Reactor, Boiler & Auxiliaries - Course 133

CHOICE OF REACTIVITY MECHANISMS

We shall now examine each of the four general mechanisms discussed previously and see why which type is actually used, what they look like and how they operate. Table 1 lists the choice made of these mechanisms for all our stations.

1. BOOSTER MECHANISMS

The advantages of using booster rods against adjuster rods are:

(a) using adjusters a large burn up penalty (up to 8% or so) is incurred due to the rods being in-core during operation; with booster rods there is essentially no burn up loss.

Related to this feature is the fact that with booster rods flux flattening is then achieved by differential fuel burn up, essentially giving flattening on the radial plane. With adjusters the flux can, however, be flattened along the radius and the axial length of the calandria by clustering the rods in the central region of the core.

(b) A booster rod system can in principle provide larger Xe override capability than adjusters, due to the smaller burn up penalty, and is more suitable if significant load following capability is required.

Traded off against these factors are the disadvantages of boosters namely:

(a) enriched U235 (~90% U235) is extremely expensive (and also a non-Canadian product).

(b) Booster rods (being essentially highly reactive reactor fuel) produce much more heat when inserted in-core than adjuster rods. For example, ~5MW (maximum)/ Bruce A booster rod versus ~15kw/ Pickering adjuster rod. Hence, a much higher pumping energy for the D_2O coolant flow is required. Of most concern though, are the stringent precautions needed for loss of booster cooling (and for low coolant flow). Typically, loss of coolant on a fully inserted booster could lead to rod meltdown after only 5 seconds or so. This feature of boosters is perhaps their major disadvantage compared with adjusters.

(c) Co^{60} produced in adjuster rods has considerable commercial value for medical purposes. This helps to balance out the alternative cost of enriched fuel boosters and the incurred burn up penalty from lost power production.

(d) The useful lifetime of booster rods depends on the number of times they are used, from nuclear rather than mechanical considerations. When their reactivity worth has typically been reduced by burn up by ~30%, (about 150 insertions or so) then they have to be replaced.

Pickering A & B Adjuster Rods

The 18 cobalt adjuster rods are located in the calandria as shown in Figure 1. Notice that they are situated around the central region of the core, compared to the more distributed positioning of the boosters used at Bruce A, Figure 3.

The adjusters are raised and lowered into the core through guide tubes by a winch and cable device. The guide tubes for the rods are made of Zircaloy-2 inside the calandria and stainless steel outside the vessel. Figure 2 shows the arrangement, the rod guide tube being perforated along its whole length to allow a continuing flow of moderator cooling water during rod insertion. In the out of core (parked) position, cooling is still required for these rods to prevent overheating.

Bruce A Booster Rods

Booster locations (16), for the Bruce A units are shown in Figure 3 and a schematic of the mechanism with a complete element assembly (6 fuel elements) in Figure 4. The Zircaloy-2 guide tube is not perforated, heavy water coolant enters the tube at the bottom, passes over the fuel and discharges through a nozzle into the top of the calandria. The booster drive (unlike the adjusters) is by a rack and pinion mechanism, allowing reliable position measurement of the rod, and provides a compact drive, space being in short supply on top of the reactivity mechanism deck, although the drive is rather tall (Figure 4). Insertion rate is about 10 cm/sec. In addition, boosters have interlocks to prevent simultaneous insertion of certain combinations of them and also have inhibits during reactor trip conditions.

As well as compensating for Xe transients, the Bruce boosters will also be able to allow plant operation for significant periods without fuelling in case of fuelling machine unavailability.

For the control room operator information on the positions of the boosters is presented on a CRT screen, rather than on a chart recorder, and Figure 5 illustrates a typical format of presentation obtained during Bruce 2 commissioning.

2. POISON SYSTEMS

Boron or gadolinium in the form of boric acid D_3BO_3 and gadolinium nitrate $Gd(NO_3)_3 .6\ H_2O$ solutions are actually used in our reactors to provide reactivity shim for:

(a) Xe equilibrium load simulation (28 mk) and

(b) fuel burn up simulation (~30 mk).

Each station is somewhat different so we will briefly look at each one and see why there are differences.

NPD

At NPD no moderator poison system is used because of the fact that the loss of revenue due to the infrequent event of power loss during Xe load build up was not sufficient to justify the cost of a poison system. However, this still left the problem of fuel burn up simulation with the fresh fuel charge at first criticality in 1962. This was solved by strategically loading the channels with 62 depleted (0.2% U235) fuel bundles and consequently shuffling the fuel as required by the differential burn up fuelling schedule as initial burn up progressed. Poison (in the form of $CdSO_4$ solution) was however used once at NPD, however during initial reactor physics measurements, being dissolved in the coolant, and used to calibrate the moderator level/reactivity control system.

Douglas Point

Originally at Douglas Point the liquid poison system was designed to use $CdSO_4$ solution, which requires a small IX resin removal capacity, but this was later changed to boric acid H_3BO_3 solution due to the radiation fields (~800 mr/h/ppm Cd) from the activated Cd isotopes which would have been produced by neutron capture, delaying access to the moderator system until removal by IX columns was adequate. Boron has no activation products produced by neutron absorption and does not suffer from this disadvantage, it does however require a larger resin removal volume than for cadmium. Gadolinium has also been used for Xe simulation since 1972.

Pickering A

At the present time only boron is used for both of the two major reactivity shim variations. In addition during normal operation a small concentration of moderator boron is maintained and controlled for general long term reactivity shim. Gadolinium is not used at Pickering as there is some concern that it may lead to high deuterium gas levels in the cover gas system due to increased radiolysis of the moderator. The experience from Douglas Point however does not seem to substantiate these fears.

Bruce A & B and Pickering B

Boric acid is used here for fresh fuel reactivity shim while gadolinium nitrate will be used for Xe load simulation. Gadolinium has the advantage over boron for Xe load simulation because the neutron burn up rate of the neutron absorbing gadolinium isotopes (Gd155 and Gd157) and the Xe build up are sufficiently complementary that little adjustment of the gadolinium concentration by IX control is necessary during start up. The IX columns are however used to remove the reactivity build up of low cross section gadolinium absorption products to limit their accumulation in the moderator.

Using boron to simulate Xe load needs closely monitored operation of the cleanup circuit to obtain the rapid reduction of boron required (3.5 ppm = 28 mk), boron removal being essentially only dependent on the IX removal rate rather than neutron burn up rate. Much more IX column capacity is also needed for B removal than for the Gd system.

Typical poison system equipment is shown schematically in Figure 6 for Bruce A. The system consists of two poison mixing and storage tanks (stainless steel), valves and piping to connect the tanks to the moderator system and a supply delay tank. The delay tank permits a 75 second delay for the flow of N-16 and O-19 in the D_2O supply, which is obtained from the moderator system.

3. VARIABLE REACTIVITY LOADS

To discuss these mechanisms we will consider each of our stations in turn, each of which uses one of (or combinations of) the methods described previously.

2. there is no depletion problem

3. cooling is easily taken care of

4. control devices do not have to be located in high radiation areas.

The large Pickering core size meant that both axial and radial flux tilting would occur. As a result the core was divided up into 14 zones as illustrated in Figure 8. Each zone contains a light water compartment (Figure 9) which can be emptied or filled independantly. These compartments are all contained within 6 vertical through tubes 2 with 3 compartments and 4 with 2 compartments. Water is fed into each compartment by small diameter tubing, ensuring that the reactivity load is essentially in the compartment and not in the tubing. About 200 kg of light water are needed to fill all the compartments. There is a constant outflow of 0.2 l/s from the bottom of each compartment and a controlled inflow from the top of 0.02 to 0.4 l/s which runs down the wall of the tube. This arrangement then ensures cooling and chemical control is taken care of. The cover gas is helium and a recombination unit is also provided. In addition a delay tank allows the induced O19 and N16 activity to decay so that valves and pumps are accessible during operation.

<u>Bruce A & B</u>

No moderator level control is provided at Bruce, the disadvantages mentioned above for this mechanism becoming quite serious for these large units.

As at Pickering, there is a <u>liquid zone control system</u> for the primary control of reactor <u>bulk power and flux tilts</u>. Again 14 individual zones and compartments are used and the system is essentially identical to the one just described.

The type of display seen in the control room of the zone levels in each compartment is shown in Figure 10 for Bruce.

Reference to Table 2, Section 50-1, shows the worth of the zone control system as 6 mk while the power coefficient for fresh fuel is at 10 mk. Hence to offset this additional power control reactivity the zone control system is supplemented by 4 mechanical <u>control absorber rods</u> worth a total of 8.7 mk. In addition to <u>supplementing the power coefficient reactivity</u> they also allow for a <u>rapid power reduction to 65% FP</u> in the event of a loss of one HT pump.

The locations of these control absorbers (cadmium cylinders sheathed in stainless steel) are illustrated in Figure 11 and mechanically identical to the shut off rods, Figure 16.

NPD

Primary reactor control is by moderator level control. The hardware involved has been illustrated previously. Disadvantages of this control method are:

(a) Power loss due to Xe equilibrium load build up.

(b) Regional or zonal control of flux is not possible. At NPD this is no problem however.

In addition moderator temperature can be manually adjusted during operation for use as reactivity shim. This control was used initially at NPD, a range of about 4 mk being available. At equilibrium fuel the temperature coefficient becomes small so no use is now made of this mechanism.

Douglas Point

Moderator level control is used here but only to start up and shut down the unit. During full power operation the calandria is normally full.

Trim and zonal control is achieved using two absorber rod mechanisms, positioned as shown in Figure 7. Each mechanism consists of two absorber elements of mildly absorbing stainless steel (1.5 mk/rod). The elements can be positioned independantly in the same tube by a drive mechanism on top of the calandria vault. Cooling (~2 kw/rod) is achieved by D_2O passing vertically down the guide tube back into the moderator.

Absorber location is astride the reactor axial centre to control radial (side to side) flux tilts. The absence of an axial reflector reduces the likelihood of axial flux tilts. Synchronous movement of the absorbers then will control bulk reactivity in addition to flux distortions.

Pickering A

Moderator level control is available but under normal full power operation the calandria will be full of moderator and level control is used only if other means of bulk control are inadequate.

For the primary control of bulk reactor power and flux tilt the light water zone control system is used. Advantages of this system over the solid absorber rods used at Douglas Point for the same function are:

1. there is no interaction between zones, which does occur to some extent on movement of solid absorbers

They can be driven in or out at a variable speed and can also be inserted very rapidly if required. Control absorber core positions as seen in the control room on CRT screens are shown in Figure 12.

As a result of all the tubes needed for the control mechanisms, and in addition flux detector tubes, the top of the calandria and the reactivity mechanism platform on top of the shield tank are fairly congested areas as illustrated in Figures 13 and 14.

