2.0 PHYSICAL DESCRIPTION OF THE CANDU-600

2.1 The Pressure Tube Concept

A CANDU reactor is a heavy water moderated, natural uranium fuelled reactor utilizing the pressure tube concept. This consists of an array of pressure tubes, containing the reactor fuel and coolant, passing through a large horizontal cylindrical vessel (the calandria) containing the heavy water moderator and reflector. The overall arrangement is shown in Figure 2.1.1. Pressurized heavy water coolant is pumped through the pressure tubes, cooling fuel and conveying heat from the fuel to the outlet header and from there to the steam generators. Each pressure tube is isolated and insulated from the heavy water moderator by a concentric calandria tube (see Figure 2.1.2). The annular space between the pressure and calandria tubes is filled with gas. This configuration results in the moderator system being operated independently of the high temperature, high pressure coolant in the pressure tube. The heat generation in the moderator is very low thus obviating the need for a high-strength pressure vessel.

Due to the physical separation of coolant and moderator the latter operates at the relatively cool temperature of approximately 70°C. This means that the cool moderator can act as the heat sink under certain accident conditions. Also, it means that the reactivity and control devices which are positioned interstitially between the pressure tubes operate in a low pressure low temperature environment.

Experimental evidence indicates that pressure tubes will leak before they break, since their thickness is less than the critical crack length. Should pressure tube leaks develop they can readily be detected by monitoring the moisture content in the gas space between the pressure tube and the calandria tube. This is normally done on a continuous basis. Also the pressure tube concept makes it possible to detect release of fission products from the fuel in an individual fuel channel due to cladding defects. This can be done while the reactor is operating.

The pressure tube concept also permits the flexibility to subdivide the primary heat transport system into more than one circuit should the process of optimizing the design of the shutdown systems to cope with loss-of-coolant accidents, the design of the emergency coolant injection system, and the design of the primary heat transport system components indicate this is desirable.

2.2 Reactor Calandria

The calandria is a horizontal cylindrical shell the primary purpose of which is to support the fuel channels assemblies and to contain the heavy water moderator and reflector. The calandria also supports guide tubes for reactor devices and in-core instrumentation. These pass between the calandria tubes and are therefore situated in a low-pressure environment.

The calandria is provided with pressure relief valves as part of a cover gas system which regulates pressure of the moderator system under normal operation. Rupture discs located at the end of the four pressure relief pipes (see Figure 2.1.1) limit the pressure rise in the calandria that would occur in the event of an accidental rupture of a pressure and calandria tube, although the probability of this actually happening is very small.

The calandria assembly is embedded within the light water filled carbon-steel lined concrete vault (see Figure 2.2-1). At each end of the calandria shell is an end shield containing biological shielding material in the form of carbon steel balls and light water. The end shield and calandria at one end is attached to the calandria vault to limit the seismic response of the calandria assembly.

2.3 Reactivity Devices

The primary method used to control the reactivity of CANDU reactors is through on-line refuelling which occurs on a daily basis. In the 600 MWe CANDU PHW there are six means of changing the reactivity state of the core besides refuelling. Four of these are used for normal control functions including controlled shutdown and two are used by special safety systems for rapid shutdown during accident conditions.

For control purposes the following are used:

(a) 14 liquid zone controllers (H_2O filled compartments)
(b) 21 adjuster rods
(c) 4 mechanical control absorbers
(d) moderator poison

For the special shutdown systems the following are used:

(a) 28 cadmium shutoff rods in one shutdown system
(b) 6 nozzles which permit rapid injection of gadolinium solution into the moderator which comprise a second, completely independent shutdown system.

Table 2.3-1 gives typical reactivity worths and maximum rates of change of reactivity of these devices.

TABLE 2.3-1

Control And Safety Systems Devices

Typical Reactivity Worths And Maximum Rates

Function	Device	Total Reactivity Worth (mk)*	Maximum Reactivity Rate (mk/s)
Control	14 Zone Controllers	7	± 0.14
Control	21 Adjusters	15	± 0.1
Control	4 Mechanical Control Absorbers	10	± 0.0075 (driving) - 3.5 (dropping)
Control	Moderator Poison	-	+0.01 (extracting)
Safety	28 Shutoff Units	80	- 50
Safety	Poison Injection Nozzles	>300	- 50

*1 mk is a $\frac{\Delta K}{K}$ value of 0.001 or 0.1%

All reactivity devices are located or introduced into guide tubes permanently positioned in the low-pressure moderator environment. These guide tubes are located interstitially between rows of calandria tubes as shown in Figure 2.1-2. There exists no mechanism for rapidly ejecting any of these rods, nor can they drop out of the core. This is a distinctive safety feature of the pressure tube reactor design. The maximum reactivity rates achievable by driving all control devices together is about .35 mk* per second, which is well within the design capability of the shutdown systems.

The locations of these devices are shown schematically in Figures 2.3-1 (Plan View), 2.3-2 (Side Elevation) and 2.3-3 (End Elevation).

2.4 Core Design Details

The use of natural uranium fuel and heavy water as moderator and coolant combined with capability to refuel the reactor on power leads to a design characterized by good neutron economy, since the fraction of all neutrons produced which are absorbed in the fuel is high throughout most of the life of the reactor.

The fuel channels are arranged on a square lattice with a 286 millimetre pitch (see Figure 2.1-2). This is a near optimum geometry from a reactivity standpoint. Figure 2.4-1 shows the reactivity change of a uniform lattice as a function of lattice pitch. A consequence of the particular lattice geometry used in the CANDU PHW is that the neutron energy spectrum is very well thermalized. The associated long migration length for neutrons and the long neutron lifetime have an important bearing on methods used in the reactor physics analysis and on the requirements for the shutdown systems from the neutronic point-of-view.

* 1 mk is a $\frac{\Delta K}{K}$ value of 0.001 or 0.1%.

2.4.1 Liquid Zone Controllers

The purpose of the liquid zone control system is to provide the continuous fine control of the reactivity and hence reactor power level. It is needed because fuelling is not truly continuous but done in small increments (usually at least 8 bundles at one time). It also compensates for other minor perturbations in parameters such as temperatures which cause small reactivity changes. This system is also designed to accomplish spatial control of the power distribution which prevents xenon induced power oscillations in the power distribution from developing.

The system is contained in six vertically oriented tubes running interstitially between the fuel channels from the top to the bottom of the core in the positions shown in Figure 2.3-1. The two central tubes are divided into three compartments each by appropriately placed bulkheads and the four outer tubes are divided into two compartments to give a total of 14 individually controllable compartments in the reactor. H_2O is fed to these compartments through small diameter tubing and the plumbing of this tubing is arranged such that the level of H_2O in the compartment can be controlled by varying the relative value of the in-flow and the out-flow rates.

The reactor regulating system adjusts the levels of H_2O in the individual compartments according to the magnitude of the signal coming from the interstitially placed incore platinum self-powered detectors of the Hilborn type[4], [5]. There is one detector associated with each of the 14 compartments (a passive spare detector is also installed to provide a backup). To ensure that the signal from each of these individual controlling detectors is representative of the power in the zone being controlled (see Figure 2.4-2 and Figure 2.4-3) the detector signal is periodically renormalized to agree with the measured integrated power in the zone as obtained from the flux mapping system. The latter is a system of 102 self-powered vanadium flux detectors that are located in 26 vertical interstitial assemblies. These detectors are typically about 30 cm long and hence provide essentially a point measurement of the thermal neutron flux. The software in the reactor regulating system is designed to convert these 102 point measurements to a local flux distribution throughout the reactor. A typical arrangement of these flux detectors are shown in Figure 2.4-4 and 2.4-5. The latter view is just one of the radial planes and is representative of a plane containing the largest number of detectors. Other radial planes have fewer detectors.

2.4.2 Mechanical Control Absorbers

The zone control system is normally designed to provide a reactivity control capability of about ± 3 mk since this is sufficient to compensate for routine reactivity perturbations that occur on a semi-continuous basis. For certain less frequent events the reactor regulating system requires more reactivity range than the zone control system can provide. Therefore, two additional control absorber systems are provided which are also operated by the reactor regulating system.

