlet and outlet lines are provided for maintenance. The valves also allow draining of the heat transport system coolant to just above the elevation of the headers without the need to drain the purification system. These valves close automatically in the event of loss-of-coolant accident.



# 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.

## Control

Reactor Regulating System action is controlled by digital computer programs which process the inputs from various sensing devices and activate the appropriate reactivity control devices.

All measurement and control devices are located perpendicular to and between rows or columns of fuel channels, in the low pressure moderator.

## Computer Programs

The principal computer programs employed provide the following:

- reactor power measurement and calibration
- the demand power routine
- reactivity control and flux shaping
- setback routine
- stepback routine
- flux mapping routine.

## Instrumentation

The principal instrumentation utilized for reactor regulation includes:

- ion chamber system
- self-powered, in-core, flux detector system
- thermal power instrumentation.

The nuclear instrumentation systems are designed to measure reactor neutron flux, over the full operating range of the reactor. These measurements are required as inputs to the reactor regulating system and the safety systems. The instrumentation for the safety systems is independent of that utilized by the reactor regulating system.

## 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 zone control system is unable 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.

## Stepback/Setback Routines

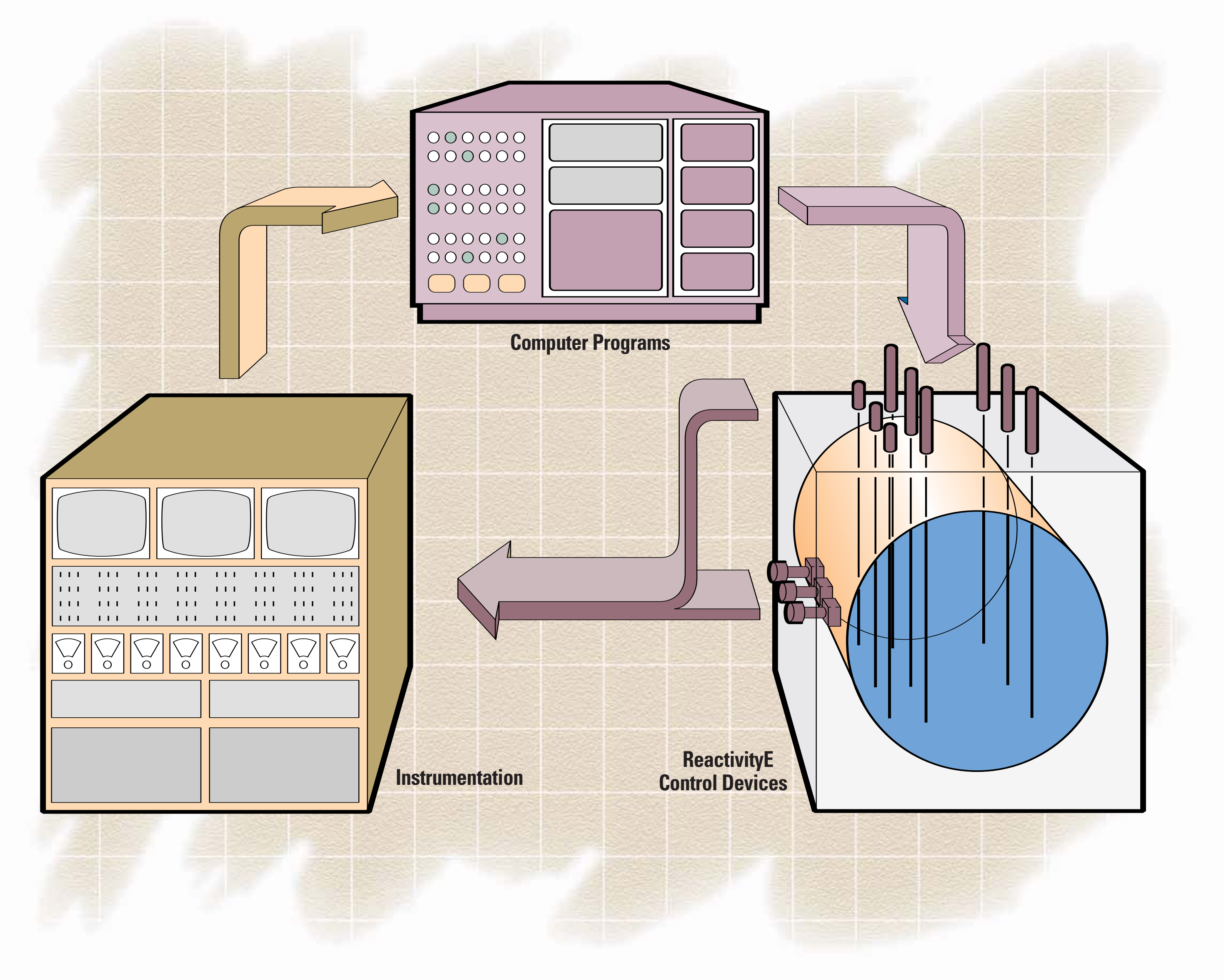
In addition to controlling reactor power to a specified setpoint, the reactor regulating system monitors a number of important plant parameters. If any of these parameters is outside specific limits, reactor power is reduced. This power reduction may be fast (stepback), or slow (setback), depending on the possible consequences of the particular parameter excursion. The power reduction/shutdown functions provided by the reactor regulating systems are completely separate and independent of the two special safety shutdown systems (see safety systems section on page 46).

* A neutron absorbing substance

## Reliability

The reliability of the reactor regulating system is of paramount importance and is achieved by:

- direct digital control from dual redundant control computers
- self-checking and automatic transfer to the standby computer on fault detection
- control programs that are independent of each other
- duplicated control programs
- duplicated and triplicated inputs
- hardware interlocks that limit the amount and rate of change of positive reactivity devices.



# Reactor Regulating System Computer Programs

## Reactor Power Measurements

For the reactor regulating system to control total reactor power and to maintain the proper power distribution in the reactor, power measurements in the reactor core are required.

In the high power range, zonal reactor power estimates based on platinum flux detectors are adjusted by comparison with thermal and vanadium flux detector measurements. In the low power range, total reactor power is determined based on measurements from uncompensated ion chambers with logarithmic amplifiers.

## The Demand Power Routine

The demand power routine serves three functions:

- selects the mode of operation of the plant
- calculates the reactor power setpoint
- calculates an effective power error that is used as the driving signal for the reactivity control devices.

## Reactivity Control and Flux Shaping

Long-term reactivity control in CANDU 6 is provided by the on-power refuelling system. Depleted fuel bundles are removed and new fuel bundles added to the core in a manner that maintains a constant long-term reactivity distribution throughout the core. The functions of short-term reactivity control and flux shaping are performed by the light water zone control absorbers, adjusters, mechanical control absorbers, and moderator poison control.

The primary method of short-term reactivity control is by varying the levels of light water in the liquid zone control system water compartments.

## Setback Routine

The 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.

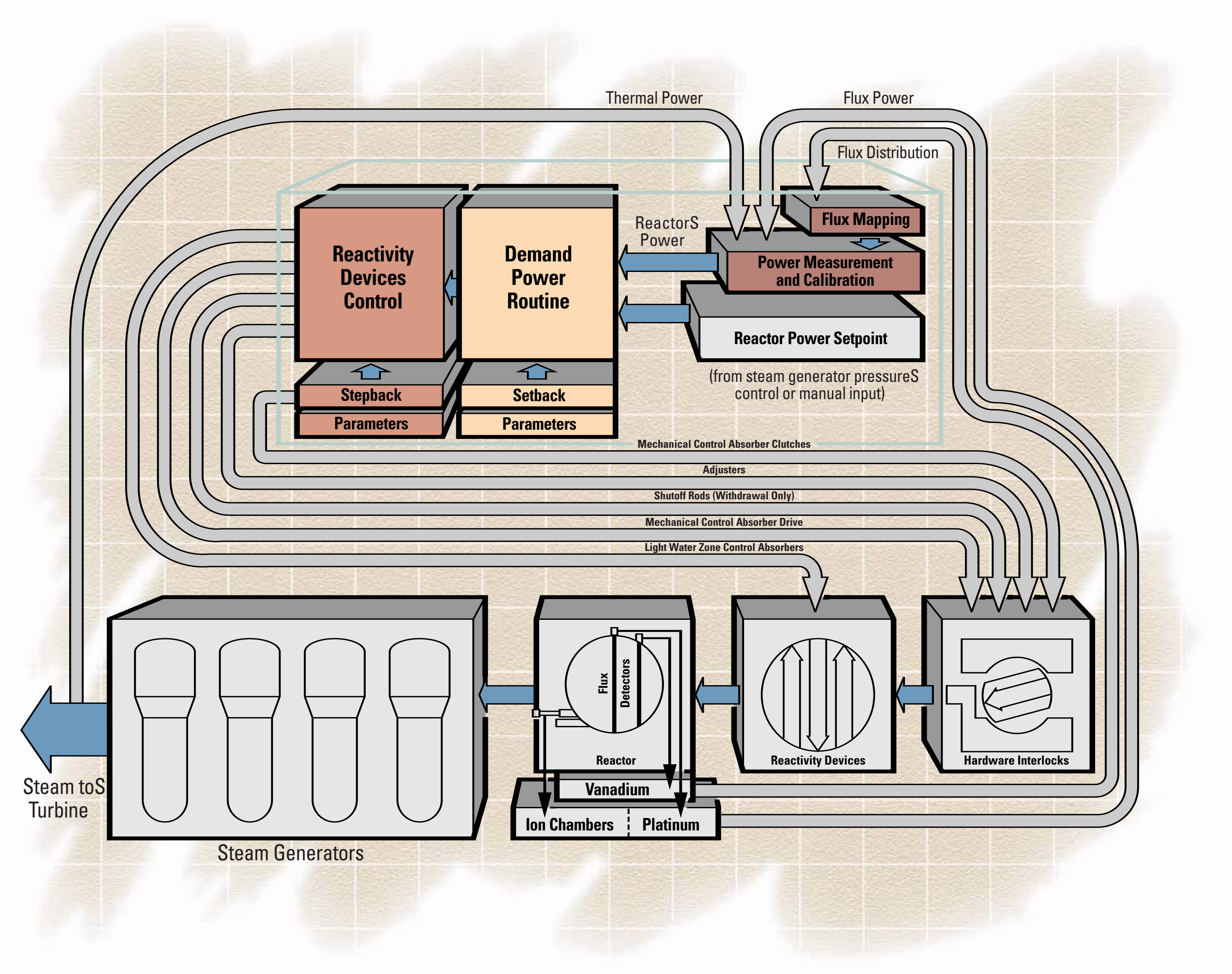
## Stepback Routine

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 Routine

The flux mapping routine uses measurements from vanadium detectors to calculate the spatial distribution of reactor power. Flux mapping serves the following functions:

- guards against locally over-rating the fuel
- helps to calibrate the zone power detectors to properly reflect the spatial flux distribution
- provides information for optimizing power output and fuel management.



Thermal Power
Flux Power
Flux Distribution
Flux Mapping
Reactor Power
Power Measurement and Calibration
Reactivity Devices Control
Demand Power Routine
Reactor Power Setpoint
(from steam generator pressure control or manual input)
Stepback
Parameters
Setback
Parameters
Mechanical Control Absorber Clutches
Adjusters
Shutoff Rods (Withdrawal Only)
Mechanical Control Absorber Drive
Light Water Zone Control Absorbers
Flux Detectors
Reactor
Reactivity Devices
Hardware Interlocks
Vanadium
Ion Chambers
Platinum
Steam to Turbine
Steam Generators

# Reactor Regulating System Instrumentation

The instrumentation systems provide the operating personnel with measurements of the reactor-neutron flux and with other core information. These systems also provide the necessary inputs for reactor regulation during start-up, shutdown, steady power and power manoeuvring conditions. Proportional counters, uncompensated ion chambers, and self-powered in-core flux detectors are used to provide continuous measurement of the reactor power from spontaneous fission level to 150 per cent full power (approximately 14 decades). A minimum overlap of one decade is provided between successive ranges of instrumentation.

## Start-Up Instrumentation

This temporary instrumentation is required during the initial reactor start-up to monitor the neutron flux over the range from the spontaneous fission flux level to the sensitivity level of the permanent ion chambers. After start-up, this instrumentation is removed and is not required for subsequent start-ups, unless a prolonged shutdown, more than 30 days, occurs. In this case, the residual flux, due mainly to photoneutron production, decays beyond the sensitivity of the ion chambers. Two sets of triplicated fission chambers are used. One set covers the very low flux range ($10^{-14}$ to $10^{-10}$ of full power). The second set covers the flux range from $10^{-11}$ to $10^{-6}$ of full power and overlaps the ranges of both the first set and the permanent ion chamber instrumentation.

## Ion Chamber System

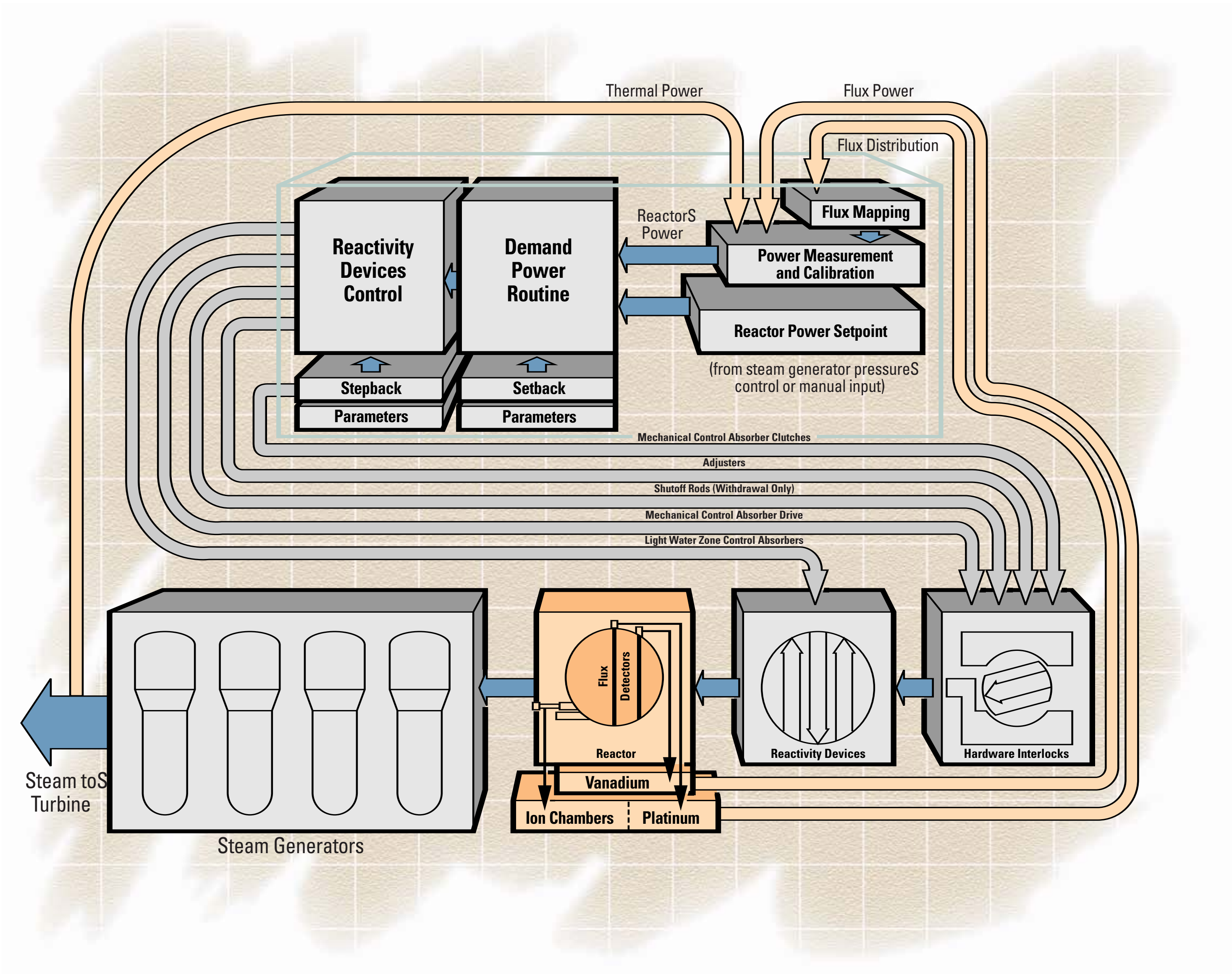
Three ion chambers are employed in the reactor regulating system, for measuring neutron flux in the range from $10^{-7}$ to 15 per cent of full power. Compensation is not required, since adequate discrimination against gamma rays is achieved by employing appropriate materials in the detector and by gamma shielding in the construction of the ion chamber housings. These ion chambers are located in housings at one side of the core. In addition to one ion chamber for the reactor regulating system, each housing also contains an ion chamber and shutter for shutdown system number 1. Each of the three channels consists of an ion chamber and amplifier unit. The solid state amplifiers upgrade the ion chamber outputs to suitable input signal levels for processing in the control computers. Three similar ion chambers, mounted on the other side of the core, provide inputs to shutdown system number 2.

