SECTION 6 Design of Reactivity Control Units (RCUs)

6.1 Functional Description of Reactivity Control Units (RCUs)

Reactivity Control Units (RCUs) form the in–reactor sensing and actuating portions of the Reactor Regulating System (RRS) and the two reactor safety Shut-Down Systems (SDS1 and SDS2). In this sense, their reactor control and safety functions can best be described collectively, as functional parts of those systems. Similarly, because all RCUs are physically parts of the reactor assembly, they share many common features of design and construction. The following sections describe these common aspects for the RCUs, and later sections give detailed descriptions of the unique aspects and construction of each device.

The reactor complement of reactivity control units is comprised of devices which serve one of three functions for these systems:

a) those which measure the fission power levels:
   Vertical Flux Detector Units (VFD)
   Horizontal Flux Detector Units (HFD)
   Ion Chamber Units (IC)

b) those which regulate power levels:
   Adjuster Rod Units (ADJ)
   Liquid Zone Control Units (LZC)
   Mechanical Control Absorber Units (MCA)

c) those which shut down the reactor in an emergency:
   Shutoff Rod Units (SOR)
   Liquid Injection Shutdown Units (LIS) & (LISS)

Their system relationships are displayed in **Figure 6-1.**

In CANDU reactors, RCUs serving as emergency shutdown devices are entirely independent of those used for reactor power regulation. Furthermore, two complete and diverse shutdown systems are provided, each having full shutdown capability, independent of the other.

Because of the wide lattice spacing of the fuel channels in a CANDU core, and because fuel is continually being changed in individual fuel channels while it operates, the power level in the core is subject to both general and local variations. Furthermore, both of these changes can have steady rates of change and periodic fluctuations. Accordingly, a relatively large number of both measuring and actuating devices are used in a CANDU, and they are distributed throughout the core. Furthermore, several different kinds of devices are used. These devices are of essentially the same design in all current CANDUs, and are considered generic designs, changed only in length and quantity to suit the different core sizes. Overview descriptions for these devices are given below, for a CANDU 6 reactor. Detail descriptions are given in subsequent sections.

The quantities and locations of the RCUs used in a CANDU 6 are shown on **Figures 6-2, 6-3, 6-4 & 6-5.**

All RCUs serving the Reactor Regulating System (RRS) and ShutDown System One (SDS1) are vertically oriented (except for the ion chamber units), with connector and actuator housings mounted on the Reactivity Mechanisms Deck (RMD). All their sensing or absorbing elements are positioned inside guide tubes immersed in the moderator, between the rows of calandria tubes. The housings communicate with the in–core components through thimble tubes which extend the calandria vessel boundary up through the reactivity mechanisms deck. Ion chambers serving SDS1 and RRS are located on the outside of the B side of the calandria, with their housings outside the vault wall. Only RCUs associated with Shutdown System Two (SDS2) are mounted on the D side of the reactor, and all SDS2 RCUs are mounted there. In this way, all RCUs for SDS2 are physically separated from those used for SDS1. This ensures the two systems cannot be disabled by the same physical accident, such as a fire, missile or steam line break.

6.1.1 Power Measuring RCUs

Overall power levels and rates of change are measured by ion chamber instruments mounted on the outside of the calandria shell sides. Local power levels are measured by flux detector elements distributed throughout the core.

6.1.1.1 Ion Chamber Units (ICUs)

Overall fission power level is measured by ion chambers in six horizontal housing units, mounted on the outside of the calandria vessel. **See Figure 6-2.**

In each of three housings on the reactor B side, separate instruments serve the RRS and SDS1systems, while an instrument in each of the three D side housings serve only SDS2. The ion chamber instruments provide electrical signals proportionate to the general fission power level in that region. **See Figure 6-6.**

A shutter is included in each housing, which is a movable mass of neutron absorber that can be rapidly moved by an air–powered cylinder, to provide on–power calibration of rate of change of flux.

A start–up instrument may be temporarily inserted in the D side housings to monitor reactor approach to criticality initially or after a prolonged plant shutdown.

6.1.1.2 Flux Detector Units (FDs)

Local levels of fission power are measured on a large number of separate, Hilborn type flux detector elements which are positioned throughout the core, on 26 vertical carrier assemblies called vertical flux detector units (VFDs). They independently provide local power measurements to the RRS and SDS1 for control and safety, and flux mapping data to the fueling engineer to optimize fuel changing programs, to improve fuel burn–up. **See Figure 6-7.**

A separate set of flux detectors is positioned on seven horizontal flux detector units (HFDs), which are dedicated to SDS2. **See Figure 6-8.**

Two types of detectors are used on these assemblies: those used for control and safety are fast–responding and sensitive to both neutron and gamma fluxes; those for fuel management are slower responding and sensitive to only neutron fluxes.

The RRS and SDS circuits to which these sensors are coupled monitor both magnitude and distribution of power, and also rate of change of power. They then initiate commands to the appropriate neutron absorber devices to effect a correction or shutdown.

6.1.2 Reactor Power Regulating RCUs

Regulation of overall power and also distribution of power is effected by the cumulative effect of three sets of neutron absorbing devices, in co–ordination with the fuel management program. These are the adjuster units, the liquid zone controller units and the mechanical control absorber units.

6.1.2.1 Adjuster Units

There are 21 metal adjuster absorber rods, which serve primarily to flatten the power distribution throughout the core, to obtain more nearly uniform power output from all the fuel. They can be inserted or withdrawn individually at any time by means of an electric motor-powered winch located on the RM deck. They also provide a means to effect a temporary increase in net reactivity in the core for re–starting after a shutdown, when they are withdrawn. **See Figure 6-9.**

6.1.2.2 Liquid Zone Control Units

There are six liquid zone controller units which provide the primary means for continuous modulation of core reactivity. **See Figure 6-10.** Each assembly contains either two or three compartments partly filled with demineralized ordinary water, for a total of 14 compartments in the core. Light water acts as an neutron absorber in a CANDU core. Therefore, by varying the quantity of water, they can be used to independently regulate power levels in their 14 local regions in the core. They also provide the means to raise or lower overall power levels in the core when they are operated in unison, and are the normal means to effect a non–emergency shutdown.

6.1.2.3 Mechanical Control Absorber Units

The four mechanical control absorber units provide metal absorber rods which are normally withdrawn, but which can be inserted or removed by their motorized winches to effect large amounts of negative reactivity. They serve to supplement the zone controller action so the latter can be maintained at about their mid–range. They can also be dropped into the core rapidly, partly or fully, to cause a quick reduction of power of any amount, down to 20% of full power. This provides a mans to deal with transient conditions such as sudden changes in electrical output demand on the plant. The Mechanic Control Absorber Units were derived from Shutoff Units, and use many of the same or similar components. Both items are shown on **Figure 6.11.**

6.1.3 Emergency Shutdown systems

6.1.3.1 Shutoff Units (SORs)

The 28 shutoff units comprise the absorber/actuator portion of SDS1. Each shutoff unit independently opens a release device when it is de-energized by the SDS1 trip circuits, to drop its metal absorber rod rapidly into the core, by gravity. These units are mounted vertically, the same as the regulating system devices. It has a motorized winch for withdrawal, but the motor is mechanically disengaged by the release device, and withdrawal is impossible until the trip is cleared.

6.1.3.2 Liquid Injection Shutdown Units (LIS)

Six horizontal liquid injection shutdown units make up the absorber/ actuator portion of the SDS2. Each unit provides a separate nozzle tube passing horizontally through the core, connected to a tank containing a neutron absorbing fluid (poison), mounted outside the vault. Each nozzle tube has numerous small nozzle holes drilled through its wall, through which the neutron absorbing fluid is injected directly into the moderator in the core when SDS2 trips. See **Figure 6-12.** The fluid is powered by high pressure helium being released from a common storage tank into the poison tanks, by the opening of a set of quick-acting valves.

The poison tanks, helium tank and actuating valves comprise the Liquid Injection Shutdown System (LISS). **See Figure 6-13**.