The system used to extend the range of control in the negative direction is the mechanical control absorber rod system. This system consists of four control absorber devices which physically are the same as the shutoff rod devices, but they do not form part of the shutdown system. These control absorbers are normally fully withdrawn from the reactor while the reactor is operating under normal steady state full power conditions. They are activated only when circumstances demand rapid reduction of the reactor power at a rate or over a range that cannot be accomplished by filling the liquid zone control system at the maximum possible rate. Modes of insertion range from driving the rods in pairs to all four being dropped in by gravity following release of an electromagnetic clutch in a manner similar to the operation of the shutoff rods. The mode of insertion depends on the nature of the event demanding a rapid power reduction.

Since the power coefficient of reactivity is negative in the CANDU reactor a power reduction tends to increase reactivity and the reactivity worth of the mechanical control absorber system is chosen so that the combined effect of this system and the zone control system acting together will reduce power to a very low value without requiring activation of either of the shutdown systems.

The positions of these absorbers are shown in Figures 2.3-1 and 2.4-4.

2.4.3 Adjuster Rod Absorber System

To extend the range of the reactor regulating system in the positive direction beyond that available from the zone control system, the reactor is designed to operate with a group of absorber rods fully inserted in the reactor during normal full power operation. This system of rods is called the adjuster rod system and in the 600 MWe reactor consists of 21 stainless steel rods. If more positive reactivity is required than the zone control system can provide, these rods are withdrawn in groups as necessary.

There are two circumstances where the reactivity decreases relative to the normal steady state power condition to a degree that demands withdrawal of some or all of the adjuster rods to permit continuing operation of the reactor.

(a) Fuelling machines being unavailable for a period of more than about one week after which the reactivity decrease due to burnout of the fuel will typically exceed the range available in the zone control system.

(b) Transient increases in the concentration of xenon 135 following a reduction of reactor power.

The adjuster system is nominally designed to have sufficient reactivity to compensate for the increase in xenon 135 concentration that occurs within 30 minutes following a reactor shutdown. Such a system provides capability to operate with fuelling machines unavailable for about a month.

Since the adjuster rods are normally fully in the core their positions in the reactor and the distribution of absorbing materials amongst the rods are chosen to flatten the power distribution in an optimum manner so as to minimize the variation in the discharge burnup of the fuel that is necessary to achieve the design power shape. The average to maximum channel power ratio in the reactor is a parameter which is chosen during the conceptual design stage and it determines the number of channels that are provided in the reactor to achieve a given total output, without overrating any one channel.

The 21 adjusters are grouped into seven banks, not all composed of an equal number of adjusters. The banks are chosen such that the reactivity worth of any one bank does not exceed the range of the zone control system. The reactivity worth of the complete system is about 15 mk. The maximum reactivity change rate associated with moving one bank of adjusters is < 0.1 mk per second.

The positons of the adjuster rods are shown in Figures 2.3-1 and 2.4-4.

2.4.4 Moderator Poison

Moderator poison is used to hold down excess reactivity during the initial fresh fuel conditions or during and following shutdown to compensate for lower than normal ^{135}Xe levels due to decay. Boron is used in the former and gadolinium is used in the latter situation. The burnout rate of gadolinium during operation at full power following an extended shutdown period is comparable to the xenon growth rate in terms of reactivity, hence the need to remove poison by ion exchange at a fairly rapid and controlled rate is much less demanding. Poison can be added to the moderator for these purposes either automatically or manually.

It should be noted that this system is completely independent of the very high speed liquid poison injection system which is used as a shutdown system. In the regulating system function the poison is inserted into the piping used to circulate the moderator whereas in the poison injection system, the poison is injected through nozzles that are installed horizontally across the core, and a completely independent source of poison is used.

2.4.5 Shutdown Systems

The 600 MWe reactor is equipped with two physically independent shutdown systems. These systems are designed to be both functionally different and geometrically separate. These differences are achieved by using vertically oriented mechanical shutoff rods in one system and horizontally oriented liquid poison injection nozzles in the second system.

2.4.6 Shutoff Rods

The shutoff rods are tubes made up of a cadmium sheet sandwiched between two concentric steel cylinders. The rods are inserted into perforated circular guide tubes which are permanently fixed in the core. The location of the rods are shown in Figure 2.3-1. The diameter of the rods is the maximum that can be physically accommodated in the space between the calandria tubes (about 113 mm), when space for the guide tubes and appropriate clearances are allowed for. The outermost four rods are about 4.4 m long while the rest are about 5.4 m long. The rods are normally fully withdrawn from the core and are held in position by an electromagnetic clutch. When a signal for shutdown is received the clutch releases and the rods are initially accelerated by a spring and then fall by gravity into the core.

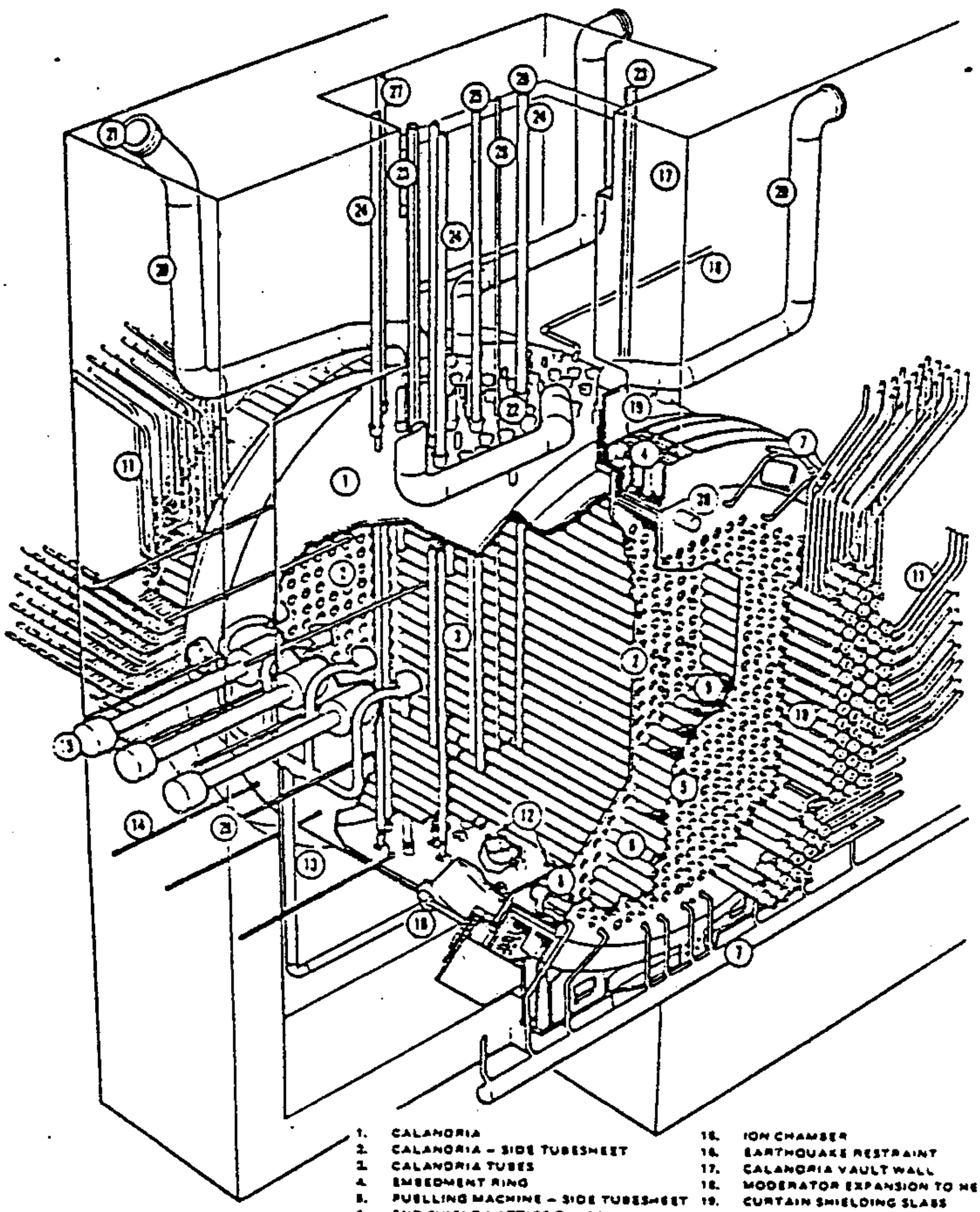
2.4.7 Liquid Poison Injection System

The alternative way of shutting down the reactor is through high speed injection of a solution of gadolinium in heavy water into the calandria. This is accomplished by opening high speed valves which normally are closed and retain the solution at high pressure in a vessel outside of the calandria. When the valves are open the liquid poison is injected into the reactor moderator through six horizontally oriented nozzles that span the core and are located in positions as shown in Figures 2.3-2 and 2.3-3. The nozzles are designed to inject the poison in four different directions in the form of a large number of individual jets. This disperses the poison rapidly throughout a large fraction of the core. The gadolinium solution is typically held in the pressure vessel at a concentration of about 8000 g of gadolinium per Mg of heavy water.

