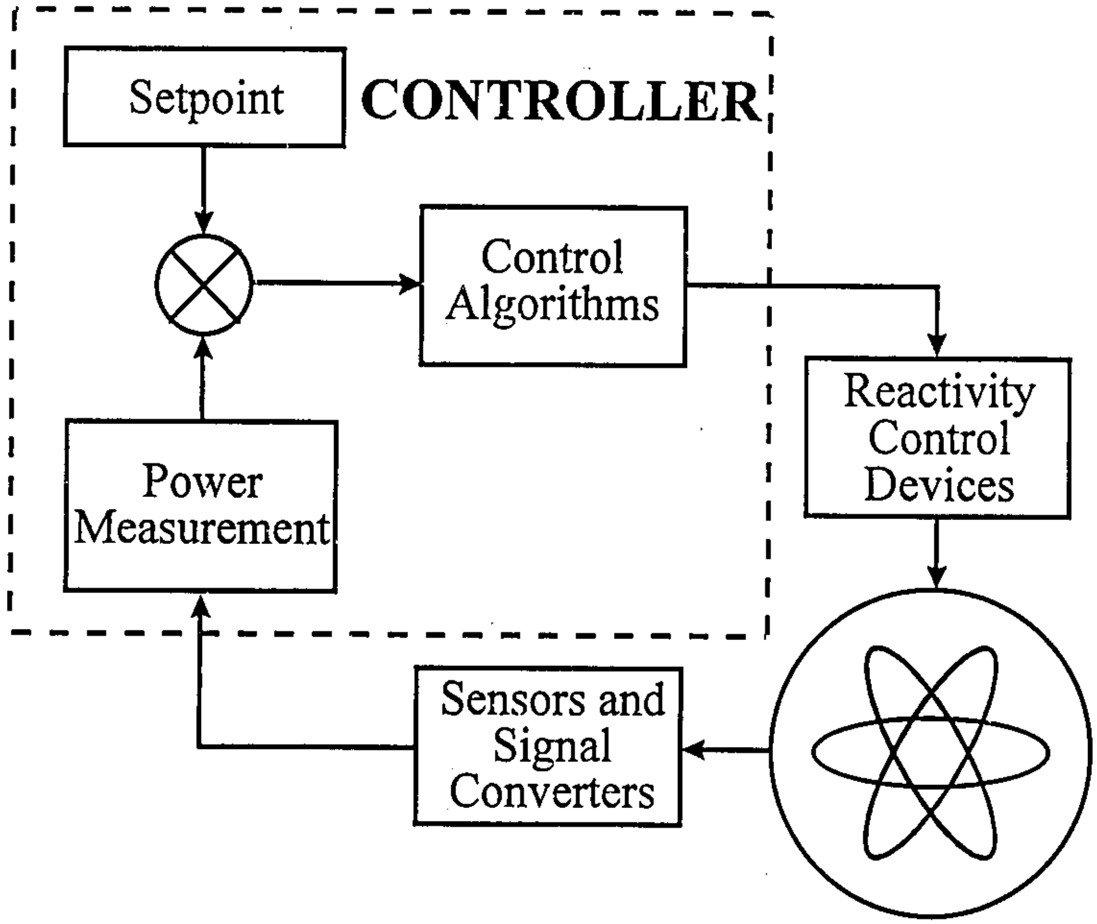
1.0 INTRODUCTION



Controlling a nuclear reactor poses the following main problems:

- how to measure neutron flux over the complete range of reactor operations
  - initial start-up
  - low power operation
  - at-power operation
  - preventing fuel damage
  - spatial distribution of flux
- how to measure the thermal power produced by the reactor
- how to ensure that reactor is at the required level of criticality
  - guaranteed shutdown case
  - approach to critical
  - maintaining criticality
  - small degrees of sub- or super-criticality
  - must avoid going prompt-critical
- reactor control is by altering the number of neutrons available for fission from one generation to the next
  - principal means is by changing the amount of neutron absorbers in the core
  - also possible to add neutron source, more fissile material, change leakage rate, resonance capture
- controller design must ensure safe, reliable & economic reactor operation within the above constraints

1.1 REACTOR CONTROL: LICENSE REQUIREMENTS

Legal obligations of the license are as follows:

- must be able to regulate bulk power at all power levels, otherwise must place the reactor into the Guaranteed Shutdown State (GSS)
- must be able to regulate the spatial distribution of power in the reactor when at high power (above 20%FP)
- there must be reactor shutdown systems that are independent of the reactor control systems, and the shutdown systems must be fully available, (i.e. "poised"), otherwise must go to the GSS
- must be able to monitor the neutron flux whenever there is fuel in the reactor

1.2 REACTOR POWER - TERMINOLOGY

- Neutron Power is proportional to fission rate, it excludes decay heat (& conventional heating)
- Reactor Thermal Power is the useful heat, i.e. the heat transferred from the reactor to the boilers to generate steam and via the turbine-generator produce electricity; it includes pump (friction) heat
- Fission Power is the total heat from all nuclear processes in the fuel, including waste heat; it excludes pump heat, or other conventional heat

2.0 REACTOR POWER MEASUREMENT

Nuclear Measuring Devices including ion chambers (IC) and self-powered in-core detectors (ICD) give primary measurements of neutron flux i.e. neutron power:

- they have fast response, but neither gives an accurate and prompt response
- they are sensitive over the whole power range, ICDs above 5%, ICs from 10^{-7} to 150% FP
- ICs are outside the core so they cannot measure neutron power and its distribution accurately
- ICDs are distributed within the core to allow spatial control, but their prompt response is inaccurate.

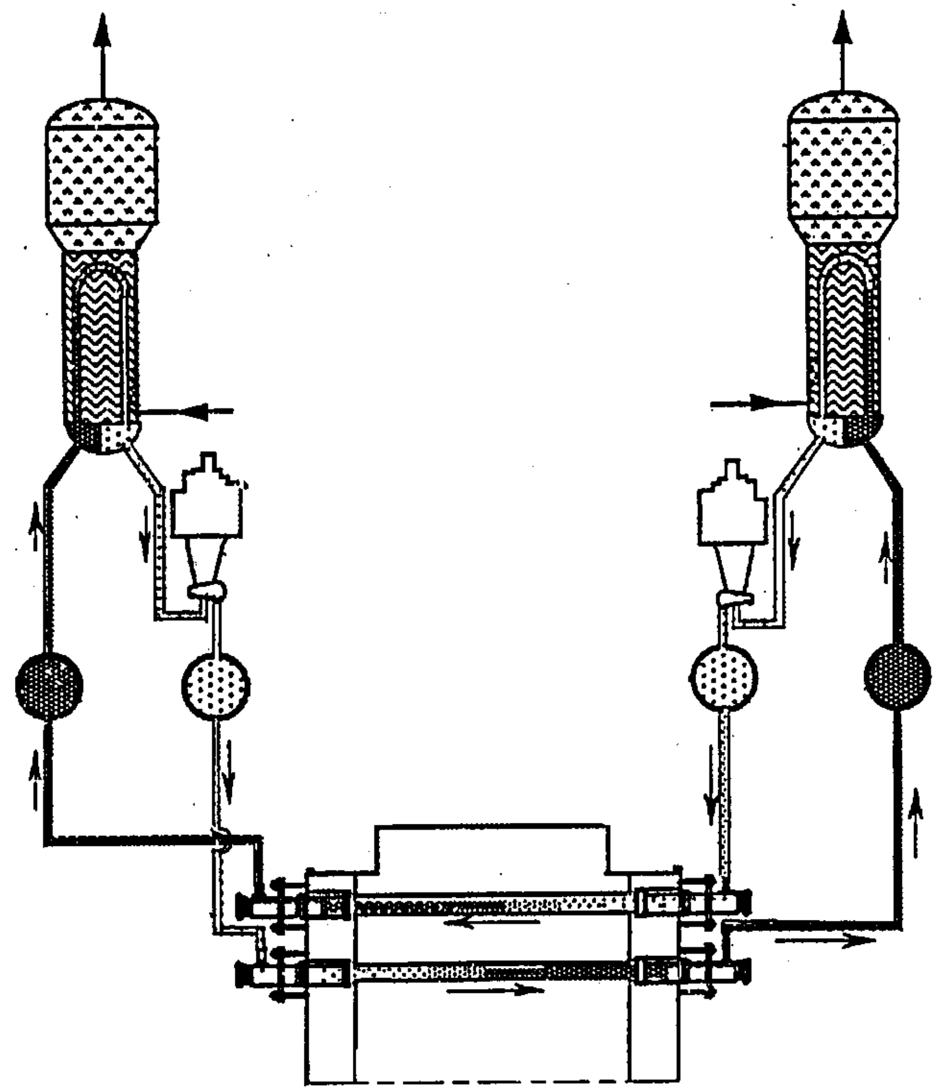
2.1 THERMAL POWER

Thermal and Neutron Power are Not Proportional: When positive reactivity is added to the core and thermal power increases:

- Neutron Power (fission) increases immediately and hence heat from fission (93% of the total) increases immediately
- Decay Heat (6%) increases gradually, since it must wait for the buildup of more fission products
- Heat input from the pumps and ambient losses stay the same (net about 1%)
- Cannot not use thermal measurements of the reactor coolant directly for reactor control because:
  - the rate of response is too slow
  - have inadequate range: at high power, temperature stops increasing as boiling sets in;
  - at low power, temperature measurements don't respond to change in fission rate because of heat from radioactive decay.
  - its difficult to measure spatial distribution of power, especially where needed (at high power); at best, channel by channel measurements give only the radial power distribution

2.2 THERMAL POWER CALIBRATION

- Accurate Thermal Power Measurements are used to calibrate fast nuclear instruments in the high power (normal operating) range.
- On very slow power changes, thermal power lags neutron power only a little, so calibration factors are nearly up to date (i.e. accurate).
- On faster transients the response of the regulating system is correct initially, and although a small error develops during the transient, the calibration catches up, allowing accurate regulation in the longer term as actual power is adjusted to match the demanded level.
- Flow and temperature measurements across the reactor give a good measure of thermal power, provided no boiling takes place
- Measurement of the power transferred to the secondary side needs to be used if boiling is taking place in the reactor; feedwater and steam flow, and steam pressure are used to calculate thermal power



3.0 REACTIVITY CONTROL DEVICES - performance requirements

- an integrated system of different types of devices, and several individual pieces of each type of reactivity control device are required, so as to be able to control the reactor under all posible conditions
- rectivity adjustments at constant power, to compensate for fuel burn-up and other slow parameter changes, and to shape the flux in different regions of the reactor
- fast shutdown (reactor trip or scram) if the power level goes too high or changes to fast, also in case of other plant parameters going outside the safe operating envelope
- rods are designated for either regulation/control or for shutdown; their size, absorbing material and mechanical drives are often different
- must limit the maximum rate of positive reactivity insertion, by controlling the speed of rod drives and the number and reactivity worth of individual devices
- the control system design must take account of the reactivity feedback effects inherent to the particular type of reactor

3.1 REACTIVITY CONTROL DEVICES - hardware implementation

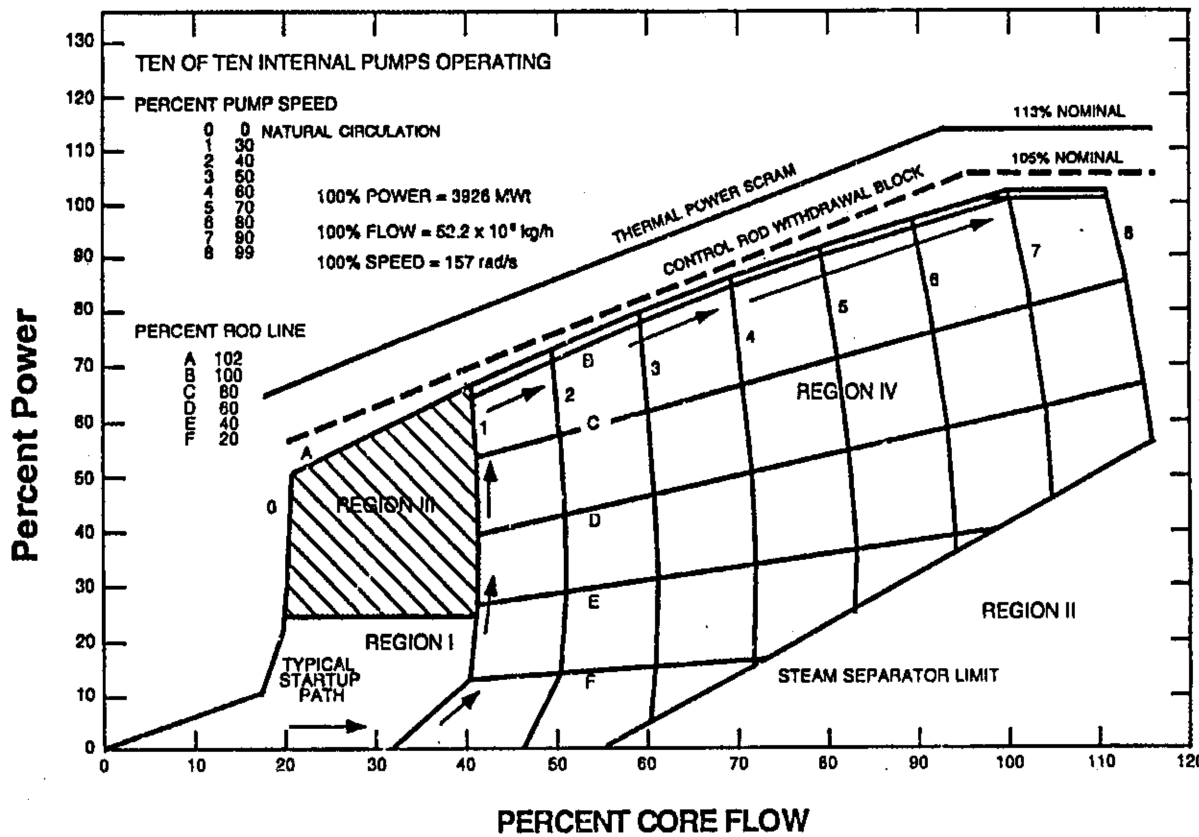
- solid neutron absorbers, in the form of rods inserted into the core and attached to mechanisms that move the rods in and out of the reactor at specified speeds; the rods are designed in a variety of shapes depending on the type of reactor and fuel configuration used; they may be moved individually or in groups; rods are the mot common means of short term reactivity control
- liquid neutron absorbers are typically in the form of a strong neutron absorber dissolved in the moderator/coolant; boric acid and gadolinium nitrate are two commonly used materials: boron is mostly used for intermediate and long term reactivity control, particularly to compensate for excess reactivity of fresh fuel, while Gadolinum is most suitable following shutdowns to compensate for the lack of Xenon - as the reactor is restarted, gadolium burn-up occurs at a rate similar to Xenon build-up; the liquid neutron absorbers are also used as a back-up to the rods, particularly for long shutdowns
- burnable poison in some designs is included with the fuel assembly in solid form, and is designed to be burned up at a rate comparable to fuel
- in some reactor systems it is also possible to change the size of the reflector, thereby changing neutron leakage and hence reactivity

4.0 PWR CONTROL

- automatic power level control is usually done by moving the control rods, some of which are partially inserted into the core, so any movement produces an immediate change in reactivity
- the liquid poison used for control ("reactivity shim") is boron dissolved in the reactor coolant system, and is usually under manual control, inlcuding its use as a longterm reactor shutdown system
- born can be added to the system quite rapidly, but removal has to be either by dilution or chemical means

5.0 BWR CONTROL

- Since a void has a neutron moderation capability considerably less than water coolant, the more voids in a core, the less fission reactions will be sustaining.
- For a boiling water reactor, core power is set by means of a pattern of control rod insertions and then controlled via the void content in the core by changing the coolant flow rate. Burnable poison (boron and gadolinum dissolved in the coolant) is used to compensate the excess reactivity. Burnable solid poison placed amongs the fuel clusters is used for shaping the axial and radial flux.
- A BWR must be operated within a designated flux-to-flow map. Above the upper boundary, further rod withdrawal will be prohibited. At a higher limit the reactor will be tripped by the high flux signal of the protection system. If all recirculation pumps are tripped, the reactor power level will drop to a fraction (about 40% of full power) while the core flow will be sustained by natural circulation.



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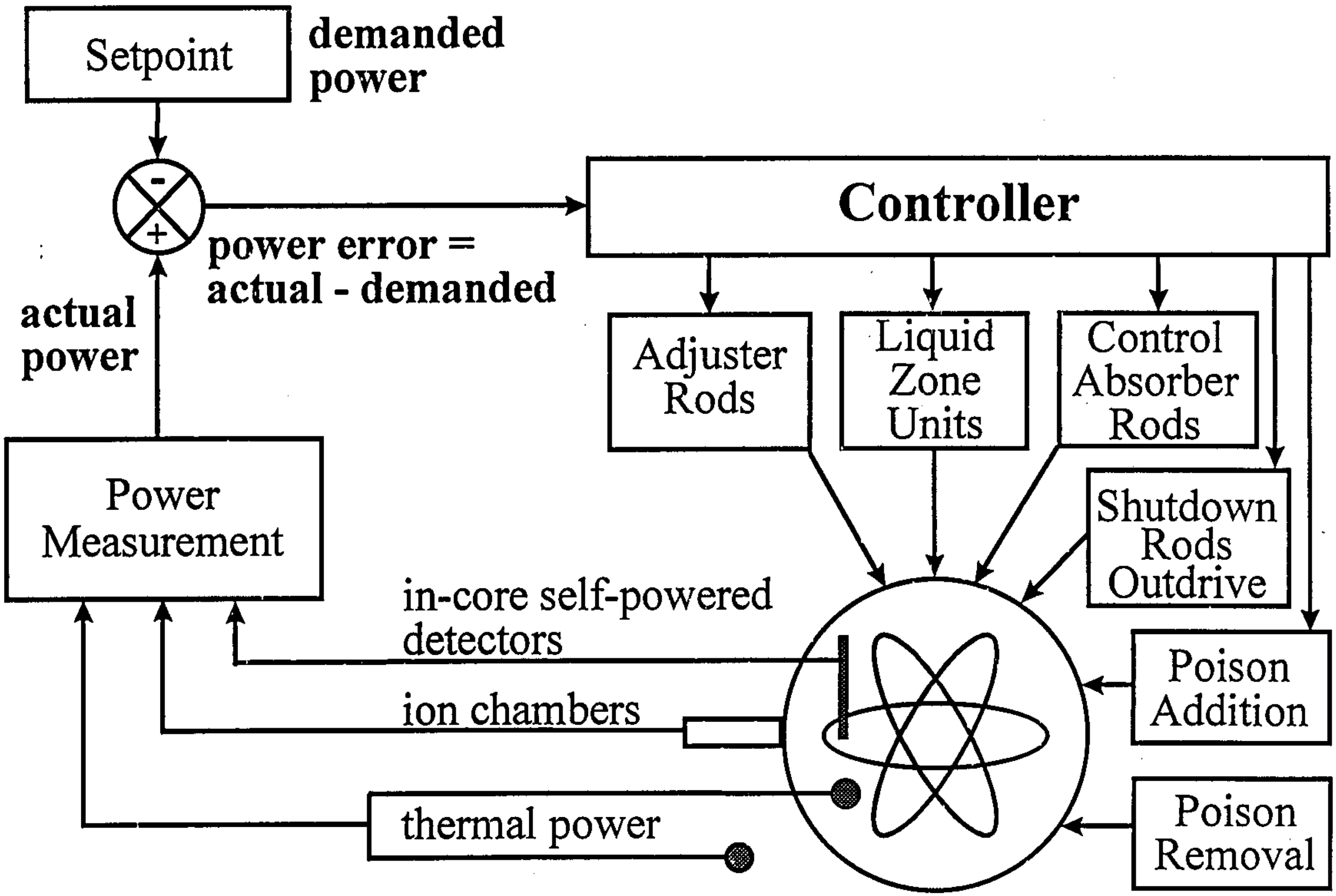
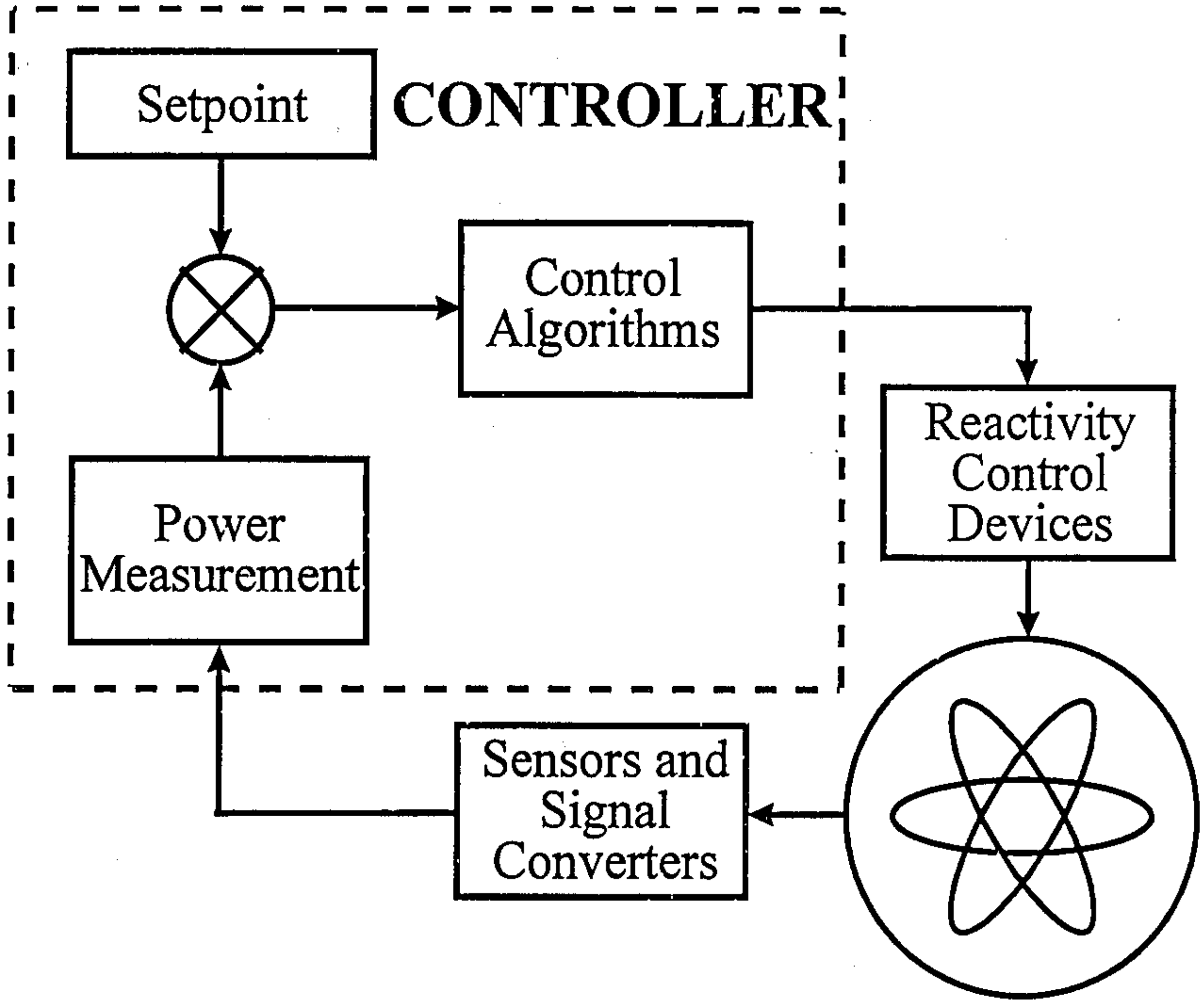
6.0 CANDU CONTROL



1.0 INTRODUCTION

- neutron flux measurement is needed over the complete range of reactor operations
  - initial start-up
  - low power operation
  - at-power operation
  - spatial distribution of flux
  - protection
    - high power level in fuel
    - high rate of change of flux
- thermal power produced by the reactor and individual fuel elements has to be known
  - how to measure total thermal power produced in the reactor
  - how to measure power produced in a given region of the core

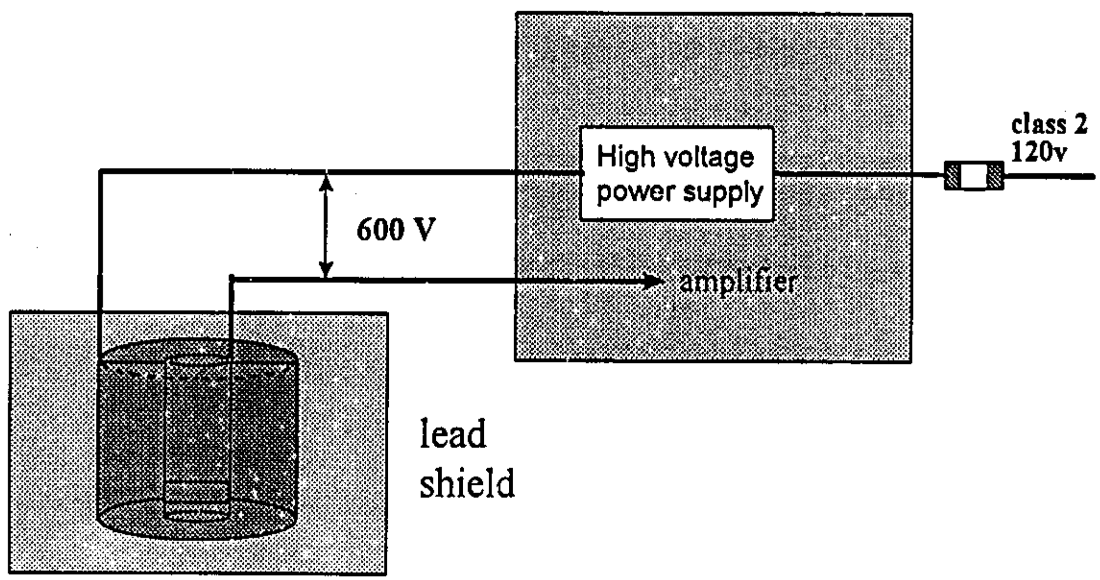


2.0 PRINCIPLES OF ION CHAMBER (IC) OPERATION

- Ion chambers used to measure the neutron flux in a reactor work on the principle that a thermal neutron reacting with Boron-10 results in the emission of an alpha particle:

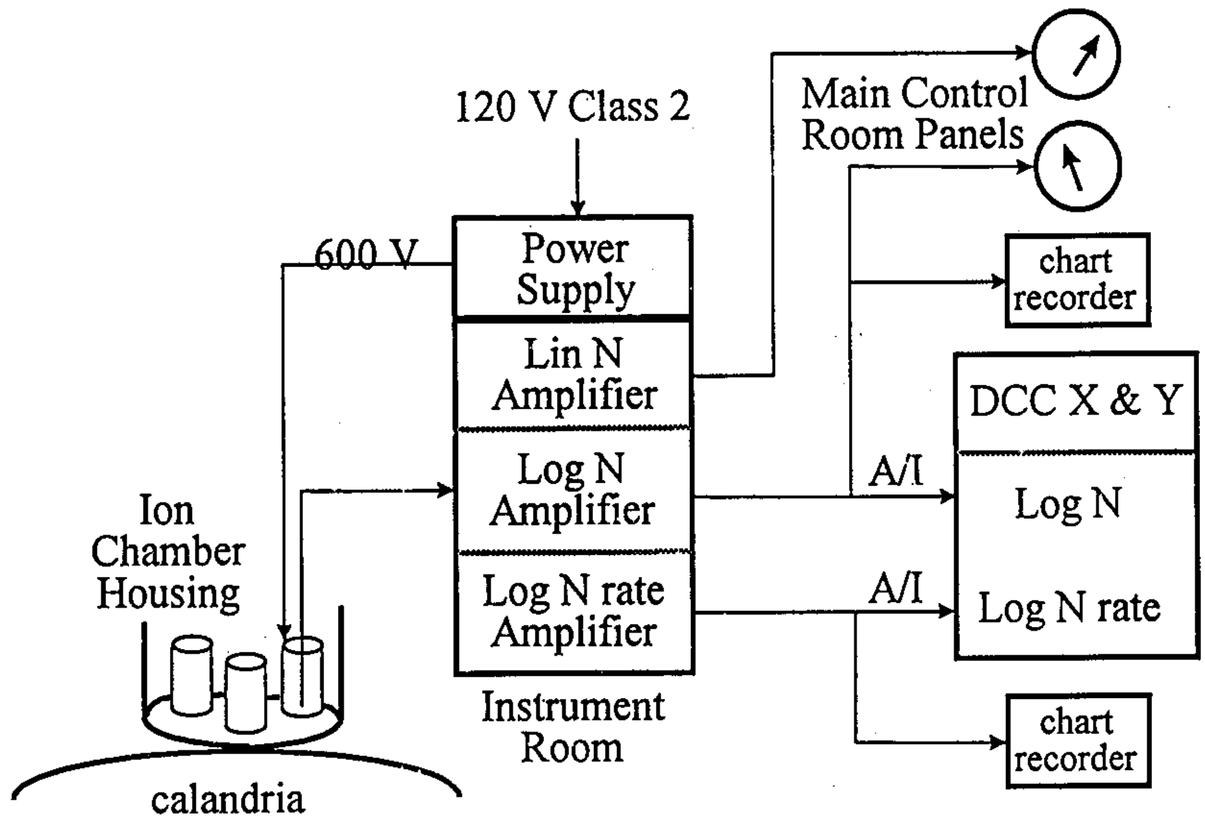
  $${}_5B^{10} + {}_0n^1 \rightarrow {}_3Li^7 + {}_2He^4(\alpha)$$

  - the emitted α particle ionizes the gas inside the ion chamber
  - applying a polarizing voltage between the anode and cathode will result in a current flow
  - the current flow is directly proportional to the neutron flux reaching the ion chamber
  - note that because the ion chambers are mounted outside the reactor they measure the leakage flux
  - lead housing around the ion chamber shields it from γ radiation
  - failure of the power supply will cause an alarm in the control room
- There are typically three ion chambers for measuring the neutron flux for the purpose of reactor control.
- Additional ion chambers are used for reactor protection.



2.1 REGULATING SYSTEM ION CHAMBERS (CANDU)

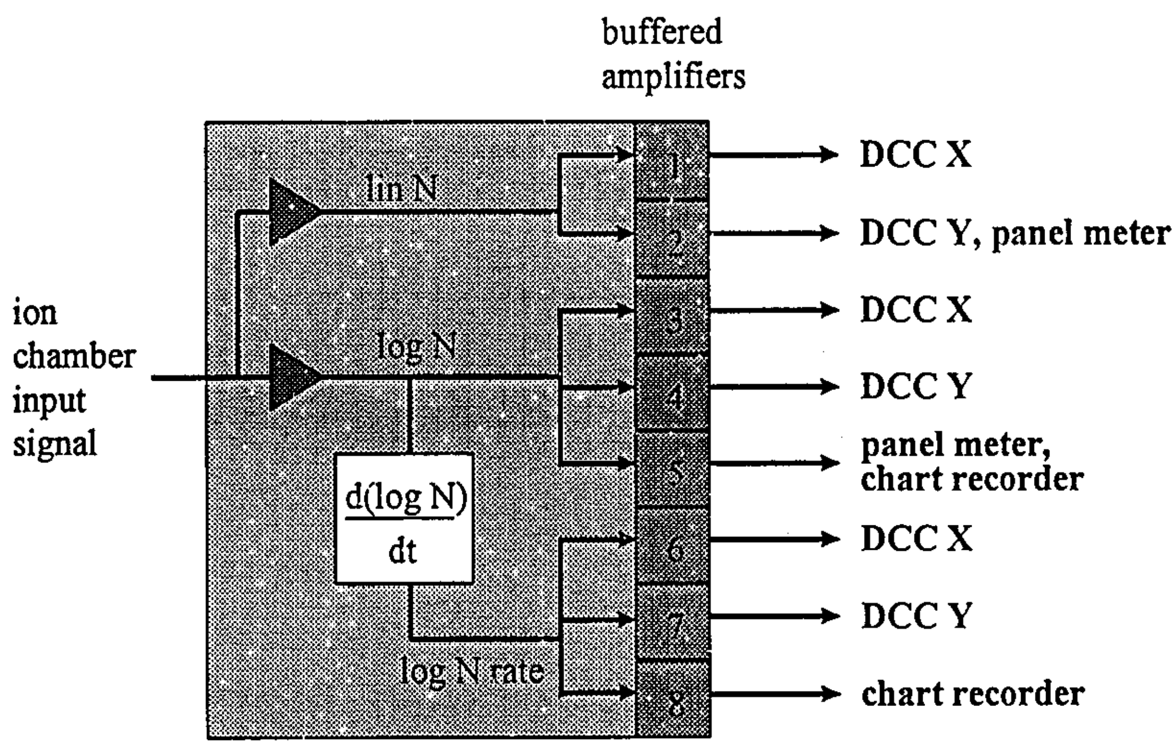
- there are three vertically mounted ion chamber assemblies each in a separate housing on top of the calandria
- each housing contains a regulating system ion chamber and an SDS#1 ion chamber
- each signal is fed to an amplifier, and the amplifier outputs of Lin N, Log N, and Log N rate are connected to the DCCs and the Main Control Room Panels (MCRPs)
- the Log N signal is used by the Reactor Regulating System (RRS) to control power below 15%FP (in RRS this signal is represented as the label P_{IULog})
- the Log N rate signal is used in RRS to ????? [in RRS this signal is represented as the label R_I]



2.2 ION CHAMBER AMPLIFIER (CANDU)

- Three types of measurements are derived from the ion chamber signal:

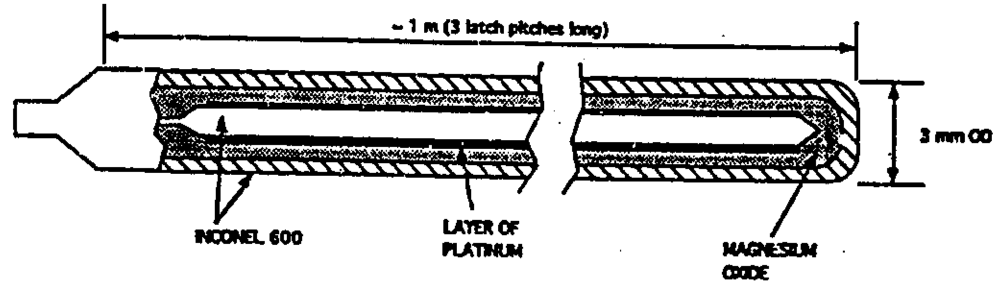
Lin N	0 to 150 %FP
Log N	-7 to 0 decades
Log N rate	-15 to +15 %/sec



- the signals go to the control computers and to the control room panels
- because the ion chamber signal is not an accurate measure of the absolute value of the flux inside the reactor, the Lin N signal cannot be used for the direct control of reactor power
- at low power levels the inaccuracy is relatively smaller and less significant, hence Log N can be used directly for control of reactor power
- the Log N signal is not affected by the inaccuracies in the absolute value of the ion chamber signal, since it is only concerned with the rate of change of the signal
- there are typically three such amplifiers, one for processing each of the three ion chamber output signals.

