SECTION 2 - CANDU Reactor Design Philosophy and Practices; Rationale for Lay-out and Configuration of the Reactor Assembly; Key Operating Parameters

2.1 CANDU Design Philosophy; Rationale for Basic Concepts & Configuration

- At the outset of the CANDU program in the 1950's, fundamental decisions were made by pioneers led by Lorne Gray, J.B. Lewis and John Foster, and others, which formed the foundations for the unique and successful CANDU configuration. They aimed to *maximize neutron economy* and *minimize the cost* to *develop* the concept *and build* plants in Canada; they also wanted to maximize use of facilities, materials and technology available in Canada and minimize dependence on other countries, *at that time*.

- The use of *natural uranium* avoids complex and costly technology for enriching uranium. This meant using *heavy water for moderator*, a large but less uncertain development challenge. It also meant almost exclusive use of Zircaloy for in-core structures, to obtain low burnup penalty and good neutron economy.

- The heavy water moderated natural uranium core is more widely distributed than light water reactors (LWR), permitting more regional control and thereby, more uniform flux and power distribution, to obtain superior neutron economy and fuel burnup.

- Relatively thin, small diameter Zircaloy *pressure tubes* are used for the Class 1 *primary coolant* pressure- retaining system, which avoids fabricating very thick, large pressure vessels as used for LWRs. Furthermore, the same standard pressure tube is used for all sizes of CANDUs, while the LWR vessels become thicker and much more difficult to design and fabricate for larger sizes.

- *On-power refuelling* is feasible because pressure tube ends can be opened inside the pressurized fuelling machine. The reactor has to deal with the extreme excess reactivity condition, due to having fresh fuel throughout, only once, at its initial start-up. Thereafter, it operates continuously at virtually constant, near- optimal conditions, with flexible shutdown scheduling.

- *Special Safety Systems* are required to be *fully separated* from, and *independent* of the normal functioning of reactor process and control systems, and are comprised of Shutdown Systems (SDS), Emergency Core Cooling (ECC), and Containment.

- *Two separate, diverse and independent reactor shutdown systems (SDS1 & SDS2)*; each fully capable and *independent of the reactor regulating system (RRS)*.

- Design of the CANDU reactor structure assembly is dominated more by functional and structural considerations than by pressure vessel aspects. It certainly imposes significant pressure vessel design challenges, but the concepts and configurations are largely dictated by the requirements for position, space and mechanical function of the supported and inter-facing items.

- The CANDU *calandria*, holding the *moderator*, is a fairly light-walled, stainless steel, Class 3 vessel operating at near atmospheric pressure and sub-boiling temperature.

2.2 Configuring the Core, Calandria, End Shields, Supports, RMD and Reactor Vault

- The design of the reactor assembly begins by setting the size and configuration of the reactor core, the vessel enclosing and supporting it, and the location and configuration of its inter-facing systems. The weights and pressures of the various component parts and fluids will then determine the thicknesses, detail shapes and materials of the structural members. This information will be compiled in the *Design Requirements* document. Simplified load and stress analyses will be performed which, at this stage, will include many assumed and estimated values. For this purpose a set of loads is selected which reflect the basic operation of the item; these are called *Design Loads*. They are defined as the highest Level A and B loads to be applied. ASME and CSA N285.0 define four levels of service load conditions, A through D, which reflect the frequency or rarity of their occurrence, and for which different allowable strength values are available. This is further discussed in section 3.1, below. Consideration must be made of the prevailing conditions and operational requirements, such as temperature, thermal expansion, radio-activation and biological shielding, radiation effects on material properties, corrosion prevention, durability or replaceability, and access for maintenance or repairs.