6.1.4 Reactivity Mechanisms Deck

The reactivity mechanisms deck closes the roof of the calandria vault to provide a sealed boundary between the vault shield water and the dry air of the steam generator room. It provides the mounting area for the mechanisms and connector housings for the RCUs, and a protected routing space for their electrical and instrumentation wiring and helium cover gas lines. **See Figure 6-14.** The drive mechanisms for RCUs having motorized winches, the ADJs, MCAs and SORs, are mounted above the tread plates, since they have moving parts and are more likely to require accessional servicing, such as to check or replace lubricating oil. The other devices, the VFDs and LZCs, have no moving parts to service and their connector housings are located below the tread plates. Manholes in the tread plates can be lifted to obtain access if ever required. This arrangement reduces clutter on the deck surface and improves physical access space for the maintainer. The RM deck also provides biological shielding for RCU maintainers, and supports the RM flask in the event of removal of RCU in-core components. (The RMD is primarily a structural item, but it is grouped with the RCUs because its configuration is dominated by RCU requirements.)

6.1.5 Viewing Ports

Viewing ports are provided to permit access into the calandria interior, in the event access is required. There is no planned maintenance operation requiring them, and they are merely vacant extra RCU thimbles. During normal reactor operation the viewing ports are capped off with a solid flange and shield plug, as shown on **Figure 6-14**. They can be used to insert temporary special start-up instrumentation, prior to first criticality, as shown on **Figure 6-15**. The viewing ports may also be used to view and manipulate the horizontal RCU guide tubes entering their locators during replacement.

6.1.6 Basic Configuration of RCUs

All vertical RCUs are comprised of an in-core sensor or absorber element which is enclosed and supported by a guide tube, passing between the rows of calandria tubes and supported at the top of the calandria shell and attached to the bottom. **See Figure 6-16.** A guide tube extension continues the support up from the calandria top to the RMD, and is within a thimble. The thimble is welded to the calandria shell, and forms a continuation of its pressure vessel boundary. The thimble top is closed by either a drive mechanism or a connector housing, mounted accessibly above the RMD structure, but above or below the RMD shielded tread plates. A shield plug under the housing blocks radiation streaming from the core. The housing is attached to the thimble by bolts, to permit its removal during a shutdown to remove the in-core parts, should that become required.

Horizontal RCUs have a similar configuration, except that their housings are mounted on the outside of the vault side walls, rather than the RM deck.

6.2 Basis for Design

The Reactivity Control Units meet the following design requirements:

a) The configurations and locations of the various sensor and absorber assemblies, as well as their actuation speeds, sensitivities and response rates, must meet the requirements for function and performance of the reactor regulating system and the shutdown systems.

b) RCUs shall comprise sensor and absorber elements and support structure members designed to operate in the reactor, subject to various types of radiation, temperatures and pressures, in moderator and cover gas. The external operating mechanisms and housings shall operate in air inside containment and shall be accessible on power, excepting only the ion chambers for RRS and SDS1.

c) In–core components shall be designed for long, maintenance–free service lives; and except for flux detector elements, they should normally remain in service for the reactor lifetime. Actuating mechanisms shall normally remain in continuous on–power service for at least five years between servicing or adjustment are required.

d) Mechanical spring elements are to be located outside the strong radiation fields as far as possible and designed with a low enough spring rate to be insensitive to small changes in length of the elements they support. They should maintain sufficient pre–tension loads for the reactor lifetime, however they should be capable of being re–adjusted using simple equipment.

e) Elastomeric and plastic materials used for seals and insulators, must have long lives, and where possible, sufficient for the reactor lifetime. Lubricants must also be able to remain in service five years or longer. These materials shall not be used inside the core area.

f) Configuration design of the reactivity mechanisms deck and vault face areas, and of the RCUs' housings must permit servicing of the mechanisms to be done in situ, on power. Shielding in the RM deck and inside RCUs shall permit servicing and removal of internal and in-core components, using simple supplementary temporary shielding, tooling and flasking equipment, with minimum exposure hazard and minimum man–Sievert dose accumulations.

g) RCUs which perform functions for either of the two shutdown systems must be environmentally and seismically qualified to demonstrate they will perform their safety functions during and after seismic excitation and then during and after exposure to the pressure and temperature cycles of severe accidents, for at least the time interval before these RCUs are required to operate.

h) Other RCUs, for regulating system service, need to be qualified only to the extent of verifying that they will not fail in an accident in a way which would increase reactivity in the core, or which would inhibit proper operation of a nearby safety system item.

i) RCUs are to be qualified by stress and seismic analyses to demonstrate they meet requirements of pressure vessel codes, and that they will continue to perform specified mechanical and electrical functions.

6.3 Configuring the RCU Layout

The types, locations and quantities of these devices are established for a new reactor configuration at the conceptual design stage. Once the basic size of the core has been established, and the calandria configuration determined, the systems of RCUs can be established.

As noted in an earlier section, the lay-out of the RCUs has little influence on the configuration of the reactor, beyond the following items: The length of the calandria sub-shell should be short, to not restrict the effective location of RCU absorbers or flux sensors in the axial direction. The elevation of the RM deck must accommodate the length of withdrawn absorbers and the part of their support cable that has become activated. Access is needed above the RM deck for the RM flask in case in-core items need to be removed. The crane will have to be high enough for the flask, whose length must enclose items which span the core, as well as shielding and tackle, a total of about 10 m. Clear height is also needed above the RM deck for installation of both original and replacement RCU items, some of which extend from the calandria bottom to the RM deck, a length of 14.5 m in a CANDU 6. Similarly, access space is needed on the vault side for maintainers to reach the RCU housings there, as well as flasking them. (However, for CANDU 6 the horizontal RCUs can be cut on removal to fit a short flask.) Finally, the RM deck crane must also have an access route to lift the main flask from the floor near the air lock up to the RM deck area.

The quantities and locations of the RCUs is determined by collaboration of designers from many different disciplines, primarily from core physics, safety systems, controls and instrumentation, reactor structures and RCUs. The core physicist would prefer a large number of small absorbers, since this would permit finer discrimination of reactivity adjustment. The mechanical equipment designer would aim for fewer, larger devices, because it would require fewer penetrations in his structures and would require manufacture of fewer devices, both factors in reducing cost. In practice, the size of the in-core items is dictated by the space available between the calandria tubes, allowing for reasonable clearances and tolerances on guide tubes and absorbers. Present components have been developed and evolved over many years and are considered to be established generic designs of essentially fixed configuration. Obviously, devices are spaced at multiples of lattice pitch intervals, across the core (ie in the A-D direction); the designer can select distances transversely to obtain acceptable diagonal distances. One restraint on inter-RCU spacing is the strength of the ligament left between the penetrations on the calandria shell, as shown on **Figure 6-17**. Minimum inter-component spacing is also determined by the size of the drive mechanism housings on the RM deck, and the need for access space between them. **Figure 6-18** shows the plan view of the CANDU 6 RM deck area, where it can be seen that the positioning, orientation and cable routing provide clear "alleyways" between the rows of the mechanisms large enough for a maintainer to pass his legs between some of the devices.

In a new design, the liquid zone controls are positioned first, since they permit maintenance of the spatial flux distribution in its optimal shape; they are positioned so as to have each absorber "compartment" neutronically centered in the corresponding regions into which the core is considered to be divided. The next items located are the banks of adjusters, so as to optimize the "flattening" of the core power spatial distribution; this is the high priority, because good flatness permits uniform fuel burn-up and therefore strongly influences the reactor's normal operating economy. The four mechanical control absorbers are located to each have influence on a quarter of the core, but their location is not critical because they are not usually in the core. Then the shutoff units are located in the remaining spaces, perhaps after minor re-adjustment to the regulating RCUs locations. Several iterations are usually attempted, with the objective of spacing the SORs relatively uniformly, such that the total "worth" or "depth" meets the specified target with the minimum number of SORs. To guarantee safety, the design must cater for the possibility of any SOR becoming spontaneously disabled at any time, and the designer calculates the "depth" with one rod discounted. Consequently, to assure this situation, the operator would have to test availability of each SOR frequently, and immediately shut down should he find one SOR actually unavailable (in case a second one becomes unavailable shortly afterwards). Logically, he would have to be testing all SORs constantly, but this would impose an unacceptable operating situation, because it would have the system impaired all the time. (Note that the SOR being tested is out of service during its test.) Therefore, on CANDU reactors the SOR system is designed on the basis of the *two best* SORs are assumed to be unavailable. The result is that the two best SORs are usually side by side, at one edge or corner of the plan, and to counter their being unavailable, the pattern of SORs usually has SORs closer together at the corners and sides. See the plan on **Figure 6-3.** Finally, the VFDs are located. Six VFD units are first located about 30 to 40 cm outboard of the six LZCs, to provide signals to the RRS, so as to modulate the variable "worth" of the LZCs and thereby maintain optimal power levels there. The remaining VFD units provide signal to the SDS1 circuits, to guard against regional overpower; they are positioned approximately uniformly in the remaining spaces in the RCU layout. One other factor that must be considered in the above process is locations of *horizontal* RCUs, shown in **Figure 6-5**. The in-core guide tubes for vertical and horizontal RCUs must cross one another, therefore they must be in different planes. The lateral locations for the horizontal RCUs are restricted to a few vertical planes and vertical RCUs cannot be located in the those planes. **Figure 6-3** shows these planes as dashed lines.