## Self-powered In-core Flux Detectors

In the high power range (above 15 per cent power), self powered in-core flux detectors provide the required spatial flux information not available from the ion chambers.

Two types of in-core detectors are used in the reactor. One type uses platinum as the sensitive emitter material, while the other uses vanadium. The sheaths of both types are made of Inconel. The platinum detectors are fast-acting, sensitive to both neutrons and gamma rays, and because of their prompt response to flux changes are used in the reactor regulating system and in the two shutdown systems. The vanadium detectors are sensitive to neutrons, but because of a relatively slow response to flux changes, are used only in the flux mapping system.

The in-core flux detectors of the regulating system and of shutdown system number 1 are mounted vertically in the core, while those of shutdown system number 2 are mounted horizontally in the core.



Thermal Power
Flux Power
Flux Distribution
Reactivity Devices Control
Demand Power Routine
ReactorS Power
Flux Mapping
Power Measurement and Calibration
Reactor Power Setpoint
(from steam generator pressureS control or manual input)
Stepback
Parameters
Setback
Parameters
Mechanical Control Absorber Clutches
Adjusters
Shutoff Rods (Withdrawal Only)
Mechanical Control Absorber Drive
Light Water Zone Control Absorbers
Flux
Detectors
Reactor
Reactivity Devices
Hardware Interlocks
Vanadium
Ion Chambers
Platinum
Steam toS Turbine
Steam Generators

# Reactor Regulating System Reactivity Control Devices

## Light Water Zone Control Absorbers

Light water ($H_2O$) is a neutron absorber (poison) in the heavy water cooled and moderated CANDU 6 reactor. The liquid zone control system takes advantage of this fact to provide short-term global and spatial reactivity control in the CANDU 6 reactor core.

The liquid zone control system in the reactor consists of six tubular, vertical zone control units that span the core. For flux control the zone control units are located such that 14 zone control compartments are formed and are distributed through the core. Each zone control unit can comprise either of two or three zone control compartments. Flux (power) in each zone is controlled by the addition or removal of light water from the liquid zone control compartment in that zone.

## Mechanical Control Absorbers

Four mechanical control absorbers, mounted above the reactor, can be driven in or out of the core at variable speeds, or dropped by gravity into the core, between columns of fuel channels, by releasing a clutch. These absorbers are normally parked out of the core; they are driven in to supplement the negative reactivity from the light water zone control absorbers, or are dropped to effect a fast reduction in reactor power (stepback). When inserted, the mechanical control absorbers also help to prevent the reactor from going critical when the shutoff rods of shutdown system 1 are withdrawn, and are interlocked, in this inserted position, until the shutdown system number 1 is energized and available.

## Adjusters

Adjusters are cylindrical neutron absorbing rods. A CANDU 6 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.

Adjusters are usually fabricated from stainless steel. In some CANDU plants the adjusters are made from cobalt, and are used to produce cobalt 60 for medical and industrial purposes.

## Poison Addition and Removal

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. Addition and removal of poison is normally controlled by the operator. However, the reactor regulating system can also add gadolinium, in special circumstances.

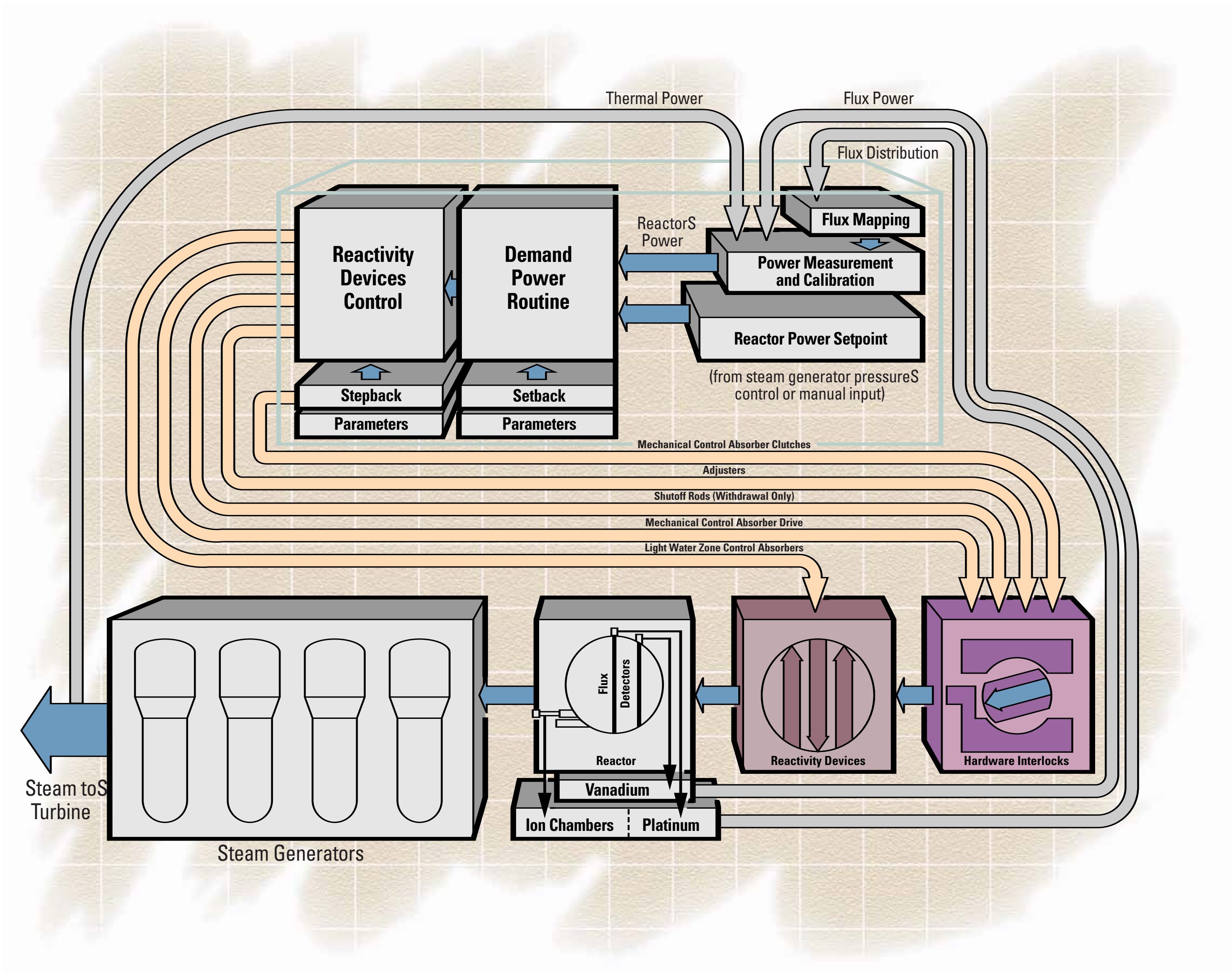
## Hardware Interlocks

The reactivity mechanisms are subject to a number of interlocks, external to the control computers, which limit the consequences of erroneous operation of these mechanisms.

When the reactor is in a tripped state (i.e., shutdown system 1 and/or shutdown system 2 inserted) these interlocks prevent withdrawal of the adjusters and mechanical control absorbers. Poison removal from the moderator is also inhibited to prevent increases in reactivity.

The interlocks remain active, preventing reactor startup, until shutoff rods are fully withdrawn and available for reactor shutdown. There are further interlocks to prevent more that a limited number of high worth adjusters from being withdrawn at the same time. This limits the rate of positive reactivity insertion.

With the exception of the light water zone controlers, which are controlled only from the computer, the reactivity control units can also be manually controlled from the control room panels.



# Feedwater and Main Steam System

## Feedwater System

Feedwater from the regenerative feedwater heating system is supplied separately to each steam generator. The feedwater is pumped into the steam generators by three 50 per cent capacity multi-stage feedwater pumps with the flow rate to each steam generator regulated by feedwater control valves. A check valve in the feedwater line to each steam generator is provided to prevent backflow in the unlikely event of feedwater pipe failure. An auxiliary feedwater pump is provided that can supply four per cent of full power feedwater requirements during shutdown conditions, or if the main feedwater pumps become unavailable.

The chemistry of the feedwater to the steam generators is precisely controlled by demineralization, deaeration, oxygen scavenging and pH control. A blowdown system is provided for each steam generator that allows impurities collected in the steam generators to be removed in order to prevent their accumulation and possible long-term corrosive effects.

*A steam generator in shipment.*

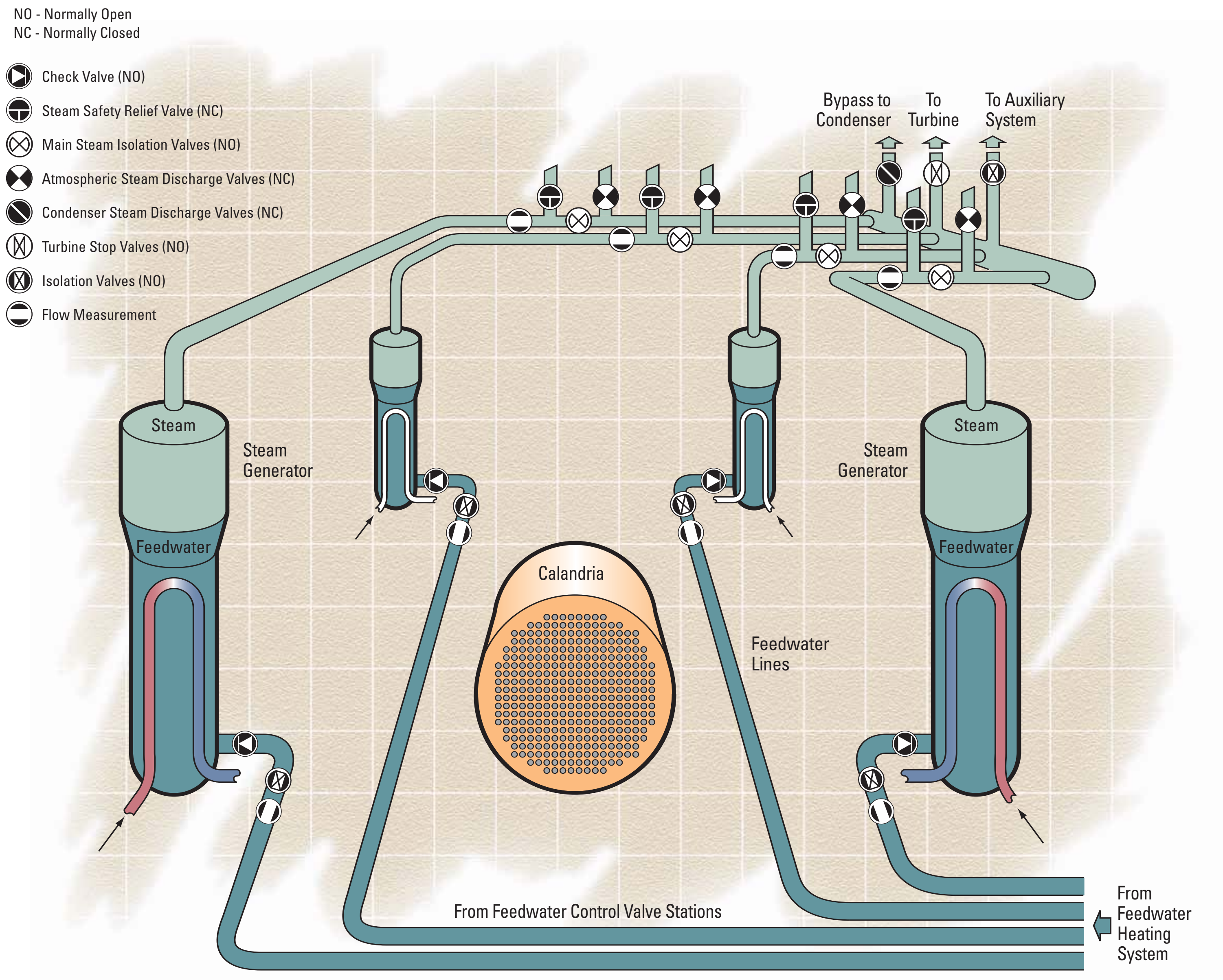
## Steam Generators and Main Steam Systems

Reactor coolant (heavy water) flows through small tubes, arranged in an inverted, vertical, U-tube bundle, within each of the four steam generators and transfers heat to the re-circulated water outside the tubes, producing steam. Moisture is removed from the steam by steam separating equipment located in the drum (upper section) of the steam generator. The steam then flows via four separate steam mains, through the reactor building wall, to the turbine where they connect to the turbine steam chest.

The steam pressure is normally controlled by the turbine governor valves that admit steam to the high pressure stage of the turbine. If the turbine is unavailable, up to 70 per cent of full power steam flow can bypass the turbine and go directly to the condenser. During this operation, pressure is controlled by the turbine bypass valves. Auxiliary bypass valves are also provided to permit up to 10 per cent of full power steam flow during low power operation.

Steam pressure can be controlled by discharging steam directly to the atmosphere via four atmospheric steam discharge valves which have a combined capacity of 10 per cent of full power steam flow. These valves are used primarily for control during warm-up or cool-down of the heat transport system.

Overpressure protection for the steam system is provided by four safety relief valves connected to each steam main.