4. SHUTDOWN MECHANISMS

NPD and Douglas Point

For these early reactor units the shutdown mechanism consists of moderator dump only. With the relatively small sizes of these units moderator dump gives adequate shutdown response times with no major mechanical difficulties or power loss penalty due to long pump-up times after dump.

Pickering A

Newer safety philosophy, requiring better reliability, dictated the design for two independent shutdown mechanisms. Shutdown System 1 (SDS1) uses a bank of 11 vertical shut off rods (SOR's); made of two concentric stainless steel tubes, with cadmium sandwiched between, in the form of open ended tubes.

Location of these shutoff rods is indicated in Figure 15. Notice that they are located fairly symmetrically about the core. Figure 16 shows the shutoff rod assembly in more detail. The rods fall under gravity and are raised by a motorized winch and cable. The cable drum is driven via an electromagnetic clutch which releases when de-energized, allowing the rods to fall freely into core. The incore Zircaloy-2 guide tube is perforated along its length apart from a 2m section which, with simultaneous moderator dump from SDS2, will still contain D_2O and provide a cushion for the last few feet of SOR travel.

Shutdown System 2 (SDS2) is moderator dump. An arrest facility is provided to arrest after 70% dumping if sufficient $-ve\Delta k$ has been inserted quickly enough in a trip by the SOR's, to reduce moderator pump-up time. With complete dump this would be ~50 minutes, whereas poison override time provided by the adjusters is only 45 minutes.

Bruce A & B & Pickering B

Shutdown System 1 utilizes, as in Pickering A, cadmium shut off rods. More rods are however needed in Bruce for adequate response in the larger core and a total of 30 will be used. (Figure 11)

The SOR design is similar to the one shown for Pickering A in Figure 16, except the Bruce designs have a spring assisted drop and the guide tubes are now perforated along their whole length.

Shutdown System 2 uses a system, new to CANDU reactors at this time, of liquid poison injection into the moderator through 9 horizontal nozzles. The poison used will be gadolinium nitrate solution (8000 ppm gadolinium in D_2O) stored in 9 separate tanks, one for each nozzle. Helium at $\sim$ 8 MPa is used to inject the poison into the calandria. The poison injection nozzles are located as shown in Figure 17. At this time some experience with this system has been gained from a similar system used at Gentilly on the G1 reactor.

Future 1200 MW(e) and 2000 MW(e) Stations

As far as SDS1 is concerned this system will be identical to that of the Pickering and Bruce units.

For SDS2 the disadvantage of moderator poison injection, namely that of gadolinium clean up after injection, will be solved by the use of vertical liquid shut off rods (LSR's). Here a gadolinium solution will be forced at high pressure vertically upwards through tubes penetrating the calandria without physical contact with the moderator via nozzle injection. A schematic of the system is shown in Figure 18.

ASSIGNMENT

1. Why do we not use Th^{232} instead of Co^{60} for our adjuster rods when Th^{232} would provide a future source of fissile U^{233} as the Co^{60} market has now almost been saturated with the Pickering production rate over the past few years?

2. What are the major reasons our future stations are unlikely ever to use enriched U-235 booster rods for Xe override? Why do we not use Pu-239 instead?

3. If we used a graphite moderator how would we compensate for Xe 28 mk build up and fuel burn up reactivity changes?

4. Suggest some reasons why we do not use a poison in
   (a) the coolant system
   (b) the annulus gas system

   as an alternative to the moderator poison system.

5. Is there a problem with moderator downgrading when using $Gd(NO_3)_3 \cdot 6H_2O$ as a poison?

6. Why do we use cadmium for shutoff rod and control absorber material compared to boron when $CdSO_4$ was rejected for use as a moderator poison because of high induced activity build up?

7. Suggest practical problems which might occur with the 4 types of shut down mechanisms we are (or will be) using in CANDU.

D. Winfield

		NPD	DOUGLAS POINT	PICKERING A & B	BRUCE A	BRUCE B
BOOSTER MECHANISMS	booster rods	1	4	-	16	-
	adjuster rods	-	-	18	-	20
POISON SYSTEMS	boron	-	✓	✓	✓	✓
	gadolinium	-	✓		✓	✓
VARIABLE REACTIVITY LOADS	moderator level	✓	secondary control	secondary control		
	control absorbers		2 (primary control)		4 (secondary control)	4 (secondary control)
	zone control			14 zones (primary control)	14 zones (primary control)	14 zones (primary control)
SHUTDOWN MECHANISMS	moderator dump	SDS1	SDS1	SDS2(A)		
	shut off rods			SDS1	SDS1	SDS1
	moderator poison injection			SDS2(B)	SDS2	SDS2
	liquid shut off rods	For 1200 MW(e) and 2000 MW(e) stations only.				