6.4 Specific Requirements and Detailed Description

All RCUs have generically similar configurations, perhaps sharing some component parts. These common items are described first.

6.4.1 Reactivity Mechanism Deck

The RM deck is a concrete–filled, carbon steel box structure, internally stiffened with bi–directional webs. The concrete is not needed for strength, but for local radiation shielding during flasking. The steel structure incorporates the penetration inserts for the vertical reactivity control units. Each insert contains an accurately located bearing to support the RCU thimble. A heavy tread plate is supported above the structure to provide a protected free space for cabling and services to the control units, while leaving an uncluttered walkway above for maintenance access. The tread plate also provides added local shielding during a flasking operation to remove a device from the reactor core. See **Figure 6-14**.

The deck structure is seated on a ledge in the top of the vault and secured by means of a wide seal web, welded around its perimeter on its underside, and to an embedment on the vault wall. This web is flexible to accommodate in-plane thermal expansion, yet sufficiently stiff to behave as a rigid horizontal and vertical coupling under seismic conditions.

Shielding provided by the deck, the RCUs, and walls around the steam generators and other equipment is designed to maintain radiation levels to below 250 mSv/hr with the reactor operating. This rate permits maintenance personnel to enter the area on power if required, but access is normally prohibited by operating rules to prevent unauthorized disablement or re-adjustment of RCUs. The RM deck area is accordingly a "regulated access" area.

A manhole penetration is provided through the vault top beside the deck. This will normally be closed with a concrete–filled plug towards the end of site construction work. This opening could provide access into the vault, outside the calandria and thimbles, if required during the reactor's life.

6.4.2 Thimbles

The vertical thimbles extend from the top of the calandria up through the RM deck, and enclose the moderator and its cover gas, while being immersed in the vault shield water. They are welded in precise locations to the calandria shell nozzles and slide freely vertically in bearings positioning them in the RM deck. **See Figure 6-9**, for example. A conical seat in the thimble bottom bell-fitting locates and supports the guide tube. Metal bellows are welded to the thimbles and deck penetrations to maintain a seal between the vault shield water and the air above the RMD. They also permit free vertical movement to accommodate differential thermal expansion between the thimbles and deck.

The horizontal thimbles extend from the shield wall through the vault wall to the calandria nozzles. Like their vertical counterparts, they are supported by bearings in the wall penetrations and are sealed flexibly by metallic bellows. Each horizontal thimble also carries a second bellows, which connects to the LISU injection tube or the HFD guide tube, acting both as a heavy water seal and a tensioner. **See Figure 6-8.**

6.4.3 Guide Tubes (GT & GTX)

Each guide tube assembly comprises a tubular Zircaloy in-core guide tube (GT) and a stainless steel out-of-core section called the guide tube extension (GTX).

The guide tubes for the shutoff, mechanical control absorber and adjuster units have many large, close-pitched perforations along their length, removing 35% of the metal. **See Figure 6-9**, for example. This minimizes the amount of neutron absorbing material and also precludes voids in the moderator. The top ends of these guide tubes are each seated in a precisely located conical seat in the bottom fittings of the thimbles, which are welded to the nozzles at the top of the calandria shell. All vertical guide tubes are secured at their bottom ends by threaded couplers screwed into locators on the bottom of the calandria shell. The locator positions are adjustable during initial installation, to permit accurate alignment of the guide tubes' bottom ends. All guide tubes are tensioned flexibly to reduce the amplitude of vibrations induced either by water turbulence or possible earthquake, while also permitting differential thermal expansion between the guide tubes and the calandria. Guide tubes for these RCUs are tensioned by coil springs at the bottoms of the tubes, acting on the couplings screwed into the locators. The guide tube extensions are installed separately, seated in a conical socket in the top end of the guide tubes, while their top ends locate freely in a bearing inside the thimble top.

In newer designs, such as the CANDU 9, the configuration of the GT and GTX for SORs, ADJs and MCAs is changed. The bottom coupler is rigidly attached to the bottom of the GT, and the GTX is screwed into the GT. This assembly is then screwed into the locator at the bottom, but the tensioning spring is at the top, in the RMD penetration. The present and new designs are compared in **Figure 6-19.** This design removes the burn-up penalty of the spring and its fittings from the core reflector region, and also simplifies re-tensioning of the spring in service.

The guide tube for the vertical flux detector unit, shown in **Figure 6-7**, is not perforated, but is vented to the moderator through small top and bottom holes. Its GTX is permanently attached to it, by means of a proprietary diffusion bonded joint. The guide tube for the horizontal flux detector unit is not perforated or vented, but is a gas-filled pressure-retaining tube. This permits its FD assembly to be removed without the moderator being drained. Vertical flux detector guide tubes for CANDU 6 are tensioned by a spring at the top of the GTX. Horizontal flux detector guide tubes are tensioned by a metal bellows on the ends of their thimbles, outside the vault wall, as shown in **Figure 6-8.** In the Bruce & Darlington VFD, the design is simplified a little, and the guide tube is sealed and gas-filled like the HFD assembly, and it is tensioned by a bellows at the top which also seals the guide tube flexibly to the thimble. **See Figure 6-20.**

The zone control unit does not have a guide tube, because it is a factory-sealed integral unit with a closed outer shell tube. Its top fitting is bolted directly to the thimble top, and it is inserted directly through the thimble into the moderator. **See Figure 6-10**.

The LIS unit does not have a guide tube, because it comprises only the nozzle tube in the core region. Its nozzle tube is supported, attached and tensioned in the same way as a HFD unit. **See Figure 6-12**.

6.4.4 Flux Detector Units (VFD & HFD)

Each flux detector unit consists of a flux detector assembly, a guide tube, a thimble, and penetration and seal components at either the reactivity mechanism deck or the vault wall, as shown in **Figures 6-7 and 6-8**.

The CANDU 6 flux detector assembly comprises a factory sealed capsule tube containing a number of Hilborn flux detector elements in individual well tubes, joined to the connector housing and enclosing individual connectors and shield plugs. This factory-sealed assembly is inserted into the guide tube and its housing flange is bolted to the thimble top. **Figure 6-21** is a schematic representation of this concept. A cluster of twelve thin well tubes is inserted into the capsule tube. Eleven well tubes can be used to insert Straight Individually Replaceable (SIR) self-powered detector elements having varied lengths of lead wires to reach specified in-core positions. Most assemblies have fewer than eleven detectors installed and vacant sites are filled part-way with wire shield plugs. The capsule is filled and sealed with pure helium at moderate pressure to provide the detectors with an assured benign environment. The helium also transfers the nuclear heat from the detectors to the cool guide tube. As noted above, in the Bruce and Darlington FD unit shown in **Figure 6-20**, the capsule tube is functionally combined with the guide tube, and this sealed assembly is directly screwed into the bottom locator and bolted and sealed flexibly to the thimble at the top by a bellows which also serves as the tensioner.

