CHAPTER 6

CONTROL AND OPERATIONS

The basic and unique dynamic characteristics associated with the reactor core have been discussed in the preceding chapter; here we will focus upon certain reactor core instruments, refer to several aspects of reactor control, and comment on reactor operation.

6.1 NEUTRON DETECTORS

The various monitors used in the measurements of variables such as temperature, flow rate, pressure, moderator level, and electrical output used in a reactor are similar to those employed in the control of more conventional dynamic systems. Indeed, the only major feature of these instruments when used in a nuclear reactor installation is the elimination, or at least minimization, of materials which are particularly susceptible to radiation damage and/or become radioactive when exposed to radiation fields. In general, materials such as plastics and rubber as well as strong neutron absorbers are avoided where possible.

One of the most important parameters in the operation of a nuclear reactor is the spatial distribution of the power density in the reactor core. We have previously indicated that some 200 MeV of energy is released per fission event. Accompanying this fission event is the release of several neutrons which maintain the fission chain. Thus, the neutron density is a direct indicator of the power density. Another way of viewing this relationship is to consider the power density in a homogeneous reactor. Using our previously defined energy averaged parameters we write the power density at the point $\underset{\rightarrow}{r}$ as

$$p(\underset{\rightarrow}{r}) = \gamma g(\underset{\rightarrow}{r}) \nu \Sigma_f(\underset{\rightarrow}{r}) \phi(\underset{\rightarrow}{r}) \ . \qquad (6.1)$$

Since the neutron flux $\phi(\underset{\rightarrow}{r})$ is defined by

$$\phi(\underset{\rightarrow}{r}) = n(\underset{\rightarrow}{r}) v \ , \qquad (6.2)$$

where v is the neutron speed and $n(\underset{\rightarrow}{r})$ is the neutron density at $\underset{\rightarrow}{r}$. We may rewrite Eq. (6.1) therefore as

$$p(\underset{\rightarrow}{r}) = \text{constant} \ . \ n(\underset{\rightarrow}{r}) \ . \qquad (6.3)$$

That is, the power density is directly proportional to the neutron density. A monitor which measures the neutron density may therefore be used directly to provide a signal which is directly related to the power density. A calibration will be necessary before such a detector can be used in an operational context. We will now consider two principle types of neutron detectors used in CANDU reactors as well as in other types of nuclear reactors.

One type of neutron detector is characterized by the use of an ion-chamber. To illustrate this type of system we consider two oppositely charged plates contained in a chamber filled with an appropriate gas or mixture of gases as shown in Fig. 6.1. As a neutron passes through the chamber wall it may interact with one of the gas nuclei and create a pair of ions which are attracted to oppositely charged plates. An example of a reaction is that occurring in a boron gas:

$$n + {}^{10}B \rightarrow {}^{4}He + {}^{7}Li \ . \qquad (6.4)$$

The helium nucleus, ${}^{4}He$, being a doubly charged positive ion (i.e. an alpha particle) will be attracted to the negatively charged plate and thus induce a measurable current signal in an external circuit. The reaction represented in Eq. (6.4) is widely used particularly for low neutron flux measurements; the gas in the chamber is commonly boron trifluoride (BF_3) and a detector which uses this process is generally called "B-F-3" neutron detector.

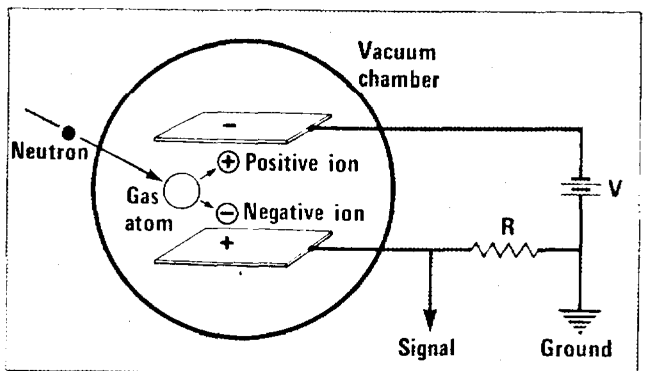

FIG. 6.1: Basic components of an ion chamber.

The basic ion-chamber neutron detector systems illustrated in Fig. 6.1 can be modified in numerous ways to make them more effective as neutron monitors depending upon the density of neutrons, magnitude of the neutron flux, and their location. Some of these modifications are listed here.

