CHAPTER 3

REACTOR CONTROL

CHAPTER OBJECTIVES:

At the end of this chapter, you will be able to describe the following features of the reactor control systems:

1. The main functions and unique requirements of reactor control;
2. The instruments and techniques used to monitor reactor power;
3. The devices and systems used to control reactor power;
4. The control algorithms used to achieve the objectives of reactor control.

This chapter describes the systems, equipment and techniques used to achieve control of reactor power throughout its designed range of operation. The requirements for reactor control are first examined, followed by the instrumentation needed to monitor reactor power. The various methods available for reactivity control are described next, including the devices and support systems needed to assure the reliable operation of these control systems. The last section explains how the computer programs implement the control algorithms that take the various power measurements and compute the reactivity device changes needed to achieve the desired reactor response.

3.1 REACTOR CONTROL REQUIREMENTS

The main functions of the reactor control system are as follows:

- Automatic control of reactor power to a given setpoint at any power level between 10^{-7} full power and 1.0 full power. The setpoint may be specified by the operator (alternate mode) or by the steam generator pressure control program (normal mode).
- Maneuvering of reactor power at controlled rates between any two power levels in the automatic control range (above 10^{-7} full power).
- Insertion or removal of reactivity devices at controlled rates to maintain a reactivity balance in the core. These devices compensate for variations in reactivity arising from changes in xenon concentration, fuel burnup, moderator poison concentration or reactor power.
- Maintaining the neutron flux distribution close to its nominal design shape so that the reactor can operate at full power without violating bundle or channel power limits. This requirement, along with the natural spatial instability of the core, dictates the need for spatial control.
- Monitoring of a number of important plant parameters and reduction of reactor power when any of these parameters is out of limits.
- Withdrawal of shutdown rods from the reactor automatically when the trip channels have been reset following a reactor trip on shutdown system number 1.

The reactor control system is an integrated system comprising reactor flux and thermal power measurements, reactivity control devices, and a set of control system programs, all coordinated to perform three main functions:

a. Monitor and control total reactor flux and power so as to satisfy the station load demands.
b. Monitor and control reactor flux shape.
c. Monitor important plant parameters and reduce reactor power at an appropriate rate if any parameter is out of limits.

There are several unique characteristics of nuclear power plants in general and CANDU generating units in particular which need to be appreciated before studying the equipment and techniques used to control such reactors. These special requirements are discussed in the following sections.

First Criticality

During and after initial fuel loading, the reactor is kept in a guaranteed shutdown condition by means of moderator poison. First criticality is achieved by gradual removal of this poison using the ion exchange columns of the moderator purification system.

The reactor regulating system monitors power level over the full operating range. Three systems of instrumentation are used, each covering a different range:

a. The startup instrumentation is used from the spontaneous fission power level (approximately 10^{-14} of full power) up to approximately 10^{-6} of full power.
b. The ion chamber system from 10^{-7} to 1.5 full power.
c. The in-core flux detector system above 10^{-1} full power.

The power range monitored by the startup instrumentation corresponds to an in-core thermal neutron flux range up to approximately 2×10^{8} n/cm^2.s. To accomplish this, BF_3 counters in conjunction with standard neutron counting equipment are used. To monitor a power range of eight decades without saturating the counting capability of the instrumentation, both in-core and out-of-core detectors are used. The startup counters provide alarm trips and indicators to trip three channels for shutdown system number 1 for: high power, high rate, and failure of detector voltage.

A small neutron source (e.g., 370 MBq Am-Be) giving approximately 2.5×10^{4} neutrons per second is used solely for testing the entire startup instrumentation system prior to installing the BF_3 counters in-core and in the ion chamber housing. Subcritical multiplication of spontaneous fission neutrons provides a sufficiently large count rate to be

Load Following

In the load-following case, if power reductions are large enough and of sufficient duration to require a significant number of the adjuster rods to be withdrawn to compensate for the associated transient in Xenon-135, restraints on the rate of recovery to full power may occur. As discussed in Section 3.1.2.6, the adjuster system can compensate for Xenon buildup after a power reduction to any level above about 60 percent of nominal power.

Assuming an initial power of 100 percent with equilibrium fuel in the reactor, the Xenon load at a steady level, and normal flux shape (all adjuster rods fully inserted, all mechanical absorbers fully withdrawn), the reactor power may be reduced to about 60 percent of full power at rates of up to 10 percent of full power per minute. The power may be held at the new lower level, indefinitely. Time to return to high power depends on the degree and duration of the power reduction. In most cases, a maximum of four hours is required to return to 98 percent of full power from 60 percent of full power.

Trip Recovery

When the reactor trips or the power is reduced in a controlled manner because of load-following or other requirements, a temporary increase in the Xenon-135 concentration occurs. The magnitude of the increase depends on the time period that the reactor is shut down or is operated at a reduced power level. It also depends on the magnitude by which the power level has been reduced and the rate at which it is reduced in the case of a controlled change in power level.

In the event of a reactor trip from full power, power must be raised again within about 35 minutes or the xenon concentration will rise beyond the capacity of the regulating system to compensate. At this point, all of the adjuster rods must be withdrawn to compensate for the xenon buildup. This results in peaking of the power distribution relative to the normal steady-state full-power condition. Consequently, power cannot be increased immediately to 100 percent. However, the power can be raised sufficiently to 'burn out' the excess Xenon- 135, and as this happens, the adjuster rods can be reinserted, which in turn permits increasing power.

Spatial Instability and Sources of Perturbation

During operation, the reactor can be subjected to perturbations such as those caused by refueling, power cycling, reactivity device movements and reactor trip with subsequent startup. The response of the reactor to these perturbations will depend upon its inherent stability - a characteristic determined largely by the lattice properties, the reactor size, the unperturbed flux distribution and the magnitude and sense of any feedback (due to change in fuel temperature, coolant density, Xe-135 concentration and control rod position).

Spatial flux instability results from neutronic decoupling of reactor regions. For an unstable reactor, a small flux perturbation can lead to power oscillations between opposite regions of the core; diverging with time, due to separation by a neutron-removing medium. In general, the larger the reactor core, the greater is its tendency to spatial instability.

The most common flux perturbations arise from on-power refueling operations and from movements of reactivity devices. Apart from exciting the flux harmonics, on-power refueling leads to local channel power variations about the nominal value. These are local effects and are allowed for in the design margins.

Automatic Spatial Control

The spatial control system in CANDU 9 prevents any global flux tilts which asymmetric fuelling would tend to induce and maintains a stable power distribution for all of the normal movements of reactivity devices (adjuster rods or mechanical control absorbers).

The zone controller compartments are used both for bulk and for spatial flux control. Bulk reactivity and flux level are controlled by varying the average zone controller fill. Spatial control is achieved by individually varying the zone controller fills.

A prompt measurement of zone flux is made with self-powered in-core detectors. A slightly delayed zonal power signal is obtained from calibration of an on-line flux mapping system. Such signals are used to drive each of the zone control compartments.