TABLE 1: CANDU STATION REACTIVITY MECHANISMS

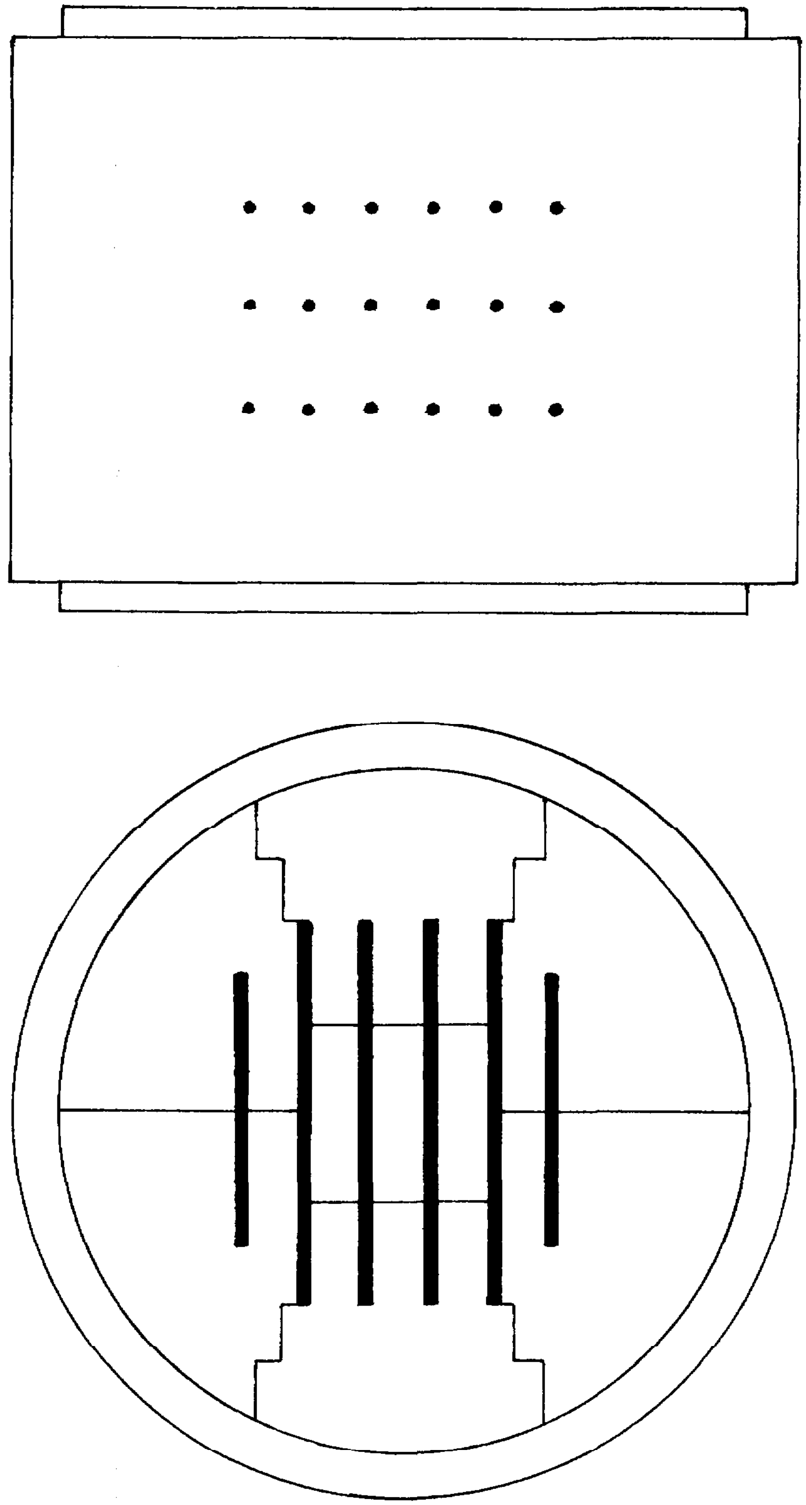

FIGURE 1: PICKERING A ADJUSTER ROD LOCATIONS

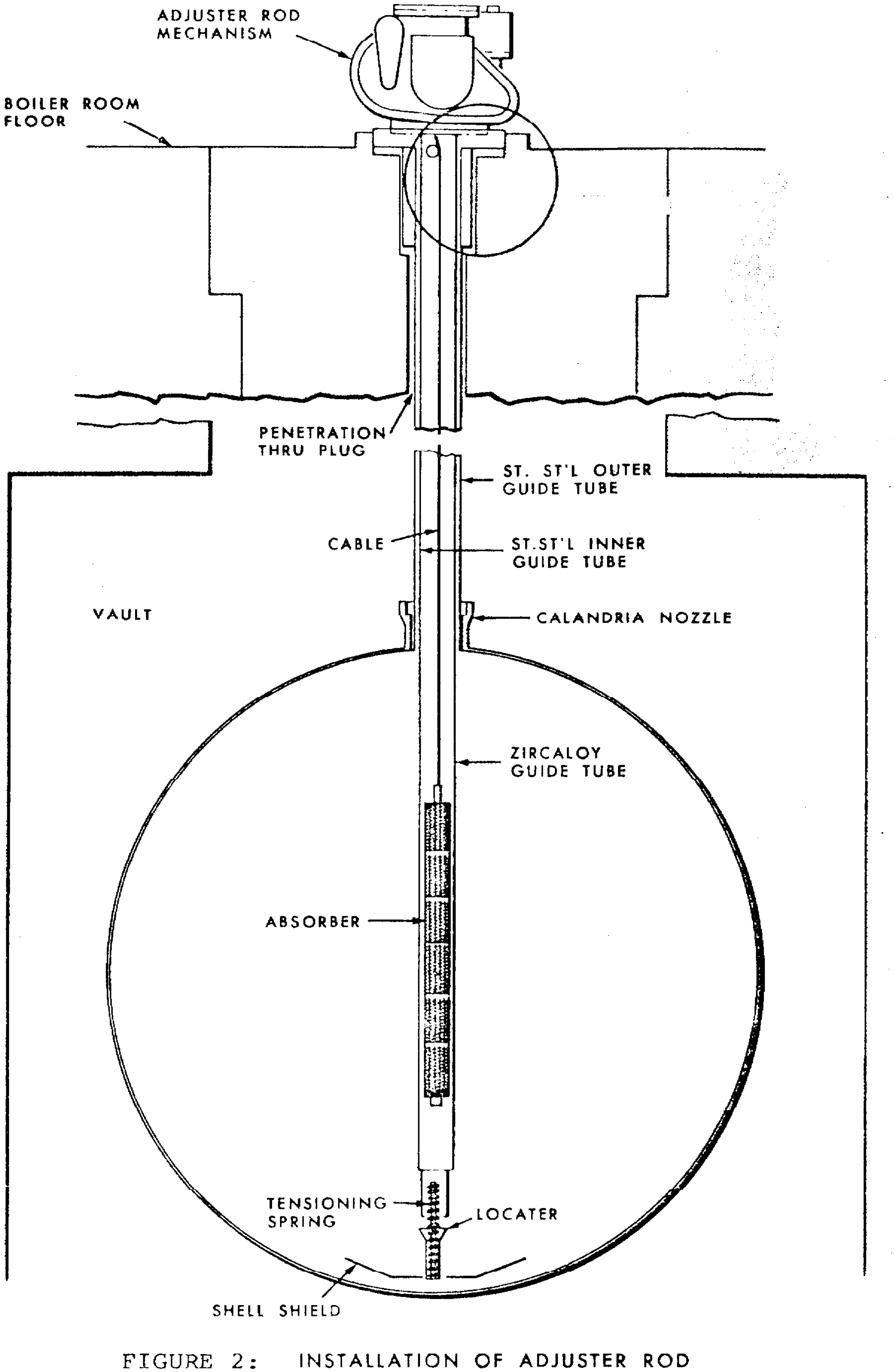

FIGURE 2: INSTALLATION OF ADJUSTER ROD (PICKERING)