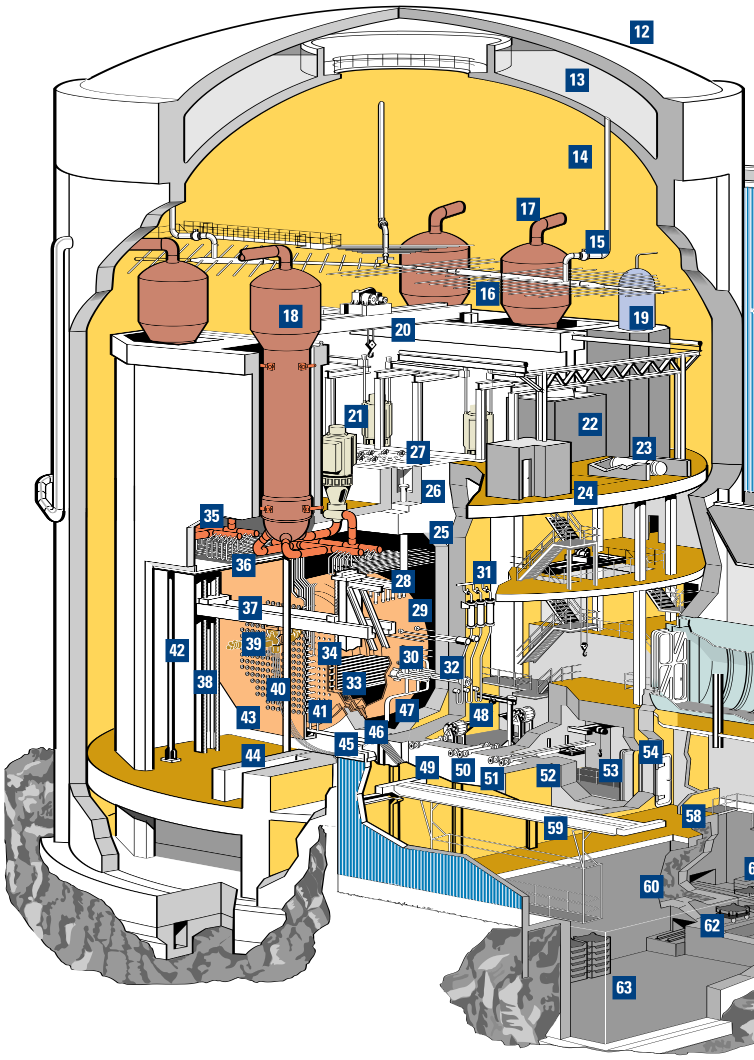

NO - Normally Open
NC - Normally Closed
Check Valve (NO)
Steam Safety Relief Valve (NC)
Main Steam Isolation Valves (NO)
Atmospheric Steam Discharge Valves (NC)
Condenser Steam Discharge Valves (NC)
Turbine Stop Valves (NO)
Isolation Valves (NO)
Flow Measurement
Bypass to Condenser
To Turbine
To Auxiliary System
Steam
Steam Generator
Feedwater
Steam
Steam Generator
Feedwater
Calandria
Feedwater Lines
From Feedwater Control Valve Stations
From Feedwater Heating System

# CANDU 6 Nuclear Power Plant

## Key to Diagram

1. Diesel room
2. Water treatment plant *
3. Crane hall
4. Turbine building
5. Turbine building crane
6. Generator
7. Condenser
8. Battery room
9. Boiler feed water tanks
10. Deaerator storage tank
11. Deaerator
12. Reactor building
13. Dousing tank
14. Dousing water supply pipes
15. Dousing water valves
16. Dousing water spray nozzles
17. Steam pipes
18. Steam generators
19. Pressurizer
20. Crane
21. Heat transport pumps
22. Bleed condenser
23. Bleed cooler
24. Hatch
25. Reactor vault
26. Pressure relief pipes
27. Reactivity mechanism deck
28. Reactivity mechanism guide tubes
29. Calandria
30. Poison injection nozzles
31. Poison tanks
32. Ion chambers
33. Fuel channel assemblies
34. End shield
35. Headers
36. Feeder pipes
37. Fuelling machine bridge
38. Bridge support column
39. Fuelling machine
40. Catenary
41. Fuel channel end fittings
42. Steam generator support column
43. Feeder pipe insulation cabinet
44. Fuelling machine vault door
45. End shield cooling
46. Fuelling machine track
47. Moderator inlet pipe
48. New fuel handling machine
49. New fuel port
50. Fuelling machine service ports
51. Rehearsal facility
52. Spent fuel port
53. Spent fuel elevator
54. Entrance to spent fuel area
55. Airlock
56. Crane
57. Spent fuel shipping area
58. Spent fuel handling area
59. Spent fuel bay gantry
60. Spent fuel bay
61. Spent fuel transfer baskets
62. Spent fuel transfer trolley
63. Spent fuel storage baskets
64. Fuelling machine maintenance area
65. Decontamination room
66. New fuel storage
67. Tool crib
68. Vapour recovery equipment
69. Office
70. Control room *
71. Control equipment room
72. Computer room

* Some items have been moved for clarity.




## Technical Data

**Reactor**

| | | |
|---|---|---|
| Type | | PHWR |
| Thermal output | (PHTS) | 2064 MW(th) |
| Coolant flow rate | (PHTS) | 7.7 Mg/s |
| Design temperature | (RIH) | 279° C |
| Design pressure | (RIH) | 12.9 MPa(g) |
| Operating temperature | (RIH) | 266° C |
| Operating pressure | (RIH) | 11.75 MPa(abs) |
| Design temperature | (ROH) | 316° C |
| Design pressure | (ROH) | 10.7 MPa(g) |
| Operating temperature | (ROH) | 310° C |
| Operating pressure | (ROH) | 10.0 MPa(abs) |

**Fuel Channels**

| | |
|---|---|
| Pressure tube inside diameter (cold, unpressurized) | 103.38 mm |
| Core Length (between calandria tubesheets) | 5.94 m |
| Number of pressure tubes | 380 |
| Coolant flow (nominal) | 24 kg/s |
| Est. pressure drop – 12 bundles | 838 kPa |

**Fuel**

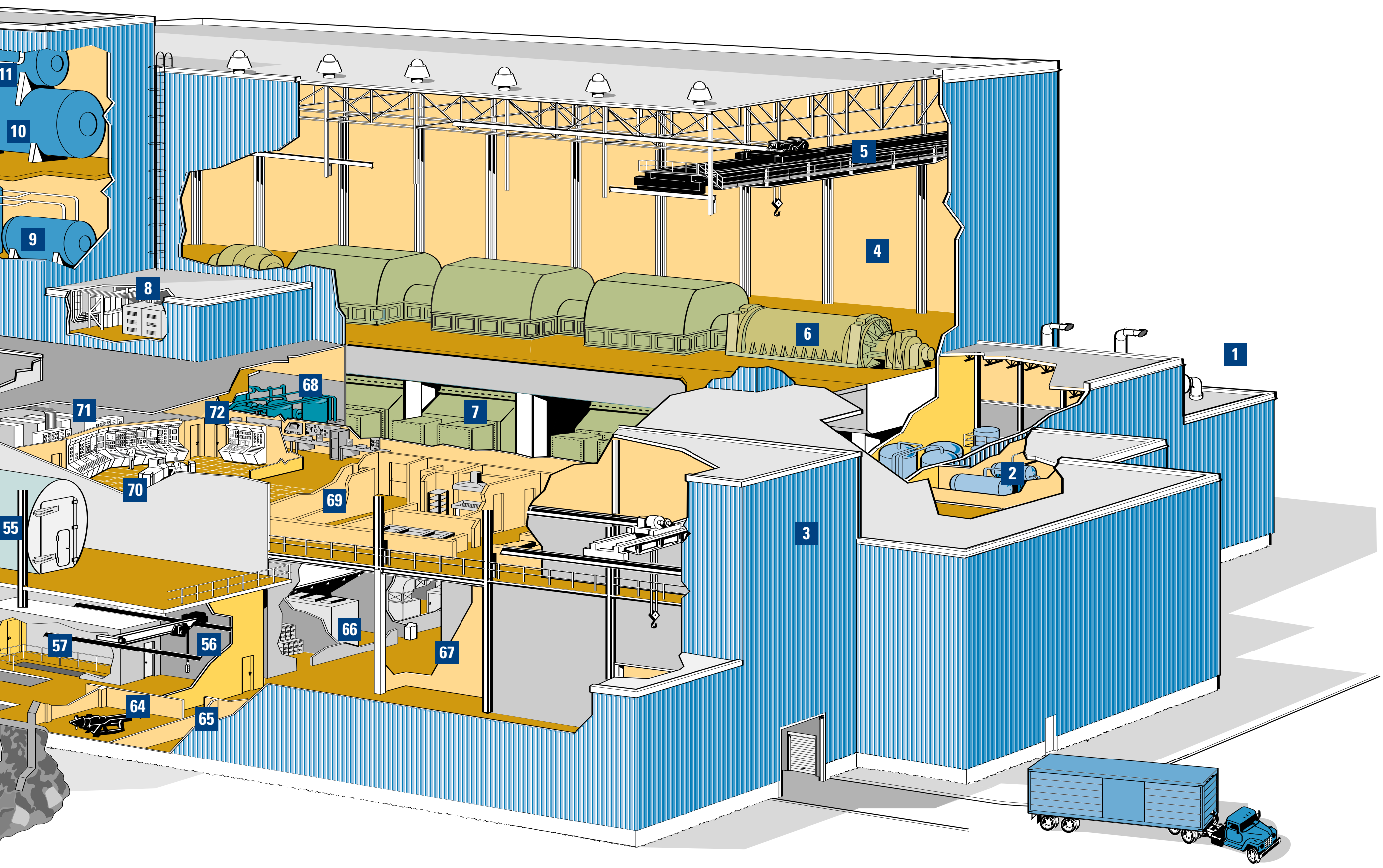
| | |
|---|---|
| Length of bundle | 495.3 mm |
| Outside dia. of bundle (over bearing pads) | 102.4 mm |
| Weight of bundle (nominal) | 23.7 kg |
| Weight of uranium per bundle (nominal) | 19.2 kg |
| Sheath outside dia. (cold) | 13.1 mm |
| Sheath thickness (average) | 0.4 mm |
| Sheath material | Zircaloy - 4 |
| Elements per bundle | 37 |
| Fuel material | Natural $UO_2$ |
| Fuel bundles in core | 4560 |
| Fuel bundles per channel | 12 |

**Heat Transport System**

| | |
|---|---|
| Number of loops | 2 |
| Primary coolant | $D_2O$ |
| Reactor inlet temperature | 266° C |
| Reactor outlet temperature | 310° C |

**Reactivity Control Units**

| | |
|---|---|
| Power control | 14 light water compartments<br>21 stainless steel rods<br>4 cadmium rods |
| Safety shutdown | 28 cadmium rods (vertical)<br>6 gadolinium nitrate injection tubes (horizontal) |




| | | |
|---|---|---|
| Materials | (out of core) | Stainless steel |
| | (in core) | zircaloy/stainless steel/cadmium |

**Steam Generators**

| | |
|---|---|
| Type, number of units | Vertical U-tube, 4 |
| Steam flow for 4 steam generators | 1033.0 kg/s |
| Steam pressure at full power | 4.7 MPa(abs) |
| Steam temperature at full power | 260° C |
| Maximum moisture | 0.25% |
| Feedwater temperature | 187° C |

**Reactor Coolant Pumps**

| | |
|---|---|
| Number | 4 |
| Motor/type | AC vertical, TEWAC induction |
| Rated capacity | 2228 l/s |
| Rated head | 215.0 m |

**Containment**

| | |
|---|---|
| Type | Prestressed cylindrical concrete |
| Inside diameter | 41.46 m |
| Height Above Grade | 46.02 m |
| Total Inside Containment | 65,500 $m^3$ |

**Turbine**

Single shaft tandem compound steam turbine directly coupled to 828 MVA generator. Steam turbine consists of one double flow high pressure cylinder, two external moisture separator/reheaters and three double flow low pressure cylinders.

**Generator**

Rated 828 MVA at 0.9 power factor and 414 kPa(g) hydrogen pressure. 1800 rpm with terminal voltage of 22,000 volts, 60 Hz.

**Condenser**

Single tube sheet shells. Each shell is connected to the three LP turbine exhausts.

Two 100% main condensate extraction pumps and one auxiliary condensate extraction pump. Three 50% main steam generator feedwater pumps and one auxiliary steam generator feedwater pump.

# Turbine Generator System

The system consists of a turbine generator unit, and associated condensing and feedwater heating systems.

Steam produced in the steam generators enters the high pressure turbine and its water content increases as it expands through this high pressure stage. On leaving this stage, the steam passes through separators where the water is removed; it then passes through reheaters where it is heated by live steam taken directly from the steam mains. The reheated steam then passes through the low pressure turbines, into the condenser where it condenses to water which is then returned to the steam generators via the feedwater heating system.

## Steam Turbine

The steam turbine is a tandem compound unit, directly coupled to an electrical generator by a single shaft. It comprises one double flow, high pressure cylinder followed by external moisture separators, live steam reheaters and three double flow, low pressure cylinders. The turbine is designed to operate with saturated inlet steam. The turbine system has main steam stop valves, governor valves, reheat intercept and emergency stop valves. All of these valves close automatically in the event of a turbine protection system trip.

*Turbine generators at Point Lepreau nuclear generating station.*

## Generator

The generator is a three-phase, four-pole machine. The generator typically operates at 1800 r.p.m. to serve 60 cycle electrical systems, and at 1500 r.p.m. to serve 50 cycle systems.

The associated equipment consists of a solid state automatic voltage regulator controlling a thyristor convertor which supplies the generator field via a field circuit breaker, generator slip rings and brush gear.

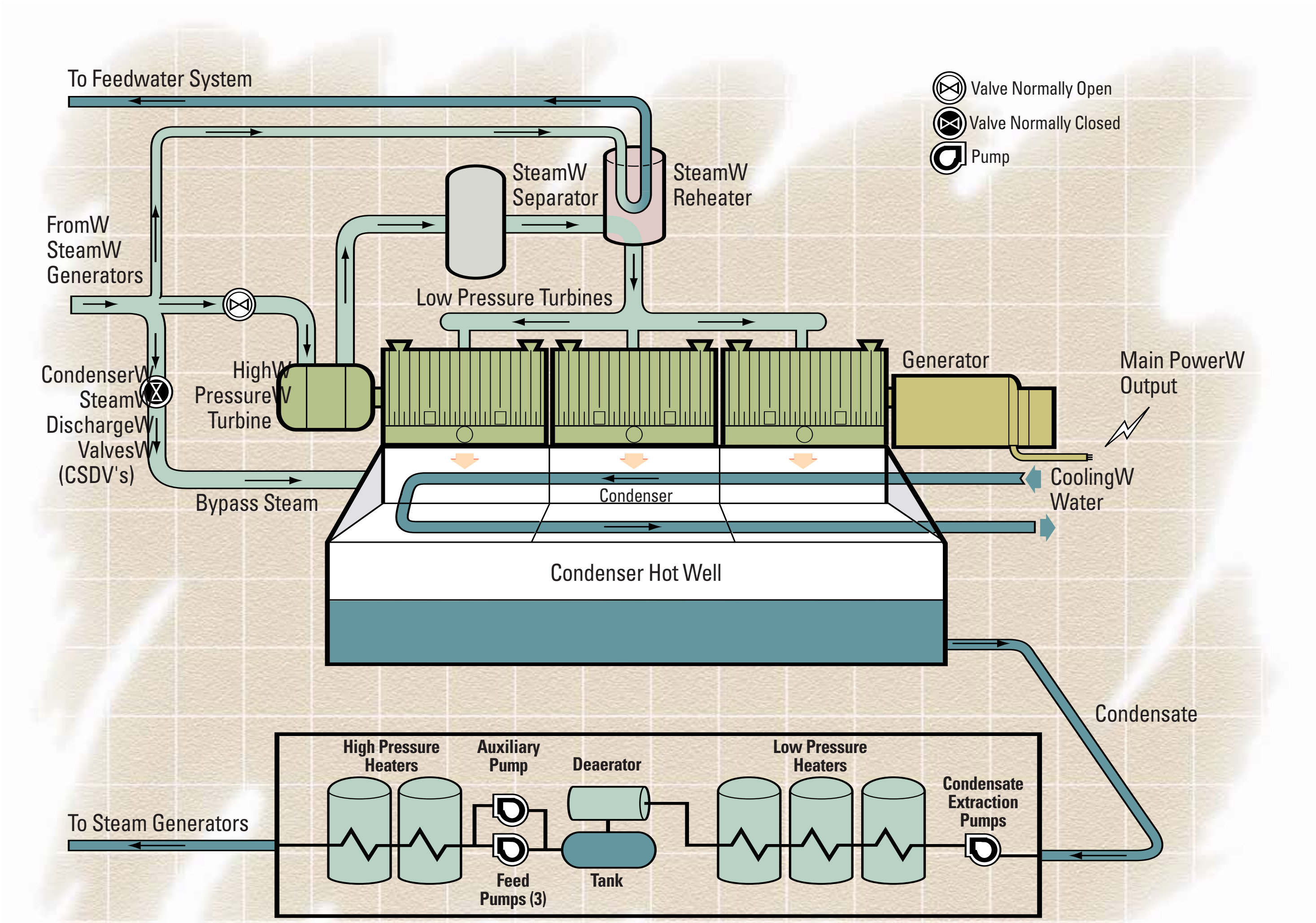
The main power output from the generator to the step-up transformer is by means of a forced air cooled, isolated phase bus duct, with tapoffs to the unit service transformer, excitation transformer and potential transformer cubicle.