- The *core size* depends on chosen output power, which determines the number of *standard fuel channels*. On average, each fuel channel delivers a net output of about 1.8 MW_e, and a 685 MW_e CANDU 6 core has 380 channels. An 850 MW_e Darlington reactor has 480 channels. The fuel channels are arranged in rows and columns on a square lattice pattern at *standard pitch* of 285.75 mm (11.25")*, and form an approximately circular array. See **Figure 2-1.** The radial thickness of the *reflector layer* of heavy water, about 654 mm, is added to determine the *calandria shell* inside diameter, which for CANDU 6 is 7.59 m (299")*. For Darlington it is 8.52 m (335.5")*. The length of the core is equal to the length of a standard CANDU fuel channel, which is 5.944 m (234")*, for all current CANDU reactors. This is the length of 12 standard CANDU *fuel bundles*, each 495 mm (19.5")* long. This is the distance between the inner tube sheets of the end shields. See **Figure 2-2.**

(*Note that current CANDUs were designed originally in Imperial measure, and this proven configuration is maintained exactly, but presently expressed in metric measure.)

- As shown on **Figures 2-2 and 2-3**, the type 304L stainless steel main shell steps down about 0.5 m radially to a *sub-shell* at each end. The intervening *annular plates* provide axial flexibility, so as to not inhibit axial thermal expansion of *calandria tubes*. The *diameter* of the sub-shell is the same as that of the *end shield*. The step in the shell also excludes part of the reflector near the end shields where it loses effectiveness, and the loss of escaped neutrons will result in only slightly higher fuel cost. The *length* of the sub-shell was initially optimized for the capital cost of heavy water versus forecast lifetime cost of fuel, allowing for forecast rates of interest and inflation, *as forecast at that time*. Not surprisingly, the sub-shell lengths for Bruce /Darlington and the later CANDU 6 are different: Bruce design has 0.46 m (18") and CANDU 6 has 0.97 m (38"). Once their main shell lengths were chosen, the designs were not subsequently changed, since the layouts of reactivity control units (RCUs) were optimized to suit, and are not readily redesigned. The number and position of the various RCUs has little influence on calandria shell design, other than the concern for re-enforcement around the very large number of penetration nozzles for the thimble tubes, which provide access to their actuator mechanism and connector housings. See **Figure 1-5**. The main shell thickness is only 29 mm (1.125"), although this is considerably thicker than that needed for hoop stresses under normal operation. This thickness was determined to accommodate local bending stresses at the joint to the annular plate, which would be theoretically generated in a postulated PT/CT rupture event, causing high internal pressurization. The sub-shell thickness is the same, but the annular plate is thinner, at 19 mm (0.75"), to provide flexibility.

- The type 304L stainless steel end shields are double-walled, disc-like vessels, welded to the sub-shells at each end, and joined by *lattice tubes* welded into the two tube sheets, one for each fuel channel. **See Figure 2-3.** The lattice tubes have 90.5 mm (7.5") bore and 6.3 mm (0.25") thickness. The end shield diameter is the minimum size which will allow acceptable edge distance on the end shield tube sheet, beyond the outermost fuel channel. On CANDU 6 the distance is 216 mm (8.5"), and the end shield diameter is 6.76 m (266"). The lattice tube diameter is made sufficient to permit the end fitting pass freely through its bore, with allowance for bearing rings. The end shields are filled with ordinary water and steel balls, and are of sufficient thickness to thermalize and absorb neutrons. This precludes activation of the outer tube sheet and permits shutdown access in the vault. CANDU 6 end shields are 914 mm thick (36"). The *tube sheets* are thick, to provide rigidity after accounting for the large amount of material removed for the lattice tube bores. In CANDU 6 the inner (calandria side) and outer (fuelling machine side) tube sheets are 51 mm (2") and 76 mm (3") thick, respectively.

- The calandria tube ends are rolled into the lattice tube ends at the inner tube sheets, to secure them, and the calandria tubes act as tie rods joining the two end shields. See **Figures 2-3 &**

2-4. The calandria tubes are made of annealed, seam welded Zircaloy-2, and have 129 mm (5.08") bore and 1.37 mm (0.054") thickness. Their thickness is much greater than that needed for the normal *external* moderator pressure; and they will withstand *internal* pressurization due to a postulated burst pressure tube.