1. Geometry:
   A cylindrical geometry for the ion chamber has been found to be a more practical neutron detector system. A central wire may be one electrode while the outer sleeve represented the other electrode.

2. Operating Voltage:
   Changing the operating voltage between the electrodes affects the acceleration of the ions. This can induce further ionization in the gas by a cascade effect.

3. Operating Pressure:
   An increase in gas density in the chamber increases the probability of neutron capture and thus increases the neutron detection sensitivity.

4. Reaction in Solids:
   Rather than allowing the reaction to take place in the gas, it is possible to coat the interior of the chamber with a suitable material to permit the reactions to take place in the wall.

5. Different Reactions:
   In addition to the (n,α) reaction in the gas discussed above, Eq. (6.4), it is possible to use a fissile material coating in the chamber; the induced fission products would then be used to induce the signal in an external circuit.

6. Gamma Compensation:
   A reaction may also be induced in many materials by gamma rays. The neutron and gamma effects may be separated by the introduction ~~of two separated by the introduction~~ of two separate ionization domains one of which contains a biasing feature.

Ion chambers are always designed for specific functions. As a consequence their properties in so far as the above six design features are concerned differ depending upon their designated purpose. Extensive testing is invariably undertaken before these ion chamber neutron detectors are installed in operating reactors.

A second type of neutron monitor which has undergone extensive development in Canada is the self-powered or Hilborn type neutron detector. These neutron detectors are characterized by the property that the neutron induced reactions produce an electron current without the aid of an external voltage source and have been particularly useful in high neutron fields.

Figure 6.2 provides a schematic representation of a self-powered detector. Its principle components consist of an emitter material and a collector material separated by an insulator. Cylindrical geometry is the most common form for these detectors; the diameter can be relatively small which permits their placement in tight locations in the core. The absence of a power source is another advantage of these detectors.

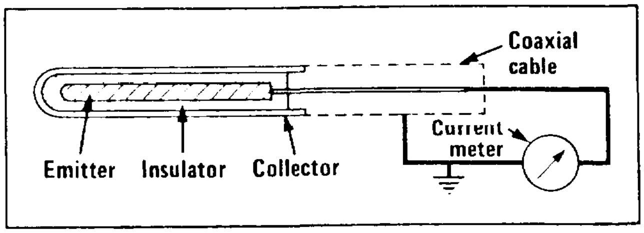

FIG. 6.2: Components of a self-powered (Hilborn) neutron detector.

The principle of operation of a self-powered detector is based on the property that, depending upon the emitter material chosen, either neutrons or gamma rays will interact with the emitter material in such a manner that electrons are ejected from the emitter with sufficient energy to penetrate through the insulator and strike the collector. This charge flow from the emitter to the collector represents a current which is measured with a current measuring device; the observed current signal is a function of the neutron or gamma ray absorption rate in the emitter and thus represents a measure of the neutron flux density in the vicinity of the detector position.

Considerable investigations have been carried out to develop and improve such self-powered detectors. Different emitter materials - such as Vanadium-52, Rhodium-104, Cobalt-60, and other materials - have been used. Of particular interest in the development of such detectors are their response times and burn-up properties; the former is associated with radioactive decay of the excited nucleus following neutron capture while the latter is related to isotopic depletion and radiation damage in a reactor core environment.

The reactor core instruments discussed above generally possess different operating ranges each spanning several decades (one decade represents a multiplication by a factor of 10). By a suitable positioning and the selective use of radiation shielding, a combination of these detectors can be used to collectively span some 14 decades of reactor power. In Fig. 6.3 we show the ranges which can be covered by these detectors. Note the additional use of thermal detectors when the reactor is near full power.

6.2 REACTOR POWER DENSITY

Before we discuss the subject of reactor control and operation, it is desirable to examine some of the spatial and temporal power density variations which may occur in a core. In Chapter 4 we have shown that, for a cylindrical core, the thermal neutron flux follows a cosine shape in the axial direction and a Bessel-function shape in the radial direction. As shown in Fig. 4.8, both of these functions are highly peaked in the centre and approach zero near the edge of the core. Since the power density is directly proportional to the thermal neutron flux, the central fuel bundle will, under such conditions, operate at a substantially higher power output than the average fuel bundle; this condition is clearly undesirable since the total reactor output is now governed by the power rating of the central bundle only. A more uniform power density throughout the reactor volume is clearly desirable.