## Condensing System

The turbine condenser consists of three separate shells. Each shell is connected to one of the three low pressure turbine exhausts. Steam from the turbine flows into the shell where it is condensed by flowing over a tube bundle assembly through which cooling water is pumped. The condenser cooling water typically consists of a once-through circuit, utilizing water from an ocean, lake or river. The condensed steam collects in a tank in the bottom of the condenser called the “hot well”. A vacuum system is provided to remove air and other non-condensable gases from the condenser shells. The condenser is designed to accept turbine bypass steam to permit the reactor power to be reduced from 100 per cent power to 70 per cent if the turbine is unavailable. The bypass can accept 100 per cent steam flow for a few minutes, and 70 per cent of full power steam flow continuously.

## Feedwater Heating System

On its return to the steam generators, condensate from the turbine condenser is pumped through the feedwater heating system. First it passes through three low pressure feedwater heater units, each of which contains two heaters fed by independent regenerative lines. (This permits maintenance work to be carried out on the heaters with only a small effect on the turbine generator output.) Two of the heater units incorporate drain cooling sections and the third a separate drain cooling stage. Next, the feedwater enters a deaerator where dissolved oxygen is removed. From the deaerator the feedwater is pumped to the steam generators through two high pressure feedwater heaters each incorporating drain cooling sections.



Feedwater Heating System

# Electric Power System

## Turbine Generator

The turbine generator system (described on page 30) consists of a turbine generator unit and associated condensing and feedwater systems. The power transmitted from the generator terminals to the main output transformer and the unit service transformer is at the generator nominal operating voltage.

## Main Transformer

The main transformer steps up the generator output voltage to the same level as the switchyard transmission voltage. The transformer is rated to meet the generator output requirements and site environment. It is equipped with all standard accessories and the necessary protective equipment.

## Switchyard

The switchyard, located near the turbine hall, contains the automatic switching mechanism, including the breakers and disconnects, which is the interface between the station and the power grid transmission lines. There are at least two incoming lines which are synchronized under normal conditions. However, the switchyard electrical equipment allows transmission of full station power through any one of the incoming lines.

## Unit Service Transformer

During normal station operation the station services power is supplied by both the unit service transformer and the system service transformer. However, either transformer can provide the total service load in the event of a failure of one supply. The transformer is fed from the output system of the turbine generator.

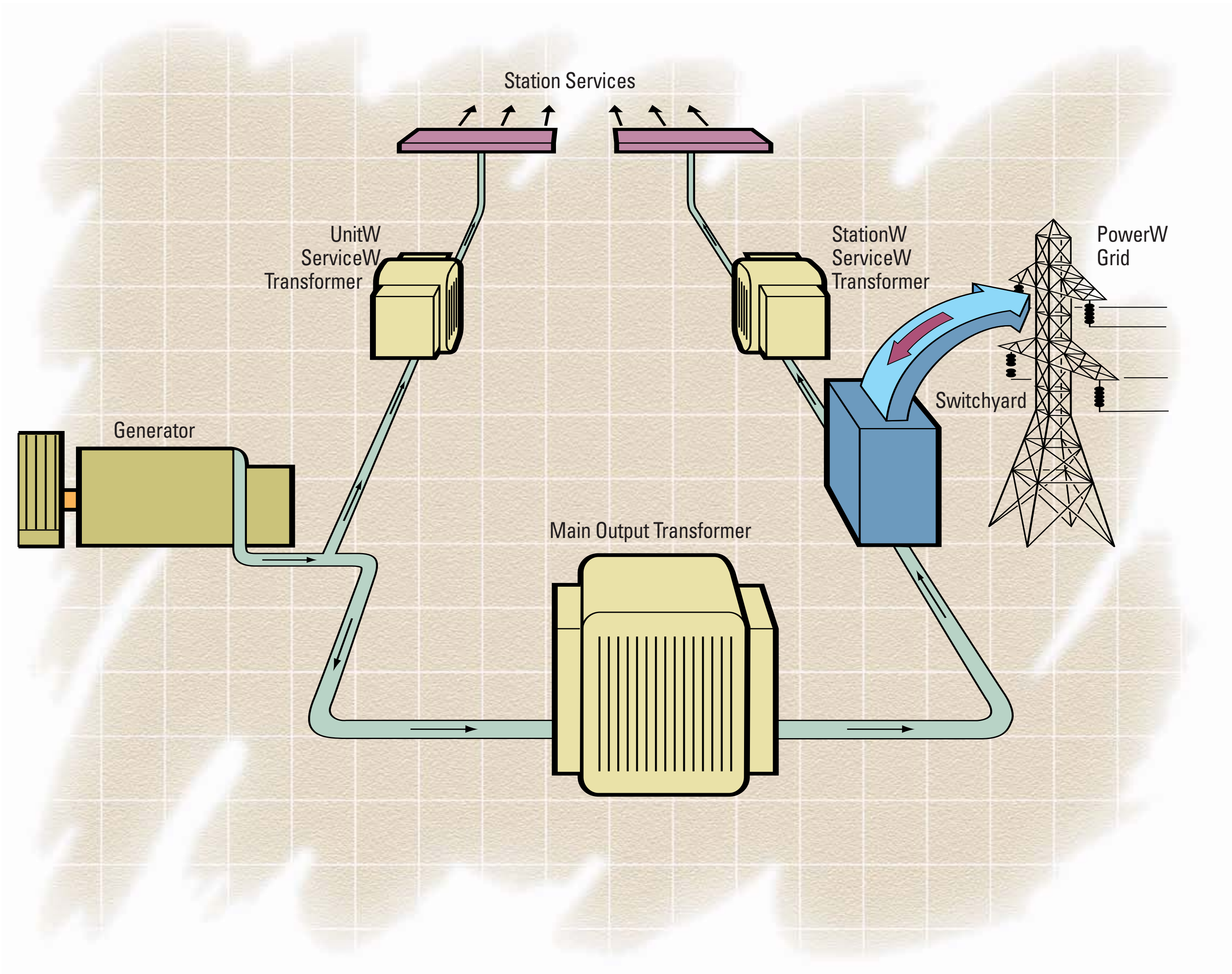
## System Service Transformer

The system service transformer is similar to the unit service transformer.

It supplies half of the plant services power requirements under normal operating conditions and is able to provide the total service load when necessary. This transformer is fed from the switchyard and supplies all plant loads during the start-up of the plant, or when the turbine generator is unavailable. It is located outdoors and feeds the station services located in the electrical equipment rooms.

Both the unit service and station service transformers are designed to automatically maintain voltage in the station services.

*Qinshan Phase III, Units 1 and 2*


Station Services
UnitW
ServiceW
Transformer
StationW
ServiceW
Transformer
PowerW
Grid
Switchyard
Generator
Main Output Transformer

# Electric Power System Station Services

## Power Classification

The station services power supplies are classified in order of their levels of reliability requirement. The reliability requirement of these power supplies is divided into four classes that range from uninterruptible power to that which can be interrupted with limited and acceptable consequences.

## Class IV Power Supply

Power to auxiliaries and equipment that can tolerate long duration interruptions without endangering personnel or station equipment is obtained from Class IV power supply. This class of power supply comprises:

- Two primary medium voltage (MV) buses, each connected to the secondary windings of the system service and unit service transformers in such a way that only one bus is supplied from each transformer.
- Two MV buses supplied from the secondary windings of two transformers on the primary MV buses. These buses supply the main heat transport pumps, feed pumps, circulating water pumps, extractor pumps and chillers.

Complete loss of Class IV power will initiate a reactor shutdown.

## Class III Power Supply

Alternating current (AC) supplies to auxiliaries that are necessary for the safe shutdown of the reactor and turbine are obtained from the Class III power supply with a standby diesel generator back-up. These auxiliaries can tolerate short interruptions in their power supplies. This class of power supply comprises:

- Two medium voltage buses supplied from the secondary windings of the two transformers on the Class IV primary MV buses. These buses supply power to the pumps in the service water system, emergency core cooling system, moderator circulation system, shutdown cooling system, heat transport system feed lines, steam generator auxiliary feed line, and the air compressors and chillers.
- A number of low voltage buses.

## Class II Power Supply

Uninterruptible alternating current (AC) supplies for essential auxiliaries are obtained from the Class II power supply, which comprises:

- Two low voltage AC three phase buses which supply critical motor loads and emergency lighting. These buses are each supplied through an inverter from a Class III bus via a rectifier in parallel with a battery.
- Three low voltage AC single phase buses which supply AC instrument loads and the station computers. These buses are fed through an inverter from Class I buses, which are fed from Class III buses via rectifiers in parallel with batteries.

In the event of an inverter failure, power is supplied directly to the applicable low voltage bus and through a voltage regulator to the applicable instrument bus. If a disruption or loss of Class III power occurs, the battery in the applicable circuit will provide the necessary power without interruption.

## Class I Power Supply

Uninterruptible direct current (DC) supplies for essential auxiliaries are obtained from the Class 1 power supply, which comprises:

- Three independent DC instrument buses, each supplying power to the control logic circuits and one channel of the triplicated reactor safety circuits. These buses are each supplied from a Class III bus via a rectifier in parallel with a battery.
- Three DC power buses which provide power for DC motors, switchgear operation and for the Class II AC buses via inverters. These DC buses are supplied from Class III buses via a rectifier in parallel with batteries.

## Automatic Transfer System

To ensure continuity of supply, in the event of a failure of either the unit or system power, an automatic transfer system is incorporated on the station service buses.

Transfer of load from one service transformer to the other is accomplished by:

- A manually initiated transfer of power under normal operating conditions, or an automatically initiated transfer for mechanical trips on the turbine.
- A fast open transfer of power, supplied automatically to both load groups of the class IV power supply system, when power from one transformer is interrupted. This fast transfer ensures that the voltage and phase difference between the incoming supply and the residual on the motors has no time to increase to a level that would cause excessive inrush currents.
- A residual voltage transfer, comprising automatic closure of the alternate breaker after the residual voltage has decayed by approximately 70 per cent. This scheme is time delayed, may require load shedding and could result in reactor power cut-back. It is provided as a back-up to the above transfers.

## Station Battery Banks

The station battery banks are all on continuous charge from the Class III power supply and in the event of a Class III power disruption will provide power to their connected buses.

## Standby Generators

Standby power for the Class III loads is supplied by two (or more) diesel generator sets, housed in separate rooms with fire resistant walls. Each diesel generator can supply the total safe shutdown load of the unit. The Class III shutdown loads are duplicated, one complete system being fed from each diesel generator. In the event of failure of Class IV power, the two diesel generators will start automatically.

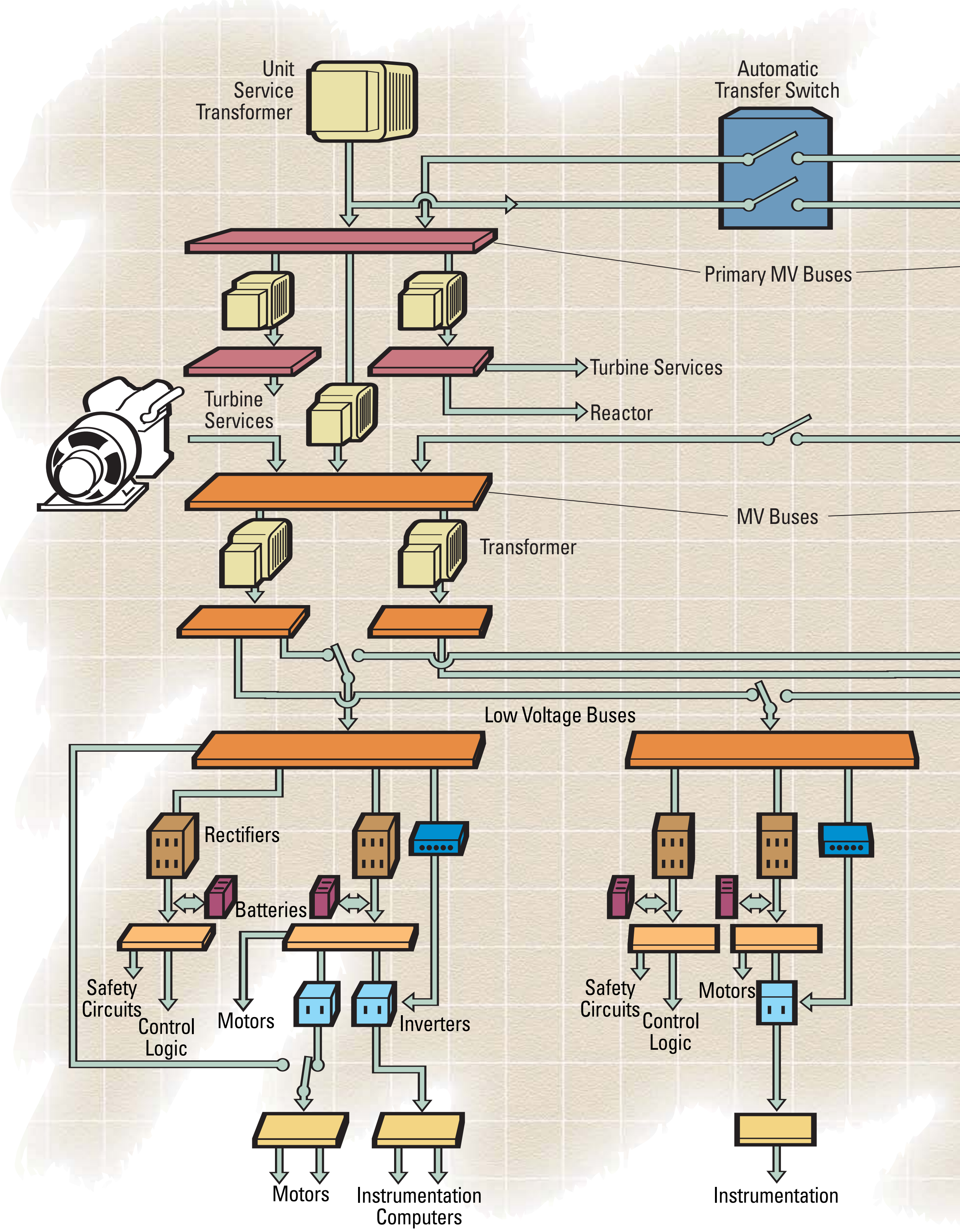
The generators can be up to speed and ready to accept load in less than two minutes. The total interruption time is limited to three minutes. Each generator automatically energizes half of the shutdown load through a load sequencing scheme. There is no automatic electrical tie between the two generators, nor is there a requirement for them to be synchronized. In the event of one generator failing to start, the total load will be supplied from the other generator.