2.4.8 Regional Overpower Protective System

Another important consideration in the design of the reactor core is the requirement to provide an array of self-powered flux detectors for application in the regional overpower protective system. This is done to insure that localized overrating of the fuel does not occur due to abnormal operation of the reactor, or as the result of malfunctions in the regulating system causing an uncontrolled power increase to occur.

A separate array of detectors is provided for each of the two shutdown systems. Those associated with the shutoff rod system are on carrier tubes that are vertically oriented while those which activate the poison injection system are on horizontally oriented carrier tubes. This complies with the philosophy of maximum independence of the two shutdown systems. The detectors for the regional overpower protective system are "prompt" platinum detectors like those used for the spatial control system in the regulating system function. Typical positions of these flux detectors are shown in Figures 2.4-6 and 2.4-7. The latter shows just one of the diametral "planes" of detectors.



1. CALANDRIA
2. CALANDRIA - SIDE TUBESHEET
3. CALANDRIA TUBES
4. EMBEDMENT RING
5. FUELLING MACHINE - SIDE TUBESHEET
6. END SHIELD LATTICE TUBES
7. END SHIELD COOLING PIPES
8. INLET-OUTLET STRAINER
9. STEEL BALL SHIELDING
10. END FITTINGS
11. FEEDER PIPES
12. MODERATOR OUTLET
13. MODERATOR INLET
14. HORIZONTAL FLUX DETECTOR UNIT
15. ION CHAMBER
16. EARTHQUAKE RESTRAINT
17. CALANDRIA VAULT WALL
18. MODERATOR EXPANSION TO HEAD TANK
19. CURTAIN SHIELDING SLABS
20. PRESSURE RELIEF PIPES
21. RUPTURE DISC
22. REACTIVITY CONTROL UNIT NOZZLES
23. VIEWING PORT
24. SHUTOFF UNIT
25. ADJUSTER UNIT
26. CONTROL ABSORBER UNIT
27. ZONE CONTROL UNIT
28. VERTICAL FLUX DETECTOR UNIT
29. LIQUID INJECTION SHUTDOWN NOZZLE
30. BALL FILLING PIPE