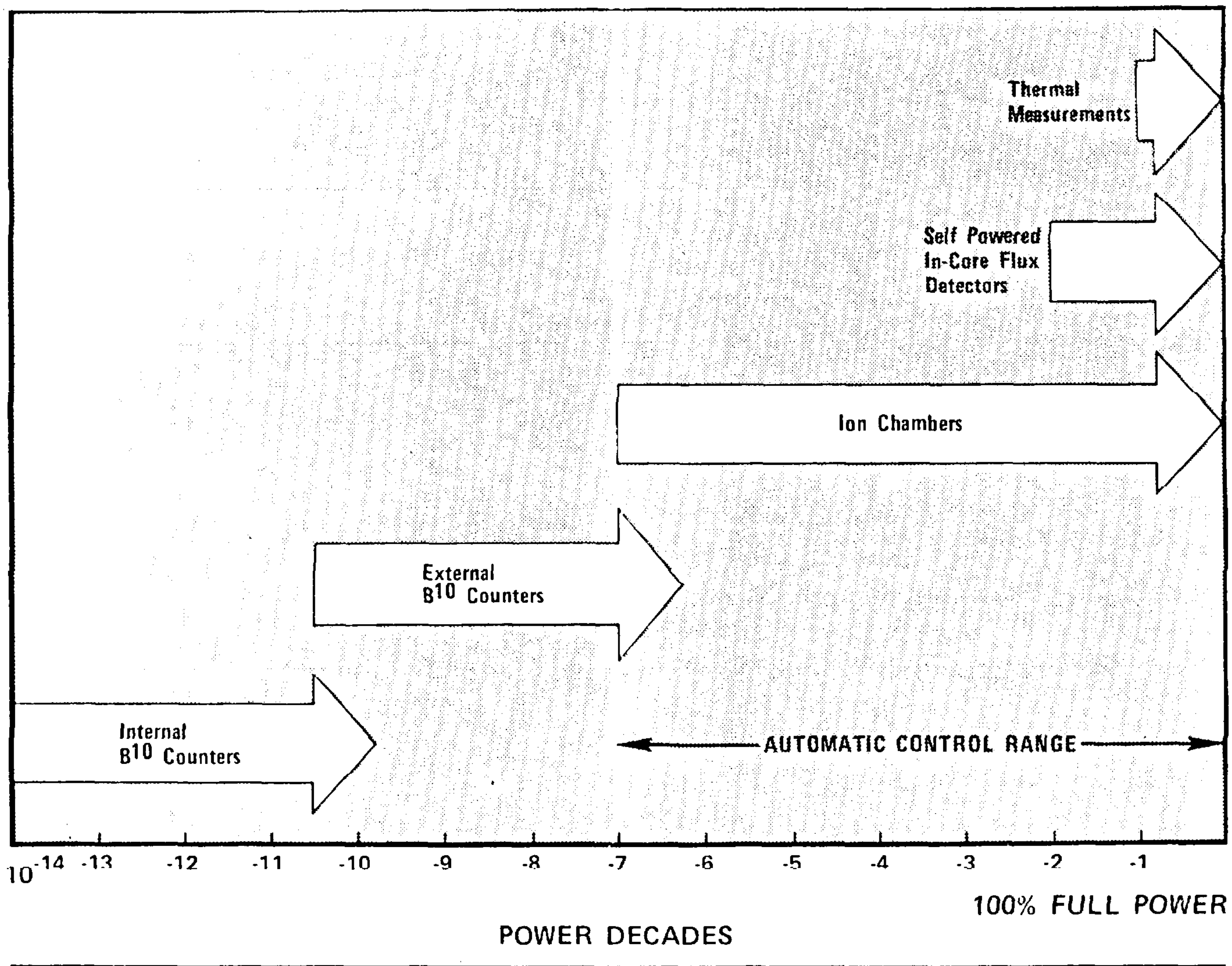

FIG. 6.3: Reactor power ranges in decades covered by several neutron detectors and other monitors.

A more uniform power density can be achieved in a reactor by (1) the judicious use of neutron absorbing materials called absorber rods, (2) the use of materials which are rich in fissile nuclei and called booster rods, and (3) by appropriate management of the refueling process. For example, in regions where it is desirable to depress the neutron flux - and hence lower the power density - neutron absorber rods or depleted fuel could be placed. The effect on reactor power is that it can generally be doubled without an increase in the central fuel bundle power output. Fig. 6.4 provides a graphical comparison of a flattened with a non-flattened thermal neutron flux.