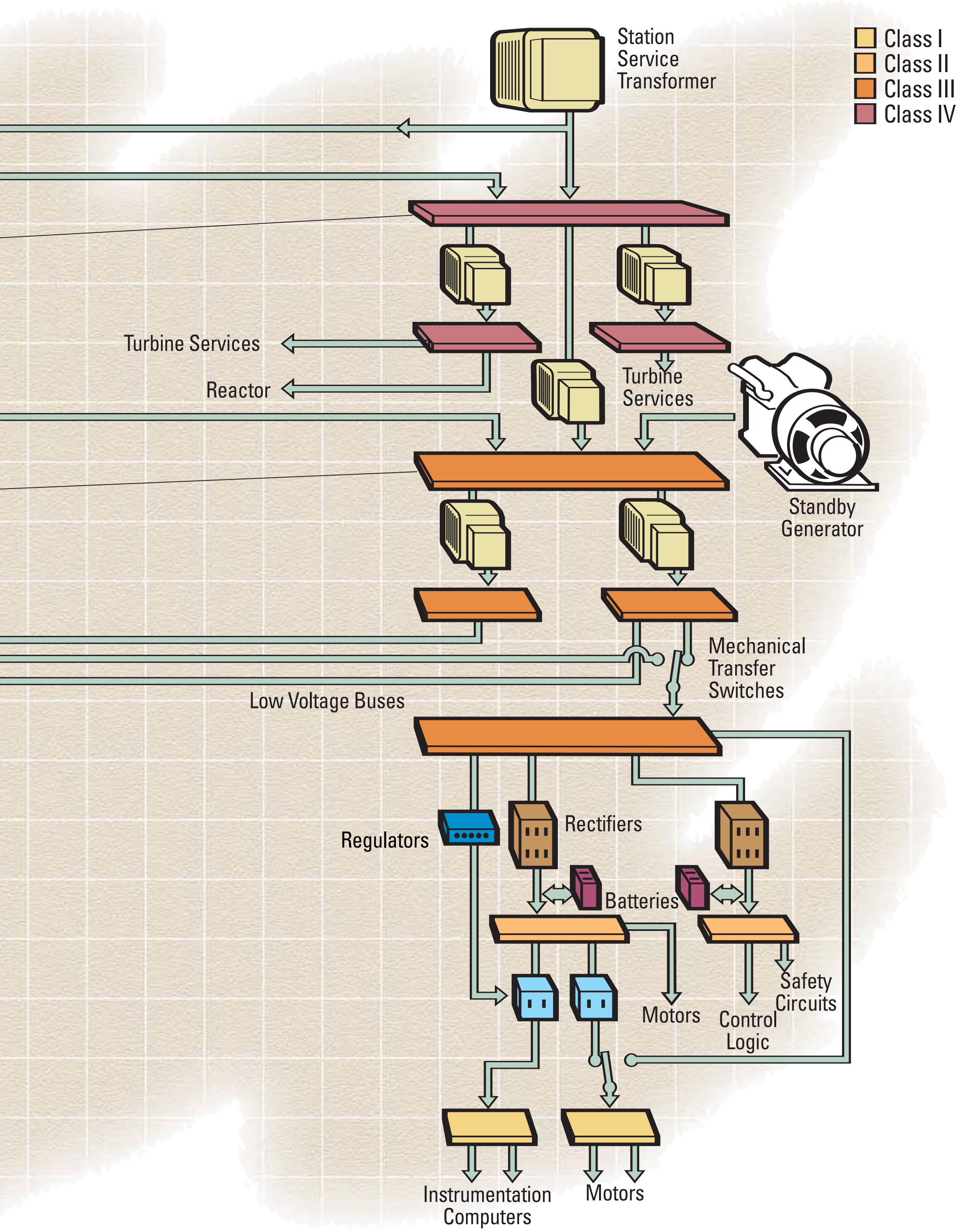
## Emergency Power Supply System

The Emergency Power Supply System can provide all shutdown electrical loads that are essential for safety.

This system and its buildings are seismically qualified to be operational after an earthquake. The system provides a backup for one group of safety systems (shutdown system number 2, emergency water supply, secondary control area) if normal electric supplies become unavailable or the main control room becomes uninhabitable. The system comprises two diesel generating sets, housed in separate fire resistant rooms, which are self-contained and completely independent of the station's normal services. There is adequate redundancy provided in both the generating distribution equipment and the loads.

# Electric Power System Station Services




Station
Service
Transformer
Class I
Class II
Class III
Class IV
Turbine Services
Reactor
Turbine
Services
Standby
Generator
Mechanical
Transfer
Switches
Low Voltage Buses
Regulators
Rectifiers
Batteries
Safety
Circuits
Motors
Control
Logic
Instrumentation
Computers
Motors

# Station Instrumentation and Control

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 transfer 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.

A spare computer is provided as a source of spare parts for the station computers. It is also used for:

- program assembling and checkout
- operator and maintainer training
- diagnosing faults in equipment removed from the station computers.

## 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

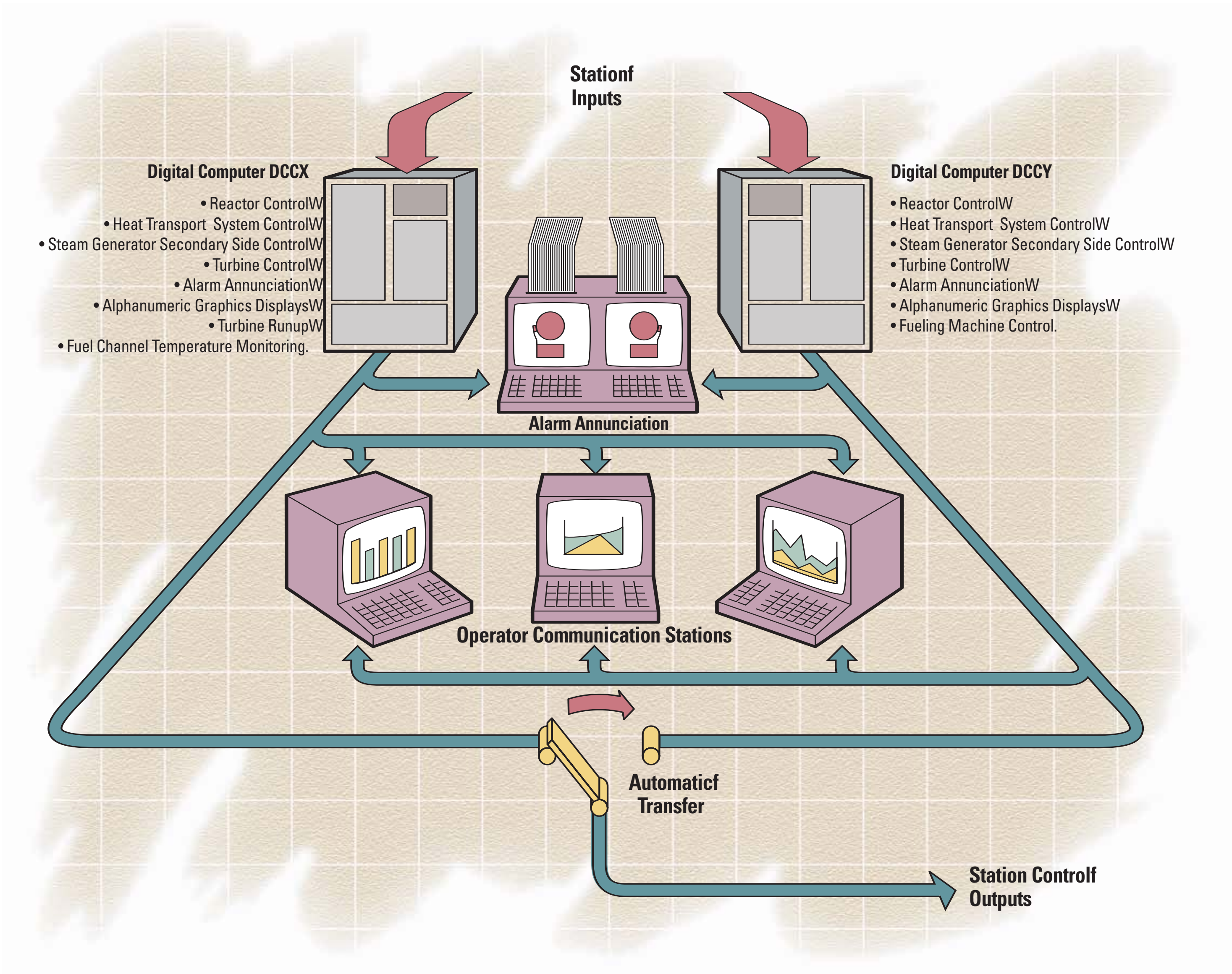
These computerized stations replace much of the conventional panel instrumentation in the control room. A number of man-machine communication stations, each essentially comprising a keyboard and colour CRT monitor, are located on the main control room panels. The displays provided on the monitors include:

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

Copies can be obtained from the line printers, 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.



Stationf
Inputs
Digital Computer DCCX
• Reactor ControlW
• Heat Transport System ControlW
• Steam Generator Secondary Side ControlW
• Turbine ControlW
• Alarm AnnunciationW
• Alphanumeric Graphics DisplaysW
• Turbine RunupW
• Fuel Channel Temperature Monitoring.
Digital Computer DCCY
• Reactor ControlW
• Heat Transport System ControlW
• Steam Generator Secondary Side ControlW
• Turbine ControlW
• Alarm AnnunciationW
• Alphanumeric Graphics DisplaysW
• Fueling Machine Control.
Alarm Annunciation
Operator Communication Stations
Automaticf
Transfer
Station Controlf
Outputs

# Station Instrumentation and Control/Instrumentation

Station instrumentation performs a number of monitoring, control and display functions. Nuclear instrumentation is provided to allow automatic control of reactor power and flux shape and to monitor local core behaviour. Conventional instrumentation provides signals for control and display of other plant variables.

The plant is automated to a level that requires a minimum of operator action for all phases of station operation. All major control loops employ the two computers as direct digital controlers. Conventional analog control instrumentation is used on smaller local loops.

The instrumentation required for the operation of the safety systems incorporates triplicated information channels that provide the system with a redundancy that ensures that single component failures will not cause spurious operation. The safety systems operate independently of the dual computers to avoid cross linked faults.

## Control Room

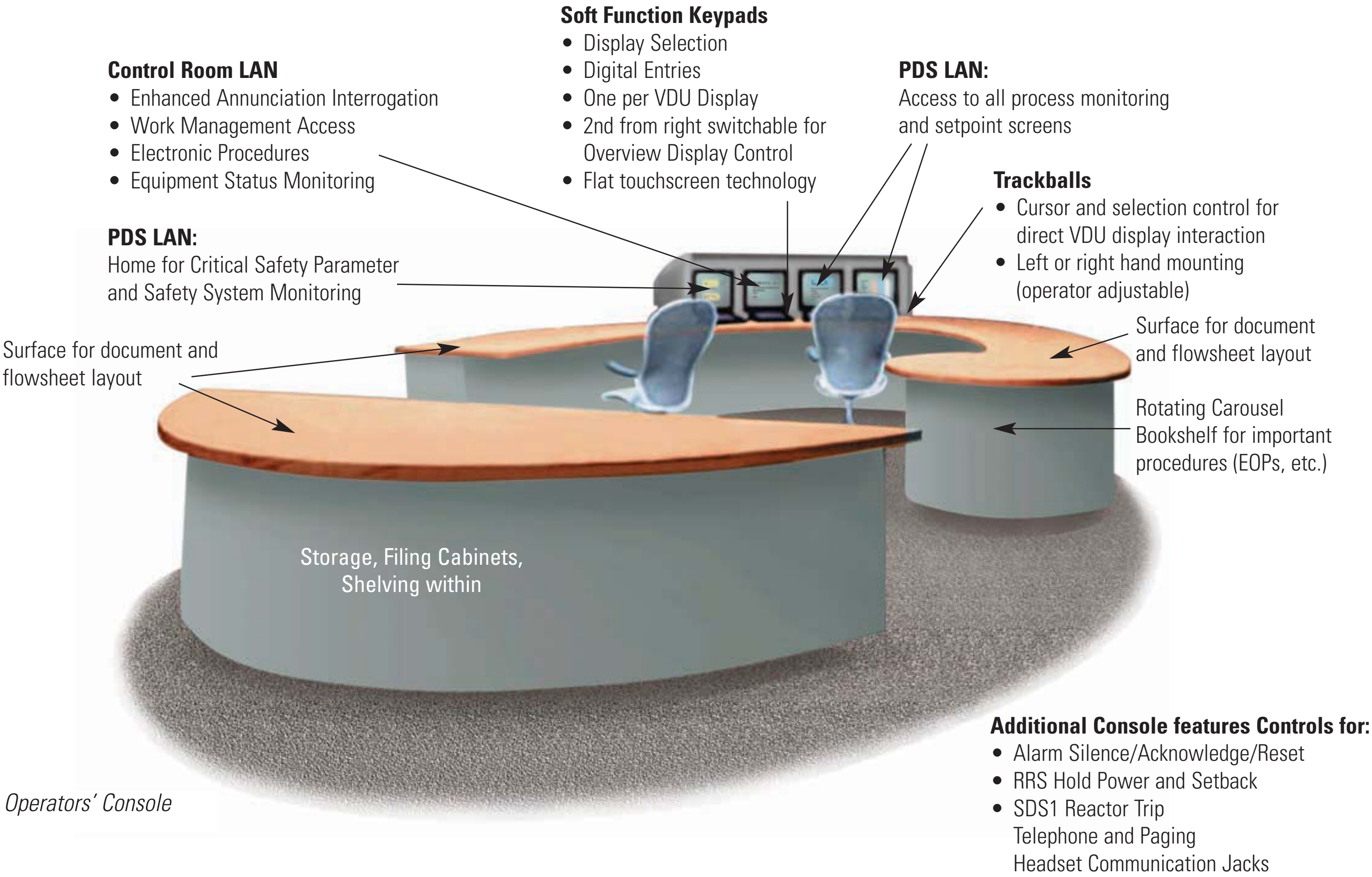
The latest CANDU 6 control room is illustrated on the opposite page. The control room features an array of panels at the perimeter with two large central display screens, and the operations console. Information is provided on the panels and at the operations console to allow the station to be safely 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.

*Control Room*




*Main Operators' Console*

Digital computers are used to perform all the control and monitoring functions of the station. The system is designed to:

- handle both normal and abnormal situations
- be capable of automatically controlling the unit at startup and at any preselected power level within the normal loading range
- be capable of automatically shutting down the unit if unsafe conditions arise
- be tolerant of instrumentation failures.

## Control Programs

The functions of the overall station control system are performed by control programs loaded in each of the two unit computers. The major control function programs are described below, but there are also programs for:

- Heat Transport System Control
- Moderator Temperature Control
- Turbine Runup and Monitoring
- Fuel Handling System Control.

## Reactor Regulation

This program adjusts the reactivity control devices to maintain reactor power equal to its desired setpoint.

## Steam Generator Pressure

This program controls steam generator pressure to a constant setpoint, by changing the reactor power setpoint (normal mode), or by adjusting the station loads (alternate mode).

## Steam Generator Level

This program controls the feedwater valves in order to maintain the water level in the steam generators at a reactor power dependent level setpoint.

## Heat Transport System Pressure

This program controls the pressurizer steam bleed valves and heaters to maintain heat transport system pressure at a fixed setpoint.