3.0 IN-CORE (SELF-POWERED) DETECTORS (ICDs)

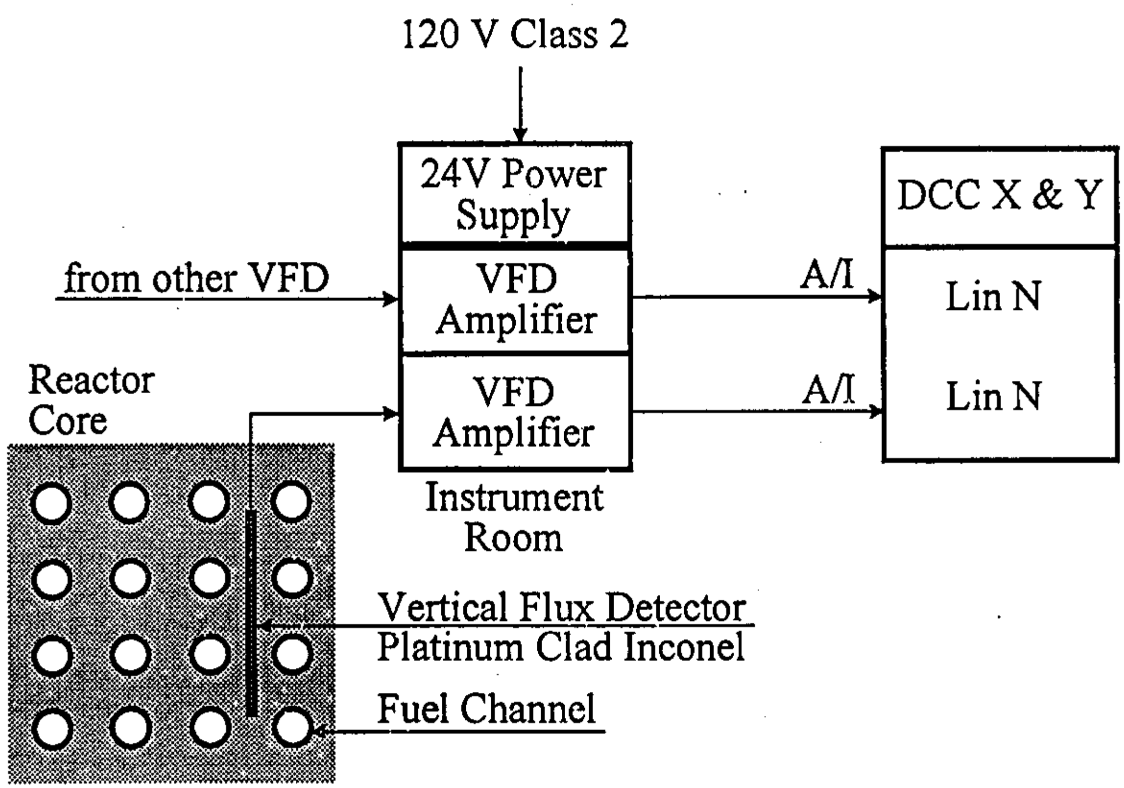
- An emitter electrode is surrounded by insulating material that separates it from a grounded conducting sheath (the collector).
- Radiation (neutrons & γ) interact with the emitter and eject electrons that travel across the insulator to the collector, creating a voltage difference
- Electrons "leak" from the ground back to the emitter via connecting wires and amplifier; amplified signal is proportional to radiation
- The Inconel type in-core detectors respond to:
  - neutrons from fission (prompt)
  - γ rays from fission (prompt)
  - γ rays from fission product decay (delayed)



- prompt radiation is $\propto$ to neutron power;
  delayed radiation is $\propto$ to decay heat; but:
- the instruments do not have a balanced response to n and γ
- typical instruments under-respond to n and over-respond to γ: not enough prompt response, too much delayed response, but they do give an immediate response, and are used from 5%FP to 120%FP
- they don't directly measure neutron power or thermal power, but give readings somewhere in between
- another type of in-core self-power detector uses Vanadium emitter that captures neutrons by
  V-51(n, γ)V-52 reaction, and the V-52 decays by (β^-, γ) with half-life of 3.76 minutes, with the energetic β^- (electrons) crossing to the collector
- these detectors are physically quite small and hence give very localized reading
- they are almost 100% neutron sensitive, but are too slow for direct control.

3.1 IN-CORE VERTICAL FLUX DETECTORS (CANDU)

- there are 28 in-core Vertical Flux Detectors (VFDs) using Platinum clad Inconel to measure the neutron flux in each of the 14 reactor zones
- there are two detectors in each zone
- two amplifiers are supplied from a given 120V Class 2 source, and each receives a signal from a VSD located in two different zones
- each amplifier outputs a Lin N signal that is connected as A/I to both DCCs
- the Lin N signal is used by the Reactor Regulating System (RRS) to control power above 5%FP (in RRS this signal is represented as the label P_{IU})



4.3 IN-CORE FLUX MAPPING DETECTORS

- there are ??? Vanadium detectors distributed throughout the core
- following amplification these local flux readings are connected as A/Is to both DCCs
- they provide a linear measure of the local flux that is used to compute a flux shape throughout the reactor
- the computed flux shapes are used to reduce reactor power if excessive local power peaks are detected

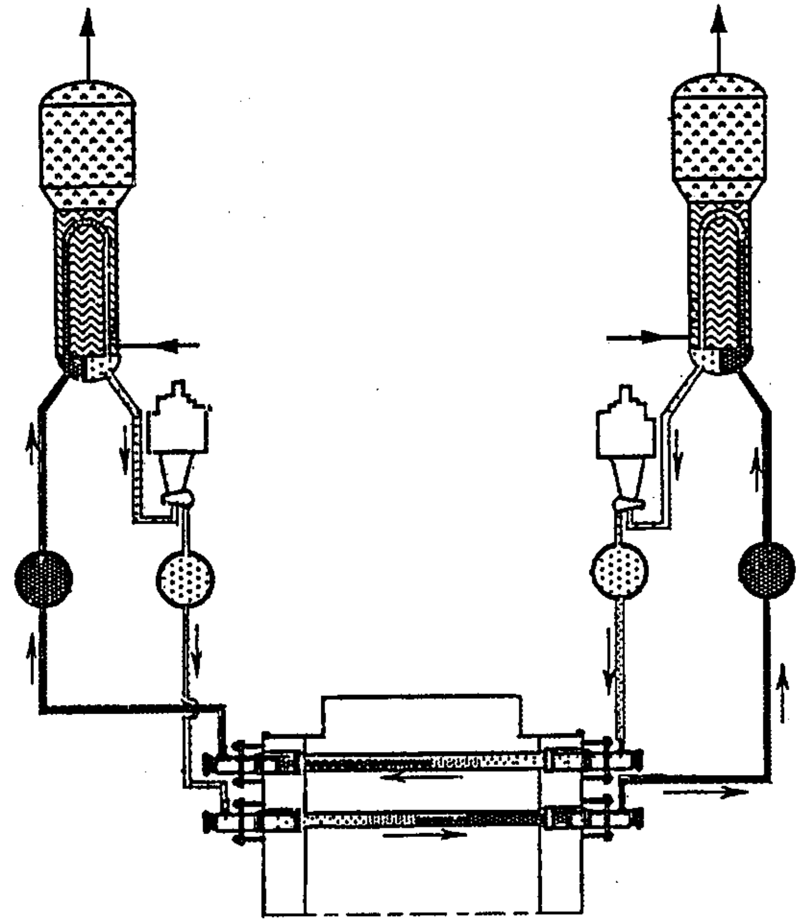
4.0 THERMAL POWER MEASUREMENT

4.1 Heat Output from the Reactor

- measure the coolant flow through the reactor and the temperature increase
- coolant flow can be accurately measured using venturies, orifice plates and similar devices
- an accurate temperature reading of the coolant can also be obtained, but only following a time delay: the sensors need time to respond to a temperature change, and due to transport lags, there is also a delay from the time the fuel temperature changed until this change appears in the coolant at the location of the sensor

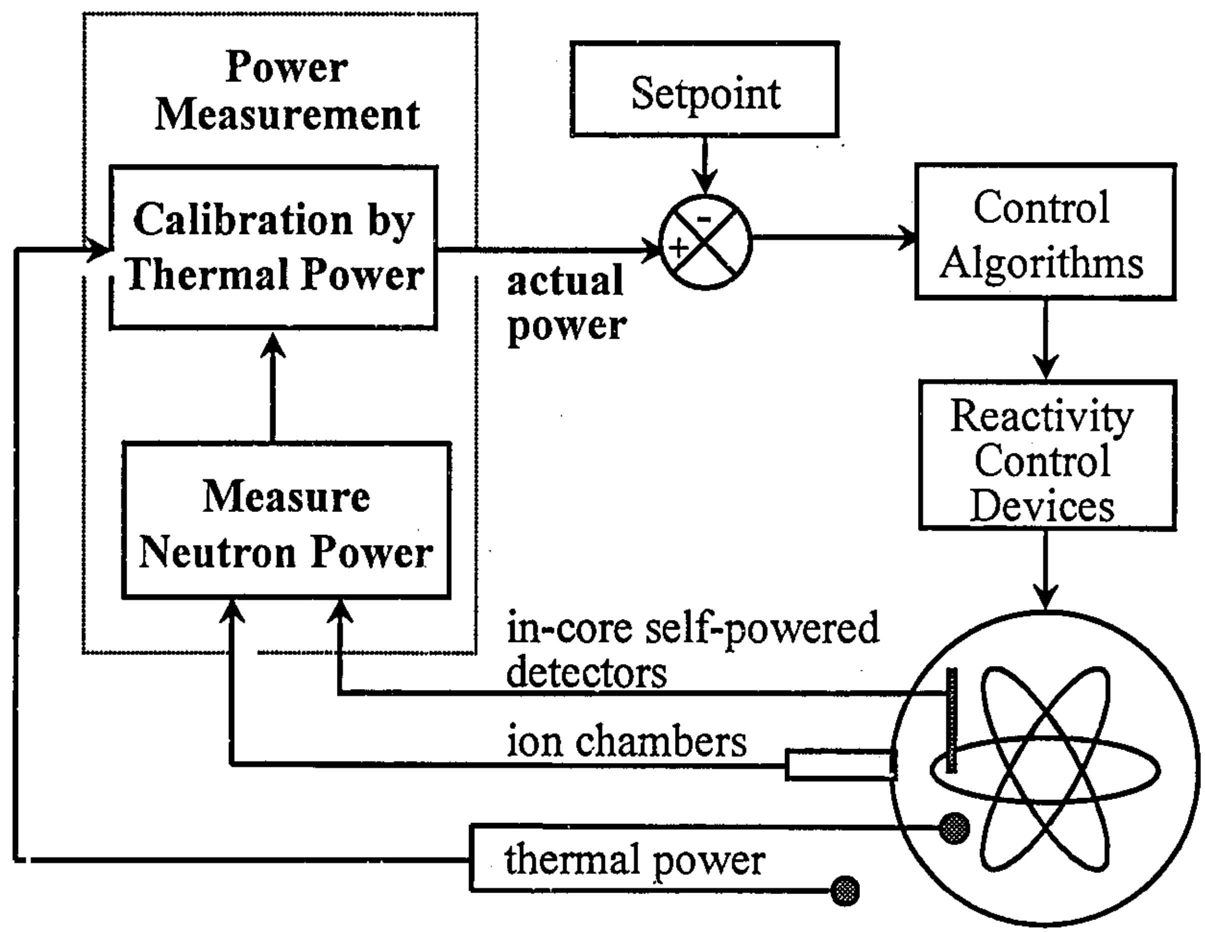
4.2 Heat Input to the Boilers

- measure steam flow & saturation pressure (\temperature), as well as feedwater flow and temperature
- this gives an accurate measure of heat transferred to the boilers at power levels > 50 %FP, but with an even longer time delay than in the case of the coolant temperature measurement



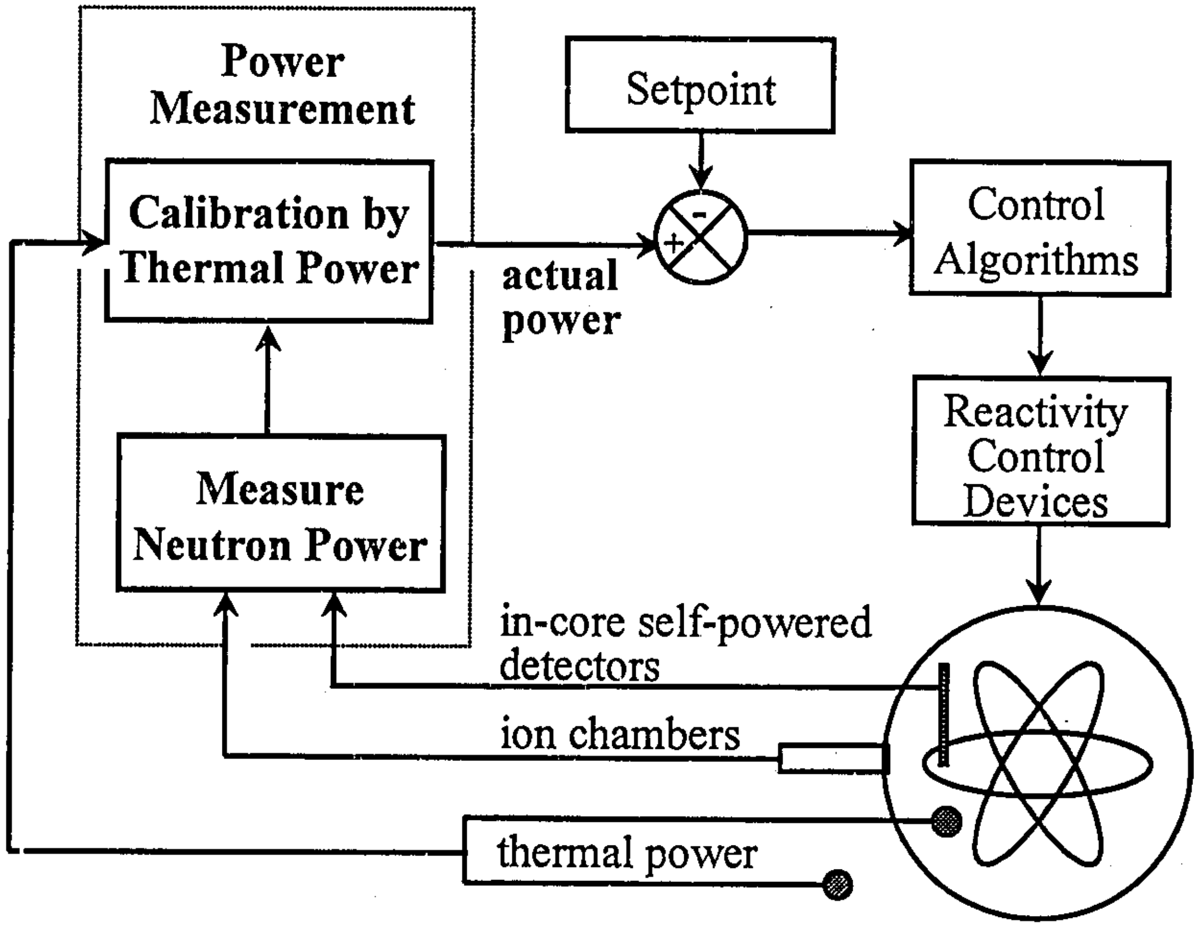
5.0 COMBINING THE FLUX AND THERMAL MEASUREMENTS

- an acceptably accurate reactor power measurement can be obtained by combining the prompt but not accurate in magnitude flux detector readings with the delayed but accurate in magnitude thermal power measurements
- recognizing that there will be a few seconds delay in obtaining thermal power measurements, the reactor should not be maneuvered at fast rates as 100%FP is approached



1.0 INTRODUCTION

- One of the many advantages of digital computer control is the ability of the software to perform a variety of calculations on the signals received from the sensors and converters, such as rationality checks, spread checks, selection of the most suitable signal under the particular circumstances, calibration, etc. This module describes how reactor power is measured based on the many signals input to the control computer that were described in Module 3B.
- The main problem to be overcome is the lack of a signal that gives the correct value of reactor power without excessive time delay.
- The Reactor Regulating System software uses the ion chamber and in-core detector signals of fission power (these are prompt but not correct in magnitude) and calibrates them with thermal power measurements (these are correct in magnitude but are delayed in time).
- For CANDUs, in addition to the total (bulk) power produced by the reactor, the spatial distribution of neutron flux and power generation must also be controlled



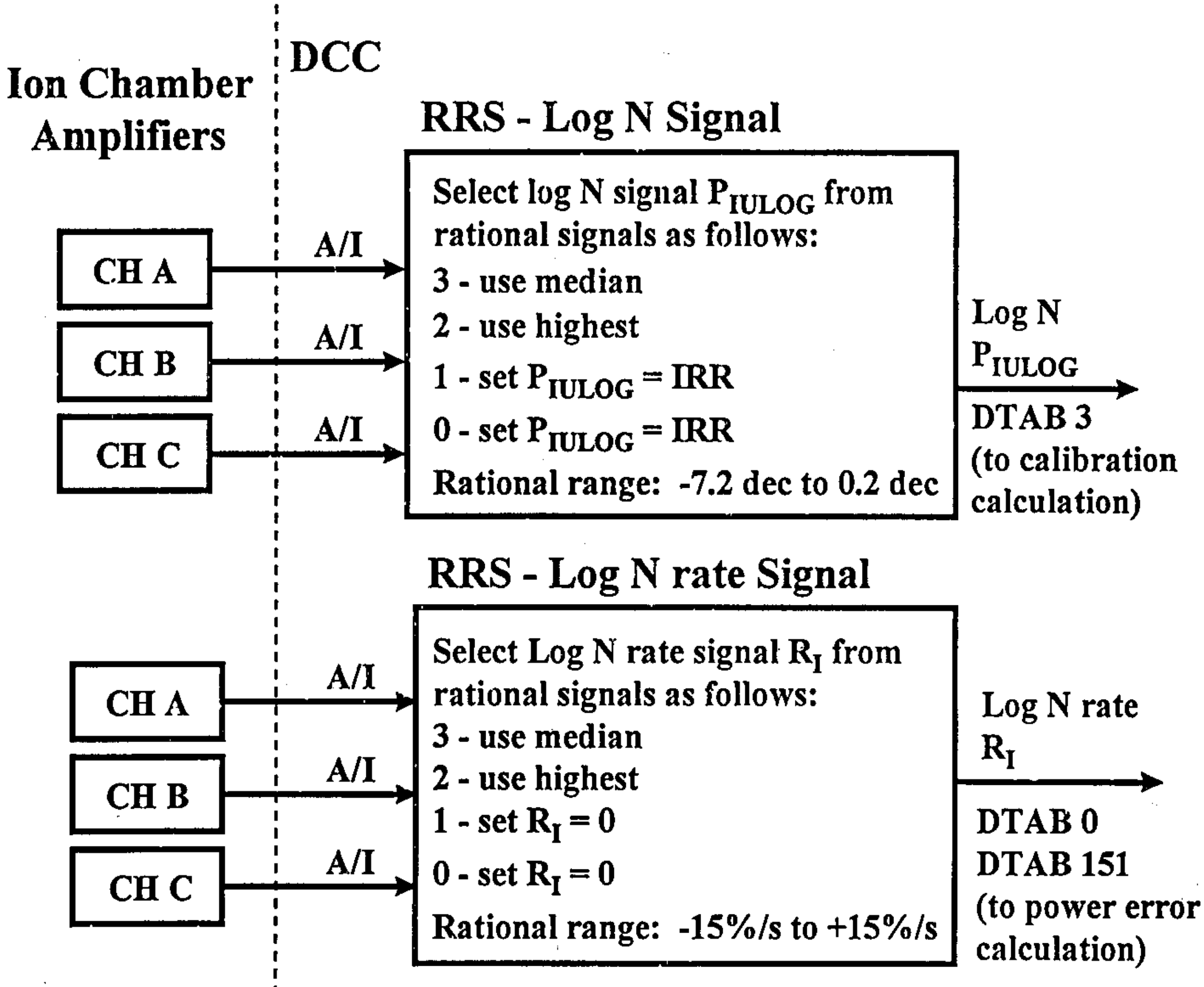
2.0 ION CHAMBER INPUTS

2.1 LOG N POWER

- rationality checks are made, any signals outside the range is made IRR and alarmed
- if all three signals are rational, the median is used for control purposes
- output is P_{IULOG}, which will be calibrated by the thermal signal to obtain the correct ion chamber power measurement P_{ICLOG}.

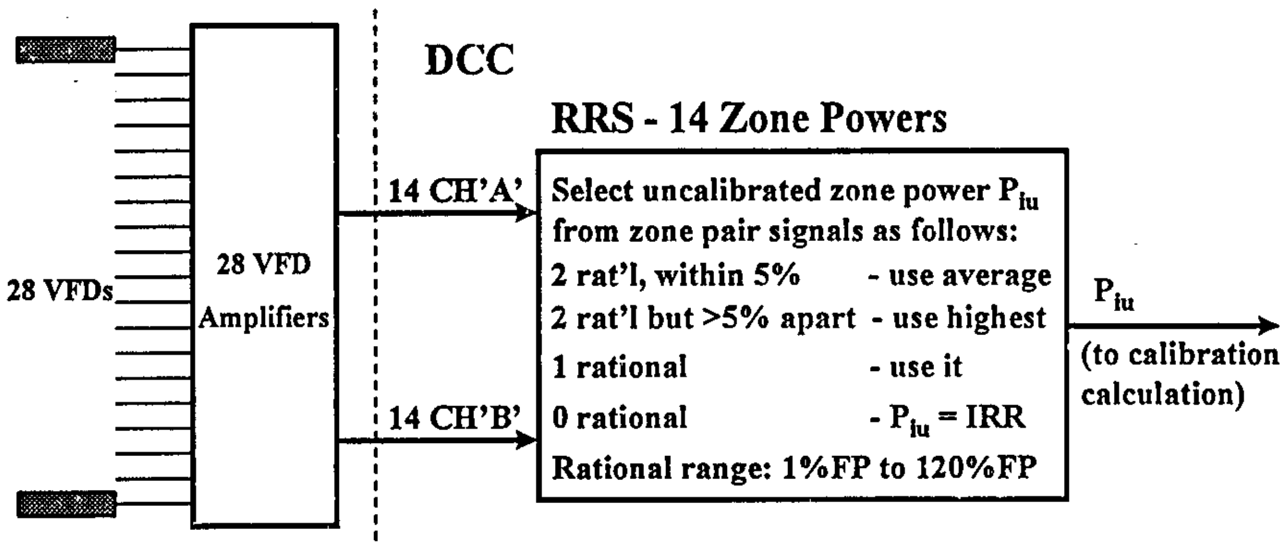
2.2 LOG N RATE

- rationality checks are made, any signals outside the range is made IRR and alarmed
- if all three signals are rational, the median is used for control purposes
- output is R_I, which is the actual Log N rate measurement. It is stored in RRS under the label DTAB 0 in units of decades/sec, and under DTAB 151 in units of %/sec.



3.0 IN-CORE VERTICAL FLUX DETECTOR (VFD) INPUTS

- there are 28 Platinum clad Inconel VFDs, two in each of the 14 zones, one set of 14 signals forming Channel ‘A’ and the second set of 14 signals form Channel ‘B’
- all 28 A/Is are input into both DCCs
- RRS checks all 28 signals for rationality, as long as thermal power > 5%FP (alarm any irrational signals)
- the zone flux measurement (P_{iu} i.e. the uncalibrated zone flux power, i = 1, 14) is determined from the two zone signals as follows:

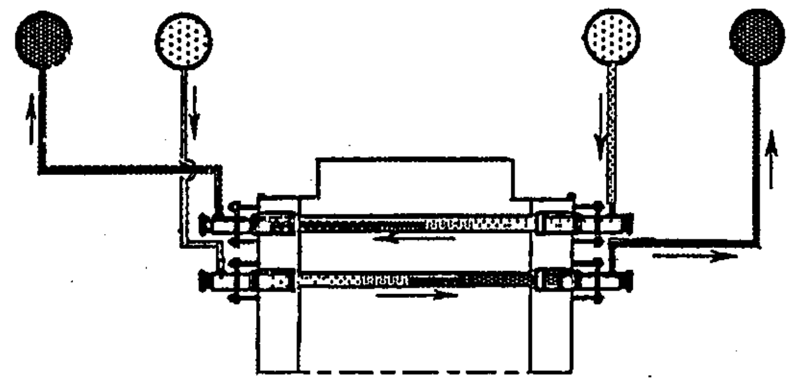


SIGNAL CONDITION	UNCALIBRATED ZONE FLUX POWER (P_{iu})
2 rational signals and within 5%FP of each other	use average (alarm if spread > 5%FP)
2 rational signals but spread > 5%FP	use highest
1 rational signal	use it
0 rational signal	set P_{iu} is IRR

- if three or more P_{iu} are irrational then RRS fails itself off

4.0 THERMAL POWER MEASUREMENT

- In CANDUs there are a wide variety of flow and temperature signals that provide indications of thermal power, but no combination of these can give a sufficiently prompt response for use in the direct control of reactor power. Instead, the various methods of determining reactor thermal power are used to correct or "calibrate" the readings of neutron power obtained from the ion chambers and in-core detectors. The following sensor inputs to the control computers are available to compute reactor thermal power:

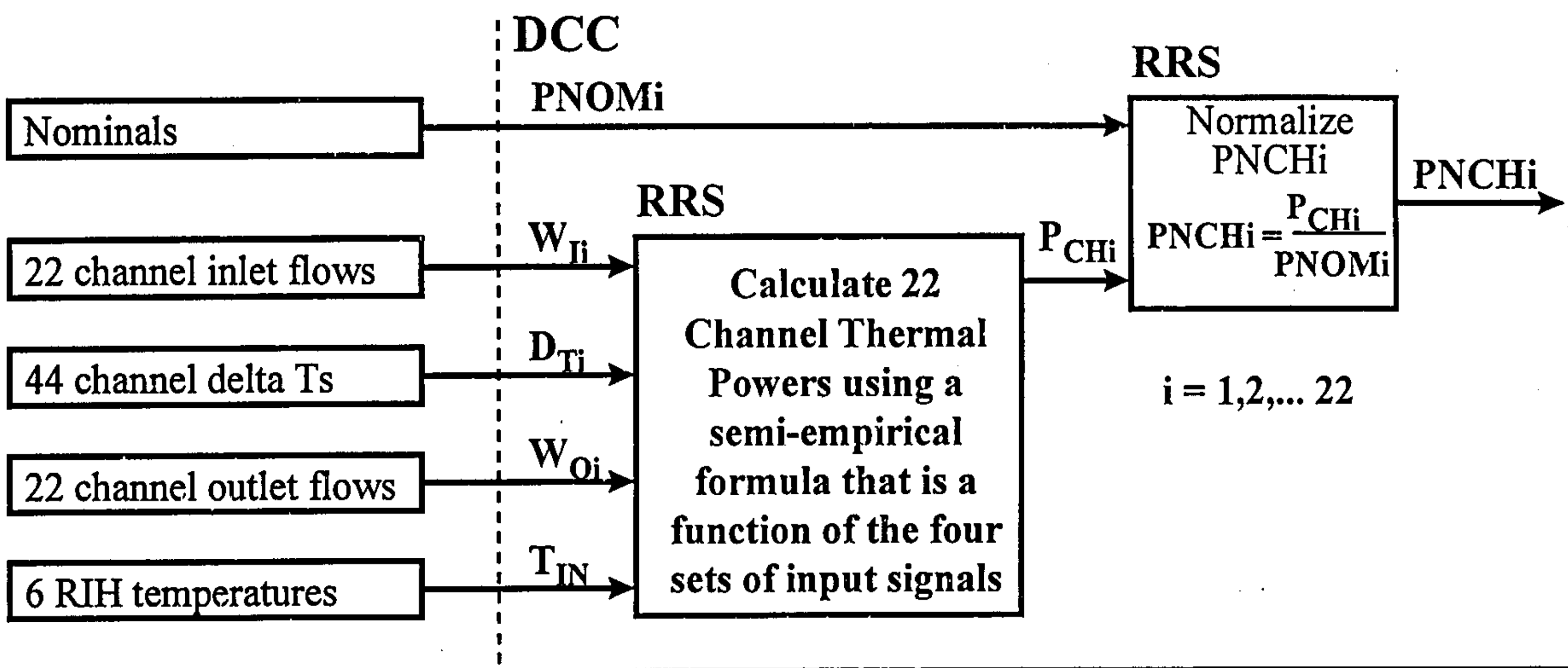


  - inlet and outlet flows in 22 fuel channels
  - the temperature increase (ΔT) in the same 22 fuel channels as above
  - reactor inlet header temperatures
  - the outlet temperature in every channel
- While the 22 fuel channel readings give an accurate value of the thermal power in these channels provided saturation is below 20%, these values are not sufficiently representative of all the channels. In particular refuelling can introduce significant local perturbations. The program "FINCH" uses these measurements to calculate an estimate of reactor thermal power.
- The outlet temperature readings of every channel provide an opportunity to compute the thermal power of each channel. The program ZOTPR uses these individual channel outlet temperature readings to compute an estimate of channel and zonal reactor thermal power. However, because the temperature sensors are mounted on the outside surface of the feeder pipes, these readings are delayed by typically 3 minutes relative to the change in neutron power. Note also that the temperature measurement cannot indicated the degree of saturation.

- The values computed by FINCH and ZOTPR are used in various ways to calibrate the neutron power readings to obtain the most accurate estimate of local, zone and bulk reactor thermal power.

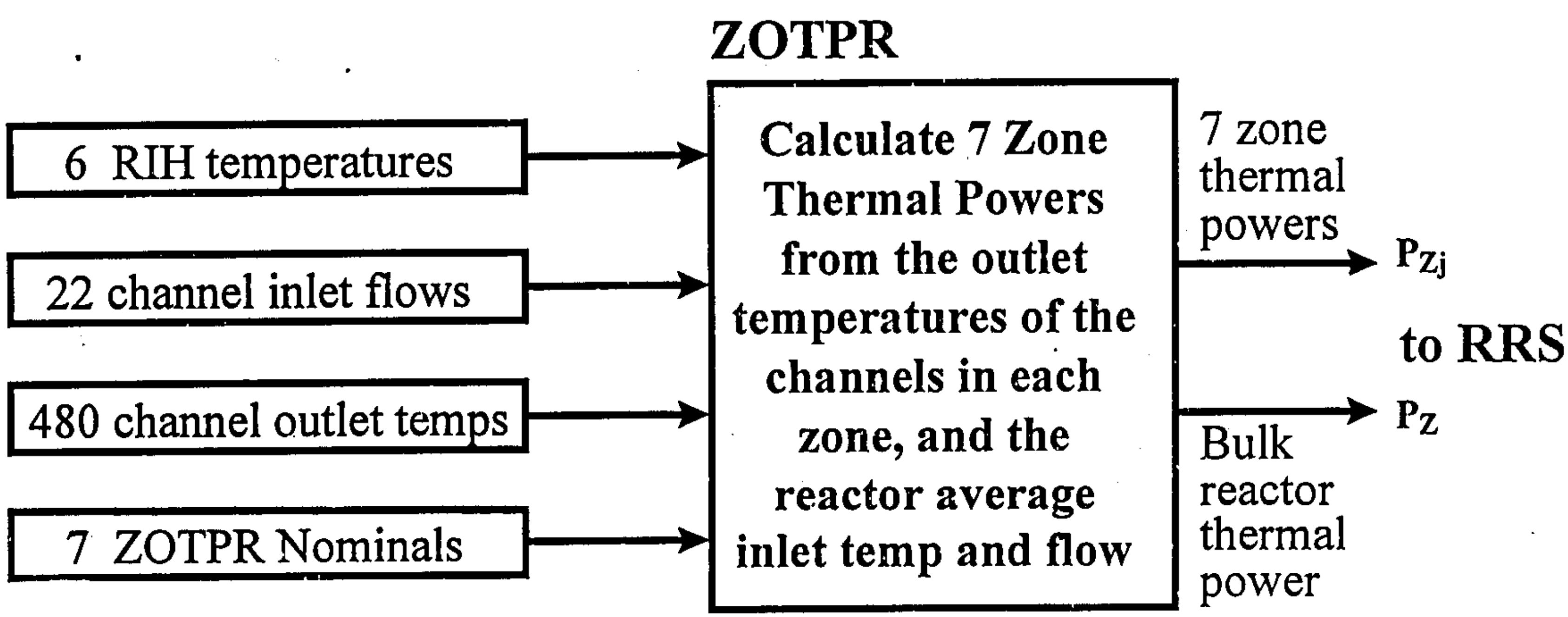
4.1 'FINCH' THERMAL POWER MEASUREMENT

- the various input signals of flows and temperatures are all checked for rationality and spread
- a semi-empirical formula, that uses the four sets of input parameters and allows for up to 20% of saturation at the outlet of a channel, computes 22 channel thermal powers in kW
- since the readings obtained from the various sensors are relative measures of power, the absolute channel powers have to be converted to a percentage in the power range and to a log measure for low power levels
- the 'NOMINAL' absolute power in kW for each channel at 100%FP is calculated and input to RRS
- RRS devides the channel power calculated from the 'FINCH' signals for channel 'i' by the corresponding nominal (PNDMi) to obtain channel power (PNCHi) as a fraction of 1 or %FP



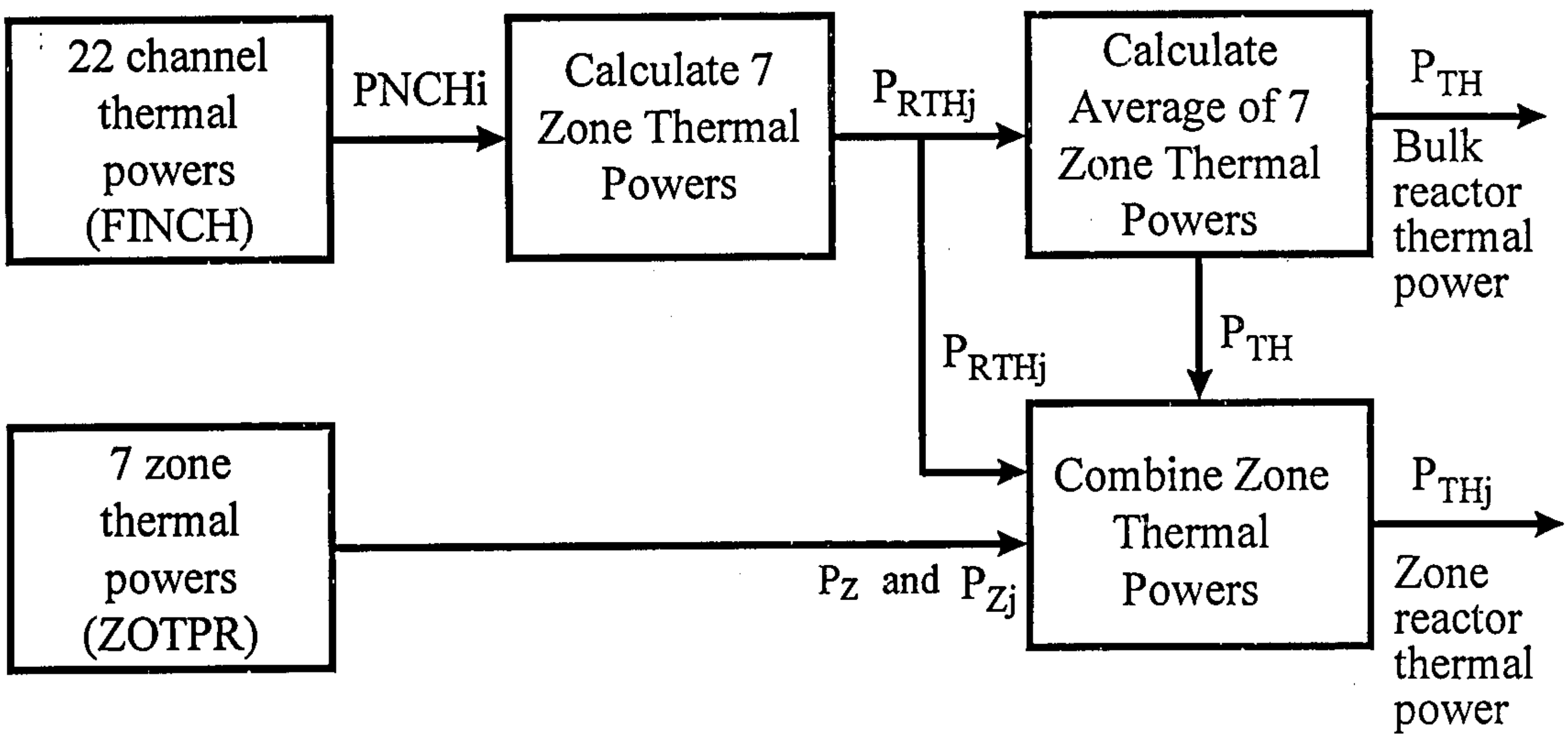
4.2 ZONE THERMAL POWER ROUTINE (ZOTPR)