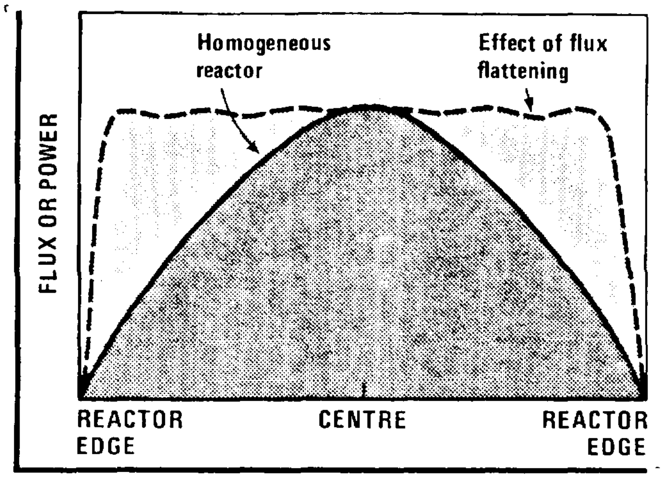

FIG. 6.4: Comparison between a peaked neutron flux associated with a homogeneous core and a flattened flux obtained by the suitable use of flux flattening options.

In the preceding chapter we discussed the role of xenon poisoning and the need for sufficient excess reactivity to overcome its poisoning effect during reactor operation and start-up. One additional important effect associated with xenon is that of spatial stability and the attendant possibility of inducing significant power density oscillations in the core. This is a very important phenomena in large thermal reactors and we will discuss it in some detail.

We recall the appearance of Xe-135 in the fission process graphically represented by

$$
\begin{array}{l}
(\text{Fission}) \longrightarrow {}^{135}\text{Te} \longrightarrow {}^{135}\text{I} \\
\qquad\qquad\qquad\qquad \downarrow \; T_{1/2} = 6.7\ \text{h.} \\
\qquad\qquad\qquad\quad {}^{135}\text{Xe} \xrightarrow[T_{1/2} = 9.2\ \text{h.}]{} {}^{135}\text{Cs}
\end{array}
\qquad (6.5)
$$

One important feature to note here is the difference in half-lives between the production of Xe-135 by the decay of I-135, $T_{1/2} = 6.7$ h, and its decay, $T_{1/2} = 9.2$ h. The additional property of this process is to recall that Xe-135 has a very large absorption cross section and hence is removed by neutron capture; thus, the more neutrons which exist, the more Xe-135 will be removed from circulation.

Consider now a reactor core operating at constant power with a fixed concentration of I-135 and Xe-135. For clarity of discussion, assume that the core can be divided into two identical regions A and B. Supposing that a small perturbation occurs whereby the flux in region A increases slightly and the flux in region B decreases slightly since we require that the net reactor power remain unchanged. In region A, the increase in neutron flux will lead to an increase in I-135 and, some time later, an increase in Xe-135 will be noticed due to the decay of I-135. Before this happens, however, the higher flux will lead to an increase in the destruction of Xe-135 by neutron absorption in Xe-135 and hence lead to its decrease. Since xenon is a significant parasitic absorber of neutrons ($\sigma_a = 3.6 \times 10^6$ b), the decrease of this isotope means an increase in the neutron population and hence a rise in the neutron flux. Concurrently, in region B the reverse process is taking place with a subsequent decrease in the neutron flux.

The above process continues for several hours: the flux and hence power density continues to rise in region A and fall in region B while all the time, the total reactor power is constant. Thus a flux tilt has been initiated by a small flux

The process discussed above, however, cannot continue forever. Even though the half-life for the decay of iodine to xenon is 6.7 hours, the production of Xe-135 by the decay of I-135, Eq. (6.5), will dominate and reverse the process. That is, the flux in region A will decrease and in region B it will increase until eventually the flux tilt is reversed and, as a consequence, also the power density in the two regions will be reversed. The cycle length of such oscillations is of the order of 24 hours and can induce severe increases in power density if not controlled. Indeed, one function of the control system of a reactor is that of suppressing such spatial oscillations which effects all large thermal reactors.

A related and easily described occurrence is that of xenon out-poisoning after shutdown, as discussed in the preceding chapter. By this we identify the phenomena of Xe-135 increasing immediately after reactor shutdown. Under certain conditions, this neutron poisoning effect may be so large that the available reactivity may be insufficient to permit reactor start-up for several hours.