## Control Modes

### Reactor following turbine

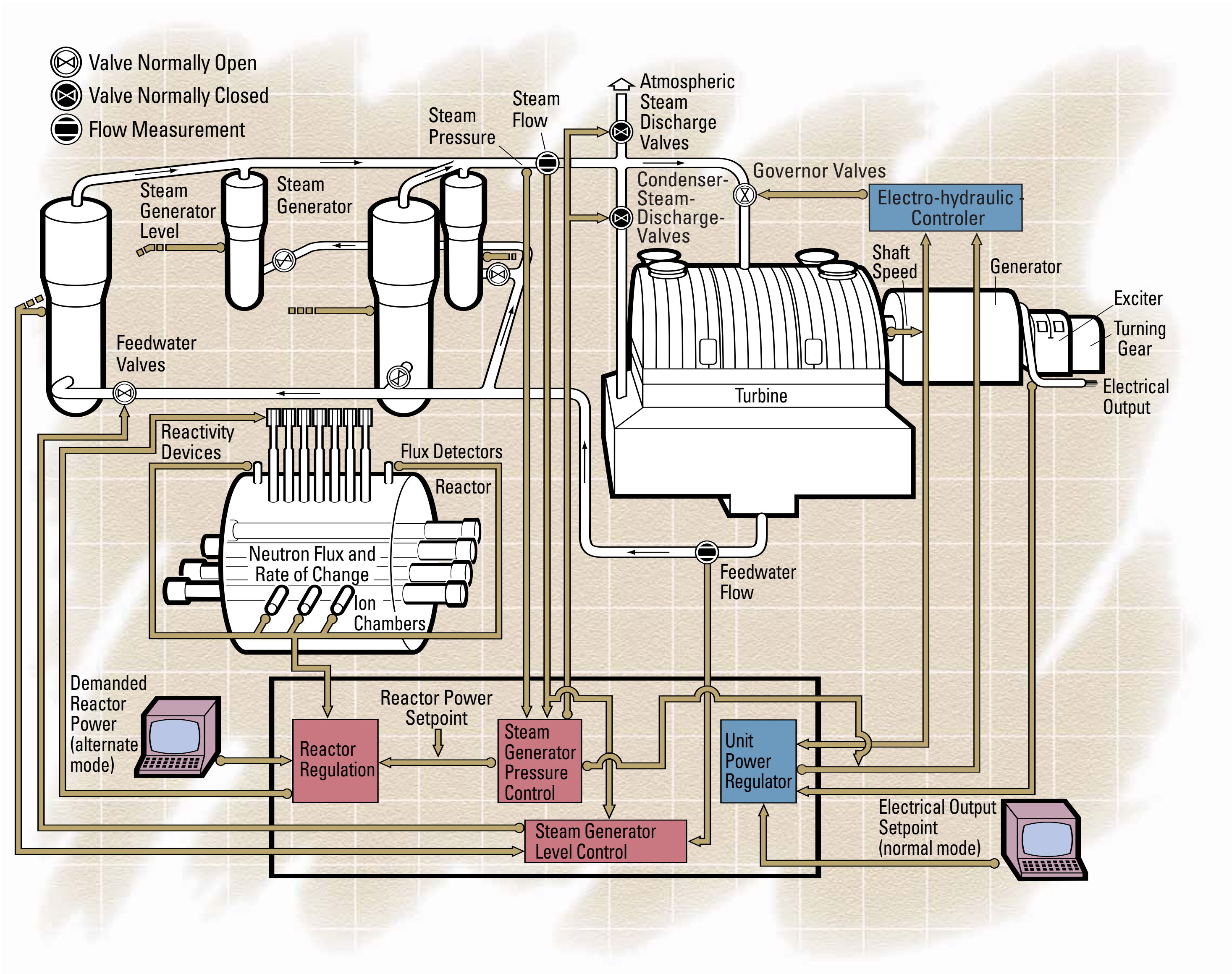
In this mode of operation the turbine-generator load is set by the operator: the steam generator pressure control program requests variations in reactor power to maintain steam generator pressure constant. This control mode is termed “reactor follows turbine” or “reactor follows station loads”.

### Turbine following reactor

In this control mode, “turbine follows reactor”, the station loads are made to follow the reactor output. This is achieved by the steam generator pressure control program adjusting the plant loads to maintain a constant steam generator pressure. This mode is used at low reactor power levels, during startup or shutdown, when the steam generator pressure is insensitive to reactor power. It is also used in some upset conditions when it may not be desirable to manoeuvre reactor power.

## Unit Power Regulation

This program manoeuvres the unit power, by adjusting the turbine load setpoint, to maintain the generator output at the level demanded by the local operator, or by a generation control signal from a remote control centre.



Valve Normally Open
Valve Normally Closed
Flow Measurement
Steam Pressure
Steam Flow
Atmospheric Steam Discharge Valves
Steam Generator Level
Steam Generator
Condenser-Steam-Discharge-Valves
Governor Valves
Electro-hydraulic Controler
Shaft Speed
Generator
Exciter
Turning Gear
Electrical Output
Feedwater Valves
Turbine
Reactivity Devices
Flux Detectors
Reactor
Neutron Flux and Rate of Change
Ion Chambers
Feedwater Flow
Demanded Reactor Power (alternate mode)
Reactor Power Setpoint
Reactor Regulation
Steam Generator Pressure Control
Unit Power Regulator
Steam Generator Level Control
Electrical Output Setpoint (normal mode)

# Site and Plant Arrangement

## Typical Site Layout

General site requirements for a nuclear power plant:

- Land must be provided for an exclusion area around the plant. A perimeter of 914 meters from all reactors, on the landward side, was provided for CANDU plants put into operation before 1990: for some newer plants this distance, known as the exclusion radius, has been reduced to less than 500 meters.
- The site should be located so as to be easily incorporated into the utility's electrical grid system.
- A relatively flat shelf of sedimentary rock a few metres above high water level is an ideal site, as both construction costs and site preparation time are reduced.
- Suitable land access by rail and/or road to transport heavy equipment. If site is on a navigable water body, water access may be used to transport the heaviest equipment.

*Point Lepreau CANDU 6 Nuclear Generating Station.*

## Buildings and Structures

### Reactor Building

The reactor building houses the nuclear reactor and auxiliaries, primary heat transport system, fuel handling equipment, and instrumentation.

The reactor building's major structural components are:

- pre-stressed concrete containment structure
- internal reinforced concrete structures
- reinforced concrete calandria vault.

The containment structure is separated from the internal structural systems. This provides flexibility in over-all building construction and no inter-dependence between the containment wall and other structures.

### Service Building

The service building houses nuclear facilities which can be located outside of the reactor building. More general service facilities, e.g., equipment maintenance shops and laboratory facilities, are located in the common area of this building.

The layout of the rooms within the service building provides for safety and efficiency of plant operation in terms of traffic patterns, radiation zoning and the routing of services between the buildings of the proposed unit. The irradiated fuel storage facility is also located in the service building.

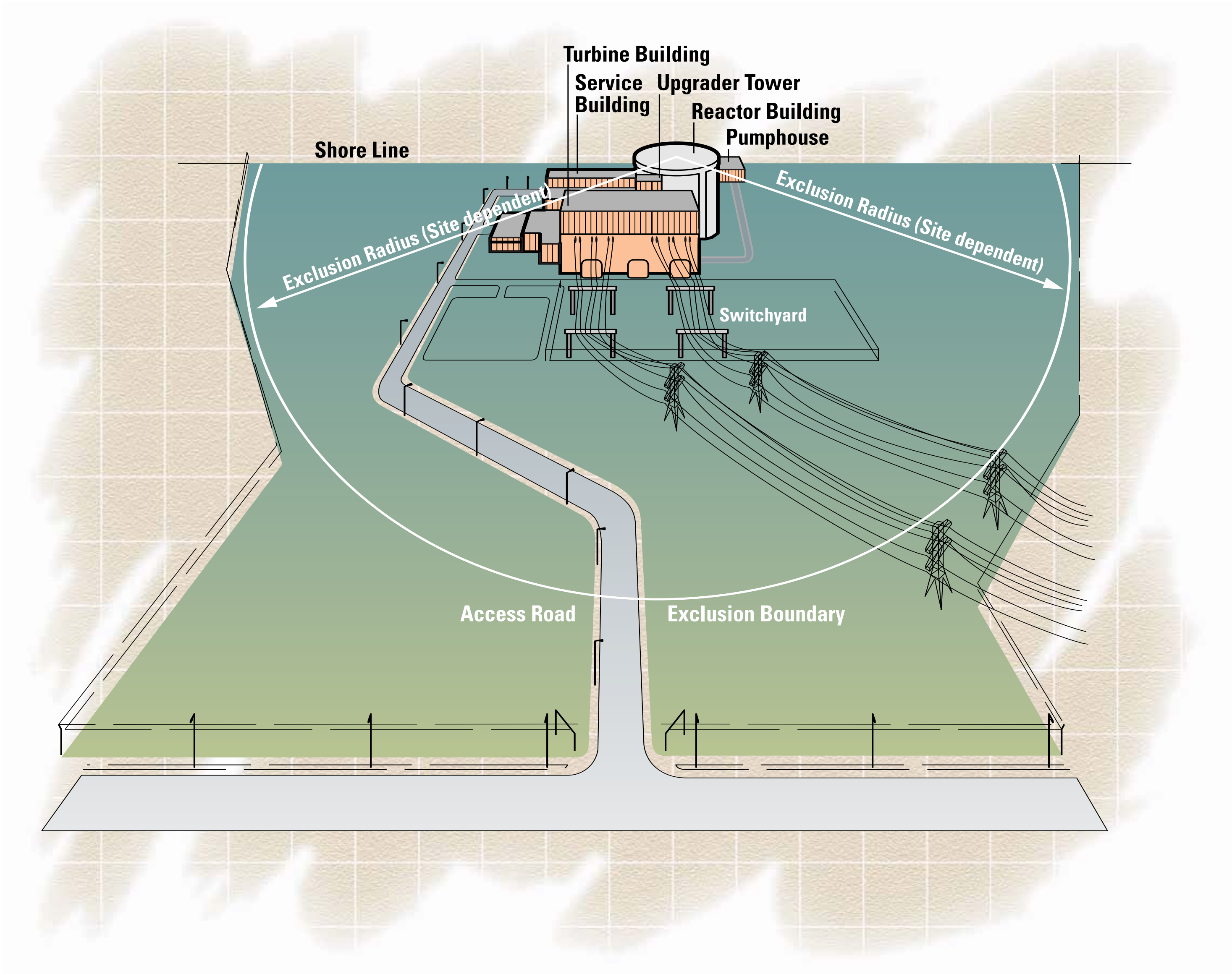
### Turbine Building

The turbine building consists of a turbine hall, auxiliaries bay and two single story annexes. Space is provided in the auxiliaries bay for the electrical power distribution equipment. Water treatment plant and diesel generators are located at grade level in the annexes.

Overhead traveling cranes are provided in the turbine hall for erection and maintenance of the turbogenerator and some of its auxiliaries. The turbine building has a reinforced concrete substructure, steel framed superstructure, steel roof trusses and insulated metal walls and roof.

## Pumphouse

The pumphouse consists of a reinforced concrete substructure containing the condenser cooling water pumps, raw service water pumps, fire pumps, screens, and racks and screen wash pumps. A steel framed superstructure provides housing for the pump motors. Roof hatches are provided for installation and maintenance of the pumps.



## Overall Requirements

Like most metals, fuel sheaths weaken at very high temperatures. Fuel sheath integrity is therefore at risk if a component failure causes the cooling of the fuel to be reduced relative to the power it produces.

If such a failure occurs, the reactor process systems can often stop its course or moderate its effects. Backing these up are special safety systems. They are independent of the process systems and of each other both functionally and physically, and are not used in the day-to-day operation of the plant. They can, if needed, shut down the reactor (shutdown systems), refill the reactor fuel channels with coolant and remove residual or "decay" heat from the fuel (emergency core cooling system) and prevent release to the environment of radioactivity which may escape from the reactor (containment systems).

Supporting these special safety systems are systems that provide alternate sources of electrical power (emergency power supply system) and cooling water (emergency water supply system).

## Shutdown Systems

There are two 'full capability' reactor shutdown systems, each able of shutting down the reactor during any postulated accident condition.

The two shutdown systems are functionally and physically independent of each other; and from the reactor regulating system.

- Functional independence is provided by utilizing different shutdown principles: solid shutoff rods for System number 1, direct liquid poison injection into the moderator for System number 2.
- Physical independence of the shutdown systems is achieved by positioning the shutoff units vertically through the top of the reactor and the poison injection tubes horizontally through the sides of the reactor.

## Post-shutdown Safety Systems

The emergency core cooling system removes decay (post shutdown) heat produced in the fuel in the event that there is a break in the heat transport system; this serves to prevent radioactivity from being released from the fuel.

The containment system confines any activity released from the fuel and heat transport system to the reactor building during an accident. Along with the other special safety systems, it ensures that the dose limits for accidents, set by the Canadian regulatory agency, the Atomic Energy Control Board, and the local regulatory authority are not exceeded.

## Safety Support Systems

These systems may be used for normal station operation and are also used to support the operation of the safety systems.

## Systems Grouping

To provide defence against low probability incidents such as local fires or missiles (turbine blades, aircraft strikes etc.), the station safety, post shutdown, and safety support systems are separated into two groups that are functionally and physically independent of each other. Each group is designed to provide the following functions:

- shut down the reactor
- to contain radioactivity in the process systems by assuring that decay heat is removed, or if the process systems are not intact, to prevent its release to the public
- supply the necessary information for post-accident monitoring.

The systems which provide these safety functions are:

- shutdown system number 1 or shutdown system number 2, to shut down the reactor
- the normal process systems, including normal electric power and service water systems; the emergency power supply and emergency water supply systems; and the emergency core cooling system, to remove decay heat
- the containment systems, to accommodate any accidental energy release and to contain the radioactivity that may be present in such a release
- the main control room or the secondary control area, for post accident monitoring.

## Shutdown System Number 1

Shutdown system number 1 is the primary method of quickly shutting down the reactor when certain parameters enter an unacceptable range. This shutdown system employs a logic system, which is independent of those utilized by shutdown system number 2 and the reactor regulating system, which senses the requirement for reactor trip and de-energizes the direct current clutches to release the absorber element portion of the shutoff units, allowing them to drop between columns of fuel channels, into the moderator. Each shutdown rod is equipped with a spring that provides an initial acceleration.

The design philosophy is based on triplicating the measurement of each variable, and initiating protection action when any two of the three trip channels is tripped by any variable or combination of variables.

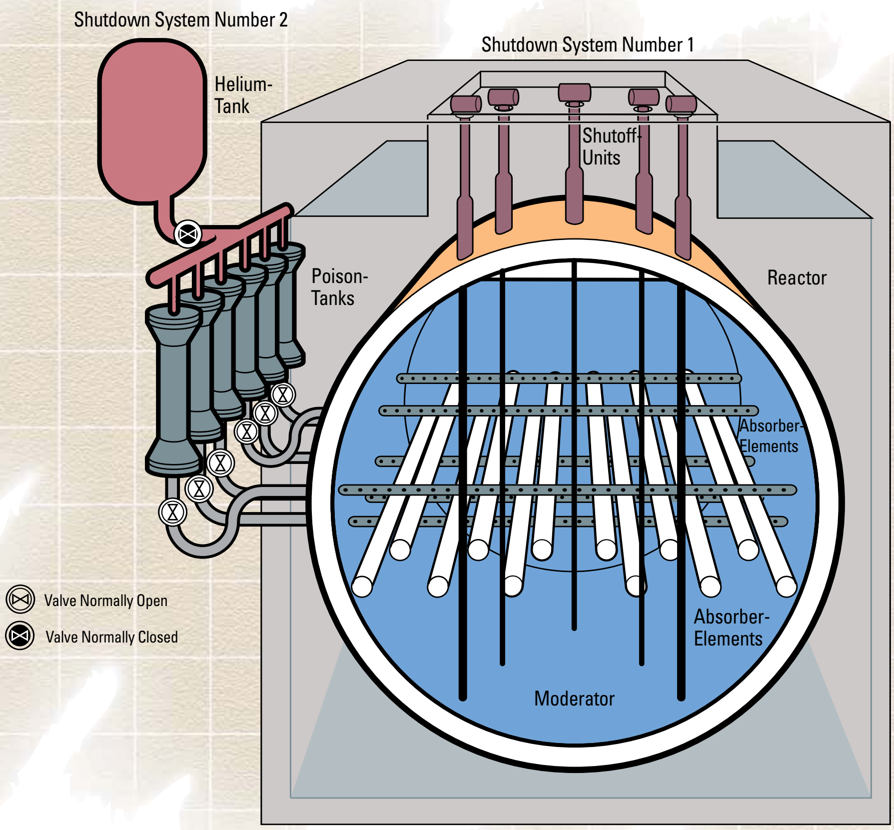
Typical variables (trip parameters) that can initiate a reactor trip through shutdown system number 1 are:

- high neutron power
- low gross coolant flow
- high heat transport pressure
- high rate log neutron power
- high reactor building pressure
- low steam generator level
- low pressurizer level
- high moderator temperature

## Shutdown System Number 2

An alternate method of quickly shutting down the reactor is the rapid injection of poison (concentrated gadolinium nitrate solution) into the moderator through horizontal tubes that enter one side of the calandria and terminate as nozzles that span the calandria, between rows of fuel channels. There are six shutdown system number 2 poison injection nozzles in a CANDU 6 reactor. This shutdown system employs an independent logic system that senses the requirement for a reactor shutdown and opens fast-acting valves located in the line between a high pressure helium tank and the poison tanks. The released helium expels the poison from the tanks, through the injection nozzles into the moderator.