- The fuel channel assemblies, comprised principally of the pressure tubes and end fittings, are supported freely on bearings inside the calandria tubes and end shields. **See Figure 2-5.** The fuel channel assembly is located axially by the positioner assembly, which connects to the end fitting by a yoke and is tapped into the outer tube sheet. The end fittings extend beyond the end shields a length sufficient to allow for the many rows of *feeders*, which transport the coolant up to the headers. **See Figure 1-3**. Each pressure tube has 104 mm (4.09") inside diameter and 4.2 mm (0.165") thickness, and is made of extruded Zirconium-2.5% Niobium alloy. The bore was established to provide acceptable clearance on the standard CANDU fuel bundle. The end fittings are of AISI 403 stainless steel with 112 mm bore, and include a liner tube of 104 mm bore.

  Note that the feeders must each be routed laterally away from the end fitting, across the face of the end shield, to then be turned up towards the headers. Accordingly, all the feeders in one row must pass across the adjacent end fittings, half each way, and the outermost end fitting will have half the feeders in that row crossing it. **See Figure 2-6.** In CANDU 6, there are 22 fuel channels in the mid-plane row, so there will be 9 other feeders crossing the outer end fitting (the 10th is run vertically up at the centre). That end fitting must accordingly be sufficiently long to allow for that bank of feeders, plus space for its own feeder connection and closure. It therefore extends 2.36 m beyond the end shield face. Note that this feature has a very large influence on the entire reactor building: an attached fuelling machine (FM) will have to have a ram stroke long enough to reach through its magazine and through this length and then through the end shield, to reach the fuel. This sets the length of the FM, and in turn sets the length of the FM vault and the diameter of the reactor building: it must enclose the reactor length including end fittings both ends, plus the FM vaults at both ends.

- The entire calandria-end shield assembly is supported by flexible cylindrical shells and annular plate rings around each end shield which are in turn supported in embedment rings in the concrete vault end walls, in CANDU 6. **See Figures 2-2 & 2-3.** In Darlington & Bruce the end shields are directly supported in fabricated steel end walls of a free-standing shield tank vessel. **See Figures 2-7a & 2-7b.**

- The reactivity mechanisms deck (RMD) is supported either in the vault roof (CANDU 6), or directly on the extensions of the shield tank end walls (Bruce). **See Figures 2-1 & 2-7b.** Its purpose is to provide a working area for access to the connector housings and actuators for the reactivity control units (RCU). The RMD elevation is set to be above the longest withdrawn RCU absorber rod, which is about 2 lattice pitches less than the core diameter.

The section of its support cable which has been irradiated has to be accommodated also. **See Figure 2-8.** The height of shield water above the calandria provides sufficient shielding to permit on-power access on the RMD. The plan area of the RMD is determined by the array of RCU; the CANDU 6 RMD is shown on **Figure 2-9.** The number and locations of the various RCUs has little influence on the design The RMD structure is 1.22 m (48") thick, made of 25 mm carbon steel top and bottom plates, with vertical internal webs. **See Figure 2-10.** The RMD is made that thick primarily to facilitate internal access in its fabrication. It is filled with concrete and fitted with 100 mm thick tread plates to provide local shielding during a possible flasking operation to remove an active RCU component from the core.

- As shown on **Figure 2-1**, the 1.1m (42") distance between the calandria shell and the vault side walls provides shield water to avoid overheating or activating the concrete. The 1.22 m (48") thickness of the vault walls adds shielding to permit shutdown access at the vault side face. An additional 1.6 m (60") concrete wall, on the side facing the containment airlock, permits on-power access to horizontal RCU connector housings, and manual loading of new fuel bundles into the fuelling ports located there.

- Access spaces, served by large cranes, are required above the RMD and outside the shielded side of the vault for large shielded flasks to remove long RCU internal members in the unusual event of replacing them. See **Figure 2-11.** A clear route is also needed for the flasks to move to and through the building air lock, for discharging. The layout of the calandria vault and the access and craning areas significantly influence the design and lay-out of the reactor building, including clear routes for transporting the flasks to and through the building air lock.