- ZOTPR uses 6 RIH temperatures, 22 channel inlet flows and 480 channel outlet temperatures to compute the power in 7 thermal zones (each thermal zone comprises an axial pair of neutron or control zones)
- the various input signals of flows and temperatures are all checked for rationality and spread
- the average of the outlet temperature of each channel in a given thermal zone is computed, and in combination with the average of the 6 inlet header temperature and the average of the 22 channel inlet flows, the thermal power in each of the 7 zones is computed in kW
- since the readings obtained from the various sensors are relative measures of power, the absolute zonal powers have to be converted to a percentage for use in calibrating the neutron power readings
- the 'NOMINAL' absolute power in kW for each thermal zone at 100%FP is calculated & input to ZOTPR



4.3 COMBINATION OF FINCH AND ZOTPR THERMAL POWERS

- both FINCH and ZOTPR calculate the thermal power in each of the 7 thermal zones
- the values obtained by ZOTPR give more accurate spatial information, but the response is slower and less accurate in absolute magnitude since boiling is ignored, than FINCH
- maximum accuracy is achieved by combining the power values computed by FINCH and ZOTPR

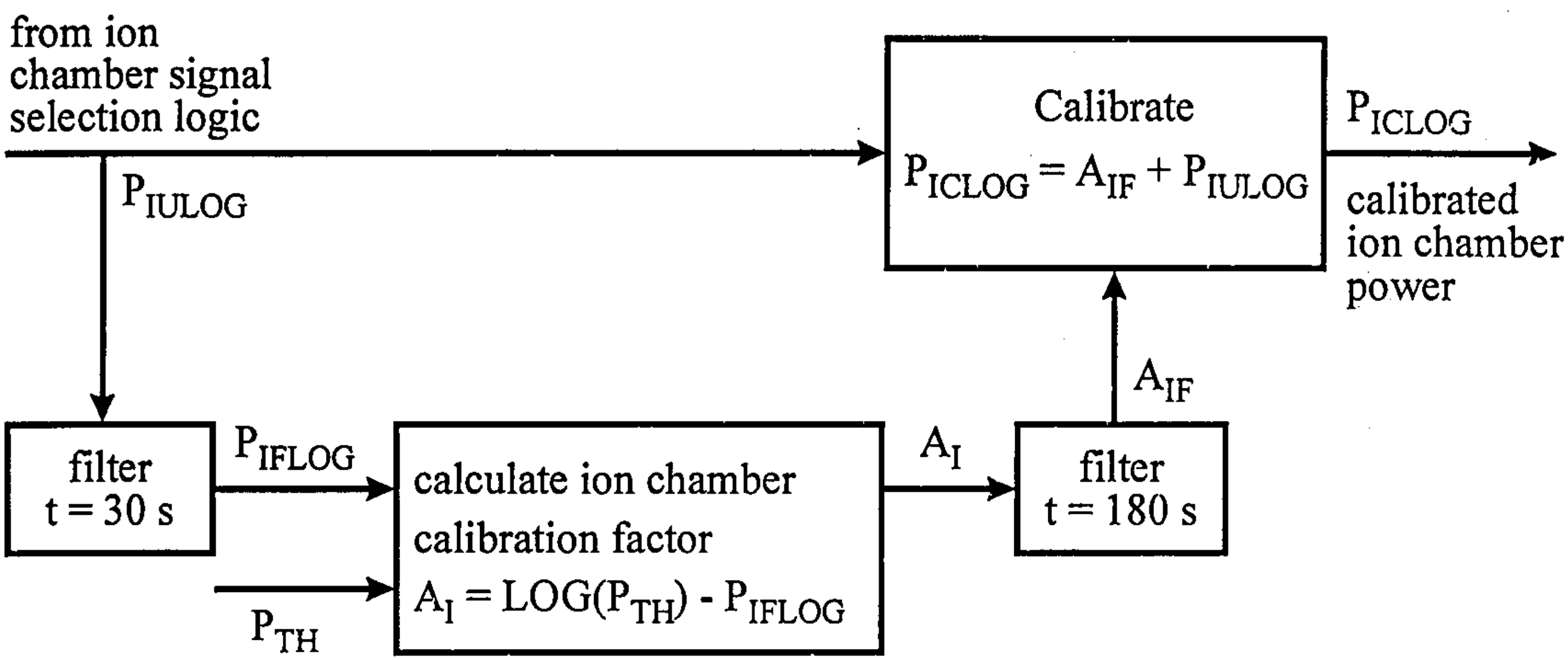


5.0 CALIBRATION OF NEUTRON POWER SIGNAL BY THERMAL POWER MEASUREMENT

- the bulk and zonal reactor thermal power measurements are used to calibrate (i.e. correct) the ion chamber and in-core detector signals that indicate neutron power

5.1 ION CHAMBER CALIBRATION

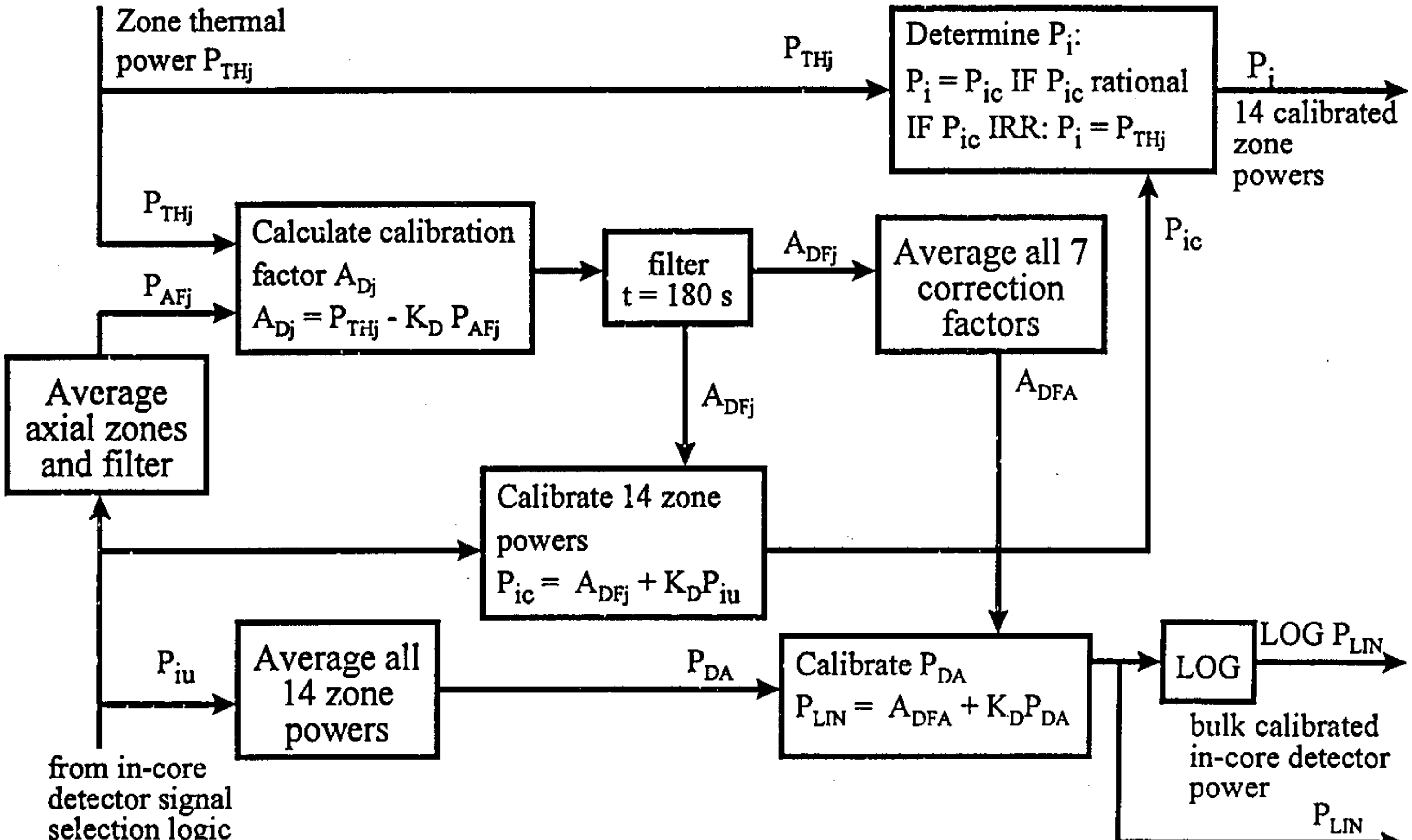
- a calibration factor (A_{IF}), computed from the difference between the uncorrected (but filtered) ion chamber signal (P_{IFLOG}) and the LOG of the bulk thermal power measurement (P_{TH}), is added to (or subtracted from) the uncalibrated ion chamber signal (P_{IULOG})
- under steady state conditions the calibrated ion chamber power measurement $P_{ICLOG} = P_{TH}$, during transients the ion chamber signal dominates



5.2 IN-CORE DETECTOR CALIBRATION

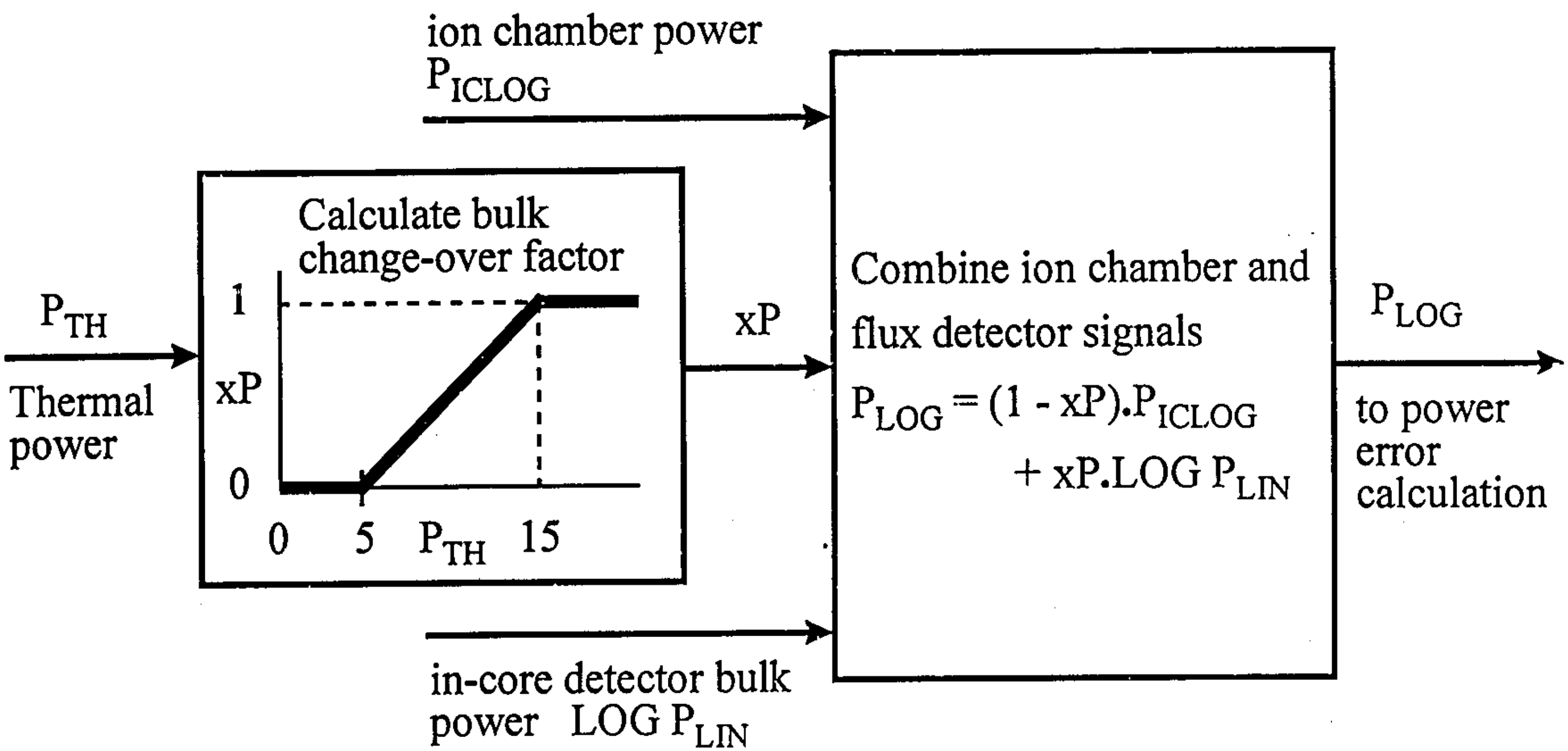
- the calibration process is similar to the one for the ion chamber: seven calibration factors (A_{Dj}) are computed from the differences between flux power (P_{AFj}) and the thermal power measurement (P_{THj}); these are added to the faster responding flux power signal (P_{iu})
- the 14 individual zone powers P_i are used for spatial power control, and LOG P_{LIN} is combined with the ion chamber power measurement for bulk power control

Note:
i = 14 zone flux powers
j = 7 zone thermal powers



5.3 COMBINE ION CHAMBER AND AVERAGE IN-CORE DETECTOR MEASUREMENTS

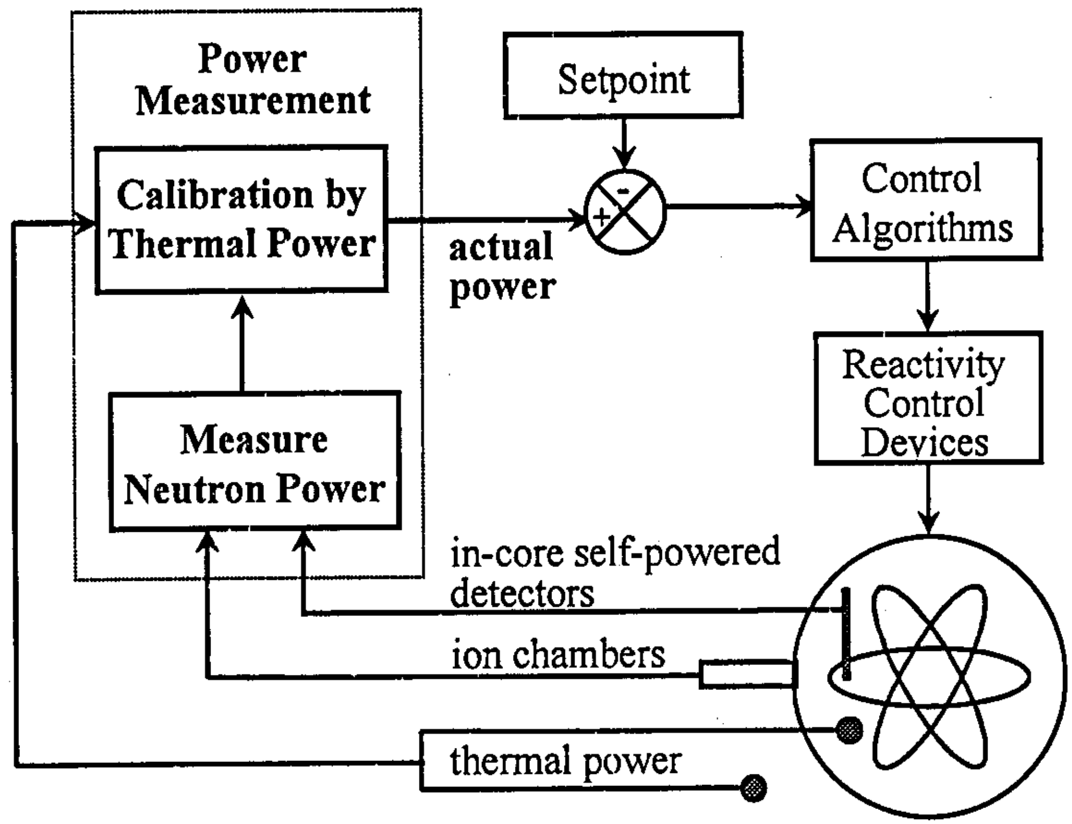
- the ion chambers operate over a range of 7 decades (10^{-7} to $10^{0.176}$, or 0.00001% to 150%FP)
- at significant thermal power levels the accuracy of the ion chambers is not sufficient for control, and being outside the core, their reading is not a sufficiently accurate measure of the reactor bulk power
- the in-core flux detectors, which give acceptable readings in the 1% to 120% power range cannot be used for operations below 1% reactor power
- the ion chamber signals are used at low reactor powers, the in-core flux detector signals are used in the power range, with a programmed transfer of control from one to the other between 5% and 15%FP



1.0 INTRODUCTION

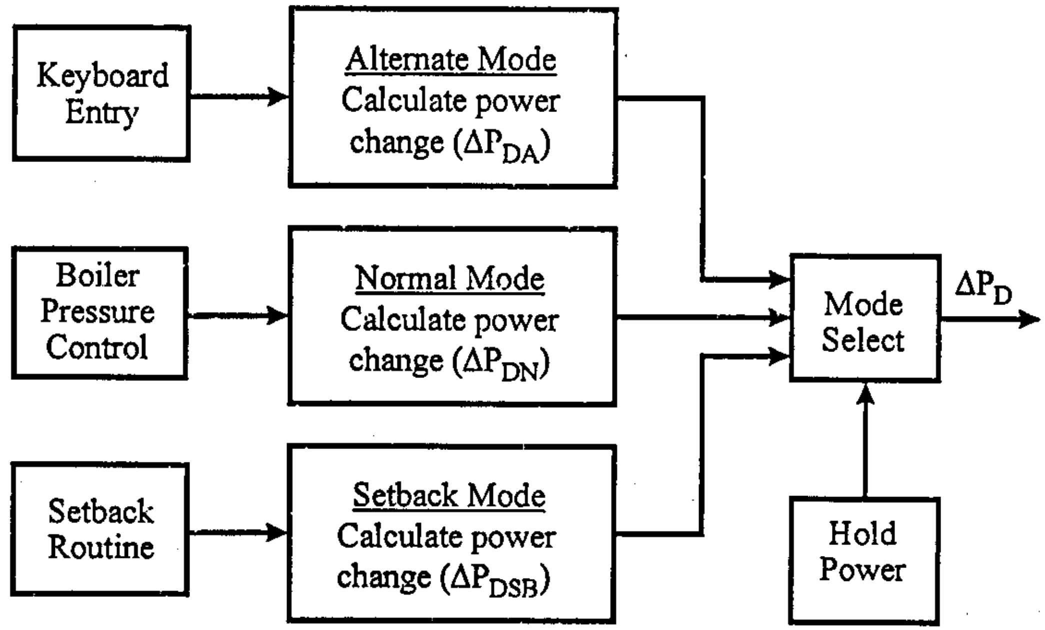
For CANDUs the Control Algorithm has the following main components:

- reactor setpoint calculations
  - mode selection
  - demanded power calculation
- power error calculation
- control of reactivity devices
  - adjuster rods
  - control absorber rods
  - liquid zone level control
  - adjuster and absorber speed control
  - poison addition
  - shutdown rods withdrawal
- reactor setback
- reactor stepback



2.0 REACTOR POWER SETPOINT CALCULATION

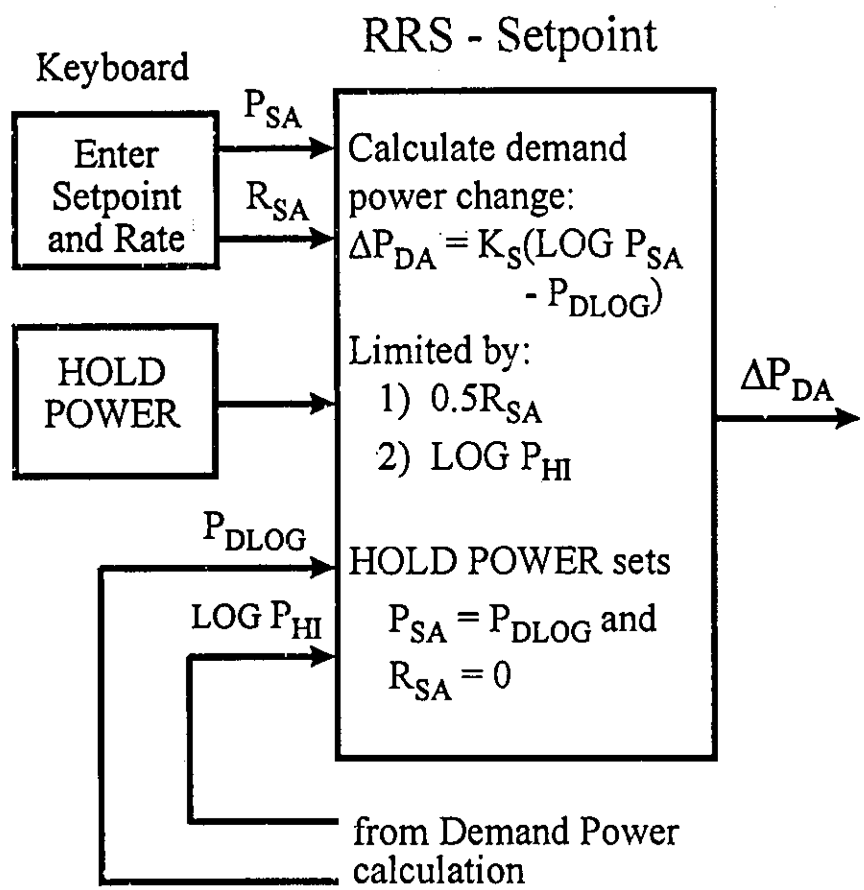
- The reactor power setpoint is determined by one of the following four sources, and the reactor control program is said to be in the corresponding "modes":
  - operator keyboard entry ("alternate" mode)
  - boiler pressure control program ("normal" mode)
  - setback program ("setback" mode, which terminates in "alternate" mode)
  - hold power program ("hold power" mode which places reactor control into "alternate" mode)

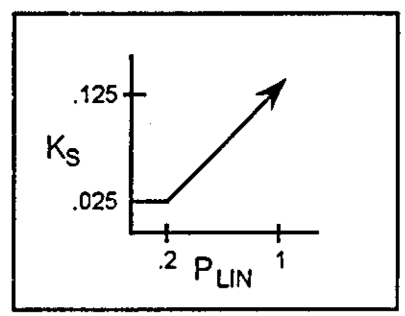


- The two basic modes of reactor control are "normal" and "alternate", since both of the other modes results in reactor control being placed into "alternate" mode. Specific operator action is required to take the reactor control from "alternate" to "normal".
- The main functions of the setpoint calculation program are the calculation of demanded power and demanded power rate.
- All power level changes are achieved by ramping the setpoint up or down at a specified rate, towards the specified target endpoint.
- On each iteration the amount of change in demanded power is computed (ΔP_D)

2.1 ALTERNATE MODE SETPOINT CALCULATION

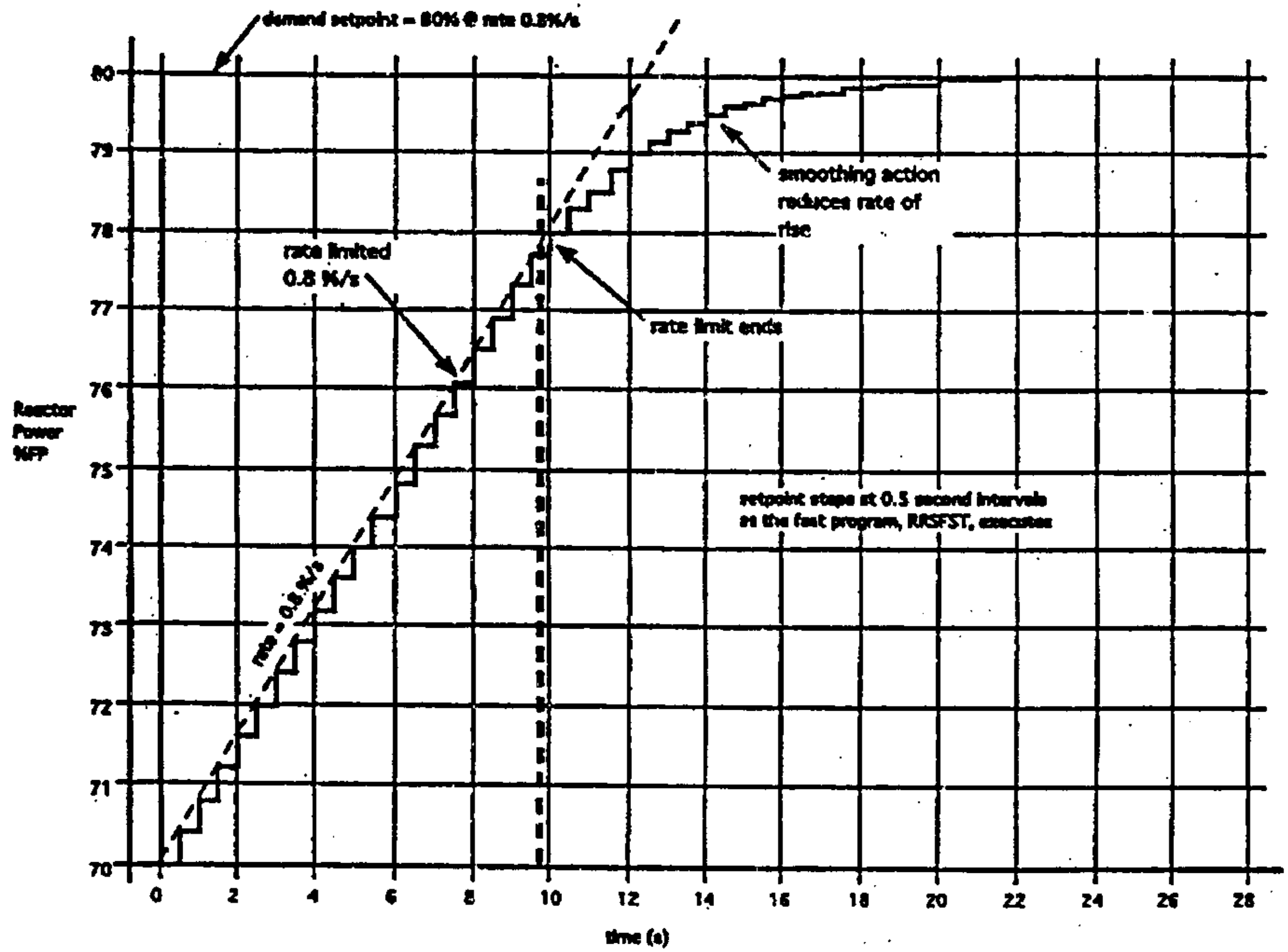
- The Setpoint Power Demand (P_S) is in the form of a target power (absolute in units of %FP or decades) and is accompanied by a Setpoint Rate (R_S)
- The Setpoint Power Demand increase is limited to a safe absolute value (LOG P_{HI}), and on each computer iteration to $0.5R_{SA}$, in order to prevent large step changes in Demanded Power
- On each program iteration the Setpoint error is computed as the difference between the Target Setpoint (P_{SA} in alternate mode and P_{NA} in normal mode) and the current value of the Setpoint (P_{DLOG}), and is multiplied by a gain factor K_S
- $K_S = 0.025$ for $P_{LIN} \leq 0.2$ (i.e. below 20%FP) and $K_S = 0.125\ P_{LIN}$ for power levels above 20% (i.e. $0.2 < P_{LIN} \leq 1$), so the gain increases with increasing power above 20%FP.





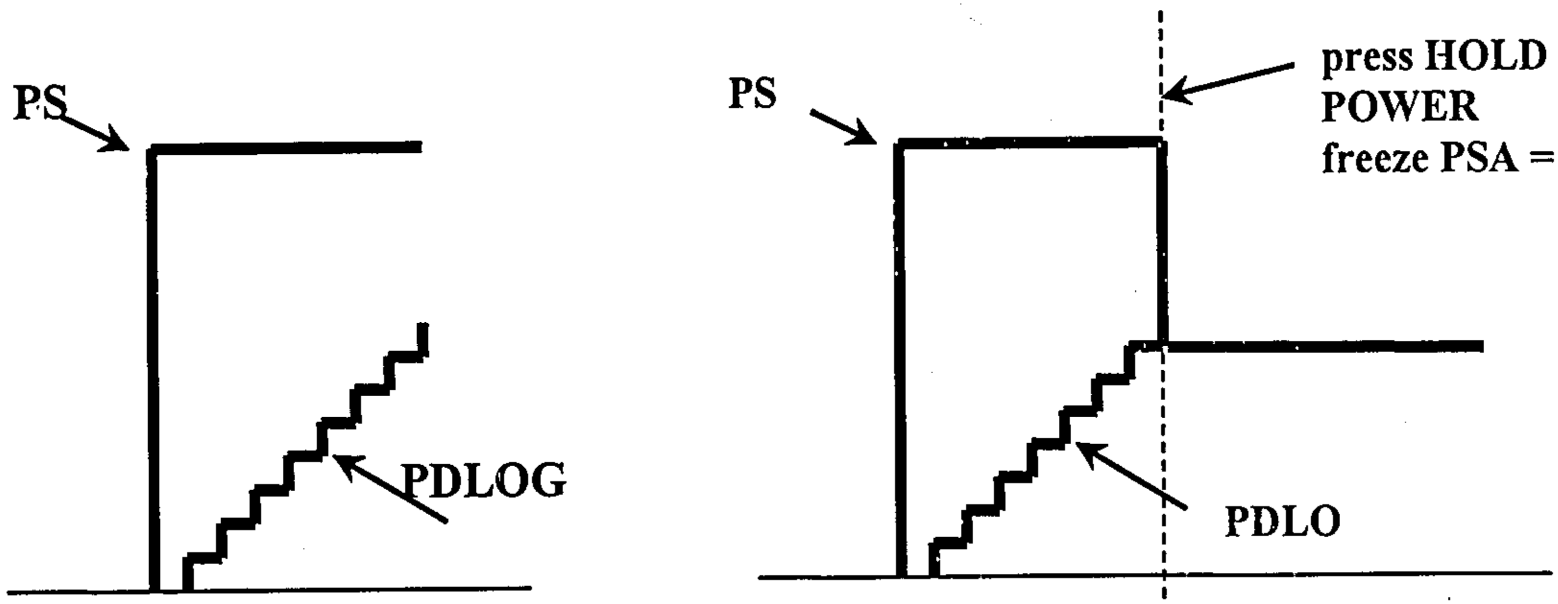
2.1 ALTERNATE MODE SETPOINT CALCULATION (continued)

- During large difference between Target (LOG P_{SA}) and Demanded (P_{DLOG}) Setpoint, the rate limit will keep the step increases between successive iterations small.
- As the Target Setpoint is approached, the error becomes progressively smaller, and the size of ΔP_{DA} will decrease, resulting in a smooth approach to the Target Setpoint, minimizing the tendency for actual reactor power to overshoot the target value.
- When the control mode is in "Normal", the "Alternate" mode demand setpoint (P_{SA}) is set equal to the current setpoint (P_{DLOG}), i.e. it tracks the current setpoint.



2.2 HOLD POWER

- HOLD POWER is initiated by a panel pushbutton which generates a computer interrupt and will override any other setpoint calculation except a Setback. The result is to place RRS in Alternate mode, and to set the Target power $P_{SA} = P_{DLOG}$, and the rate term $R_{SA} = 0$; i.e. the Setpoint is frozen at its current value.