Each detector element is comprised of a central emitter wire enclosed in a sealed, thin Inconel sheath tube, 3.0 mm OD, as shown in **Figure 6-22.** A ceramic insulator separates the two items and they are each conductors connected to an amplifier circuit as shown. Each element is about 0.7 m long and carries an integrally–connected sheathed lead wire, terminated at an individual connector inside the housing. These devices generate a voltage between the two conductors because the emitter and the sheath respond differently to neutron, β and γ radiation acting on them in the core. **Figure 6-23** illustrates these processes. Different metals are used for emitters to provide the different response characteristics for different purposes. Detectors used for regulation and safety should be fast responding, to permit quick system changes to deal with undesirable power transients. Both platinum and Inconel emitters provide an instantaneous response to a step change in neutron flux, to within 10% of their final value, reaching their full values after a few hours, and are well suited for this purpose. Detectors used for input to the fuel management program need average signals to permit long-term integration of power, ignoring short term transients. Vanadium emitters respond only 15 minutes after a flux change, but reach final values directly, and suit this purpose well. The responses of these detectors to a step increase in neutron flux are shown on **Figure 6-24.** For reference, it also shows that the power generated in the fuel has an instantaneous response to the step change in the flux, to 95% of its final value, reaching final value after several hours.

The twelfth well tube in the assembly normally carries a shield plug and is reserved for possible use of a travelling flux detector (TFD), which is a small fission chamber approximately 3.0 mm OD and 25 mm in length. The TFD sensor is part of an optional auxiliary unit which may be used to perform in–core calibration of detectors. Its lead is wound on a large diameter spool in a shielded cabinet, with connectors and adaptors to join to the flux detector housing and to provide the electrical signal. The TFD can be moved to any point within the reactor at reduced power, to avoid difficulties due to the transients its mass will generate in nearby detector signals.

6.4.5 Ion Chamber Units (IC)

Each ion chamber unit consists of the ion chamber housing, access tubes and vault wall penetration assembly, shield plugs, ion chamber instruments and cables and the shutter assembly and its air connections. Brackets welded to the calandria shell are also parts of these units. As shown in **Figure 6-5**, each housing contains three cavities which can accommodate an ion chamber unit, a test shutter cylinder or temporary start–up instrumentation. The housing is filled with lead surrounding the instrument cavities, to absorb gamma flux and make the instruments sensitive only to neutrons. **See Figure 6-25.**

Ion chamber housings do not penetrate inside the calandria, and their interior is vented through the access tubes to the reactor building atmosphere outside the vault side wall. The housings and the access tubes penetrating the vault wall are uniquely designed as low pressure vessels with vault water on their exterior surface. They are fabricated of stainless steel.

The stainless steel access tubes pass through a penetration assembly in the vault side wall. They permit direct manual installation or removal of the instruments, shutter assembly, shield plugs and electrical and air connections. They are enclosed by a protective sleeve in the vault wall penetration. A bellows maintains a light water seal in the vault wall penetration, while being flexible to allow for relative movement between the calandria and the vault. The bellows is formed from 2 or 3 laminated layers of Inconel sheet, about 0.2 to 0.3 mm thick. A freezing coil is provided to permit repairs to the bellows in the event of its being damaged. Liquid nitrogen would be flowed through the coil to cause an ice plug to form in the shield water in the annulus, permitting removal of the bellows.

The shutter assembly is comprised of a boral cylinder mounted on a push rod which extends back through the inner shield plug segment, on bearings, to an air cylinder which is buried in the outboard segment of the shield plug. An electric switch on the rod signals the stroking position of the shutter. When the shutter is pushed forward, its boron gathers most of the neutrons in the vicinity of the instrument, to depress its signal. When rapidly drawn back, the rate of change of the neutron flux provides a calibrating signal for the instrument.

A set of aluminum shield plugs is inserted in each channel, behind the instruments and the shutter and cylinder assembly. Each segment of the shield plug is split lengthwise to permit passage of the instrument signal leads and shutter cylinder air lines. **See Figure 6-26.**

6.4.6 Adjuster Units

Each adjuster unit comprises an adjuster rod, a vertical guide tube and guide tube extension, thimble and shield plugs, and a drive mechanism, as shown in **Figure 6-9.**

The adjuster rod consists of a thin–walled stainless steel tube with a central stainless steel shim rod, shown in **Figure 6-27.** The absorber element and its shim centre rod are of controlled thicknesses along their lengths to provide the specified neutron absorption characteristics. Adjusters are only partially absorptive of the neutrons in their vicinity, because of their special function. That is, they only slightly depress the flux locally, to provide more uniform power production throughout the core. Besides being an economical material for this absorber, stainless steel fortuitously has very well suited transmutation characteristics, for the neutron energy spectra in a CANDU core. As some component elements transmutate to isotopes or elements of lower absorptivity ("cross-section"), other elements transmute to increasing absorptivity, and the net "worth" of the rods remains essentially constant throughout the reactor lifetime.

The adjuster rod is suspended by a stainless steel wire rope from its winch mechanism. The vertical location of the rod is indicated by a potentiometer coupled to the drive mechanism sheave shaft.

The adjuster drive mechanism, shown in **Figure 6-28,** is a permanently coupled, electric motor powered, geared winch. The high reduction ratio in the gearing makes it self–locking. The sheave is enclosed in a cast stainless steel pressure vessel housing, whose interior is open to the moderator cover gas in the thimble. It is an extension of the calandria vessel's pressure boundary.

Its shaft passes through a carbon and ceramic face seal to the non–pressurized gear case. The seal is a proprietary design which is wetted by the lubricating oil in the gearbox, to effect a leak rate below 10^{-3} cc/min of Helium at 100 kPa pressure. The drive housing is bolted and sealed to the thimble top.

The movement of the rods as they are raised or lowered is guided within perforated guide tubes within the calandria, and in plain guide tube extensions above. The cable passes through an upper and lower shield plug, and the route through the lower plug is zig-zagged, to block streaming of core radiation up to the RM deck area. See **Figure 6-29.** Pulleys ensure smooth motion of the cable. The upper plug is split to permit its being removed and re-used, should the element ever need to be replaced. The small lower plug is captive on the cable, and would be replaced with the element in such an operation. This arrangement allows for the maintainer to work in the area without the awkwardness of remotely operated tools or auxiliary shielding. The lower plug alone provides sufficient shielding during shutdown conditions for him to disconnect the cable from the drive sheave, and remove the upper plug, and to then to install the replacement element.

An optional variant of the standard adjuster unit has been installed in some CANDU plants where, in order to produce a useful by-product for commercial sale, the elements are made of cobalt, instead of stainless steel. The cobalt is in the form of stacked metal slugs encased in Zircaloy tubes to make pencils, and several of these pencils are then clustered together to form a bundle. A rod is made up of several bundles, assembled onto a Zircaloy central support rod. After one to two years irradiation in the core, the cobalt has been converted to radio-active Cobalt 60, which is used for medical purposes, sterilization of medical materials, and preservation of food. The relative ease of element replacement is conducive to rapid replacement during a normal annual or bi-annual maintenance outage of the plant, with no effect on other planned work in the plant. In order to adopt this option, a special flask, with thicker shielding than the usual RM flask, is required, and a layer of supplementary shielding plates is spread over the RM deck tread plates. A set of special handling tools and underwater work tables is installed in the receiving bay of the irradiated fuel by, to dismantle elements and transfer the bundles or pencils into a shipping flask.

6.4.6 Mechanical Control Absorber Units (MCA)

The mechanical control absorber units are essentially the same as the shutoff units, except that the shutoff unit accelerator spring and rod ready indicator are not incorporated, and the control absorber rod is provided with an orifice to reduce the insertion velocity for a free drop insertion. See **Section 6.4.8** for the shutoff unit description.

6.4.7 Liquid Zone Control Units (LZC)

The zone control units are tubular assemblies divided into either two or three compartments. Referring to the plan of the RCU layout in **Figure 6-3**, two-zone units are installed in the four corner locations and three-zone units in the two central locations, to provide a total of 14 compartments within the reactor core. These correspond to the 14 zones into which the core is theoretically divided, as shown on **Figure 6-30**, to permit differential control of the fission power levels in the core. Each compartment is partly filled to a controllable level with demineralized ordinary water, independent of the others. Ordinary water is an effective neutron absorber in a CANDU core.

