AECL EACL

ABSORBER MATERIALS IN CANDU PHWR'S

AECL-11107

By

E.G. Price, C.R. Boss, W.Z. Novak
and R.W.L. Fong

1995 March

1995 mars

AECL
2251 Speakman Drive
Mississauga, Ontario
Canada L5K 2B2

EACL
2251, rue Speakman
Mississauga (Ontario)
Canada L5K 1B2

AECL-11107

ABSORBER MATERIALS IN CANDU PHWR'S

E.G. Price[1], W.Z. Novak[2], C.R. Boss[1], and R.W.L. Fong[3]

[1]AECL Sheridan Park
2251 Speakman Drive
Mississauga, Ontario, L5K 1B2

[2]AECL Saskatoon
446A 2nd Avenue North
Saskatoon, Saskatchewan, S7K 2C3

[3]AECL CRL
Chalk River Laboratories
Chalk River, Ontario, K0J 1J0

ABSTRACT In a CANDU reactor the fuel channels are arranged on a square lattice in a calandria filled with heavy water moderator. This arrangement allows five types of tubular neutron absorber devices to be located in a relatively benign environment of low pressure, low temperature heavy water between neighbouring rows of columns of fuel channels.

This paper will describe the roles of the devices and outline the design requirements of the absorber component from a reactor physics viewpoint. Nuclear heating and activation problems associated with the different absorbers will be briefly discussed. The design and manufacture of the devices will be also discussed.

The control rod absorbers and shut off materials are cadmium and stainless steel. In the tubular arrangement, the cadmium is sandwiched between stainless steel tubes. This type of device has functioned well, but there is now concern over the availability and expense of cadmium which is used in two types of CANDU control devices. There are also concerns about the toxicity of cadmium during the fabrication of the absorbers. These concerns are prompting AECL to study alternatives. To minimize design changes, pure boron-10 alloyed in stainless steel is a favoured option. Work is underway to confirm the suitability of the boron-loaded steel and identify other encapsulated absorber materials for practical application.

Because the reactivity devices or their guide tubes span the calandria vessel, the long slender components must be sufficiently rigid to resist operational vibration and also be seismically stable. Some of these components are made of Zircaloy to minimize neutron absorption. Slow irradiation growth and creep can reduce the spring tension, and periodic adjustments to the springs are required. Experience with the control absorber devices has generally been good. In one instance liquid zone controllers had a problem of vibration induced fretting but a designed back-fit resolved the problem.

AECL-11107

MATÉRIAUX ABSORBANTS DANS LES RELP DE TYPE CANDU

E.G. Price[1], W.Z. Novak[2], C.R. Boss[1] et R.W.L. Fong[3]

[1] EACL Sheridan Park
2251, rue Speakman
Mississauga (Ontario) L5K 1B2

[2] EACL Saskatoon
446A, 2e Av. Nord
Saskatoon (Saskatchewan) S7K 2C3

[3] EACL LCR
Laboratoires de Chalk River
Chalk River (Ontario) K0J 1J0

RÉSUMÉ

Dans un réacteur à eau lourde sous pression (RELP) CANDU, les canaux de combustible sont disposés selon un réseau orthogonal dans une cuve remplie d'eau lourde (modérateur). Cet agencement permet de placer cinq types de dispositifs tubulaires absorbeurs de neutrons dans un milieu ne présentant relativement pas de danger et constitué d'eau lourde à faible pression et à basse température entre des rangées voisines de colonnes de canaux de combustible.

Le présent document décrit le rôle de ces dispositifs et trace les grandes lignes des spécifications des éléments absorbants du point de vue de la physique des réacteurs. Les problèmes d'échauffement et d'activation nucléaires associés aux différents absorbeurs y sont examinés. On y traite aussi de la mise au point et de la fabrication de ces dispositifs.

Les matériaux absorbants des barres de commande et les matériaux utilisés pour l'arrêt sont le cadmium et l'acier inoxydable. Dans le dispositif tubulaire, le cadmium est placé en sandwich entre des tubes en acier inoxydable. Ce type de dispositif a bien fonctionné, mais on se préoccupe maintenant de la disponibilité et des coûts du cadmium, qui est employé dans deux types de dispositifs de commande des réacteurs CANDU. On s'inquiète également de la toxicité du cadmium au cours de la fabrication des barres absorbantes. Ces préoccupations incitent EACL à étudier des solutions de remplacement. Afin de restreindre le plus possible les modifications apportées à la conception, l'option préférée est l'emploi du bore 10 allié à l'acier inoxydable. Des travaux sont en cours en vue de confirmer si l'acier chargé de bore convient à cet usage et de trouver d'autres matériaux absorbants enrobés pour des applications pratiques.

Étant donné que, en position basse, les mécanismes de réactivité et leurs tubes-guides traversent la cuve en profondeur, les éléments minces et allongés doivent être suffisamment rigides pour résister aux vibrations pendant la marche du réacteur et être également stables au point de vue sismique. Quelques-uns de ces éléments sont fabriqués en Zircaloy afin de réduire au minimum l'absorption de neutrons. Le lent effet de fluage et d'allongement sous irradiation peut réduire la tension des ressorts et celle-ci doit être réglée à intervalles réguliers. On a généralement obtenu de bons résultats avec les barres absorbantes de commande. Dans un cas, les barres liquides partielles ont présenté un problème de frottement dû aux vibrations, mais une modification a été apportée à la conception qui a résolu le problème.

n:\data\c\ed\price\930714\wpwin
93\11\26

Absorber Materials in CANDU PHWR's

E.G. Price, C.R. Boss, W.Z. Novak, R.W.L. Fong

1. INTRODUCTION

The CANDU reactor has two major circuits circulating heavy water through the reactor. The primary heat transport water, operating at temperatures between 260°C and 312°C, at pressures up to 10.7 MPa and a pH of 10.0 to 10.5, circulates through the pressure tubes and transports heat from the fuel located inside the pressure tubes, to the steam generators. The other circuit is the moderator heavy water circulating at 65°C to 80°C at a low pressure and neutral pH, into the calandria vessel and through the matrix of calandria tubes which isolate the hot pressure tubes from the moderator, and then into the heat exchangers where the required temperature of the moderator heavy water is maintained. The moderator heavy water contained in the calandria is the environment in which are operated the reactivity mechanisms of the CANDU reactor.

