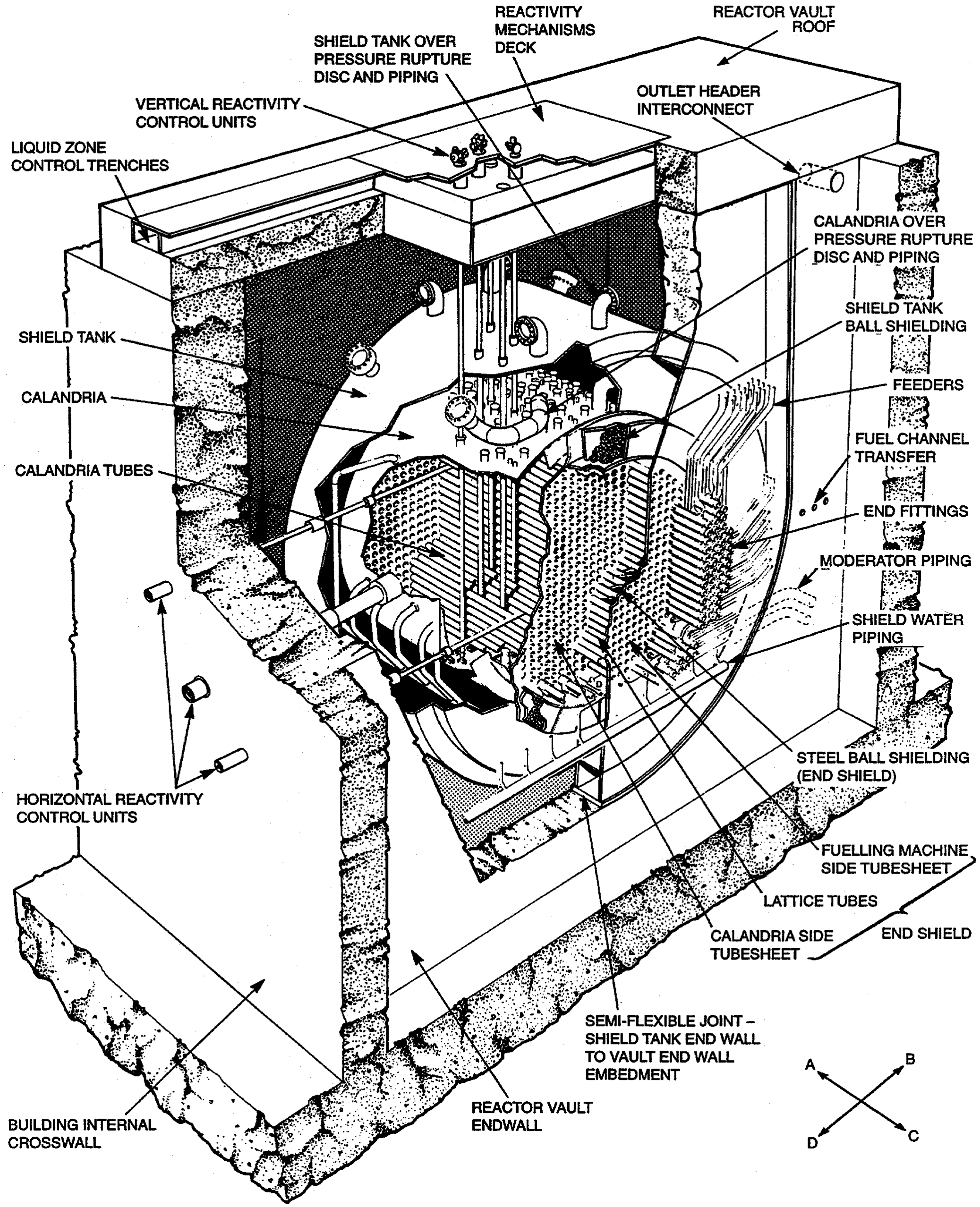
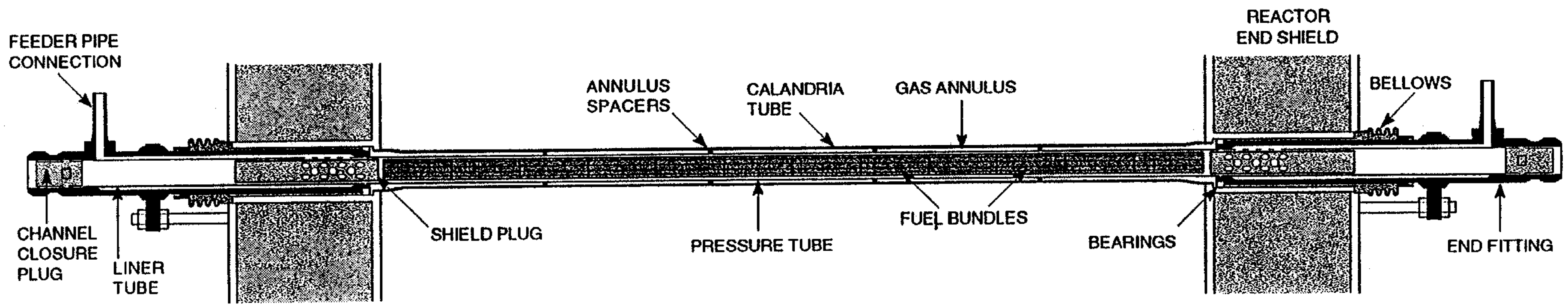
1. REACTOR ASSEMBLY

- **reactor vault is approximately 20 m high, 20 m wide and 12.5 m deep**
- **reactivity mechanism deck holds all vertical flux measuring devices, vertical reactor control and safety devices**
- **horizontal reactivity control units (liquid poison injection) and flux measuring devices**
- **shield tank and end shields are filled with steel balls and light water: 13.3 m diameter and 8.1 m long**
- **calandria is 8.5 m diameter and 6 m long**
- **reactor core is 7 m diameter and 6 m long**



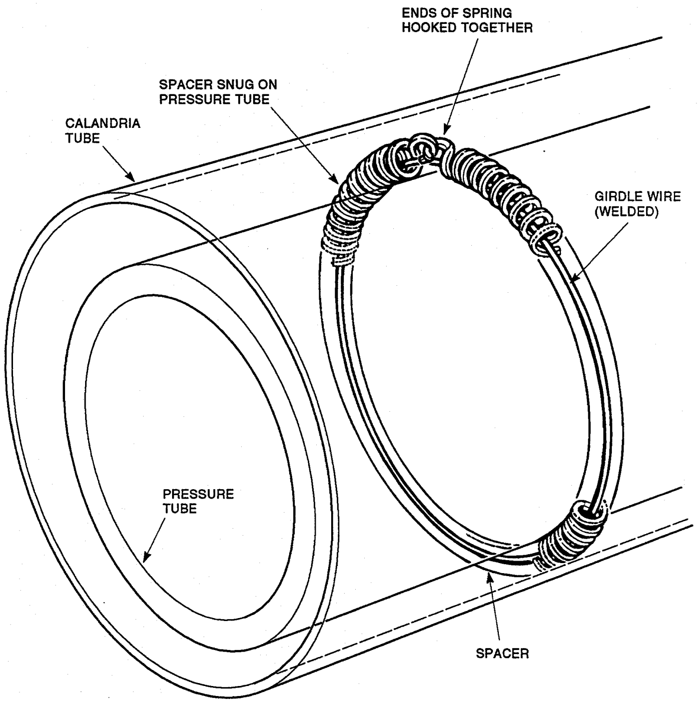
1.1 FUEL CHANNEL ASSEMBLIES

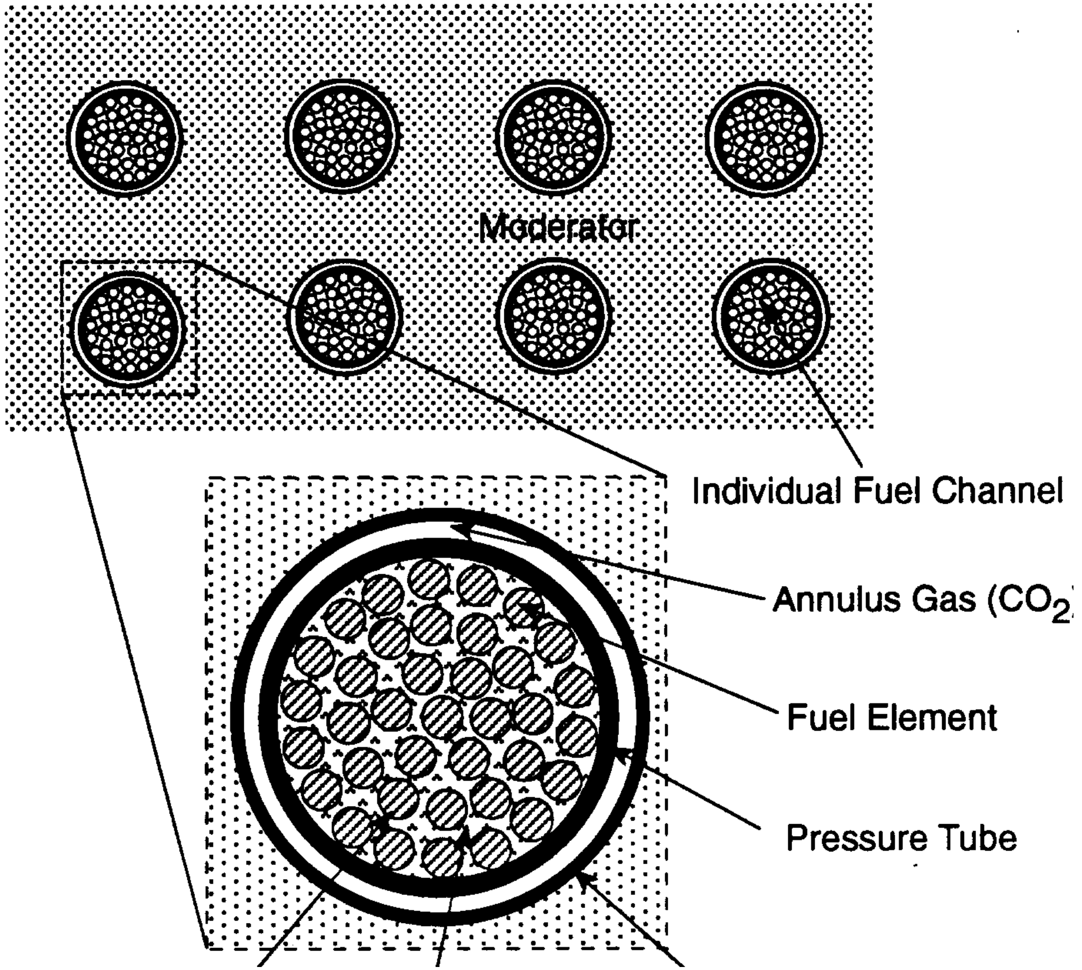
- **the main function is to provide a low neutron-absorbing pressure tube to support and locate the fuel within the reactor core, and to allow for a controlled flow of the high pressure heat transport coolant around and through the fuel;**
- **leaktight connections are provided to the heat transport inlet and outlet feeder pipes as well as to the channel closures at both ends;**
- **the fuel channel end fitting assemblies include a liner tube and shield plug at each end;**
- **a second tubular member, the calandria tube, forms a concentric container around the pressure tube;**
- **the annulus between the pressure tube and calandria tube is gas-filled, and provides thermal insulation to minimize heat loss from the high temperature heat transport system coolant to the cool moderator;**
- **overall length including end fittings is 12.4 m;**
- **pressure tube length is 6.35 m, inside diameter 103 mm, wall thickness 4.2 mm;**
- **calandria tube lattice pitch (square) 286 mm, length 5.9 m, inside diameter 129 mm, wall thickness 1.4 - 3.8 mm;**
- **fuel bundle diameter 102 mm.**