As shown in **Figure 6-10**, the upper and lower boundaries of each compartment are formed by bulkheads to which the outer tube is welded. each zone control compartment has four tubes extending to a terminal block at the top of the zone control unit, on the RM deck. Two tubes are used for inflow and outflow of water and two are used for inflow and outflow of the helium cover gas. The water flows continuously to take away the heat generated by the radiation in the core region. Water level is sensed by the back-pressure on the helium gas being bubbled in from the compartment bottom, and adjusted by varying the water inflow rate while outflow rate is kept steady. The water flow is controlled by an external system of valves and pressure- and flow-measuring devices, as commanded by the RRS, based on signals from the corresponding flux detectors. The detail on the figure shows that the helium gas lines are located inside the water lines, and either terminate at the bulkheads between compartments, or pass through a bulkhead to service the compartment below. The flow pattern is as follows: Water enters the top of a compartment where the water lines passes through the bulkhead and splashes onto and over the baffle plate. The helium return line from that compartment draws from the underside of the baffle plate. The water return is drawn from the bottom of the compartment through a side hole in the water tube just above the bulkhead. The helium inlet flow runs down through the bulkhead and turns back up through the diagonal drilling to bubble up through water, and the back pressure it meets is the measure of the water level in that compartment.

The volume above the top compartment is filled with cooling water up to a shield plug under the terminal block, and provides additional shielding. The water and gas lines are zig-zagged in this region to prevent radiation streaming up through the gas lines.

The lower end of each zone control unit is attached to the calandria bottom by a spring-loaded, threaded locator, like the guide tubes of other RCUs.

The zone control units are designed and registered as pressure vessels.

6.4.8 Shutoff Units (SORs)

6.4.8.1 Description of Components of SOR Unit

As shown in **Figure 6-11**, each shutoff unit is comprised of a tubular shutoff rod, a vertical guide tube, a drive mechanism and accelerator spring, a thimble, shield plugs and deck penetration components, and a rod ready indicator.

Each shutoff rod (SOR) is suspended from stainless steel wire rope that is wound onto the sheave of its drive mechanism.

The shutoff rod is a tubular lamination, comprised of inner and outer stainless steel sheath tubes, enclosing a thin cadmium layer. Its construction is shown on **Figure 6-31.** The sheath tubes are welded closed at each end, and welded to an end ring at the bottom and the stainless steel push rod at the top. The supporting cable is attached to the push rod by means of a special nut, which traps a ball swaged onto the cable end. The push rod also carries a collar part way up, on which the compressed accelerator spring locates through a travelling spacer ring, when the SOR is in the withdrawn (poised) position.

The accelerator spring is enclosed in a casing attached to the underside of the shield plug. When the SOR is poised, it compresses the spring. When the SOR is released, the spring provides energy supplementing gravity, to accelerate the SOR into the core. The spring acts only over the initial metre or so of travel, then is arrested by the bottom travelling spacer nesting on the bottom of the casing.

The drive mechanism is an electric motor-powered winch which includes an electro-magnetic clutch to couple the sheave shaft to the motor gear train. The mechanism is bolted and sealed on the top of the thimble directly above the reactivity mechanism deck. Its components are schematically shown on the detail of **Figure 6-11.**

6.4.8.2 Operation of SOR

De-energization of the clutch by a trip on the SDS1circuit permits the sheave to rotate freely, under the torque due to gravity and the accelerator spring acting on the rod. The sheave shaft is permanently coupled to the damper through the position limiter device. This device is a series of "dog-plates" on which a protruding lug connects to a similar lug on the next plate, after 0.875 revolutions. There are eleven such plates, so they all become connected after 9.625 revolutions of the shaft. The last plate connects to a damper vane which will contact a stop on the housing end plate after it travels 0.875 revolutions, making a total shaft travel of 10.5 revolutions. This provides a positive down stop position at the end of travel. When the SOR is withdrawn, all of the plates rotate back to their original positions, and the damper connects to the up stop on the housing end plate. The damper vane is enclosed in a sealed, cylindrical, oil-filled cavity which has a small by-pass groove in the end plate. This acts as a rotary hydraulic damper to resist the rotation of the shaft as the damper vane makes its rotation at the end of travel, and forces the oil in front of it through the by-pass into the space behind it. This acts to arrest the momentum of the falling SOR to bring it to a smooth stop at the end of its travel.

When the clutch is energized by clearance of the trip signal, the rod is raised by its motor. The vertical position of the rod is measured by a rotary electrical potentiometer on its sheave shaft. When the rod is driven up or down, the motion is stopped by the motor being shut off by the control system via the position sensing circuit run from the potentiometer output, before the end of mechanical travel is reached.

A second position sensor, the "rod ready" indicator, directly monitors the presence of the rod in the up position, to verify it is "ready" for use. It consists of a set of magnetic switches mounted in a well in the shield plug, actuated by a permanent magnet mounted inside the top of the SOR push rod.

To meet the CANDU safety philosophy of separating safety and regulating functions, the clutch and "rod ready" indicator are part of safety circuits only. The withdrawal motor is part of the regulating system, and this mechanical configuration guarantees that it cannot withdraw the rod until the safety trip holding the clutch de-energized is cleared.

6.4.8.3 SOR Performance

An operating SOR unit is required to insert its rod into the core within a specified performance profile as shown on **Figure 6-32.** Acceptable insertion performance is defined by the elapsed times to travel to three specified "gate" distances, 1.83 m, 3.96 m and 6.09 m from its normal poised position. The second gate is at the core centre. Time to full insertion is not specified because the damper decelerates it over the last 0.6 m of its 6.64 m full travel. The SORs typically perform significantly faster than this, as shown on the figure. To be acceptable, a CANDU 6 SOR must meet or exceed the following performance values.

Elapsed Distance	Typical SOR	SOR Performance Test Requirement
First Gate	*0.67 seconds*	*0.71 seconds, average* *0.75 seconds, max. each rod*
Second Gate	*0.98 seconds*	*1.17 second*
Third Gate	*1.35 seconds*	*1.57 seconds*

The corresponding rate of increase of negative reactivity when all SORs are inserting is shown on **Figure 6-33.** This performance specification has been determined by reactor safety analysts, for the SDS1 design condition, a break in an inlet header in the core coolant circuit, ie, a Loss of Coolant Accident (LOCA). At the beginning of this event, the coolant flow to half the channels in the core rapidly slows and stops, while the reactor continues to run. Consequently, the fission causes a rapid increase in thermal power in the fuel channels. **Figure 6-34** is a plot of computed local power levels, in several bundles in the core, during such an event. In a CANDU, the loss of the coolant in the channel also causes an instantaneous increase in neutron flux, and this causes a trip signal in the SDS1 flux detectors, which immediately releases the shutoff rods. The times when the SORs enter the core edge and reach their gate positions are noted on the figures. This graph shows that heat in the bundles at the top of the core stops increasing as the SORs enter the core edge, and many bundles show decreasing in power when the SORs reach first gate; but all bundles show decreasing power when the SORs reach mid-core, after only 1.2 seconds.

This graph shows that the speed of SORs near the core centre is the dominant characteristic for the system of SORs. However, once the fission power has been shutdown, there is a second phenomenon to deal with as well. Secondary decay processes continue and generate delated neutron flux, which causes secondary heating. The system of SORs must have sufficient depth of distributed negative reactivity to suppress these reactions, and this is independant of the speed of shutting down.

Following clearance of the abnormal reactor condition causing the trip, the trip circuit can be reset by the operator, and he can withdraw the SORs. The SORs are withdrawn in groups, at a fixed speed, each being re-poised ("armed") in 150 seconds. This slow removal is necessary to avoid the ion chambers causing a re-trip, due to an excessive rate of change of neutron flux.

CANDU practice is to withdraw all the SORs as soon as a trip is removed and to keep them poised whenever there is no trip applied. For example, they remain poised while service tasks are to be done elsewhere in the plant before re-starting, or throughout all plant maintenance outages. This ensures that the negative reactivity of the SORs is available to be inserted should there be an unexpected rise in core reactivity during the shutdown, eg, an inadvertent removal of dissolved boron from the moderator, say, *through* test running of the pumps on the ion exchanger circuit. The SORs cannot be made unavailable unless the reactor is first placed in a "guaranteed" shutdown state, ie, the moderator poisoned by boron and the boron circuit valved out and locked; or the moderator drained and locked out.