The reactivity control devices in a CANDU reactor consist of reactivity control devices, i.e. adjusters, control absorber, liquid zone control units and poison addition system, and two shutdown units. These are backed by neutron flux measuring devices (flux detectors and ion chamber units). The reactivity control devices span the calandria vessel, vertically and horizontally; those with active mechanical elements operate vertically to take advantage of gravity. The devices operate either from a platform above the reactor or from their support at the shield tank wall (see Figure 1).

The control devices are tubular components, designed to be simple and rugged and highly reliable. All components except the stainless steel thimbles which protect the out of core sections of the devices, can be readily removed and replaced.

Six systems are available for introducing absorber material into the reactor core, and these can be classified as mechanical or non-mechanical:

(i) Mechanical Devices

Shutoff rods (shutdown system #1) consist of thin cadmium elements sandwiched and sealed between stainless steel tubes.

Control absorbers are of similar design to the shutdown rods but with slightly thicker cadmium elements.

The adjusters consist of stainless steel tubes or cobalt pins that are used to axially flatten the flux and are operated inserted into the core.

(ii) Non Mechanical

The liquid zone controllers are the main reactivity control devices which operate by adjusting the neutron absorbing quantities of light water contained in compartments in Zircaloy tubes, to control the flux in different zones of the reactor.

The liquid poison injection system, which injects a solution of gadolinium nitrate through horizontal Zircaloy tubes into the moderator forms the second shutdown system. The gadolinium is extracted by circulating the moderator through ion exchange columns.

The poison addition system maintains a low boron concentration in the moderator water. The concentration of boron can be reduced when reactivity is low. It is injected into the circulating moderator water, and removed by the purification system. Table 1 details the various reactivity control devices or systems used in the various groups of reactors.

2. PHYSICS OF ABSORBER MATERIALS IN CANDU

From a physics viewpoint there are four properties which have been considered in the selection of the absorber materials used in CANDU reactors. These are as follows: -

2.1 Absorption Cross-Section

The thermal neutron flux in a CANDU reactor is typically 2.0×10^{18} n/m^2.s at the mid-lattice position in the moderator. At this flux level for an irradiation time of one year, there will be significant burnout of any isotope which has an absorption cross-section greater than 10 barns. There can also be significant transmutation of one element into another over the life of some of the absorber components.

Burnout and transmutation would eliminate the use of strong absorber elements such as boron, cadmium, hafnium or gadolinium for components continuously in-core, such as the adjusters or the mechanical zone control assemblies under development. These devices are relatively weak absorbers and do not provide a large local flux depression. The absorbers can be exposed to high fluxes for relatively long periods of time, and although a weak absorber device with a low concentration of a strong absorber element could be fabricated for this service, the individual atoms would have a high probability of destruction. The destruction of absorber atoms would reduce the macroscopic absorption cross section of the material with time. There is a 15% drop in the absorption cross-section of type 304L stainless steel over thirty years even though the component element cross-section is less than 10 barns. For hafnium, the drop would be about 70%.

2.2 Activation Products

Cobalt-60 isotope is one example of an activation product which has a long half-life and decays with the release of high gamma energy. The gamma fields can create a radiation hazard which must be considered during flasking operations or during decommissioning activities.

The transmutation process creates new sources of cobalt in stainless steel. Typically the cobalt would be present at low concentrations of about 500 ppm as impurity, but the transmutation of iron-58 forms iron-59, and the subsequent beta decay of iron-59 forms cobalt-59. Although the natural abundance of iron-58 is relatively low the process of transmutation promotes the formation of iron-58 from the lower mass isotopes of iron. After 20 years of exposure to a flux of 1.0×10^{18} $n/m^2.s$ the cobalt-60 activity is type 304L stainless steel with no initial cobalt impurity would be indistinguishable from that in a steel with an initial impurity of 200 ppm.

2.3 Nuclear Heating

Energy is released as a result of the absorption process or during the decay of activation products, which then dissipate as heat. This heat may create the potential to melt the absorber material, e.g., cadmium in the parked shutoff rods which are located in a relatively high neutron flux outside the calandria. The decay energy, in the form of heat, must be allowed for in the flasking of devices for removal.

Nuclear heating has the potential to raise the temperature of shutoff rods to a level at which the auto-ignition of deuterium in the moderator cover gas could occur. The temperature of each component is a function of the nuclear energy deposited in the component and the transfer of heat from the component. The energy released following absorption in boron-10 is carried by two recoil particles namely, a lithium-7 nucleus and an alpha particle. All the energy will be deposited essentially at the point of release. Energy released following absorption in cadmium is by high energy gamma radiation which have a high probability of escaping from a thin walled cylinder. Although the energy released from boron is low the heating problems may be as severe as those with cadmium.

2.4 Nuclear Damage

Some of the nuclear absorption process can form protons as recoil particles. These particles have a short range and they can be stopped by the absorber material. Thus the absorption process can introduce hydrogen and helium into the structure of the absorber. For the fluxes and absorbers used in CANDU reactors this form of nuclear damage is considered unimportant (18 ppm hydrogen and 66 ppm helium after 30 years).

The neutron damage from the fast flux irradiation of the absorbers has also been unimportant because the mechanical duties of the absorber elements are relatively light.

3. DESIGN

3.1 Description of Reactivity Control Devices

3.1.1 Mechanical Control Absorbers (MCA)

The mechanical control absorbers (Figure 2) are under the control of the reactor regulating system (RRS). Should the liquid zone controllers be incapable of responding quickly enough to a demand to reduce power, then the MCAs would be driven in. The MCAs also allow the addition of negative reactivity should high levels of light water develop in the liquid zone controllers.

The absorber elements for the mechanical control absorbers are thin walled cylinders of cadmium sandwiched between type 304L stainless steel tubes (Figure 3). The internal diameter of the absorber element is 114.3 mm. The wall thickness of cadmium is 0.91 mm and each steel tube is 0.76 mm thick. The cadmium thickness was chosen to provide ten mean-free-paths of thermal neutron absorption, so that the absorber material will be black even after intermittent irradiation in the core at high power. The internal diameter was chosen to present the largest surface area to thermal neutrons between the calandria tubes in adjacent columns of fuel channels.

At the top (or trailing end) of each absorber rod there is a support rod to which a cable connecting the absorber to the drive mechanism is attached. The support rod is attached to the absorber rod by means of a stainless steel spider located approximately at the mid-span of the rod. The cadmium sandwiched tubes are welded to the top and bottom surface of the spider rim as shown in Figure 3.