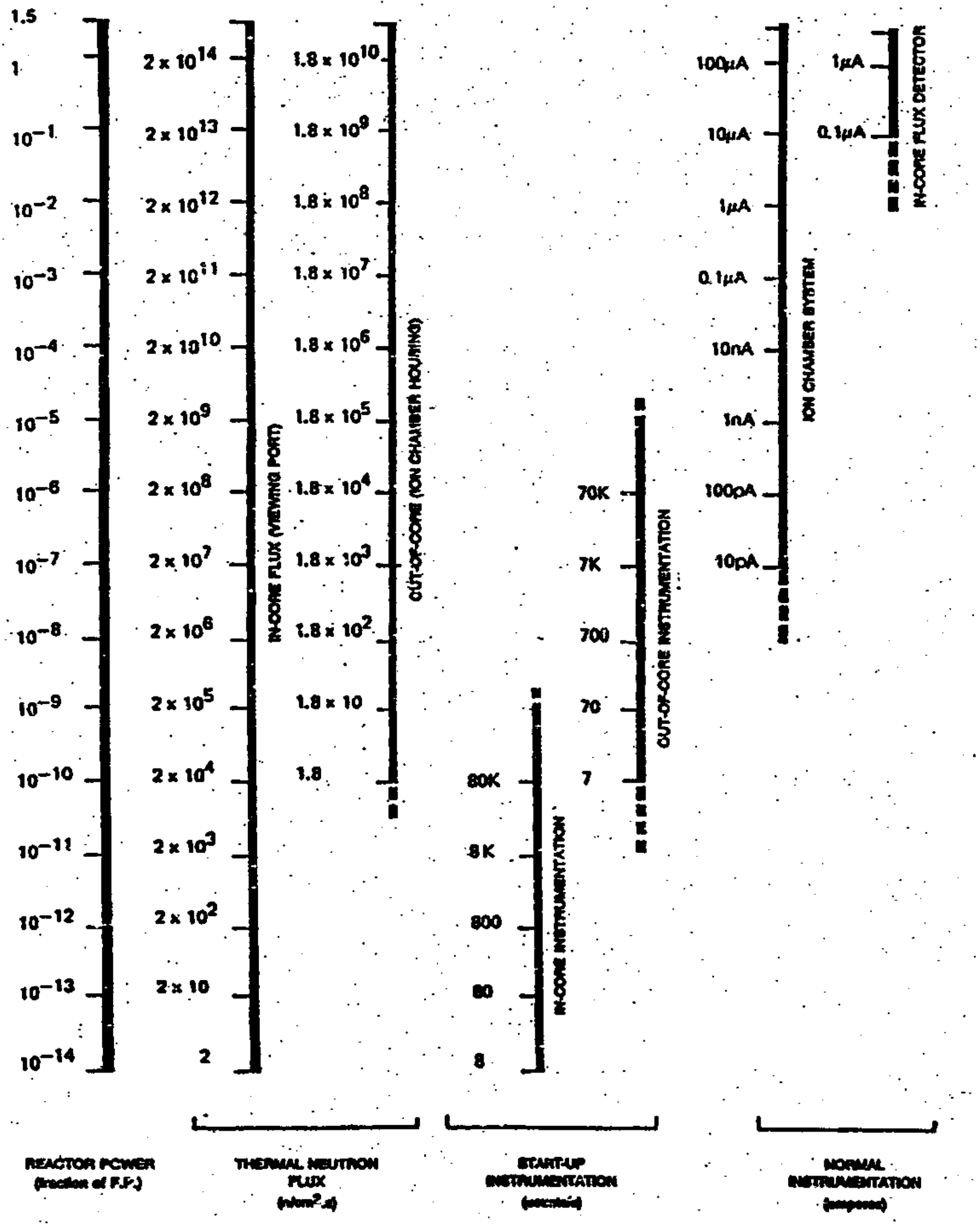

Figure 3.1. Range of Sensitivity of Nuclear Instrumentation for Reactor Power Measurement.

3.2 REACTOR INSTRUMENTATION

Three instrumentation systems are provided to measure reactor thermal neutron flux over the full power range of the reactor. Startup instrumentation covers the eight-decade range from 10^{-14} to 10^{-6} of full power; the ion chamber system extends from 10^{-7} to 1.5 of full power, and the in-core flux detector system provides accurate spatial measurement in the uppermost decade of power (10 percent to 120 percent of full power). This is shown graphically in Figure 3.1.

The fuel channel temperature monitoring system is provided for channel flow verification and for power mapping validation.

Startup Instrumentation

This system is used on initial plant startup or after a prolonged shutdown, and performs a dual regulating and protective role over the lowest power range when the normal flux measuring instrumentation of the regulating and shutdown systems is off scale. This occurs on the initial reactor startup and during a shutdown of 40 to 70 days or more when the photo-neutron source decays below the sensitivity of the ion chamber system.

Two sets of neutron detectors (BF_3 counters) are used covering the range from 10^{-14} of full power up to 10^{-6} of full power. One set, located in-core, covers the range from spontaneous source level (10^{-14} full power) to 10^{-9} full power. The in-core detectors are installed via the vertical viewing port penetration from the reactivity deck. This instrumentation is removed after the low power commissioning period.

The other set of neutron detectors is located out of core in the three spare cavities of the shutdown system number 2 ion chamber housings.

The detector outputs are connected to startup monitoring instrumentation located temporarily in the main control room. The signals are processed to give log and linear count rate indications and rate of change information. This information is used for protection and monitoring during the approach to criticality.

In this range, the reactor is controlled manually by the operator from the control room. The operator monitors and records the output of the neutron counting instrumentation which is mounted in a mobile cabinet. This instrumentation is divided into three redundant channels and includes trip comparators which are connected into the D, E and F channels of the trip logic of the shutdown system number 1. Shutdown rods will drop into the core under any one of the following three conditions:

a. the count rate exceeds the setpoint,
b. the rate of change is excessive,
c. two or more channels of the instrumentation fail.

On restart after an extended shutdown, the system is normally on-scale with the out of core detectors; in-core counters are used only on the initial startup. The arrangement of the system is shown in Figure 3.2.

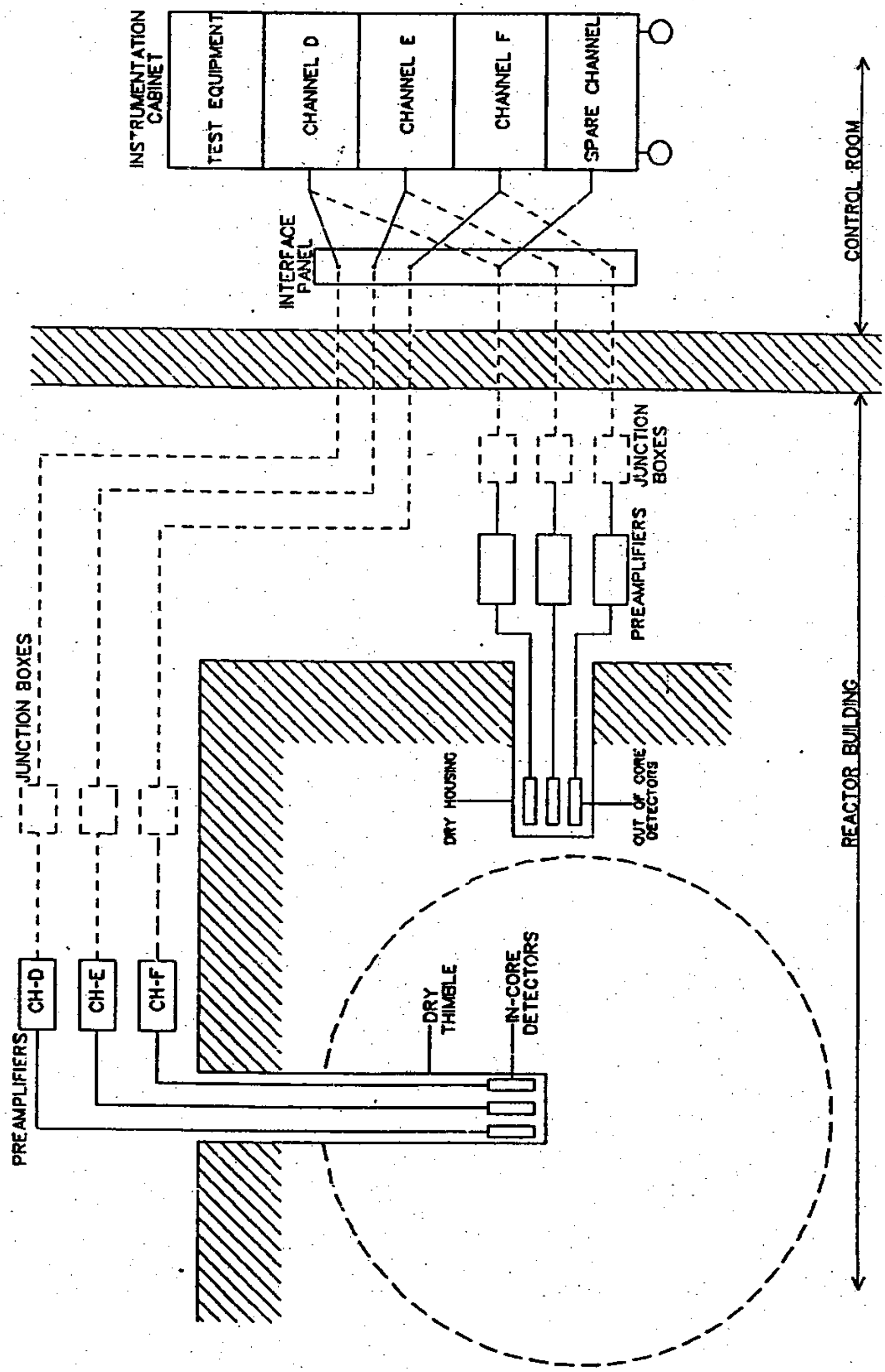

Figure 3.2. Arrangement of Startup Instrumentation.

Ion Chamber System

The ion chamber system is a part of the on-line power measurement equipment of the reactor control system. This instrumentation is on-scale during normal operation, and remains on-scale during a normal shutdown. If the shutdown lasts more than 40 to 70 days (depending on reactor operating history and ion chamber neutron and gamma sensitivity), the flux decays below 10^{-7} of the full power value and start-up neutron detectors are needed.

The ion chamber units consist of lead-shielded housings mounted on the outside of the calandria shell, in which ion chamber instruments and calibration shutters are installed. The lead attenuates gamma radiation so that the ion chambers measure neutron flux, primarily. The output current from separate ion chamber instruments is amplified to generate independent inputs for the reactor control system and each shutdown system, as follows:

a. log neutron power, 10^{-7} to 1.5 full power,
b. linear neutron power, 0 to 1.5 full power,
c. rate of change of log power, -15 percent to +15 percent of present power per second.

Ion chambers measure only the average flux, as seen at the side of the core, but are sensitive to very low flux levels, for monitoring sub-critical as well as full power behavior. Because they are outside the calandria, the neutron flux they detect has been attenuated by the moderator and any poison dessolved in the moderator.

In-Core Flux Detectors

In-core flux detectors are used at high power levels (above 10 percent of full power) because they provide spatial information needed, at high power, to control xenon-induced flux tilts and to achieve the optimum flux distribution for maximum power output.