- At both ends of the reactor, the fuelling machines (FM) can be attached onto the end fittings to exchange fuel; one receiving irradiated fuel and the other inserting new fuel. See **Figure 1-1.** As shown **Figure 2-12**, each FM is comprised principally of a snout to temporarily attach to the end fitting end, a rotating magazine to hold fuel and tools, and an actuating ram to control fuel movement. This figure also shows the cradle supporting the FM via the trunnions, which permit it to align freely on the end fitting. At both ends of the reactor, a FM and cradle assembly is in turn mounted on a carriage, bridge and column system, which permit it to be positioned opposite any fuel channel, for fuel changing. **See Figure 2-13 (plan and elevation).** Stationary extensions to the bridges permit the FM and carriage to also traverse to the ports located to the side of the reactor, for accepting new fuel and for discharging irradiated fuel. This figure also shows the catenary system of hydraulic hoses and electrical cables which supply the PHT coolant, the oil hydraulic power, and the electrical signals which control the motions of the fuelling operation. To complete the fuelling system, **Figure 2-14** shows the new fuel loading machine located between the two new fuel ports, on the reactor "B" side, which is accessed by a crane servicing the main air lock. Similarly, a discharge elevator is located between the two discharge ports, which transfers irradiated fuel through under-water channels to the storage bays outside the reactor building, on the reactor "B" side.

The space required for the two fuelling machine vaults, the transfer areas and the loading and storage facilities obviously has a dominant influence on design and lay-out of the reactor building and its service areas. See **Figures 2-15, 2-16 & 2-17.**

2.3 Normal Operating Fluid Conditions - Temperatures, Pressures and Flows

- The Primary Heat Transport (PHT) system *only* applies inside the Pressure Tubes (PT) and End Fittings (EF), supplied through the feeders at high temperature, high pressure and high flow rate. Current CANDUs have peak temperatures between *297°C (Pickering A & B) and 313°C (CANDU 6 & Darlington)*, respectively. The flow in each channel is up to 24 kg/s. The maximum neutron flux on the pressure tubes is $3.2(10^{17})$ n/m^2.s. The PHT fluid also fills the Fuelling Machine and its external supply lines, but at reduced temperature and flow.

- Carbon dioxide gas at near-atmospheric pressure fills the annular space between the pressure tube and the calandria tube bore, to provide insulation against parasitic heat loss from the PHT to the moderator. It is supplied from the Annulus Gas System through small tubing attached at each end fitting, at very low flow. This gas is maintained at about 20 kPa pressure.

- Moderator heavy water fills the calandria, between and around the calandria tubes. It also fills the access thimbles for horizontal RCUs. It is supplied at near-atmospheric pressure, sub-boiling temperature and modest flow rate, through a number of pipe nozzles on the calandria sides, each fitted with a tangential flow diffuser. The flow conditions are therefore very gentle for the components inside the calandria. The internal flow is basically that caused by natural convection due to heat transferred from the fuel channels, such that moderator flows is upwards in the core and down along the cooled shell walls and end shields. The shell is cooled by the slowly circulating shield water surrounding it, and the end shields by the vigorous upwards shield water flow inside them.

  As shown in **Figure 2-18**, in current CANDUs, the inlet diffusers are located at mid-height and aimed upwards, and the entire flow is returned through a single bottom outlet nozzle. This tends to counter the convective flow, so as to promote mixing and more uniform in-core temperatures. In the more recent CANDU 9 design, shown in **Figure 2-19**, the inlet diffusers are located higher up the sides and aimed downwards, and the return flow exits through sets of nozzles near the top on each side (CANDU 9). This design maintains good temperature uniformity under normal conditions through higher total flow (more inlet nozzles), but provides another benefit, for a possible upset condition. The diffuser flow direction is supplementary, rather than counter, to the natural convection. In the event of a loss of the moderator circulation pump, the moderator flow patterns do not have to change when the counter flow is lost as in CANDU 6, and the transitory local stagnation is avoided. In all current CANDUs, moderator is supplied at about 49°C and exits at 69°C. Flow velocity is about 0.5 m/s at the diffuser exit but quickly diffuses to the general convective velocity of about 0.1 m/s. Thermal neutron flux on in-core RCU components is of the order of $2(10^{14})$ n/cm^2.s. Thermal neutron flux on calandria shell and inner tube sheet of the end shield is of the order of $2(10^{10})$ n/cm^2.s.