FIGURE 2.1-1 REACTOR ASSEMBLY

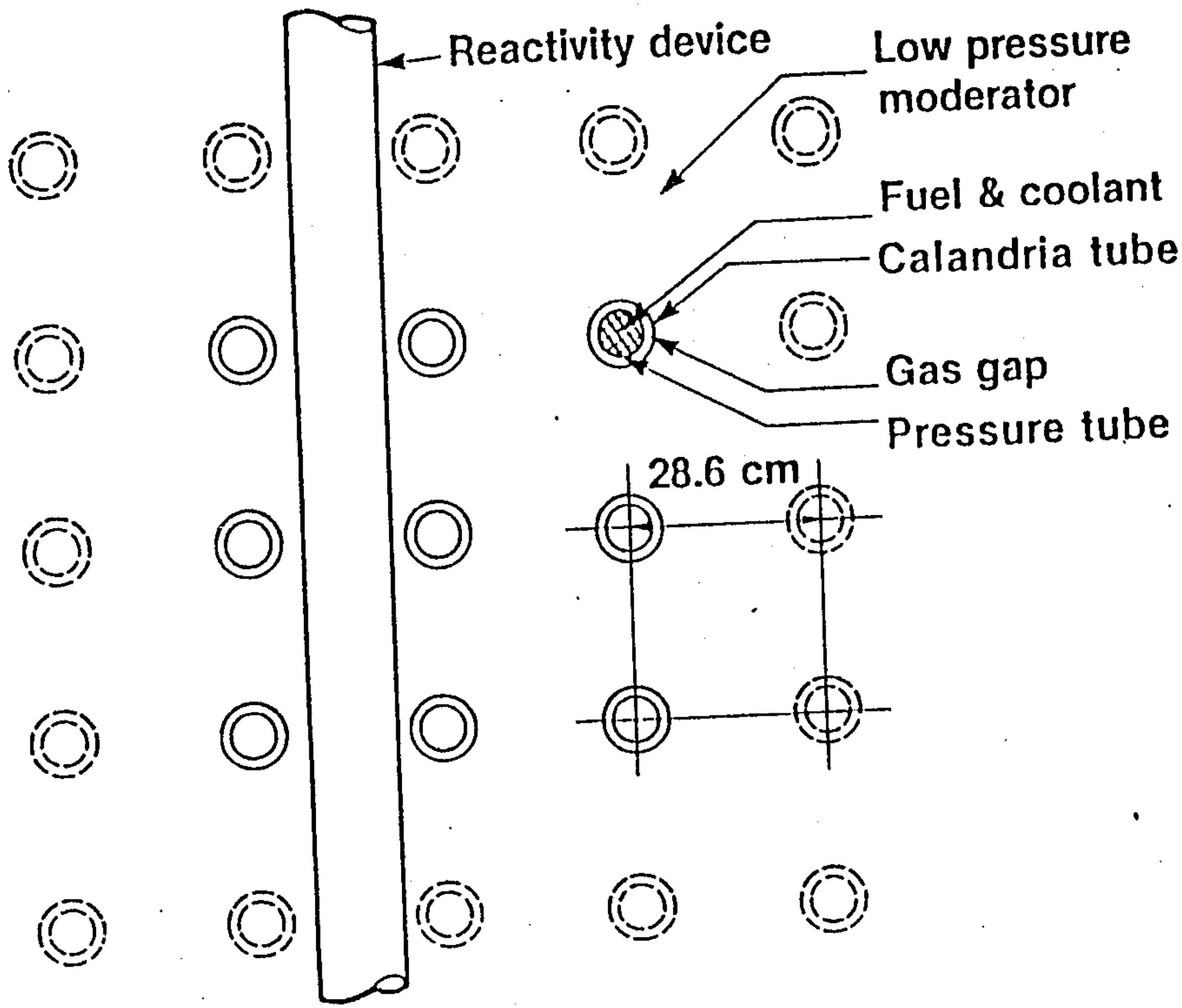


FIGURE 2.1-2 SCHEMATIC OF CANDU-PHW LATTICE

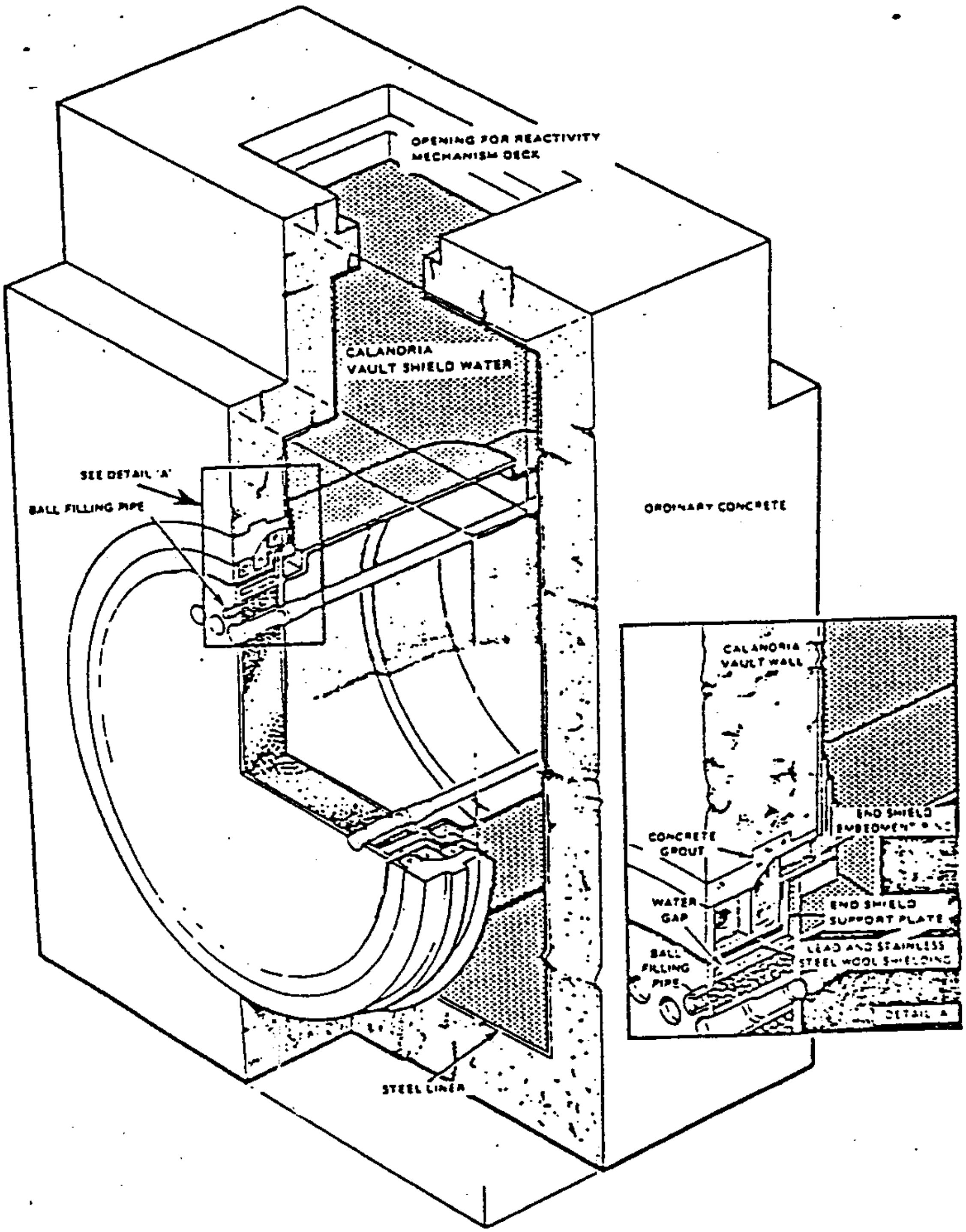


FIGURE 2.2-1 CONCRETE CALANDRIA VAULT