Similar trip parameters used to activate shutdown system number 1 also initiate a trip condition on shutdown system number 2. The instrumentation for these trips is however physically and electrically separate.



## Emergency Core Cooling (ECCS)

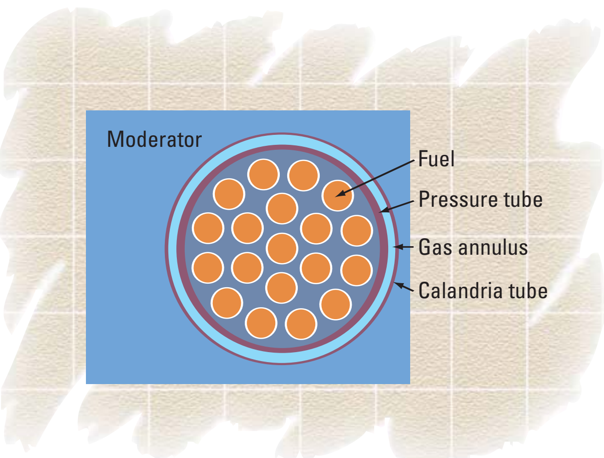
### System Operation

The emergency core cooling system provides ordinary water to the heat transport system to compensate for the heavy water coolant lost in a postulated Loss of Coolant Accident (LOCA), and recirculates and cools the heavy water/ light water mixture that collects in the reactor building floor to the reactor headers to maintain fuel cooling in the long term.

The CANDU 6 ECCS has three stages of operation: high, medium and low pressure. System operation is triggered, on a loss-of-coolant accident (LOCA), when the heat transport system pressure drops to 5.5 MPa (800 psia) and a loop isolation system (independent of ECCS logic) closes the applicable valves to isolate the two HTS loops.

### High Pressure (HP) Operation

The initial LOCA signal isolates the two HTS loops, opens the gas inlet, HP injection and the applicable heat transport system $H_2O/D_2O$ isolation valves simultaneously and also initiates the rapid cooling of the steam generators: the latter is accomplished by opening the main steam safety valves on the steam generator secondary side, and discharging steam. Emergency coolant (ordinary water) is forced from the ECCS water tanks into the ruptured HTS loop




when pressure in that loop falls below the injection pressure – 4.14 MPa (600 psia). This period to ECC injection can take about 10 seconds for a maximum pipe-size break. Coolant escaping from the ruptured circuit collects in the reactor building sump. Minimum time to empty the water (maximum break) is 2.5 minutes. The entire HP phase is initiated automatically.

When the ECCS water tanks reach a predetermined low level, the HP injection valves close automatically.

### Medium Pressure (MP) Operation

The medium pressure stage consists of water supplied from the dousing tank, and delivered to the HTS headers via the ECC pumps. The valves connecting the dousing tank to the ECC pumps are opened on the LOCA signal, while the MP injection valves open on a delayed signal. The water in the dousing tank provided for MP ECC is sufficient for a minimum of 13 minutes operation with the maximum design basis HTS break.

There are two ECC pumps each capable of providing 100 per cent of the water needs at a pressure of 150 psia. Class IV electrical supply to the ECCS pumps is backed up by Class III power and the emergency power supply system.

### Low Pressure Operation

As the dousing tank nears depletion, the valves between the reactor building floor and the ECC pumps open. Water collected in the reactor basement is returned to the heat transport system via heat exchangers, to provide long term fuel cooling.

The heat exchanger maintains the temperature of the coolant flow at about 49°C. Temperature of the water ($D_2O$ and $H_2O$) from the sump would be about 66°C at the ECC pumps.

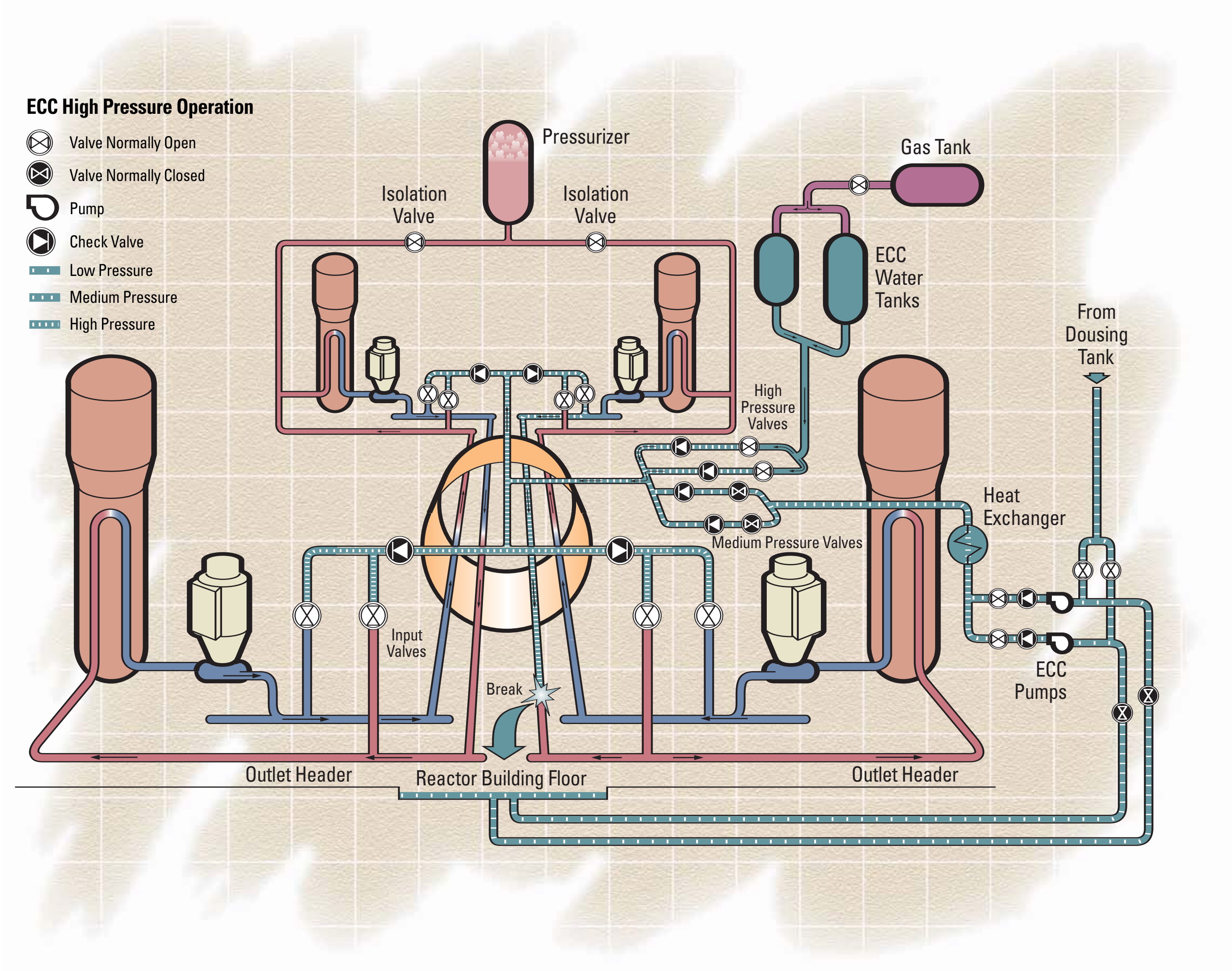
For small breaks decay heat is transferred to the steam generators and rejected via the main steam safety valves, which have a total steam flow capacity greater than that of the steam generators. For large breaks, the break itself acts as the heat sink in combination with ECC injection.

## Undamaged HTS Loop

During the ECCS operating sequence decay heat in the undamaged HTS loop is transferred to the steam generators by natural circulation. Coolant losses from this circuit prior to its isolation will be less than 20 per cent. This inventory loss can be made up by opening the isolating valves to the feed circuit with the override control in the control room or, if the circuit pressure falls below that of the injection tanks, by the ECCS.

## Backup Decay Heat Removal

In the very unlikely event that the emergency core cooling system fails during or following a LOCA, decay heat is transferred from the fuel to the moderator by radiation and conduction. The centre element of the CANDU 6 fuel bundle is only 50 mm from the cool heavy water moderator (see fuel channel section shown on previous page): hence decay heat removal from the fuel following shutdown is assured without melting the uranium dioxide, even if no coolant is present in the fuel channel.



## Containment

Containment comprises a number of systems that operate to provide a sealed envelope around the reactor systems if an accidental radioactivity release occurs from these systems. The structures and systems that form containment are:

- a lined, post-tensioned concrete containment structure
- an automatic dousing system
- air coolers
- a filtered air discharge system
- access airlocks
- an automatically initiated containment isolation system.

### Systems Operation

If a large break in the heat transport system occurred, the building pressure would rise and, at an overpressure of 3.5 kPa (0.5 psig), would initiate containment closure (if closure had not already been initiated by an activity release signal). Other sensors associated with the reactor would have caused a reactor trip and ECCS operation. The dousing system will start to operate automatically at an overpressure of 14 kPa (2 psig) and stops when the pressure drops to 7 kPa (1 psig). The operation can be continuous or cyclic, dependent on the size of the break.

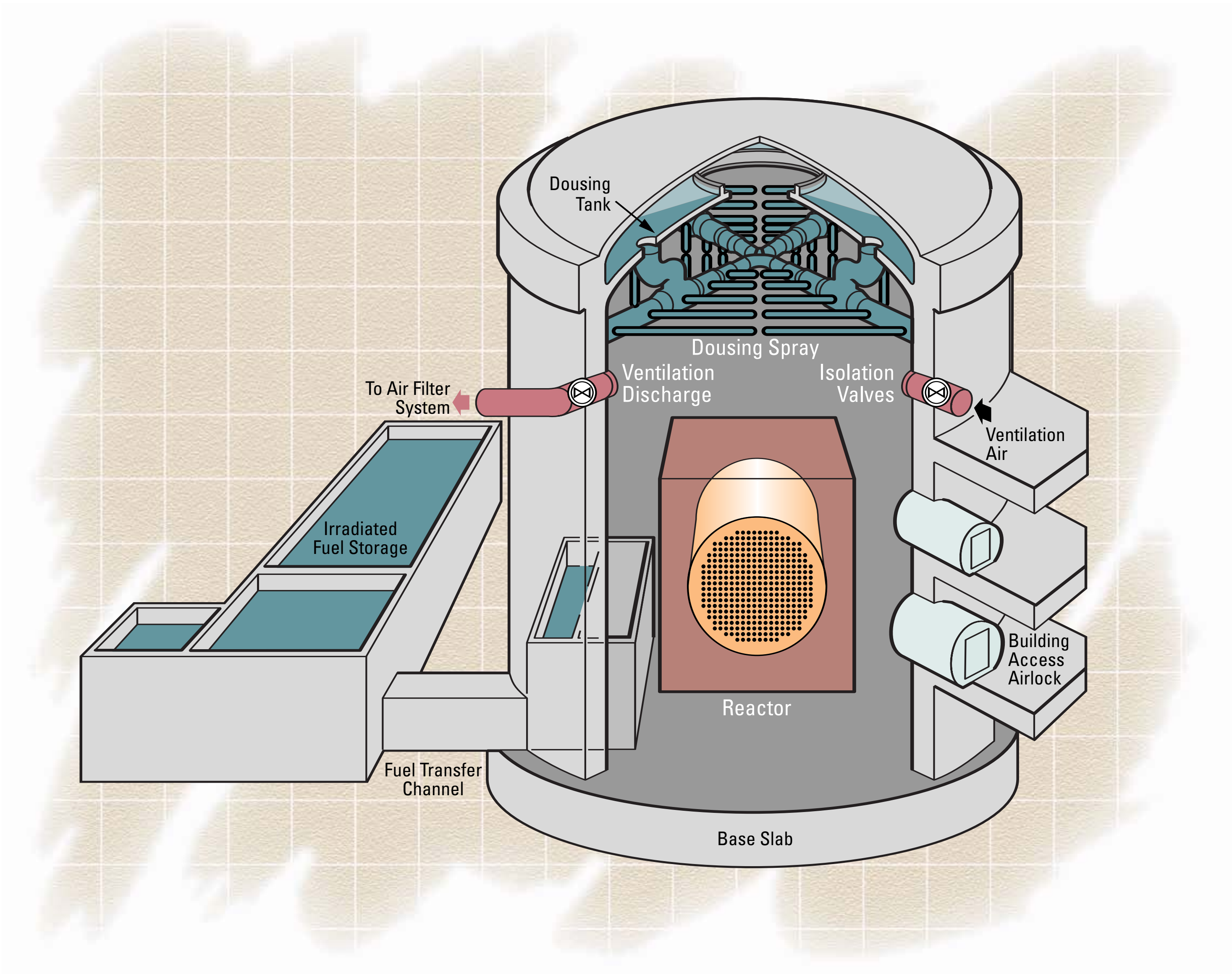
Condensation, on the building walls, and operation of the building air coolers subsequently reduce the pressure from 7 kPa (1 psig) to about atmospheric. Vapour recovery dryers initially clean up the containment atmosphere when the dewpoint has reached about 16°C. This is followed by a fresh air purge that is discharged through the dryers and reactor building ventilation system filter train, removing the particulate and radioiodine activity prior to atmospheric release.

For a small break in the heat transport system the building coolers would condense discharging heat transport system coolant and maintain the building pressure at atmospheric level.

Gamma activity, if sensed in the ventilation discharge ducts and/or vapour recovery system will initiate signals that close the containment dampers and valves to prevent activity releases.

A fission product release in a fuelling machine room, caused by damaging one or more fuel elements, would be sensed in the ventilation discharge ducts and would initiate containment isolation.

The fuelling machine room, vaults and boiler room can be purged through the reactor building ventilation system filter train to remove the particulate and radioiodine activity prior to atmospheric venting.


Dousing Tank
Dousing Spray
Ventilation Discharge
Isolation Valves
To Air Filter System
Ventilation Air
Irradiated Fuel Storage
Building Access Airlock
Reactor
Fuel Transfer Channel
Base Slab

# Heavy Water ($D_2O$) Management

The station is designed to prevent the loss of $D_2O$ from the reactor systems. Special measures are taken to recover and upgrade $D_2O$ which does escape.

Provisions ensuring optimum $D_2O$ managements are:

- use of welded joints, with the number of mechanical joints in heavy water systems is kept to a minimum
- heavy water and light water systems are segregated as much as possible
- a $D_2O$ liquid recovery system is provided
- the building containing most heavy water systems is sealed and has a minimum through ventilation flow
- 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 and drying systems so that any increase in humidity can be readily detected. 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.

## Cleanup System

The $D_2O$ cleanup system purifies the downgraded $D_2O$ collected in the station by removing most of the impurities, with the exception of $H_2O$.

The $D_2O$ cleanup system contains three ion exchange columns, one charcoal filter and two feed pumps.

The ion exchange columns remove lithium, iron and boron ions and other corrosion products. The columns also remove fission products that may be present.

The charcoal filter removes any oil present in the heavy water, as well as impurities such as amines and carbonates. The clean downgraded $D_2O$ is transferred to the $D_2O$ upgrading 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 accessible only during reactor shutdown

- fuelling machine operating areas
- boiler room, including shutdown cooler areas
- moderator room (exclusive of enclosure around equipment).

### Moderator areas

- enclosure space around moderator equipment

### Areas accessible 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.

The $D_2O$ in the holding tank is transferred, by two pumps, to either the pressure and inventory control system or, if downgraded, to the $D_2O$ cleanup system.

## $D_2O$ 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 per cent to 99 per cent $D_2O$ and upgrades them to reactor grade 99.8 per cent $D_2O$. The overhead distillate has a concentration of less than 2 per cent $D_2O$.