Because of the build-up of Xenon in the fuel following a shutdown, and the total amount of reactivity change that the RCUs can collectively provide, a CANDU reactor must re-started within 20 minutes to avoid a poison out. Re-starting takes about 10 minutes, by removal of ADJs, MCAs and LZCs. This means that if the shutdown had been caused by a spurious trip, (ie, a "false alarm"), and there is no real reactor abnormality, the reactor can be returned to full power if the situation is properly identified within 10 minutes. If the restart is not started by then, the reactor poisons out, and the plant must stay shutdown for 40 hours, until the Xenon decays to a sufficiently low level.

As part of a special safety system, the shutoff unit must be qualified to insert while enduring both a LOCA event and a DBE seismic event, although not simultaneously; and it must also be able to insert immediately following either event. However, the ability to withdraw is not a requirement during or after those events. Accordingly, insertion qualification tests are performed on a complete SOR unit under both simulated LOCA and earthquake conditions. Since its safety system function is not dependant on the enclosed pressure during those events, it remains a class 3 item, as an extension to the calandria, enclosing the moderator. Accordingly, its pressure boundary components are designed and pressure tested in the same way as other RCUs, but its mechanical performance must be demonstrated by testing. Note that a major LOCA event, such as a PHT header break, applies *external* pressure and temperature on the SOR, but the SOR will have already inserted to shut down the reactor due to a PHT process trip, well before these conditions act on the outside of its housing. The most critical LOCAs for SOR insertion performance are smaller LOCAs such as a feeder break, where hot conditions may prevail for several minutes, or even hours, before the trip occurs.

6.4.8.4 Kinematics and Dynamics of SOR Insertion Process

When SOR performance is measured in testing, the SO unit's own potentiometer signal is first calibrated against physical height measurements of the element being lowered slowly. An electronic chart recording then provides an accurate record of position versus time, with time measured from the point of interruption of clutch power. Mathematically, the shutoff unit is simply represented as a mass which accelerates downwards under the influence of a number of varying forces. The inertia of the rotating sheave and of the spring and the cable act as added parasitic masses equivalent to about 1/3 the weight of the standard rod. The forces acting are gravity plus the decreasing initial spring force, less the initial drag of the gradually releasing clutch plates and increasing hydraulic drag and buoyancy as the rod inserts into the moderator. This results in an approximately parabolic acceleration to about the 2 m mark, after which the forces virtually reach equilibrium and it continues at essentially constant speed. See the graph in **Figure 6-32.** An acceptable CANDU 6 SOR has a brief delay of about 0.14 seconds, then accelerates and travels to about 1.87 m in the first 0.75 seconds, then continues at essentially constant velocity to reach 6.14 m at 1.57 seconds and then is decelerated in the last 0.6 m travel. Actual rods are usually faster, by typically 0.075 seconds. The initial 0.14 second delay is due to excess capacity of the clutch compared to the torque applied by the spring and the weight of the rod. This is a margin to preclude slippage of the rod off the poised position. When released, the electro-magnetic field clamping the friction plates has to decay until it drops to equal the value of the applied torque, where it can start to slip. Even then, the difference between the clutch's instantaneous capacity and the torque applied is only gradually increasing, to cause increasing acceleration as the field continues decaying.

6.4.8.5 Performance Verification In Service for SOR

In-service, shutoff unit insertion performance is measured by recording the drive's potentiometer signal against time elapsed after the electric power to the clutch is opened. Each SOR is tested on power by a "partial drop" approximately once a month, to confirm its availability and the proper initiation of its release. This is not a full insertion, but a momentary opening and re-closing of its release device, for a carefully controlled standard time interval. The rod inserts only about 10% of its stroke, i.e., to just reach the vicinity of the first row of calandria tubes. The actual distance travelled is not of consequence, since it is the consistency of the measured distance compared to its previous history that is important. The small perturbation in the core is also monitored on the flux detectors. For rods near the centre, some upper detectors will indicate a change of up to a few percent of their normal reading. A deviation of more than 15% from its normal test results is grounds for declaring that SOR unavailable for service, subject to closer examination at the next shutdown.

6.4.9 Liquid Injection Shutdown Units (LIS)

The in-reactor portion of each liquid injection shutdown unit consists of an in-core injection nozzle tube, an injection pipe, a thimble and a calandria vault wall penetration assembly. These components are shown in **Figure 6-12**. The remainder of the liquid injection shutdown system consists of injection piping and a liquid poison storage tank for each nozzle tube, a common pressurized helium supply tank, a set common of triplicated, fast-acting release valves arranged in a series/ parallel circuit, a poison mixing tank, and a drain tank. A schematic diagram of the LISS is shown in **Figure 6-13.**

The moderator in the calandria fills the nozzle tubes and the injection piping, all the way back to bottom of the poison tanks. The liquid in the poison is moderator water which has 2000 parts per million of Gadolinium Nitrate dissolved in it, which is a strong neutron absorber. There is no physical boundary between the poisoned fluid and the pure moderator in the pipe circuit. The elevation of the liquid poison tanks is set such that the free surface of the fluid inside is at the elevation of the moderator in the calandria. A small pipe connects the top volume in the tanks to the calandria cover gas system, to ensure a pressure balance. Inside each tank, a polyethylene ball floats on the fluid surface. When a tank drains out the ball drops down and seats on the pipe exit at the bottom, to seal it off.

The injection nozzles are machined Zircaloy extrusions, screwed into the stainless steel injection tubes at their inlet ends. **See Figure 6-35.** They are secured by a bayonet at their locators (in place of the coupler screw of other RCUs) on the opposite side of the calandria. Each nozzle is perforated by rows of small nozzle holes spaced and oriented to optimize poison dispersal in the moderator. It is tensioned by using the light water bellows as a spring.

The liquid poison storage tanks, quick-opening valves and the dedicated high pressure helium storage tank are mounted on the D side shield wall attached to the vault wall. **Figure 6-36** shows this arrangement. The routing of the LIS piping from the tanks is designed so as to ensure clear access to the housings for the other horizontal RCUs, including clear space at each site for a temporary shielded nose piece for the flask in the event of a removal.

When a trip signal is initiated in the SDS2 circuit, the solenoid-operated quick opening valves open to admit the high pressure helium to the top of the poison tanks, where its pressure causes the fluid to accelerate through the injection pipes and nozzle tubes, to inject through the nozzle holes into the moderator. The plumes of injected fluid travel rapidly into the entire core region, and to quickly shut down the fission process. The fluid rapidly disperses and mixes thoroughly. **Figure 6-37** shows the increase of negative reactivity. Comparing this figure to **Figure 6-33**, for the SOR, it appears that the SOR reaches *its* full reactivity much faster than the LISS (1.6 second vs 15), but in fact, the LISS final "depth" is very much greater, and it reaches the necessary -50 mk after only 1 second, while the SOR takes 1.6 seconds. Since the fluid has completely mixed with the bulk of the moderator throughout its entire circuit, the LIS cannot be re-poised quickly, and a LISS firing inevitably causes a Xenon poison out for 40 hours. The gadolinium nitrate solution is removed by pumping all the moderator through an ion-exchanger.

The strength of the gadolinium nitrate solution is assured by monitoring it by an electrical conductivity probe in the injection pipe close to the core. As there is no physical barrier between the moderator in the calandria and the poisoned fluid in the tank, the two fluids mix slowly through diffusion. If poison is detected at the probe, the fluid it is drained from the tank and piping and a new solution mixed and inserted in the tank. This can be done while on power, on one LISS circuit at a time, by valving that unit out.

The availability and proper operation of the LISS actuating valves is checked periodically in service, by closing sections of the triplicated, series/parallel circuit; this permits closing and actuating part of the valve set while the other part remains available for service.