1.2 ARRANGEMENT OF FUEL ELEMENTS, PRESSURE AND CALANDRIA TUBES

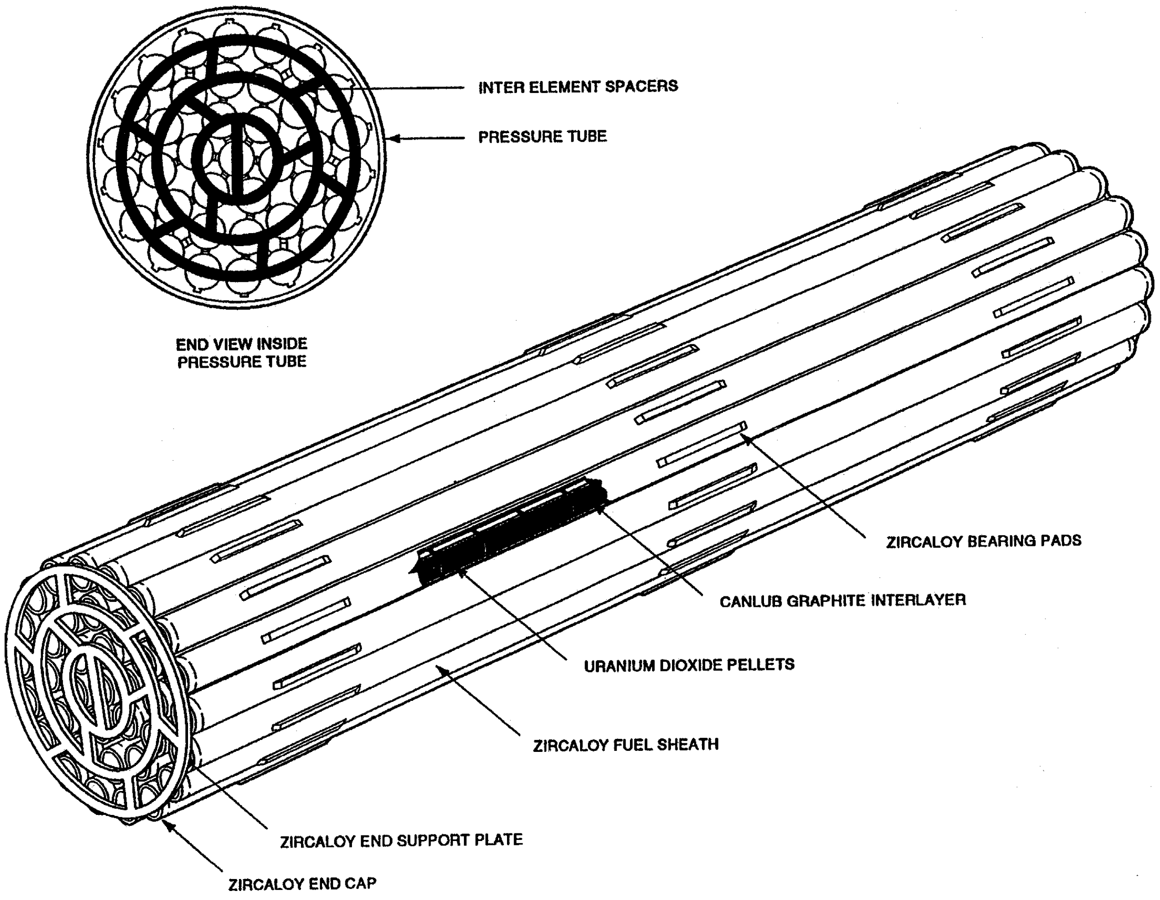
- **bundles of thin fuel elements allow fast neutrons to escape from the fuel;**
- **the relatively wide spacing of the fuel channels promote thermalization of neutrons**
- **the large surface area of the fuel bundle promotes heat removal from the fuel**





1.3 MAIN FEATURES OF THE FUEL BUNDLE:

- **CANDU 6 and CANDU 9 reactors use the 37-element fuel bundle design;**
- **the fuel bundle must maintain its structural integrity, leaktightness and dimensional stability during:**
    - ⇒ **transportation and storage before and after irradiation,**
    - ⇒ **reactor operation,**
    - ⇒ **during refueling.**
- **the fuel sheath is made from Zircaloy-4:**
    - ⇒ **low neutron absorption,**
    - ⇒ **good corrosion resistance,**
    - ⇒ **low hydrogen pickup;**
- **the fuel pellets are made from uranium dioxide with 0.71% U235;**
- **a fully loaded fuel bundle weighs about 24 kg, of which more than 90% is uranium oxide fuel.**



1. COMMON FEATURES OF NUCLEAR POWER PLANTS USING WATER COOLED AND MODERATED REACTORS

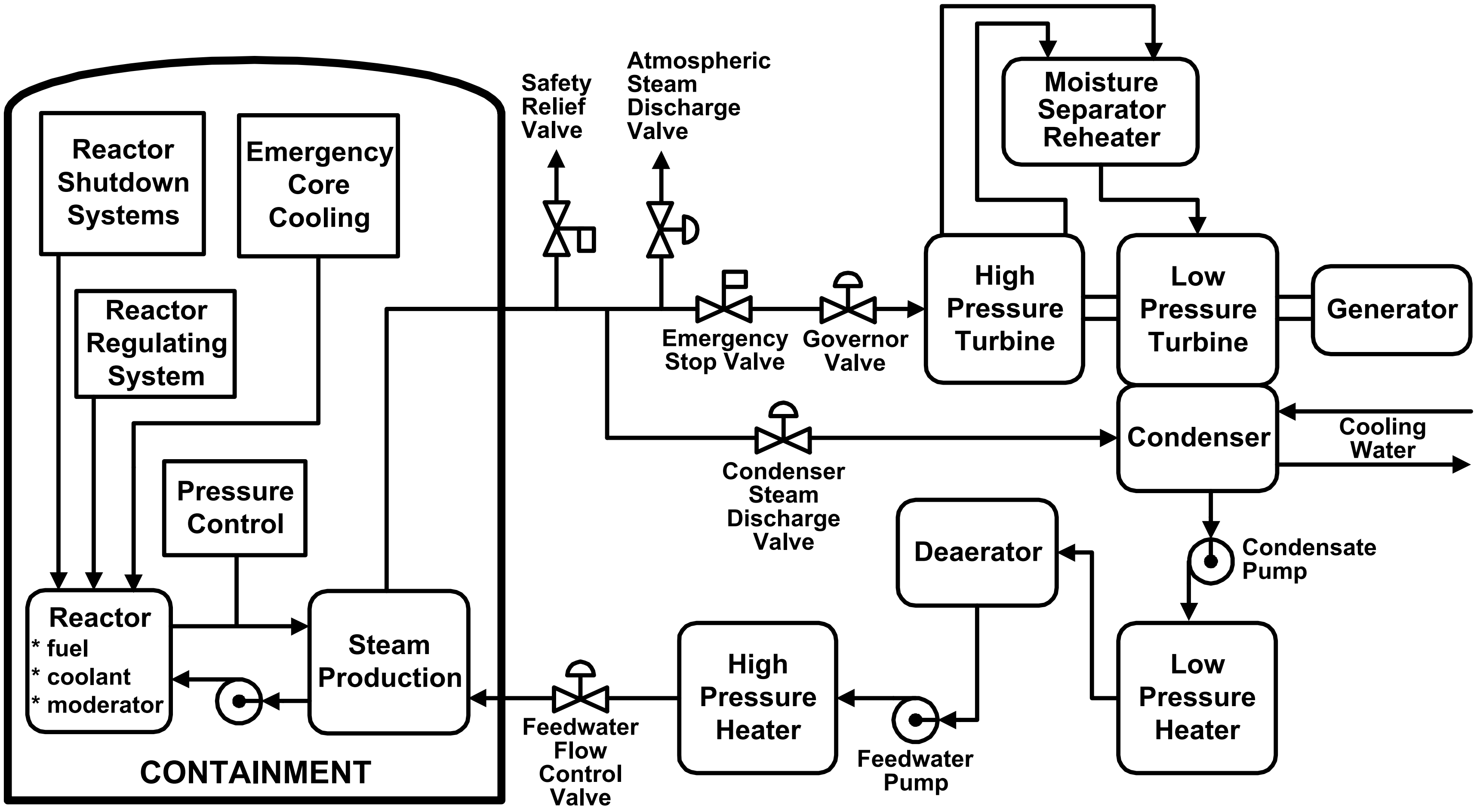


Figure 1: Major process and emergency systems common to NPPs using water cooled reactors.