Vertical Flux Detector Assemblies

The control system flux detectors are of two types. One type has an Inconel emitter and is used for the zone control system. The other type has a vanadium emitter, and is used for the flux mapping system.

Both types of control system detectors, along with the Inconel detectors used for the shutdown system number 1 high neutron power trip, are contained in vertical flux detector assemblies located throughout the core. These assemblies extend from the reactivity mechanisms deck to the bottom of the reactor.

The assemblies are of the straight individually replaceable type with each detector housed in individual well tubes. There are 13 well tubes, 12 for detectors of various types and a central tube reserved for a potential traveling flux detector (for periodic detector recalibration).

The self-powered detectors are in the form of a coaxial, mineral-insulated cable. A lead cable portion joins the detector to a channelized, environmentally qualified connector on the deck. From there the signals are fed through twisted-pair shielded cables to amplifiers and multiplexer stations in the Group 1 instrumentation.

Zone Control Flux Detectors (Inconel)

The self-powered in-core flux detectors are installed in flux detector assemblies to measure local flux over two decades, 10^{-1} full power to 1.2 full power, in the regions associated with the liquid zone controllers. At each location there are two detectors for redundancy. An amplifier converts each detector current to a suitable input signal for the distributed control system.

These detectors have an Inconel emitter which provides a prompt response to a change in neutron flux. The control system transforms this response into a signal which closely matches corresponding changes in reactor power. The Inconel detectors have a relatively slow rate of burnup (loss of sensitivity due to accumulated exposure to neutron flux).

The zone control detectors and their amplifiers are grouped into two redundant channels and supplied by Class II power buses. Special measures are taken to avoid ground loops and noise pickup.

Flux Mapping Detectors (Vanadium)

The flux mapping system (described in Section 3.4) uses vanadium detectors distributed throughout the core to provide point measurements of the flux.

These detectors are almost totally neutron-sensitive; however, their response is delayed by 5.4 minutes due to the half-life of the beta emission from vanadium-52. The signals, approximately 3 μA at full power, are fed to amplifiers in a stand alone distributed control system station inside the reactor building, where they are multiplexed and sent to the plant display system computer. The flux mapping instrumentation is powered by a Class II bus.

Fuel Channel Temperature Monitoring

The channel temperature monitoring system serves the following two functions:

a. Channel flow verification: On startup, before boiling starts in the channels, channel outlet temperatures are calculated from channel powers provided by the flux mapping routine and estimated channel flows, and compared with the measured outlet temperatures. After the onset of boiling, the system only monitors the detectors for possible malfunctions.

b. Power mapping validation: The channel temperature differentials are used with measured flows (instrumented channels) or predicted flows (other channels) to determine the estimated channel powers, which are then compared with the powers calculated from the flux mapping readings; this provides an ongoing validation of the accuracy of the flux-mapping channel powers.

The channel temperature monitoring system has resistance temperature detectors mounted on each of the outlet feeders. These detectors are externally mounted, thermally insulated from adjacent feeders, and have a reliable and secure mounting design to provide system sensitivity and reliability.

Since coolant boiling occurs at full power, the reactor power must be reduced somewhat for the channel temperature monitoring system measurements to be meaningful. Hence, channel flow verification is done while the reactor is returning to full power, especially if the heat transport system has been opened for maintenance purposes. In addition, several times a year, the reactor power is reduced to a level that results in zero quality in the coolant for channel flow verification and power-mapping validation.

Thermal Power Measurement

The fast, approximate estimate of reactor power is obtained by either taking the median ion chamber signal (at powers below 5 percent of full power) or the average of the in-core Inconel flux detectors (above 15 percent of full power) or a mixture of both (5 percent to 15 percent of full power). These signals are filtered and calibrated by comparison with estimates of reactor power based on thermal measurements from one of the following two sources:

a. Several pairs of resistance temperature detectors are located on the reactor inlet and outlet headers. Each pair measures the temperature rise across the reactor. At power levels below the onset of coolant boiling in the fuel channels, the average temperature rise generates an accurate estimate of reactor power; this estimate is used to calibrate the Inconel flux detectors on-line below 50 percent of full power.
   Reactor thermal power is directly proportional to average heat transport system coolant flow. The calculation of reactor power therefore requires an estimate of heat transport coolant flow. Since the reactor regulating program does not have access to heat transport system coolant flow measurements a constant value based on off-line calculations and commissioning measurements is used. In the power range of interest (below 50 percent of full power) there is no boiling and the heat transport system coolant flow does not vary significantly with power. A constant precalculated value is therefore adequate.

b. At high reactor power, boiling commences in the fuel channels. With boiling in the fuel channels, the average temperature rise across the reactor fuel channels does not provide a good estimate of reactor power; flow variations also become significant. Therefore reactor power estimates above 70 percent of full power (for calibration purposes) are based on secondary side measurements. Steam flow, feedwater flow and feedwater temperature are measured and reactor power estimated from on-line enthalpy/flow calculations.

In the intermediate power range (50 percent - 70 percent of full power) a linear combination of the temperature differential measurements (used below 50 percent of full power) and the secondary side measurements (used above 70 percent of full power) are utilized as the calibrating signal. This assures a smooth and accurate transition.

3.3 REACTIVITY CONTROL DEVICES

Reactivity devices are provided to alter the rate of neutron multiplication (either as controllers or as shutdown devices). Control is provided for the following effects:

- Long-term bulk reactivity, mainly controlled by on-power fuelling.
- Small, frequent reactivity changes, both global and spatial-controlled by the liquid zone control system.
- Additional positive reactivity for xenon override and fuelling machine unavailability, mainly resulting from the withdrawal of adjusters.
- Additional negative reactivity for fast power reductions and to override the negative fuel temperature effect, provided by the insertion of mechanical control absorbers.
- Initial excess reactivity and decay of xenon following a long shutdown, compensated by moderator poison.

Because of on-power refueling and relatively small thermalhydraulic feedback effects, the flux shape, and hence the worth of reactivity devices, varies only marginally with power level and with time. In the following sections, the given reactivity worth of the various devices are typical nominal values and correspond to the reference adjuster design with the following core conditions: equilibrium fuelling, steady-state xenon, and full reactor power.

The reactivity control mechanism layout is shown in Figure 3.3. All reactivity control devices are located between rows of fuel channels, in the cool low pressure moderator.

Liquid Zone Control System

The zone control system is designed to perform two main functions:

a. To provide short term reactivity control to maintain reactor power at the demanded level during normal operation (i.e. operating control of reactivity). This must be adequate for compensating the zero to full power reactivity change when equilibrium fuelling is achieved.
b. To control spatial power distribution by suppressing regional power transients associated with space dependent reactivity perturbations. The dimensions of the CANDU 9 reactors are large in comparison to the thermal neutron diffusion length of the lattice and the reactor flux levels are high enough that the rate of burnup of xenon-135 is about 10 times its decay rate. These are sufficient conditions for xenon induced spatial power oscillations to occur and these must also be controlled.

For the purpose of spatial control, the reactor is divided into zones, as shown in Figure 3.4. Spatial control is obtained by means of light water zone control assemblies and associated thermal neutron detectors in each zone. The zone control assemblies consist of compartmentalized vertical Zircaloy tubes which traverse the core; as shown in Figure 3.5. Bulk reactivity control is achieved by varying the light water level in all compartments by the same proportion. Spatial flux control is achieved by differential adjustment of the light water level in individual compartments.