- As shown in **Figure 2-18**, low pressure helium gas covers the free surface of the moderator at the top of the calandria, up inside the access thimbles for the vertical RCUs and inside four large emergency calandria discharge ducts leading to the vault air space, but capped with rupture discs. These ducts will vent surplus moderator in case of a postulated extreme accident of an in-core rupture of both a pressure tube and its calandria tube. Helium in the emergency discharge ducts is circulated at very low flow rates through heat exchangers and re-combiners, to minimize build-up of dissociated deuterium and oxygen. The helium is maintained at a pressure of about 20 kPa.

- Shield water fills the end shields and surrounds the calandria and the RCU thimbles inside the reactor vault, extending up to the underside of the RM Deck (RMD), where it is vented to the reactor building air. It is pumped through the end shields at fairly high flow to cool the lattice tubes, then circulates at low flow inside the vault at well below boiling temperatures. Shield water enters the bottom of the end shields at about 50°C and exits their top end at about 60°C to flow into the vault and then exits the vault at about 65°C. Temperature distributions inside the calandria and end shields are shown in **Figure 2-20.**

- Boiler room air covers the top of the RMD and the RCU housings, and surrounds the vault. See **Figure 1-4**. It is maintained at a few kPa below atmospheric pressure to ensure any leakage is inwards. It is circulated through the reactor building and through coolers and de-humidifiers. It is maintained at about 30°C and below 20% relative humidity near the air locks and stairways, but reaches temperatures up to 100°C on the RMD, because of heat radiated from the nearby PHT pumps and piping to the steam generators.

2.4 Normal Operating Weight and Pressure Loads

- Structurally, the pressure tubes are primarily beams, built in at their end fittings and loaded by their own mass plus that of the fuel and coolant. Current CANDUs have the PHT peak pressure between *9.5 (Pickering A & B) and 11.1 Mpa (CANDU 6 & Darlington)*, with peak temperatures between *297 and 313°C*, respectively. They are supported at several places along their length by spacer rings in the gas annulus, which are in turn supported inside the calandria tubes. They are also subjected to hoop tension and axial tension due to the internal coolant pressure. **Figure 2-21** shows this loading system. Each fuel channel weighs 470 kg, including fuel, spacers and coolant. Each end fitting weighs 300 kg, including coolant, closure and internal components.

- The calandria tubes are also primarily beams, built in at the end shields and vertically loaded by their own mass, less the buoyancy of the moderator, plus part of the weight of the filled pressure tube acting through the several spacers. Their internal pressure is negligible, but they carry external pressure due to the static depth of the moderator. **Figure 2-22** shows this loading system. The pressure inside the calandria varies between 20 kPa at the top and 80 kPa at the bottom. They also carry significant axial loads, due to their connection to the end shields, ie, due to their tension reaction to the moderator static head acting on the end shield area (ie, it varies with the height). There is also an axial load which varies radially across the end shields, caused by 'dishing' of the end shields due to different thermal expansion on their inner and outer tube sheets. Each calandria tube weighs 20 kg.

- The calandria shell carries a small external net pressure, because the static head of the moderator liquid inside it is more than balanced by the static head of the shield water outside it. It consequently carries and consequently a little "hoop"-type compression. Consequently, as a thin-shell vessel, buckling must be considered. (In fact, its thickness and curvature are sufficient that this is not a concern.) For a CANDU 6, the pressure inside the calandria varies between 20 kPa at the top and 80 kPa at the bottom. The pressure outside the calandria varies between 68 kPa at the top and 182 kPa at the bottom. The shell is also loaded by the static weight of its own shell material plus the weight of the moderator liquid inside, partly balanced by the buoyancy of the shield water outside it. **Figure 2-23** shows this loading system. The calandria shell weighs 32,700 kg; the moderator enclosed weighs 298,800 kg, and the buoyancy of the shield water is equivalent to 1,148,000 kg. Its diameter is bigger than its length so that it cannot properly act as a *simply-supported beam*; and furthermore, the annular plates on the main shell prevent it from carrying the axial reaction end loads of *a built-in beam*. The vertical loads are transferred to the ends mostly as shear, and the reaction load is basically vertical shear acting along the sub-shell edges. Similarly, because the pressure load acting on the end shields is reacted on the calandria tubes, there is negligible axial tension in the shell, except for that small portion acting on the area of annular plates. This relatively flimsy shell structure cannot really be assessed by simple classical representations and is best analysed by FEM methods, but studies like the above nonetheless help the designer visualize the general behaviour of his design.