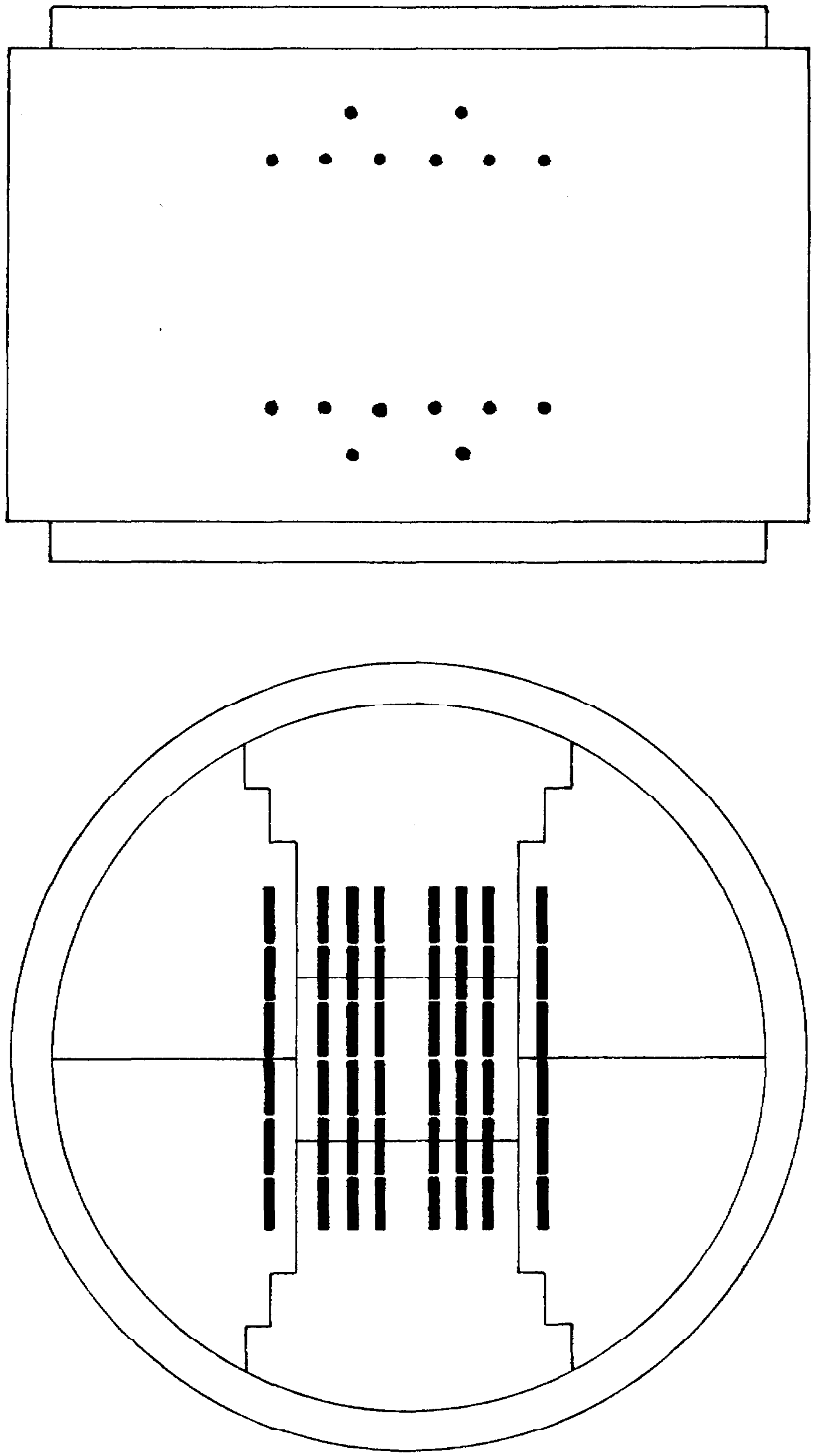

FIGURE 3: BRUCE A BOOSTER ROD LOCATIONS

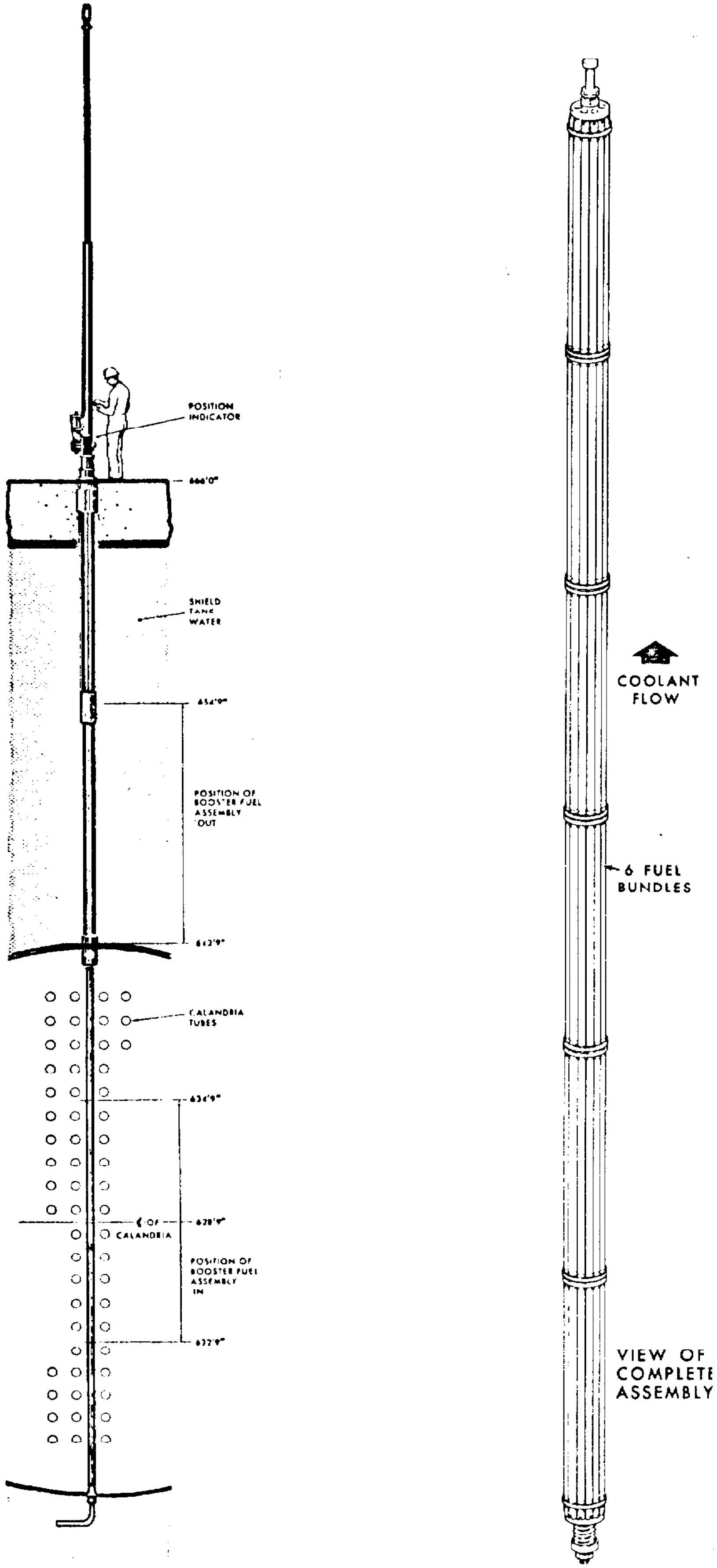

FIGURE 4: BRUCE A BOOSTER FUEL STRING AND BOOSTER ROD MECHANISM SCHEMATIC

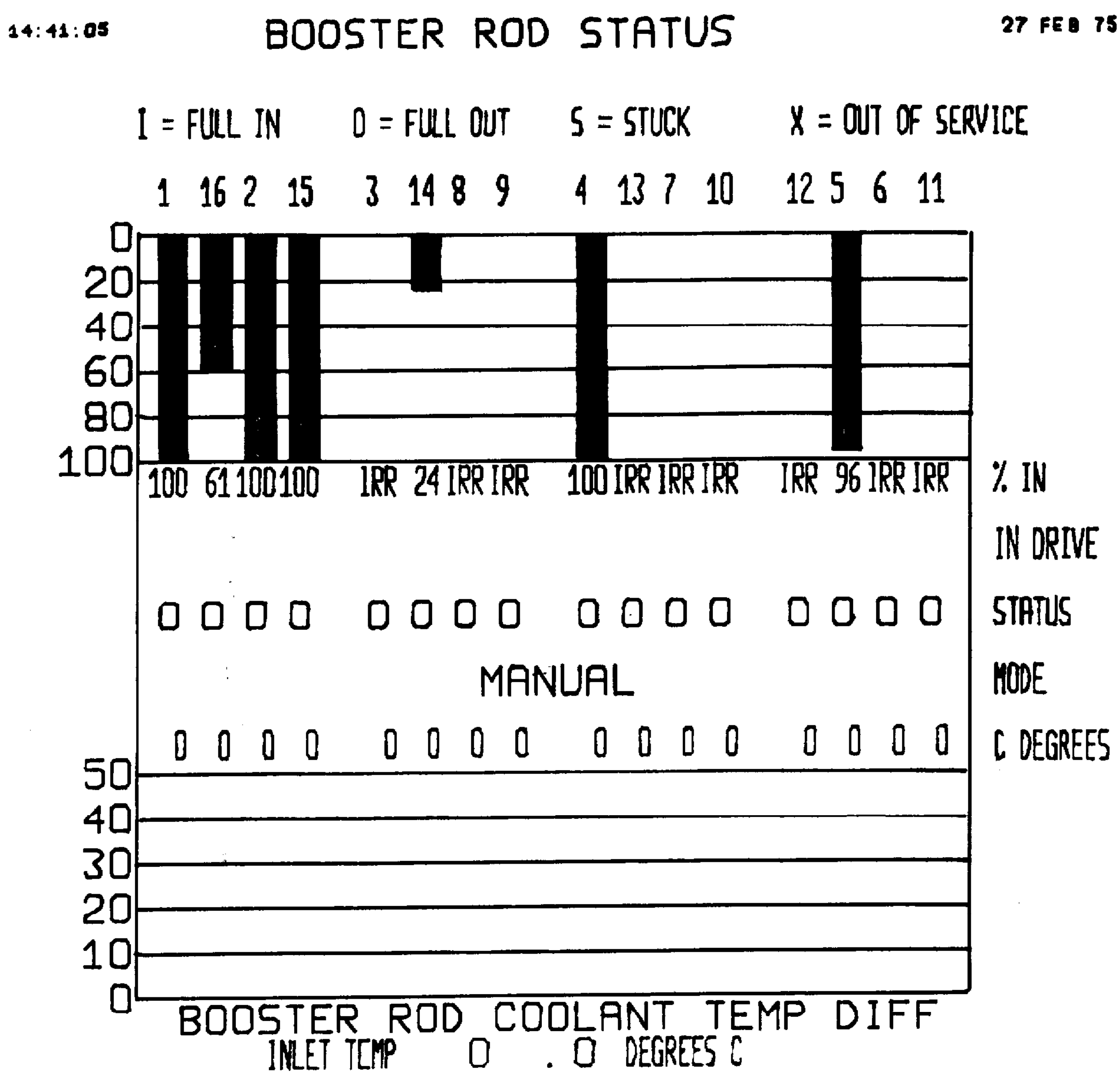

FIGURE 5: CONTROL ROOM INDICATION OF BOOSTER ROD STATUS (BRUCE A)

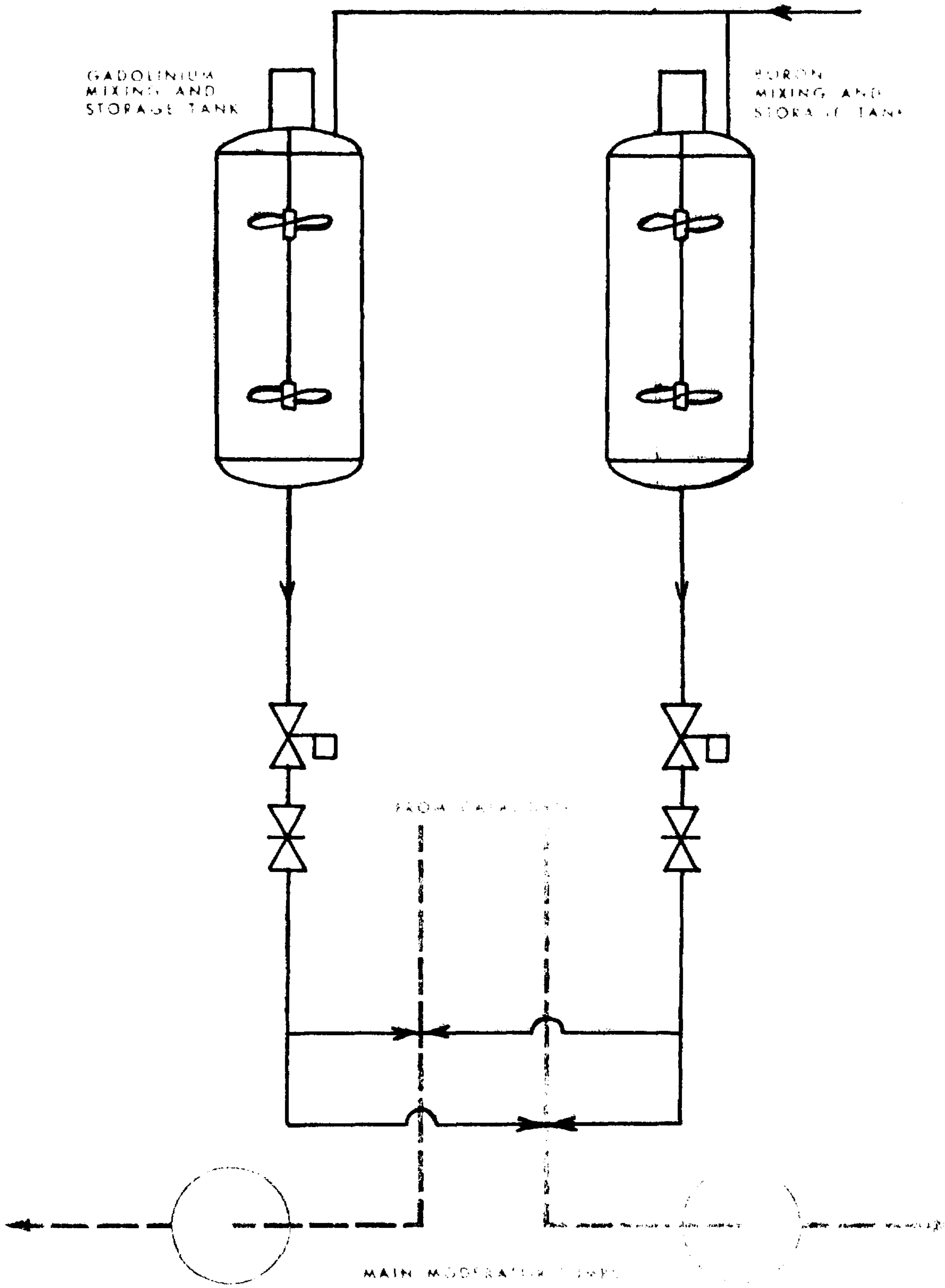

FIGURE 6: BRUCE A POISON SYSTEM

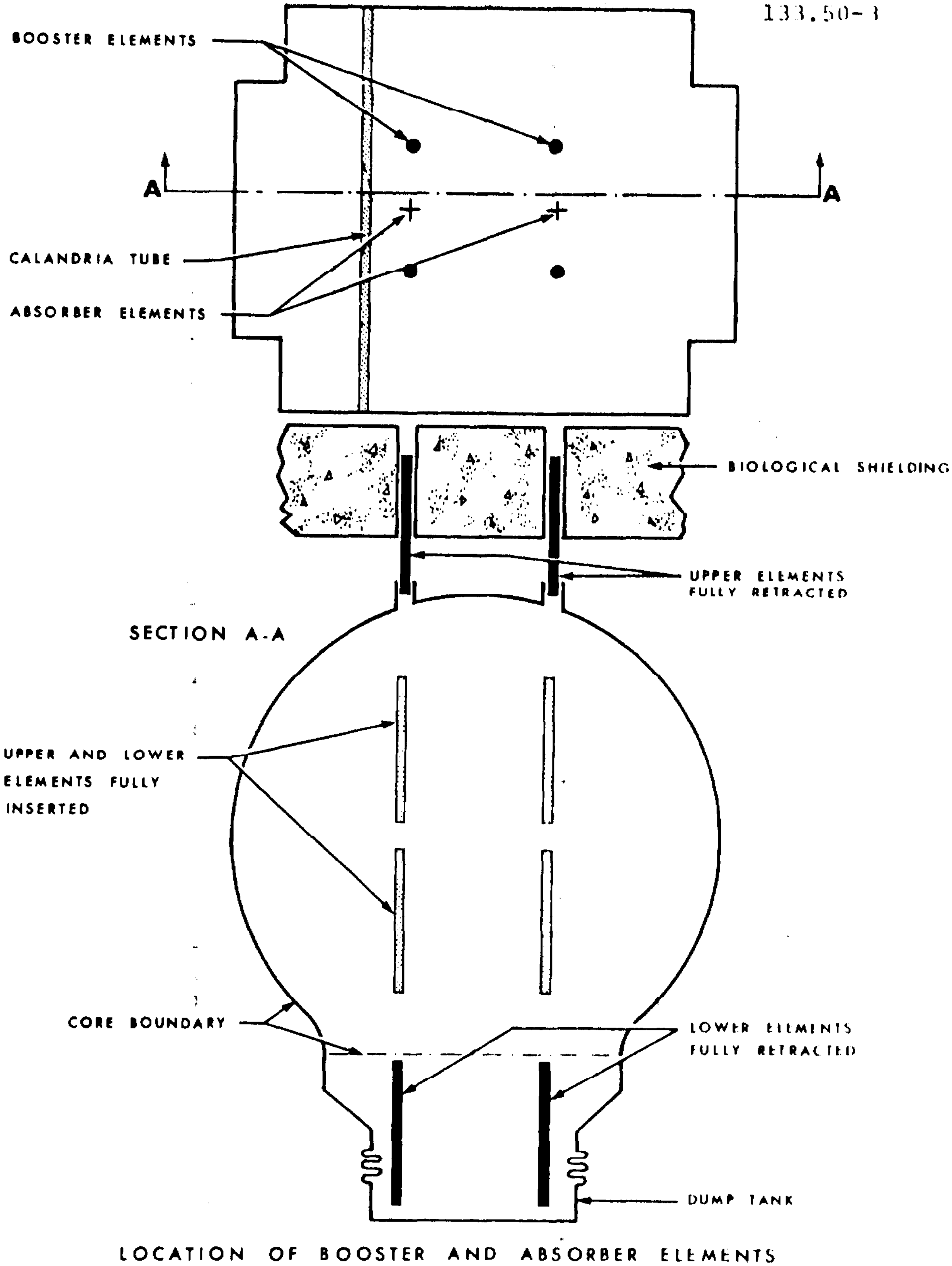

FIGURE 7: LOCATION OF BOOSTER AND ABSORBER ELEMENTS (DOUGLAS POINT)