6.3 CONTROL AND OPERATION

In the preceding chapter we have discussed some reactor sensing instruments and have indicated some desirable spatial flux distributions and xenon poisoning effects. These factors are but some of the unique features associated with reactor control and operation. We can summarize some of the long and short term effects in terms of the phenomena discussed thus far.

1. Transient Control:
   Control of time-variations-caused system faults or scheduled disturbances.

2. Fuel Management:
   Continuous refueling of CANDU reactors involves long-term reactivity effects.

3. Power Coefficient:
   Changes in reactor power introduces reactivity effects due primarily to the effect of temperature on neutron absorption.

4. Spatial Reactivity:
   This includes specifically xenon oscillations as discussed in the preceding section.

Several reactivity control devices have developed and adapted to the CANDU reactors. These can be grouped as follows:

1. Absorbers:
   Solid or liquid movable neutron absorbers can be inserted or withdrawn from the reactor and are particularly effective for fast reactivity and spatial flux control.

2. Boosters:
   Boosters are rods containing enriched fissile materials. They can be used for poison override control.

3. Poisoned Moderator:
   Small quantities of neutron absorber such as boron can be mixed with the moderator to provide large compensating reactivity control. This is of particular utility during reactor start-up with fresh fuel.

4. Miscellaneous:
   These control systems involve varying the moderator level, selective fuel bundle shuffling, and varying the coolant density in a boiling reactor.

Some of the control devices are often incorporated into a control system where they serve a specific function only. This may include shut-off functions and zone control functions. The location of some of these devices is shown in Fig. 6.5. A detail of the shut-off rod for the CANDU-Bruce is shown in Fig. 6.6.

In the above discussion we have emphasized primarily the role of physical processes in the reactor core and the associated core instruments. The core, however, is but one element of a system which includes, among others, a turbine, generator, boilers, and condensors. This requires not only the collection of many system variables but also their analysis. A dual-computer system is invariably used for this purpose. Figure 6.7 shows a general block diagram representation. Here we note particularly the complex interrelationship between the reactor core and the associated system components. This feature is further illustrated in Fig. 6.8 which shows a typical control room instrumentation layout for a CANDU reactor.