3.1.2 Mechanical Shut-Off Rods

The shutdown system 1 shut-off rods use essentially the same design of absorber element as in the MCAs. During normal operation they are parked just outside the calandria. In the event of a trip signal, the shutoff rods are dropped into the reactor core under gravity when the electromagnetic clutches in the shutoff drive mechanisms are de-energized. An accelerator spring, which is compressed by the absorber element when it is withdrawn from the core, imparts an initial acceleration to the elements to reduce insertion time. To withdraw the elements, the drive mechanism clutches are energized and the elements are driven up by motor and parked outside the calandria. Poised in this position, they are instantly available for further use. A magnet in the element support rod, is used to activate the magnetic reed switches in a device called a Rod Ready Indicator. This ready signal, together with the electric output from the drive mechanism potentiometer, indicates the absorber element is availabile for use. A typical shutoff device is shown in Figure 4.

The rods are fully inserted within 2 seconds, and begin to reduce the thermal neutron fluxes in the core several hundred milliseconds after clutch release. Their rapid insertion and consequent reactor shutdown mean the shut-off rods accumulate exposures at the rate of 2 full power seconds per insertion.

The dynamic worth of the shutoff rods, (a measure of the negative reactivity added) is typically -91 mk.

3.1.3 Adjuster Assemblies

The adjuster assemblies are the third absorber system under the control of the RRS. Physically the adjusters are light absorbers and have a large surface area. The mass per unit length was dictated by the need for axial flattening of the neutron flux profile, (see below) and a xenon override capability. The absorber element is either a thin-walled tube and a central shim rod both made of type 304L stainless steel, or a string of bundles of zircaloy-clad cobalt-pencils (Figure 5). The outer diameter of the steel tube is 76.2 mm with a wall thickness of 0.5 to 2.0 mm. In the cobalt adjusters there are 2 to 6 pins of cobalt in a circular arrangement of 51.7 mm pitch; each pencil contains 52.8 grams of cobalt.

The adjuster assemblies are normally fully inserted in the reactor core. They are arranged across three vertical planes along the reactor axis with 7 or 8 adjusters in each plane. In this arrangement the adjuster assemblies provide axial flattening of the fuel bundle powers in a fuel channel. Consequently with the adjusters, the power extracted from each fuel channel can be increased over a channel that has no axial flattening.

The adjusters also provide a xenon override capability. By removal of the adjusters, the operator can correct a fault which prompted the trip and then return the reactor to full power without incurring a poison-out. Typically there is a period of thirty minutes in which the operator can correct a fault and return to power before the growth of xenon-135 adds more negative reactivity than the withdrawal of adjusters can offset.

3.1.4 Liquid Zone Control Units (LZCU)

The liquid zone control system uses light water as absorber in a compartment formed with Zircaloy 2 walls. The rest of the compartment is filled with a helium cover-gas. The level of light water in each compartment is altered by changing the water flow to a compartment thereby allowing the compartment to drain or fill (Figure 6).

Typically there are 14 compartments arranged in six LZCU-assemblies. The compartments are distributed throughout the central regions of the reactor core. Each compartment "controls" the flux level in that part of the reactor core. The core is divided into fourteen zones and the power of each zone can, to a degree, be controlled independently of the power in the other thirteen zones.

The liquid zone control system is the primary control system of reactor power. It is under the control of the RRS. The RRS uses the measurements of the local flux from the in-core flux detectors to regulate the flow of light water to each compartment. A demand by the RRS to reduce reactor power globally would prompt an increase in light water levels. A demand to raise power would prompt a drop in light water levels. Ideally the compartments should be 40% to 60% filled to allow addition or removal of reactivity from any part of the core.

For the CANDU 3 reactor under development the liquid zone control units will be replaced by a system of telescoping stainless steel mechanical zone controllers.

3.1.5 Liquid Injection Shutdown System 2 (SDS2)

The second shutdown system is made up of six liquid injection nozzles. These are roughly 50 mm internal diameter Zircaloy 2 tubes and supported horizontally in the calandria. These tubes, which are normally full of moderator heavy water, contain hundreds of small diameter holes which distributes the gadolinium nitrate solution in the calandria.

One end of each tube is connected to a pressurized tank of gadolinium nitrate solution. When a trip signal is received, the gadolinium nitrate is flushed into the calandria through the small holes.

The system is capable of adding -200 mk to -300 mk of negative reactivity. Typically the system adds -55 mk in the first minute and -300 mk over the first hour. The gadolinium is removed from the moderator water by the ion exchange resins of the moderator purification system.

The choice of gadolinium was driven by its large absorption cross section and high solubility in water. A boron salt has been used in some designs. There have been no identified problems with this system. However, one concern is the tendency of the gadolinium to precipitate out of solution when the pD of the moderator heavy water is too high.

3.1.6 Liquid Poison Addition

One of the moderator auxiliary systems is a liquid poison addition system. The system allows the addition of a small amount of negative reactivity to the moderator and consequently globally to the reactor core. The addition of the boron (or gadolinium) is made as a small flow to the suction of the main moderator pumps. A small concentration (0.5 ppm) of boron in the moderator adds -3 to -4 mk of reactivity to the core.

The negative reactivity may be used to control excess reactivity in new fuel (referred to as poison shim). Operating the core with a low concentration of boron in the moderator allows greater flexibility in fuelling operations. (A refuelling operation could be delayed by reducing the boron content in the moderator to zero through a purification system, thus maintaining core reactivity.) The reduction of boron is more attractive than removing a bank of adjusters because there are no changes to the relative flux distribution in the core.

The negative reactivity would also compensate for the loss of reactivity after a poison out or a long shutdown when the xenon-135 decays. Finally the system provides enough poison to the moderator to prevent criticality during a shutdown and guarantee the shutdown.

3.2 Manufacturing

The fabrication process employed in the fabrication of the cadmium sandwich absorber and shutoff rods basically consists of the following steps:

a. A 99.9 percent pure cadmium sheet is wrapped around the inner cladding tube with the joint between the sheet ends running along the axis of the tube. The cladding tube inside diameter is slightly larger than the required final size.

b. The inner cladding tube complete with the cadmium sheet is inserted into the outer cladding tube which again is oversized to facilitate assembly.

c. The cladding tubes are crimped at one end to accommodate the attachment of a pulling mechanism and the cladding tube/cadmium assembly is drawn down to size by pulling it through dies.

d. The assembly is then trimmed to proper length and the ends sealed by welding and swaging prior to attachment by welding to the support rod.