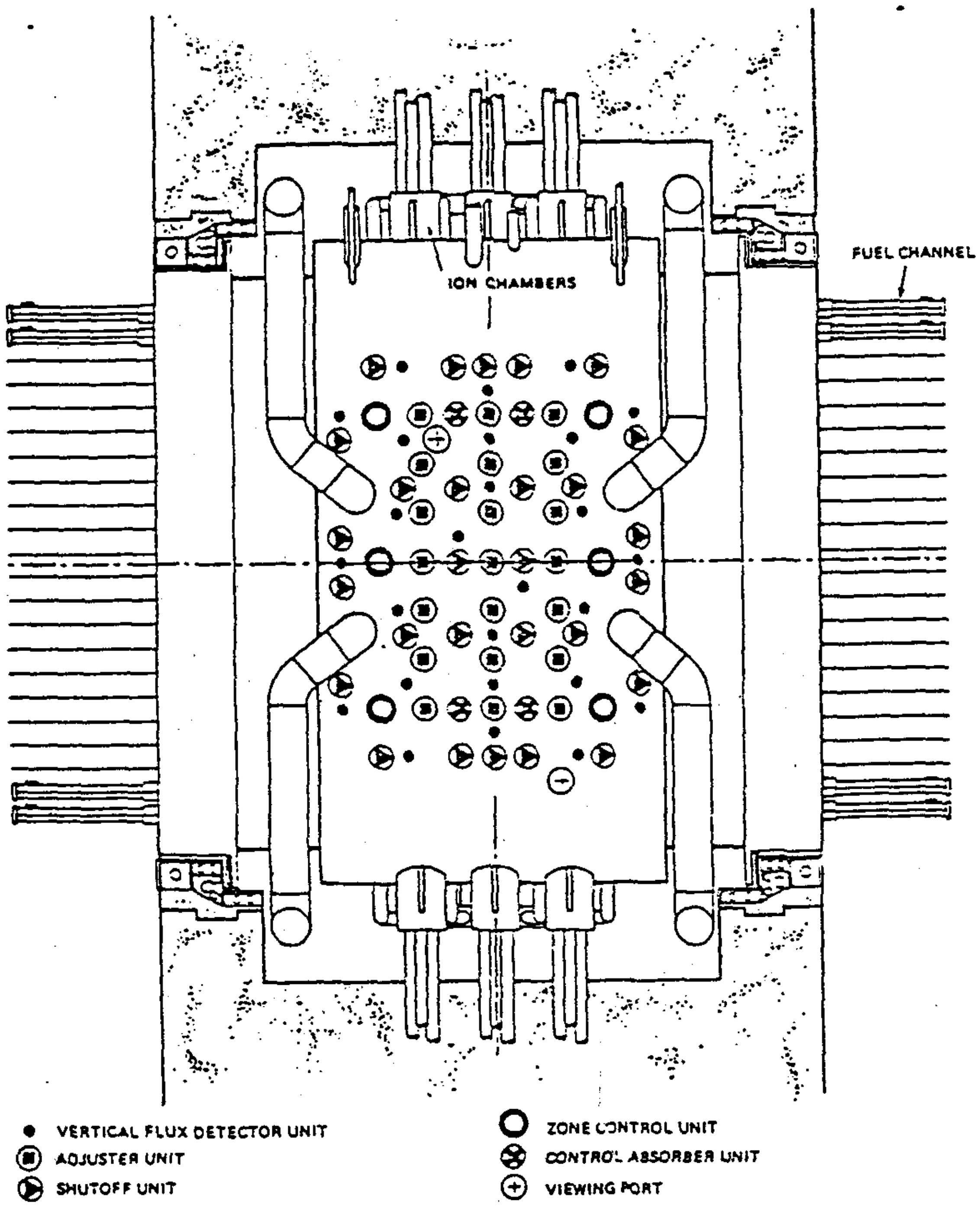


FIGURE 2.3-1   REACTOR GA PLAN

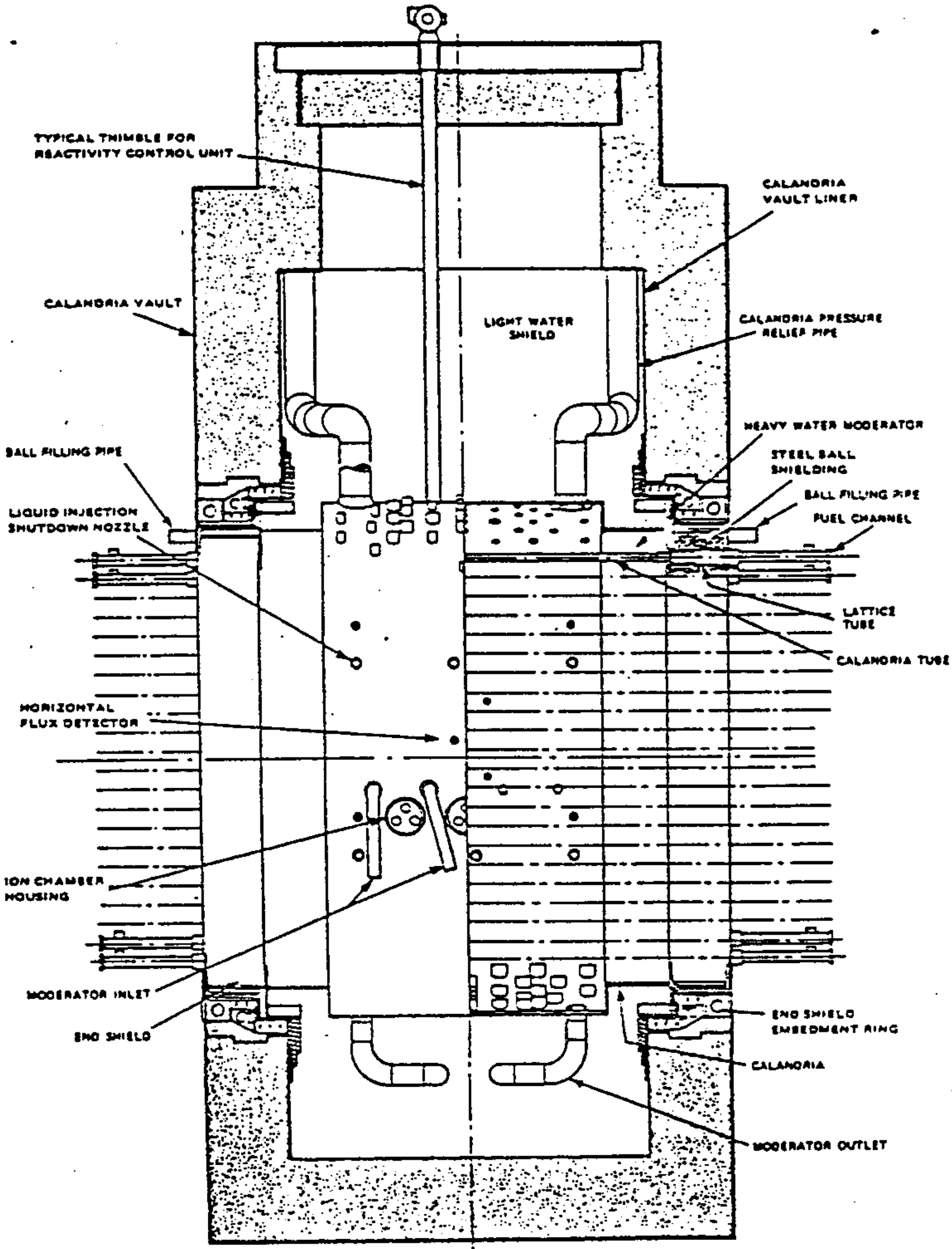


FIGURE 2.3-2 REACTOR GENERAL ASSEMBLY (SECTION)