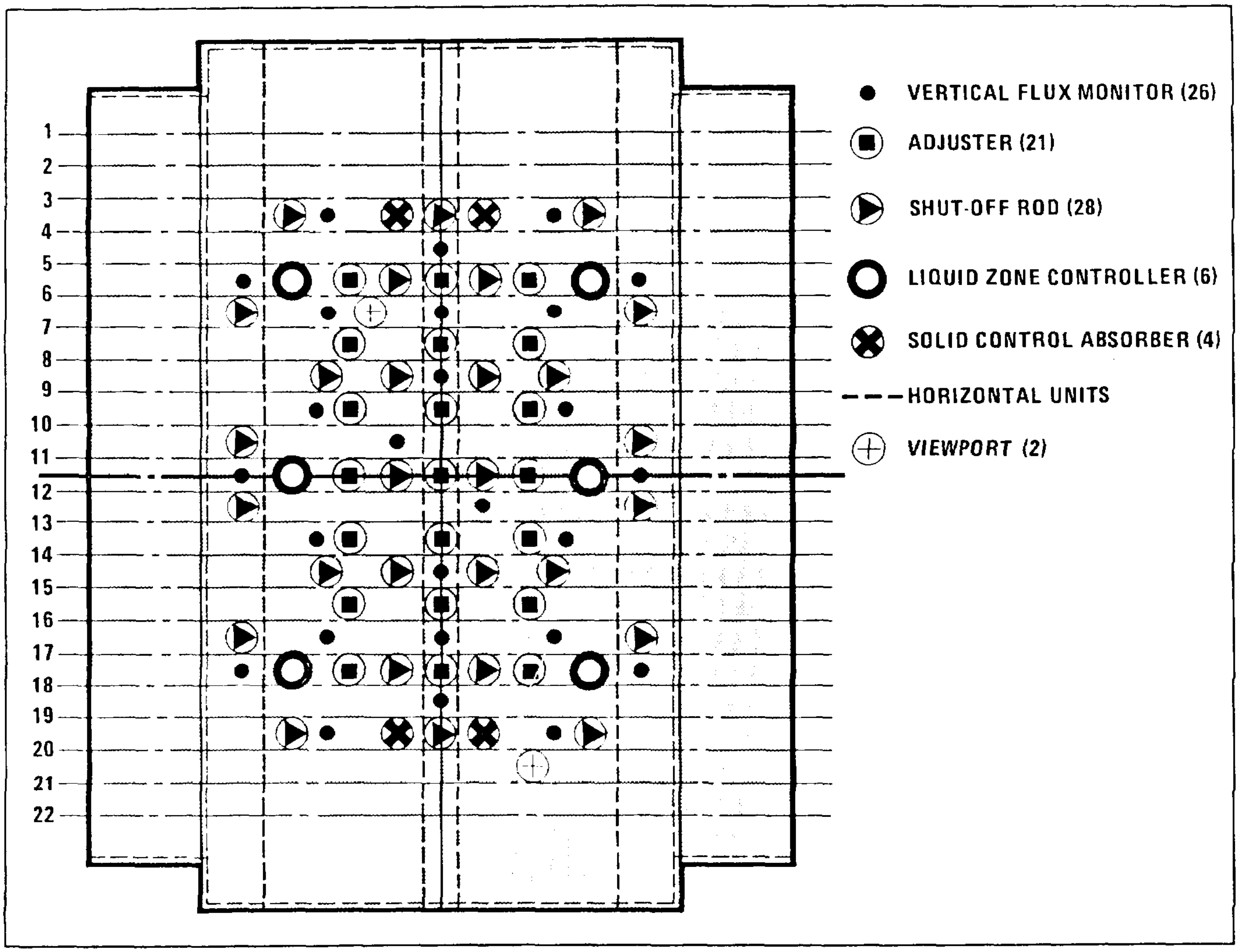

FIG. 6.5: Plan view of reactor showing location of reactor core control devices.