- Each end shield is a complex structure comprised of two plates linked all over by relatively flexible lattice tubes; ie, the two plates share the moderator pressure load, and the calandria tube reaction loads, but they bend out of plane (dish) almost as individual plates. **Figure 2-24** shows this loading system. The moderator pressure load is due to the static head of moderator, which, for a CANDU 6, varies between 20 kPa at the top and 80 kPa at the bottom, reacted by the calandria tubes. The vertical load due to the weight of the calandria shell, plus the moderator, less the shield water buoyancy, is applied all around the edge of the inner (calandria side) tube sheet. Added to this are the vertical loads at every lattice tube due to the weight of the calandria tube (less its buoyancy), plus the pressure tube including fuel and coolant, and the end fitting and its internal items. Finally, the weight of the end shield tube sheets, lattice tubes, shielding balls, water, and supplementary shield slabs are also added; these items total 189,900 kg. The total of these loads is reacted all around by vertical shear loads from the support ring assemblies.

- The entire calandria-end shield assembly is supported by flexible annular plate rings, acting all around each end shield. These assemblies are in turn supported in cylindrical shells called embedment rings, set into the concrete vault end walls in CANDU 6. In Darlington & Bruce the end shields are directly supported in fabricated steel end walls of a free-standing shield tank vessel. These assemblies each carry half the "all-up" weight of the reactor assembly and all its contents, less the buoyancy of shield water on the calandria shell, ie, for a CANDU 6, this is a weight load of 707,650 kg. Their loading can also be seen on **Figure 2-24.**

- The Reactivity Mechanisms (RM) Deck is a box structure which has its internal webs running in the same direction. It can thus be thought of as a series of side-by-side I-beams, each 857mm (33.75" = 3 lattice pitches) wide. The strength of the holes removed for the penetrations is compensated for by local "doubler" plates. It is supported all around its edge on a relatively thin flexible vertical plate, so the beam can be assumed to be simply supported. See **Figure 2-10**. Each beam-section carries the weight of its top and bottom plates and their doublers, its internal web, its concrete fill and its top tread plate. The RM Deck total weight is 115,200 kg. It has no external loads normally applied to it, except for the rare event when the R M Flask is positioned on a deck penetration fitting, to remove an active Reactivity Control Unit (RCU) component from the core. In fact, this is the design load for the RM Deck. The RM flask weighs 13,000kg, and the design assumes a 2.5 g impact due to rough handling on the crane. The flask load is therefore a point load on the beam section supporting it. In fact, the penetration is between two beam webs, and short stiffeners attached to the top plate transfer the load to the webs on either side. **Figure 2-25** shows this loading system.

2.5 Normal Operating Thermally Induced Loads

Loading Conditions:

- The thermally induced loads are those caused by restraint of thermal expansion.

- If an item is uniformly heated and is free to expand, there will be no thermal loads induced in it.

- If a restrained item is heated sufficiently to generate yield level stresses, it will elastically deform such as to limit stresses to those levels, and consequently will not fail by rupture; therefore, in pressure retaining items thermal stresses are not included for assessment of accident cases, where factored ultimate strength is the acceptance criterion.

- The pressure tubes slide in bearings in the lattice tubes and are connected at only one end to an end shield, via a positioner assembly; they are therefore essentially unrestrained axially.