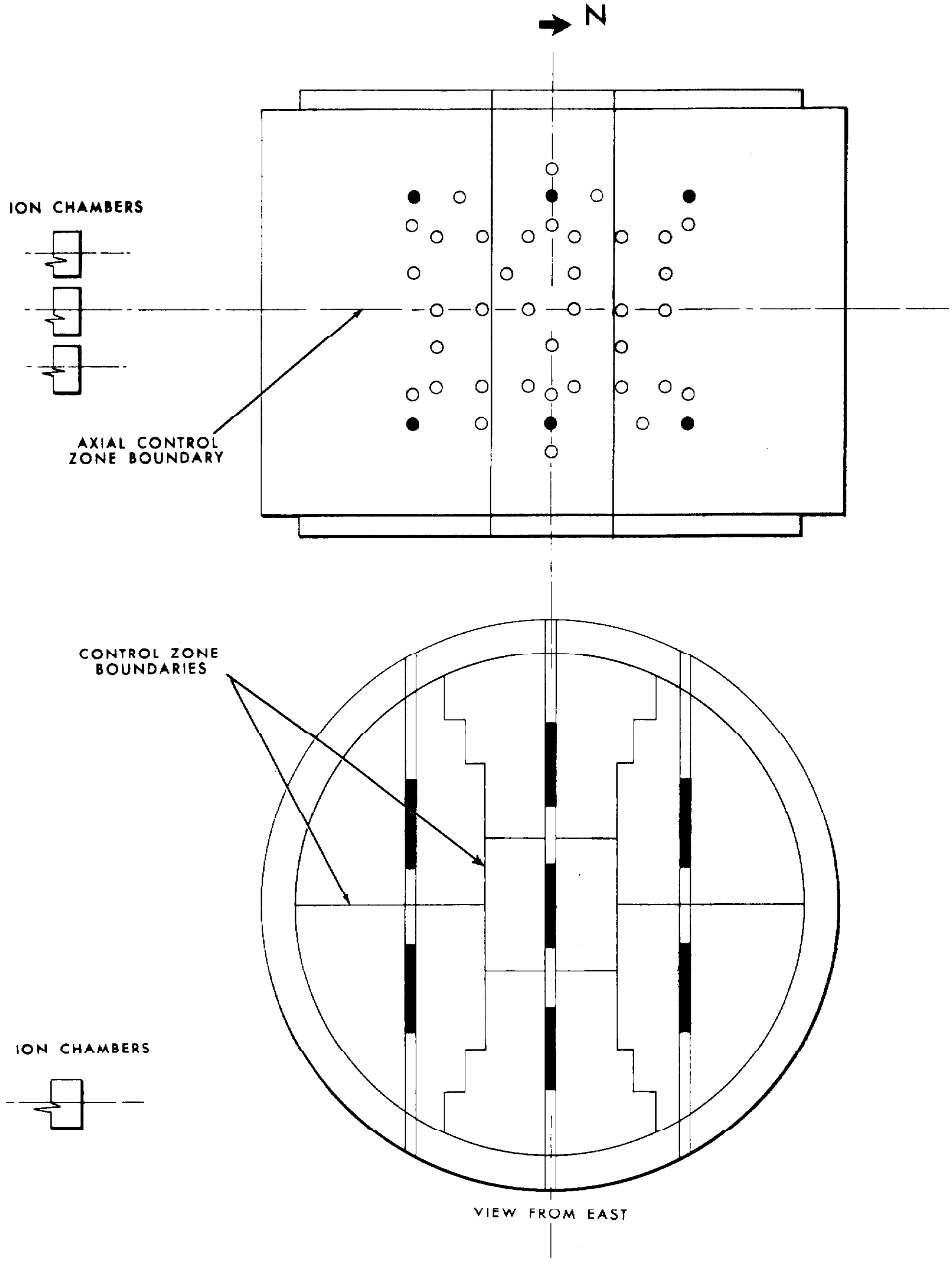

FIGURE 8: PICKERING ZONE CONTROL ABSORBER LOCATIONS

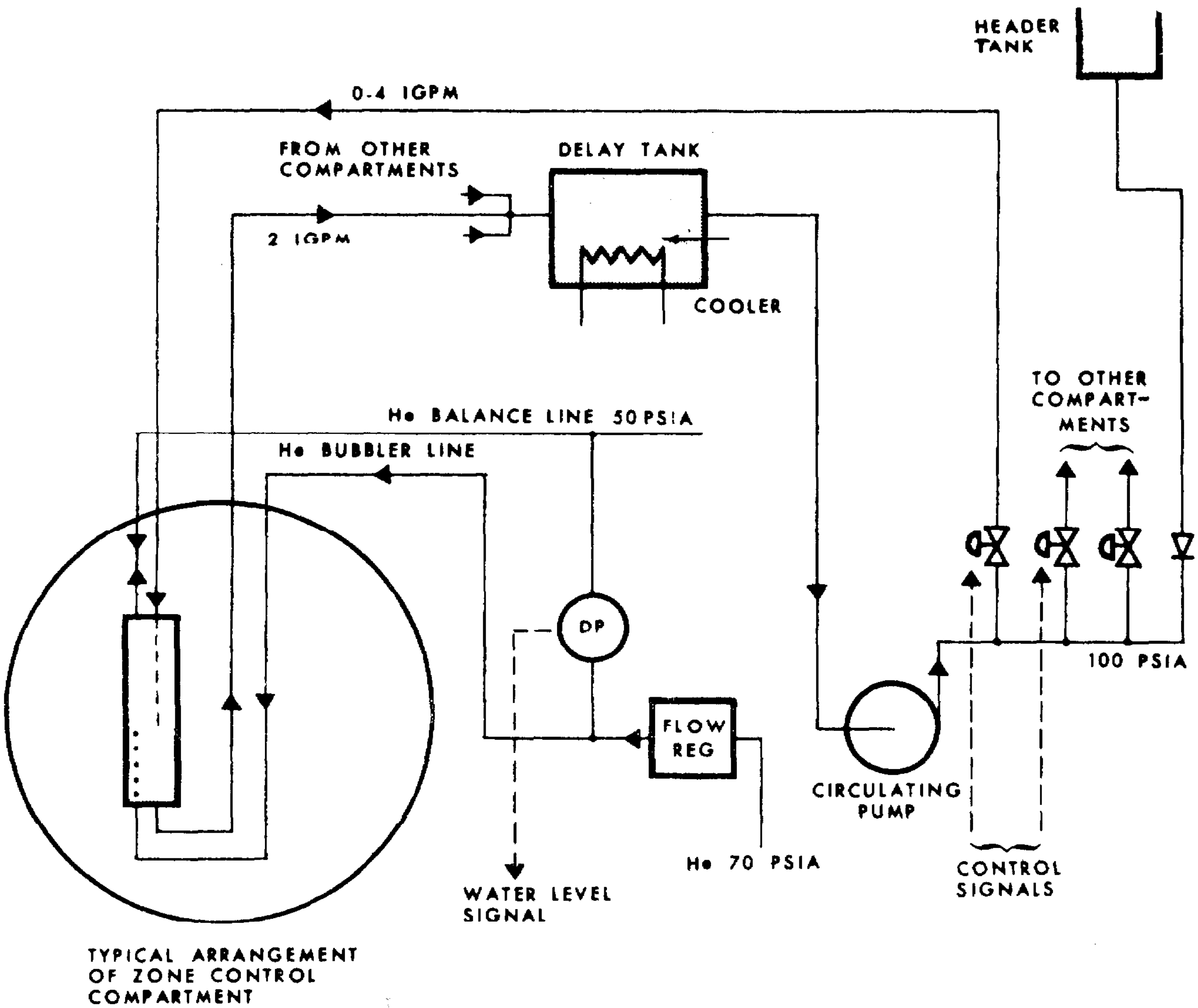

FIGURE 9: LIQUID ZONE CONTROL SYSTEM (SIMPLIFIED)

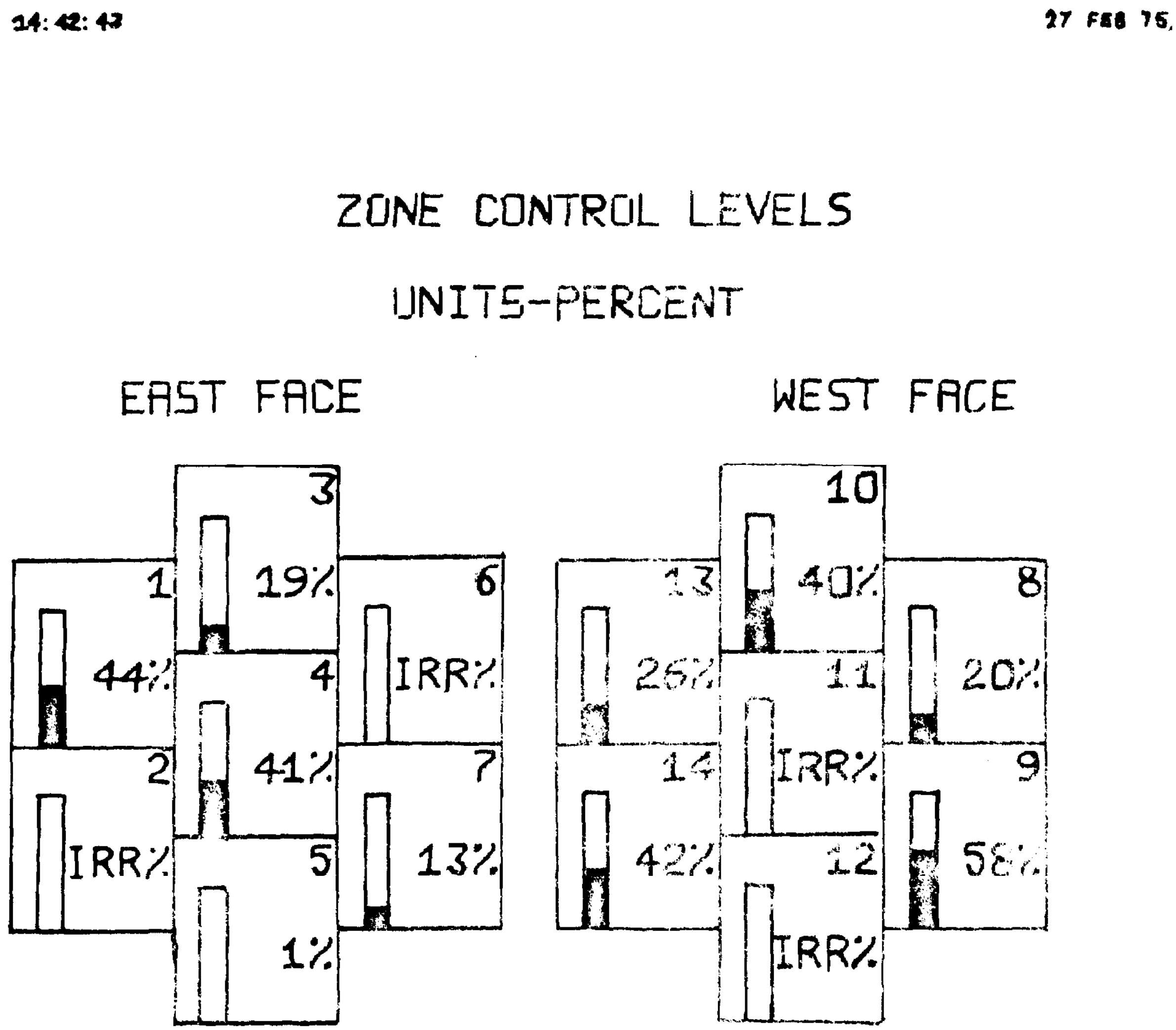

FIGURE 10: CONTROL ROOM INDICATION OF ZONE LEVEL STATUS (BRUCE A)