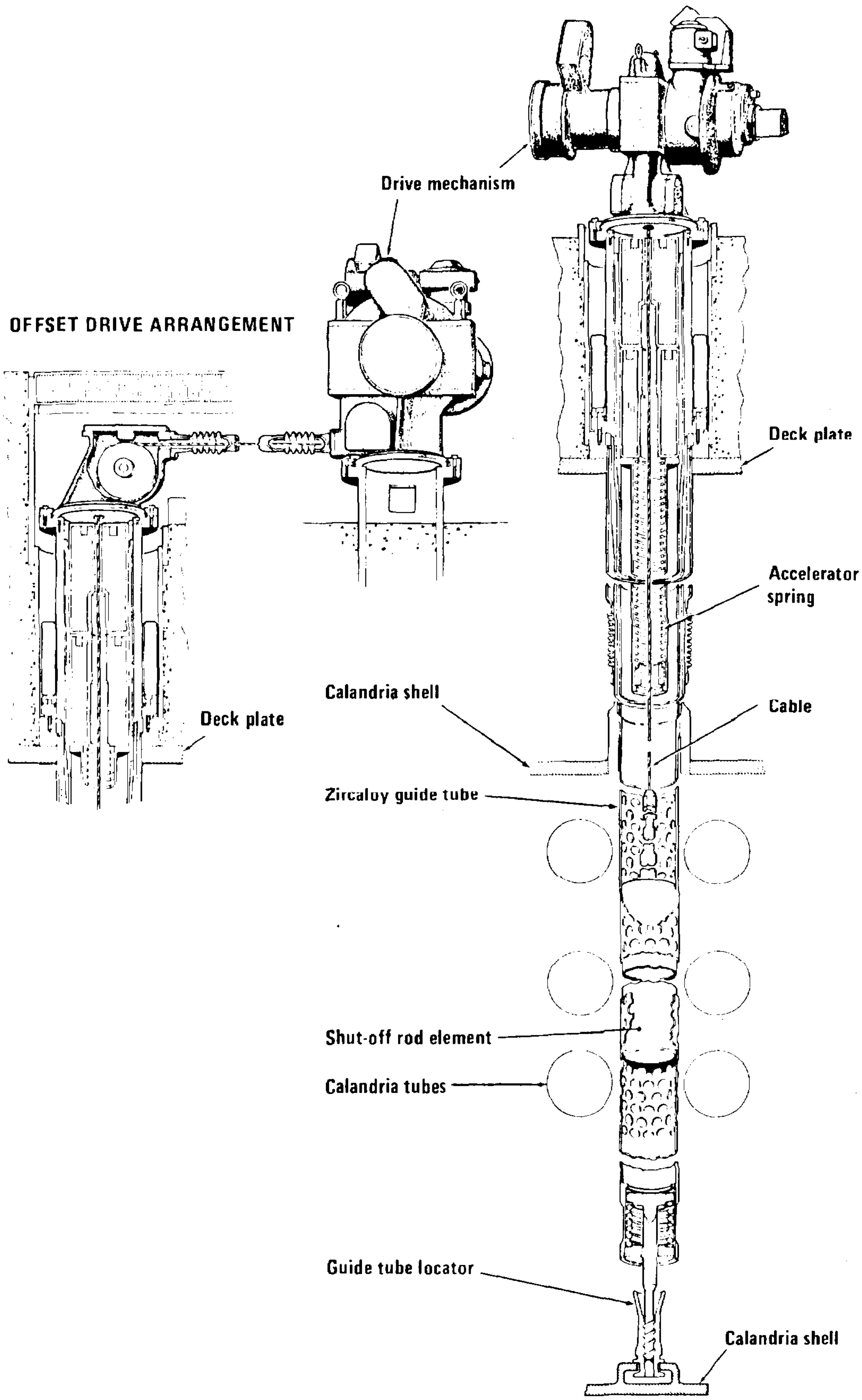

FIG. 6.6: Detail of a shut-off rod.

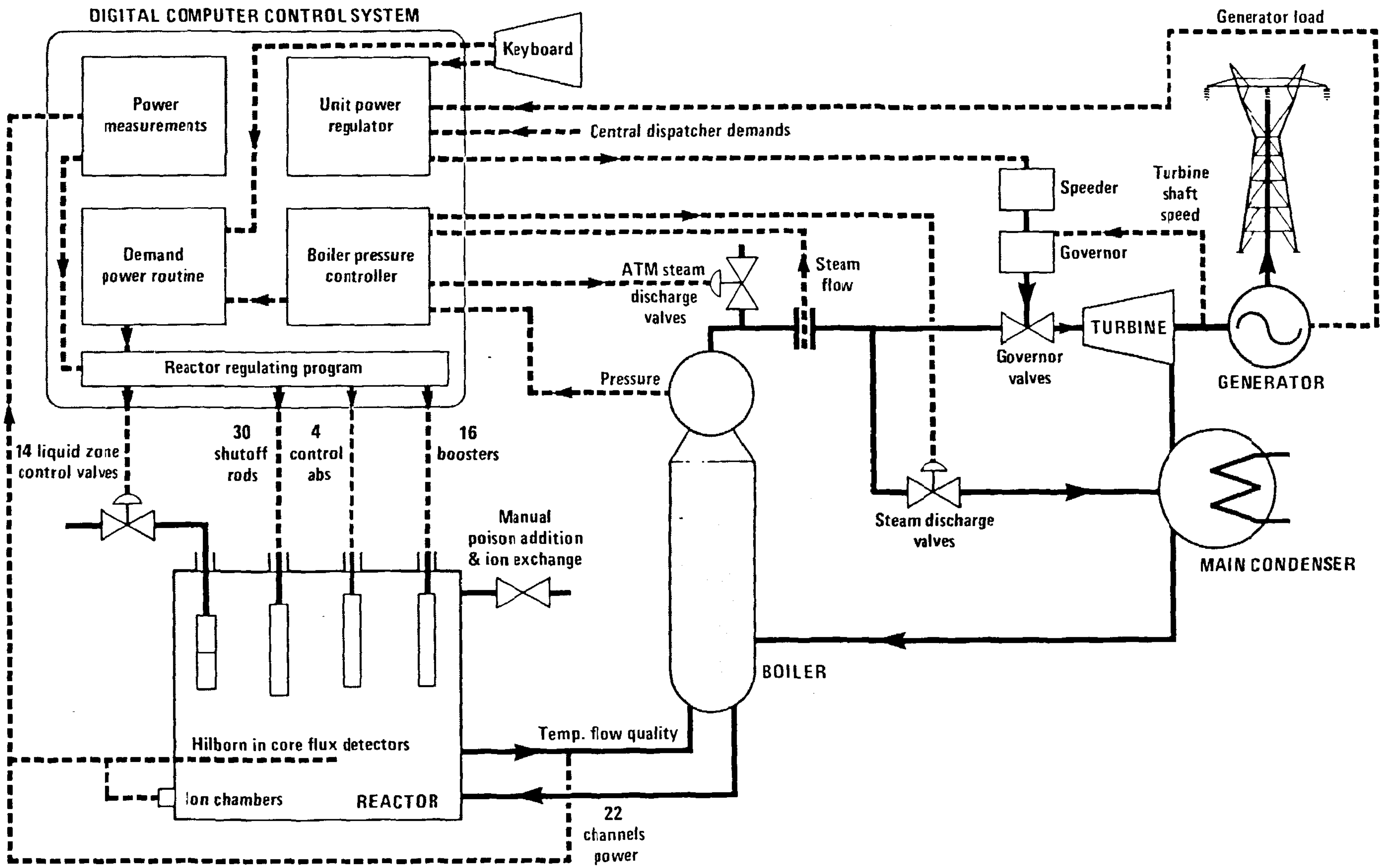

FIG. 6.7: Diagrammatical representation of a reactor control system.