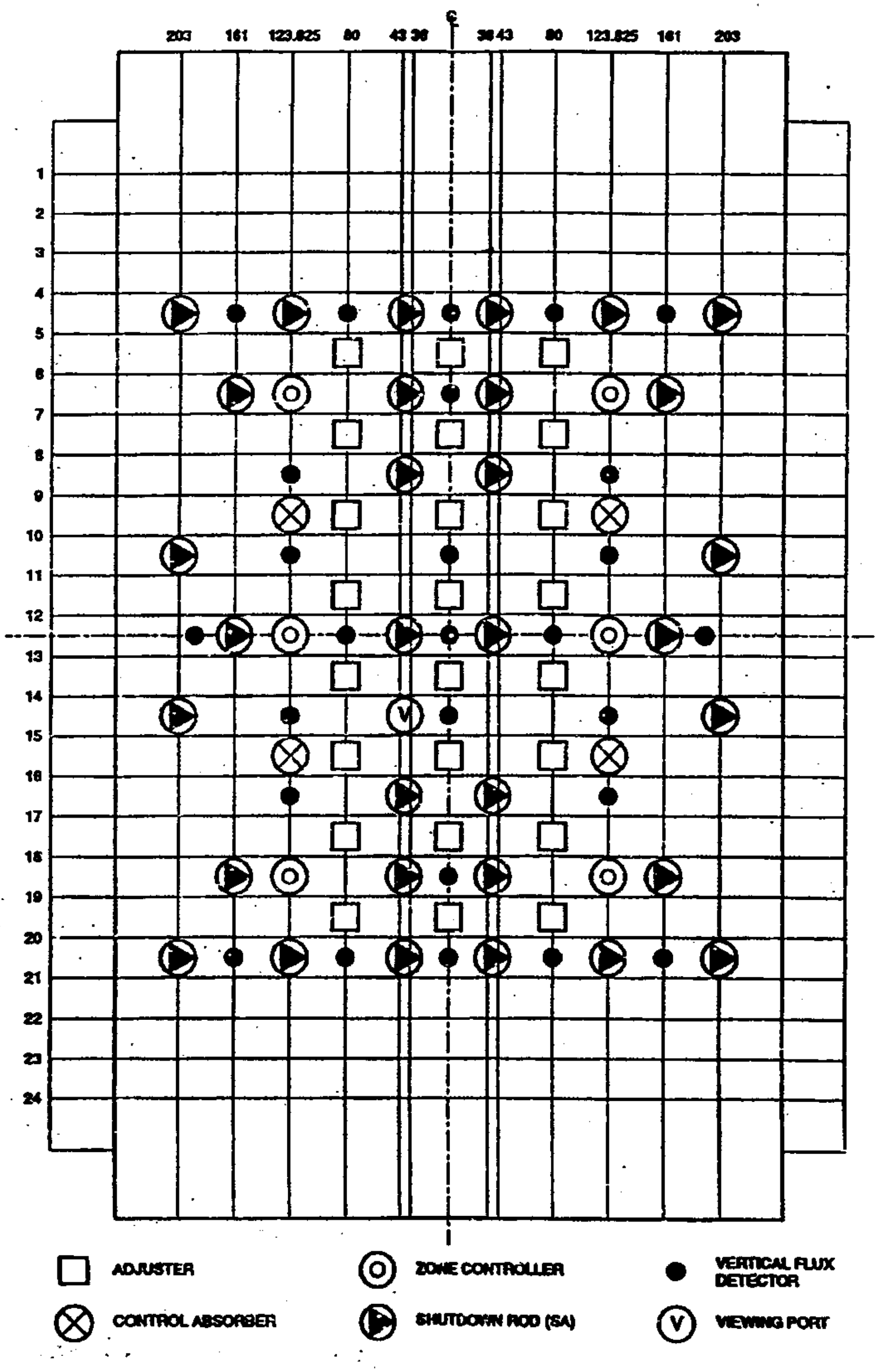

Figure 3.3. Reactivity Mechanism Layout.

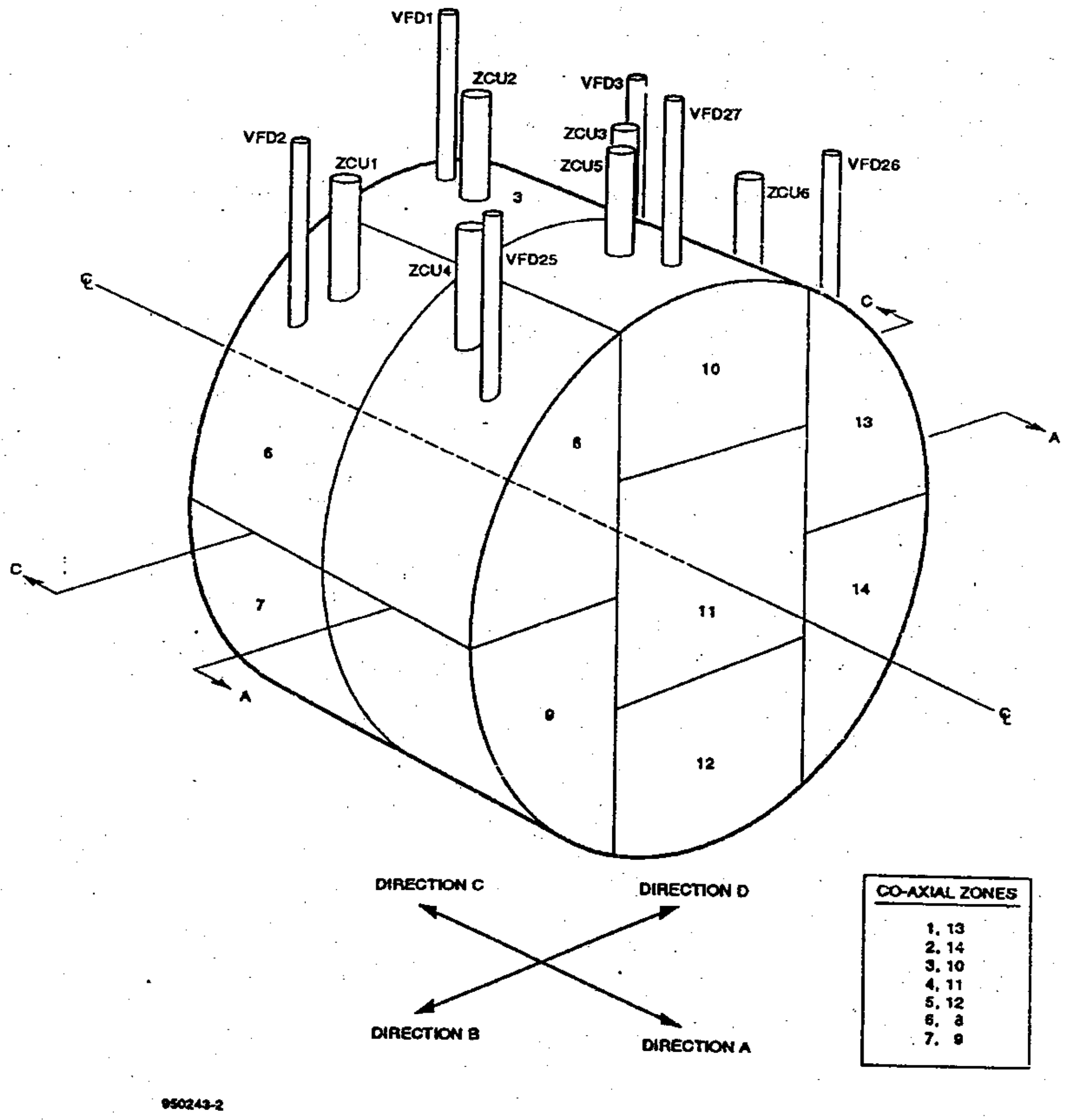

Figure 3.4. Relation of Zone Control Units to the Fourteen Zones and the Reactor Regulating Detector Assemblies (Vertical Flux Detectors) 1, 2, 3, 25, 26, 27.

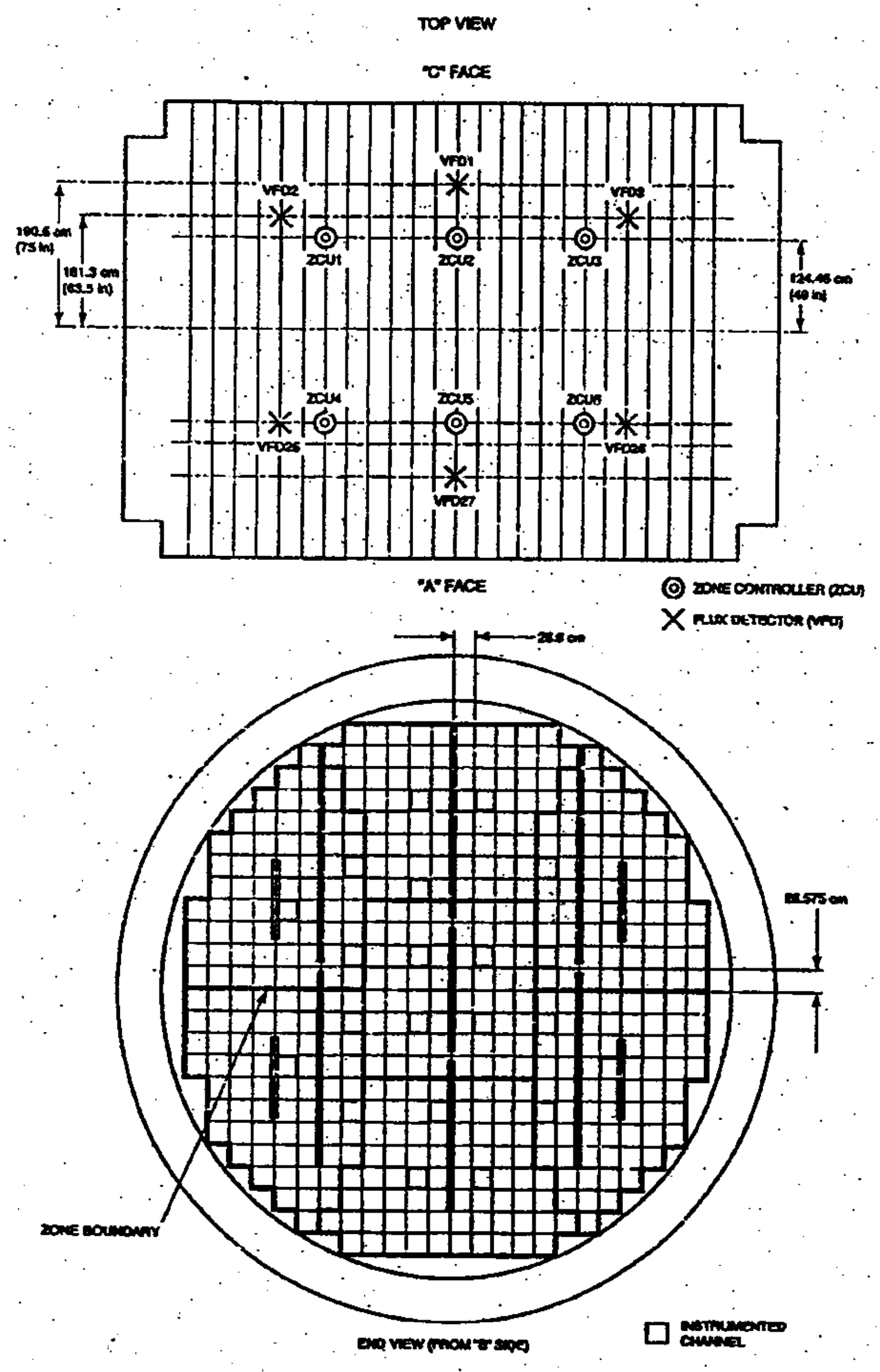

Figure 3.5. Zone Control Absorbers and their Associated Flux Detectors.