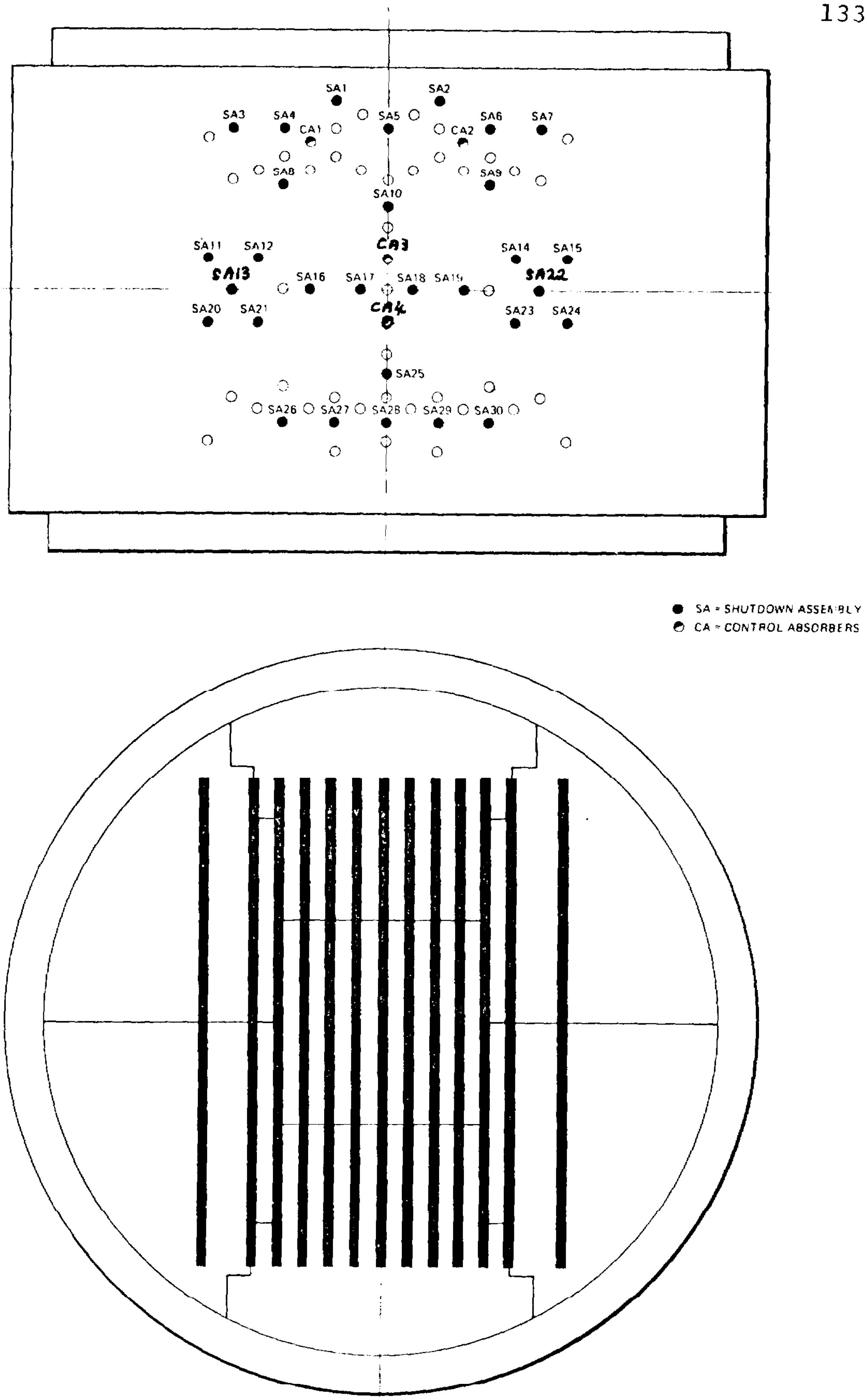

FIGURE 11: SHUT-OFF ROD AND CONTROL ABSORBER LOCATIONS (BRUCE A)

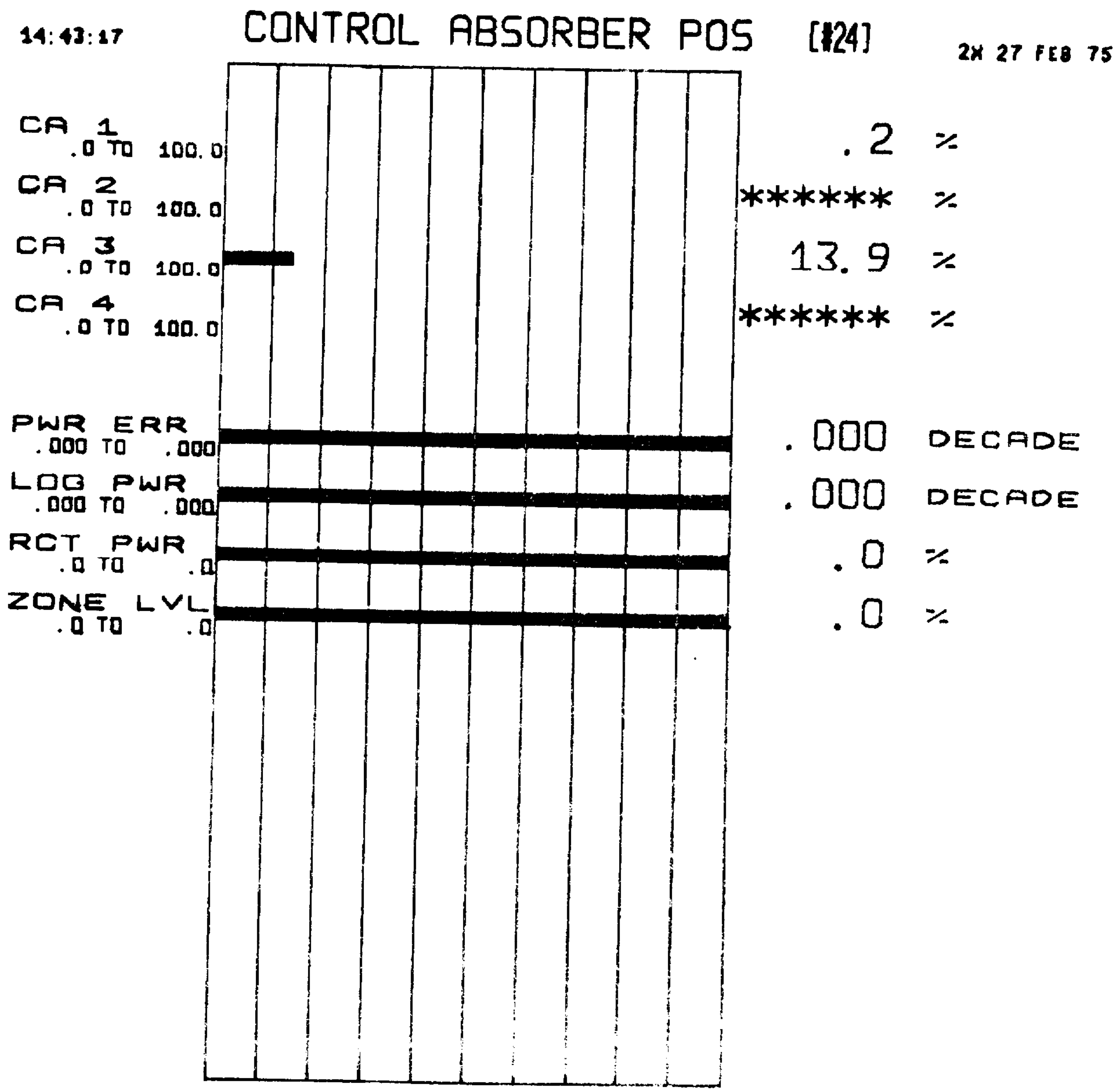

FIGURE 12: CONTROL ROOM INDICATION OF CONTROL ABSORBER STATUS (BRUCE A)