- In CANDU 6, the calandria shell, calandria tubes and concrete vault are all joined to the end shields and are of different materials at different temperatures. However, axial thermal restraint between the *calandria shell and the calandria tubes* is minimized by the flexibility of the annular plate-rings *in the calandria shell*. Similarly, axial thermal restraint between the *calandria tubes and the concrete vault* is minimized by the flexibility of another set of annular plate-rings *in the end shield* supports. Two rings of tie-bolts, at one end only, position the calandria shell and one end shield in the vault. See **Figure 2-26**. (But in a seismic event, the axial inertia reaction to the mass of the *entire* reactor assembly is carried through the ring of bolts on *one* end wall embedment. There is also a smaller second row of bolts to attach that end of the main shell to the embedment, to react just the mass of the shell plus the small portion of moderator within the annular plates.) In Bruce, the end wall of the steel shield tank (in place of the concrete vault) has flexibility itself and end shield annular plate-rings aren't needed.

- Radial thermal restraint in the end shield is minimized by the annular shell in its supports in CANDU 6. In Bruce, there is no annular shell between the end shield and the shield tank end wall, because the carbon steel shield tank wall expands also, but not as much as the end shield, and a small radial stress due to the radial restraint is tolerated. See **Figures 2-7a & 2-7b**.

- In the end shield itself, the inner tube sheet is much cooler than the outer, so it expands less, and the entire ES assembly acquires a slightly spherical shape. The calandria tubes in the central region are therefore strained in tension, while those around the edges are compressed to balance the loads. See **Figure 2-27**.

- The RMD rests on fairly tall vertical webs secured to the embedment in the vault roof and is not restrained vertically by the RCU thimbles. It is not restrained thermally in the plane of the roof because the shear webs flex transversely. See **Figure 2-10**. The thermal expansion pattern is shown in **Figure 2-28**. The RMD's upper and lower surfaces are at similar temperatures and the same pressure, so there is no out-of-plane thermal load.

2.6 Other Operating Conditions:

2.6.1 The Fuel channel is designed for the normal operating conditions listed above, plus normal start-up and shutdown transients, since these are the highest pressure it is subjected to. These are Level A and B loads. Service load levels and allowable stresses are discussed in section 3.1. Other cases to be considered in design include those resulting from the postulated Header Break-LOCA + LOECC accident, which results in dry-out and overheating of the PT. A Design Basis Earthquake (DBE) seismic event is also a major design case. The case of a fuelling machine being attached at the time of the event is usually the dominant seismic case. These are Level C or D design cases. Note that in CANDU design, the reactor does NOT shut down on a *seismic* trip of the safety system, and the entire PHT system is designed to accept seismic inertia loads *added to* normal operating conditions, until a PHT system trip occurs due to PHT pump run-down. The PHT pumps are seismically qualified, but the Class IV electrical system powering them is not.

2.6.2 For the entire reactor structure, a severe Level C or D load case is a postulated, spontaneous rupture of both the PT and the CT, causing a brief (30 millisecond) overpressure pulse inside the calandria, as the PHT coolant flashes into steam. A steam bubble rapidly expands and displaces moderator, then cools and condenses inside the cool moderator, and collapses. This causes a spherical pressure wave to grow and transmit to the calandria shell. The displaced moderator travels up the emergency discharge ducts to break the rupture discs and vent into the boiler room. The pressure pulse also places a momentary external pressure on the calandria tubes, which *elastically* collapse onto the pressure tube. The highest stress on the calandria shell in this event occurs at the main shell/annular plate intersection, caused by its self-constraint, as the plate inhibits elastic deflection (increased diameter) of the shell. This corner endures local yielding in bending, part way through. This is entirely acceptable for this unlikely, postulated Level C event, as no permanent change of shape has occurred in the vessel. Stresses everywhere else in the structure remain quite modest. Other transient conditions result from conditions such as loss of circulation of moderator, or loss of circulation of shield water, which cause abnormal temperature distributions and associated thermal loadings. The latter event is more significant for the end shield than for the calandria shell, since a significant heat load is injected into the end shields through the end fitting and lattice tube, but relatively little heat is lost to the shell from the cool moderator.

The entire reactor structure assembly is designed to accept seismic inertia loads *added to* normal operating conditions, as an emergency operating (Level C or D) load case. The case of a fuelling machine being attached to a central fuel channel, at the time of the event, is the dominant seismic case.