The insertion of fluid through the injection piping and injection nozzles cannot be tested on power, because the poison from even one nozzle would cause an unacceptable perturbation flux distribution in the core. Furthermore, the LIS units cannot be tested one at a time because they have a common helium supply and a common set of actuation valves. Consequently, the LIS system is tested only at a planned plant shutdown. When the LIS system is tested, all units are actuated at once, and the system performance (including that of the trip circuitry) is verified by measuring the reactivity run-down on the flux detectors. Verification that each unit released is indicated by observing proper run-down of signal from appropriate nearby detectors, and acceptability of total reactivity is determined from integrating the rates from all detectors

As a safety system, the liquid injection shutdown unit is qualified for both seismic and LOCA environmental conditions, as well as being designed as a pressure–retaining system. As a safety system relying on pressure to function, its injection circuit is designated a class 1 system. Because its operating pressure is the highest pressure it can ever be subjected to, that is also its design pressure, ie, the LOCA which causes its actuation is a Level C condition for the reactor, but it is a level A service condition for the LIS nozzle.

6.5 Manufacturing Aspects

All in-core RCU components are made from Zircaloy-2 or -4, except the absorber elements and the flux detector sensing elements. The large guide tubes are made from perforated strip, formed and seam welded, with end fittings welded on, then annealed, straightened and stress relieved. Smaller tubular members are of pilgered seamless tube.

Out-of-core members are of seamless stainless steel tube, or machined from bar, generally of AISI type 304L. Housings are generally of cast stainless steel or machined from bar stock.

The in-core components of the flux detector assembly, other than the detectors themselves, are fabricated from seamless Zircaloy tubing which extends up to the connector housing, where it is welded or clamped to Zircaloy bolting flanges. The housing is machined from stainless steel bar stock. The central shield plug and individual well shield plugs are aluminium extruded rod and wire, respectively. The individual detectors are proprietary items, drawn and compacted from initially loose assemblies of emitter core wires or lead wires, Inconel sheath tubes and beads of ceramic insulation.

The ion chamber housing shell is a welded stainless steel fabrication that is filled with cast, reactor grade lead alloyed with small amounts of bismuth and tin. Brackets welded to the calandria shell to support each ion chamber housing are stainless steel. The access tube assembly is a stainless steel fabrication that is welded to the housing and is connected to the vault wall via the stainless steel bellows. The ion chamber instruments are enclosed in aluminium sleeves and shielded and supported by high purity aluminium shield plugs.

The adjuster and shutoff drive mechanisms consist of stainless steel housings with nodular cast iron used for some non-pressure retaining sections. The internal mechanical components of the mechanisms are mostly of carbon, alloy or stainless steel. The proprietary shaft seal has a Stellite bellows with carbon and ceramic faces. This seal and the drive motor are shared in common by ADJ, MCA and SOR drive mechanisms.

The liquid zone control assemblies are manufactured from Zircaloy tubing and welded to Zircaloy bulkheads separating the compartments. Internal tubes are given small zig–zag bends so they will be sprung against the outer tube when they are inserted. Near the top of the unit there are a stainless steel shield plug and a Zircaloy flanged terminal block. The bottom of the assembly is fitted with a Zircaloy locator coupling which is tensioned by an Inconel spring.

The construction of the shutoff rod involves the drawing and sizing of a cadmium sheet between two annealed stainless steel tubes so that the cadmium is completely enclosed and sealed when the ends are welded closed. The stainless steel end rings, support rod and spider ring are then welded to these composite cadmium and stainless steel tubes.

The LIS injection nozzle is fabricated from a Zircaloy extruded tube, machined to remove surplus material. The end pieces are machined from Zircaloy bar stock and welded to the tube. The Zircaloy surfaces which slide in the bearing bores at the calandria penetration nozzles are treated by an AECL proprietary process to generate a very hard, durable zirconium oxide surface layer. The injection tube is made of stainless steel pipe, with bearing sections made from machined bar, welded to the pipe. The nozzle tube and injection pipe are joined by a screw thread.

The RM deck is a closed, welded carbon steel fabrication with pre-machined penetration inserts and internal webs welded in after the main box is completely welded and machined. Concrete filling is poured in place after the structure's support webs have been welded to the vault embedments. The gap above these webs, between the sides of the deck box and the vault roof concrete, is filled with soft Styrofoam to provide an elastic filler, and the joint above closed with thiokol rubber caulking.

6.6 Analysis, Qualification Testing and Production Acceptance Testing

Only RCUs which perform functions for either of the two shutdown systems need to be environmentally and seismically qualified. Other RCUs, for regulating system service, need to be qualified for those events only to a limited extent, in two respects:

(a) for any accident, it must be assured that they will not fail in such a way as to cause an increase of reactivity (ie, they must either fall into the core or remain in place, if already in)

(b) it must be assured that, for any accident, they will not fail in such a way which would inhibit proper operation of a nearby safety system item.

This means that flux detector assemblies, ion chamber instruments and the two shutdown units are subjected to testing to demonstrate they will perform their safety functions during and after seismic excitation and then during and after exposure to the temperature and pressure cycles of severe accidents. The methodology of testing of these items is further discussed in the following sections.

All components for all RCUs are subjected to stress and seismic analyses to demonstrate they meet requirements of appropriate standards for design for mechanical components and/or pressure retaining items, and that they retain their structural and pressure boundary integrity under all normal and extreme conditions. All pressure retaining items are pressure tested to the required margin above their design pressures, as sub-assemblies during manufacture and/or at installation after their final closure joints are made.

6.6.1 Structural items

For all RCUs, the thimble assemblies are pressure tested after installation, so as to include the welds to the calandria nozzles; for horizontal devices, this will include their bellows. The sealed, bolted joints where the mechanisms seat on the thimble are pressure and leak tested as part of the leak test of the completed calandria assembly.

6.6.2 The Flux Detector Unit

The flux detector unit design was qualified by seismic performance testing and environmental testing, on irradiated/ aged specimens which included the detector elements. They were tested to simulated Design Basis Earthquake (DBE) response excitation levels and for LOCA-LOECC and small LOCA conditions to confirm both structural and electrical durability and operability. This was in addition to normal stress and seismic analyses performed to demonstrate conformance to mechanical and pressure vessel design standards.

6.6.2.1 Seismic Testing of the Flux Detector Unit

Because it is a very long and flimsy assembly, seismic testing of a full scale, full length assembly was impossible, especially considering that the housing and the in-core portion are subjected to totally different conditions. Instead, a complete housing assembly (with internal wiring) and a *representative*, 2-metre length of the in-core assembly were separately tested.

For the housing specimen, analysis demonstrated that there were no resonant responses in the housing itself, for the prevailing input FRS at the RM deck level. (See **Section 4,** also **Figure 4-10,** on vibration and seismic behaviour.) Therefore, the specimen was mounted on a dummy section of thimble top and the corresponding *unamplified floor motion* excitation for the vault top was applied, (not the FRS *response* acceleration levels). Accordingly, this would generate responses of internal items, like the connectors and wiring, if they had resonant frequencies.

None were found. During this test, the electrical resistance and circuit continuity of the detector leads and connectors was monitored continuously. Flux detector performance relies on maintaining insulation resistance above 10^6 ohms. No inconsistencies were found.

In the case of the in-core section, it was observed that there was a very large variety of lengths of guide tubes used, to span chordal distance across the calandria at various location in the reactor. Furthermore, it was accepted that there would be a large variation in tension applied during the life of the assemblies. Accordingly, analysis showed that it was probable that one member or another in the set of assemblies would respond resonantly at almost every part of the applied spectrum, when it is mounted at the top and bottom of the calandria shell. Consequently, in a test situation, it was necessary to apply excitation that would *obtain a resonant response* everywhere across the frequency range. Since the test specimen was only a short length, *it* would not have a resonant frequency of its own in the test range, and it accordingly had to have excitation level *applied* equal to the expected response amplitude, ie, it would have to have the envelope of the floor *response* spectrum (FRS) graph applied (not the floor *motion* levels, as for the housing test). **Figure 6-38** shows this relationship.