The total reactivity worth of the liquid zone control system from empty to full is -8.2 mk for the fresh initial core, and -7.2 mk for the equilibrium core using the homogeneous model. The difference in the liquid zone control system reactivity worth in the two states is mainly due to the difference in core flux distributions.

Table 3.1 gives the reactivity worth of the liquid zone control system for the CANDU 9 equilibrium core as a function of the average percentage fill. In the nominal operating range of between 20 percent and 70 percent fill, the worth of the liquid zone control system is essentially proportional to the average level; the corresponding reactivity coefficient is -0.077 mk/percent of fill.

Table 3.1. Variation of Zone Control System Reactivity Worth with Average Zone Level (Equilibrium Core Homogeneous Model).

Average Zone Level (% Fill)	Zone Control System Reactivity (mk)
0	0
10	0.86
20	1.70
30	2.53
40	3.34
50	4.12
60	4.87
70	5.56
80	6.17
90	6.73
100	7.19

A simplified flowsheet for the liquid zone control system is presented in Figure 3.6. A typical liquid zone control unit is shown in Figure 3.7.

The system consists of two subsystems; one for demineralized water circulation and one for gas circulation. With the exception of the delay tank and helium storage tank, the system equipment is located in an area of the reactor building which is accessible during operation.

The demineralized water subsystem is a closed circuit consisting of three 100 percent centrifugal pumps, a 100 percent tube and shell heat exchanger, a delay tank, two ion exchange columns, supply and return headers, pneumatic control valves and interconnecting piping and tubing, which connects to each liquid zone compartment via supply and drain lines.

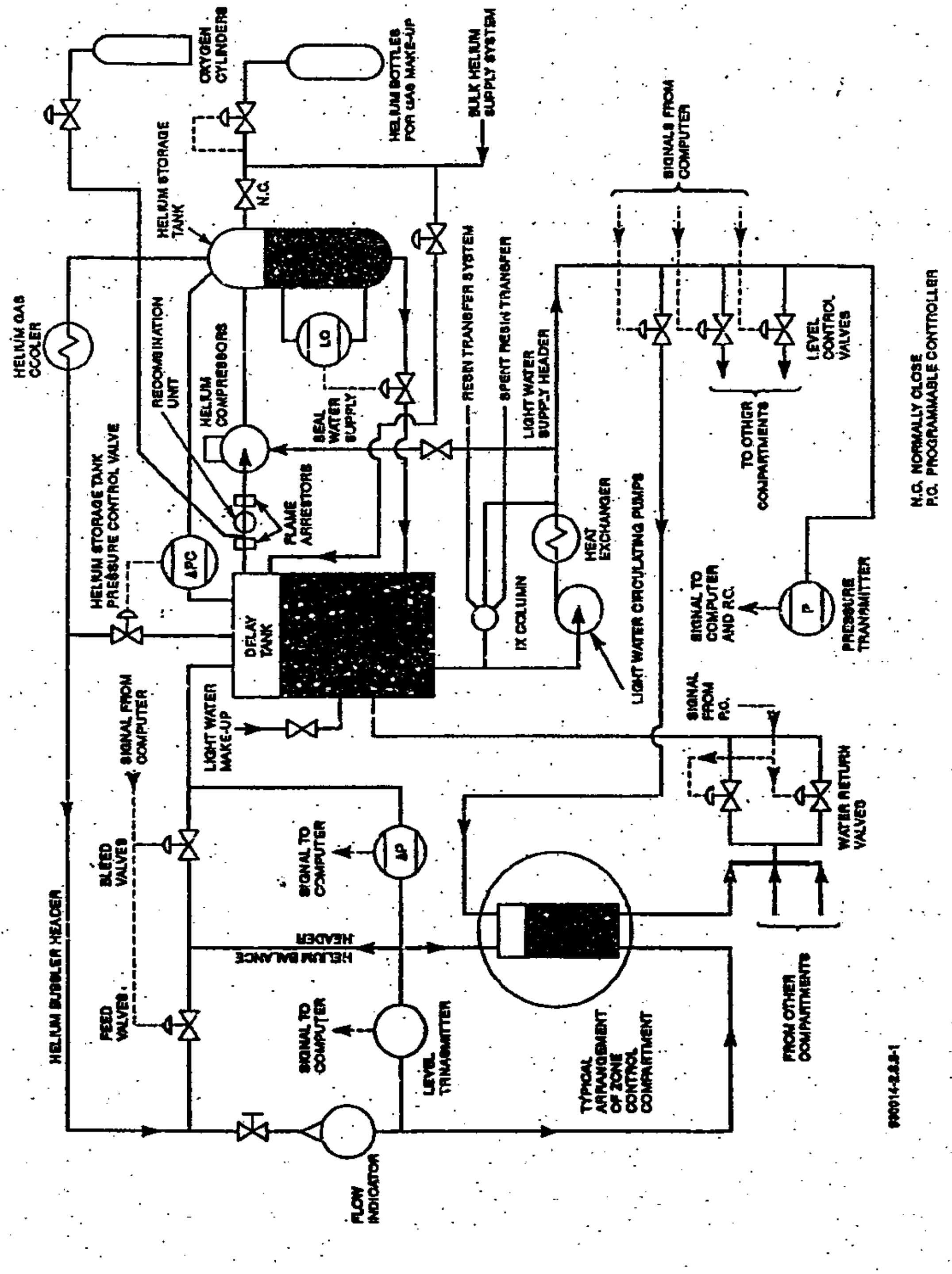

Figure 3.6. Liquid Zone Control Flow Diagram.

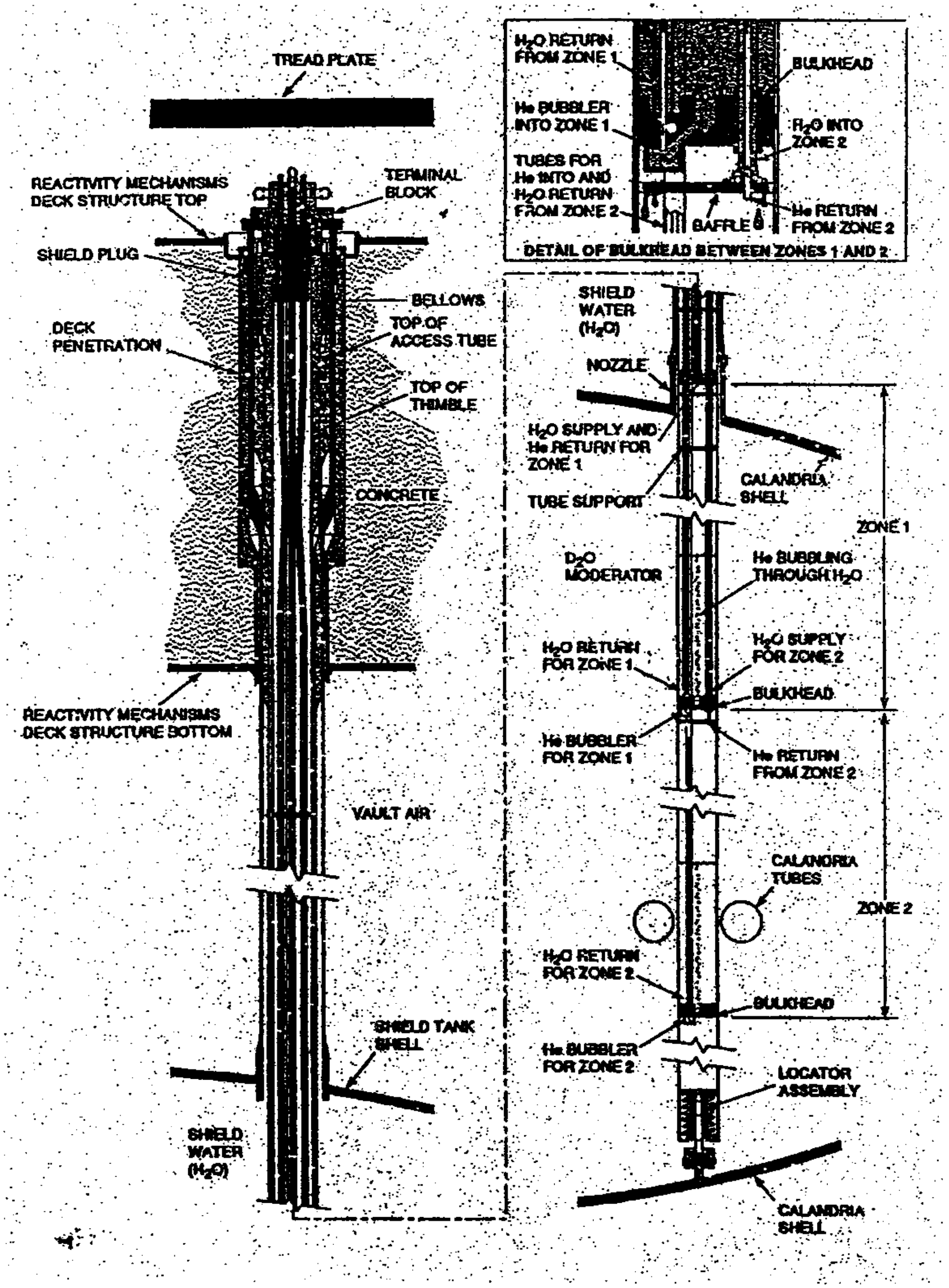

Figure 3.7. Liquid Zone Control Unit (2 Zone).