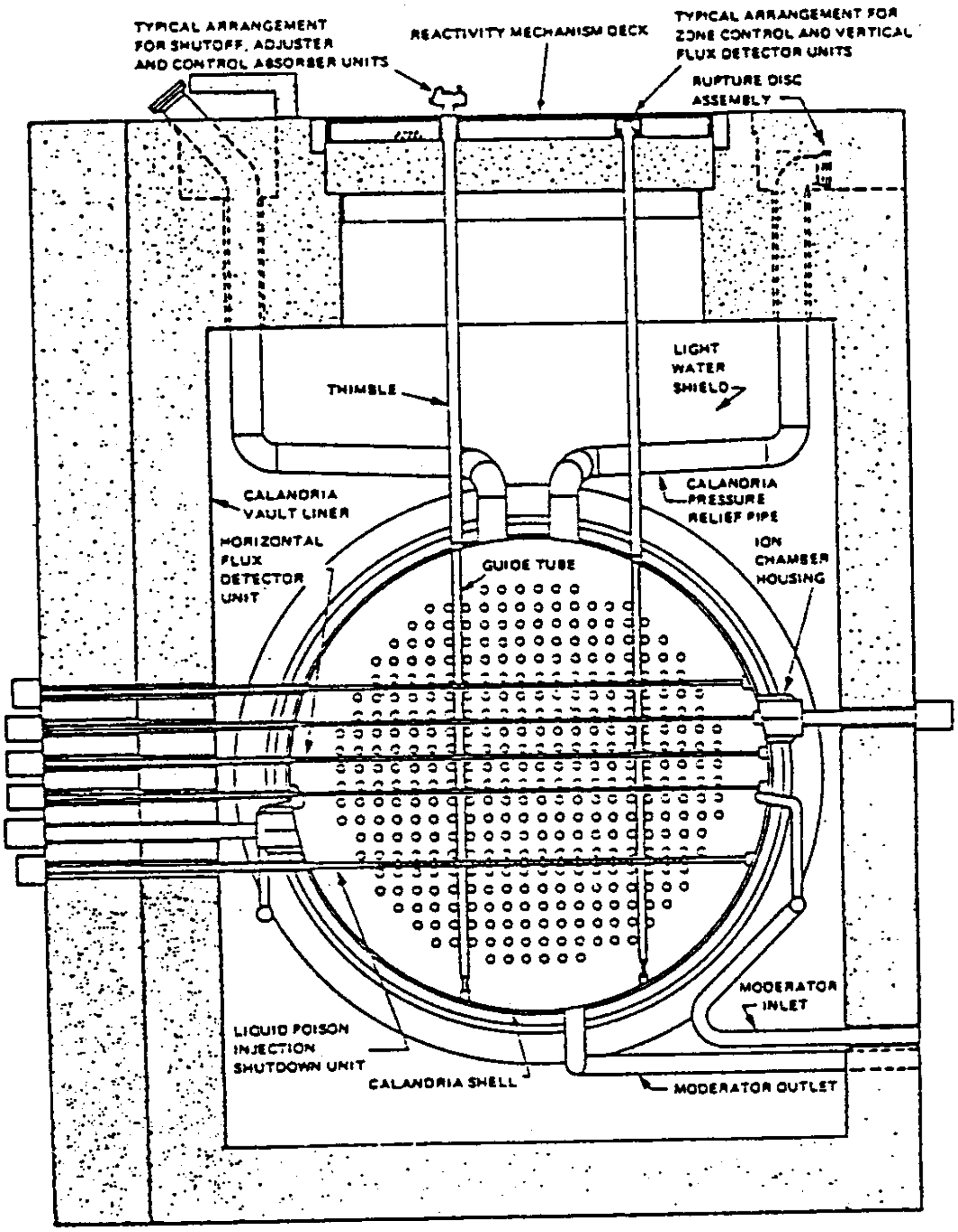


FIGURE 2.3-3 REACTOR LAYOUT — ELEVATION

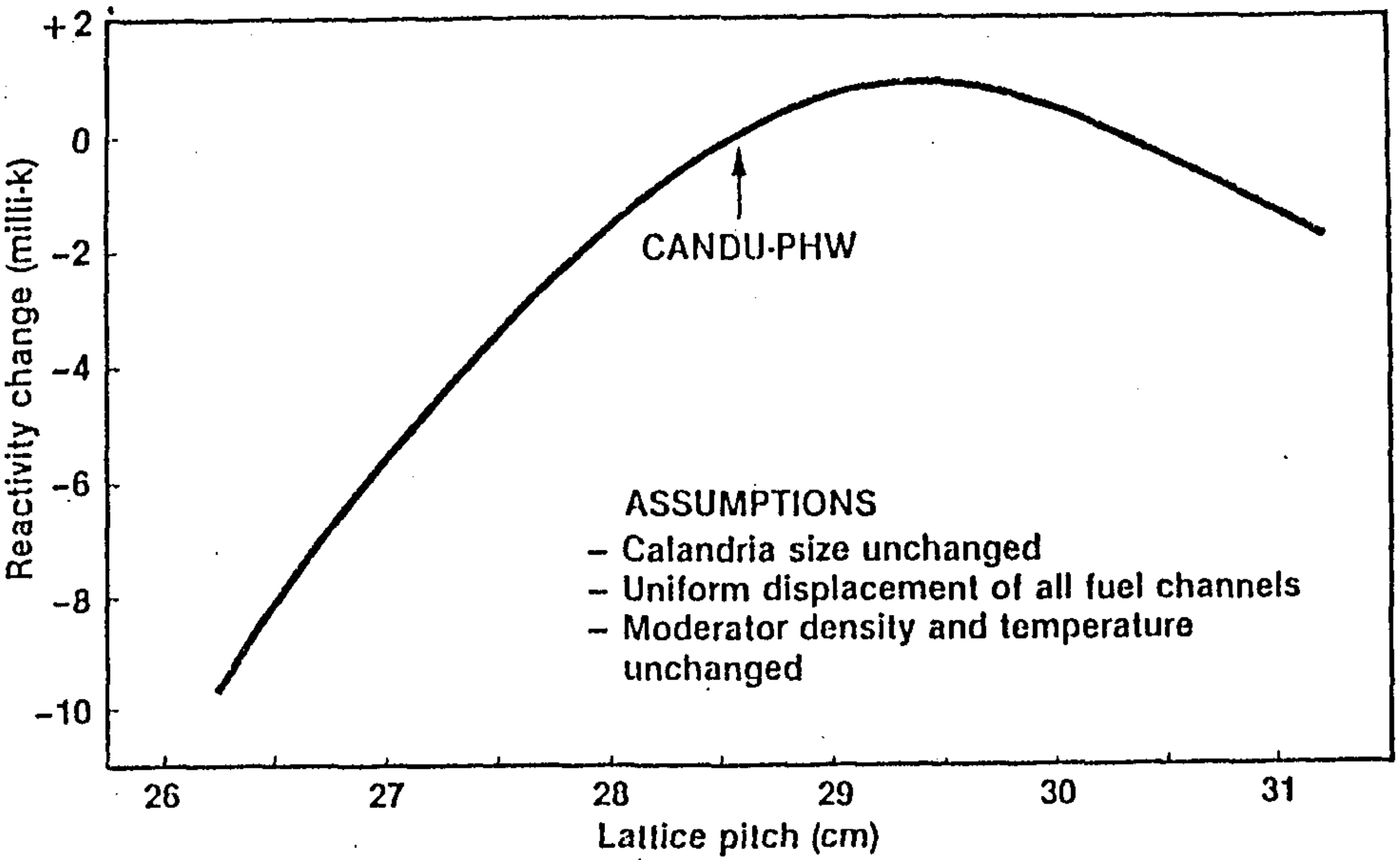


FIGURE 2.4-1 VARIATION OF REACTIVITY