CANDU NUCLEAR POWER PLANT MAIN SYSTEMS

- **the three main groups of process systems are the**

- nuclear steam supply system

- the steam utilization and turbine-generator system

- the electric power system

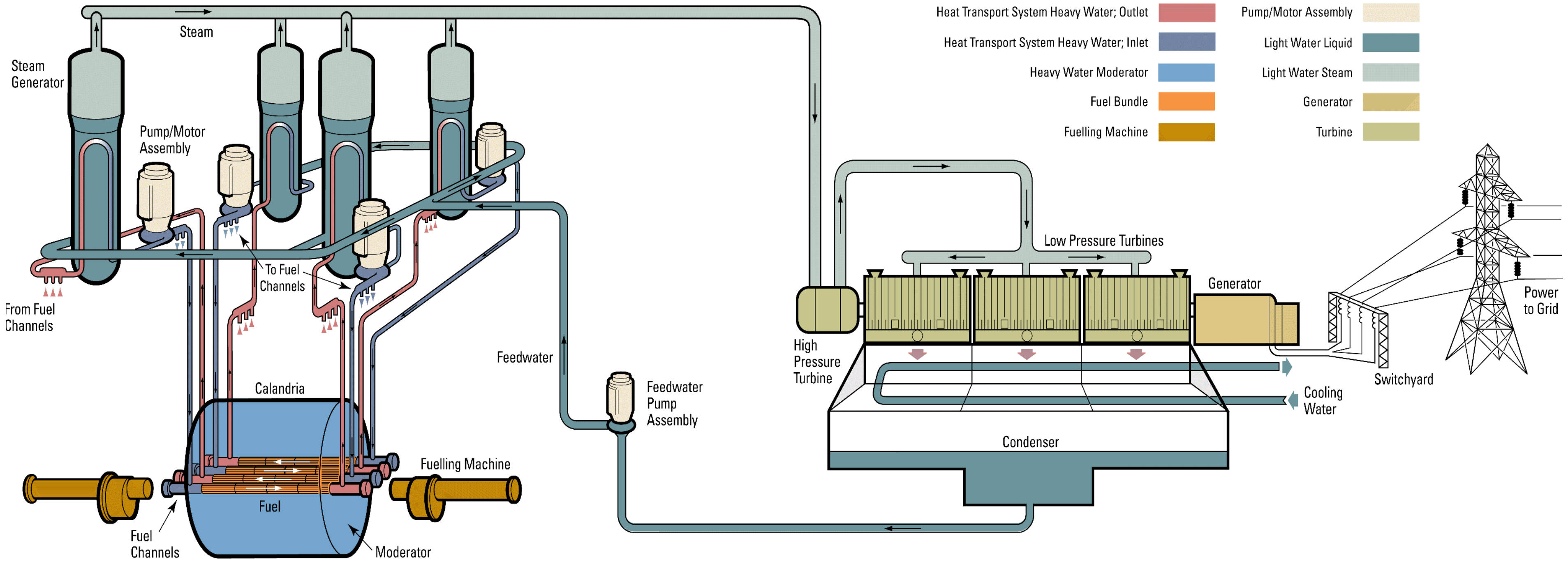
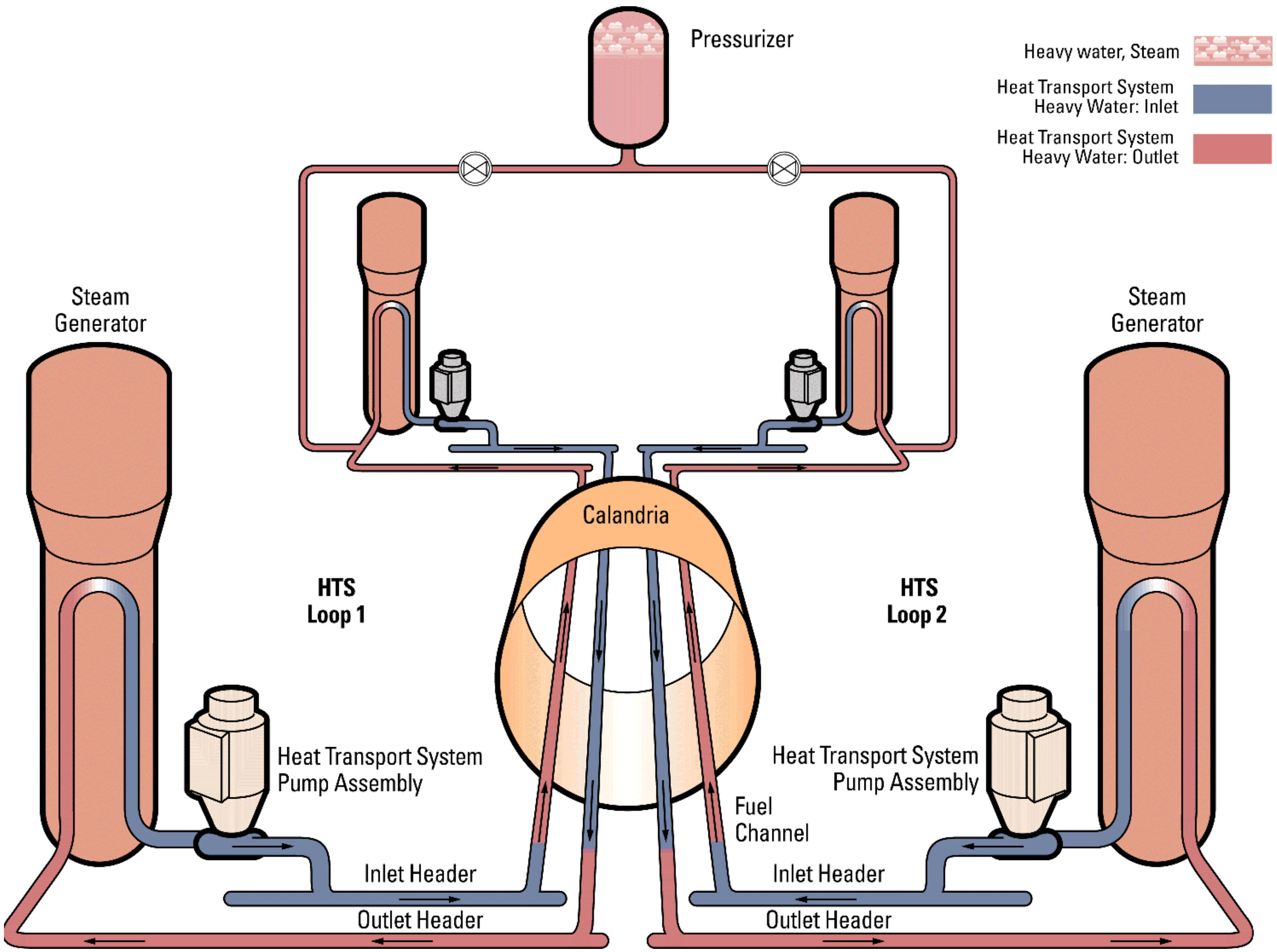
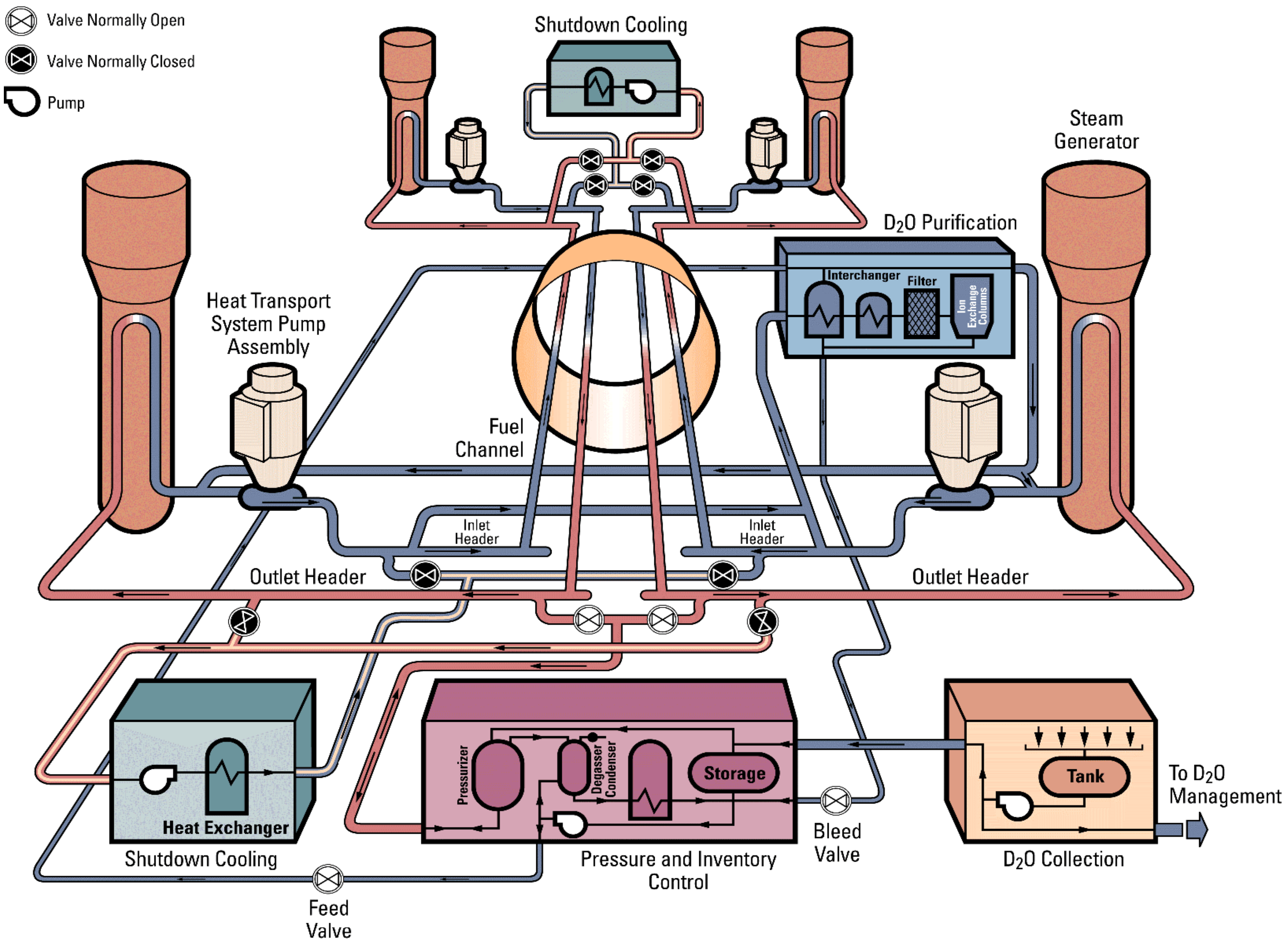