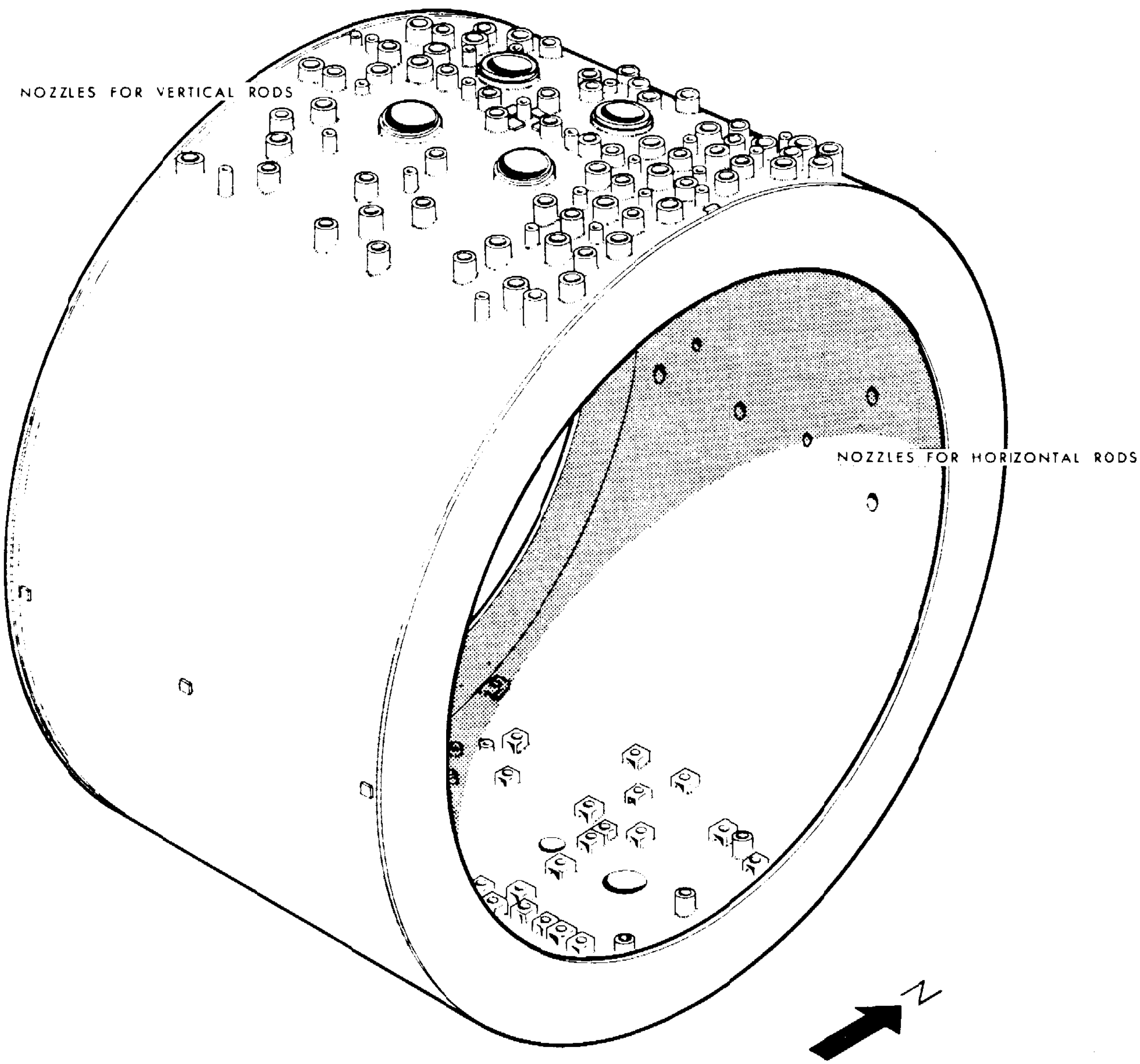

FIGURE 13: **BRUCE GENERATING STATION CALANDRIA SHELL**

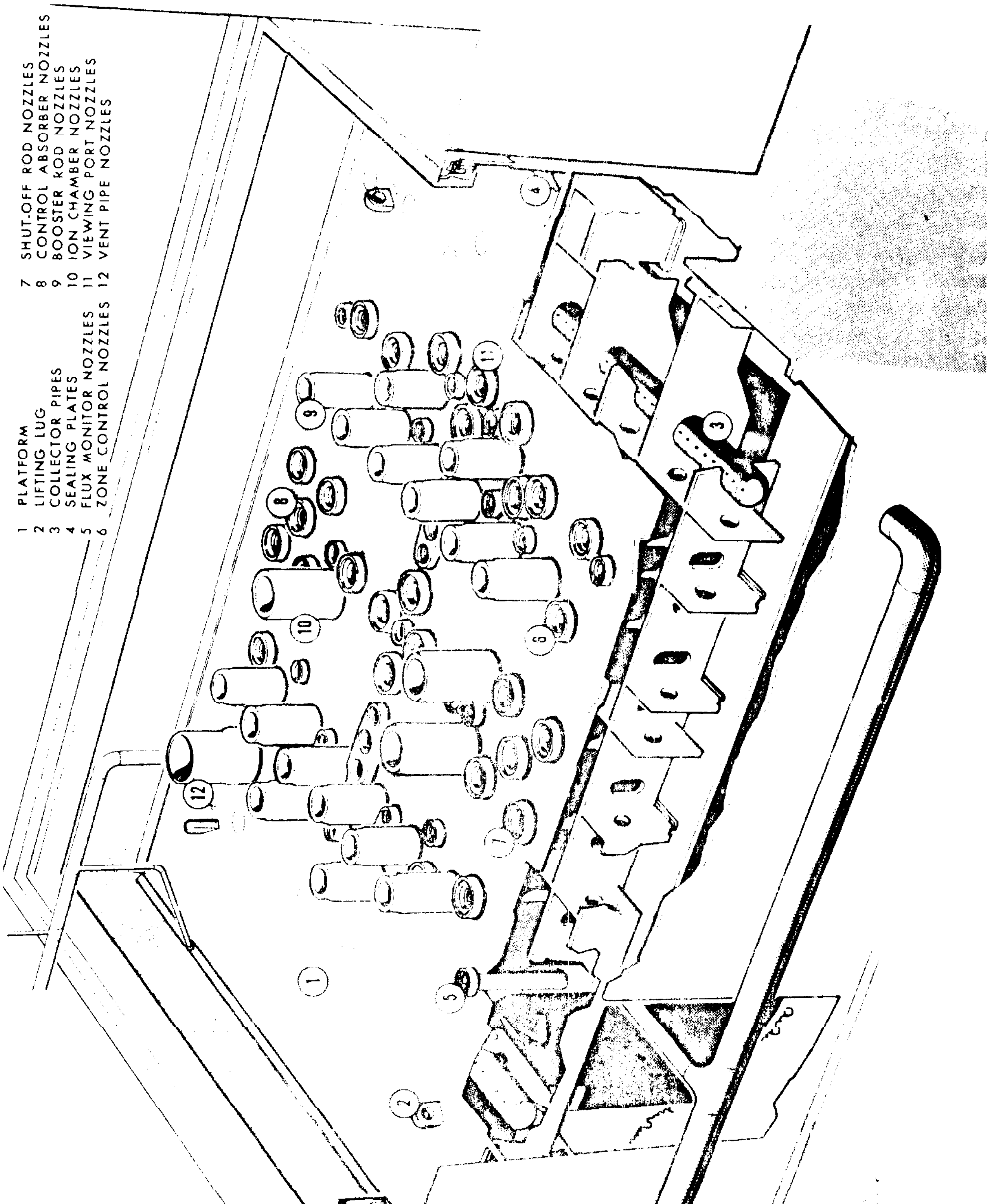

FIGURE 14: REACTIVITY MECHANISM PLATFORM
(BRUCE A

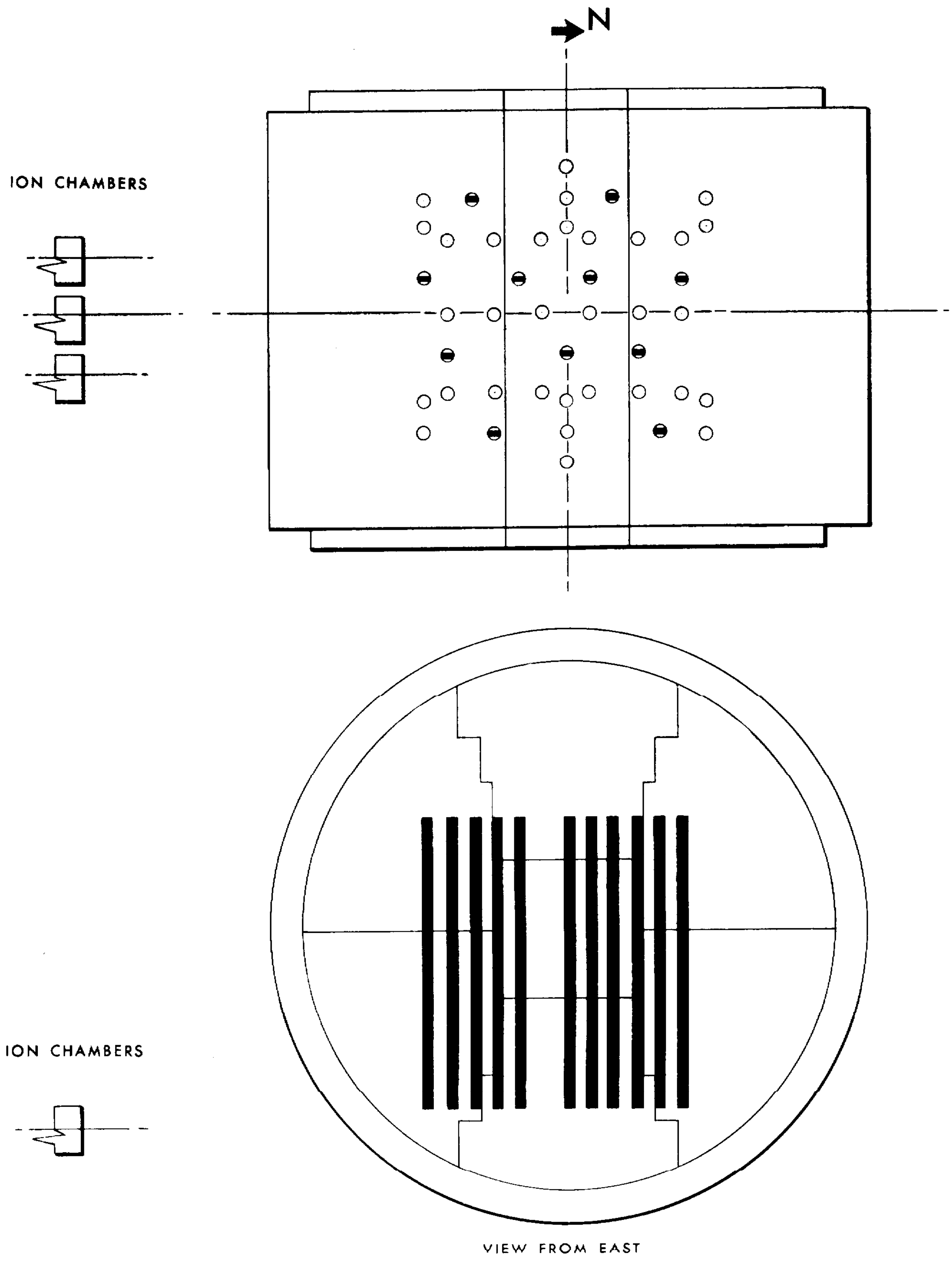

FIGURE 15: SHUT-OFF RODS (PICKERING)