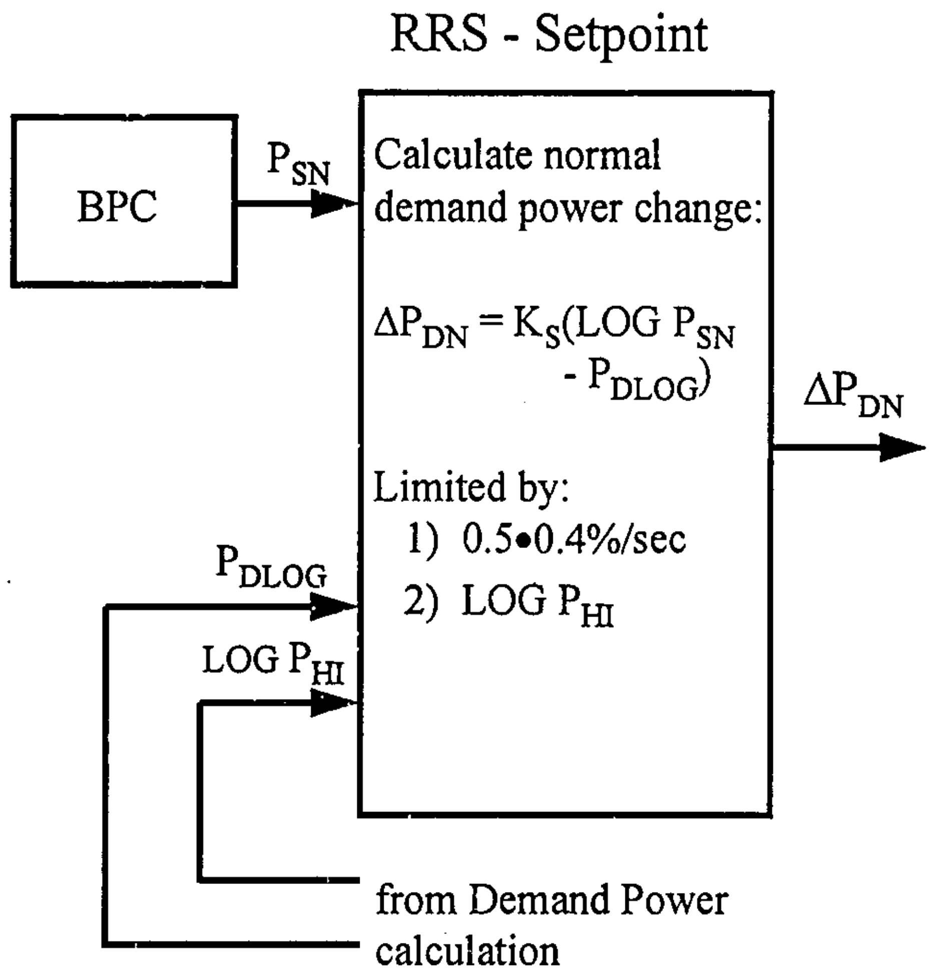


2.3 NORMAL MODE SETPOINT CALCULATION

- The Target Setpoint value (P_{SN}) is generated by BPC, which RRS converts a log value
- No rate term is supplied because in Normal mode the rate is always 0.4%FP/sec.
- The change in Demanded Power Setpoint is calculated in the same way as in Alternate mode, including the limits and smoothing action as the target value is approached

2.4 SETBACK MODE SETPOINT

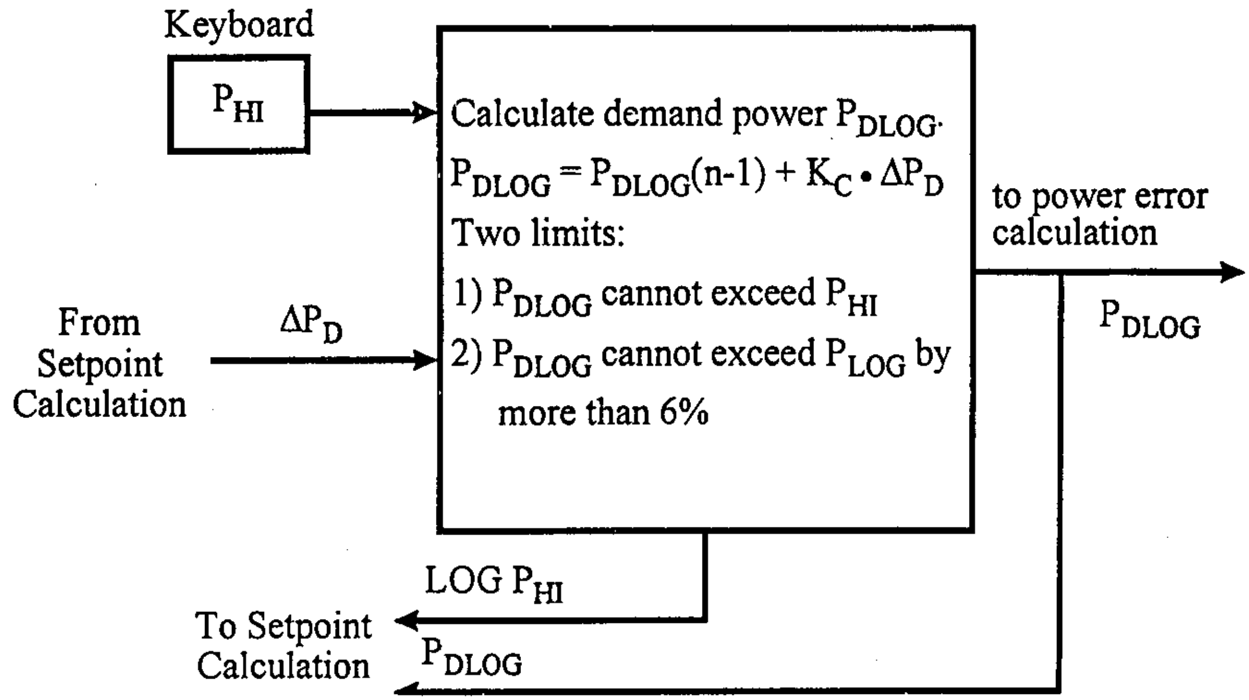
- The Setpoint calculation is similar to the other two cases, with the following differences:
  - if the Setback condition clears before the Target Setpoint is reached, then the Setback is terminated
  - while the Setback is in effect, the Setpoint is ramped at the specified rate all the way to the Setback Endpoint
  - there is no smoothing action on the Setpoint calculation; $\Delta P_{DSB} = 0.5 \bullet R_{SSB}$
  - when the Setback terminates a HOLD POWER is executed and the control mode is transferred to Alternate



3.0 CALCULATE DEMAND POWER (CURRENT SETPOINT)

- The Demand Power portion of the RRS program takes the requested Change in Demand Power ΔP_D and adds it to the value of Demand Power from the previous iteration, $P_{DLOG}(n-1)$. In this way the Demand power is incremented up or down from where it was every 0.5 second until the target is reached.
- The constant K_C is used to convert the logarithmic rates into linear rates when above 20%FP.
- If a HOLD POWER is executed, then ΔP_D is set to 0 to terminate the change in demand power.
- P_{DLOG} cannot exceed P_{HI}, which is an absolute upper limit on reactor power setpoint, which is entered by the operator through the keyboard.
- A "Deviation Limiter" program is in RRS to ensure that the calculated setpoint P_{DLOG} does not exceed the actual power P_{DLOG}. by more than 6%

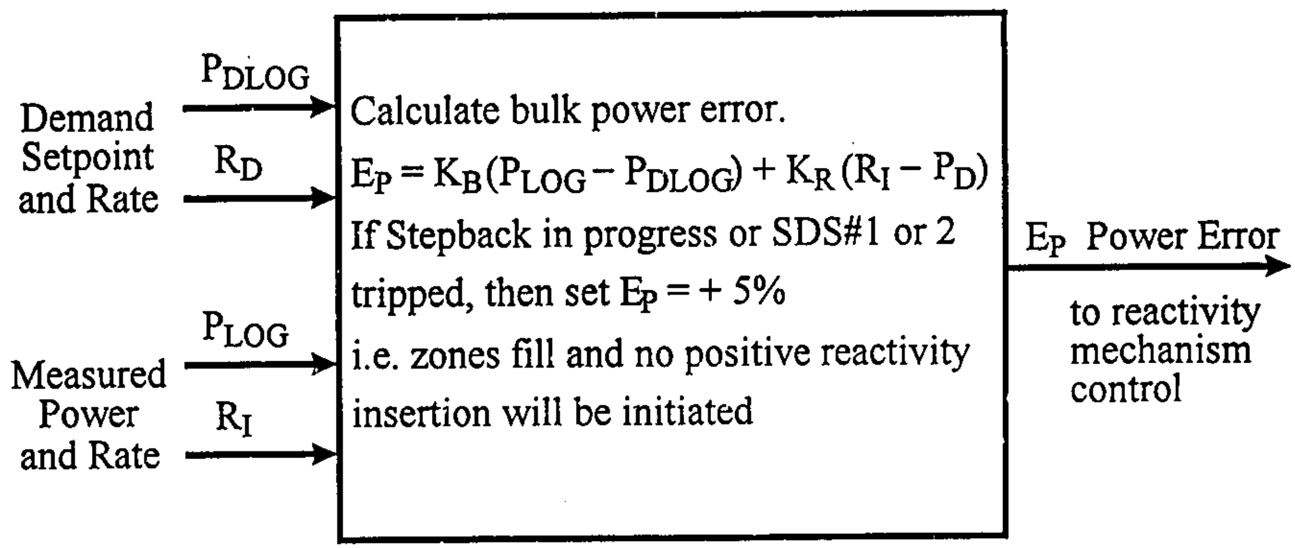
RRS - Demand Power



4.0 BULK POWER ERROR CALCULATION

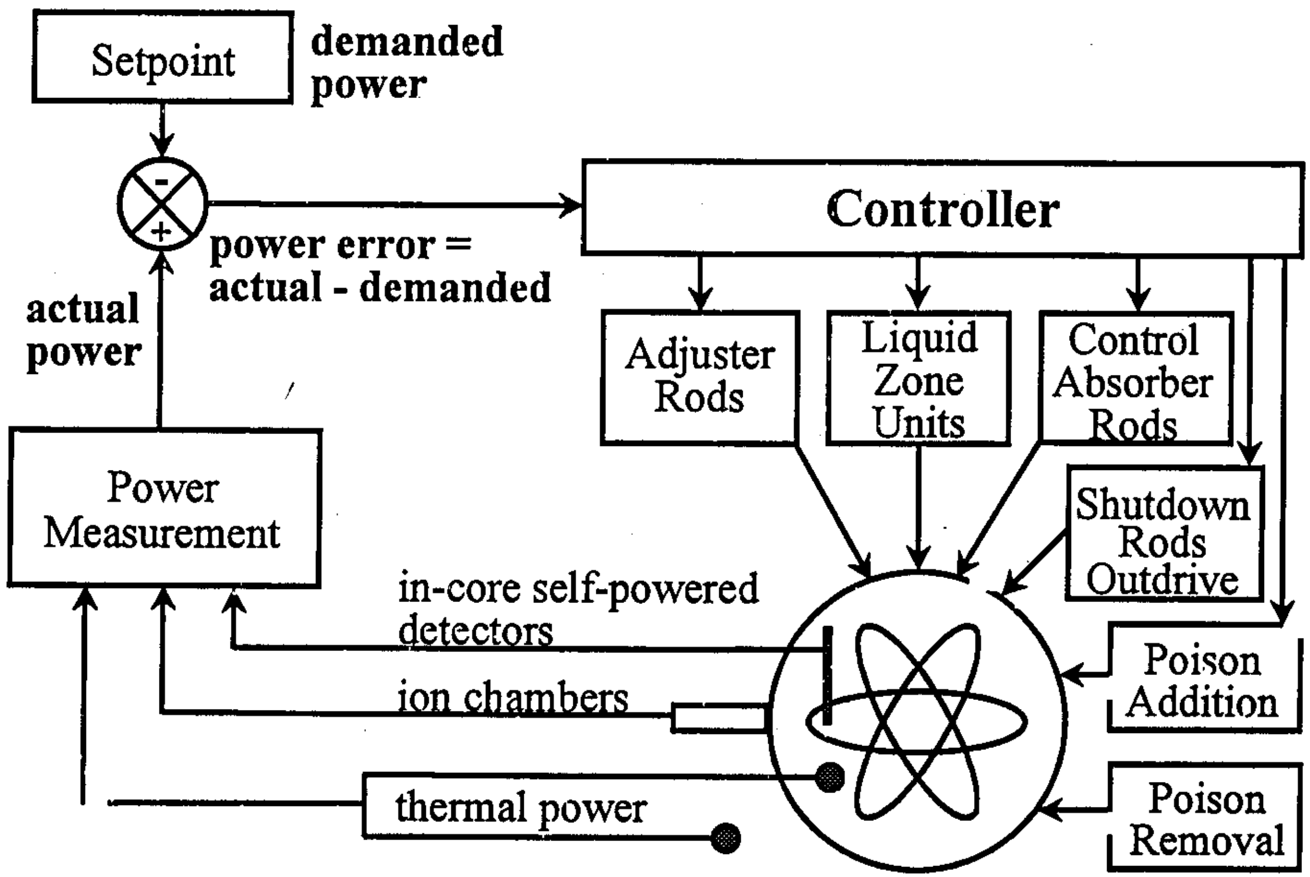
- The Power Error is the sum of the bulk power error and the rate error.
- The proportional gain is K_B and the derivative gain is K_R.
- K_R is fixed 0.5; K_B is a variable based on the measured power P_{LOG}. The value of K_B is 1 at 100%FP and 0.2 at 20%FP and below, with a linear variation in between.
- The reduction of the gain at power levels below 20%FP is designed to maintain good control stability, reducing the destabilizing effects of ion chamber signal delays and noise.
- The power error term cannot normally be overridden, but when a reactor stepback or a completed SDS trip is in effect, the bulk error is set equal to +5%.
- The bulk power error is a key parameter in controlling reactor power through the operation of the reactivity devices.

RRS - Power Error



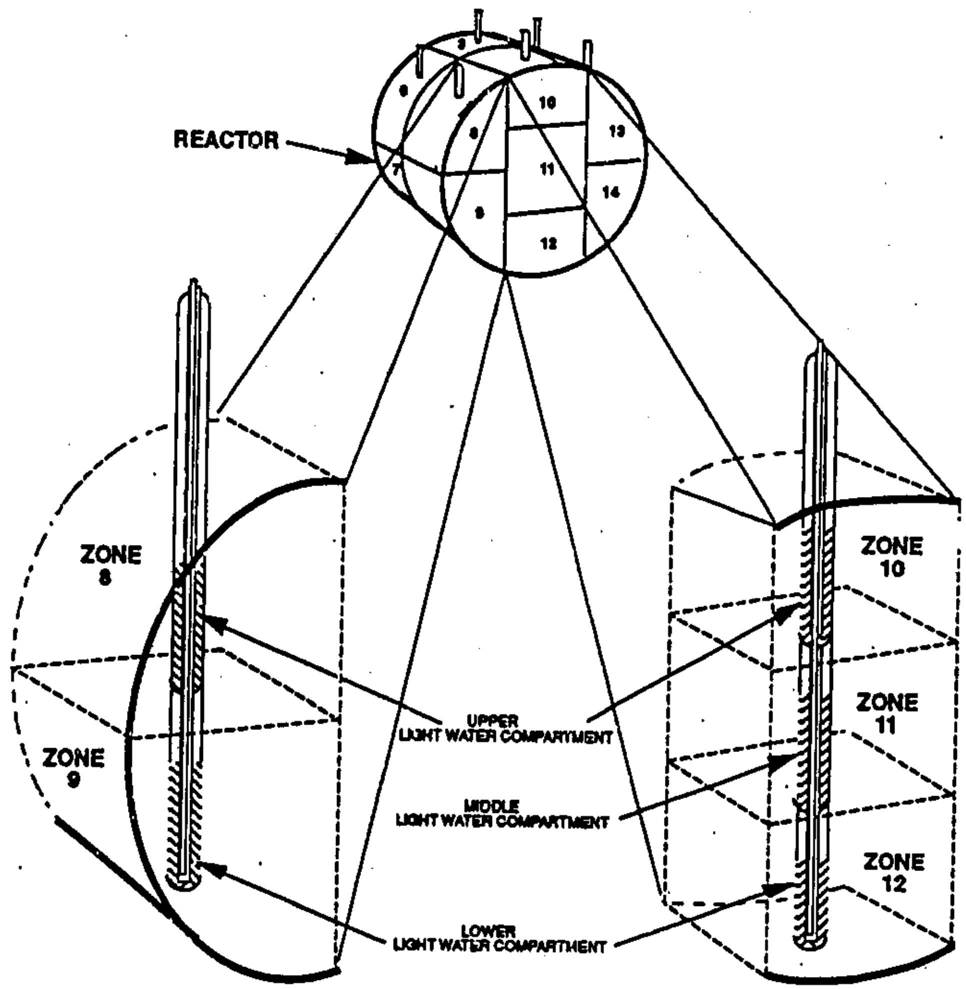
1.0 INTRODUCTION

- In Module 3A we briefly considered the various types of reactivity devices that may be used in power reactor applications.
- Control rods made of neutron absorbing material and absorbers that could be desolved in the coolant/moderator were considered
- This module looks at in some detail the types of reactivity control devices used in CANDUs.
- A unique aspect of CANDUs is that the neutron flux must be controlled not only as the total reactor flux, but spatially as well.
- While large PWR and BWR reactors also have some spatial control by the careful positioning and partial insertion of solid rod, in CANDU a light water zone system is used for the fine control of overall reactivity as well as to control spatial flux distribution
- In this module we look at each of the reactivity mechanism types used in CANDU



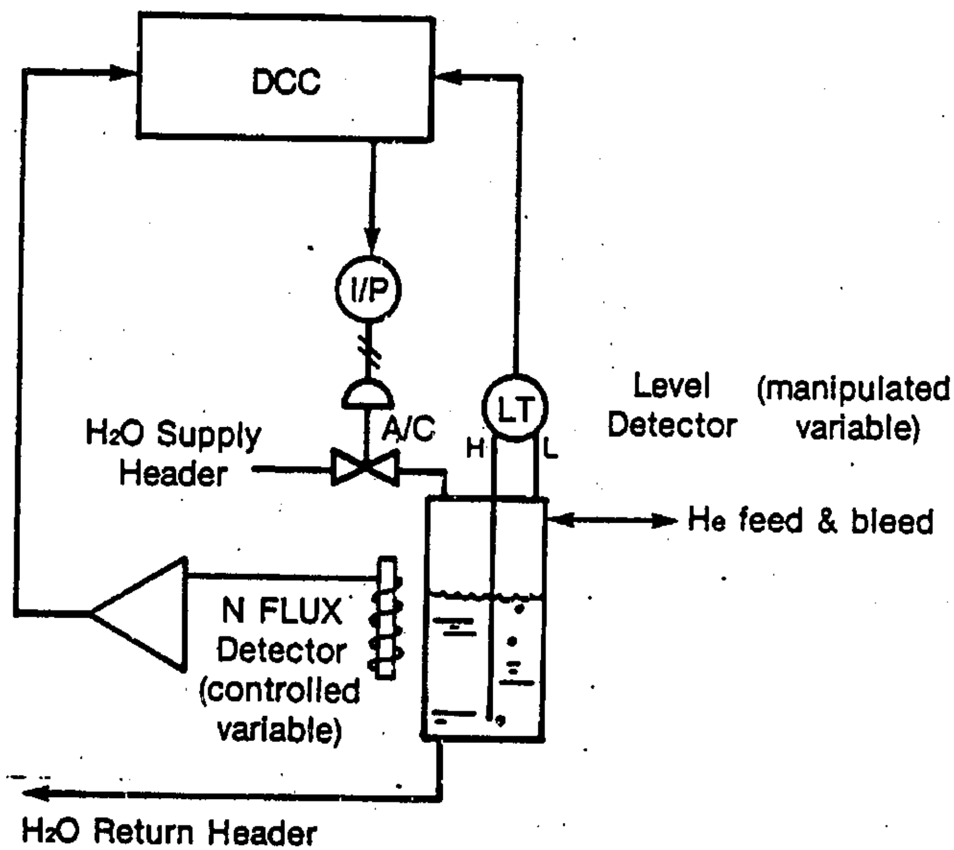
2.0 LIQUID ZONES

- because in CANDUs the moderator and coolant are heavy water, light water in the core will act as a neutron absorber that can be used as a reactivity control device, by controlling the amount of light water present in each designated "zone compartment" i.e. a cylindrical container
- with a finite water level always present, any change in level will alter the volume of water and hence the reactivity worth of the zone, hence changing the neutron flux in the region around the core
- if all the zone levels increase or decrease in unison, bulk reactor power will change
- if one or more zone levels increase and others decrease, the total reactor power can remain the same, but the flux distribution and hence the power produced by each "zone" (if fact by each fuel element) will have changed
- as such, the liquid zone control system provides both a fine control of bulk reactor power and of spatial power distribution – it is at the "heart" of the CANDU Reactor Regulating System
- the systems and equipment required to vary the amount of water in each zone is described in the following sections



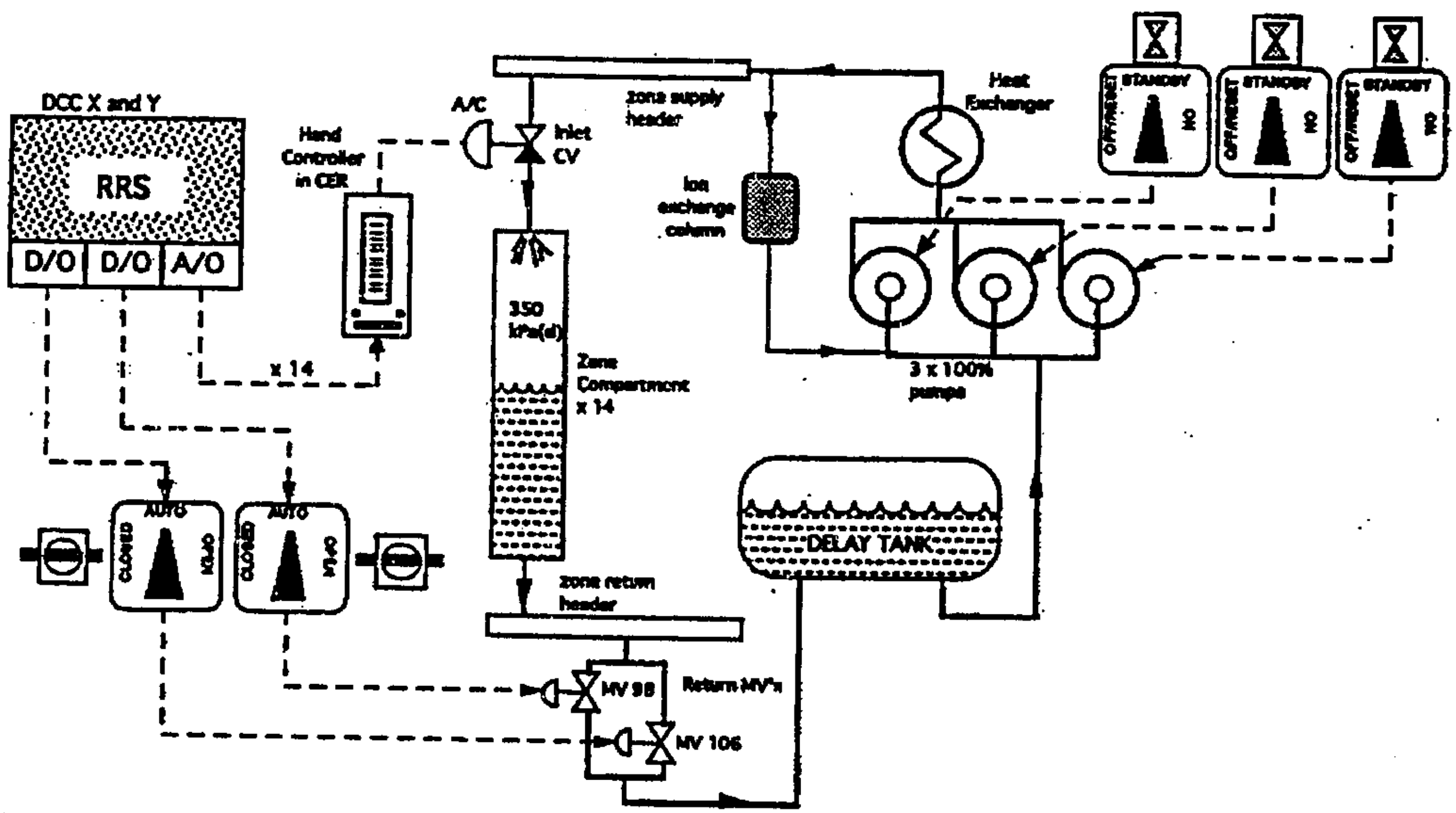
2.1 Light Water Circuit

- The water level in each zone is controlled by maintaining a constant outflow rate and adjusting the inflow rate. A difference between the inflow and outflow will cause the level to go up or down.
- Maintaining a constant differential pressure between the helium atmosphere in the zones and the helium atmosphere in the delay tank creates the constant outflow rate. The inflow rate is controlled by the inlet control valve.
- The inlet control valve is an air to close pneumatic valve that fails open on loss of control signal or air supply. The control signal is normally derived from an analogue output on the controlling DCC via hand-controllers that can be selected to either computer control or to manual control.
- Normally one DCC or the other is in control, and the transfer of control relays for that computer connect the analogue outputs to the hand-controller. The other DCC analogue outputs are put into a bypass loop to ensure the loop is complete and to allow monitoring via the feedback A/I.



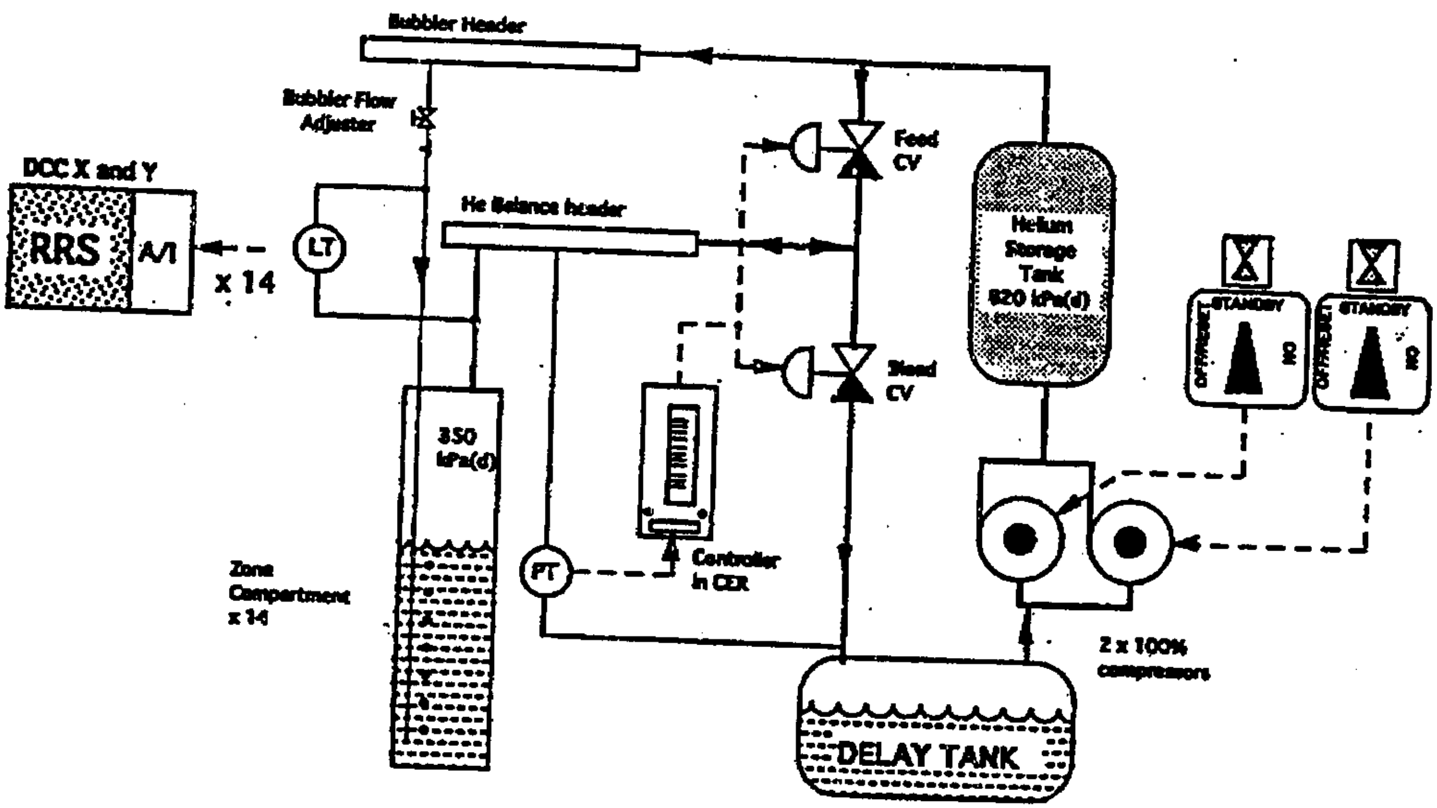
2.1 Light Water Circuit (continued)

- The zone outlet flow MV's, MV98 and 106, are air operated and fail closed on loss of air. The valves are 100% capacity each. Their control hand-switch logic is: CLOSED - MV is closed, OPEN - MV is open, and AUTO - MV is closed by RRS on loss of zone water supply pressure.
- Normally one water pump is 'ON', one is STANDBY, and one is selected to OFF/RESET.
- Each of the 14 zone inlet CV hand-controllers can be selected to either COMPUTER or MANUAL control mode via pushbuttons, and if in MANUAL then the raise or lower output buttons can be used. The manual output tracks the computer output when in COMPUTER mode to allow bump-less transfer to MANUAL if required.



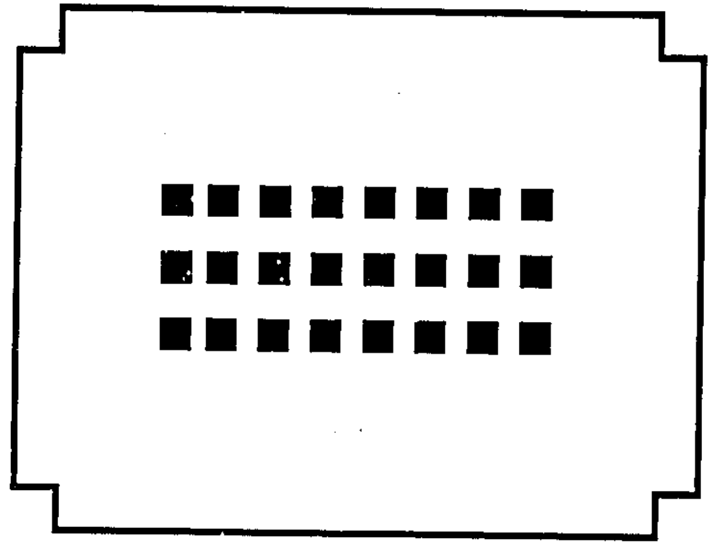
2.2 Helium Circuit

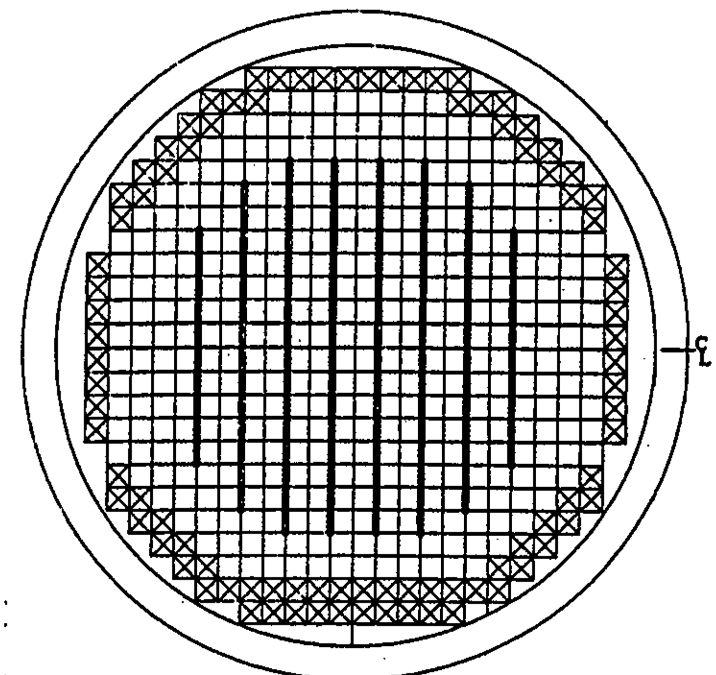
- The main purpose of the helium circuit is to create the constant zone water outflow.
- The pressure differential between the balance header and the delay tank is controlled at a fixed setpoint of 350 kPa(d) by means of the feed and bleed control valves.
- The 2 compressors return the helium to the storage, which provides the source of helium to the balance header, and also to the zone level measuring bubblers.
- The water level in each zone is measured by use of a helium bubbler. The transmitter signals go to the DCC X and Y as analogue inputs and also to the hand-controllers.
- One He compressors is always 'ON'. the other is either OFF/RESET, or STANDBY
- The helium balance header pressure is controlled via the feed and bleed valves



3.0 ADJUSTER RODS (24 in CANDU 9)

- purpose:
  - shape the neutron flux for optimum reactor power and fuel burnup;
  - supply positive reactivity beyond the normal control range of the zone controllers when required;
  - compensate for the negative xenon reactivity for up to 35 minutes after a shutdown from full power ("poison override").
- made of neutron absorbing, stainless steel clad, cobalt rod, suspended by a stainless steel cable from a motor driven cable drum;
- normally fully inserted in the core, and due to the curvature of the reactor, there are four different lengths of adjusters rods, and hence their reactivity worth is different;
- moved in banks at varying speeds, each of the 8 banks of adjusters have approximately the same total reactivity worth, but varying number of rods;
- the maximum total reactivity which may be gained on withdrawal of all adjuster rods is about 16 mk;
- the maximum reactivity change rate of any one bank of adjusters is ± 0.07 mk/s.
- the adjusters position is normally controlled by the reactor regulating system, but can also be manually operated.





3.1 Adjusters – Control signals and hand-switches

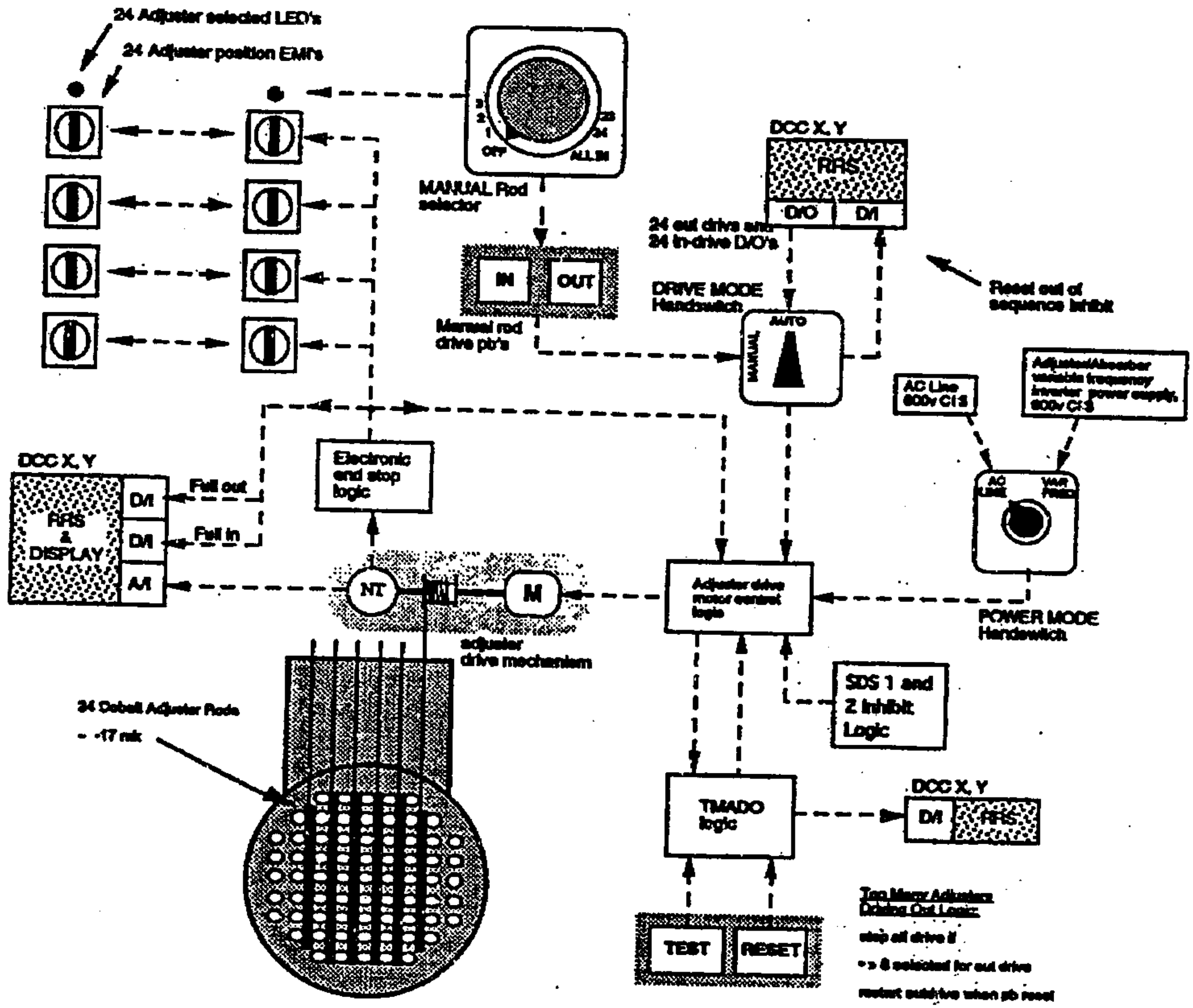
- Rod Position is measured by a potentiometer installed on the drum and this outputs as follows:
  - rod position directly to DCC X and Y as analogue inputs, and,
  - to the electronic end stop circuitry (EES), which in turn outputs full in or full out logic position which is used in:
- Adjuster Controls are located in the Main Control Room:
  - DRIVE MODE hand-switch.

    This has two positions: AUTO and MANUAL: in AUTO the panel controls are disabled and it allows RRS to control the in/out drive of the adjuster rods via the DCC digital outputs; in MANUAL, the RRS control is disabled and the panel rod drive controls are enabled.
  - Manual Rod Selector is used when the panel controls are enabled to select the rod to be driven. The ALL IN position is used when it is desired to drive all the rods in, but it can only be used when the POWER MODE is selected to AC LINE. There is no ALL OUT selection. When a certain rod is selected, an LED is lit to confirm the selection.
  - IN/OUT Pushbuttons are used when in MANUAL mode, to drive a selected rod in or out. The pushbutton must be held in to continue a rod drive.
  - TEST/RESET Pushbuttons are used to test and reset the TMADO logic.
  - POWER MODE Hand-switch has two positions: AC LINE and VAR FREQ. In the VAR FREQ mode the variable frequency (VFI) power supply is applied to the motor drives. In AC LINE mode, the normal 60Hz power supply is applied to the motor drives.

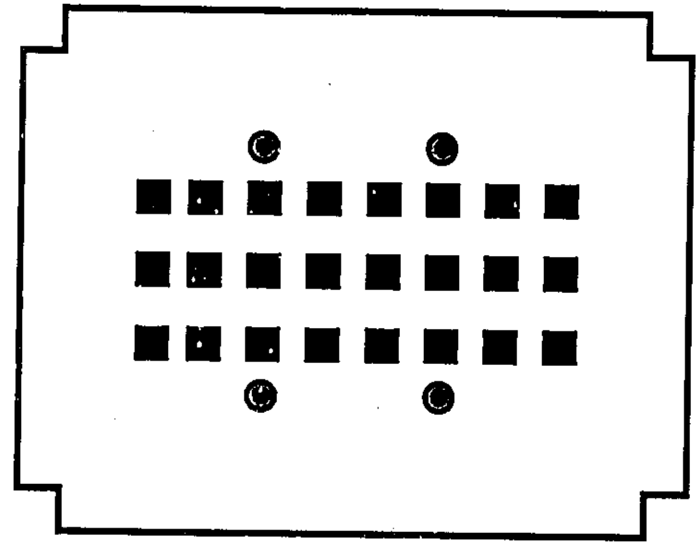
3.2 Adjusters – control logic

- Motor Control Logic: each adjuster has a forward and reversing contactor, which will close when a signal to move the rod is received. A drive demand will be made by either the DCC D/O's or the IN/OUT push-buttons, and the rod will drive until either:
  - the DCC D/O opens; or
  - the push-button is released; or, .
  - the rod reaches the end of its travel (from the Electronic End Stop logic); or
  - the TMADO logic inhibit is made (out drive only); or
  - the SDS logic inhibit is made (out drive only).
- TMADO Logic (Too Many Adjusters Driving Out): this hardware logic senses the number of adjuster rods driving in the OUT direction only. If more than 8 are driving then the TMADO logic will inhibit ALL out-drives, and alarm. The logic is reset by using the RESET pushbutton.
- SDS 1 and 2 Tripped Logic: when 2 out of 3 channels are tripped, taken from the unsealed trip relays, on SDS1 or SDS2 then hardware logic will prevent out-drive only. This is in addition to the RRS interlocks discussed in Module 3F.