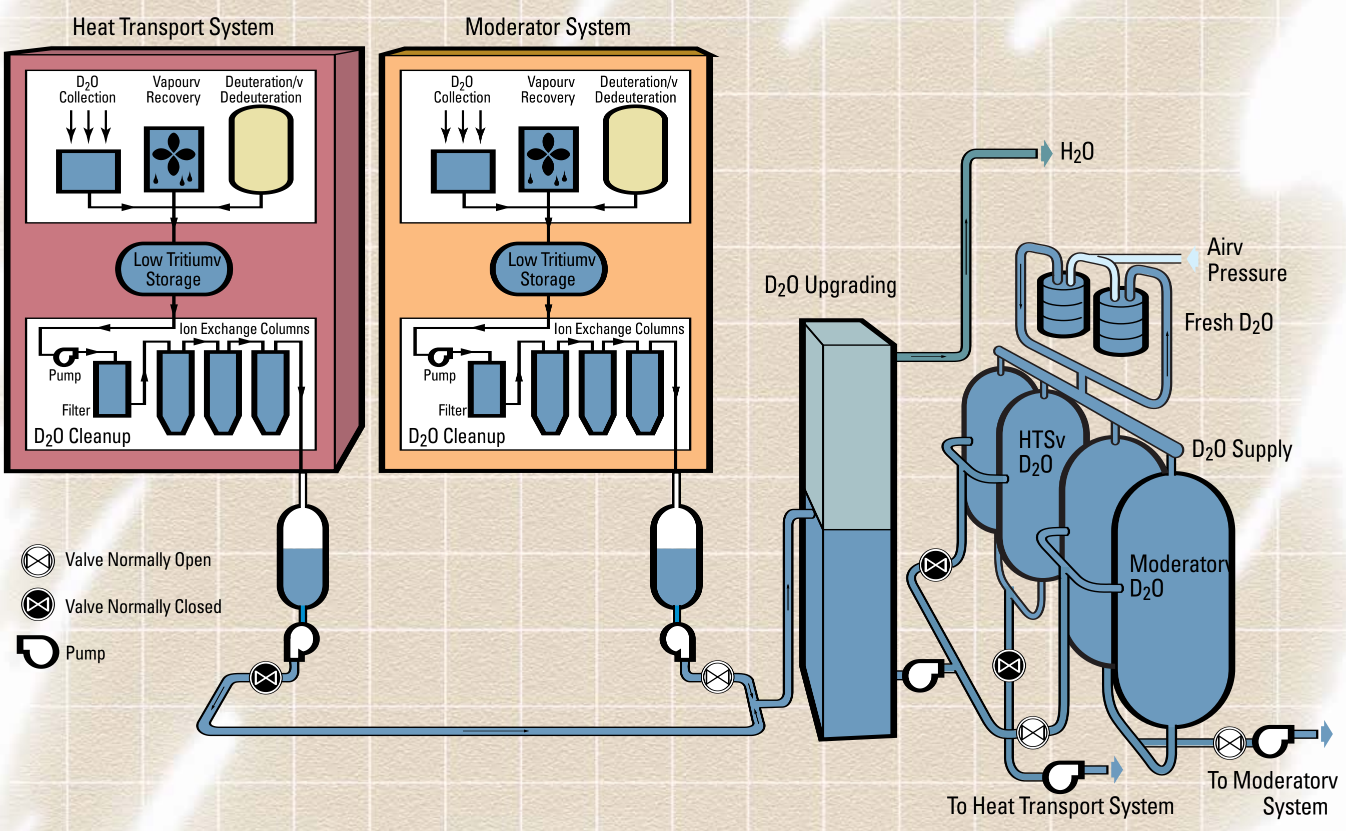
## $D_2O$ Supply System

The $D_2O$ supply system receives $D_2O$ from two sources:

- fresh $D_2O$ is received from tank trucks or drums
- upgraded $D_2O$ is received from the upgrading system.

The four storage tanks of the $D_2O$ supply system contain inventory for one moderator or one heat transport system.

The four tanks also act as a high isotopic $D_2O$ storage facility during normal reactor operation.



# Fuel Cycle Flexibility

## Overview

High neutron economy is the feature of the CANDU reactor that allows it to operate with a variety of low fissile content fuels. Several possible fuel cycles are illustrated in the following figure. These include natural uranium (NU cycle) and slightly enriched uranium (SEU cycle). Also, this feature of CANDU provides a unique synergy between CANDU and Light Water Reactors (LWRs) as there is sufficient fissile content in spent LWR fuel to provide new fuel in CANDU (Tandem cycle) as mixed uranium and plutonium oxide (MOX) fuel. Alternately, the recovered uranium from the LWR spent fuel can be used in CANDU without the plutonium (RU cycle) to operate in synergy with LWRs that recycle the plutonium.

In addition to burning the products of conventional LWR fuel reprocessing, the CANDU reactor can operate on LWR spent fuel, refabricated without chemical reprocessing (DUPIC Cycle), a process that is easier to safeguard against diversion of fissile material. This fuel cycle is particularly suitable for LWR owners and operators that do not have access to indigenous resources of uranium and conventional spent fuel reprocessing technology.

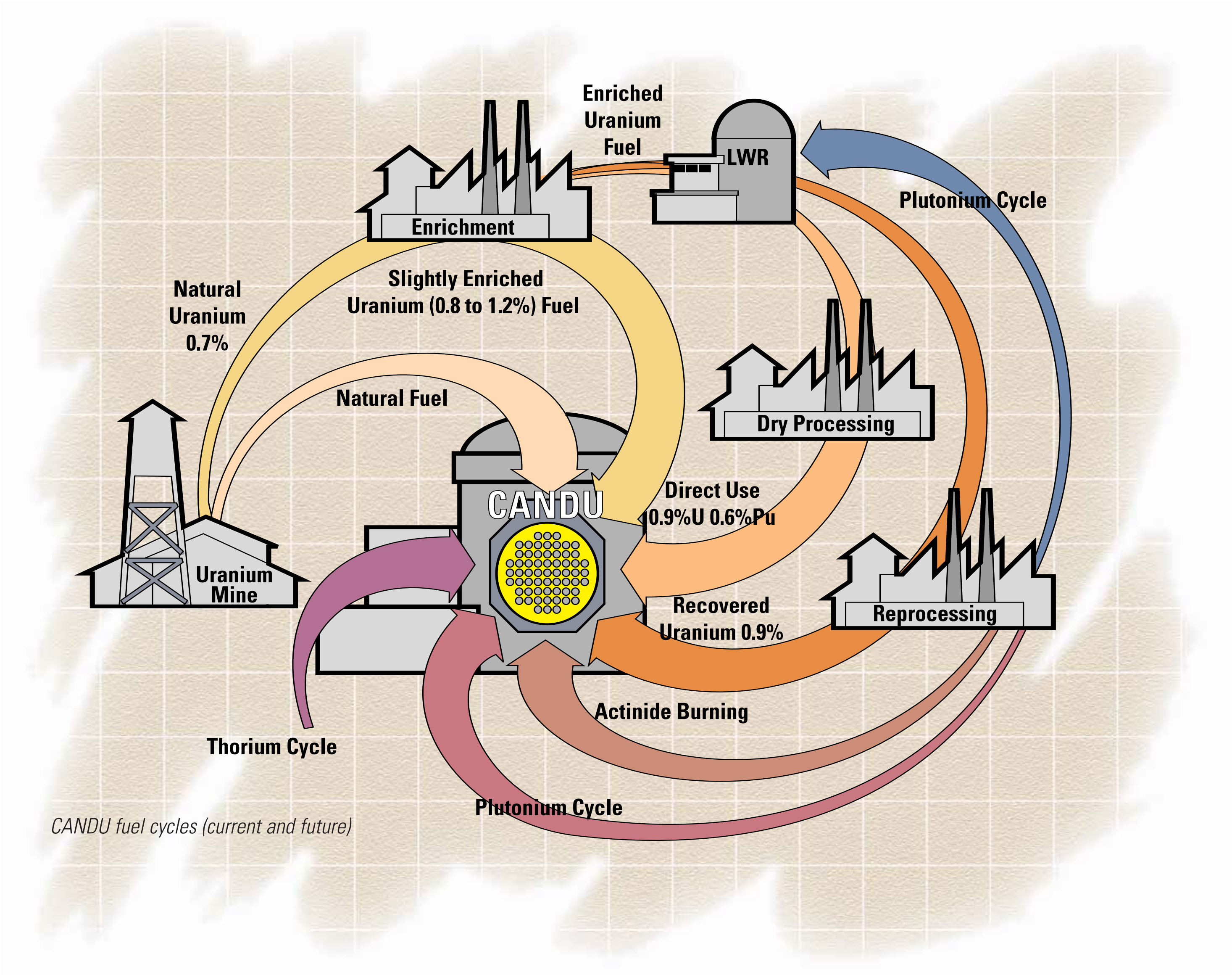
The option of recycling reprocessed LWR fuels in CANDU leads to higher energy output by 30 to 40 per cent compared with recycling using LWRs alone. Furthermore, the recycling of plutonium in the LWR is limited in capacity by otherwise unacceptable changes in the dynamic behaviour of the reactor. No such limitation exists with CANDU.

The high neutron economy of CANDU also has implications in the area of waste disposal, in particular, in the reduction of the radiotoxicity of spent fuel. There is sufficient fissile content in the mixture of plutonium and the higher actinides (a by-product of LWR spent fuel reprocessing) to be used as fuel in CANDU; no addition of uranium is required. The absence of uranium prevents the formation of plutonium. The fissile content of the transuranic mix depletes rapidly due to the lack of plutonium formation. As a result, the level of neutron flux increases rapidly in order to maintain reactor power at the rated level. The high level of neutron flux is instrumental in transmuting and annihilating the toxic material. The CANDU reactor can therefore produce energy through the destruction of toxic waste and without producing any such waste in the process, and falls into the category of "green" technology.

CANDU fuel cycle options of current interest include: natural uranium (NU), slightly enriched uranium (SEU), recovered uranium (0.9 per cent $U_{235}$) (RU), direct use of spent LWR fuel in CANDU (DUPIC), the thorium/$U_{233}$ cycles and the transuranic mix. The fuel cycle options are illustrated in the following figure, and are discussed further in the following sub-sections.

An important feature of CANDU's versatility is that alternate fuel cycles can be implemented in operating CANDU reactors, with little or no equipment change. As a result, fuel cycle benefits do not require a big investment in new designs. This versatility also allows "reversibility" of fuel cycle options. Even if a CANDU has been optimized for a particular fuel cycle, the operator can convert to alternate fuel cycles, if required. This is a major attraction of the advanced fuel cycles, since it preserves the option of national independence of enrichment supply even while using the advanced fuel.

The ability to switch to alternative nuclear fuels that become available in the global market allows CANDU to take advantage of global fuel availability, thereby reducing cost and providing increased security of fuel supply.




*CANDU fuel cycles (current and future)*

## Natural Uranium Fuel Cycle

CANDU Nuclear Power Plants now in operation or under construction utilize natural uranium (NU) fuel. The ability to burn natural uranium is a direct consequence of the excellent neutron economy provided by CANDU.

Historically, the ability to use NU fuel has had many benefits to CANDU owners, including low fuelling costs compared to other nuclear power plants, no reliance on supply of uranium enrichment or fuel reprocessing, and low uranium resource consumption.

These benefits, coupled with competitive capital cost, have made natural uranium fuelled CANDU reactors a competitive electricity supply option. Although CANDU spent fuel volumes are greater than for LWRs, the economic impact is offset by the lower specific activity and the absence of criticality concerns in handling and storage. Thus, on-site dry spent-fuel storage has been implemented with relative ease at operating CANDU plants. The dry storage technology is also applicable to the alternative fuel cycles mentioned above.

## Short Term Advanced Fuel Cycles – RU & SEU

The short-term SEU and RU cycles involve very little development and can be implemented into existing CANDU plants as no significant hardware changes are required. The choice of the enrichment level for the SEU fuel is dictated primarily by the limit placed on fuel discharge burnup.

There is a specific enrichment level (and burnup) that maximizes the utilization of the natural uranium which is the starting material for the SEU fuel. This enrichment level is approximately 1.2 wt per cent $U_{235}$. This is due to the opposing effects of enrichment and the production rate of plutonium (which is the source of more than 50 per cent of the energy generated by natural uranium CANDU fuel). The enrichment reduces the production rate of plutonium but it also extends the fuel life in the core, which tends to increase the total energy contribution of the plutonium. A burnup of 22 MWd/kgU, which requires 1.2 wt per cent enrichment to achieve, minimizes uranium resource requirement. The spent fuel volume is reduced to 33 per cent of that of the natural uranium cycle as the burnup is increased by three times.

The RU cycle essentially uses a waste product of LWR spent fuel reprocessing since only the plutonium from the spent LWR fuel is currently recycled into the LWR; Therefore the cost of the RU fuel material is potentially low. The exit burnup of this fuel in CANDU is between 14 and 18 MWd/kgU (depending on the $U_{235}$ content of the RU which varies between 0.8 to 1.0 wt per cent). The additional energy obtained in CANDU is approximately 40 per cent of initial LWR fuel burnup. The reduction in CANDU spent fuel volume with the RU cycle is approximately 50 per cent that of the natural uranium cycle.

## DUPIC Cycle

The DUPIC cycle facilitates the use of spent LWR fuel in CANDU without the need for chemical reprocessing, via relatively simple fuel refabrication technologies.

The DUPIC cycle is particularly suitable for countries that have spent LWR fuel and which do not have reprocessing technology, due to the simplified refabrication technology utilized by the DUPIC process.

The DUPIC cycle offers strategic benefits, such as security of supply and protection from uranium and enrichment price changes. The development of LWR-CANDU fuel cycles, such as DUPIC, transforms spent LWR fuel inventory from a “waste-disposal” cost into a valuable energy resource. A mix of LWRs and CANDUs incorporating the DUPIC fuel cycle would generate electricity utilizing 40 per cent less uranium resources than LWRs alone.

The DUPIC cycle has important non-proliferation advantages; fissile plutonium is never separated from the remaining heavy metals, so that no stream of material exists which could be diverted to non-peaceful use.

## Thorium Cycle

Thorium, which is abundant in many areas of the world, is a fertile material and produces a fissile material, $U_{233}$, by neutron capture. Hence, thorium can largely displace uranium in CANDU operation.

Some fissile material is required to initially (fresh core) make the reactor critical. This fissile material can be NU fuel, SEU fuel, RU fuel or DUPIC fuel. Once the process of neutron capture in thorium has started, significant quantities of $U_{233}$ are produced and fissioned during the life of the thorium fuel in CANDU. The production of $U_{233}$ is highly efficient (more so than the production of plutonium in the natural uranium cycle). There is, under optimum circumstances, almost one atom of $U_{233}$ produced per atom of $U_{233}$ destroyed. This makes the CANDU reactor a near-breeder as it breeds most of its own fuel.

There are essentially two types of thorium/$U_{233}$ cycles that can be used in CANDU, one without reprocessing spent fuel and one with reprocessing and recycling of the $U_{233}$ that is extracted. The reprocessing option results in more efficient fuel utilization but fuel cost depends on reprocessing cost. The fissile fuel production efficiency of the CANDU thorium/$U_{233}$ cycle ensures security of resources almost indefinitely.

Another advantage of the thorium/$U_{233}$ cycle is the lower radiotoxicity (by a factor of 10 to 100, compared with the uranium based cycles) of the spent fuel. This simplifies spent fuel disposal significantly. The lower radiotoxicity of the spent fuel is a result of the absence of $U_{238}$ which is the starting material for the production of the transuranic actinides, the main contributors to long-lived radiotoxicity of the spent uranium fuel.

The thorium fuel cycles are of immediate interest to countries that have thorium reserves while lacking significant uranium reserves and are of general interest to all countries as the price of uranium increases.

# Notes

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