WITH LATTICE PITCH FOR CANDU-PHW LATTICE

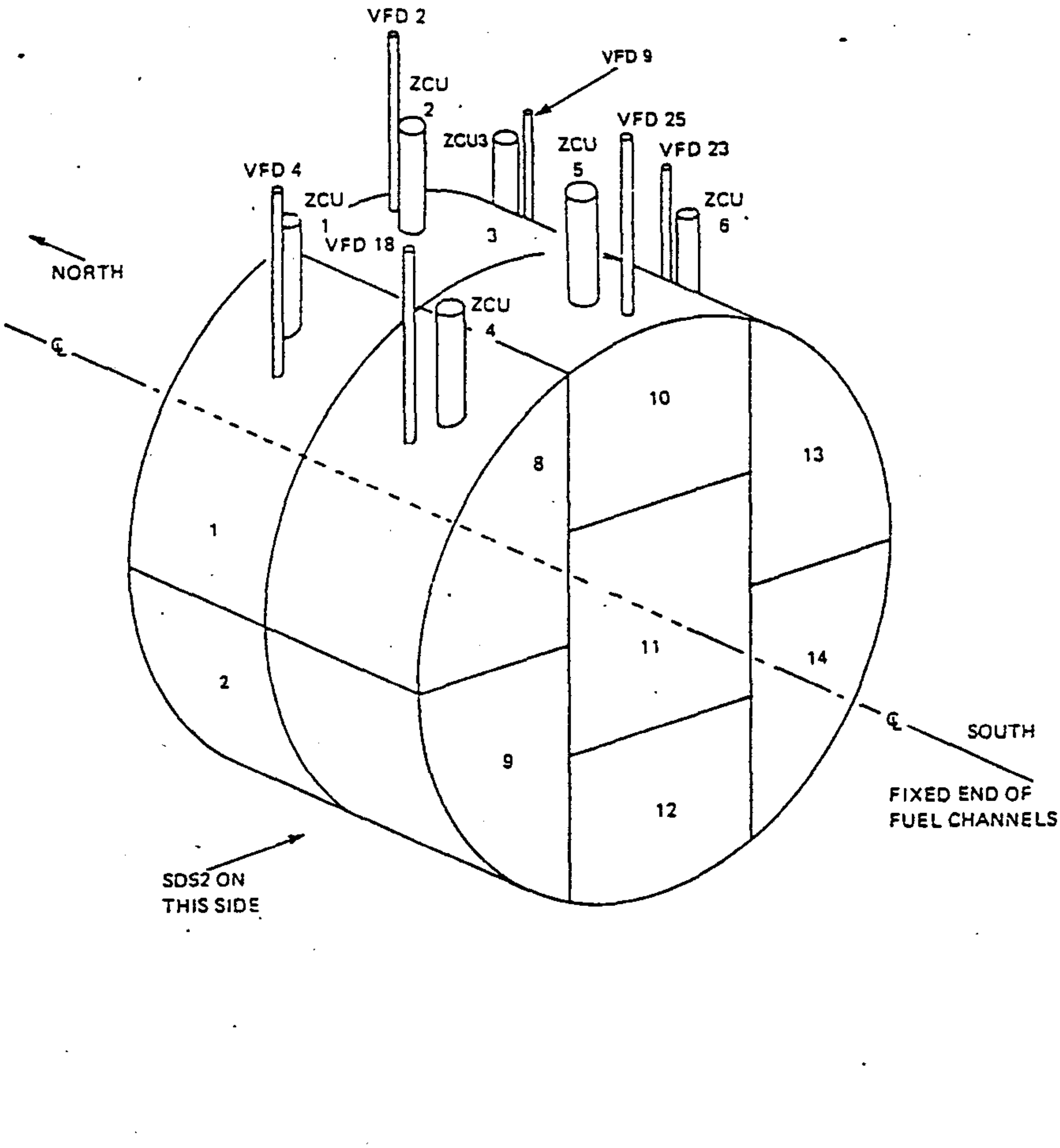
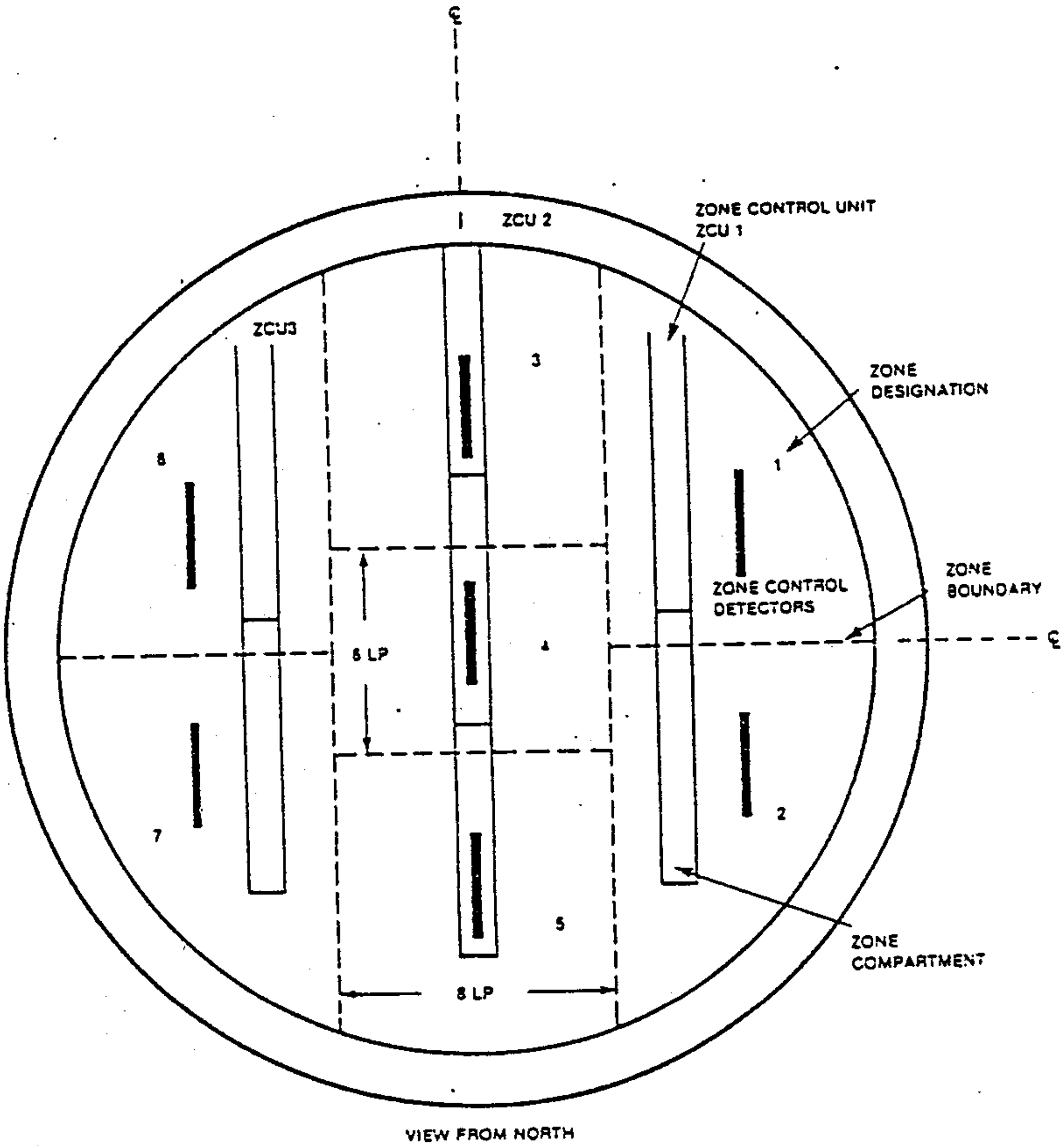
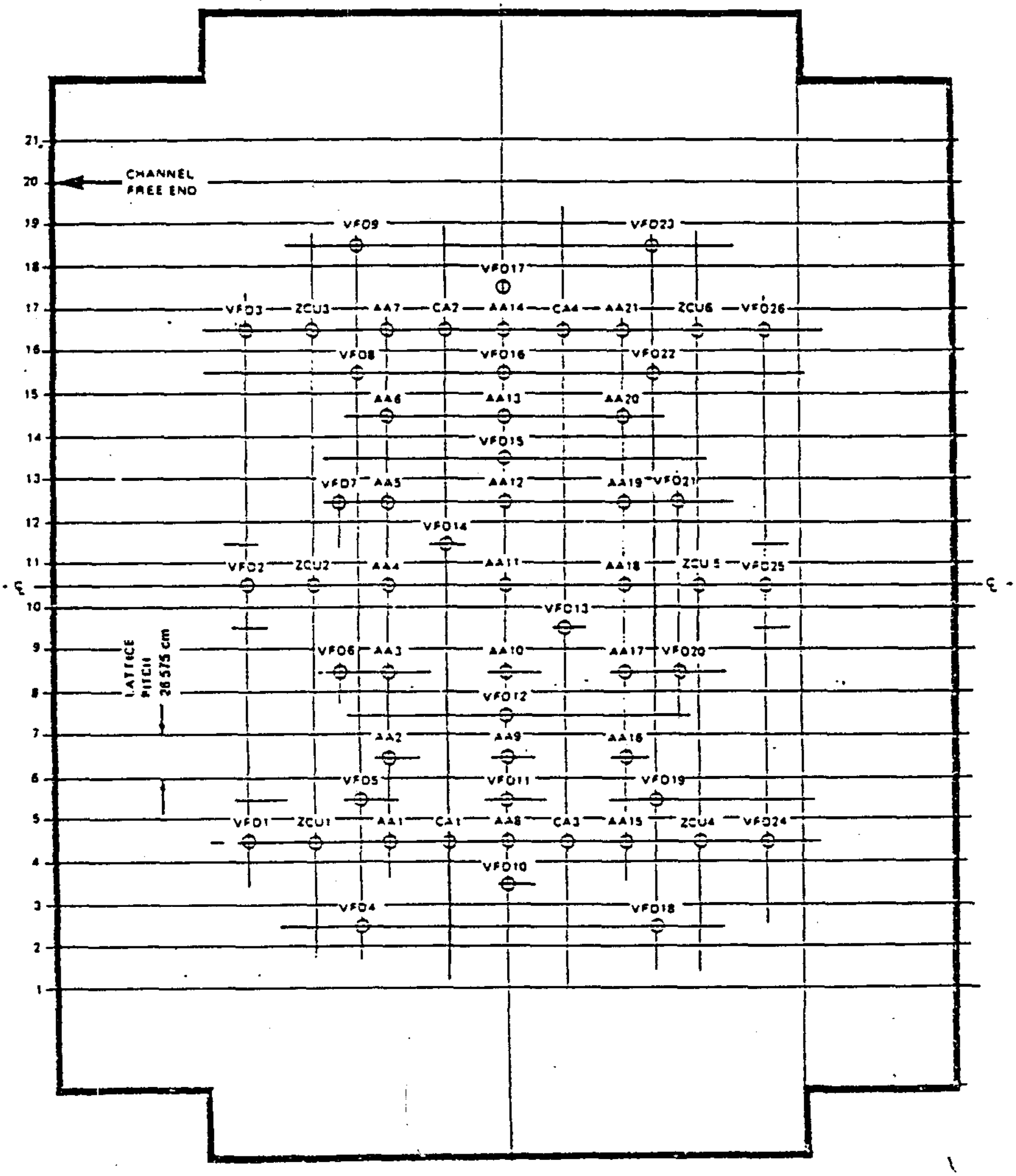