The cladding tubes are made of type 304L austenitic stainless steel to ASTM A269 or ASTM A270. Initially this material is in a fully annealed condition to facilitate draw down. Fabrication development was required to ensure adequate location of the cadmium with the specified joint gap and internal void.

The finished rods are extensively tested for weld and cladding quality for structural integrity to prevent deterioration of the cadmium which could occur with the ingress of heavy water.

The fabrication of the stainless steel adjuster elements involves a three stage process. First, the type 304L stainless steel is purchased to dimensions calculated by the core physicist based on the nominal chemistry in the material specifications. Second, the actual chemical analysis of the material is obtained and is used to determine the reactivity worth of the element. Third, the centre rod or shim rod (Figure 5) is then sized to fine tune the reactivity worth.

The guide tubes for the shutoff rods, control absorbers and adjusters, which run vertically through the calandria (see Figure 7 and 8) are seam welded tubes made from perforated Zircaloy-2 sheet, (to minimize neutron absorption and preclude voids in the moderator, while ensuring proper cooling of the in-core devices). These tubes are spring loaded to limit vibration in the circulating moderator water.

The other tubes for the reactivity devices are mostly made from extruded and annealed zircaloy or stainless steel materials.

4. OPERATING EXPERIENCE

The operating experience of the CANDU reactivity devices has been very good. Only a limited number of problems have occurred, predictably related to vibration. In the early prototype reactor Douglas Point, a threaded joint in a flow tube of one booster unit failed permitting the flow tube to vibrate against a calandria tube, eventually perforating the calandria tube. In the same reactor after decommissioning, it was observed that very slight vibration over a 23 year period of operation, caused a booster guide tube to fret a groove and perforate the tube wall at the position where the tube was guided by a support ring.

In one Bruce A unit, the vibration of the liquid zone control unit centring guide (for the internal light water and helium tubes) against the inside wall of the enclosing tube, caused perforation of the tube and necessitated its replacement. This problem is unique to the Bruce A reactors where the moderator heavy water enters the calandria through the booster guide tubes and is discharged into the vessel through nozzles located near the top of the vessel. Vibration of the liquid zone control unit was caused by impingement of the moderator flow from these nozzles onto the wall of the liquid zone control unit.

The Zircaloy-2 guide tubes operate with an axial load applied to them to provide seismic and vibrational stability, by increasing the natural frequency of vibration above that expected in service. The guide tubes are exposed to high neutron fluence during service. We would expect these tubes to elongate slightly from irradiation creep and growth, and the elongation would reduce the spring tension load on the tube. Periodic adjustments of the tension can be done from adjustment nuts at the reactivity mechanism platform. However the elongation rate has been low and few adjustments have been needed.

5. CONCERNS

The most important concern relates to the use of cadmium. The shutoff rods and absorbers have performed well but concerns have arisen from the viewpoint of (a) expense of the cadmium and restrictions on its use and (b) nuclear heating of the bottom of the shutoff rods in the parked position.

Cadmium is receiving attention as a hazardous material and possibly faces restrictions on its usage. A problem of effective disposal or neutralization of the waste from the refining processes used to produce it, adds another concern for the economics of its use in the future. Thus a substitute material is being sought as a back up. The favoured option is type 304L stainless steel alloyed with pure boron-10[1][2][3]. A boron-10 concentration of about 2% would be required for control absorbers and shutoff rods. The relatively easy incorporation of boron-10 stainless tubes into the existing design favours the material selection.

Nuclear heating of the cadmium in the parked shutoff rods has previously been a concern but the satisfactory performance has not indicated any need for replacement. The concern relates to the conditions where the moderator level gets too low and the additional neutron flux seen by the bottom of the parked rod produces extra heat. This could lead to the potential melting of the cadmium or the possibility that the rods could reach a temperature which could ignite deuterium gas that could occasionally build up to higher concentrations in the helium atmosphere as a result of radiolysis of the moderator heavy water. While there is no evidence that such conditions have even been approached the use of borated stainless steel may eliminate this concern if the steel is capable of disseminating the heat generated by the boron more effectively.

6. CONCLUSION

The relatively benign environment in which the reactivity devices of the CANDU reactor operate has contributed to a reliable performance record for these devices. The potential future substitution of borated stainless steel for cadmium is under consideration from economic concerns but such substitution will possibly alleviate some potential operating concerns.

7. REFERENCES

(1) Stephens, J.J.; Sorenson, K.B.; and McConnell, P., Sandia National Laboratories, Albuquerque, New Mexico, USA; "Elevated Temperature Tensile Properties of Borated 304 Stainless Steel: Effect of Boride Dispersion on Strength and Ductility"; PATRAM '92 International Symposium on the Packaging and Transportation of Radioactive Materials, Yokahama, Japan, 1992 September 13-18.

(2) Brown, R.S.; "Grade A Boron-Stainless Steel: Your Flexible Friend"; Nuclear Engineering International, 1992 June 37 No. 455 p41-42.

(3) Soliman, S.E.; Youchison, D.L.; Baratta, A.J.; and Balliett, T.A.; "Neutron Effects on Borated Stainless Steel"; Nucl. Technol. 96 Dec. 1991 p364.

Table 1

Reactivity Devices Used in Various CANDU Reactors

	Liquid Zone Controllers	Telescoping Mechanical Zone Controllers	Mechanical Control Absorbers	Mechanical Adjusters	Mechanical Shutoff Rods	Liquid Poison Injection	Boosters	Moderator Dump
Pickering A (1-4)	6	-	0	18	21	0	-	√
Pickering B (5-8)	6	-	4	21	28	6	-	-
Bruce A (1-4)	6	-	4	0	30	7	16	-
Bruce B (5-8)	6	-	4	24	32	8	-	-
CANDU 6's (12)	6	-	4	21	28	6	-	-
Darlington (1-4)	6	-	4	24	32	8	-	-
CANDU 3	0	4	4	12	24	8	-	-
CANDU 9	6	-	4	24	32	8	-	-