Two additional factors had to be considered in determining the amplitude of the test spectrum to be applied, for both tests:

(a) The earthquake motions act in three directions simultaneously. It might be assumed that the three directions are in phase with each other, therefore, if three-axis test equipment is available, three inputs would be applied simultaneously, and in phase. However, if only single-axis testing is available, then the input would have to be applied in the three directions consecutively, in case the specimen had a response in one direction, but in each case, allowance must be made for cross-coupling. That is, for a mass enduring three directions of in-phase excitation, one can resolve them into a single vector of magnitude equal to the square root of the sum of the squares of the three inputs (SRSS). For three equal inputs Z the net vector would be $\sqrt{3} \times Z = 1.73 \times Z$, and in theory, the equivalent single axis *test* input should be 1.73 times the *single axis spectrum* input. In practice the three inputs are rarely in phase, because base structures have directionality which influence their amplifications of the basic ground motion. Therefore, a smaller single-axis testing factor is more common, say, 1.4, to avoid gross over-testing.

(b) The earthquake applies all frequencies simultaneously, but the input at any one frequency is fluctuating in amplitude. In any resonating system, the instantaneous magnitude of response does not instantaneously reach the value of the amplification curve. **(See Figures 4-1 & 4-2)**. In fact, when the excitation starts in an undamped system, the amplitude of the mass increases by a factor of 3.14, on each succeeding cycle of vibration. In a moderately damped system, it will take three or four cycles to generate the maximum amplitude. Consequently, in a test where broadband excitation can be generated, a steady input with amplitudes matching the ground motion (or floor response motion) at all frequencies would over-excite the specimen by a factor of 2 or 3. Consequently, testing is preferably done with a constantly varying input excitation, whose maxima reach the test spectrum envelope. If only steady input can be generated, it is prudent to derate the input, by a factor of, say, 0.7.

On the other hand, if broadband excitation cannot be generated, and testing is done by sweeping through the frequency range, only a single frequency is applied at any instant. In this case, the potential for coupling two inputs at close frequencies is missed, and the system is under tested. (See the graphs on **Figure 4-8**). If single frequency sweep testing must be done, wherever two responses are found at close frequencies, it is prudent to increase the input amplitude at those frequencies by a factor of, say, 1.4.

In any given test, the above factors must be considered, and the product of those various suggested factors would be applied.

During this test, as on the housing test, the electrical resistance and circuit continuity of the detector leads was monitored continuously. No inconsistencies were found.

6.6.2.2 Environmental Qualification Testing of the Flux Detector Unit

Only the housing needs to be LOCA qualified for the flux detector unit as the LOCA conditions do not act inside the calandria. The housing assembly used for seismic testing was mounted and sealed to a dummy thimble top and installed in a test chamber and a simulated LOCA was applied. No inconsistencies were found, although some acceptable decrease was observed in insulation resistance in the commercial connectors, which recovered upon cooling. No leaks were observed.

6.6.2.3 Production Tests on Flux Detector Units

Each flux detector assembly is leak tested and pressure tested at manufacture. The assembly pressure boundary is hydraulically pressure tested in manufacture. The joints to the thimble are checked for leak–tightness during functional commissioning of those systems. The electrical resistance and capacitance of the individual detectors are also checked at both manufacture and at installation. The location and operability of each detector, and the correctness of circuit connections is finally confirmed by low power reactivity experiments during commissioning.

6.6.3 Ion Chamber Unit

The ion chamber unit, including the housing, access tubes, penetrations and internals is qualified for both pressure vessel design and seismic response by analysis. Seismic and environmental qualification of the instruments and its electrical components and connectors is assured by their manufacturer.

The calandria external pressure test provides the pressure test for the ion chamber housing, access tubes and bellows. Mechanical operation of the shutter mechanism is checked during manufacture and after installation. The location and operability of each instrument, and the correctness of circuit connections is finally confirmed by low power reactivity experiments during commissioning.

6.6.4 Shutoff Unit

6.6.4.1 Performance Qualification Testing

The development testing for performance of the CANDU 6 unit was an extension of that for the Bruce A unit, of which it is virtually a copy. For the Bruce design, a prototype unit built to full production standards was installed in a full scale test rig in a water–filled tank, and extensively tested to determine its basic insertion performance, and to prove efficacy of the basic componentry, including its bearings, seals, clutch, gearing, etc, with especial attention to the rotary hydraulic damper which decelerates the rod at the end of travel. Other tests ensured its insensitivity to likely variations in conditions, such as temperature or level of moderator, etc. Continuous cycling tests ran for 3000 cycles, to demonstrate its durability without maintenance or adjustment; this is many times the lifetime service requirement. These tests were done using ordinary water at room temperature, but computer modelling, verified by subsequent in-reactor tests, showed that the slight change in density is offset by a similar slight change in viscosity, to obtain a virtually identical performance. Most of these tests have been repeated on CANDU 6 units and some of them again on actual reactor installations.

6.6.4.2 Seismic Testing of the SOR unit

Seismic performance testing was done on complete shutoff units, to Design Basis Earthquake (DBE) response excitation levels. The seismic test rig was comprised of a large vertical tank representatively supporting the SO unit at the calandria top and bottom and at the RM deck. See **Figure 6-39.** It had short lengths of calandria tube alongside the guide tube in the in–core section, to accurately simulate in-core pressure transients caused by water displaced by an inserting rod. Electro-magnetic exciters were mounted horizontally at the top and bottom of the guide tube, where it attaches to the calandria; another was at the mechanism, where it mounts in the RM deck. They were excited by time history signals simulating a real earthquake, amplified and damped to represent the local structural response. Instruments measured response accelerations and displacements on key components. Other tests were done with discrete, steady frequency inputs applied, swept over the entire frequency range, to determine component characteristics.

The seismic qualification testing of the SOR was done in two parts. First, the mechanism alone was subjected to excitation as the rod was repeatedly released. The applied test excitation included a 1.65 times factor on the design spectra values to conservatively account for testing characteristics. The mechanism was shown to be entirely free of resonances and insertion performance was identical for all tests.

The second phase was done on a complete, instrumented SOR unit installed on the full sized seismic test rig shown in the figure. It was excited by electronically controlled hydraulic actuators at the RM deck and at the top and bottom of the immersed guide tube. Time histories simulating several families of actual earthquakes were applied, with varied amplification to represent varied severity of earthquake. These are equivalent to about 0.3 g ground motion input at the reactor building base, well above any current CANDU site requirements. There were also supplementary excitation tests on the individual guide tubes, thimbles and the absorber, to determine their individual resonant frequencies. **Figure 6-40** shows a typical recording of the key parameters for the SOR dropping while the simulated earthquake is being applied.

These tests demonstrated that the unit inserts within specified times during and after application of any one of these conditions. The seismic tests showed that the shutoff insertion is slowed by a small amount of time, directly proportionate to the response acceleration of the in-core guide tube, reaching only 0.04 seconds for 0.4 g input ground motion. For environmental accident conditions, the stainless steel housing ensures the extreme temperature and pressure have negligible effect on internal components in the brief exposure time before the rod is dropped; there is no measurable retardation.

6.6.4.3 Environmental Qualification of the SOR unit

The LOCA test rig comprised a steam chamber enclosing the mechanism, and an adjacent water-filled tower containing the rod and guide tube. Thermocouples monitored appropriate points in the mechanism. The rod was repeatedly dropped at varied time intervals following the chamber being filled with steam, at programmed temperature and pressure.

6.6.5 LIS Unit

The pattern of the liquid poison's distribution into the moderator fluid, and its rate of growth was determined by extensive underwater testing. The influence of varied nozzle hole sizes, distributions, attitudes, tube positions and also pressures was learned from extensive testing and a computer code was developed, from which designs can be optimized. It is also used to predict performance for new reactor designs, where a larger reactor size requires a longer nozzle tube, effecting insertion time. Parameters can also be varied to study means to change insertion speed, or its initial delay.

6.6.6 Adjuster

The adjuster is a relatively simple device, and its development testing was limited to endurance qualification for the components, particularly the high ratio, single pass gearing. The assembly pressure boundary is hydraulically pressure tested in manufacture. The joints to the thimbles are checked for leak-tightness during functional commissioning of those systems.

6.6.7 LZC

The liquid zone control has no moving parts, and no qualification or functional testing is required. The CANDU 6 design is only slightly changed from the Pickering A unit from which it has evolved. Component durability was proven on those original prototypes.

The assembly pressure boundary is hydraulically pressure tested in manufacture. The joints to the water and gas systems are checked for leak–tightness and correctness of connection during functional commissioning of those systems.