A constant outflow of water from each liquid zone compartment permits the quantity of water in the compartment to be controlled by varying the rate of inflow. The outflow from the liquid zone control compartments is discharged to the delay tank through the return header. The delay tank is used for the decay of short lived neutron activation products before they enter the accessible area of the reactor building. The delay tank also functions as a water storage tank.

The delay tank is connected to the suction of three centrifugal pumps, one of which normally operates with the other two on standby. The pumps are driven by electric motors connected to the Class IV power supply. The discharge from the pumps supplies water to the compartments, through individual control valves and also supplies seal water to the two compressors. A portion of the pump discharge flows to the ion exchange columns for removal of ionic and suspended particles.

The helium subsystem is a closed circuit, consisting of two liquid ring type compressors, a storage tank, two flame arrestors, a preheater, a recombination unit, a balance header pneumatic control valve train and interconnecting pipe and tubing which connects to each liquid zone compartment via supply and return lines.

Helium is used as the cover gas because it is chemically inert and does not become activated. The helium for the liquid zone control system is supplied from the bulk helium supply system. A back up helium supply is provided from cylinders.

The compressors maintain pressure in the helium storage tank and supply gas to bubblers in each of the compartments and to the helium balance header. The helium storage tank pressure is kept constant and higher than that of the delay tank by means of control valves. The helium feed and bleed valves control the gas pressure in the compartments. The feed valves open as the pressure decreases when the water inventory in the compartments decreases and the bleed valves open as the pressure increases when the water inventory increases. The bleed valves return the helium to the delay tank.

A catalytic recombination unit upstream of the compressors reduces the concentration of radiolytic hydrogen in the helium to acceptable limits. The recombination unit uses palladium as a catalyst and is capable of operating at a high temperature without damage.

Oxygen is added manually from cylinders when required to facilitate recombination. Flame arrestors are provided at the inlet and outlet of the recombination unit.

The helium balance header pressure is controlled by feeding helium from the storage tank into the header or by bleeding excess helium from the helium balance header into the delay tank. The pressure difference between the delay tank and the helium balance header is used to control the feed and bleed valves.

The helium balance header triplicated differential pressure transmitters provide measurement signals to the computers in the distributed control system, which compute feed and bleed valve lifts to maintain a fixed differential between the helium balance header and the delay tank. One pair of feed and bleed valves is used for primary control while the second pair provide backup operation should the primary valves fail.

<u>Adjuster Rods</u>

The adjuster rods are provided to shape the neutron flux for optimum reactor power and fuel burnup, and to supply positive reactivity beyond the normal control range of the zone controllers when required.

The adjusters are arranged in rows, as shown in Figure 3.3. The rods are normally fully inserted in the core, and their movements are controlled in banks. The maximum total reactivity which may be gained on withdrawal of all adjuster rods is about -16 mk. This is sufficient to compensate for the negative xenon reactivity at 35 minutes after a shutdown from full power (during fresh fuel conditions the adjuster worth is somewhat less than -16 mk; however, the xenon override capability is not significantly affected).

The operation of the adjusters is normally controlled by the reactor regulating system, but can also be manually operated under prescribed conditions. The maximum reactivity change rate of any one bank of adjusters is ± 0.07 mk/s.

Mechanical Control Absorbers

The mechanical control absorbers are normally poised out of the core, and are driven in by the reactor control system to supplement the negative reactivity of the liquid zone control units, or dropped to effect a fast reactor power reduction (stepback). They can be driven into or out of the reactor core, at variable speed, or dropped by releasing their clutches. When dropped, the elements are fully inserted in three seconds. By re-energizing the clutch while the elements are dropping, a partial insertion to any intermediate position can be achieved.

The maximum total reactivity worth of the mechanical control absorbers is about -11.0 mk in the initial core and -9.4 mk in the equilibrium core. These absorbers consist of tubes of cadmium sandwiched between stainless steel. Their arrangement is shown in Figure 3.3.

Moderator Poison

Moderator poison is used to reduce excess reactivity during fresh fuel conditions or during shutdown to compensate for xenon decay. Boron is used in the former situation and gadolinium in the latter situation. The burnout rate of gadolinium on a subsequent startup is comparable to the xenon growth rate, hence smooth control is possible when gadolinium is used for this purpose (this poison addition system is independent of the liquid poison injection system used as a shutdown system).

The design rate of poison addition is equivalent to -0.75 mk/min. Removal rates depend on poison concentration. At a poison level of -30 mk, the removal rate is approximately +0.05 mk/min.

3.4 REACTOR REGULATING SYSTEM PROGRAMS

A block diagram of the reactor regulating system is shown in Figure 3.8. Some logic blocks are shown only for convenience and do not necessarily imply separate, self-contained programs. The functions of each program logic block are discussed in detail below.

The regulating system is characterized by a high degree of immunity to small process upsets, and measurement failures, by redundancy in control devices and process measurements. Extensive checks are performed in the programs to ensure that faulty signals are discarded. In case of loss of a signal or an entire set of signals, alternative measurements are used. In case of failure of a control device, a backup is used. However, it may be necessary to derate the reactor because of limited information or imperfect flux shape.

This ability to maintain control in the presence of partial system failures, combined with the high reliability of the distributed control system, leads to a very high availability of the reactor control system.

Power Measurement and Calibration

The regulating system controls bulk reactor flux level and flux shape, by increasing or reducing the level of the light water in the zone controllers to equalize and/or change the powers in the power zones of the core. Spatial flux control is required to prevent xenon-induced instabilities and other space dependent perturbations.

Total reactor power is determined by a combination of ion chamber signals (at low power) and Inconel zone detector signals (at high power). The crossover occurs around 10 percent of full power. Because neither measurement is absolute, the flux signals are continuously calibrated against reactor power measurements based on thermal signals.

The zone power measurements are based on the Inconel flux detectors. Absolute measurements are less important here because the spatial control system acts to equalize the measurements. However, a single flux measurement may not be exactly representative of average power in a region of the core because of local flux disturbances such as refueling. Therefore, the Inconel detector signals are calibrated continuously using the flux mapping routine.

Flux Mapping Routine

The flux mapping routine collects readings from the Vanadium flux detectors distributed throughout the reactor core and computes a best fit of this data with respect to flux modes expected for the given core configuration. Flux mapping provides an accurate estimate of average zone flux in each of the power zones. These estimates are available once every two minutes and lag the neutron flux by approximately five minutes, the Vanadium detector time constant. Spatial calibration in a zone is done by matching the average zone flux estimate generated by flux mapping with appropriately filtered zone Inconel flux detector readings. The flux mapping routine rejects individual detectors whose readings disagree with the rest of the detectors. The net result is a smoothed accurate steady state estimate of relative zone power.