Figure 2: CANDU Nuclear Power Plant Main Process Systems

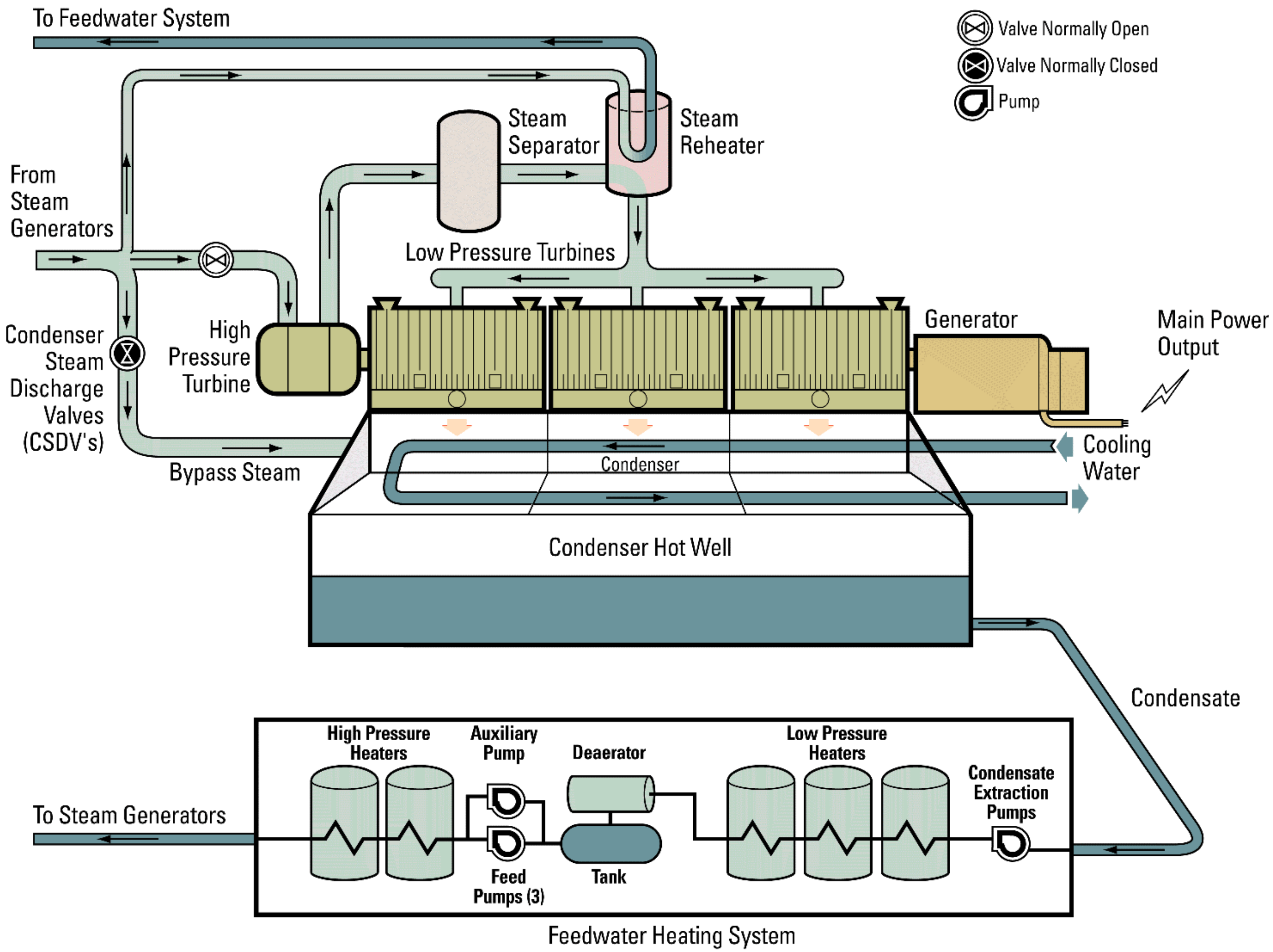


Heat Transport System

Heat Transport Auxiliary Systems

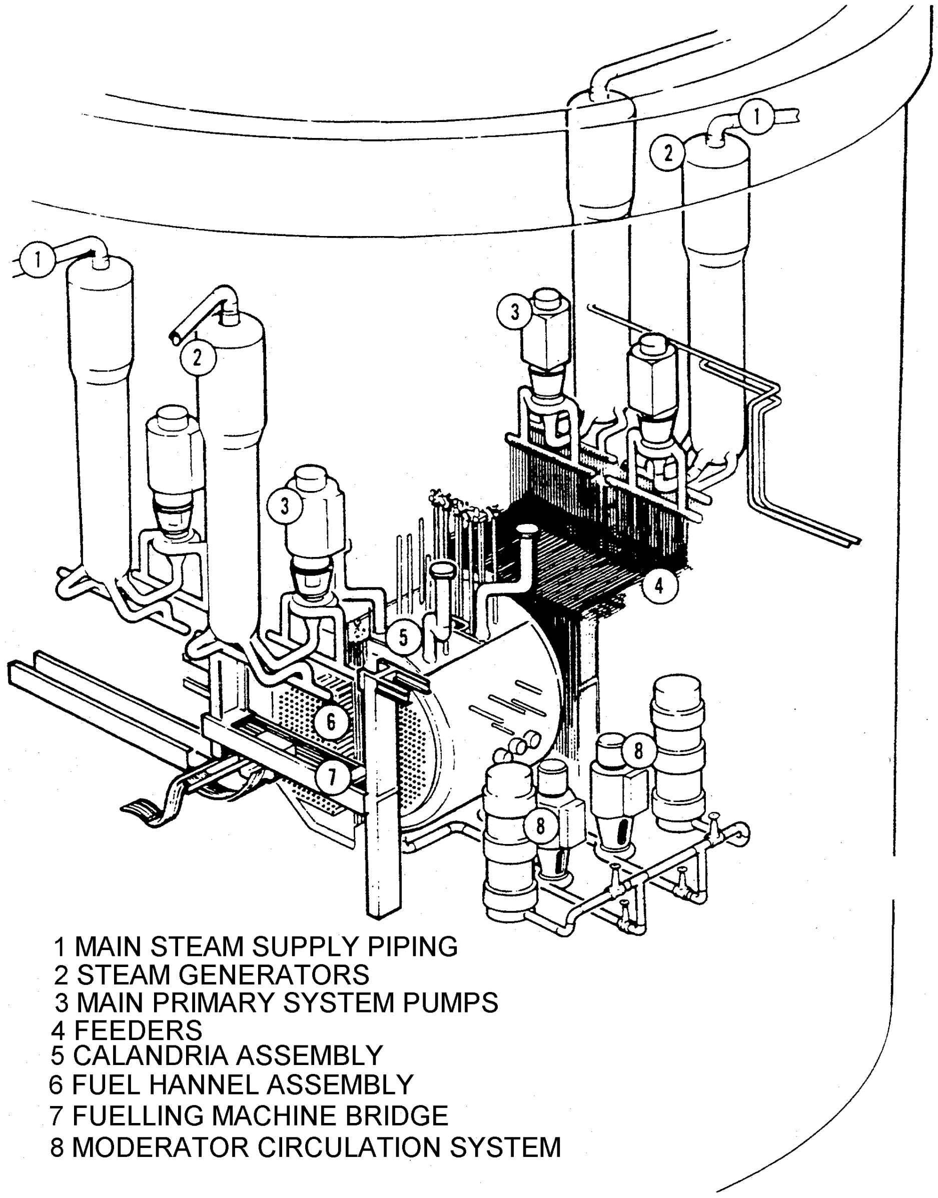


Turbine, Generator, Condensate and Feedheating Systems



2. REACTOR CONTROL

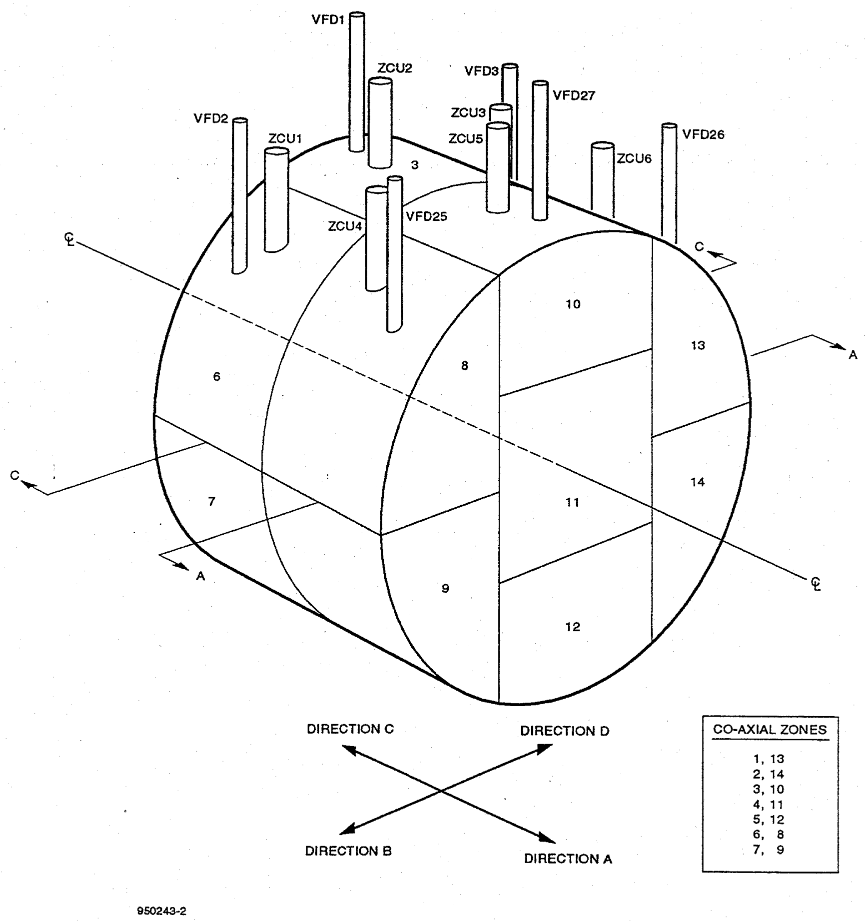
- Reactor power must be controlled to match the power generation requirements of the turbine-generator, subject to the safe operating limits of the fuel and the heat removal system.
- In a CANDU reactor both the total power generated and its regional distribution must be controlled.
  - ⇒ the physical dimensions of the core is large in relation to the average distance traveled by a neutron, hence local neutron flux disturbances could develop while bulk power is constant;
  - ⇒ an even flux distribution is necessary to achieve maximum extraction of energy ("burn-up") from each fuel bundle;
  - ⇒ preventing local flux peaks is essential to minimizing damage to the fuel;
  - ⇒ safety system independence is enhanced by locating devices for the different systems in different orientations.
- To achieve spatial control of the neutron flux there must be a spatially varied distribution of flux detecting, controlling and shutdown devices.



2.1 SPATIAL CONTROL OF NEUTRON FLUX

For the purpose of spatial control, the reactor is divided into zones. Spatial control is obtained by means of light water zone control assemblies and associated thermal neutron detectors in each zone.

- **the zone control assemblies consist of compartmentalized vertical Zircaloy tubes which traverse the core;**
- **bulk reactivity control is achieved by varying the light water level in all compartments by the same proportion;**
- **spatial flux control is achieved by differential adjustment of the light water level in individual compartments.**
- **the reactivity worth of the liquid zone control system for the CANDU 9 equilibrium core is 7.2 mk from completely empty to full;**
- **in the nominal operating range of between 15% and 80% full, the total worth of the liquid zone control system is approximately 5 mk;**
- **between these limits the reactivity worth is essentially proportional to the average level; the corresponding reactivity coefficient is -0.077 mk/% full.**