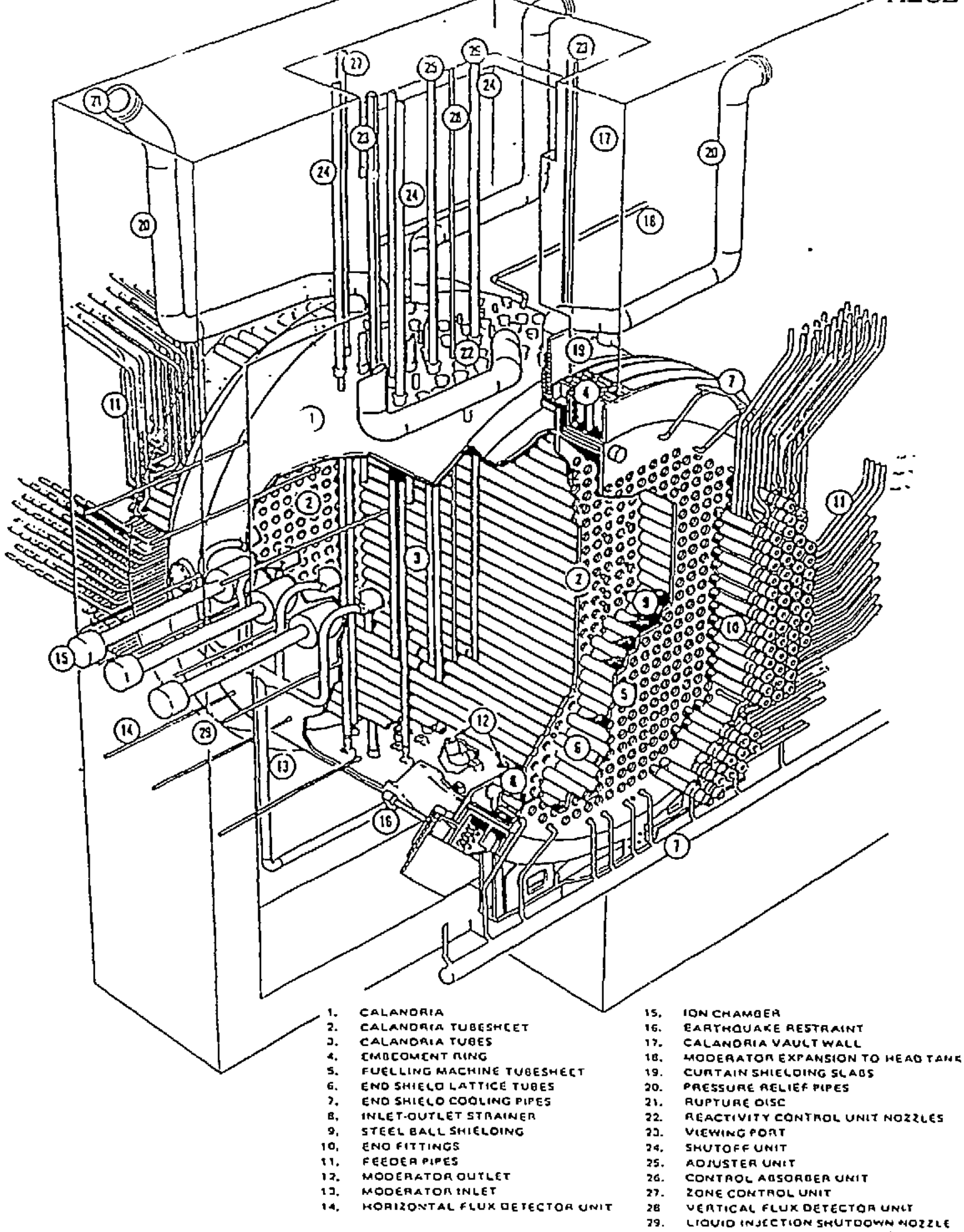

Figure 1 An Illustration of a CANDU Reactor Showing the Locations of the Vertical and Horizontal Reactivity Control Devices