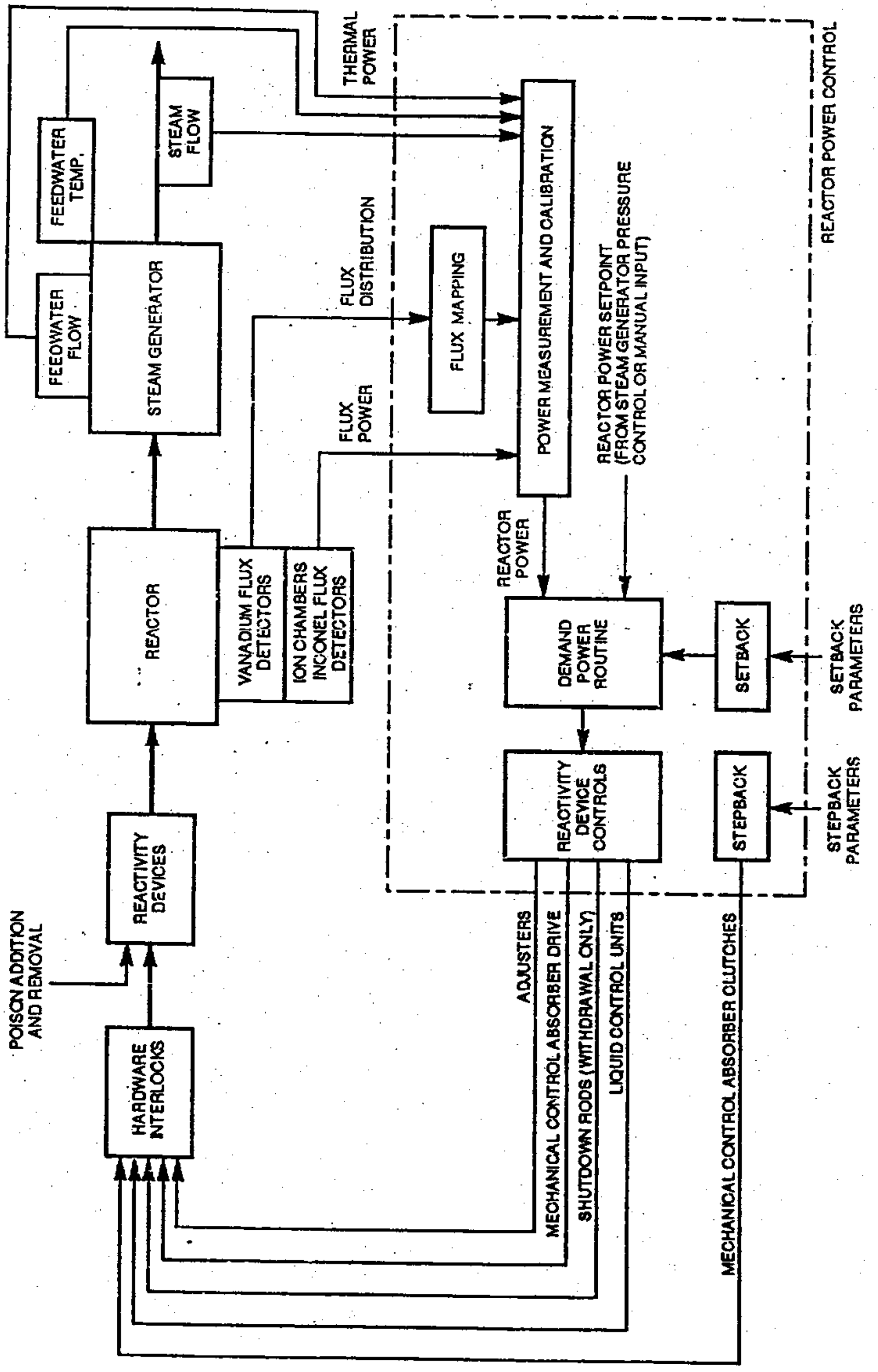

Figure 3.8. Reactor Regulating System-Block Diagram.

Demand Power Routine

The demand power routine generates the reactor power setpoint on the basis of demands from three sources:

a. the steam generator pressure control program (normal mode),
b. the operator (alternate mode),
c. the setback routine.

Normally at high power the steam generator pressure control program dictates reactor power changes to give a reactor-follows-turbine type of control.

At low power, during upset conditions or at the operator's discretion, the reactor power setpoint is under manual control via the keyboard.

Setbacks override both of the above modes to ensure that reactor power is reduced when selected plant parameters exceed acceptable operating limits.

All reactor power setpoint changes are limited by the control program to safe rates and safe upper limits. A deviation limiter prevents the power setpoint from being more than 5% above the actual power to preclude the possibility of a large power increase at excessive rates.

Reactivity Mechanism Control

The reactivity mechanism control logic is summarized in Figure 3.9. The primary method of short-term reactivity control is by varying the liquid level in the zone controllers. Normally, the adjusters are fully inserted, the control absorbers are fully withdrawn and the average liquid zone control compartment level is between 30 percent and 50 percent. The total control signal to the zone control valves consists of the bulk power control term plus a differential component proportional to that zone's power error.

In case of a shortage of negative reactivity, indicated by a high zone controller level or a positive power error, the mechanical control absorbers are driven in, one bank at a time.

In case of a shortage of positive reactivity, indicated by a low zone controller level or a negative power error, the adjusters are driven out in a specific sequence.

The adjusters and mechanical control absorbers are driven at a speed proportional to power error to minimize, at low power errors, the shim reactivity rate which must be canceled by the zone controllers.

The program also automatically withdraws all the shutdown rods unless: all rods are fully out, the reactor is tripped, the power error is too large, mechanical control absorbers are not in the core or the measured lograte is too large.

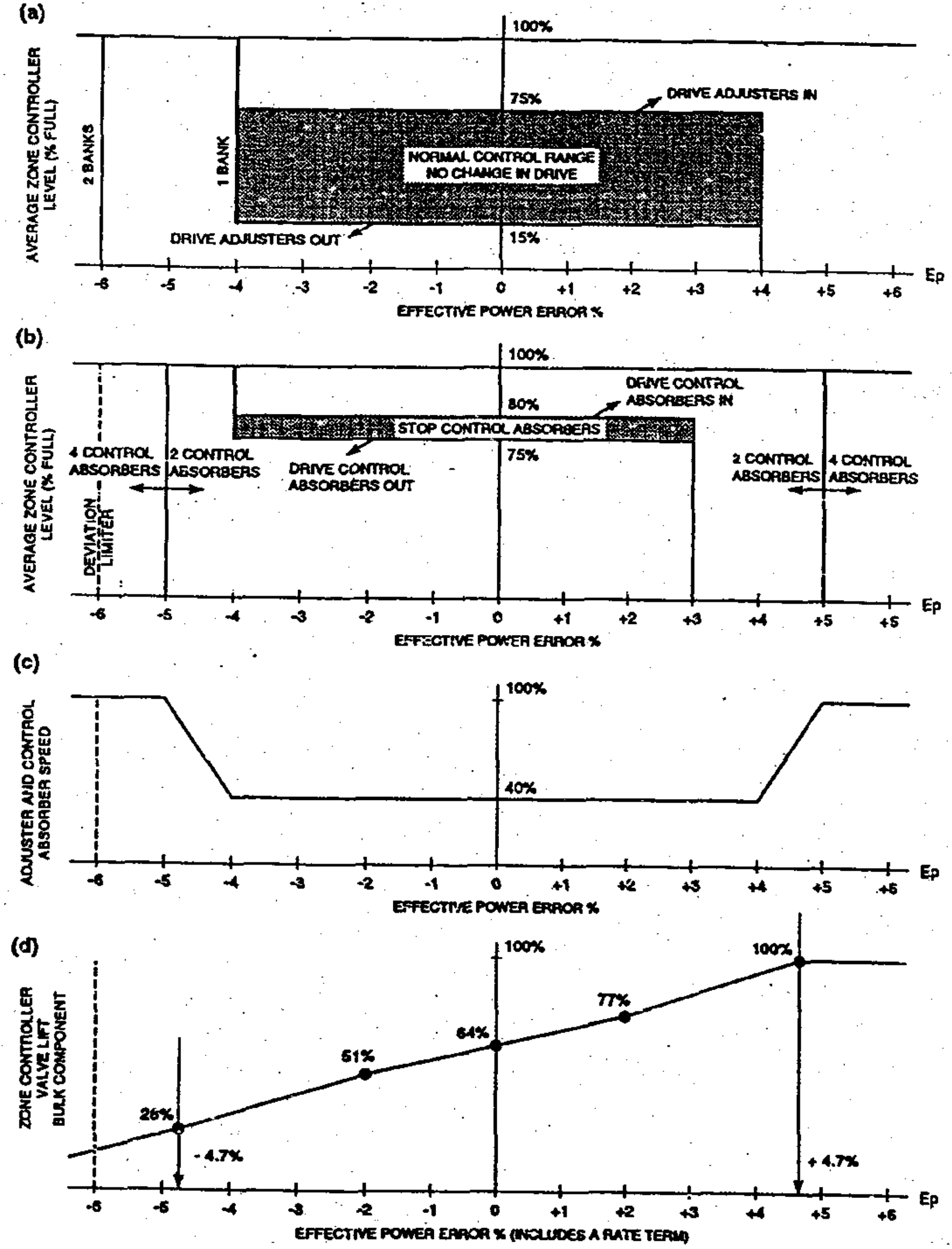

Figure 3.9. Reactivity Limit Control Logic Diagram.

Setback Routine

The setback routine monitors a number of plant parameters and reduces reactor power promptly in a ramp fashion if any parameter exceeds specified operating limits. The rate at which reactor power is reduced and the power level at which the setback ends will be appropriate for each parameter. Typical conditions leading to setbacks are listed in Table 3.2.

The setback overrides other reactor power demands and is accompanied by alarm window annunciation.

Table 3.2 Typical Setback System Conditions

Conditions	Setback Rate (percent per second)	End Point (percent of Full Power)
Zone Control System Failure	0.2	60
Spatial Control Off Normal	0.1	-
Zone power > 1 10 percent at full power	-	60
Flux tilt >20 percent above 60 percent full power	-	20
Flux tilt >40 percent between 20 percent and 40 percent full power	-	20
High Local Neutron Flux	0.1	60
High Steam Generator Pressure	0.5	10
Low Deaerator Level	0.8	2
High Moderator Level	0.8	2
Turbine Trip or Loss of Line	0.8	60
Endshield Flow	0.8	2
Endshield Temperature	0.8	2
Sustained Low Condenser Hot Well Level	0.8	2
Manual	0.5	2

Stepback Routine

The stepback routine also reduces reactor power, but instead of reducing reactor power gradually like the setback routine, it drops the mechanical control absorbers either fully or partly into the reactor, causing a sudden power reduction. Typical plant upsets causing stepbacks are summarized in Table 3.3.