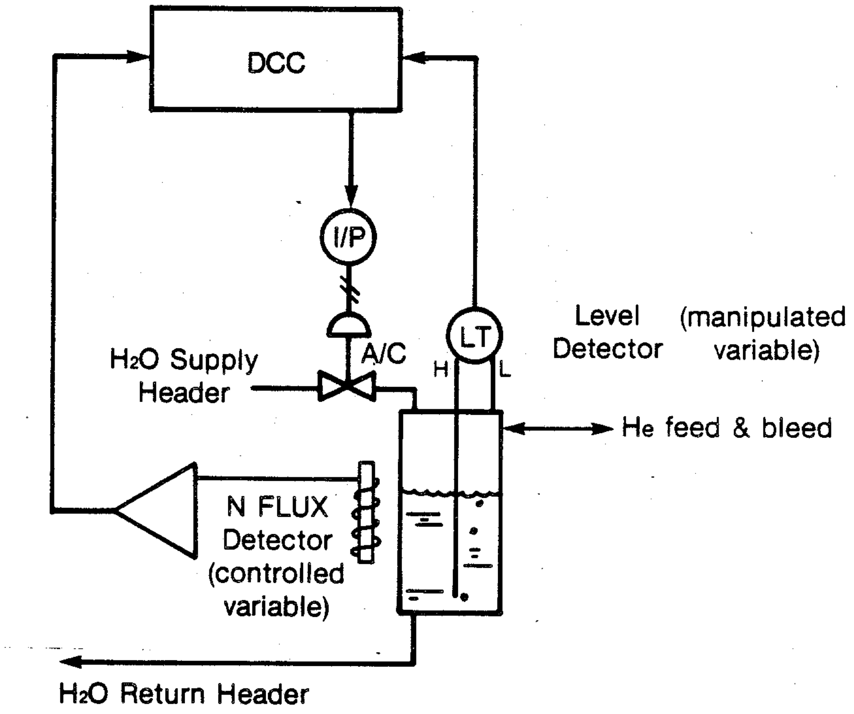


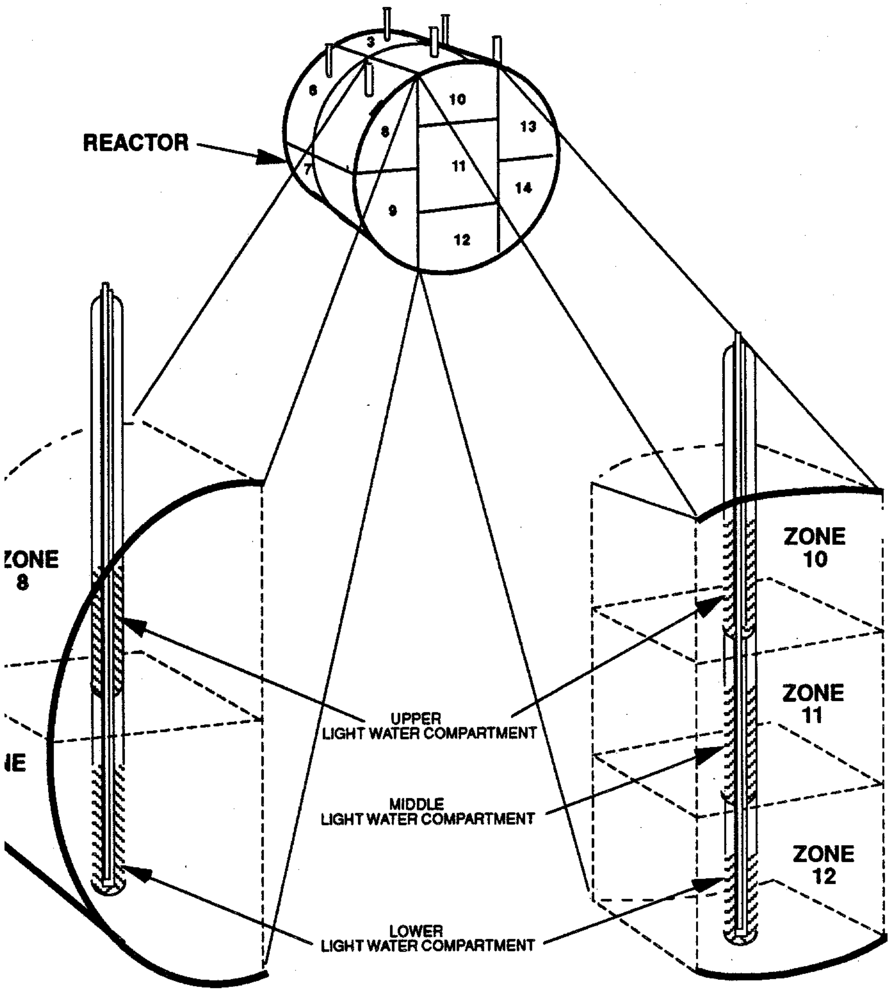
2.2 LIQUID ZONE CONTROL SYSTEM

The zone control system is designed to perform two main functions:

- **to provide short term reactivity control to maintain reactor power at the demanded level during normal operation (i.e. operating control of reactivity).**
- **to control spatial power distribution by suppressing regional power transients associated with space dependent reactivity perturbations.**

2.3 ADJUSTER RODS



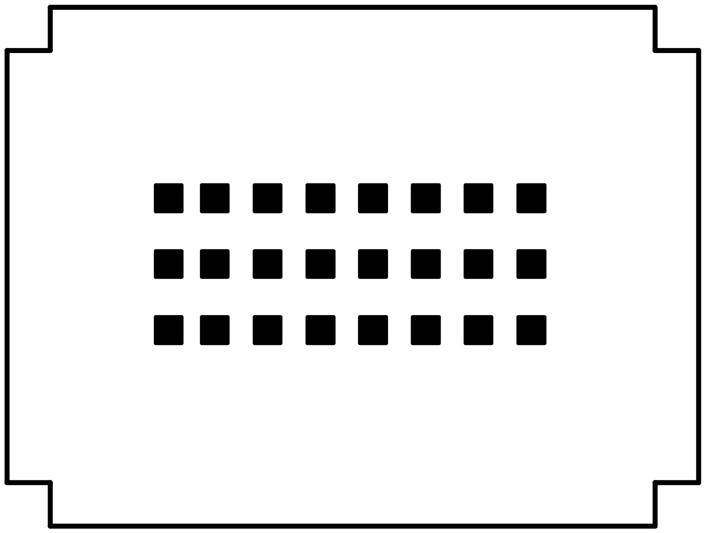


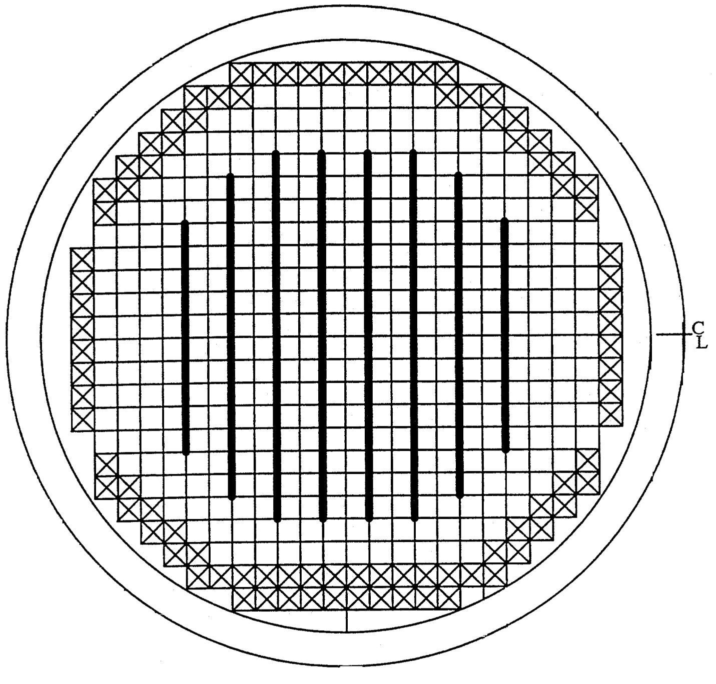
The adjuster rods are provided to:

- **shape the neutron flux for optimum reactor power and fuel burnup;**
- **supply positive reactivity beyond the normal control range of the zone controllers when required;**
- **compensate for the negative xenon reactivity up to 35 minutes after a shutdown from full power ("poison override").**

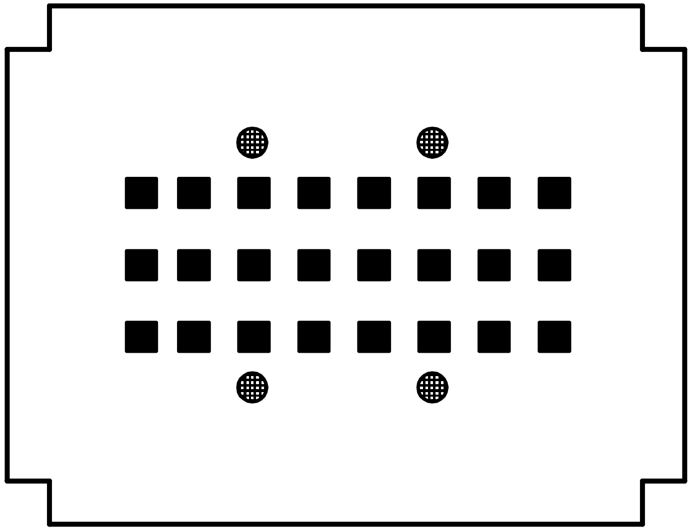
There are 24 adjuster rods:

- **the rods are made of stainless steel;**
- **they are arranged in three rows each containing eight rods;**
- **the rods are normally fully inserted in the core;**
- **the rods are moved in banks;**
- **the maximum total reactivity which may be gained on withdrawal of all adjuster rods is about 16 mk;**
- **the maximum reactivity change rate of any one bank of adjusters is ± 0.07 mk/s.**
- **the operation of the adjusters is normally controlled by the reactor regulating system, but can also be manually operated under prescribed conditions.**





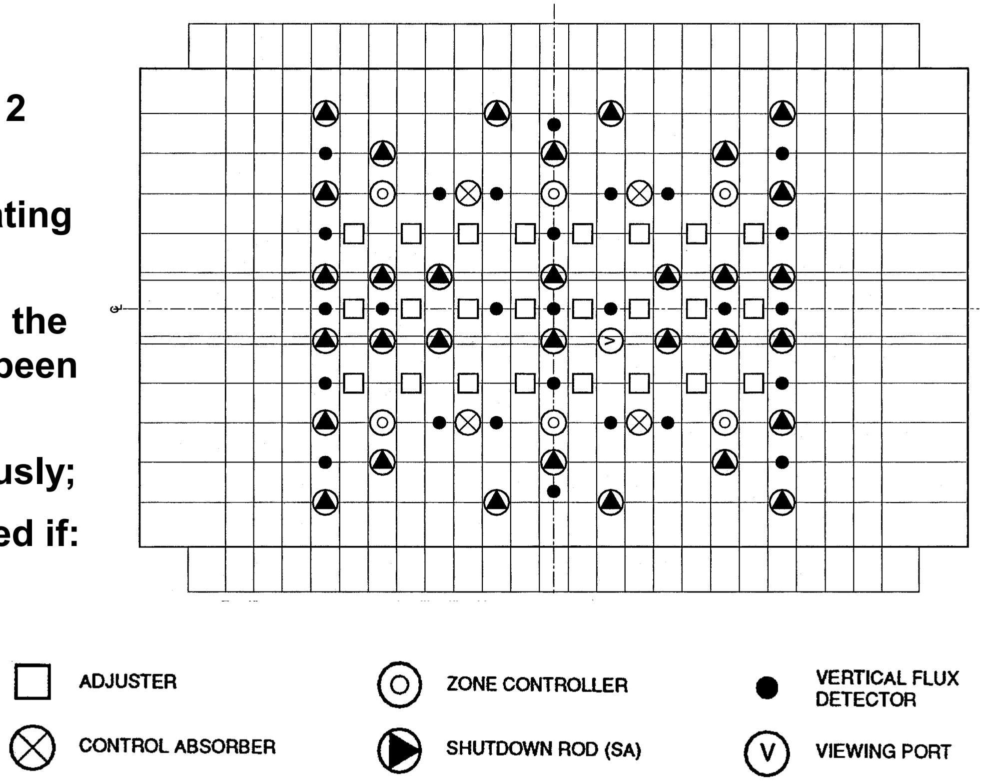
2.4 MECHANICAL CONTROL ABSORBERS



- **the mechanical control absorber rods consist of tubes of cadmium sandwiched between stainless steel;**
- **there are four MCAs;**
- **they are normally poised out of the core;**
- **they are driven in by the reactor control system to supplement the negative reactivity of the liquid zone control units, or dropped to effect a fast reactor power reduction (stepback);**
- **they can be driven into or out of the reactor core in one of two banks, at variable speed;**
- **they can be dropped by releasing their clutches; when dropped, the elements are fully inserted in three seconds;**
- **by re-energizing the clutch while the elements are dropping, a partial insertion to any intermediate position can be achieved;**
- **the maximum total reactivity worth of the mechanical control absorbers is about 10 mk.**