3.3 Adjuster schematic



4.0 MECHANICAL CONTROL ABSORBERS (MCA)



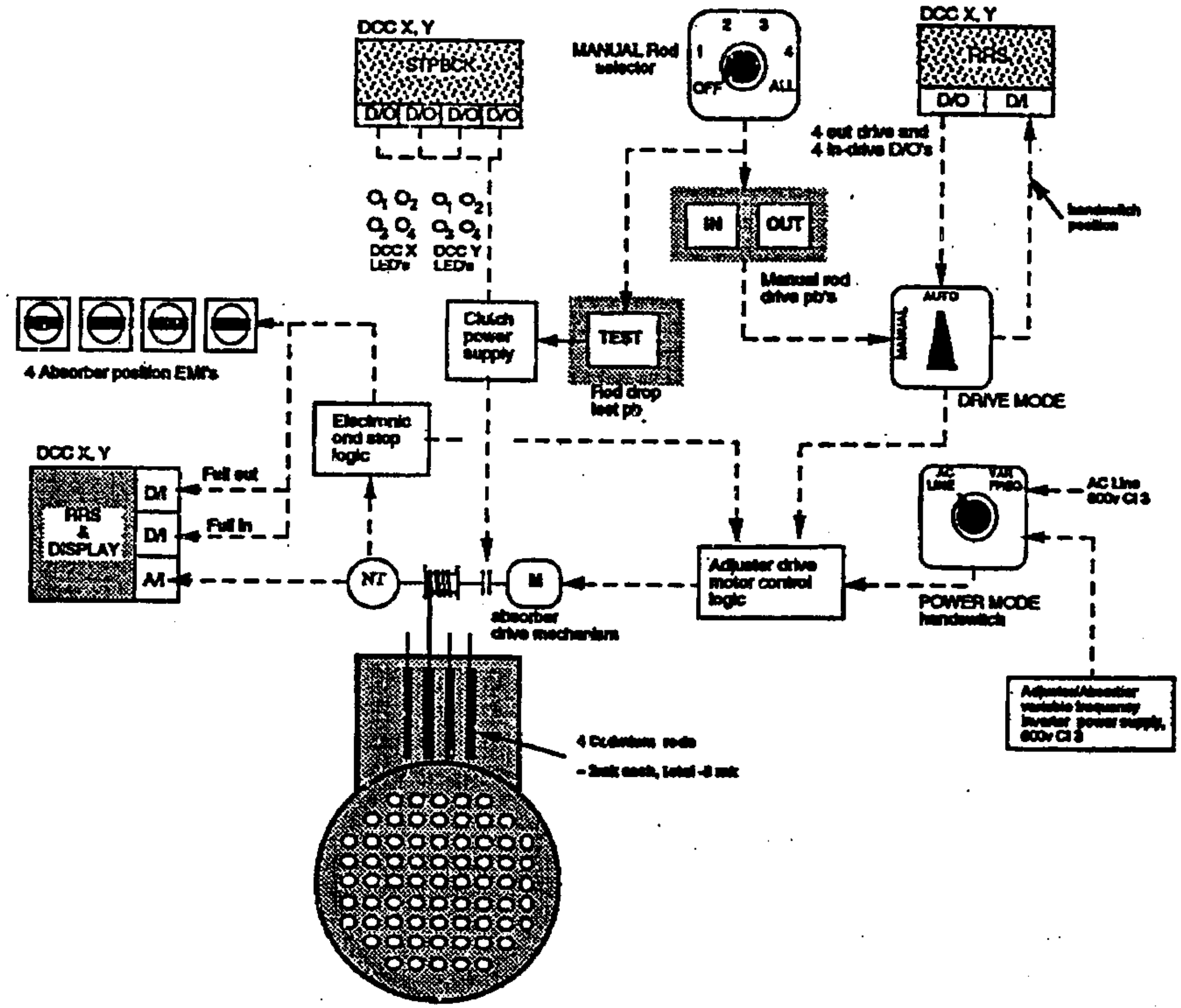
- purpose:
  - supply negative reactivity beyond the normal control range of the zone controllers when required;
  - provide a means of rapidly reducing neutron flux to a value intermediate between the given operating level and a full trip (stepback);
  - provide additional shutdown margin on a SDS#1 trip
- the mechanical control absorber rods consist of tubes of cadmium sandwiched between stainless steel, suspended by a stainless steel cable from a motor driven cable drum. The drum is connected to the motor via an electromagnetic clutch, which is normally energized and held closed by the STEPBACK program.;
- there are four MCAs;
- they are normally poised out of the core;
- they are normally driven in by the reactor control system, but can also be manually controlled;
- they can be driven into or out of the reactor core in one of two banks, at variable speed;
- they can be 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 10 mk.

4.1 Absorbers – Control signals and hand-switches

- Rod Position is measured by means of a potentiometer installed on the drum and this outputs as follows:
  - rod position direct to DCC X and Y as analogue inputs; and,
  - to the electronic end stop circuitry (EES), which in turn outputs full in or full out logic position
- Absorber Panel Controls are located in the Main Control Room.
  - DRIVE MODE hand-switch has two positions: AUTO and MANUAL. In AUTO the panel controls are disabled and it allows RRS to control the in/out drive of the absorber rods via the DCC digital outputs. In MANUAL, the RRS control is disabled and the panel rod drive controls are enabled.
  - Manual Rod Selector is used when the panel controls are enabled to select the rod to be drive. The ALL position is used when it is desired to drive all the rods in, but it can only be used when the POWER MODE is selected to AC LINE. There is no ALL OUT selection.
  - IN/OUT Pushbuttons are used when in MANUAL mode, to drive a selected rod in or out. The pushbutton must be held in to continue a rod drive.
  - DROP Pushbutton is used to initiate the partial rod drop test.
  - POWER MODE Hand-switch has two positions: AC Line and VAR FREQ. In the VAR FREQ mode the variable frequency (VFI) power supply is applied to the motor drives. In AC LINE mode, the normal 60hz power supply is applied to the motor drives.

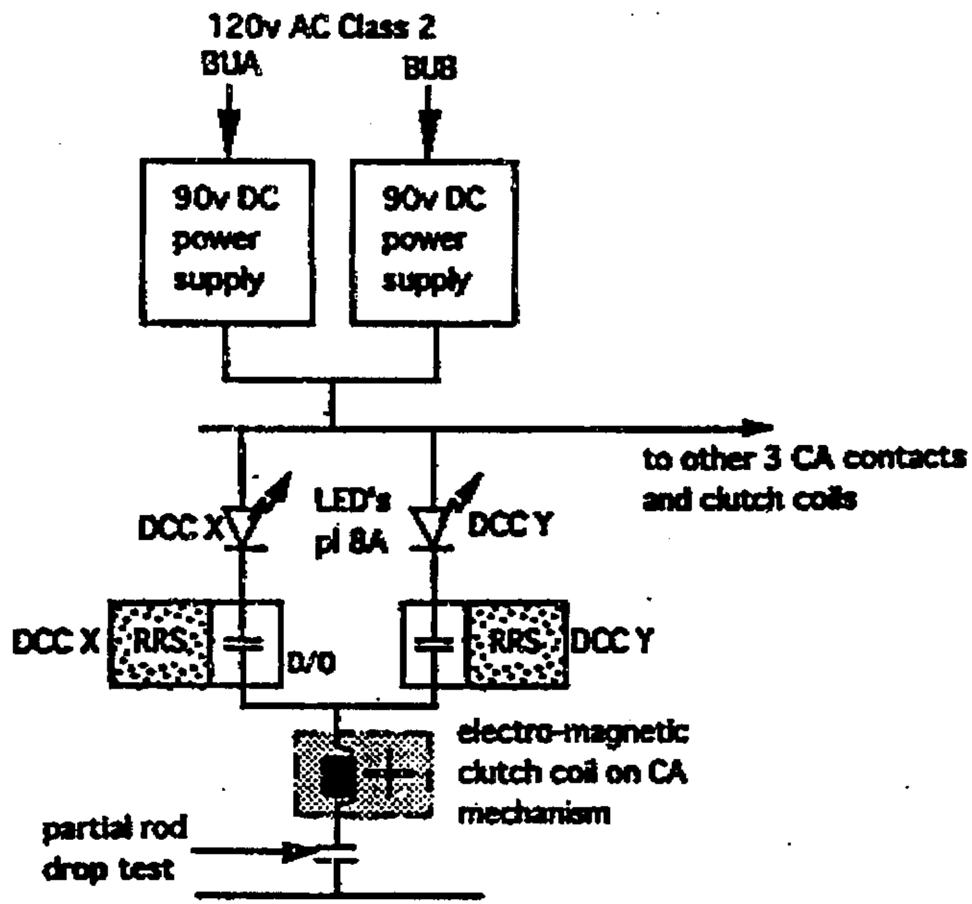
4.2 Absorbers – control logic

- Motor Control Logic. Each absorber has a forward and reversing contactor, which will close when a demand is received. A drive demand will be made by either the DCC D/O's or the IN/OUT pushbuttons, and the rod will drive until either:
  - the DCC D/O opens, or
  - the pushbutton is released, or
  - the rod reaches the end of its travel (from the Electronic End Stop logic)



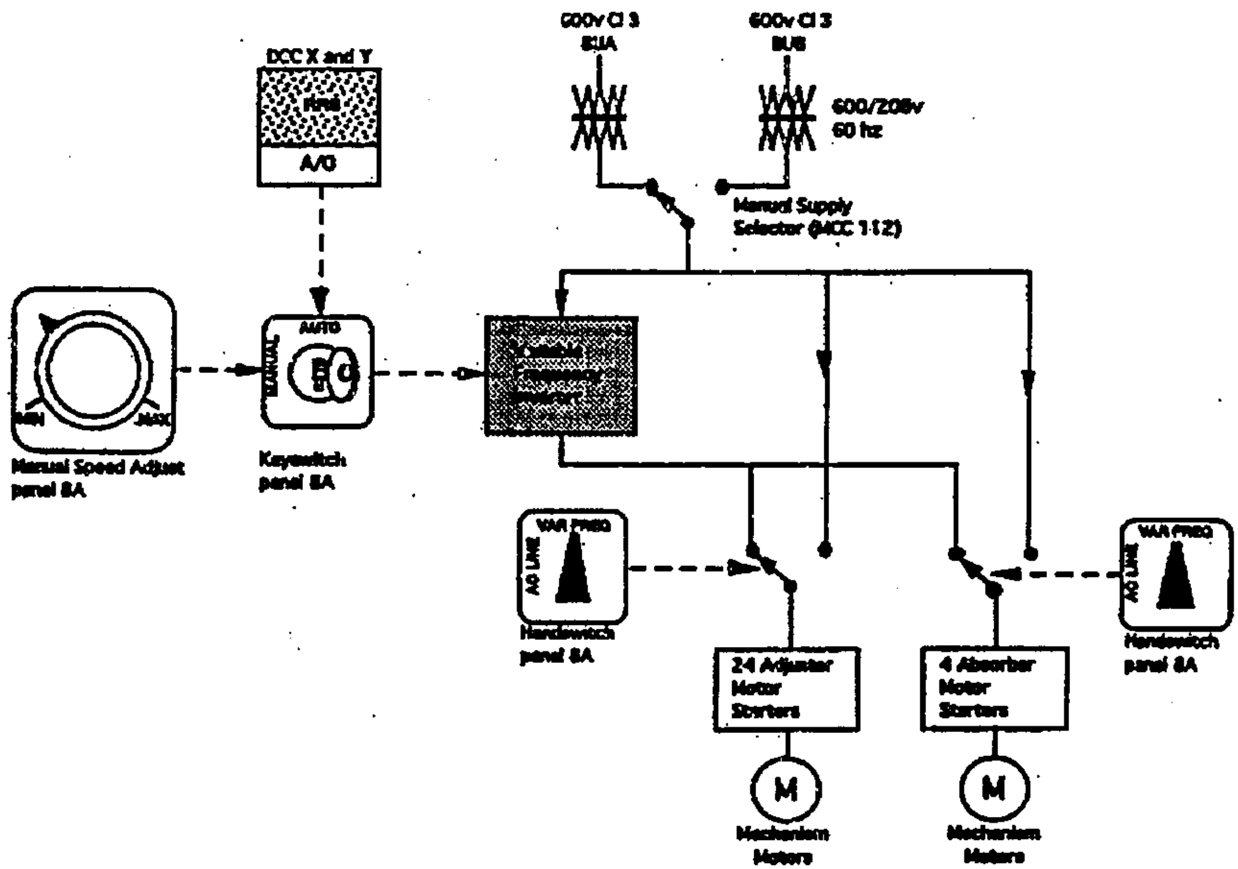
4.3 Absorbers – clutch control

- Clutch Controls are supplied by 2 x 90v DC power supply units each capable of 100% duty which are connected to different Class 2 120 V AC busses.
- Normally the DCC D/O's are closed (Stepback poised) which ensures that the clutches are energized and held closed. Since the D/O contacts from DCC X and Y are in parallel, it requires both DCC's to open their D/O's to interrupt the clutch current and de-energize the clutches.
- When a partial rod drop test is performed, the test contacts are opened for a few milli-seconds then closed, and the rod will drop approximately 10% in that time.



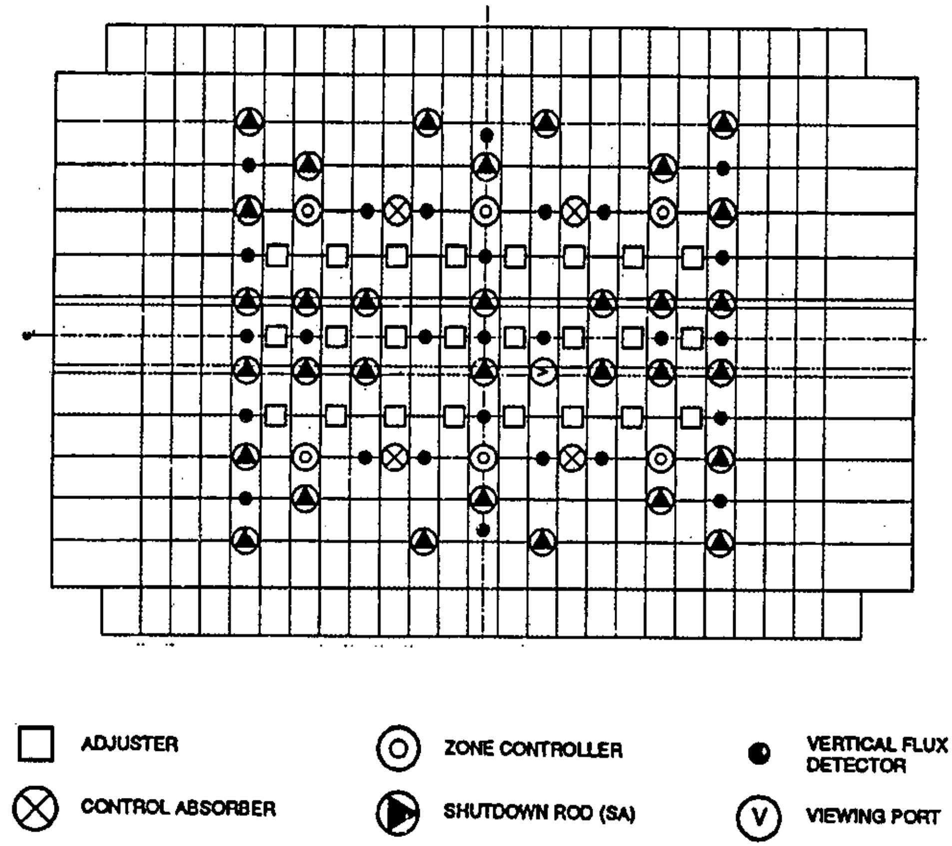
5.0 REACTIVITY MECHANISMS SPEED CONTROL

- The in/out drive speed of the adjusters and absorbers can be varied by changing the frequency of the power supply. Normal grid frequency is 60 Hz, which is referred to as AC LINE.
- The Variable Frequency Inverter (VFI) can vary its output frequency from 60 Hz down to 12 Hz (100% down to 20%).
- There are two power supplies, taken from 600v Class 3, each of which is transformed down to 208v. The 208v LINE supply feeds to, (a) the VFI, (b) an AC LINE supply to the adjusters and (c) an AC LINE supply to the absorbers
- The VFI can be controlled in either MANUAL or AUTO mode. In MANUAL the output frequency can be controlled by the operator using the speed control knob.
- In AUTO the output frequency is controlled by RRS via the DCC X or DCC Y A/Os.
- The drive speed of the devices, in AC LINE (i.e. 100% speed) are:
  - Adjusters - 100% travel in 60 seconds
  - Absorbers - 100% travel in 150 seconds.



6.0 SHUTDOWN RODS

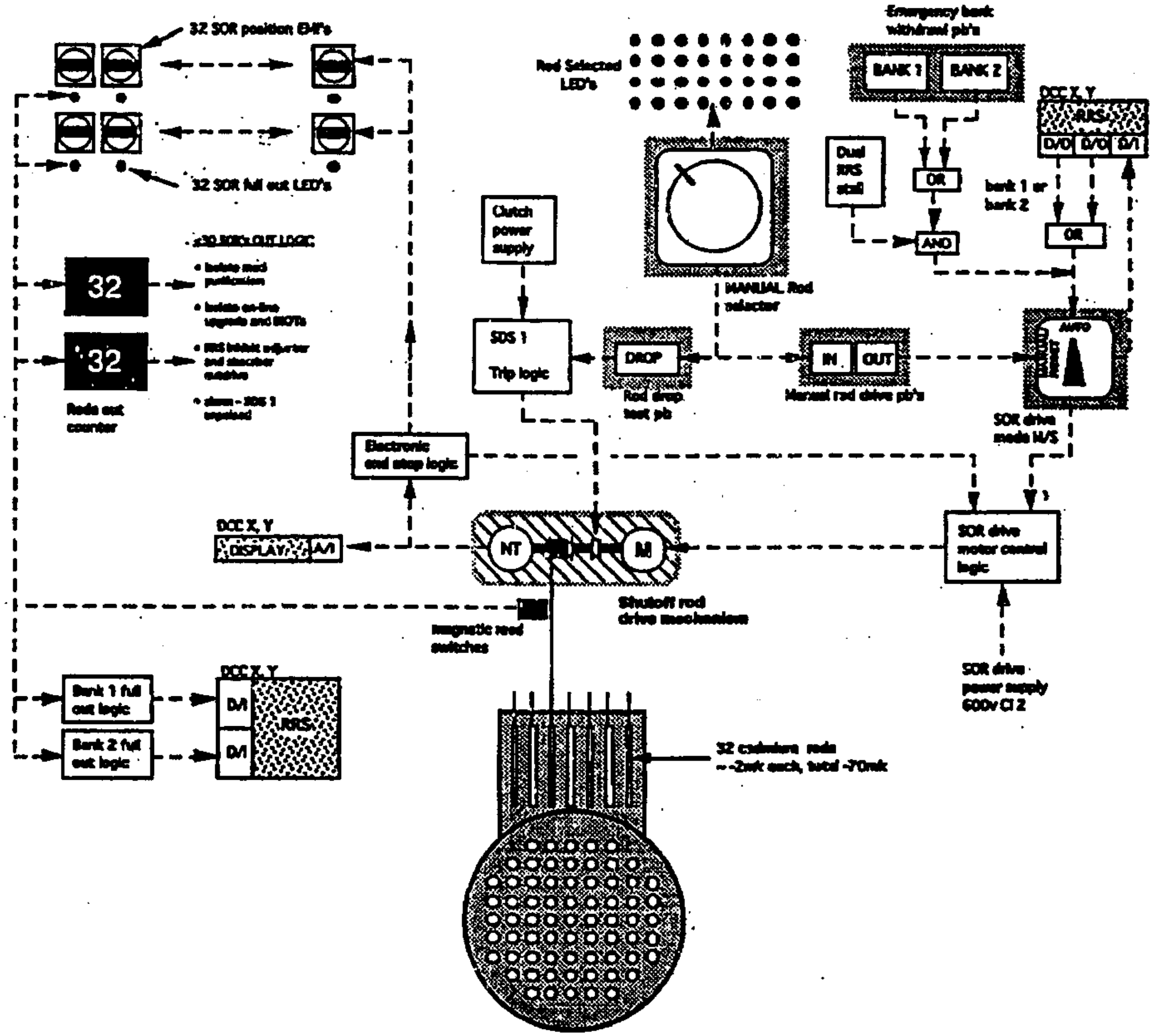
- the shutdown rods (SOR's) are part of the SDS #1 system, and their function is to stop the chain react5ion on a reactor trip
- the only involvement RRS has with the SOR's is to automatically withdraw the rods whenever they are not fully out of the core, for example, following a reactor trip or partial or full rod drop.
- 32 rods of cadmium and stainless steel;
- reactivity worth is -60 to -70 mk;
- spring assisted gravity drop, fully inserted in 2 seconds;
- normal withdrawal is controlled by the regulating system;
- the shutdown rods are withdrawn as soon as the trip signal has been cleared and the trip has been reset by the operator;
- all shutdown rods are withdrawn simultaneously;
- withdrawal of the shutdown rods is interrupted if:
  - ⇒ control is switched to manual, or
  - ⇒ the flux power error is excessive, or
  - ⇒ the reactor is tripped;
  - ⇒ if the log-rate exceeds 7 percent per second.



6.1 Shutdown Rods – Control signals and hand-switches

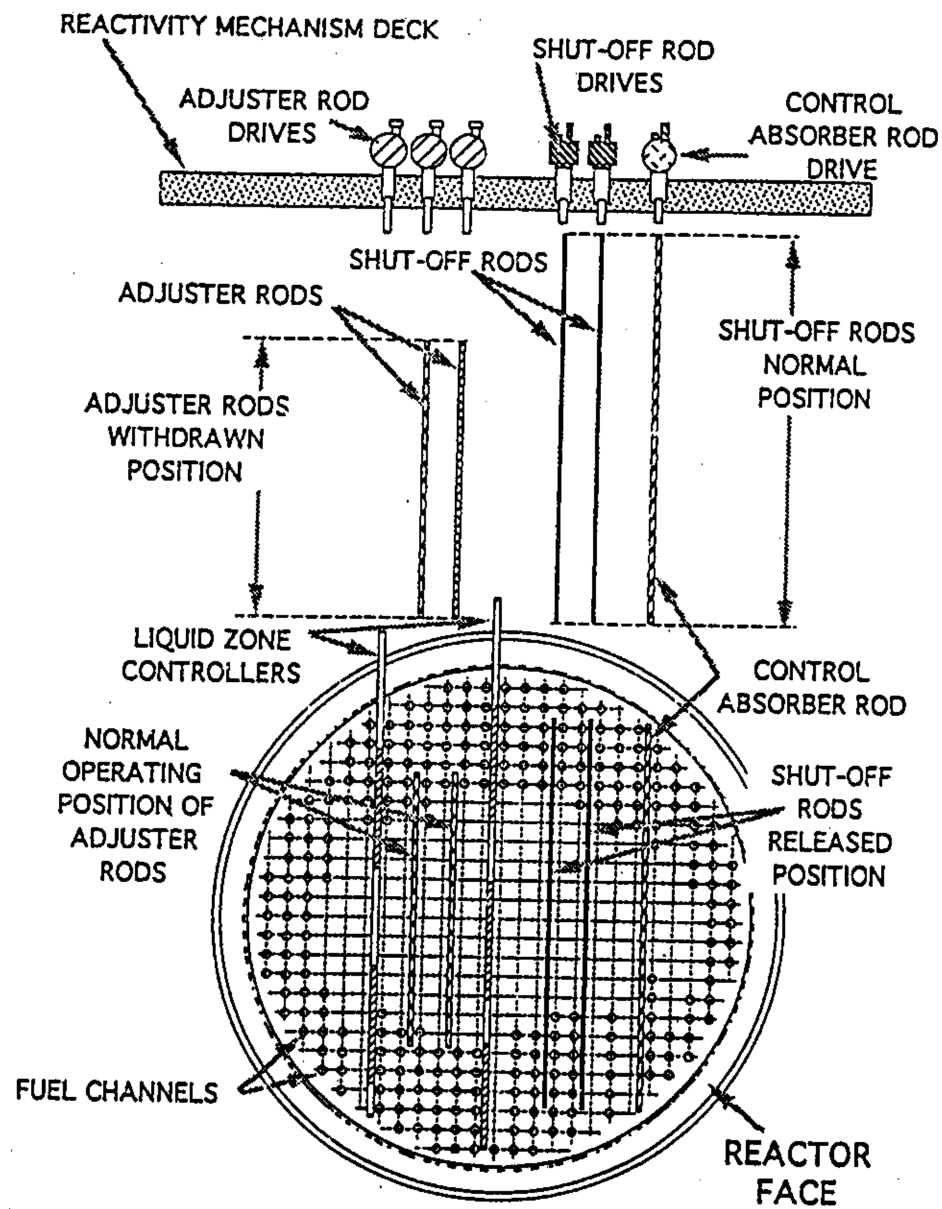
- The SOR drive mechanism is similar to that of a control absorber; it is controlled by means of the mode hand-switch that can be selected to MANUAL/RESET or AUTO.
- In MANUAL/RESET individual rods can be driven using the IN or OUT pushbuttons and the rod selector knob.
- In AUTO mode RRS is enabled to drive the rods by means of DCC X or Y D/Os to the 32 motor starters. The position of the mode hand-switch is monitored by DCC X and Y D/Is and is used to reset the Lograte drive inhibit on SOR withdrawal.
- Each SOR has a position potentiometer which is used to input rod position via DCC X and Y as A/Is. The potentiometers are also used for the electronic endstop circuit (EES) to provide logic for full in and full out status.
- Each SOR also has a 'full out' magnetic reed switch, and they are input to digital counters. The 2 digital counters have comparator circuits to detect less than 30 SOR fully out and output contact status, and they supply this signal to DCC X and Y as D/Is. These are used to cause the adjuster inhibit logic.

6.2 Shutdown rod schematic



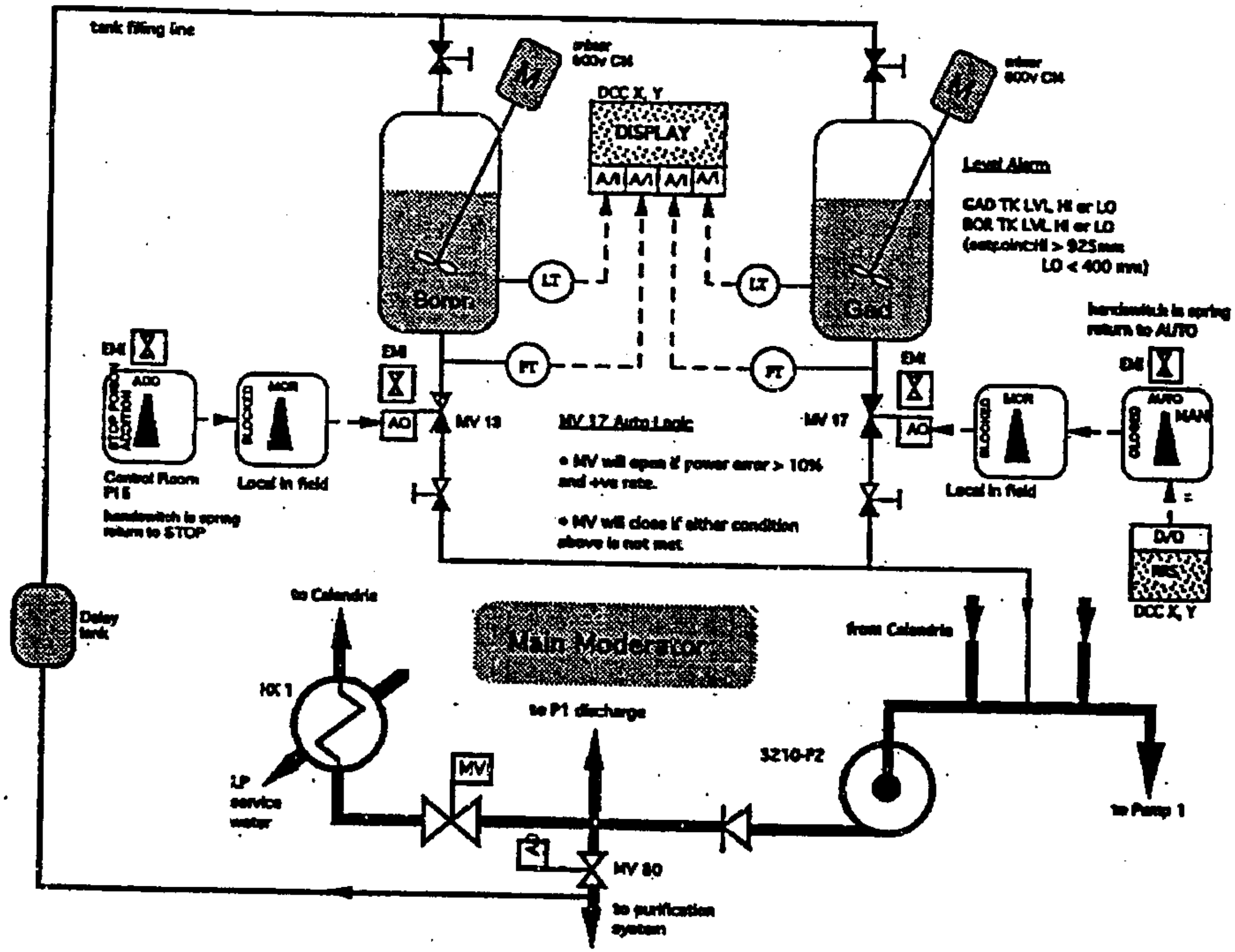
7.0 LOCATION OF REACTIVITY CONTROL DEVICES

- **all the reactivity devices discussed so far in this Module are located in a vertical position, between the fuel channels, in guide tubes inserted into the calandria – no reactivity control devices are located within the heat transport pressure boundary**
- **note the position of the reactivity deck: it must be high enough above the calandria to allow space for the rods when they are fully withdrawn from the core**
- **note also that from the fully withdrawn position the rods must travel past the reflector before they enter the core and can have a significant reactivity effect**



8.0 Liquid Poison Addition

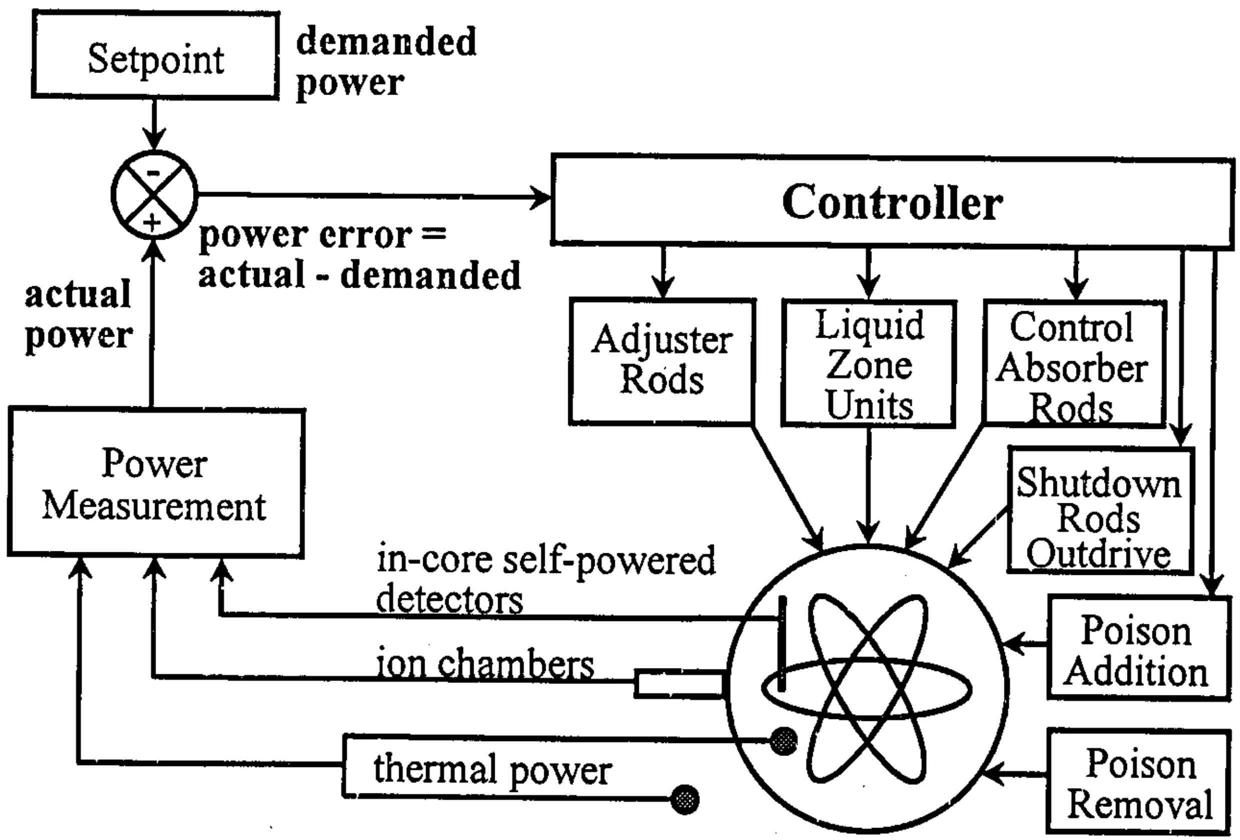
- Gadolinium addition valve 3271 MV17 is an air to open pneumatic valve, which is opened when its solenoid valve is energized.
- The controls for MV 17 are located in the Main Control Room; the handswitch has 3 positions:
  - STOP - the valve will close or remain closed;
  - AUTO – which is the normal setting, allowing the valve to be operated by RRS;
  - MANUAL, which is spring return to AUTO: while the H/S is in this position the valve is open



1.0 INTRODUCTION

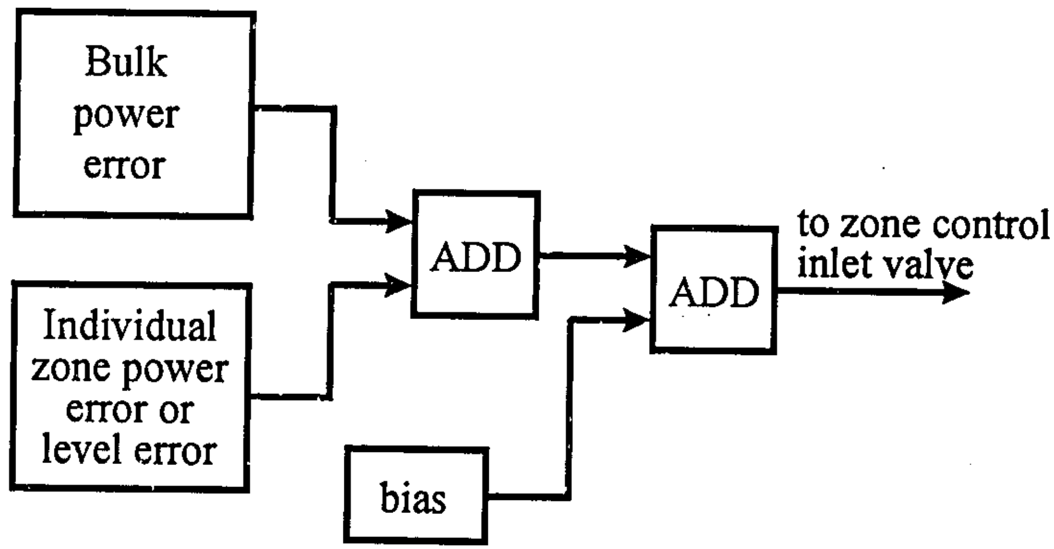
This module looks at the control algorithms in the CANDU Reactor Regulating System (RRS) which calculate the control signals to be sent to the various reactivity control devices. The control algorithms will be described for:

- liquid zone level control
- adjuster rods
- control absorber rods
- adjuster and absorber speed control
- poison addition
- shutdown rods withdrawal



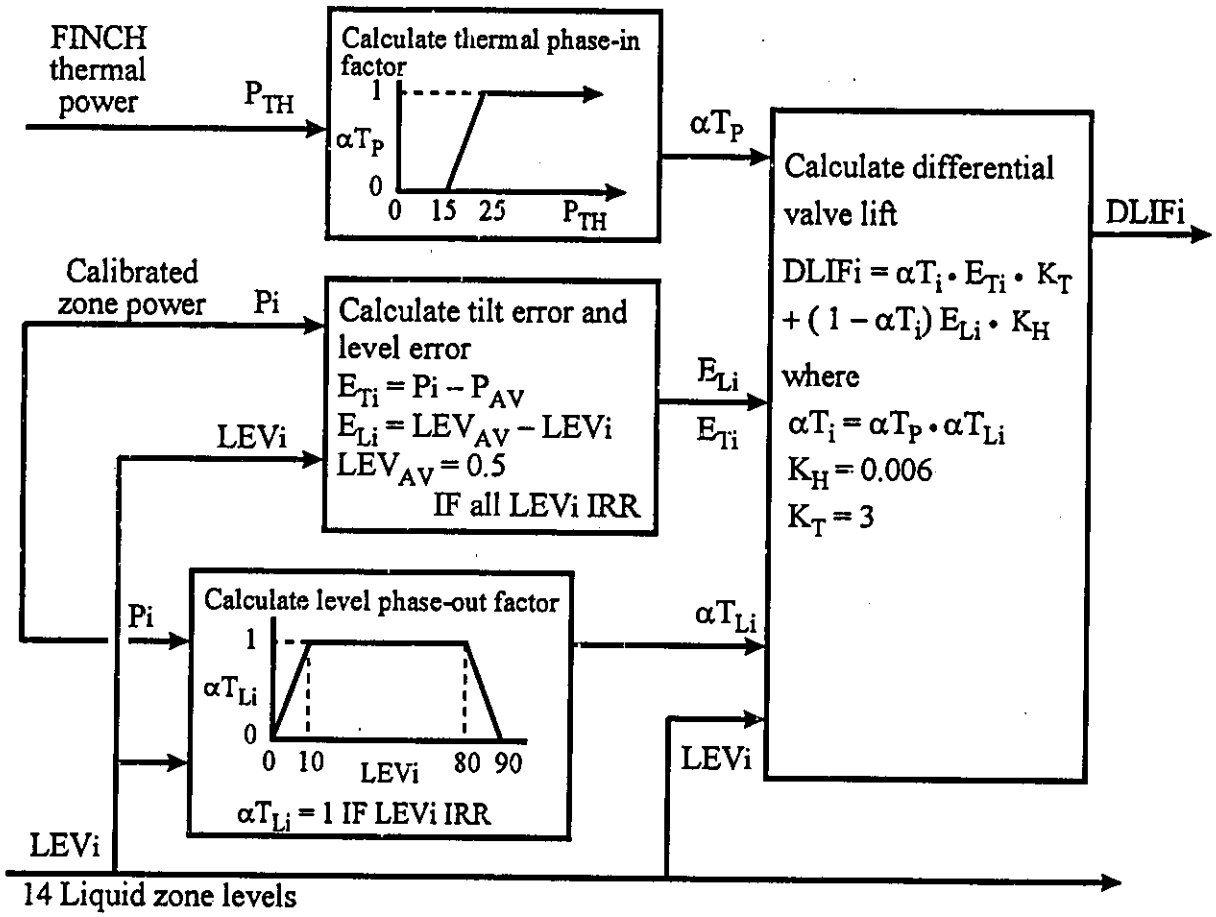
2.0 LIQUID ZONE LEVEL CONTROL

- the zones are the primary means of reactivity control in CANDU
- they are continuously adjusted to ensure bulk and spatial reactor power control, in response to setpoint changes as well as other reactivity variations
- the bulk power control signal is applied equally to each of the 14 zones
- in addition, each zone level control valve receives a specific control signal for spatial power distribution
- at low power control of the zones is based on liquid level, and is the same for every zone
- since the inlet valve must be open at steady state (zero error) to compensate for the constant outflow, a bias signal is applied to each valve
- a positive error will add to the bias, increasing the opening of the valve, hence the inflow, hence the level, producing more negative reactivity, and therefor reducing power and power error
- a negative error will have the opposite effect
- the bulk power error is simply multiplied by a conversion factor to produce the required signal to drive the valve to the required position



2.1 DIFFERENTIAL RELATIVE LIFT TERM

- at high power the differential lift term primarily controls the spatial (zone) flux
- to ensure that the water in the control compartments does not go too high or too low, water level control takes over from spatial flux control if the water level nears the full or empty levels
- at low power spatial flux control is not needed, and liquid level control is used to keep the water level in all the compartments at the same value
- the differential lift term is driven from a combination of zone power error (flux tilt) and water level error



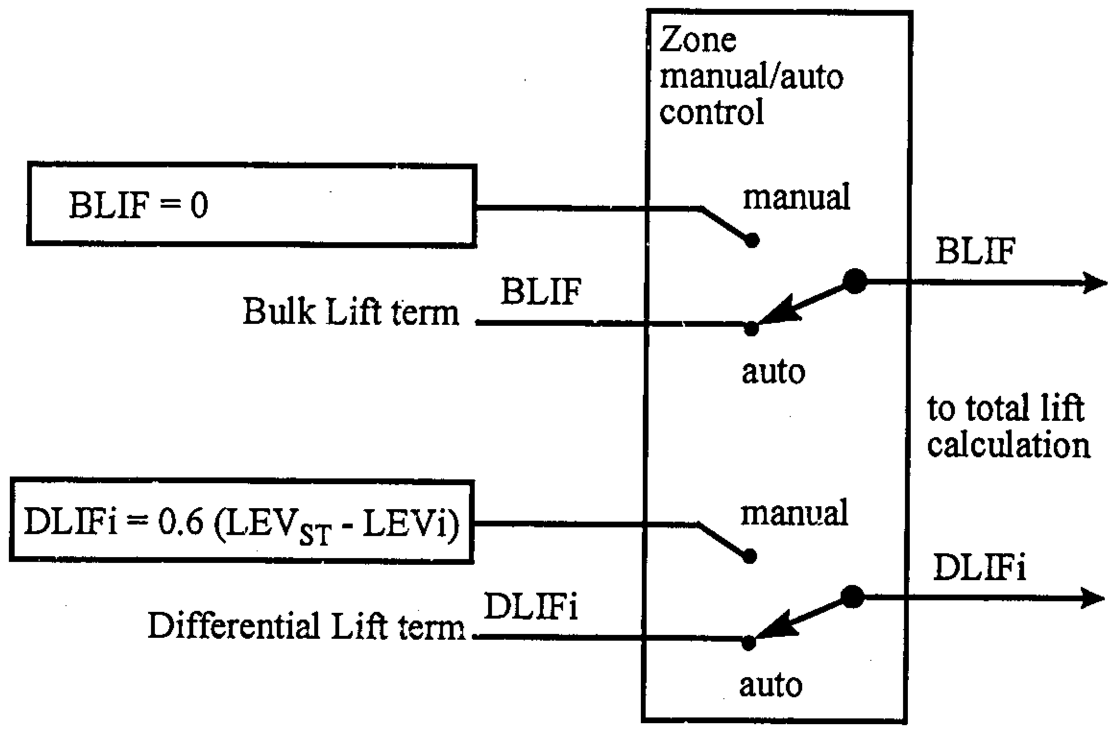
- the zone power tilt error is the difference between the measured power in the given zone and the average of all the 14 zones; if the in-core detector readings are IRR then zone thermal power is used instead of the flux measurement

2.1 DIFFERENTIAL RELATIVE LIFT TERM (continued)

- the zone level error is the difference between the measured water level in a given zone and the average of the 14 zone water levels (only rational zone level readings are used in computing the average, if all zone level readings are IRR, the average is set equal to 50%)
- the differential lift signal is calculated by combining the zone power error and level error signals in such a way that the level error predominates at low power and the power error at high power, but the level error can override flux tilt error if the level approaches the empty or full values
- the term αTi controls the extent to which power error or level error are in control: it is the product of the "Thermal Phase-in" factor and the "Level Phase-out" factor
- the "thermal phase-in factor" controls the extent to which spatial power control takes effect as thermal power rises, producing a gradual phase-in between 15% and 25% (and phase out on a power decrease)
- the "level phase-out factor" gradually removes the power error control signal from calculating the differential lift term as the zone level drops below 10% or goes above 80%, ensuring that the zones do not go either too low or too high.

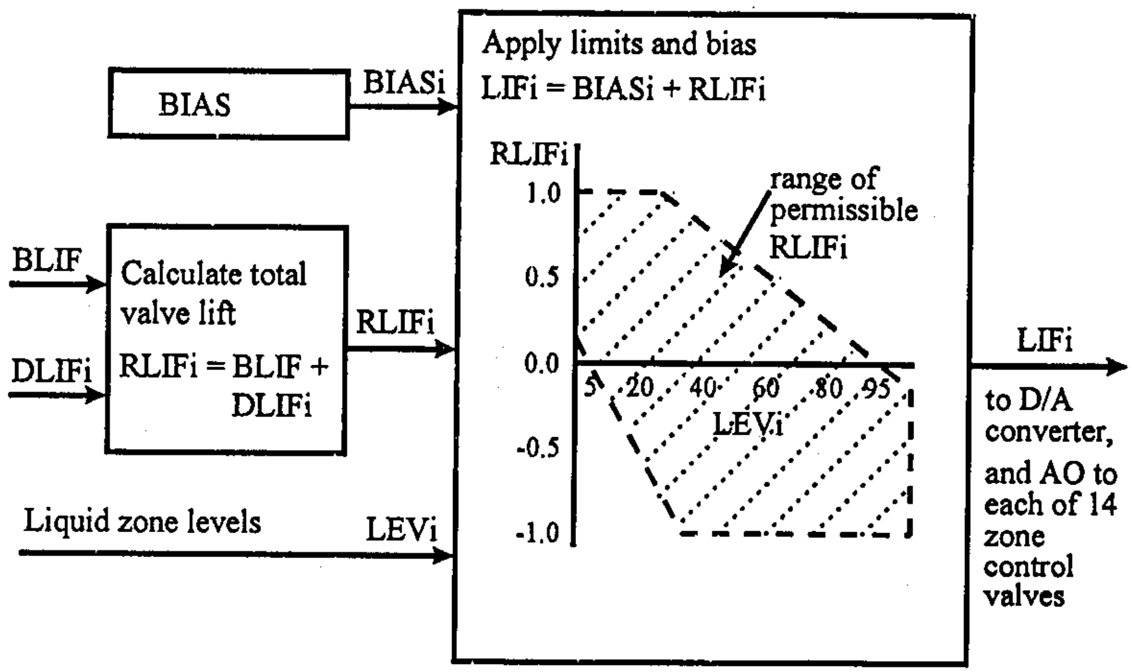
2.2 MANUAL ZONE CONTROL TERM

- when the reactor is shut down, it does not respond to power error, and the control of the zones is transferred to level control, and this condition is refereed to as "manual zone control"
- under "manual zone control" RRS is still controlling, but to a manually entered zone liquid level setpoint LEV_{ST}
- the following three conditions must be met for manual zone control to take effect:
    - the operator has entered a valid value for
    - measured power $P_{LOG} < 0.1\%FP$
    - power error E_P is -ve
- as soon as one of the above three conditions is no longer true, RRS will terminate manual zone control mode and resume normal power error control (i.e. revert to auto zone control)



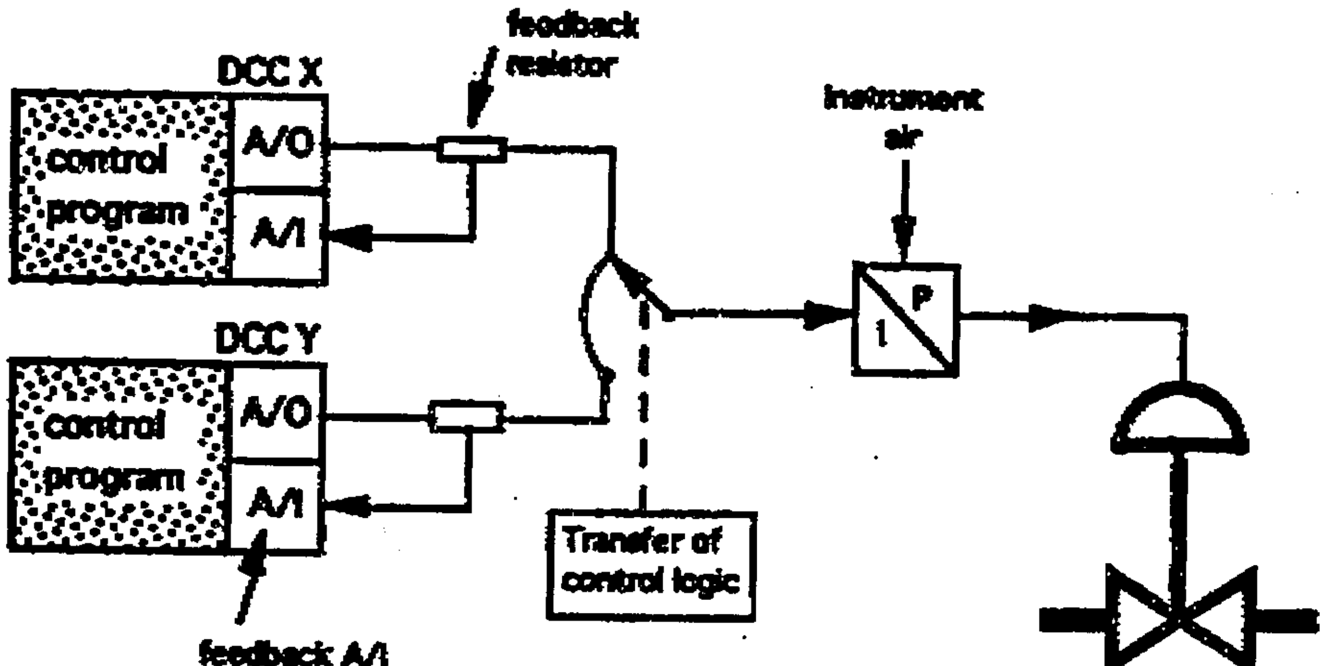
2.3 TOTAL LIFT TERM, BIAS AND LIMITS

- the valve lift term LIFi for each zone is the sum of the bias, the bulk and the differential lift terms
- the bias term is determined manually to provide the valve opening that matches the outflow from the zone, i.e. provides for constant zone liquid level
- the relative lift term RLIFi is the signal that provides the valve opening deviation from the bias signal for each valve; it has upper and lower limits applied to it so as to ensure that the zones do not fill or empty completely
  - if the zone level reaches 95% RLIFi becomes zero, i.e. only the bias signal is applied to the valve, which will just match the outflow and hence the level will not rise further (any further increase in zone level will result in a negative RLIFi, subtracting from the bias, and hence will begin reducing the zone liquid level)
  - if the zone level falls to 5% RLIFi is once again reaches zero, and at even lower levels the signal will go positive, i.e. adding a small amount to the bias value and producing additional lift, additional inflow and hence raising zone liquid level



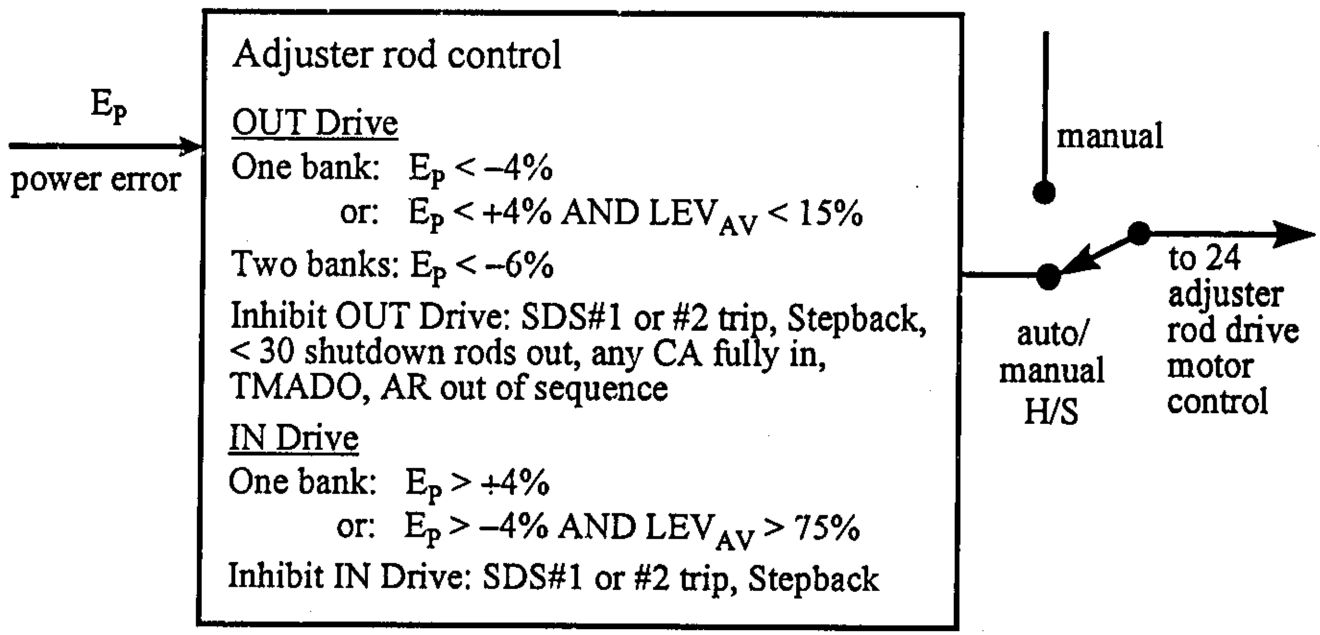
2.4 VERIFYING THE ANALOGUE OUTPUTS

- all 14 A/O signals are monitored as feedback A/Is in order to warn the operator of possible computer output problems that could affect zone control. The conditioned monitored and alarmed are:
  - signal irrational, if the loop current is either below 4 mA or above 20 mA
  - if the A/O has deviated more than 10% from the demanded lift signal LIFi; if 4 or more zones detect such a feedback error, then RRS will fail off, and transfer control to the standby computer



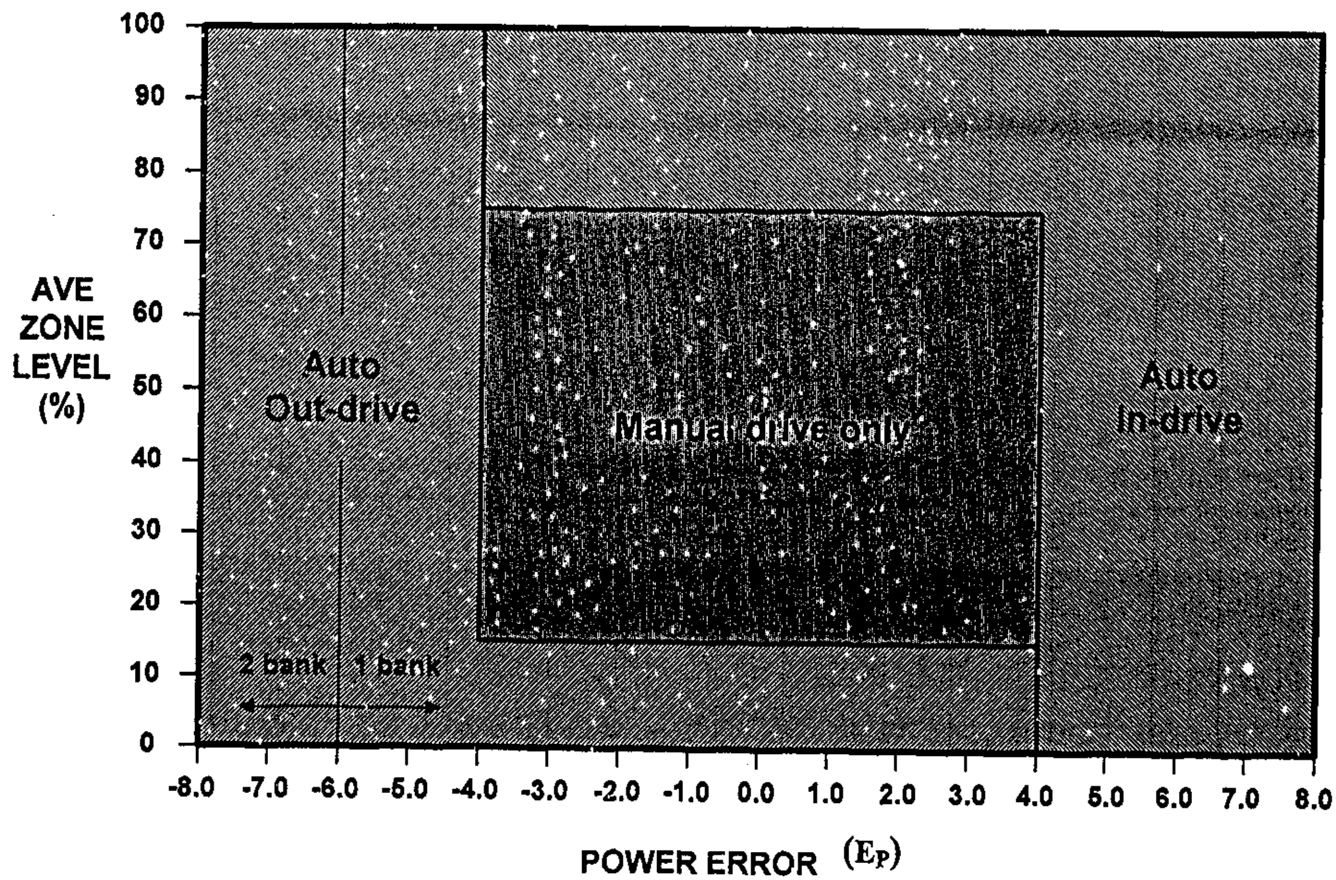
3.0 ADJUSTER RODS

- the Adjuster rods are normally fully inserted into the core, resulting in a flattening of the flux and providing a reserve of positive reactivity when the liquid zones have used up their range of control (reached the low level limit), and in particular as a reserve of positive reactivity (approximately 17 mk) to override xenon transients following certain power level reductions.
- CANDU-9 reactors are designed to have 24 adjusters, CANDU-6 units have 21 adjusters.
- the adjuster rods are normally on AUTO and controlled by RRS, they are moved in "banks", i.e. in groups of 2, 3 or 4 rods, in a predetermined sequence arranged in such a way as to have approximately the same reactivity worth, and to minimize the spatial flux distortion when a given bank is moved
- can be controlled manually, either in "banks" or as individual rods
- once a "bank drive" has been initiated, it will continue to completion, unless it enters the opposite auto drive zone, or a drive inhibit is encountered
- RRS monitors the movement of each rod and will alarm if one is stuck or moves out of sequence, or if more than 8 adjusters are driving out



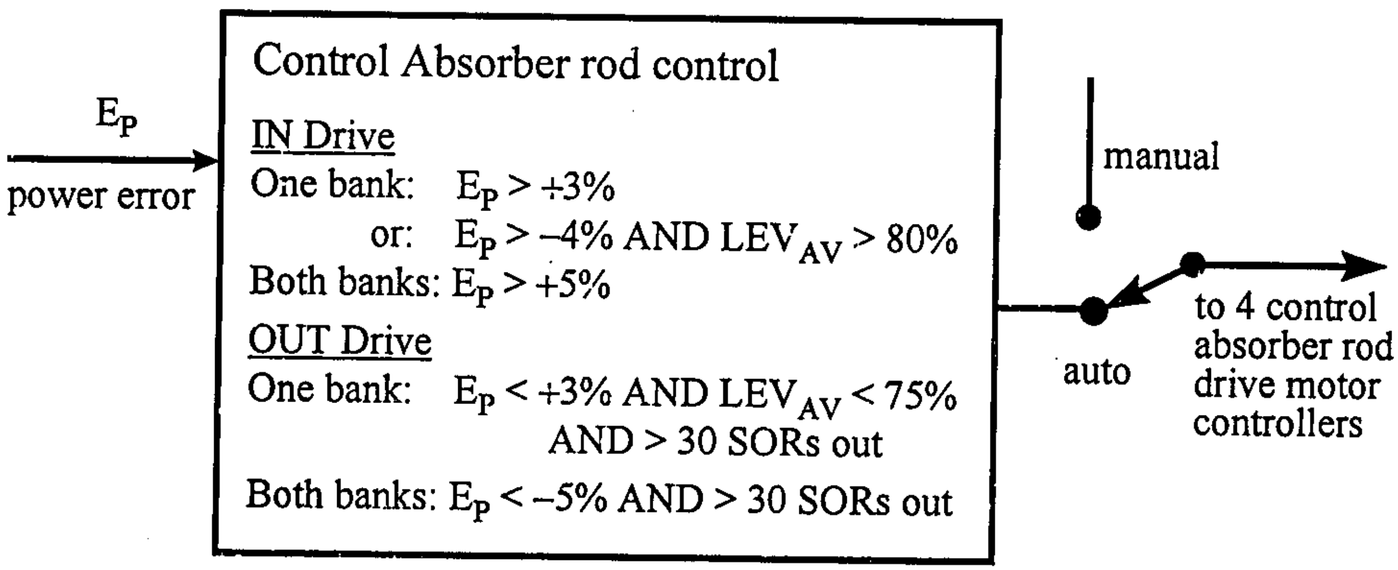
3.1 REACTIVITY LIMIT CONTROL DIAGRAM FOR ADJUSTERS

- the reactivity limit control diagram is the key to the RRS control algorithm: the horizontal scale is power error E_P (i.e. includes both proportional and derivative terms), and the vertical scale is Average Zone Level (LEV_{AV})
- under steady state conditions or during small power level changes are slow rates, the liquid zones are able to control reactor power
- under conditions when the magnitude of the power error is too large and/or the average zone level is too high or too low, then the liquid zones alone cannot control the reactor and the adjuster rods are needed to provide additional reactivity (positive or negative, but depending on the position of the rods at the time the control request is made, they may or may not be able to have the desired effect)



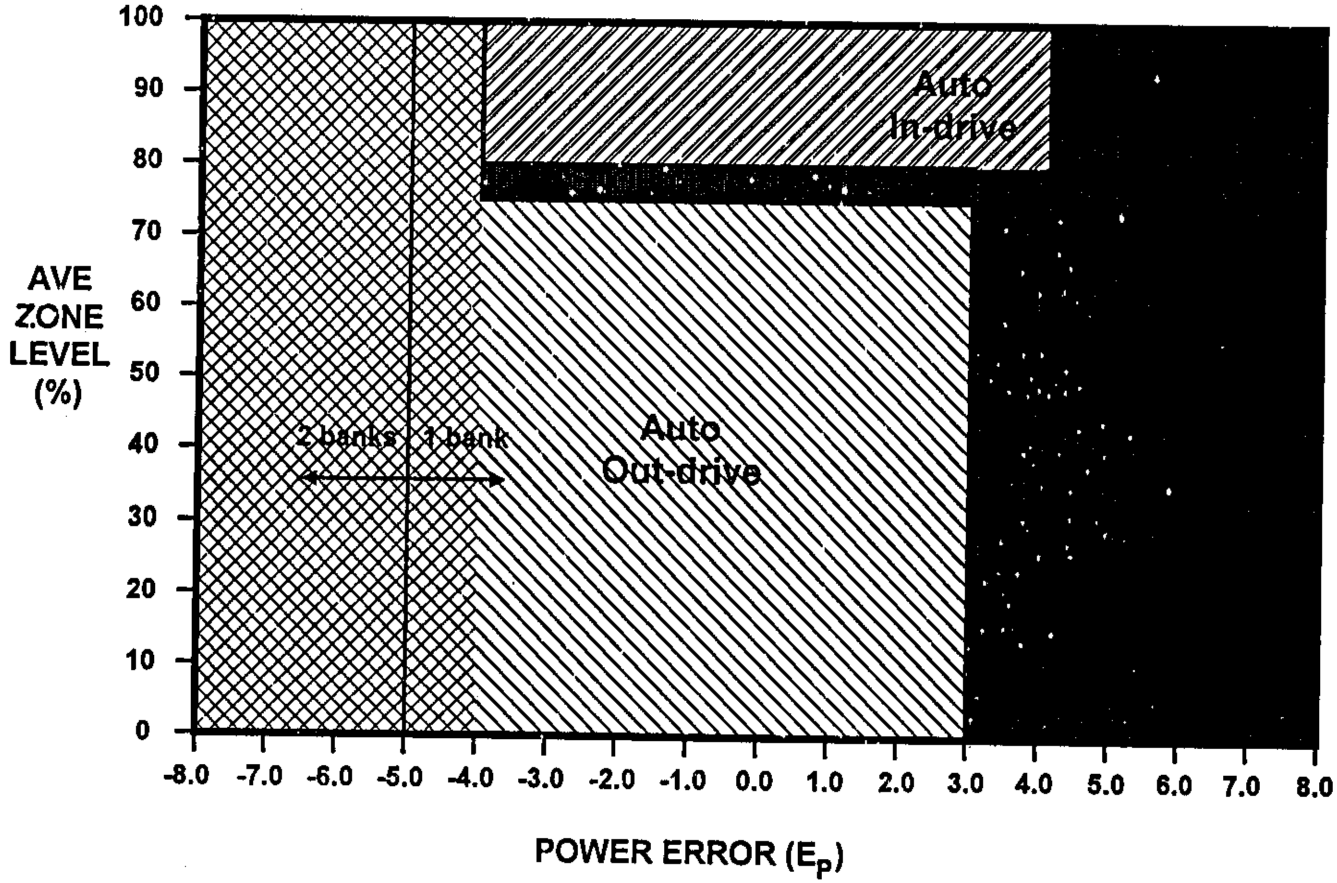
4.0 CONTROL ABSORBER RODS

- the usual position of the Control Absorber rods is completely outside the core; they can be driven into the core to provide negative reactivity when the liquid zones have used up their range of control (reached the high level limit)
- there are four control absorber rods, in two banks of two rods each, normally on AUTO and controlled by RRS, but can also be controlled manually, either in "banks" or as individual rods
- the control absorbers can also be dropped into the core fully or part way, but this function is not controlled by RRS, but is part of the Stepback program, and will be discussed in Section 8
- total reactivity worth of the four control absorbers is 9 mk
- RRS monitors the full in and out status of the control absorbers and will generate end-of-travel alarms if discrepancies exist (the same function is present for adjuster rods)



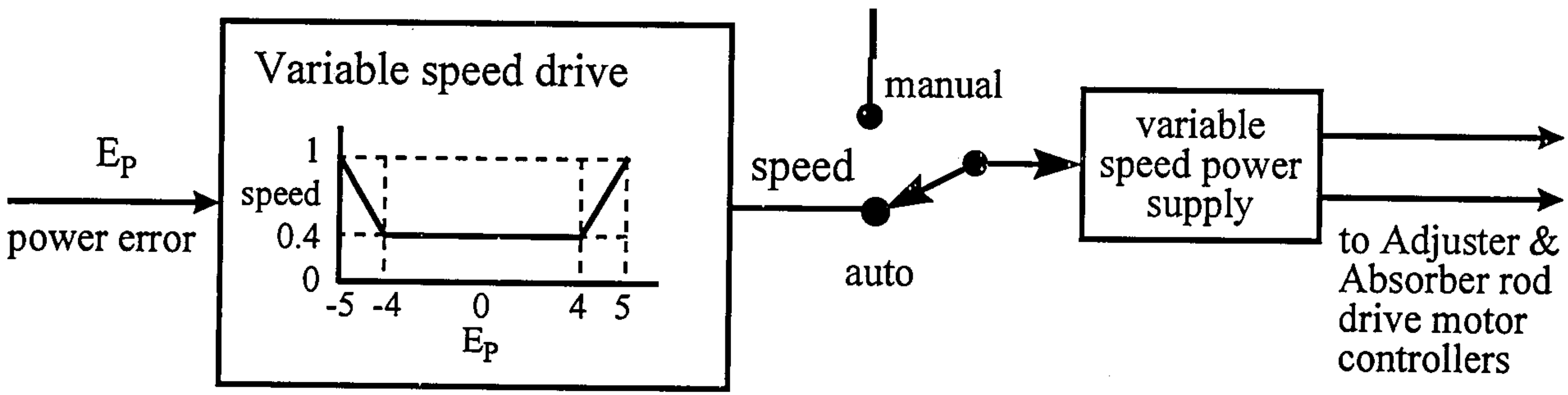
4.1 REACTIVITY DIAGRAM FOR CONTROL ABSORBERS

- the in- and out-drive regions for the control absorbers reinforce the actions of the adjusters as seen on the reactivity limit control diagram
- there is a narrow "deadband" between 75% and 80% liquid zone level in which rod drive is stopped from either direction, this is to prevent the cycling of the in- and out-drives as the liquid zone level responds to the control absorber action, for example following a Xenon transient
- when in the "in-drive" zone, the first bank will continuously drive in until either the power error is sufficiently reduced or the average zone level falls below the "in-drive" line; similarly when in the "out-drive" zone there will be a continuous out-drive until either the power error increases sufficiently or the average zone level rises above the "out-drive" line



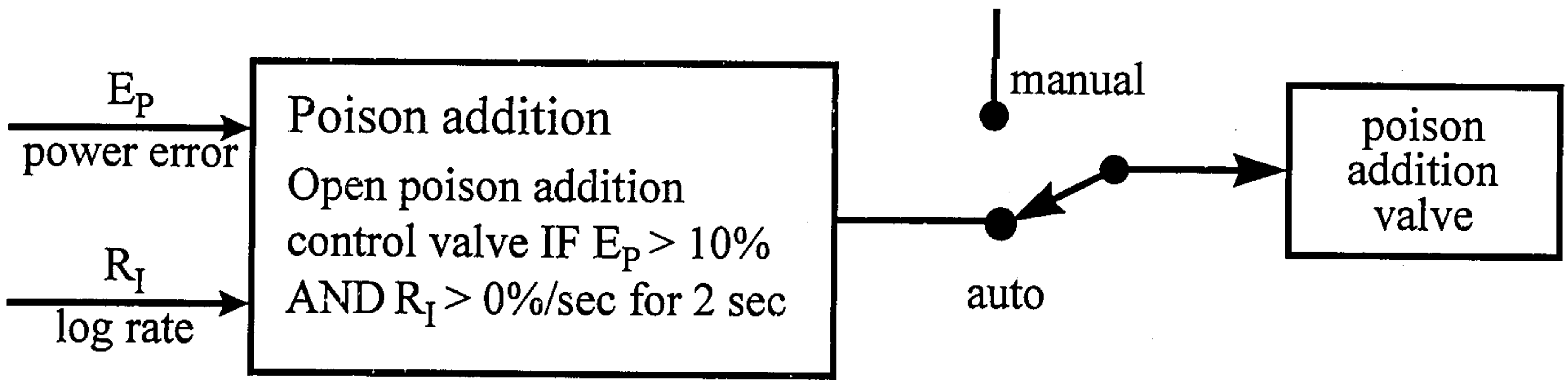
5.0 VARIABLE SPEED CONTROL FOR ADJUSTERS AND ABSORBERS