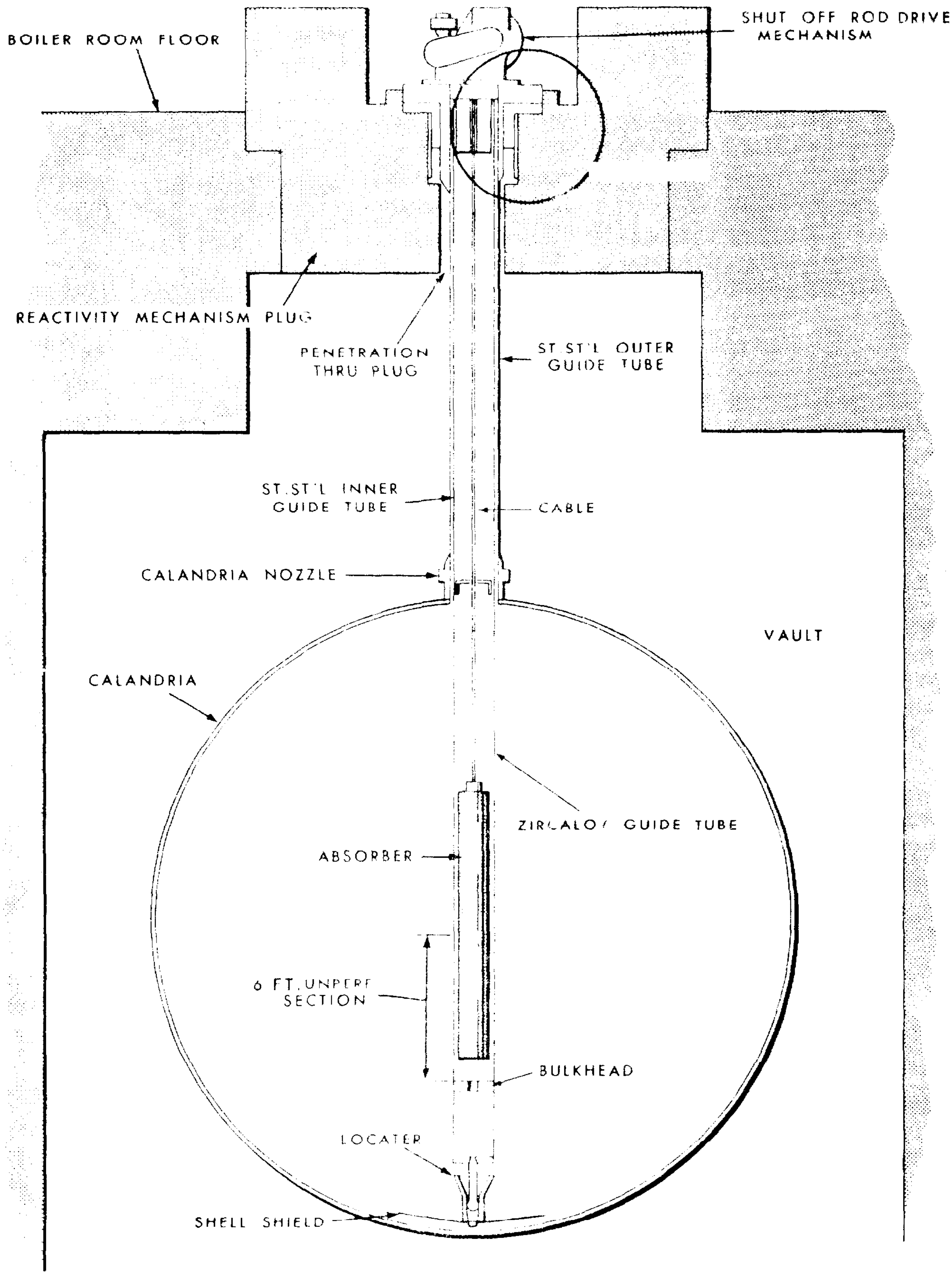

FIGURE 16: SHUT OFF ROD GUIDE TUBE PENETRATION (PICKERING)

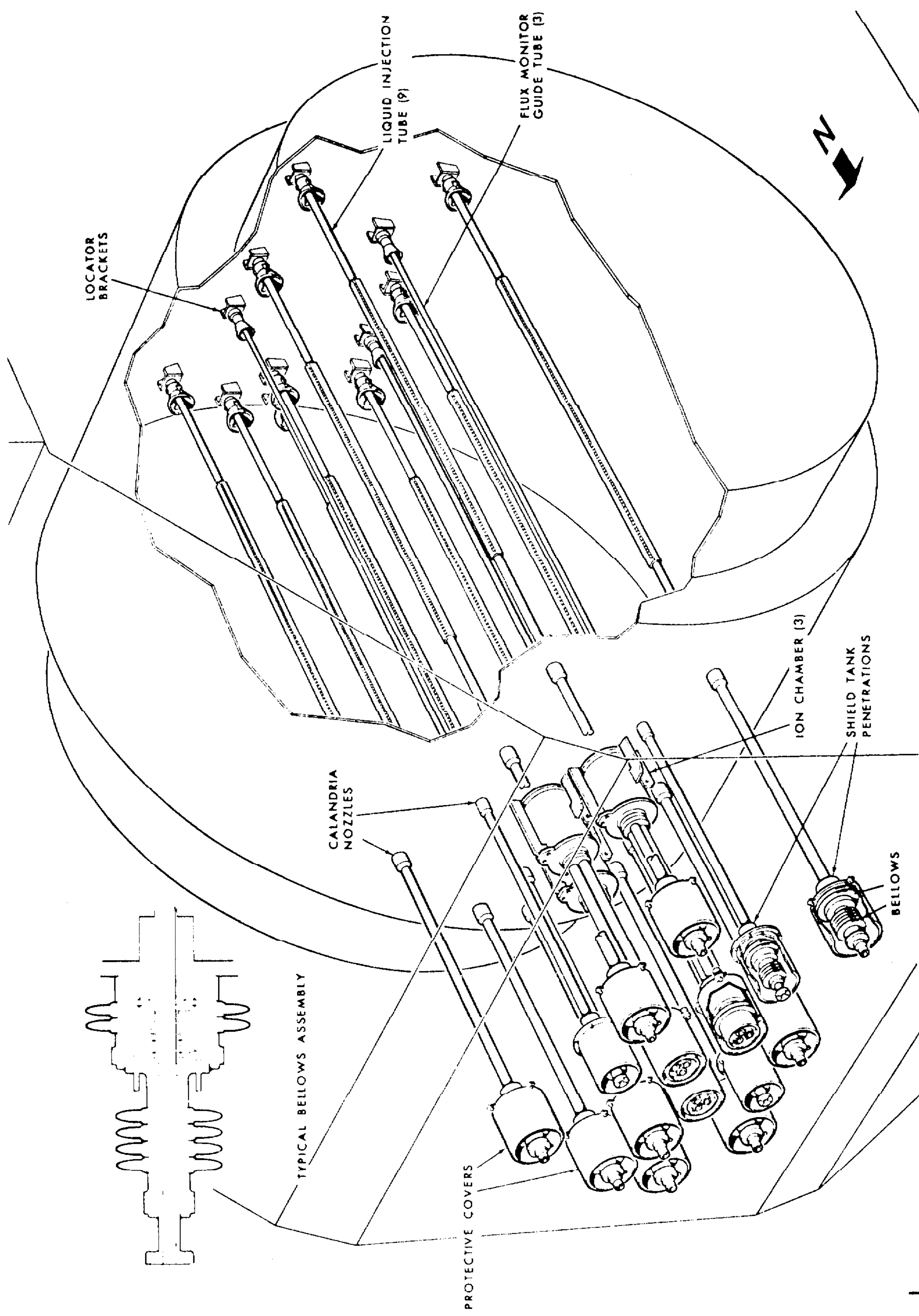

FIGURE 17: BRUCE SECOND SHUTDOWN SYSTEM REACTOR COMPONENTS

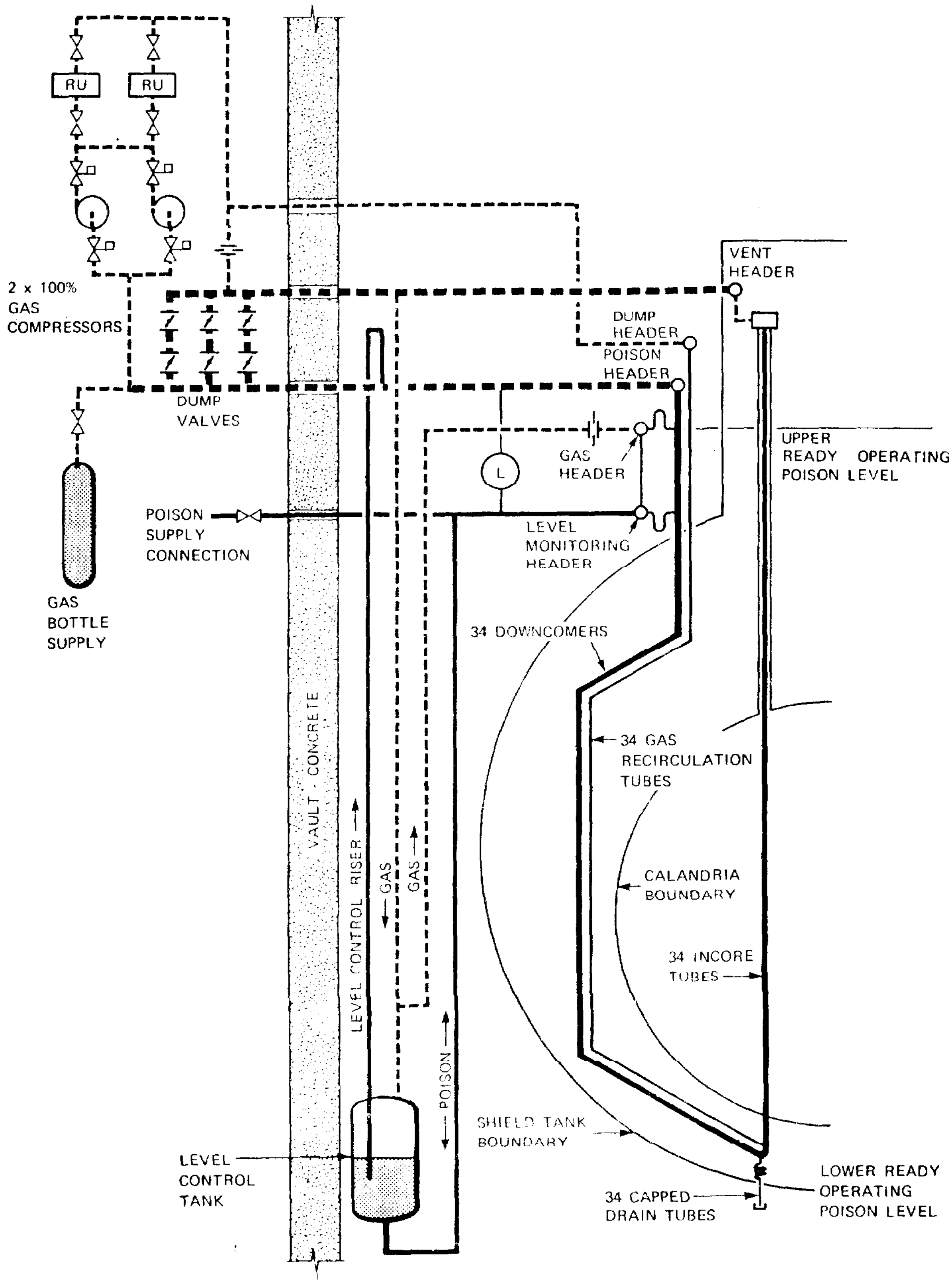

FIGURE 13: LIQUID SHUTOFF ROD SYSTEM.