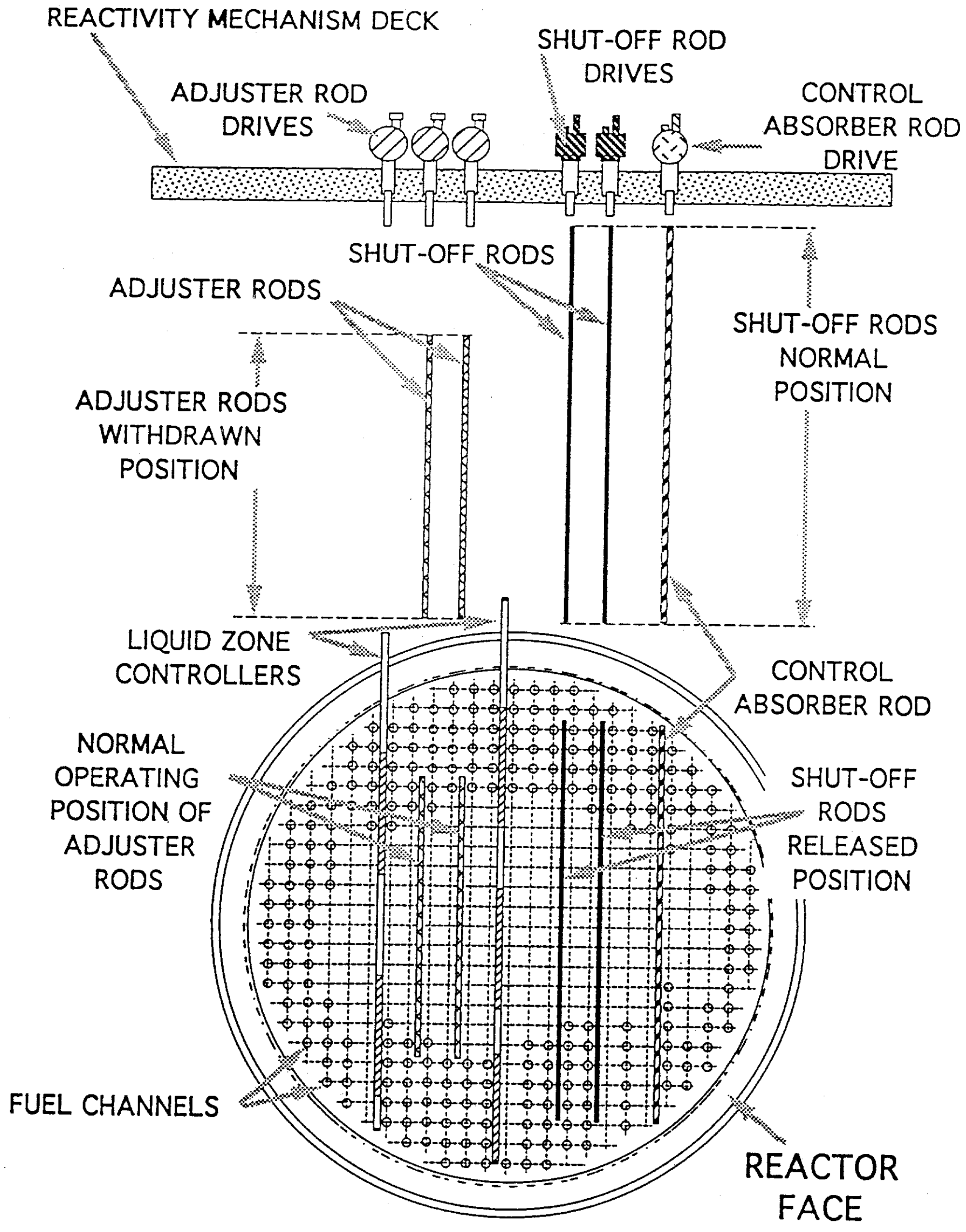
2.5 SHUTDOWN RODS

- **32 rods of cadmium and stainless steel;**
- **reactivity worth is -60 to -70 mk;**
- **spring assisted gravity drop, fully inserted in 2 seconds;**
- **normal withdrawal is controlled by the regulating system;**
- **the shutdown rods are withdrawn as soon as the trip signal has been cleared and the trip has been reset by the operator;**
- **all shutdown rods are withdrawn simultaneously;**
- **withdrawal of the shutdown rods is interrupted if:**
  - ⇒ **control is switched to manual, or**
  - ⇒ **the flux power error is excessive, or**
  - ⇒ **the reactor is tripped;**
  - ⇒ **if the log-rate exceeds 7 percent per second.**



2.6 LOCATION REACTIVITY CONTROL DEVICES

- **all the reactivity devices discussed so far are located in a vertical position, between the fuel channels, in guide tubes installed within the calandria;**
- **note that no reactivity control devices are located within the high pressure heat transport system;**
- **the reactivity deck is at a height above the calandria that allows the full withdrawal of the rods from the calandria;**
- **from the fully withdrawn position the rods must travel past the reflector before they enter the core itself and can have a significant reactivity effect.**

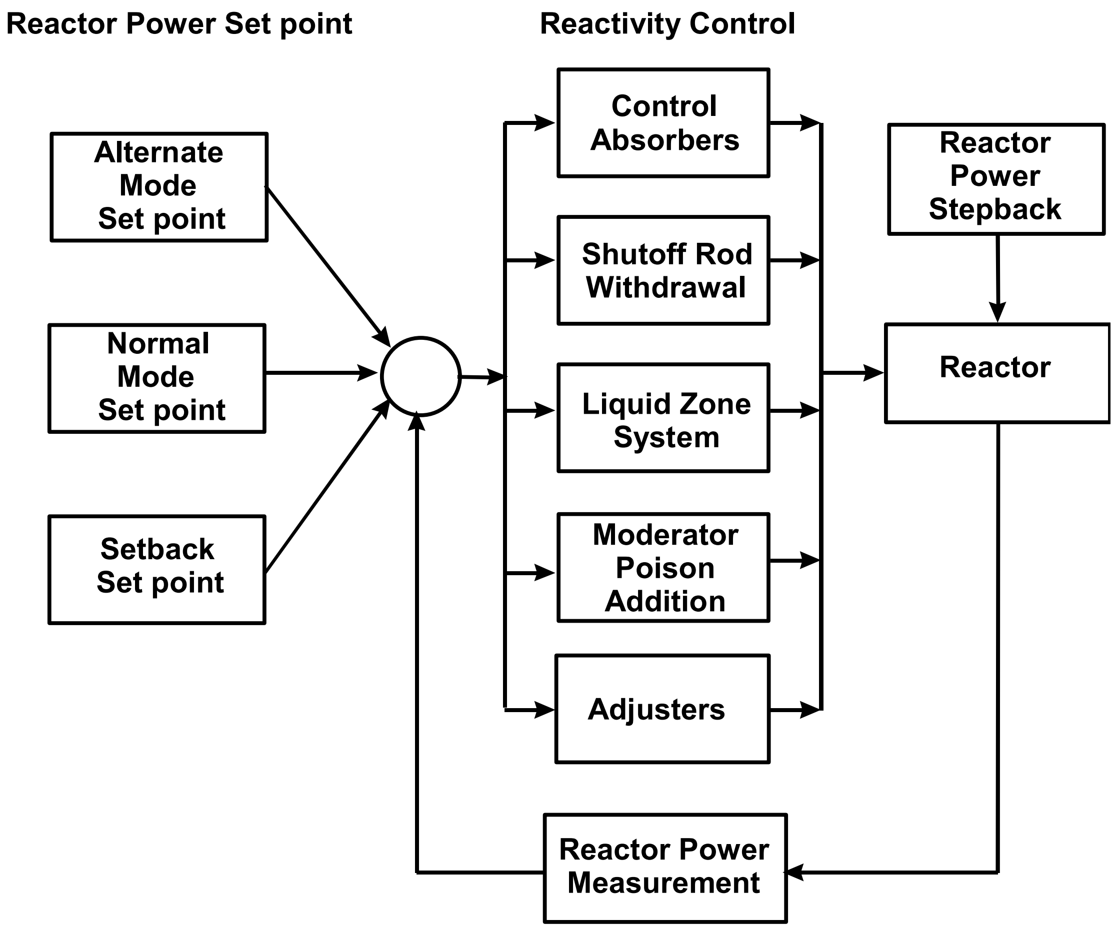


2.7 MODERATOR POISON

- **moderator poison is used to reduce excess reactivity to compensate for xenon decay**
- **during fresh fuel conditions Boron is used;**
- **during shutdown conditions Gadolinium is used;**
- **since the burnout rate of gadolinium on a subsequent startup is comparable to the xenon growth rate, a smooth control is possible when gadolinium is used for this purpose;**
- **note that this Gadolinium poison addition system is independent of the liquid poison injection system;**
- **the design rate of poison addition is equivalent to -0.75 mk/min;**
- **removal rates depend on poison concentration;**
- **at a poison level of -30 mk, the removal rate is approximately +0.05 mk/min.**