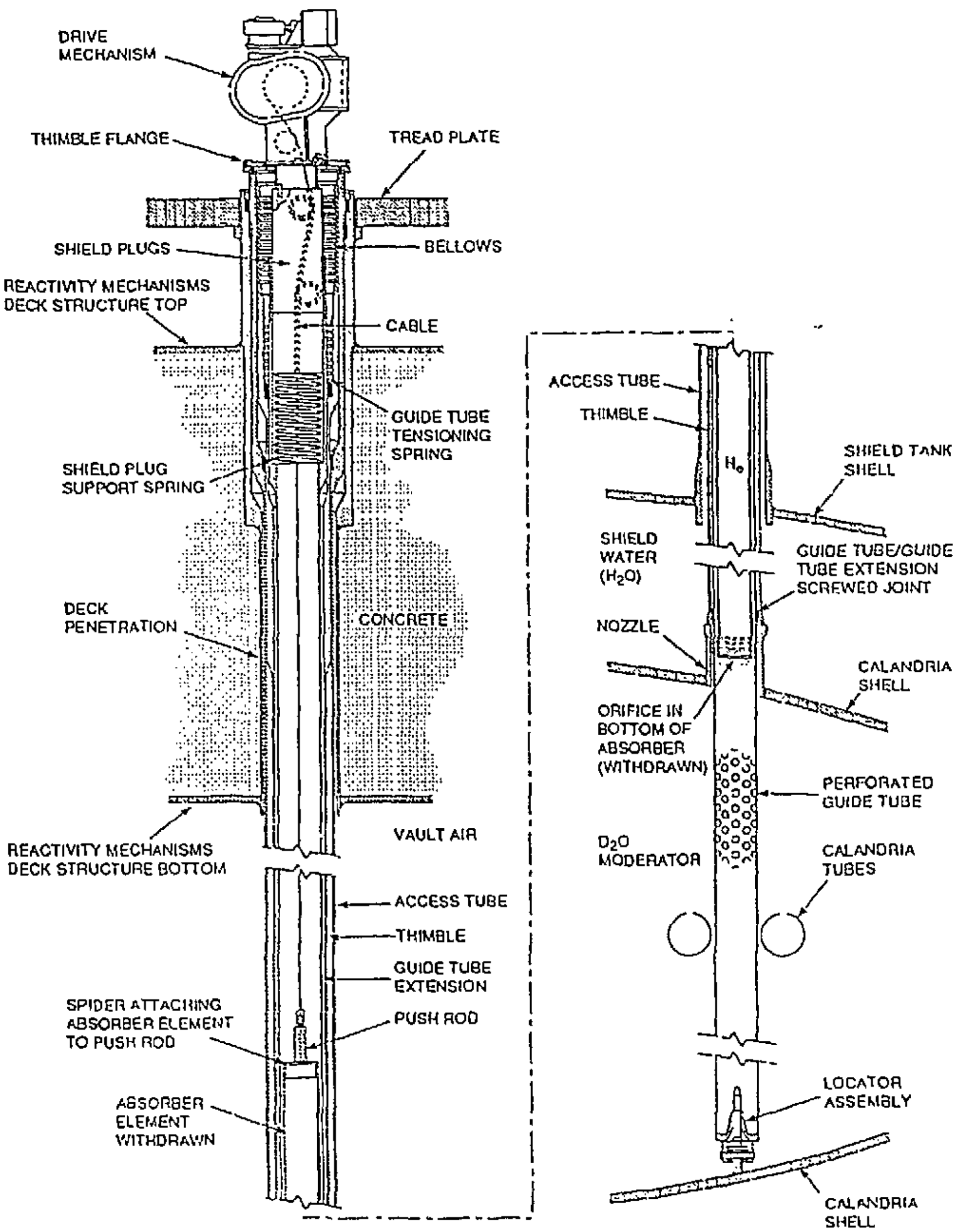

Figure 2 Mechanical Control Absorber Unit

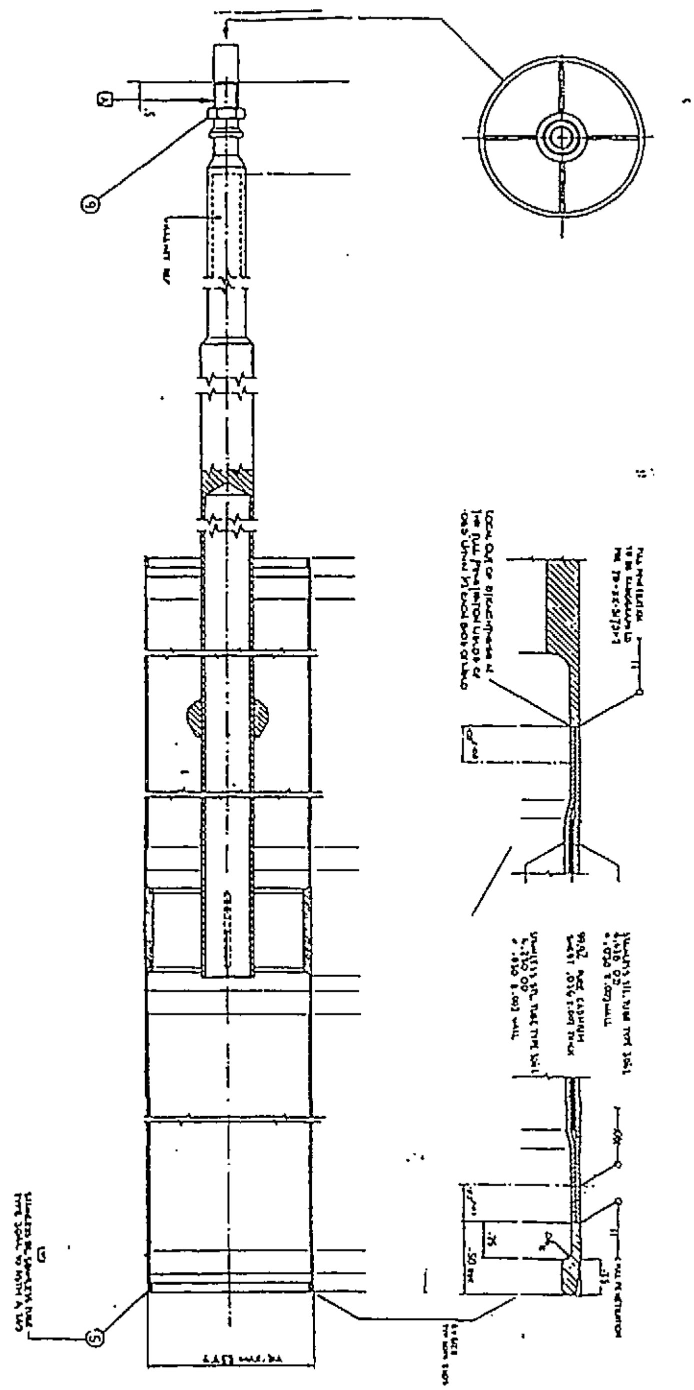

Figure 3 Absorber Elements Formed by Sandwiching Cadmium Between Type 304L Stainless Steel Tubes