FIGURE 2.4-2 RELATION OF ZONE CONTROL UNITS (ZCU) TO THE FOURTEEN ZONES AND THE REACTOR ZONE CONTROL DETECTOR ASSEMBLIES VFD 2, 3, 9, 18, 23, 25



NOTES
1. LP = LATTICE PITCH
2. ALL ZONE CONTROL DETECTORS ARE 3 LATTICE PITCHES LONG
3. THE BANK OF CONTROLLERS ON THE SOUTH SIDE IS SYMMETRIC TO THIS.

FIGURE 2.4-3 POSITION OF ZONE CONTROL DETECTORS WITH RESPECT TO ZONE COMPARTMENTS



VFD — VERTICAL FLUX DETECTOR
AA — ADJUSTER ROD
CA — CONTROL ABSORBER ROD
ZCU — ZONE CONTROL UNIT

FIGURE 2.4-4 VERTICAL FLUX DETECTOR ASSEMBLY LOCATIONS

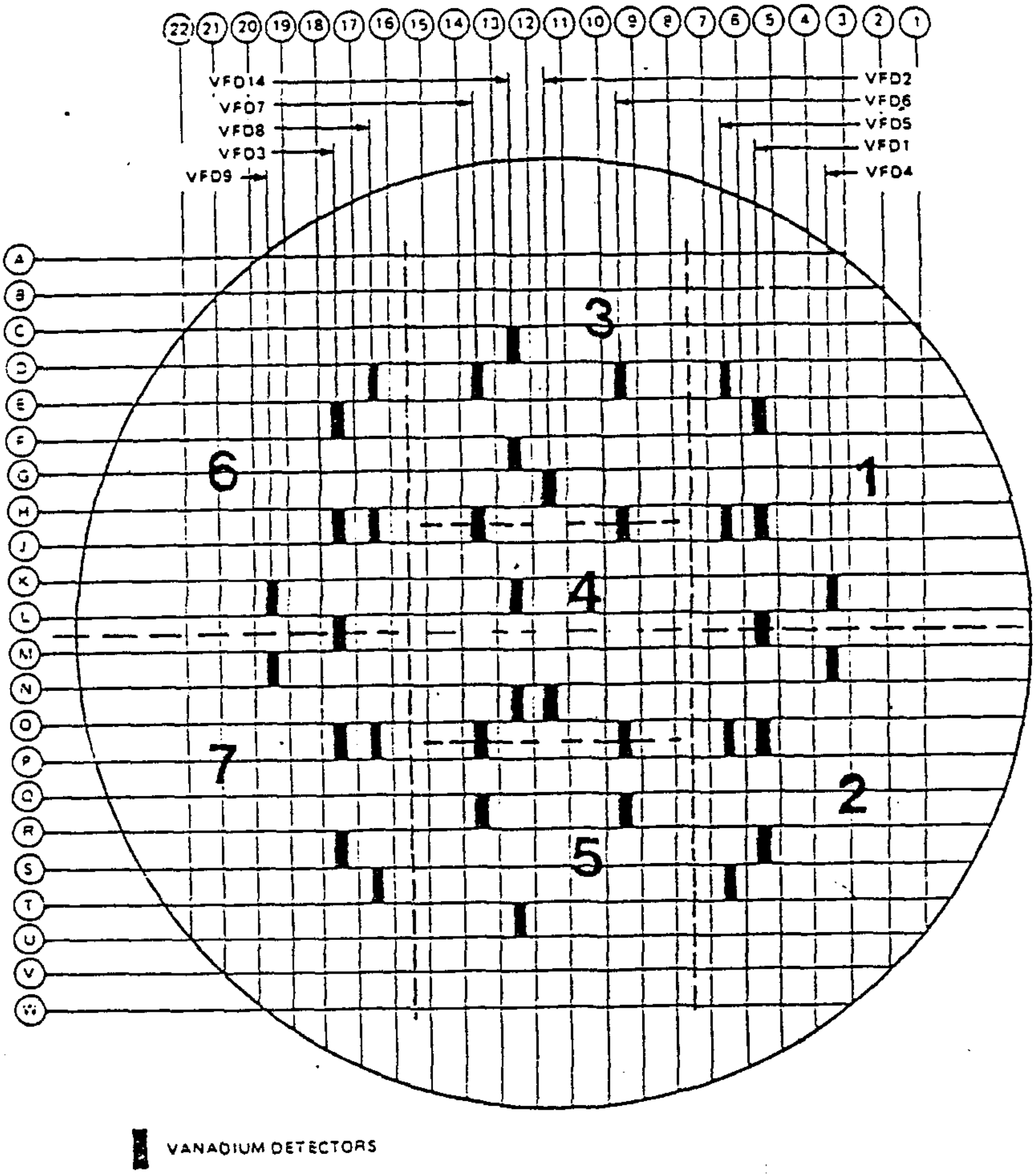


FIGURE 2.4-5 FLUX MAPPING DETECTOR LOCATIONS — VIEW 1

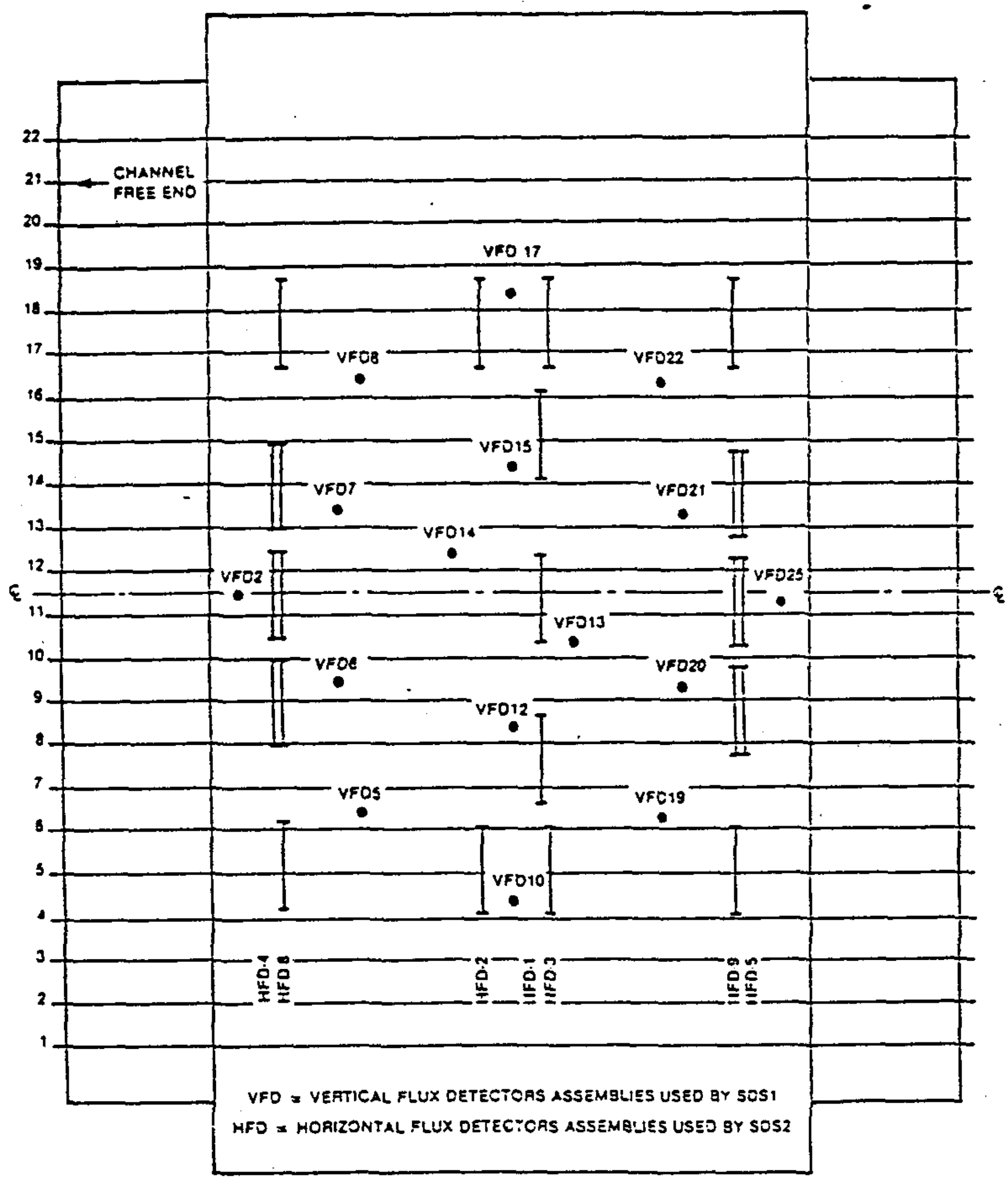
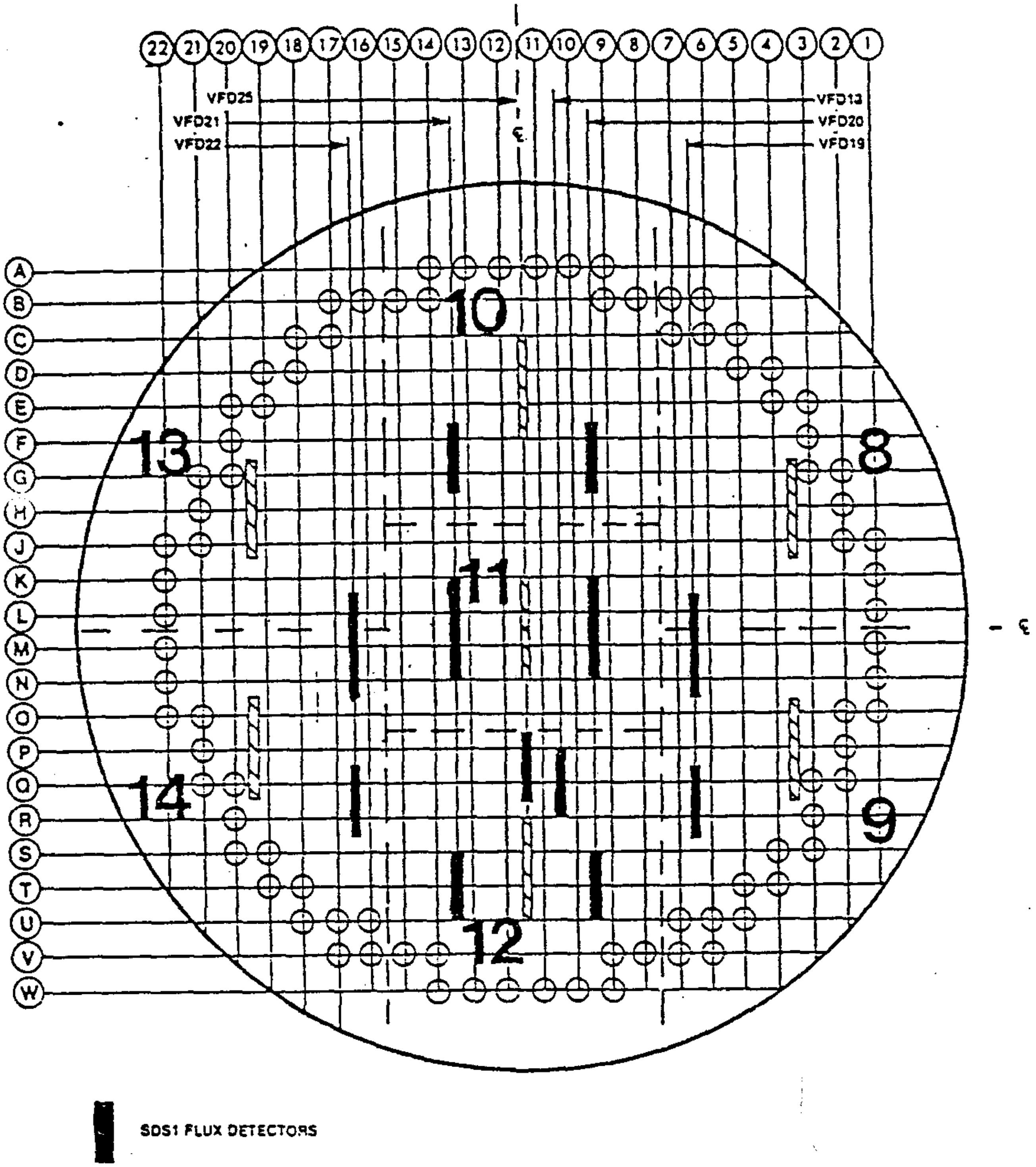


FIGURE 2.4-6 CALANDRIA PLAN SHOWING SDS1 AND SDS2 DETECTORS (TOP VIEW)



SDS1 FLUX DETECTORS

ZONE CONTROL DETECTORS

FIGURE 2.4-7 (continued) — VIEW 3