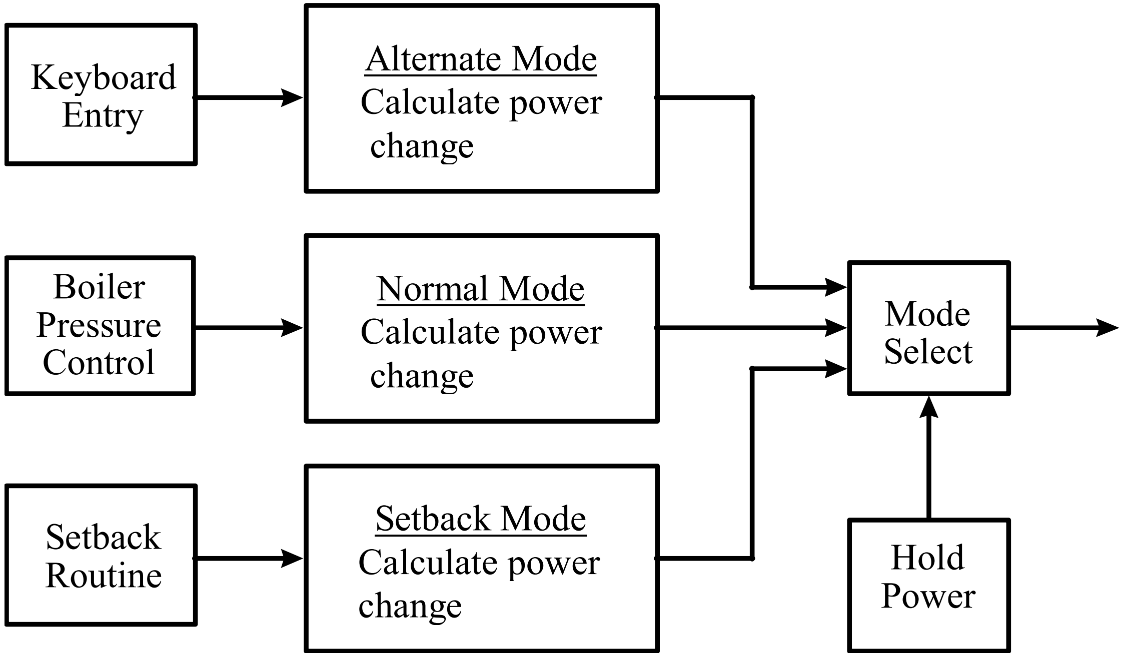
3. REACTOR REGULATING SYSTEM PROGRAMS

- **For CANDUs the Control Algorithm has the following main components:**
- **reactor setpoint calculations**
  - ⇒ **mode selection**
  - ⇒ **demanded power calculation**
- **power error calculation**
- **control of reactivity devices**
  - ⇒ **adjuster rods**
  - ⇒ **control absorber rods**
  - ⇒ **liquid zone level control**
  - ⇒ **adjuster and absorber speed control**
  - ⇒ **poison addition**
  - ⇒ **shutdown rods withdrawal**
- **reactor setback**
- **reactor stepback**



3.1 REACTOR POWER SETPOINT CALCULATION

- **The reactor power setpoint is determined by one of the following four sources, and the reactor control program is said to be in the corresponding “modes”:**
  - ⇒ **operator keyboard entry (“alternate” mode)**
  - ⇒ **boiler pressure control program (“normal” mode)**
  - ⇒ **setback program (“setback” mode, which terminates in “alternate” mode)**
  - ⇒ **hold power program (“hold power” mode which places reactor control into “alternate” mode)**



- **The two basic modes of reactor control are “normal” and “alternate”, since both of the other modes results in reactor control being placed into “alternate” mode. Specific operator action is required to take the reactor control from “alternate” to “normal”.**
- **The main functions of the setpoint calculation program are the calculation of demanded power and demanded power rate.**

3.2 DEMANDED POWER ROUTINE

- **All power level changes are achieved by ramping the setpoint up or down at a specified rate, towards the specified target endpoint.**
- **On each iteration the amount of change in demanded power is computed and added to the value of demanded power from the previous iteration**
- **During large difference between Target Setpoint and Demanded Power, the rate limit will keep the step increases between successive iterations small.**
- **As the Target Setpoint is approached, the error becomes progressively smaller, and the size of demanded power change on each iteration will decrease, resulting in a smooth approach to the Target Setpoint, minimizing the tendency for actual reactor power to overshoot the target value.**
- **On a “HOLD POWER” operation the change in demanded power is set equal to zero**
- **All reactor power setpoint changes are limited by the control program to safe rates and upper limits.**
- **A deviation limiter prevents the power setpoint from being more than 5% above the actual power to preclude the possibility of a large power increase at excessive rates.**

3.3 POWER ERROR CALCULATION

- **The power error is a measure of the difference between the measured power and the demanded power of the reactor, plus a rate of change of power error term.**

POWER ERROR = K1(ACTUAL POWER - DEMANDED POWER) + K2(ACTUAL RATE - DEMANDED RATE)

This relationship has a fundamental role in RRS determining the movements of reactivity devices:

- **the sign of the power error determines whether to**
  - ⇒ **increase or decrease the levels of the zones**
  - ⇒ **remove or insert adjuster rods**
  - ⇒ **remove or insert the mechanical control absorbers.**
- **When the power error is zero, no movement of devices will be ordered, although device movements ordered before will be completed.**
- **A zero power error during a given time interval implies that the reactor is critical.**
- **Note that a reactivity balance is not computed for reactor control.**
- **The design of the devices and how they are controlled (i.e. individually or in a group) is based on the reactivity worth and design purpose of each device.**

3.4 SETBACK ROUTINE

- **The setback routine reduces reactor power promptly in a RAMP fashion if any parameter exceeds specified operating limits - designed to protect fuel from overheating, reactor structures, turbine and against loss of heat sink.**
- **The rate at which reactor power is reduced and the power level at which the setback ends will be appropriate for each parameter.**
- **The setback overrides other reactor power demands and is accompanied by alarm window annunciation.**
- **Unit control mode will be placed in ALTERNATE mode whenever SETBACK is activated.**

Conditions	Setback Rate (percent per second)	End Point (percent of Full Power)
Zone Control System Failure	0.2	60
Spatial Control Off Normal	0.1	-
Zone power > 110 % at full power	-	60
Flux tilt >20 % above 60 % full power	-	20
Flux tilt >40 % between 20 & 40 %FP	-	20
High Local Neutron Flux	0.1	60
High Steam Generator Pressure	0.5	10
Low Deaerator Level	0.8	2
High Moderator Level	0.8	2
Turbine Trip or Loss of Line	0.8	60
Endshield Flow	0.8	2
Endshield Temperature	0.8	2
Sustained Low Condenser Hot Well Level	0.8	2
Manual	0.5	2

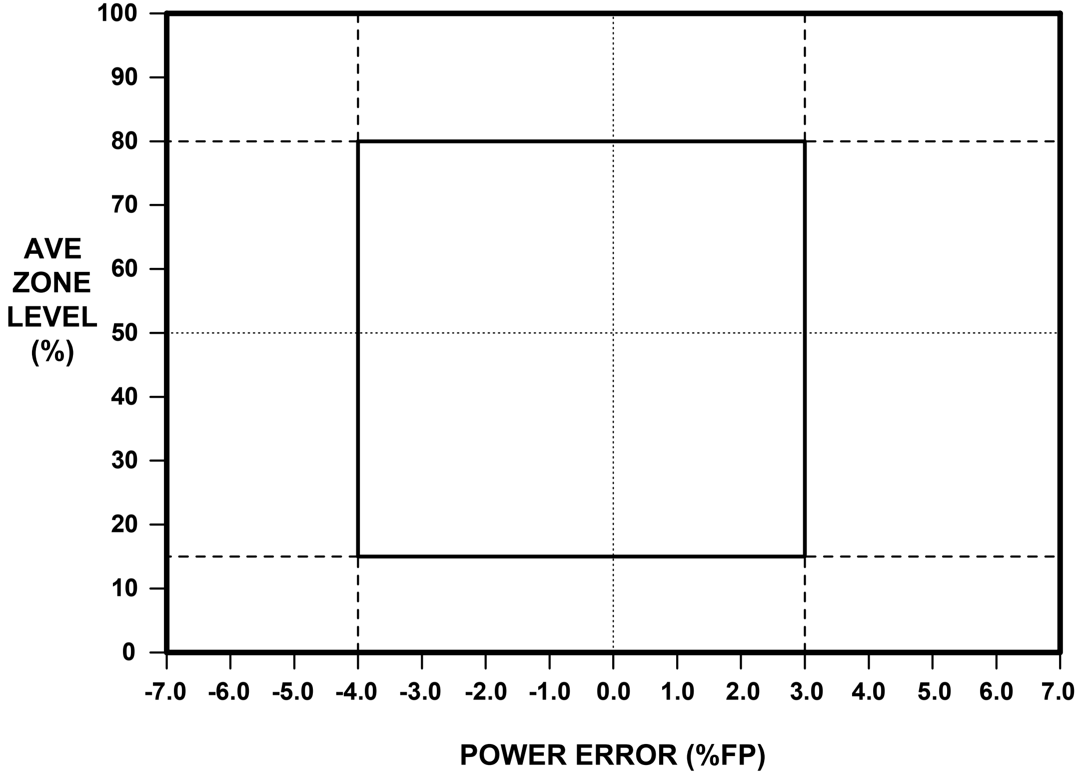
3.5 STEPBACK ROUTINE

- **The stepback routine monitors a number of plant parameters and reduces reactor power in a STEP fashion by dropping the mechanical control absorbers either fully or partly into the reactor - the action is designed to avoid reactor trip.**
- **Unit control mode will be placed in ALTERNATE mode whenever SETBACK is activated.**

Conditions	Control Absorber Response
Reactor Trip 2/3 contacts on SDS1 or SDS2	Full rod drop
All Heat Transport Pumps Trip	Full rod drop
Single pump trip	Full rod drop
Trip of two pumps at same end of reactor	Full rod drop
Heat Transport High Reactor Outlet Header Pressure & Reactor Power > 1 %FP	Full rod drop
High Zone Power	Full rod drop
High Rate of Log Neutron Power	Full rod drop
Low Moderator Level	Full rod drop
Low Steam Generator Level	Full rod drop

3.6 REACTIVITY DEVICE CONTROL

- **The primary method of short-term reactivity control is by varying the liquid level in the zone controllers.**
- **Normally, the adjusters are fully inserted, the control absorbers are fully withdrawn and the average liquid zone control compartment level is between 30% & 50%.**
- **If the zones are unable to provide the required reactivity effect, other devices are operated by the reactor regulating system.**
- **A shortage of negative reactivity will be indicated by either a high zone controller level or a positive power error, and will cause the mechanical control absorbers to be driven in, one bank at a time (if any adjusters are not fully in the core, they too will be inserted).**



- **A shortage of positive reactivity will be indicated by either a low zone controller level or a negative power error, and will result in the adjusters driven out in a specific sequence (if any absorbers are not fully out of the core, they too will be driven out).**

3.7 SPEED CONTROL SYSTEM FOR THE REACTIVITY MECHANISMS

- Variable speed control is provided to drive the adjuster and mechanical control absorber elements into or out of the core.
- Dedicated reversing motor starters control the elements individually. Speed, normally on automatic control, can be manually set from the main control room. A manual speed setting will also apply to the automatic control of adjusters and mechanical control absorbers.