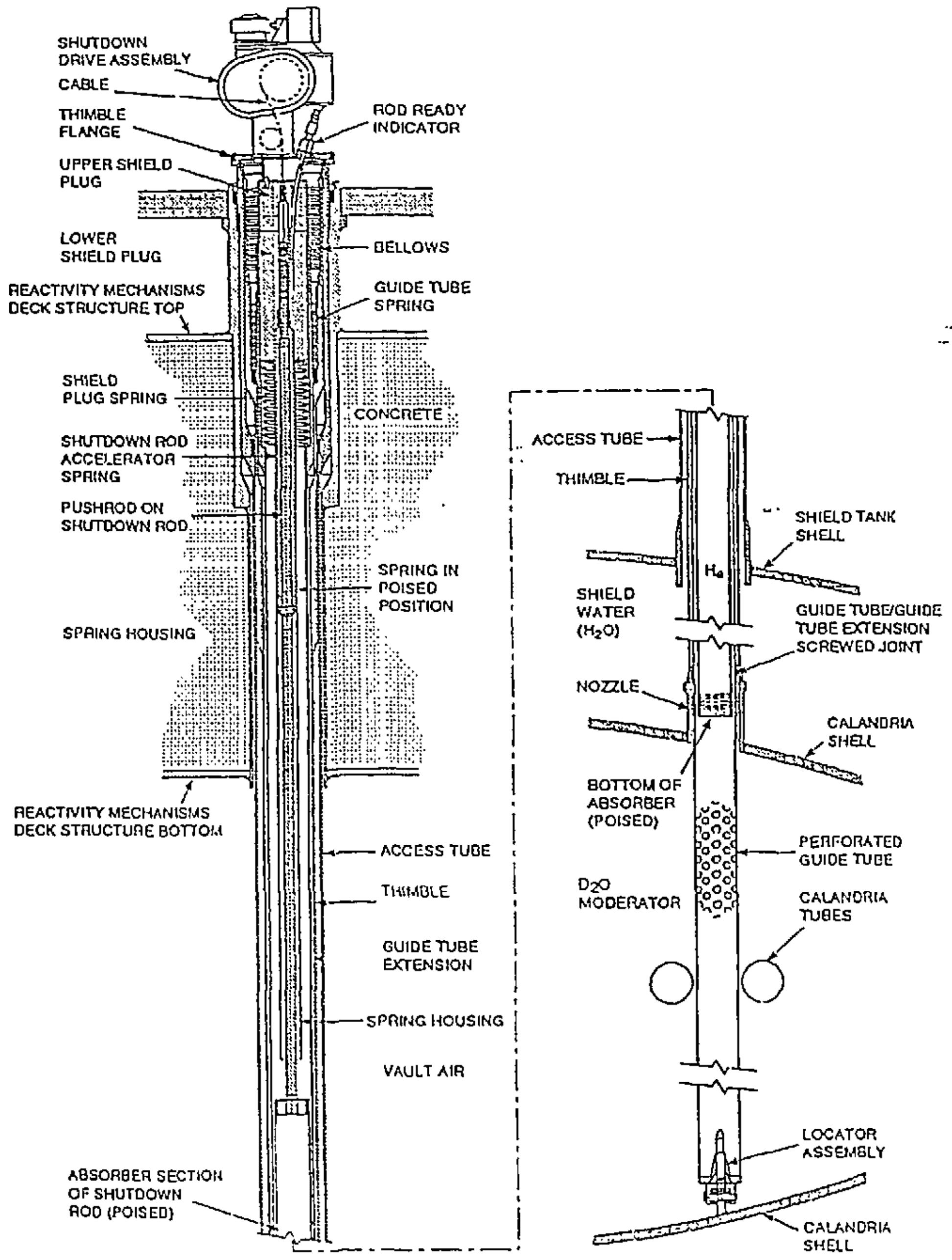

Figure 4 Mechanical Shut-Off Rod

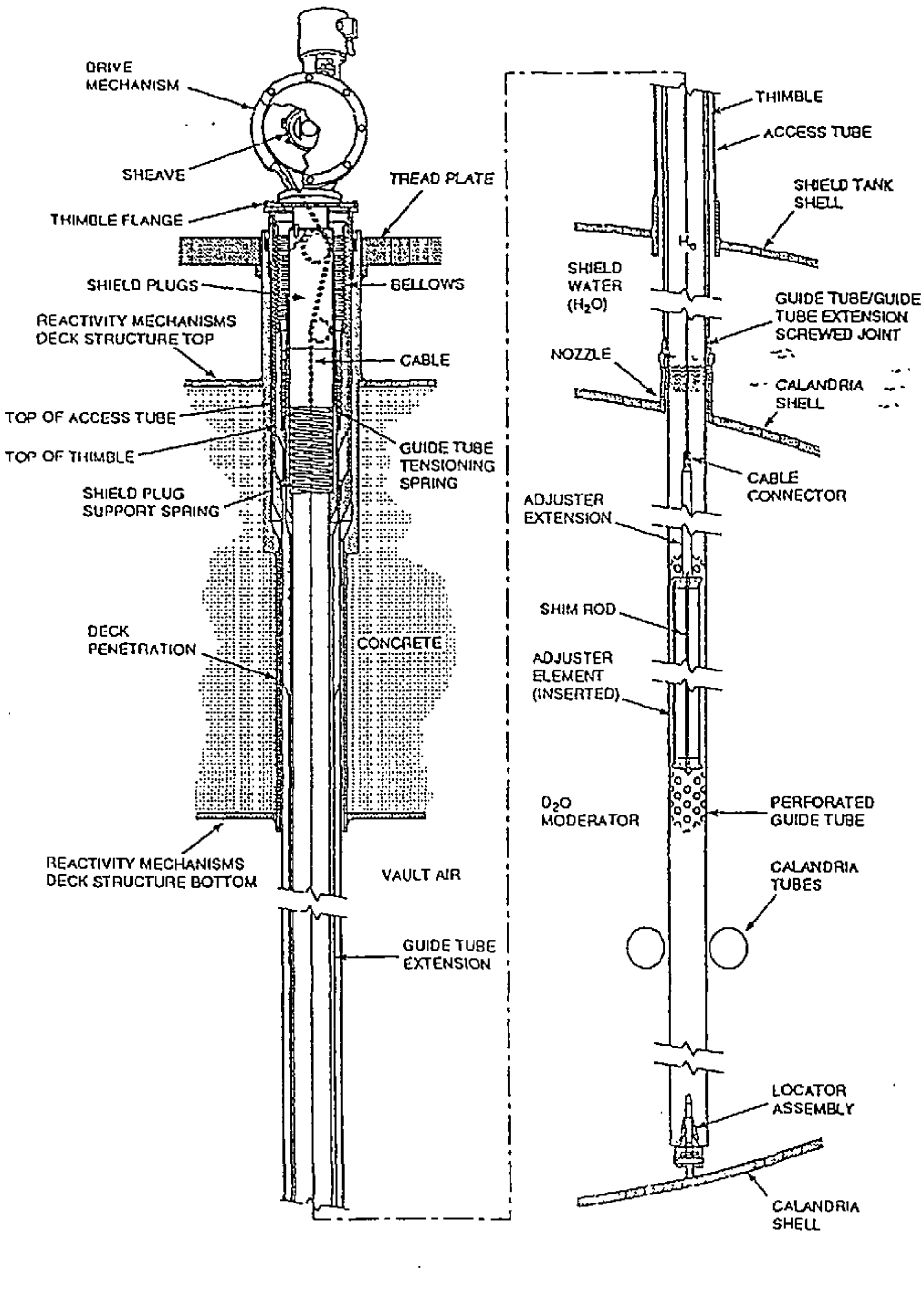

Figure 5 Adjuster Unit Assembly

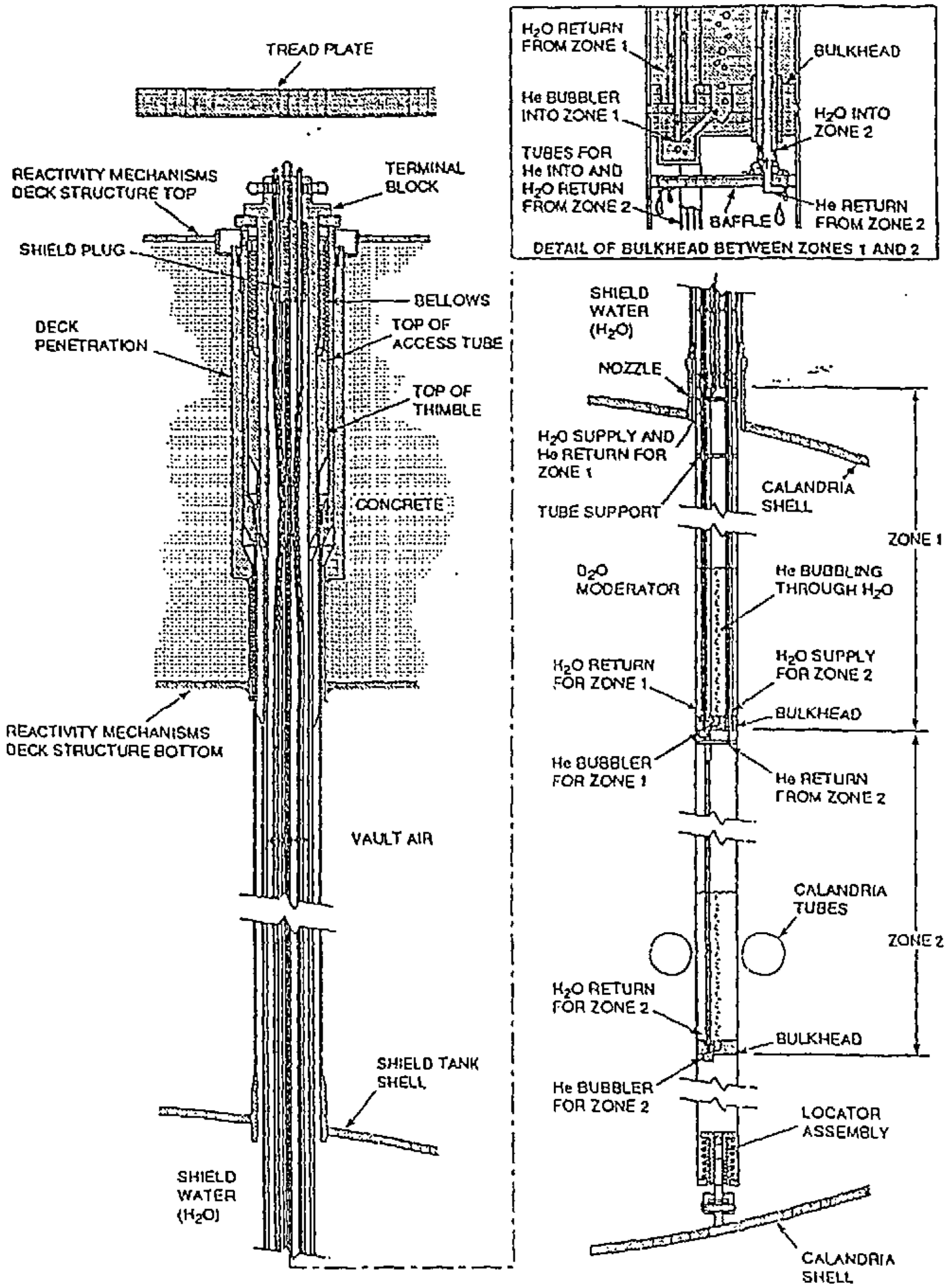

Figure 6 Two Zone Liquid Zone Control Unit

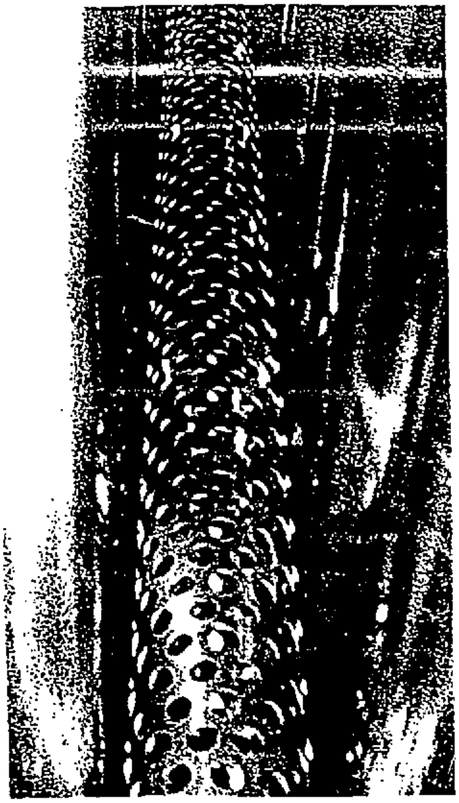