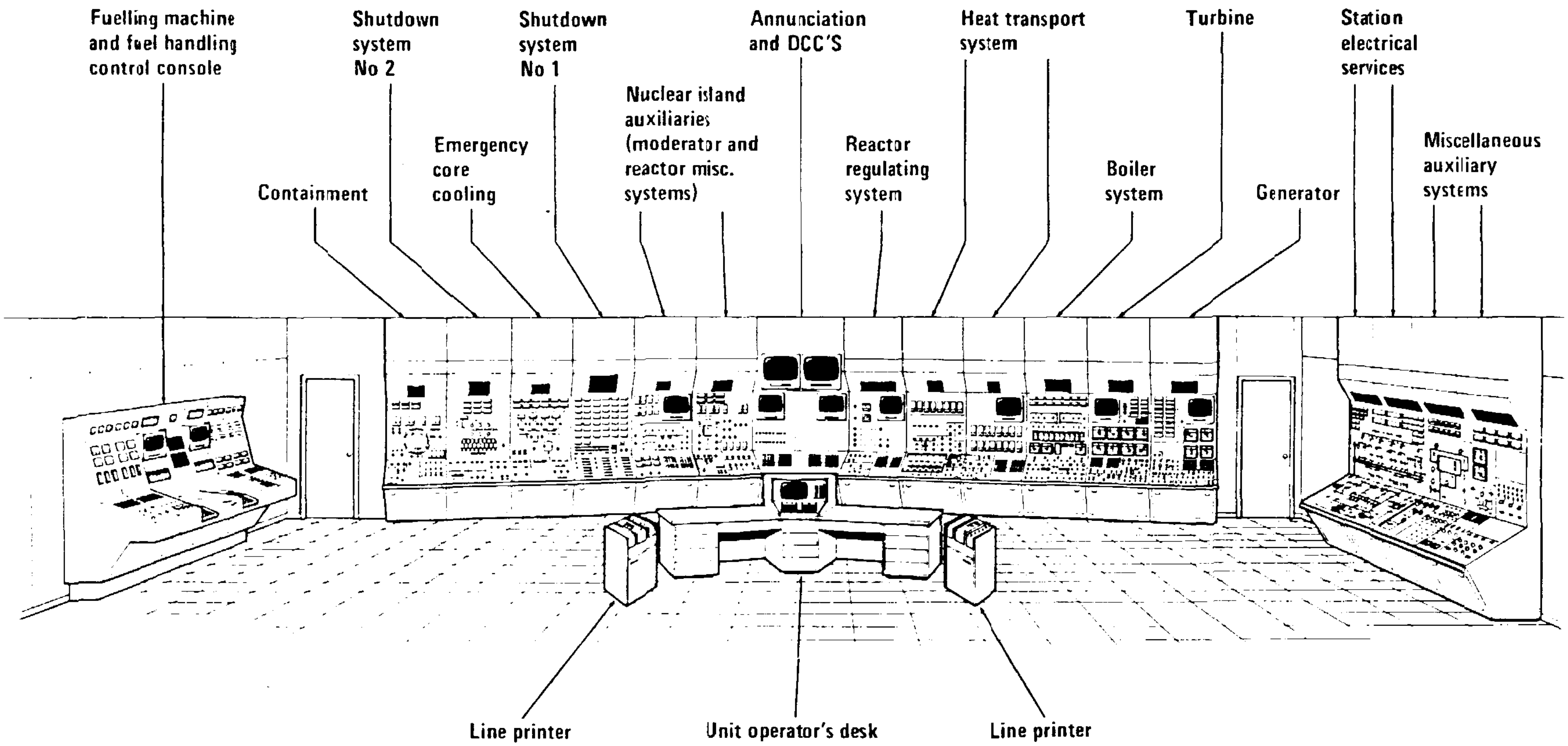

FIG. 6.8: Typical control panel layout.