- when the power error is large it is desirable to change reactivity at the maximum permissible rate (for example when attempting a poison override operation), while at small power errors a much slower rate of reactivity change is desired to achieve smooth and stable control
- the above design objective is achieved by having a variable speed drives for the adjuster and absorber rods
- the maximum speed is used when the magnitude of the power error is above 5%, while below 4% the speed is reduced to 40% of the maximum, with a linear variation between 4% and 5%; on manual the speed is fixed at 20% of the maximum rate



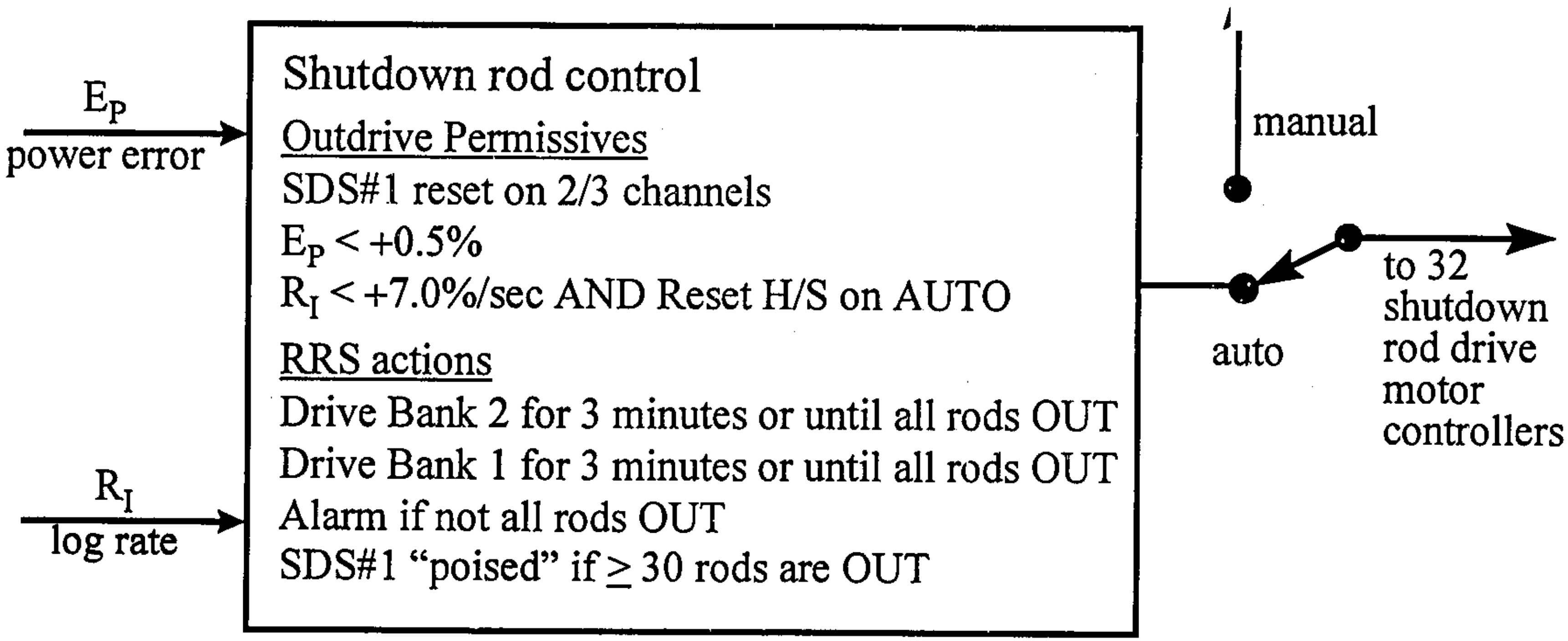
6.0 POISON ADDITION

- auto poison addition will only occur if the power error exceeds +10% of present power and there is a positive log rate (i.e. power is rising), and these conditions must exist for four consecutive program executions (i.e. 2 seconds)
- this method of reactivity control is a back-up to the liquid zones and control rods, when these do not have the desired effect



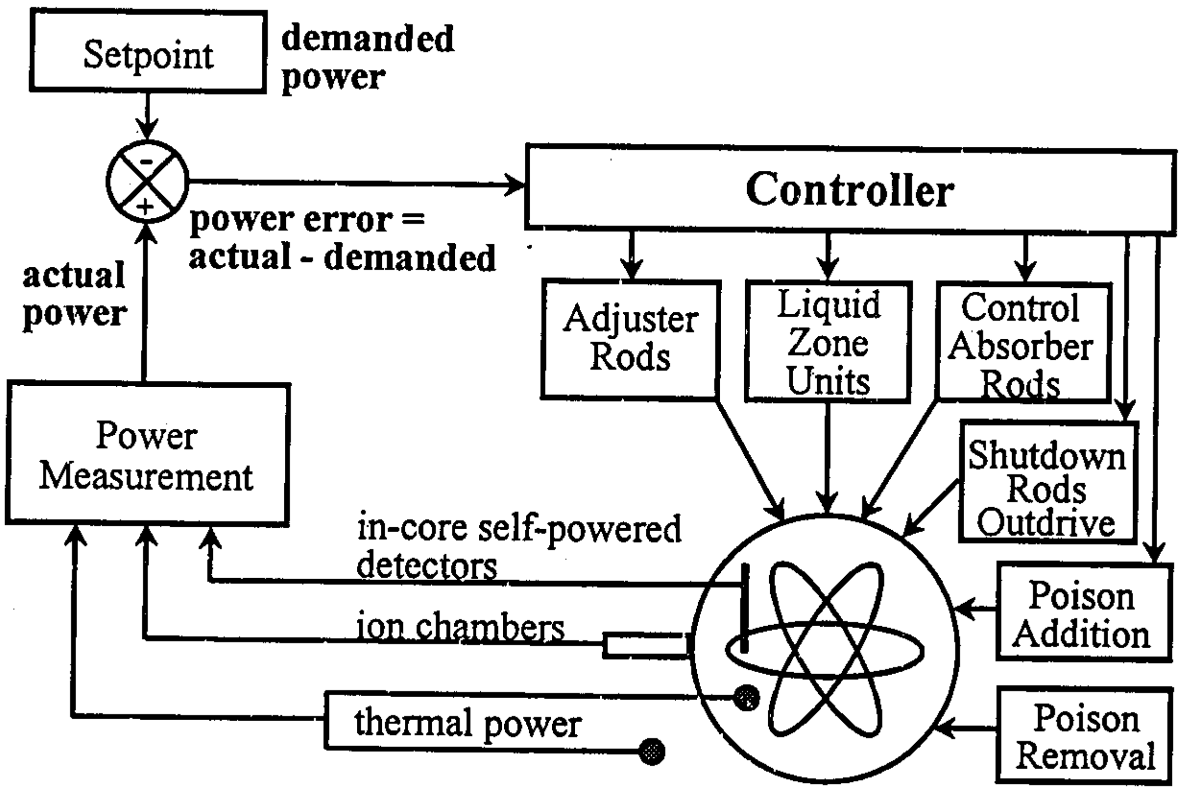
7.0 SHUTDOWN RODS CONTROL

- the purpose of the Shutdown rods is to shut down the reactor on an SDS#1 trip by dropping the rods into the core
- the shutdown rods are only controlled by RRS for the purpose of withdrawing them from the core following a SDS#1 trip, or after a partial rod drop test: RRS has the necessary information to withdraw the shutdown rods while maintaining control of reactor power at the setpoint
- the 32 shutdown rods are arranged in two banks of 16, and only one bank at a time may be driven out: the bank driving times are monitored and an alarm is given if all rods are not out within the required time



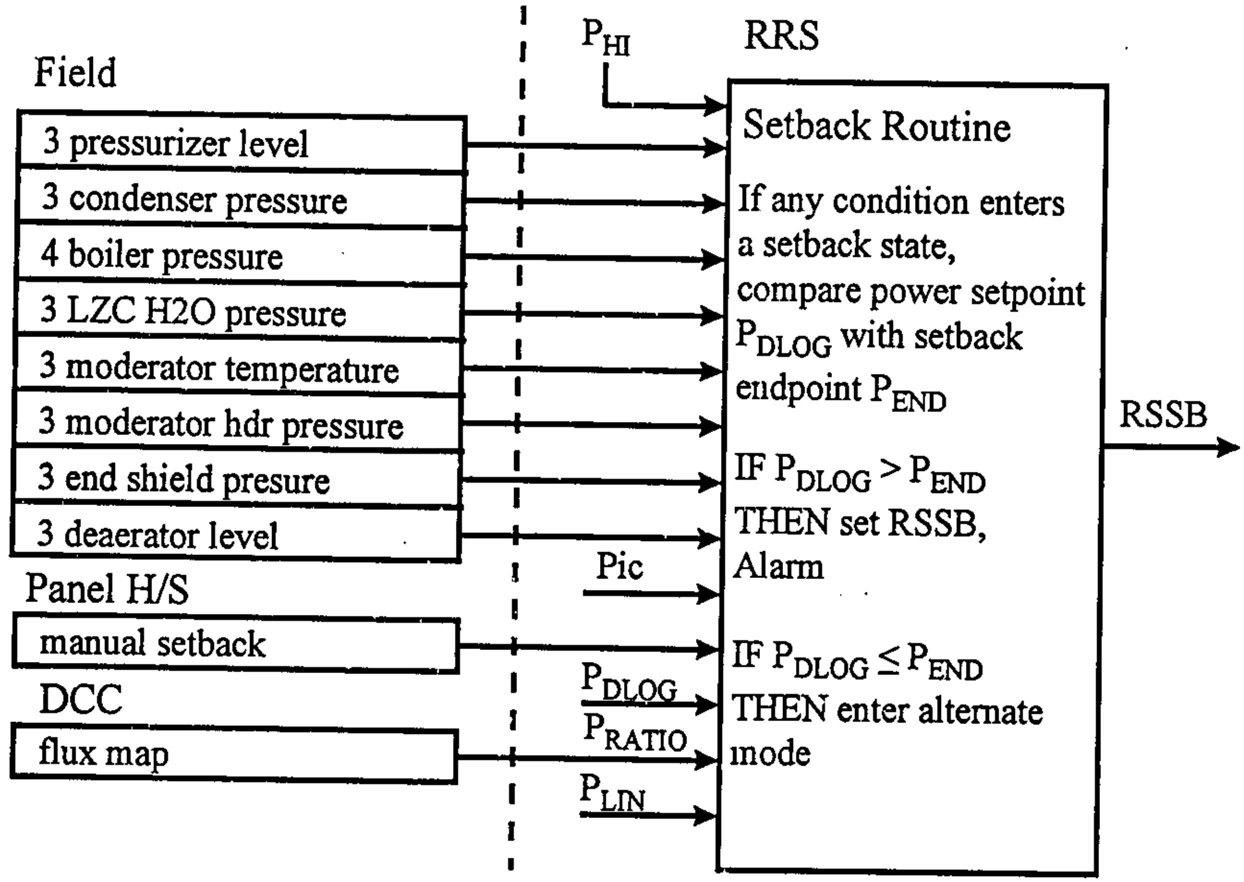
1.0 INTRODUCTION

- There are special plant operating conditions (usually as a result of some operation outside the normal design envelope) where the Reactor Regulating System is not able to reduce reactor power sufficiently quickly and the potential for a reactor exists. In many such cases it is possible to avoid the reactor trip by a rapid reduction of reactor power.
- If the power reduction should take place by ramping down the reactor power setpoint, the SETBACK function is called into operation.
- If the power reduction needs to take place in a step, the STEPBACK function is called into operation
- SETBACK is a part of RRS, and works via the demanded power routine
- STEPBACK is independent of RRS, but is a program located in both DCCs, it acts by de-energizing the control absorber clutches to allow the rods to drop completely or partially into the core



2.0 SETBACK ROUTINE

- reactor setback is the forced reduction of the reactor power setpoint at specified rates and endpoints, depending on the condition that initiated the setback
- the Setback Routine in RRS determines from either field inputs or from RRS generated values when a Reactor Setback is required
- if a condition requiring Reactor Setback exists, and if the current reactor power setpoint P_{DLOG} is above the setback endpoint, then the setback rate term RSSB is set and passed to the setpoint calculation (note that reactor setback only acts on the reactor setpoint calculation)



- if the process condition recovers, or the reactor power setpoint reaches the required endpoint, then the setback automatically ends, and the setback term is reset to +0.8%FP/sec
- whenever reactor setback has been activated, unit control mode is transferred to 'Alternate' mode, and stays this way when setback is terminated; BPC and UPR change to 'Alternate' mode when setback starts

2.1 SETBACK CONDITIONS

- to protect fuel and reactor structures

Condition	Initiation logic	Clear logic	Endpoint	Rate
high local flux	$P_{PEAK} > P_{HI} + 7\%$	$P_{PEAK} \le P_{HI} + 5\%$	$P_{DLOG} \le 60\%$	–0.1%/sec
spatial control off normal	1) 3 or more Pic are IRR AND FLUX is OFF 2) highest Pic > P_{HI} + 10% 3) when $P_{DLOG} > 60\%$ $Tilt_{max} > 20\%$ or when $20\% < P_{DLOG} < 60\%$ $Tilt_{max} > 40\%$	< 3 Pic are IRR OR FLUX is turned ON highest Pic < P_{HI} + 5% when $Tilt_{max} < 15\%$ when $Tilt_{max} < 39\%$	$P_{DLOG} \le 60\%$ $P_{DLOG} \le 60\%$ $P_{DLOG} \le 60\%$ $P_{DLOG} \le 20\%$	–0.1%/sec
liquid zone water pressure low	zone supply press < 550 kPa	zone supply press > 650 kPa	$P_{DLOG} < 60\%$	–0.2%/sec
high moderator temperature	moderator temp > 72°C	moderator temp < 71°C	$P_{DLOG} < 2\%$	–0.8%/sec
low moderator header pressure	2 of 3 pressure readings < 166 kPa(g) for 25sec	0 or 1 pressure readings < 166 kPa(g) for 25sec	$P_{DLOG} \le 2\%$	–0.8%/sec
pressurizer high level	level > 9.53 m	level < 9.14 m	$P_{DLOG} \le 2\%$	–0.1%/sec
low end shield cooling supply pres	supply press < 350kPa for 25 sec	supply press ≥ 350kPa	$P_{DLOG} \le 2\%$	–0.8%/sec

2.1 SETBACK CONDITIONS (CONTINUED)

- to protect against loss of heat sink, damage to turbine and in case of operator observed events

Condition	Initiation logic	Clear logic	Endpoint	Rate
low deaerator level	D/A level < 50%	D/A level > 52%	$P_{DLOG} \leq$ 2%	–0.8%/sec
high boiler press	BP > 4850 kPa	BP < 4800 kPa	$P_{DLOG} \leq$ 11%	–0.5%/sec
high condenser pressure	cond pres > 17 kPa(a)	cond pres < 17 kPa(a)	$P_{DLOG} \leq$ 30%	–0.2%/sec
manual setback	SETBACK handswitch in main control room selected ON	SETBACK handswitch in main control room selected OFF	$P_{DLOG} \leq$ 2%	–0.5%/sec

3.0 STEPBACK PROGRAM

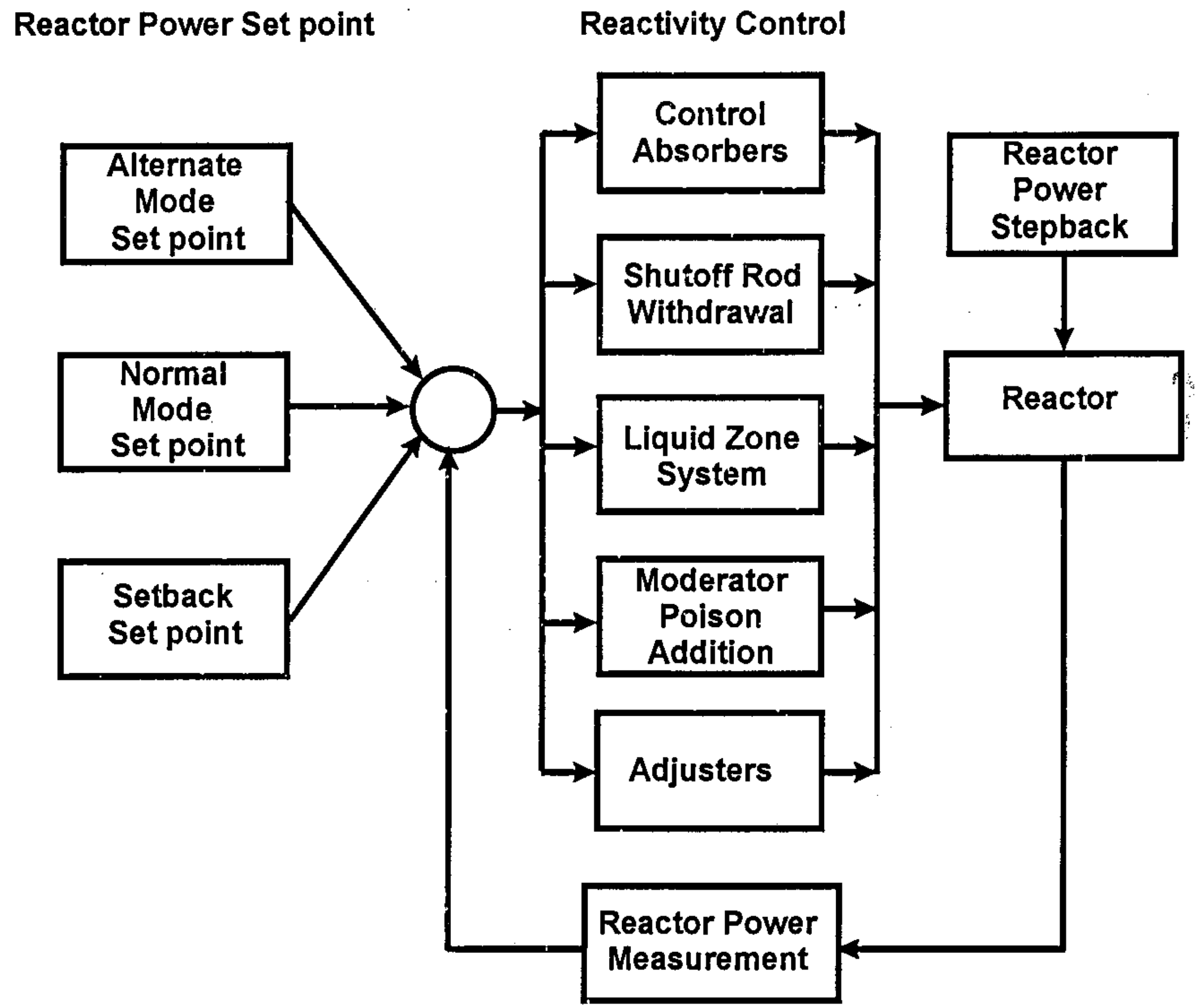
- reactor stepback provides the means by which reactor power can be reduced very quickly without tripping the reactor: it is used principally to avoid reactor trips under certain conditions that only require a rapid reduction of reactor power
- the Stepback Program is independent of RRS and executes in both control computers: both DCCs must identify the requirement for Stepback to occur
- a dual computer stall will result in a Setback
- the fast power reduction is achieved by dropping (partially or completely) the four control absorbers in the core
- if the initiating conditions clear before the stepback is completed the clutches can be re-energized and the rod drop terminated
- whenever reactor stepback has been activated, unit control mode is transferred to 'Alternate' mode, and stays this way when stepback is terminated; BPC and UPR change to 'Alternate' mode when stepback starts

3.1 STEPBACK CONDITIONS

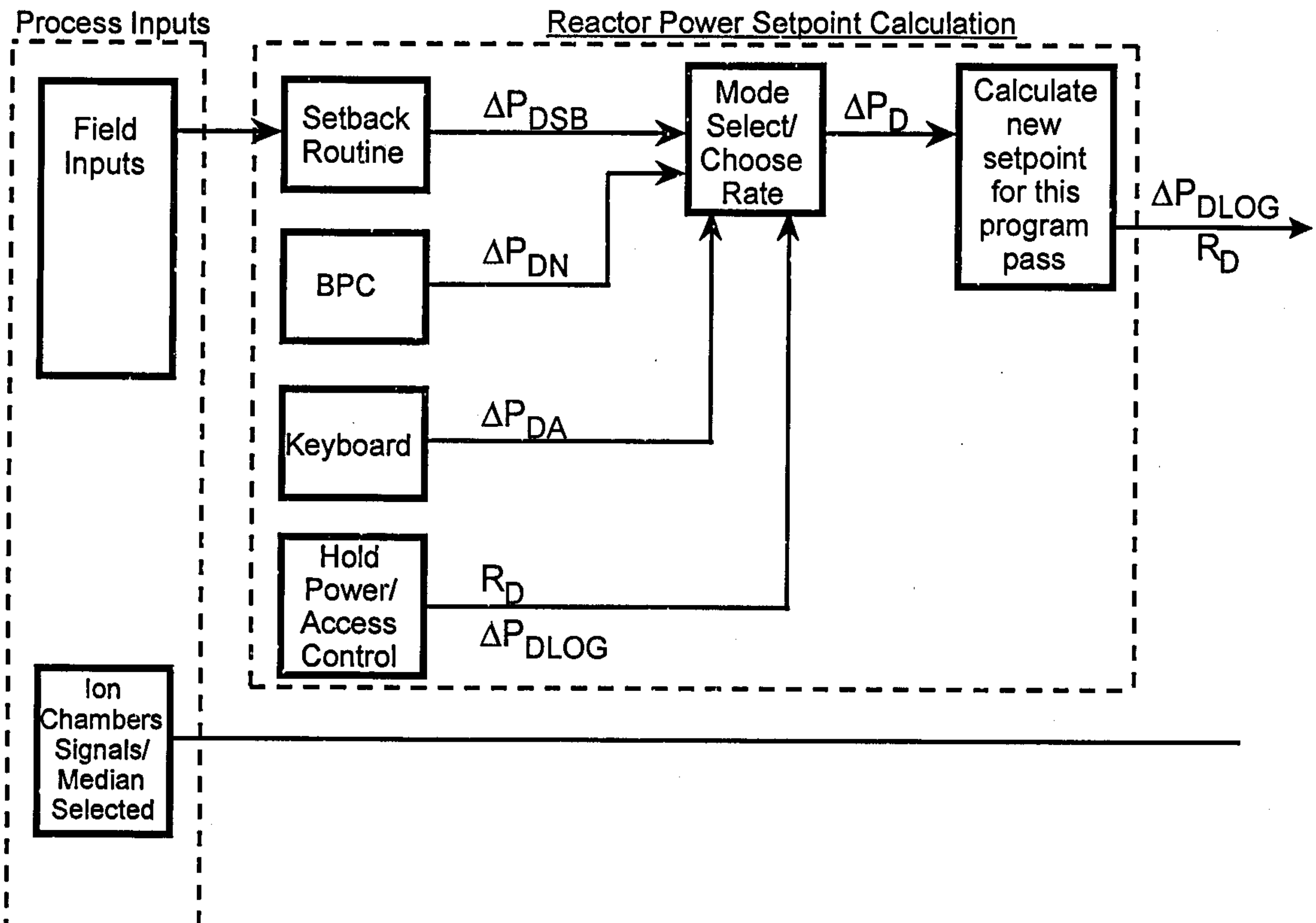
Condition	Purpose	Initiation logic	Clear logic	Endpoint
reactor trip	provide additional negative reactivity	either SDS#1 or SDS#2 trip	reactor trip reset AND > 30 SORs out of core	full drop
high log N rate	protect against loss of regulation	log N rate > 7%/sec	log N rate < 7%/sec	full drop
high zone flux	protect fuel	4 zone powers > P_{HI} + 4%	fewer than 4 zone powers > P_{HI} + 4%	full drop
1 HT pump trips	protect fuel	1 pump trips AND P > 70%	P < 65%	partial drop
2 or more HT pumps trip	protect fuel	2 or more pumps trip	P < 1%	full drop, 1%FP
high HT pressure	protects against reactor trip	ROH Press > 10.3 MPa	ROH Press < 10.1 MPa	partial drop, 70%FP
turbine trip or loss of line	protects against reactor trip	2 of 3 turbine trip or loss of line signal AND P > 75%	2 of 3 turbine trip or loss of line clears OR P < 70%	partial drop, 70%FP
low boiler level	degradation of heat sink	1 boiler level < SP_{LOW} AND P > 60%, or 2 boiler levels < SP_{LOW} AND P < 60%	1 boiler level > SP_{LOW} OR P < 1% 2 boiler levels < SP_{LOW} OR P < 1%	full drop, 1%FP

1.0 RRS SUMMARY

- simplified block diagram
- setpoint calculation
- power error calculation
- reactivity device control
- stepback
- reactor power measurement

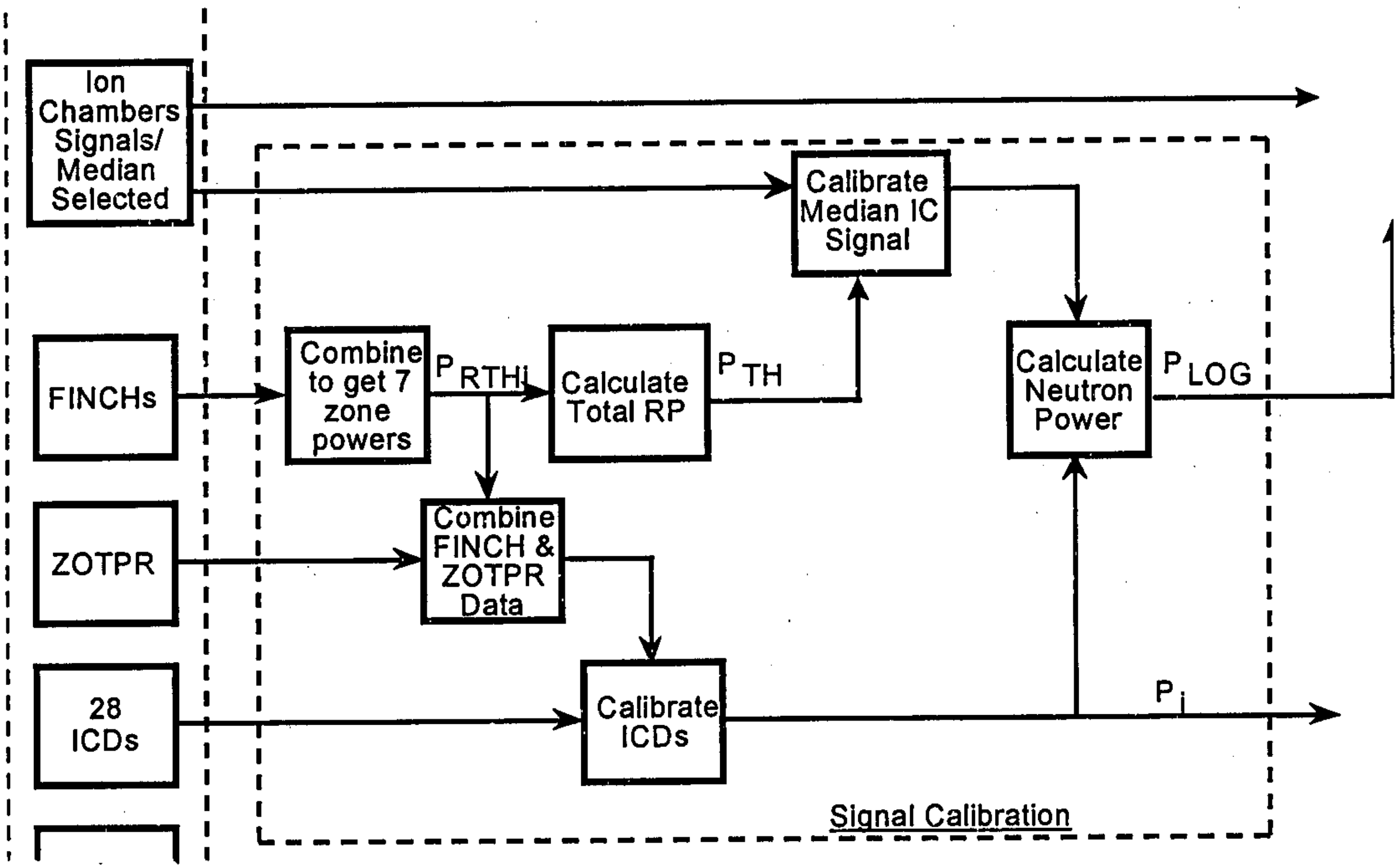


2.0 REACTOR POWER SETPOINT CALCULATION

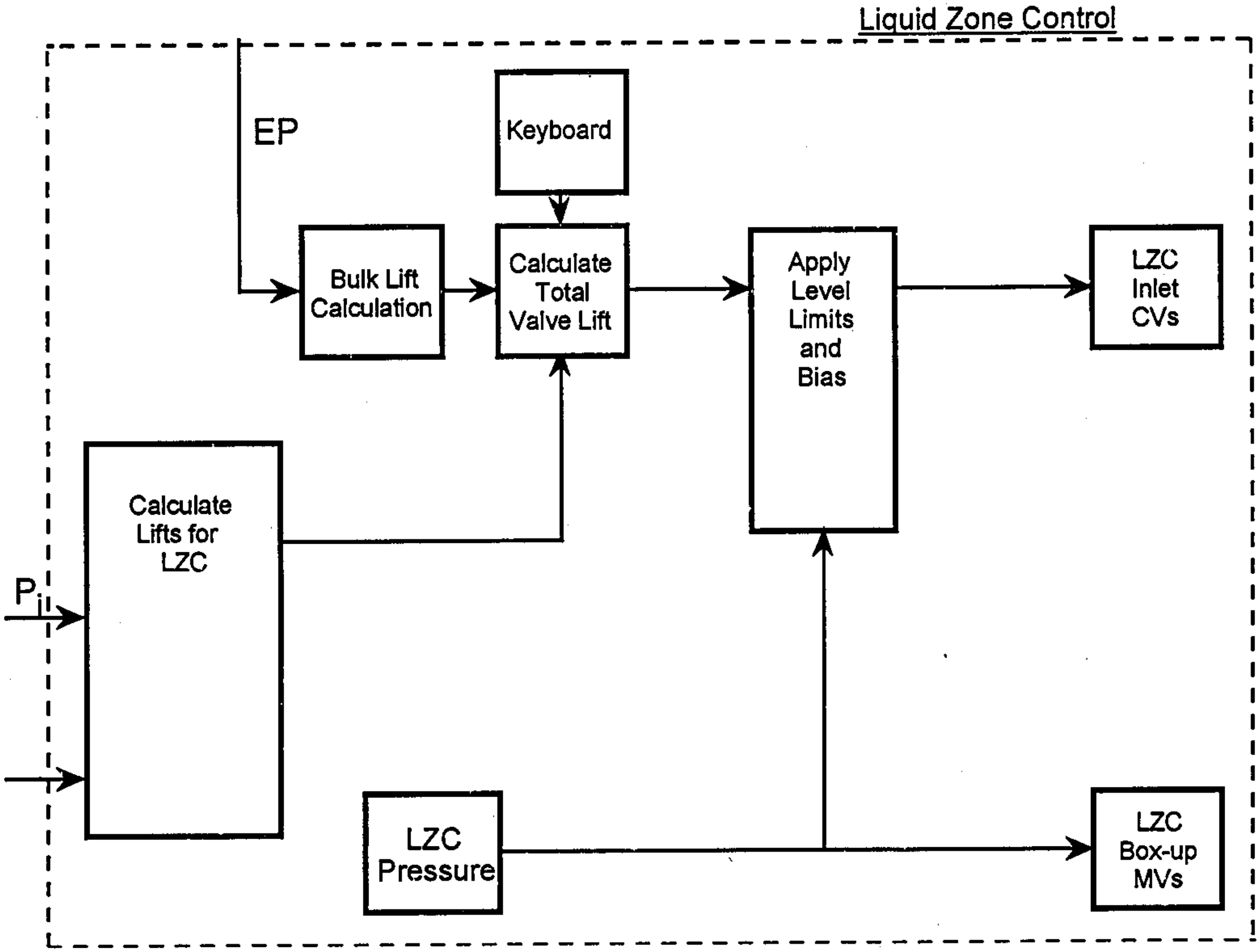


4.0 BULK REACTIVITY MECHANISMS

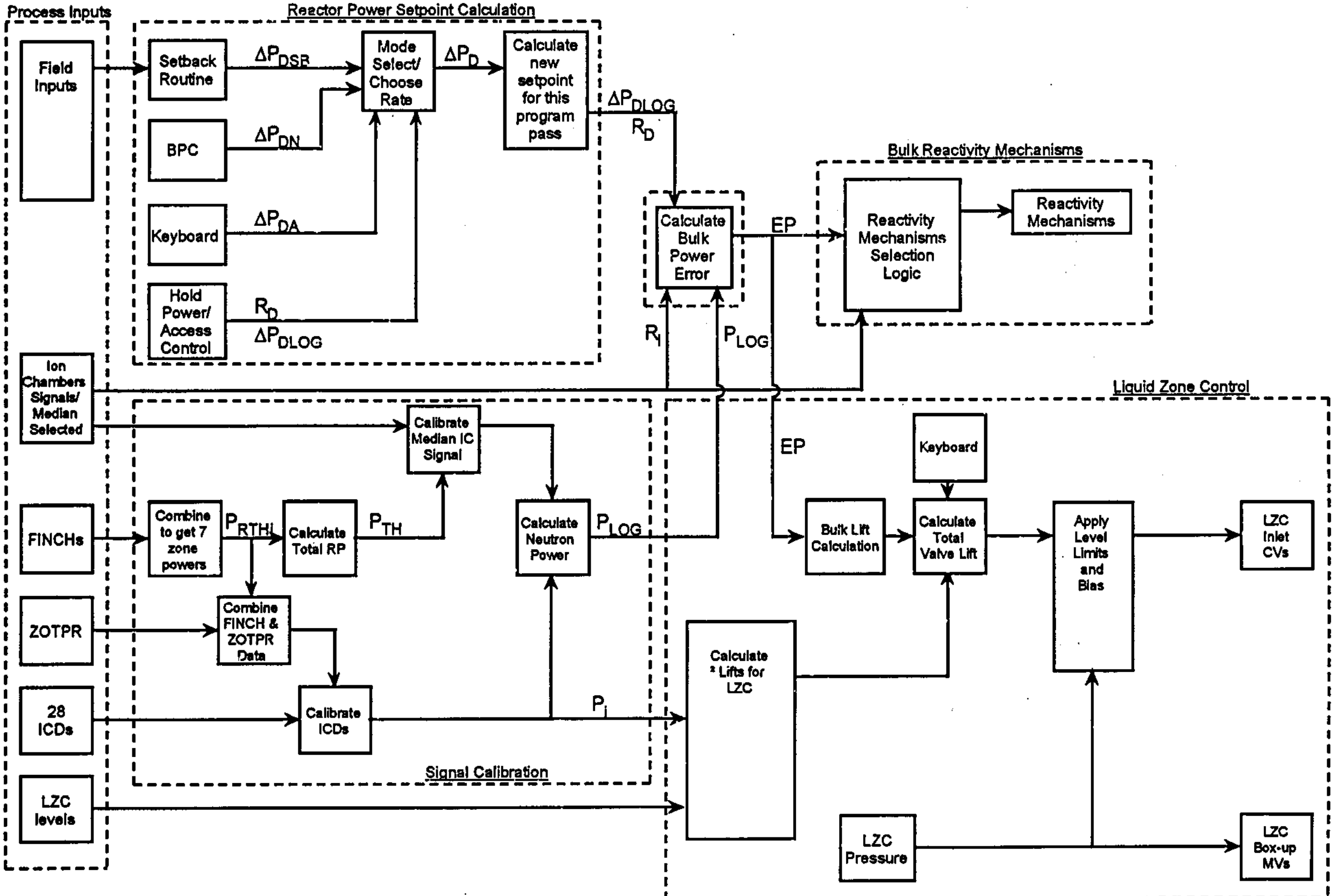
3.0 SIGNAL CALIBRATION



5.0 LIQUID ZONE CONTROL

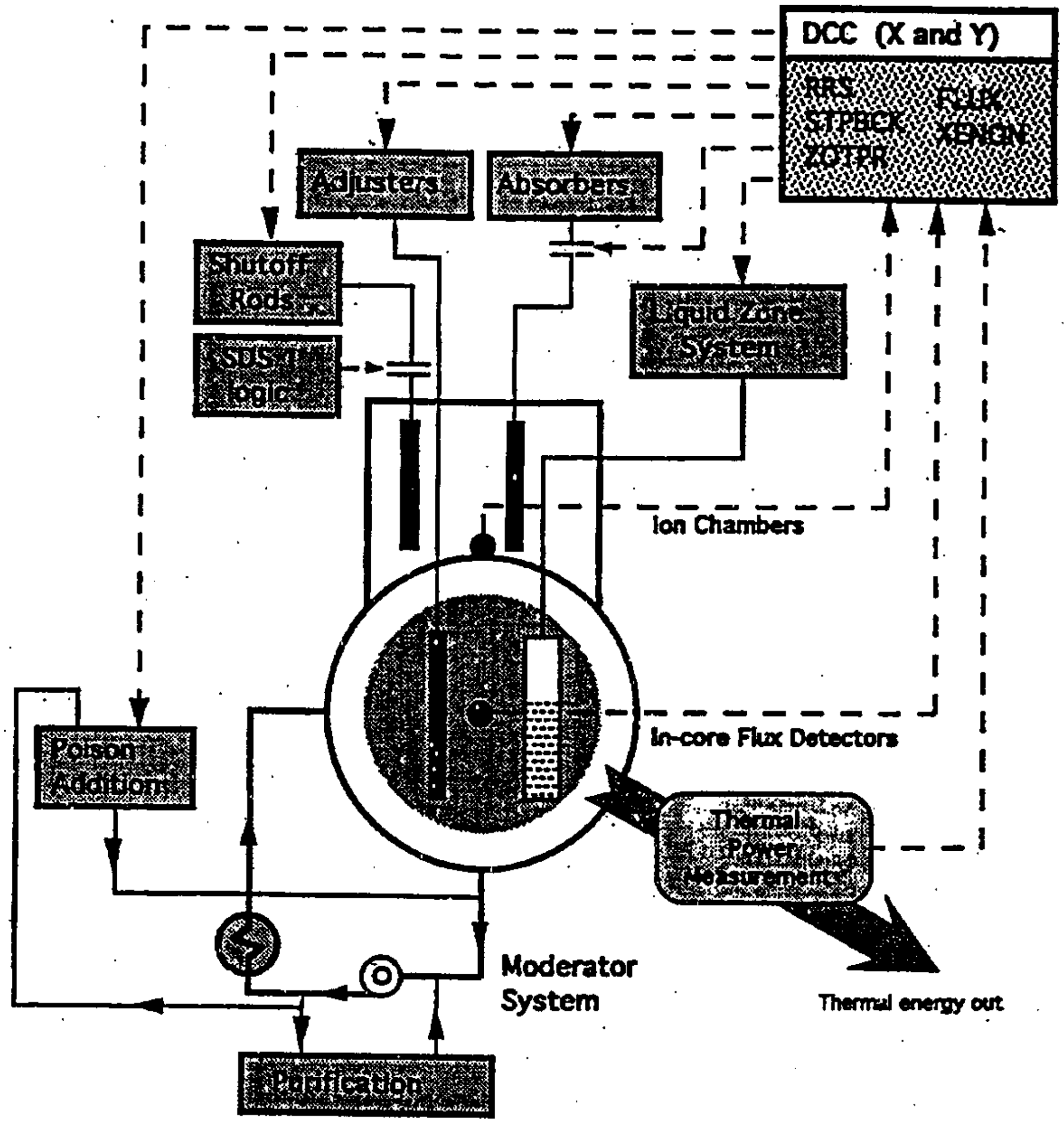


6.0 REACTOR REGULATING SYSTEM BLOCK DIAGRAM



7.0 REACTOR CONTROL SCHEMATIC

- simplified block diagram
- shows actions of SDS#1 on Shutoff rod clutches
- shows actions of Stepback on Control Absorber rod clutches
- shows poison removal via purification