Figure 7 Vertical Shutoff Guide Tube Penetrating the Reactor Core Between Rows of Calandria Tubes

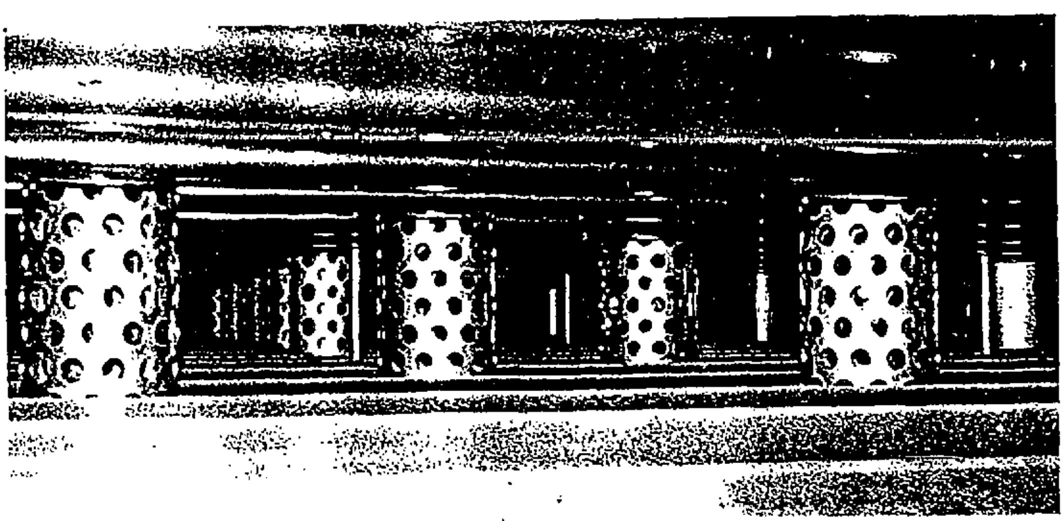

Figure 8 View Looking Horizontally Between Rows of Calandria Tubes Showing the Variety of Vertical Penetrations