Table 3.3 Typical Stepback System Conditions

Conditions	Control Absorber Response
Reactor Trip 2/3 contacts on SDS1 or SDS2	Full rod drop
All Heat Transport Pumps Trip	Full rod drop
Single pump trip	Full rod drop
Trip of two pumps at same end of reactor	Full rod drop
Heat Transport High Reactor Outlet Header pressure and reactor power > 1 percent full power	Full rod drop
High Zone Power	Full rod drop
High Rate of Log Neutron Power	Full rod drop
Low Moderator Level	Full rod drop
Low Steam Generator Level	Full rod drop

Control Logic for the Reactivity Mechanisms

This logic functions as an interface with the power circuits of the motor control centers and the clutch coils of the mechanical shutdown units and mechanical control absorber units. This logic incorporates interlocks to limit the consequences of a gross loss of regulation.

Adjuster Control Logic

A block diagram of the system is shown in Figure 3.10. It incorporates 'in' drive logic, 'out' drive logic, element position indication, end stop logic, manual controls and interlocks.

The logic allows the operator to select either the automatic or the manual mode of adjuster control. The logic stops the drive motor when the element is fully in or fully out (end stop), as determined by the signal from one of the two potentiometers on the mechanism. The logic inhibits the 'out' drive if either or both of the shutdown systems are not poised and overrides any attempt made to withdraw, simultaneously, more than a specified number of adjusters from the core. This limits the potential rate of reactivity addition; however, this rate interlock and the end stops can be bypassed, if the 'emergency manual' mode is selected by the operator.

The logic provides the operator with information on the status of the system and generates alarm signals if faults occur (e.g., motor trouble, too many adjusters driving out).

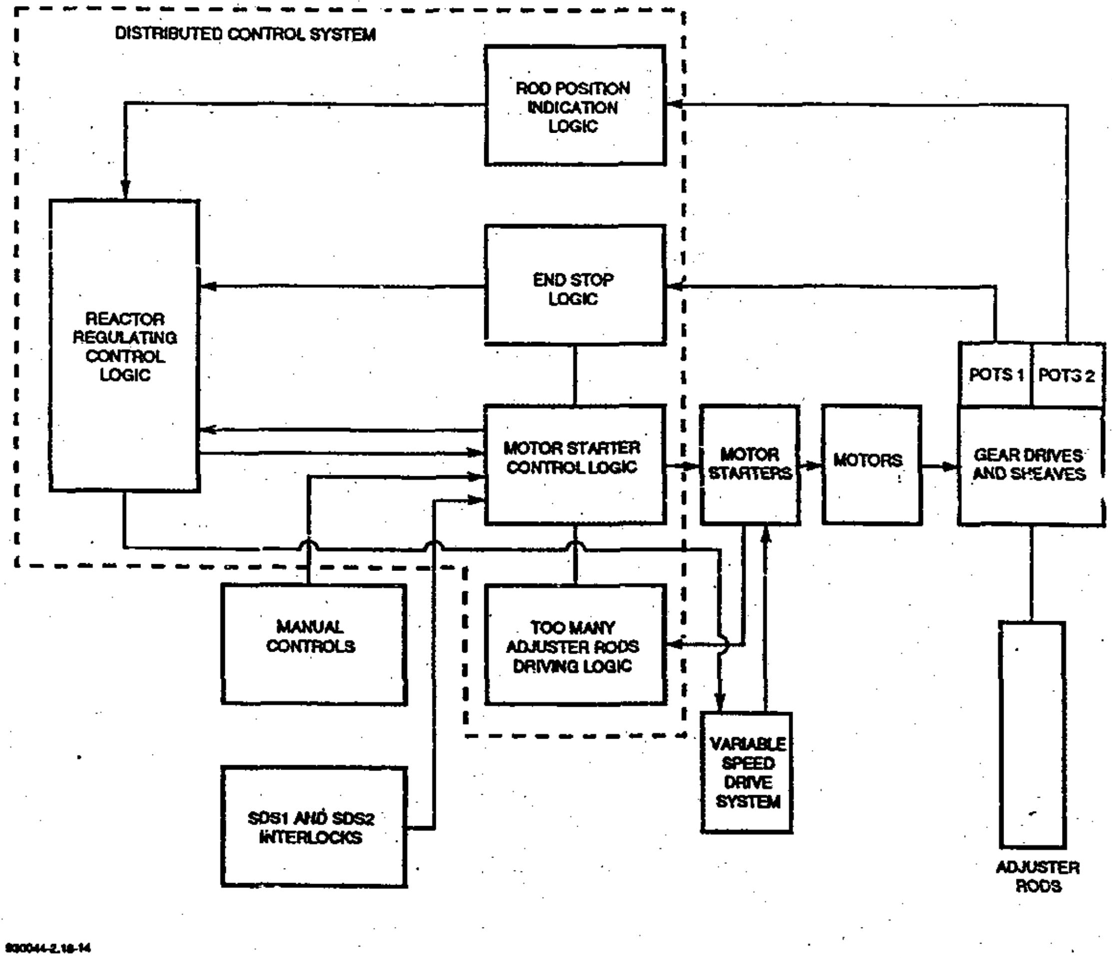

Figure 3.10. Block Diagram of the Adjuster Control System.

Mechanical Control Absorber Control Logic

This logic is similar to that of the adjusters, but includes power supplies and control circuits for the clutches. The clutches allow the mechanical control absorber elements to be dropped into the core to achieve a fast power reduction (stepback).

The mechanical control absorber logic allows the operator to select either the automatic or the manual mode of mechanical control absorber drive.

The logic stops the drive motor when the element is fully in or fully out, as determined by the signal from the potentiometer on the mechanisms. The drive motor is inhibited if either or both of the shutdown systems are not poised. The logic over-rides any 'out' drive command if the 'in' drive is requested. The status of the system is displayed and alarm signals are generated if faults occur.

The clutch control circuit drops the mechanical control absorber elements when a stepback is demanded. The clutches can be re-energized during the drop to terminate the stepback at an intermediate power level.

Two clutch power supplies, fed from different buses, are provided to ensure that failure of one supply does not initiate a stepback. The units are set at different voltages, 90 and 93 V direct current. They provide supply power through diodes, so that the 90 V unit is on "hot" standby.

The instrumentation permits the operator to perform a partial drop test on the rods. The duration of the test is controlled by an adjustable time delay. Software test circuits are also provided.

Shutdown Rod Withdrawal Logic

Dropping of the shutdown rods is controlled by shutdown system number 1. However, withdrawal of the rods is controlled by the regulating system. Withdrawal is inhibited until the shutdown signal is cleared. The design of this logic is similar to that for the adjuster and mechanical control absorber rods, except that constant speed drive is used. The logic counts the number of shutdown rods withdrawn to determine when shutdown system number 1 is poised.

For withdrawal, the shutdown rods are arranged in two banks. For normal withdrawal, controlled by the reactor regulating system, both banks are withdrawn simultaneously, with withdrawal being stopped if the power error or the rate log power change exceeds a specified limit. Manual withdrawal is by separate banks and is allowed only if computer control is unavailable. The operator may also select individual rods to be driven in or out under manual control. Analog rod position signals are provided from potentiometers on the mechanisms for all shutdown rods to the distributed control system.

Speed Control System for the Reactivity Mechanisms

Variable speed control is provided to drive the adjuster and mechanical control absorber elements into or out of the core. Each mechanism has a reliable, three-phase induction motor whose speed is controlled by varying the frequency of the input power. This is done by means of a variable frequency inverter which functions as a voltage-controlled oscillator over the range from 12 to 60 Hz. It is powered from redundant, three-phase, Class III buses. If bus C fails, the system can be switched to bus A. Operation without variable speed control is satisfactory for the time necessary to repair or replace the inverter. A manually controlled contacter bypasses the variable frequency inverter and supplies all induction motors with line frequency power.

Dedicated reversing motor starters control the elements individually. Speed, normally on automatic control, can be manually set from the main control room. A manual speed setting will also apply to the automatic control of adjusters and mechanical control absorbers. The main control panel also annunciates major failures of the system.

Hardware Interlocks

The automatic control of the reactivity mechanisms are subject to a number of interlocks to limit the consequences of a gross loss of regulation.

To prevent the reactor from being started up with the safety systems unavailable, the adjusters and mechanical control absorbers are inhibited from being withdrawn unless both shutdown systems are poised.

The adjusters are further interlocked to prevent more than a certain number of rods from being withdrawn at the same time. This limits the maximum rate of addition of positive reactivity. Another interlock is provided which prevents the reactor from coming critical on shutdown rod withdrawal. It prevents the shutdown rods from being withdrawn unless the mechanical control absorbers are in the core.