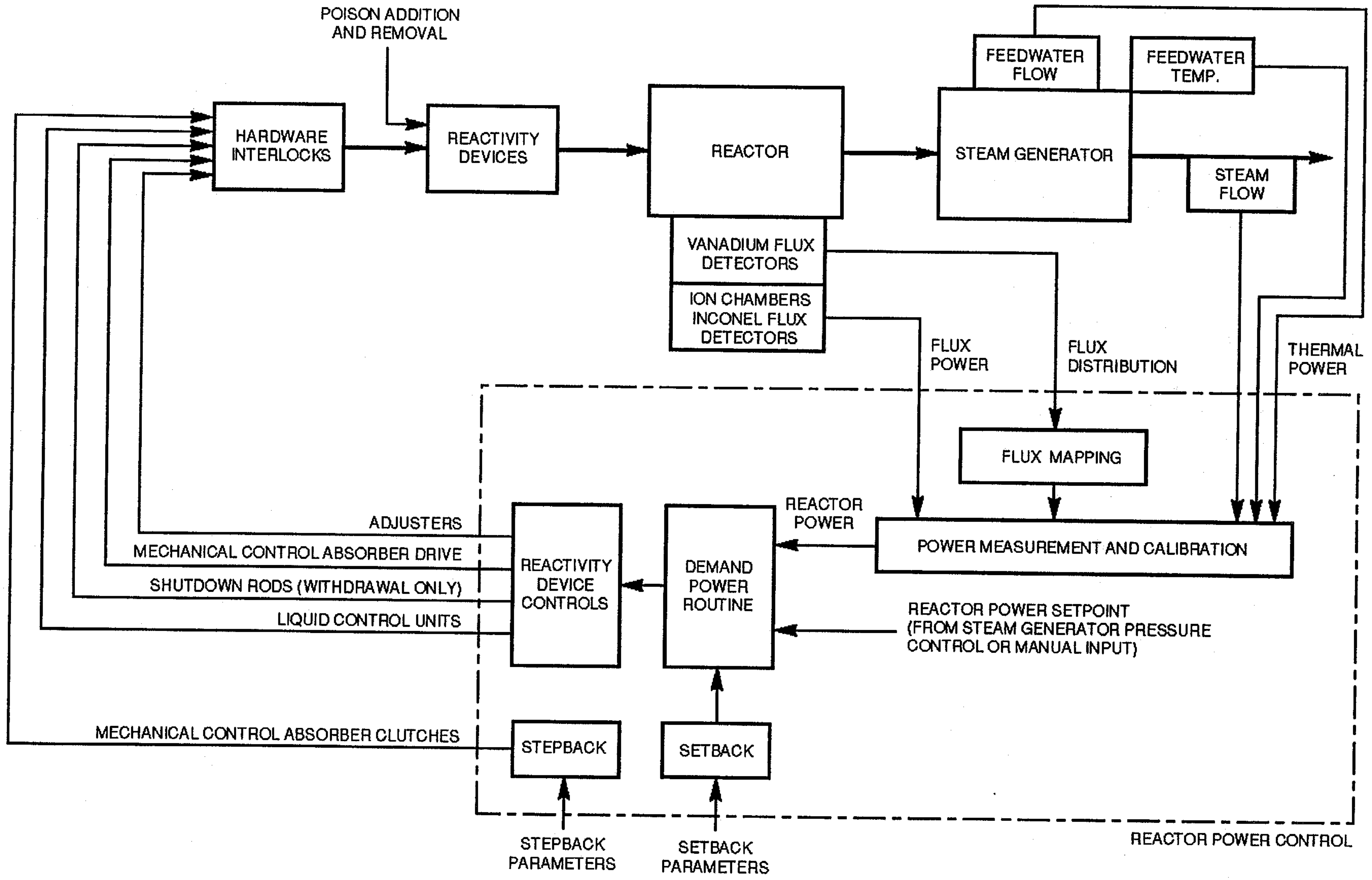
3.8 HARDWARE INTERLOCKS

- The automatic control of the reactivity mechanisms are subject to a number of interlocks to limit the consequences of a gross loss of regulation.
- To prevent the reactor from being started up with the safety systems unavailable, the adjusters and mechanical control absorbers are inhibited from being withdrawn unless both shutdown systems are poised.
- The adjusters are further interlocked to prevent more than a certain number of rods from being withdrawn at the same time. This limits the maximum rate of addition of positive reactivity. Another interlock is provided which prevents the reactor from coming critical on shutdown rod withdrawal. It prevents the shutdown rods from being withdrawn unless the mechanical control absorbers are in the core.

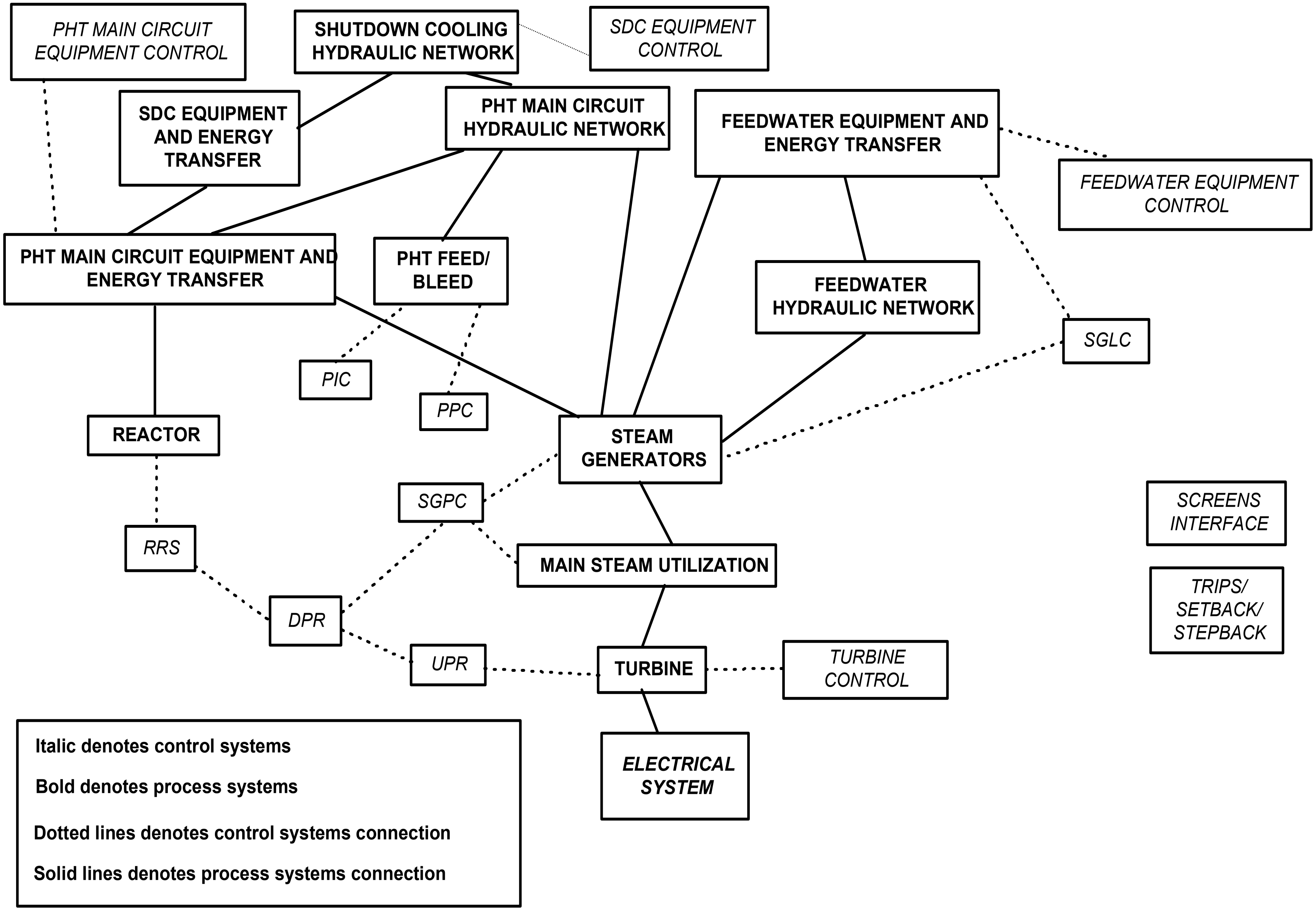
3.9 SHUTDOWN ROD WITHDRAWAL LOGIC

- **Dropping of the shutdown rods is controlled by Shutdown System #1.**
- **Withdrawal of the rods is controlled by the Reactor Regulating system.**
- **Withdrawal is inhibited until the reactor trip signal is cleared and SDS#1 is ‘RESET’.**
- **For withdrawal, the shutdown rods are arranged in two banks.**
- **For normal withdrawal, controlled by the reactor regulating system, both banks are withdrawn simultaneously, with withdrawal being stopped if the power error or the rate log power change exceeds a specified limit.**
- **Manual withdrawal is by separate banks and is allowed only if computer control is unavailable. The operator may also select individual rods to be driven in or out under manual control.**

6. REGULATING SYSTEM BLOCK DIAGRAM



CANDU 9 COMPACT SIMULATOR INTER-SYSTEM DIAGRAM



SYSTEM	**SIMULATION SCOPE**	**DISPLAY PAGES**	**OPERATOR CONTROLS**	**MALFUNCTIONS**
REACTOR	• neutron flux levels over a range of 0.001 to 110% full power, 6 delayed neutron groups • decay heat (3 groups) • all reactivity control devices • xenon and boron poison • reactor regulating system • reactor shutdown system	• reactivity control devices • shutdown rods • reactor regulating system	• reactor power and rate of change (input to control computer) • manual control of reactivity devices • reactor trip • reactor setback • reactor stepback	• reactor setback and stepback fail • one bank of control rods drop into the reactor
HEAT TRANSPORT	• two phase main circuit loop with four pumps, four steam generators, four equivalent reactor coolant channels • pressure and inventory control (pressurizer, degasser condenser, feed & bleed control, pressure relief) • operating range is zero power hot to full power	• main circuit • pressure control • pressurizer control • feed and bleed control • inventory control • degasser condenser control	• circulating pumps • pressurizing pumps • pressurizer pressure • pressurizer level • degas cond. Pressure • degas cond. Level • feed & bleed bias • isolation valves for: pressurizer, degasser cond., feed and bleed	• main circuit relief valve fails open • pressurizer relief valve fails open • pressurizer isolation valve fails closed • feed valve fails open • bleed valve fails open • reactor header break

STEAM & FEEDWATER	• boiler dynamics, including shrink and swell effects • steam supply to turbine and reheater • turbine by-pass to condenser • steam relief to atmosphere • extraction steam to feed heating • steam generator pressure control • steam generator level control • boiler feed system	• steam generator feed pumps • steam generator level control • steam generator level trends • steam generator pressure control • extraction steam	• level controller mode: computer or manual • manual level control gain & reset time • level control valve selection • level control isolation valve opening • extraction steam valves • feed pump operation	• all level control isolation valves fail closed • one level control valve fails open • one level control valve fails closed • all feed pumps trip • all safety valves open • steam header break • flow transmitter fails
TURBINE-GENERATOR	• very simple turbine model • mechanical power and generator output are proportional to steam flow • speeder gear and governor valve allow synchronized and non-synchronized operation	• turbine-generator	• turbine trip • turbine run-back • turbine run-up and synchronization • atmospheric and condenser steam discharge valves	• turbine spurious trip • turbine spurious run-back
OVERALL UNIT	• fully dynamic interaction between all simulated systems • unit power regulator • unit annunciation • computer control of all major system functions	• overall unit • unit power regulator		