CHAPTER 3: REACTOR POWER CONTROL

MODULE I: SIMULATOR EXERCISES

MODULE OBJECTIVES:

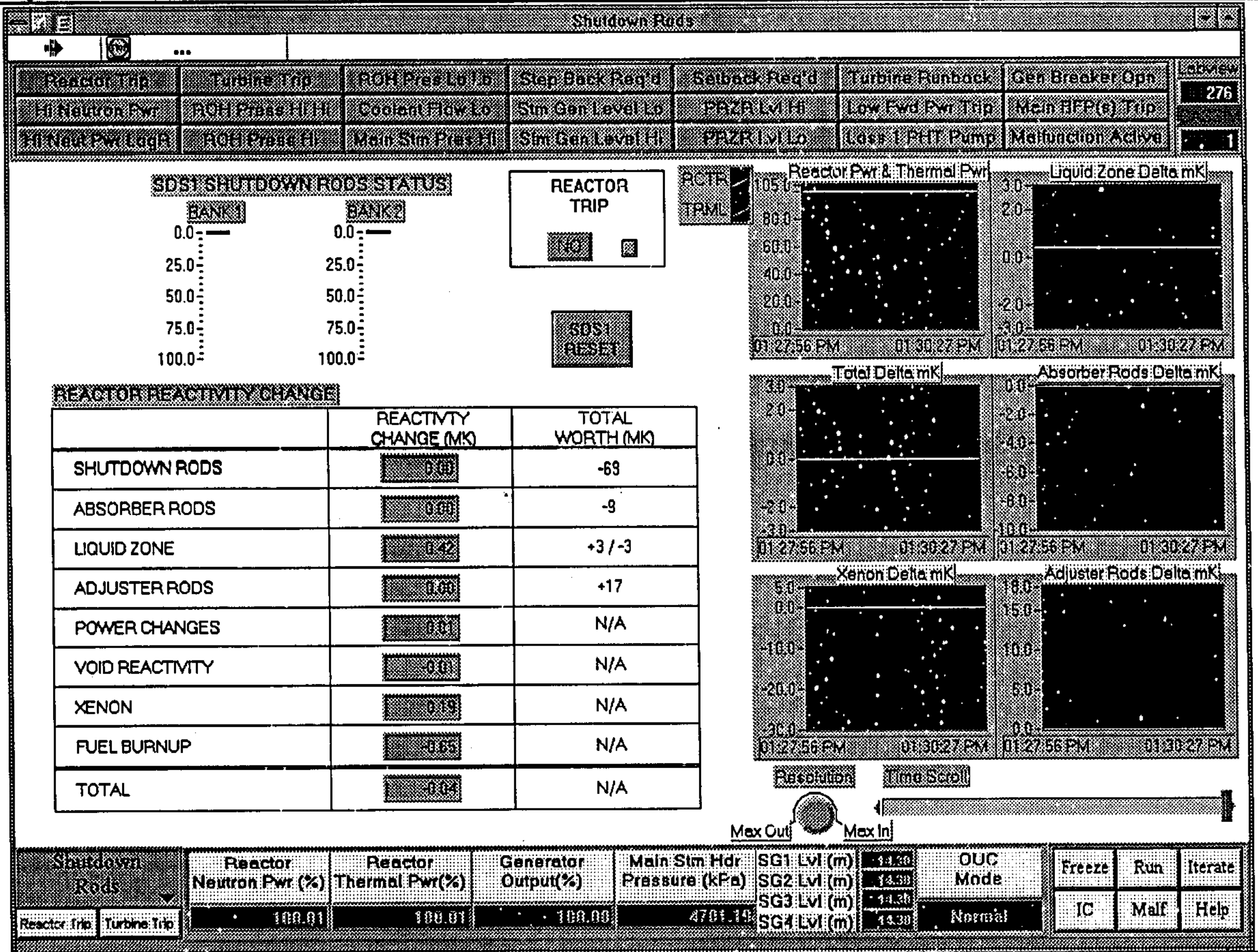
At the end of this module, you will be able to:

1. **Identify the parameters associated with reactivity and reactor control;**
2. **Respond correctly to the following events:**
    - **Reactor Stepback and Recovery**
    - **One Bank of Absorber Rods Drop**
    - **All Liquid Zone Pumps Trip**
    - **Fail Open Liquid Zone 1 & 2 Inlet Valves**

SHUTDOWN RODS PAGE

The screen shows the status of SDS#1, as well as the reactivity contributions of each device and physical phenomenon that is relevant to reactor operations.

- **The positions of each of the two SDS1 SHUTDOWN ROD banks are shown relative to their normal (fully withdrawn) position.**
- **REACTOR TRIP status is shown as NO (green) or YES (yellow), the trip can be reset here (as well as on the RRS / DPR page); note that SDS1 RESET must also be activated before RRS will begin withdrawing the Shutdown Rods.**
- **The REACTIVITY CHANGE of each device and parameter from the initial 100% full power steady state is shown, as well as the range of its potential value.**
  - **⇒ Note that reactivity is a computed not a measured parameter, it can be displayed on a simulator but is not directly available at an actual plant.**
  - **⇒ Note also that when the reactor is critical the Total reactivity must be zero.**


Shutdown Rods
Reactor Trip
Turbine Trip
ROH Pres Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
ROH Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
ROH Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
PRZR Lvl Lo
Loss 1 PHT Pump
Malfunction Active
276
1
SDS1 SHUTDOWN RODS STATUS
BANK1
BANK2
0.0
25.0
50.0
75.0
100.0
REACTOR TRIP
NO
SDS1 RESET
RCTR
TRML
Reactor Pwr & Thermal Pwr
Liquid Zone Delta mK
Total Delta mK
Absorber Rods Delta mK
Xenon Delta mK
Adjuster Rods Delta mK
01:27:56 PM
01:30:27 PM
REACTOR REACTIVITY CHANGE
REACTIVTY CHANGE (MK)
TOTAL WORTH (MK)
SHUTDOWN RODS 0.00 -69
ABSORBER RODS 0.00 -9
LIQUID ZONE 0.42 +3 / -3
ADJUSTER RODS 0.00 +17
POWER CHANGES 0.01 N/A
VOID REACTIVITY -0.01 N/A
XENON 0.19 N/A
FUEL BURNUP -0.65 N/A
TOTAL -0.04 N/A
Resolution
Time Scroll
Max Out
Max In
Shutdown Rods
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%) 100.01
Reactor Thermal Pwr(%) 100.01
Generator Output(%) 100.00
Main Stm Hdr Pressure (kPa) 4701.19
SG1 Lvl (m)
SG2 Lvl (m)
SG3 Lvl (m)
SG4 Lvl (m)
OUC Mode
Normal
Freeze
Run
Iterate
IC
Malf
Help

REACTIVITY CONTROL PAGE

This screen shows the Limit Control Diagram, and the status of the three reactivity control devices that are under the control of RRS.

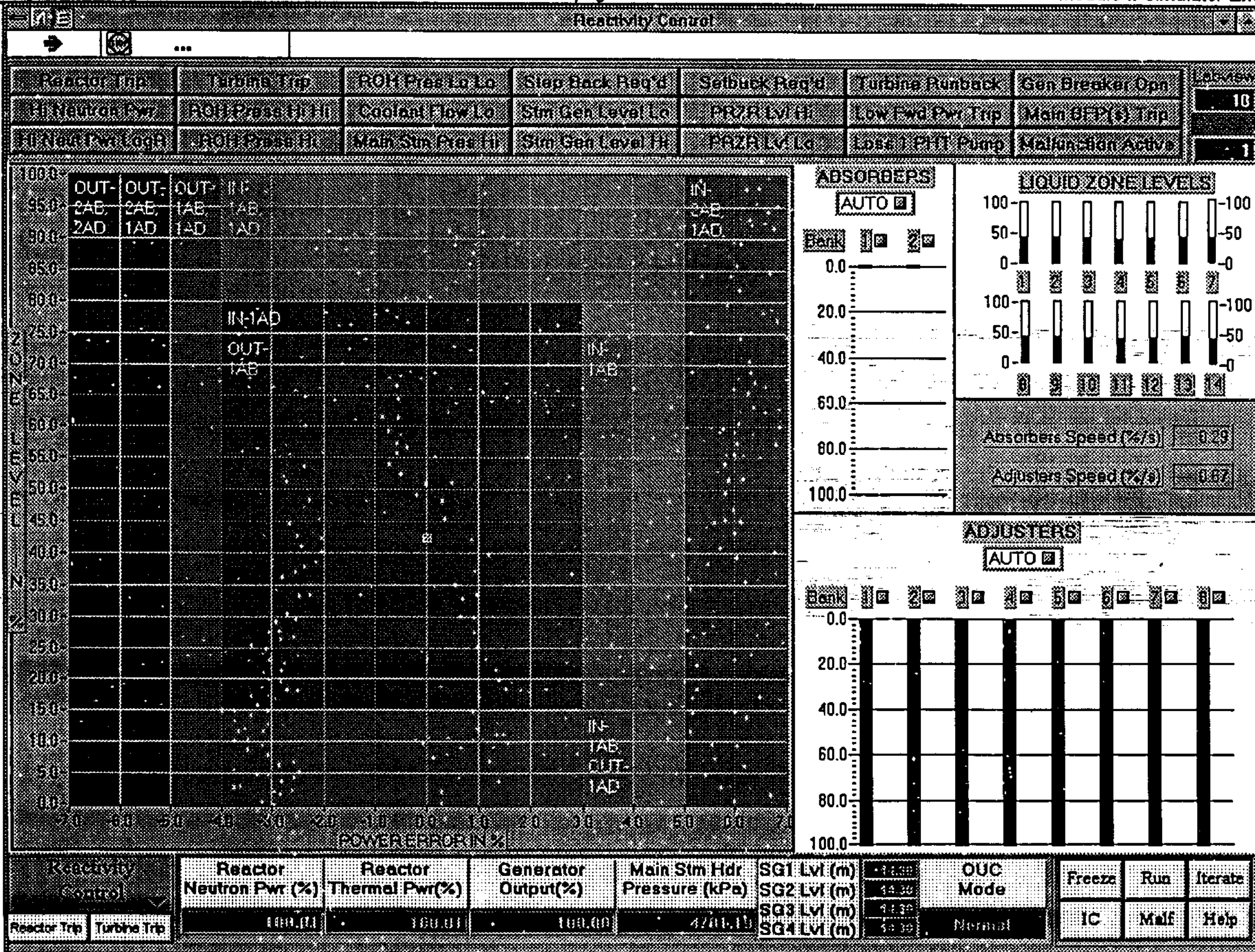
- The Limit Control Diagram displays the Operating Point in terms of Power Error and Average Liquid Zone level.

POWER ERROR = ACTUAL POWER - DEMANDED POWER

⇒ If power error is negative, more (positive) reactivity is needed, hence liquid zone level will decrease and if this is insufficient, absorber rods and adjuster rods will be withdrawn from the reactor.

⇒ If power error is positive, negative reactivity is needed, hence liquid zone level will increase and if this is insufficient, absorber rods and adjuster rods will be driven into the reactor.

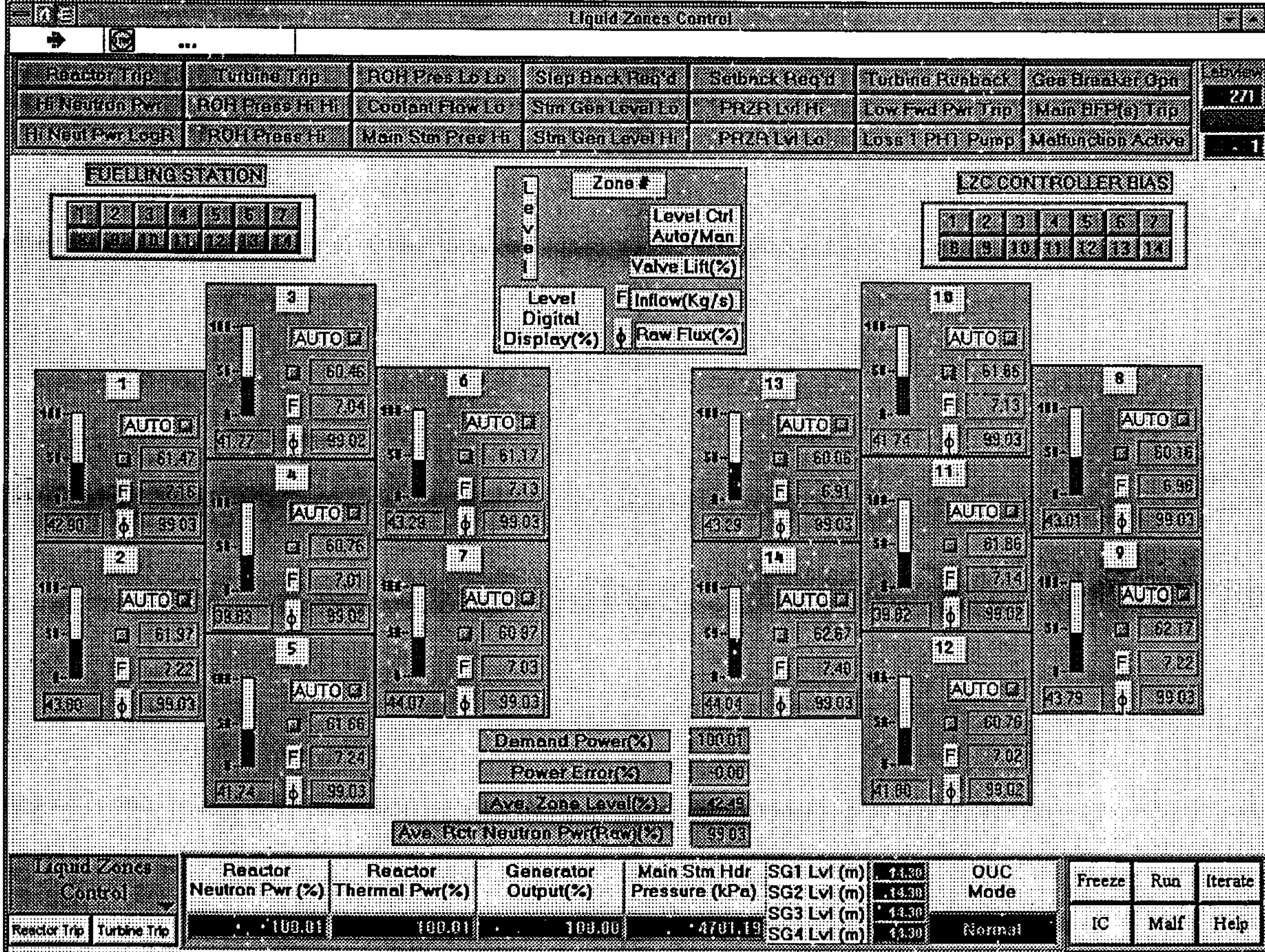
- The ABSORBERS are moved in two banks, and are normally outside the core. They can be moved by RRS if AUTO is selected, or manually if they are placed in MANUAL mode.
- The ADJUSTERS are moved in eight banks, and are normally fully inserted into the core. They can be moved by RRS if AUTO is selected, or manually if they are placed in MANUAL mode.
- The level in each of the 14 liquid zones is displayed but cannot be controlled from this page.
- The speed of the Absorbers and Adjusters is displayed but cannot be controlled from this page.


Reactivity Control
Reactor Trip
Turbine Trip
ROH Pres Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
ROH Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
ROH Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
PRZR Lvl Lo
Lose 1 PHT Pump
Malfunction Active
ADSORBERS
AUTO
LIQUID ZONE LEVELS
ADJUSTERS
AUTO
Absorbers Speed (%/s)
Adjusters Speed (%/s)
POWER ERROR IN %
ZONE LEVEL IN %
Reactivity Control
Reactor Neutron Pwr (%)
Reactor Thermal Pwr(%)
Generator Output(%)
Main Stm Hdr Pressure (kPa)
SG1 Lvl (m)
SG2 Lvl (m)
SG3 Lvl (m)
SG4 Lvl (m)
OUC Mode
Normal
Freeze
Run
Iterate
IC
Malf
Help
Reactor Trip
Turbine Trip

LIQUID ZONES CONTROL

This screen shows the status of each of the 14 Liquid Zones Controllers. The block near the top middle part of the page gives the key to the various parameters displayed on this page.

- **Each of the 14 Liquid Zone Controllers shows:**
  - ⇒ **the zone's number**
  - ⇒ **zone level (% full)**
  - ⇒ **zone level numerical display (% full)**
  - ⇒ **level controller status (AUTO or MANUAL), which can be selected here**
  - ⇒ **valve lift, i.e. % open of the inlet valve to the zone**
  - ⇒ **inflow of water to the zone compartment (kg/sec)**
  - ⇒ **raw (uncorrected) flux measurement for the zone**
- **LZC CONTROLLER BIAS allows the setting of the control point which gives the inlet valve opening that corresponds to the steady state position .**
- **FUELLING STATION allows the introduction of a predetermined amount of positive reactivity into the particular zone, to simulate refuelling operations.**
- **Parameters critical to reactor regulation are shown on a global basis:**
  - ⇒ **Demand Power (%)**
  - ⇒ **Power Error (%)**
  - ⇒ **Average Zone Level (%)**
  - ⇒ **Average Reactor Neutron Power (Raw) (%)**

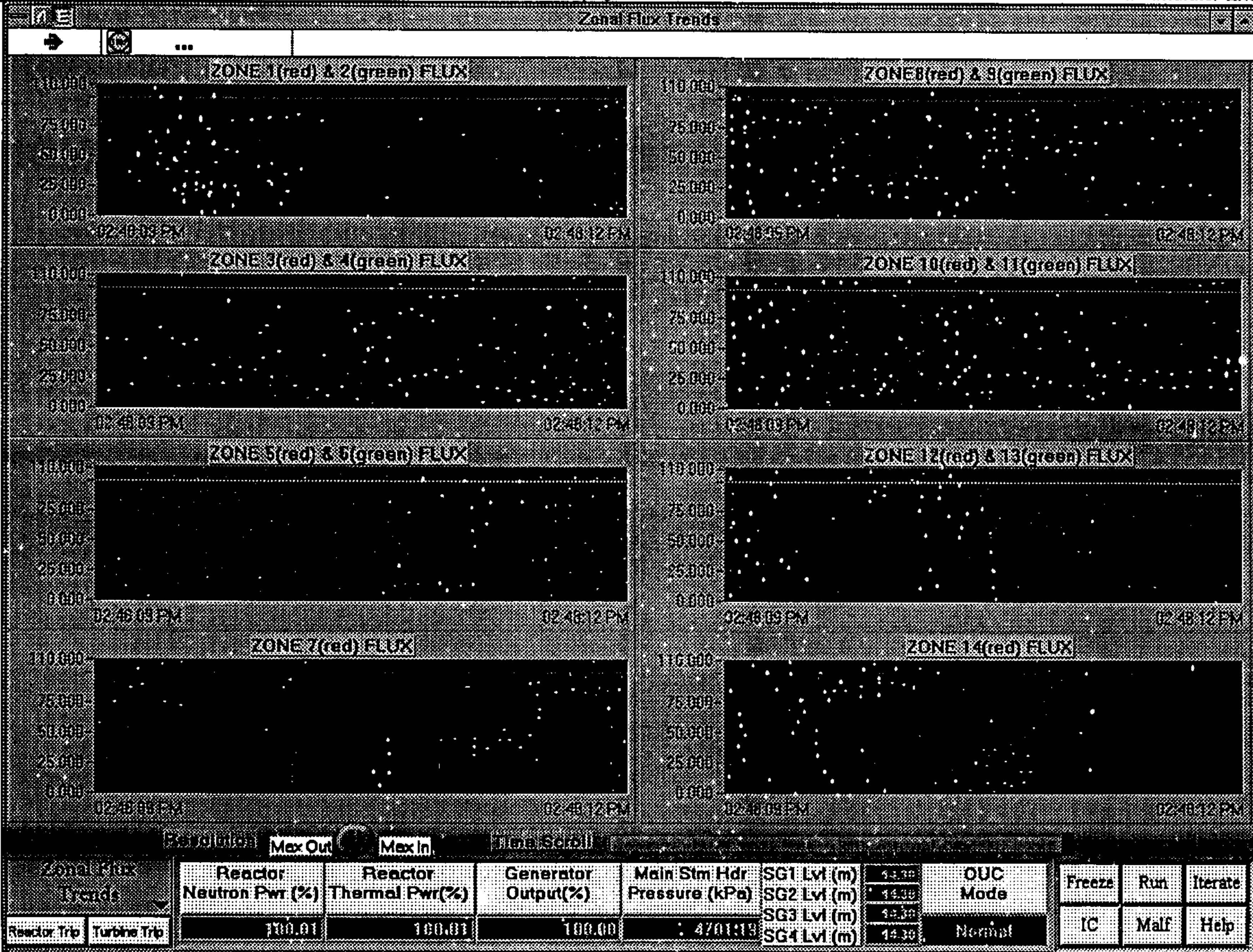

Liquid Zones Control
Reactor Trip
Turbine Trip
ROH Pres Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
ROH Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
ROH Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
PRZR Lvl Lo
Loss 1 PHT Pump
Malfunction Active
FUELLING STATION
LZC CONTROLLER BIAS
Zone #
Level
Level Ctrl Auto/Man
Valve Lift(%)
Inflow(Kg/s)
Raw Flux(%)
Level Digital Display(%)
AUTO
Demand Power(%)
100.01
Power Error(%)
0.00
Ave. Zone Level(%)
42.49
Ave. Rctr Neutron Pwr(Raw)(%)
99.03
Reactor Neutron Pwr (%)
100.01
Reactor Thermal Pwr(%)
100.01
Generator Output(%)
100.00
Main Stm Hdr Pressure (kPa)
4701.19
SG1 Lvl (m)
SG2 Lvl (m)
SG3 Lvl (m)
SG4 Lvl (m)
OUC Mode
Normal
Freeze
Run
Iterate
IC
Malf
Help

ZONAL FLUX TRENDS PAGE

Each of the fourteen zonal fluxes are displayed as % Full Power.

Note that zone fluxes 1-6 and 8-13 are displayed in pairs while each of the fluxes in zone 7 and in zone 14 is shown as a single plot.

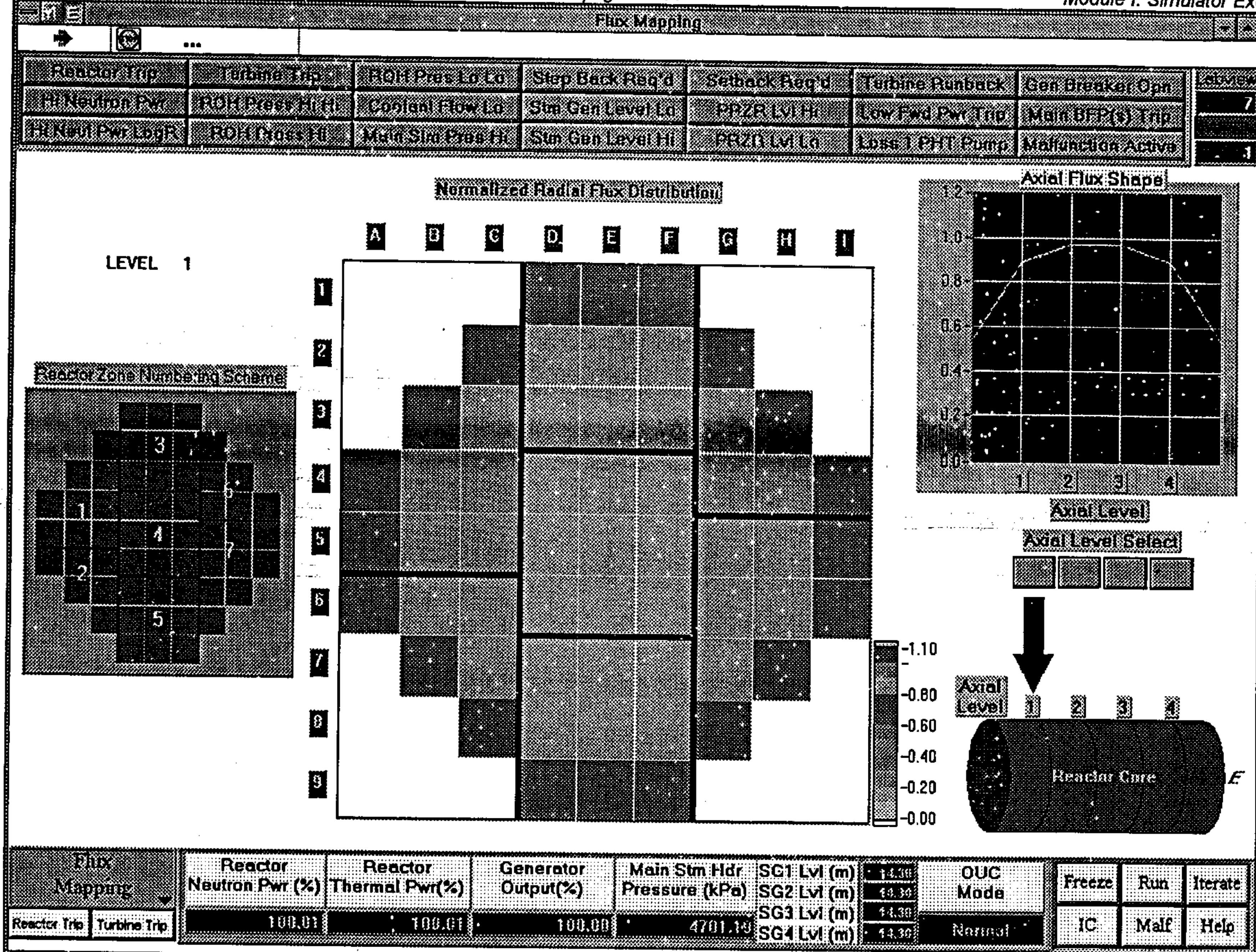
Whenever there are disturbances in the spatial flux distribution this page will show the extent of the differences between the fluxes in the various zones. Note that, as with all other such time plots on the Simulator, only the values computed when this page is displayed will be shown.


Zonal Flux Trends
ZONE 1(red) & 2(green) FLUX
ZONE 8(red) & 9(green) FLUX
ZONE 3(red) & 4(green) FLUX
ZONE 10(red) & 11(green) FLUX
ZONE 5(red) & 6(green) FLUX
ZONE 12(red) & 13(green) FLUX
ZONE 7(red) FLUX
ZONE 14(red) FLUX
Max Out
Max In
Time Scroll
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%)
Reactor Thermal Pwr(%)
Generator Output(%)
Main Stm Hdr Pressure (kPa)
SG1 Lvl (m)
SG2 Lvl (m)
SG3 Lvl (m)
SG4 Lvl (m)
OUC Mode
Freeze
Run
Iterate
IC
Malf
Help

FLUX MAPPING PAGE

This screen shows the spatial distribution of reactor flux along the reactor's axis parallel to the pressure tubes, as well as the radial flux distribution perpendicular to the pressure tubes. Because of the simplified models used, the flux is displayed only at four axial planes, and each radial plane shows only 57 flux regions.

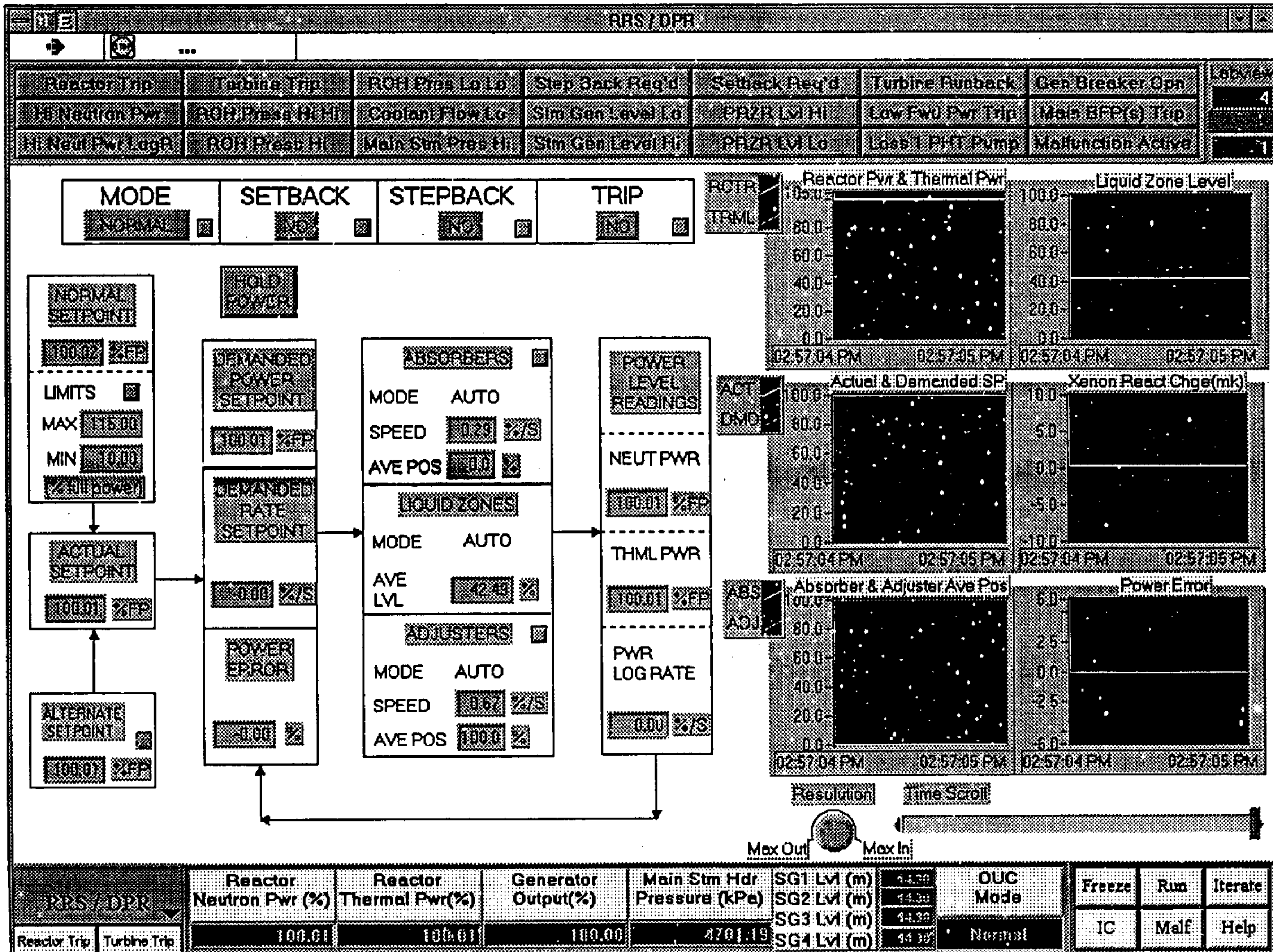
- The Axial Flux Shape is shown on the diagram at the upper right hand side of the screen. The flux is normalized and corresponds to computations made at four "Axial Levels". The cross section along the axis where the flux is to be displayed is chosen via the "Axial Level Select" buttons.
- The center of the screen shows the "Normalized Flux Radial Distribution" corresponding to the axial level that was selected.
- The left hand side of the screen shows the number of the Axial Level currently selected as well as the zone numbering (East or West) that corresponds to the Axial Level selection.


Flux Mapping
Reactor Trip
Turbine Trip
ROH Pres Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
ROH Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
ROH Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
PRZR Lvl Lo
Loss 1 PHT Pump
Malfunction Active
Normalized Radial Flux Distribution
LEVEL 1
Reactor Zone Numbering Scheme
Axial Flux Shape
Axial Level
Axial Level Select
Axial Level
Reactor Core
Reactor Neutron Pwr (%)
Reactor Thermal Pwr(%)
Generator Output(%)
Main Stm Hdr Pressure (kPa)
SG1 Lvl (m)
SG2 Lvl (m)
SG3 Lvl (m)
SG4 Lvl (m)
OUC Mode
Normal
Freeze
Run
Iterate
IC
Malf
Help

RRS / DPR PAGE

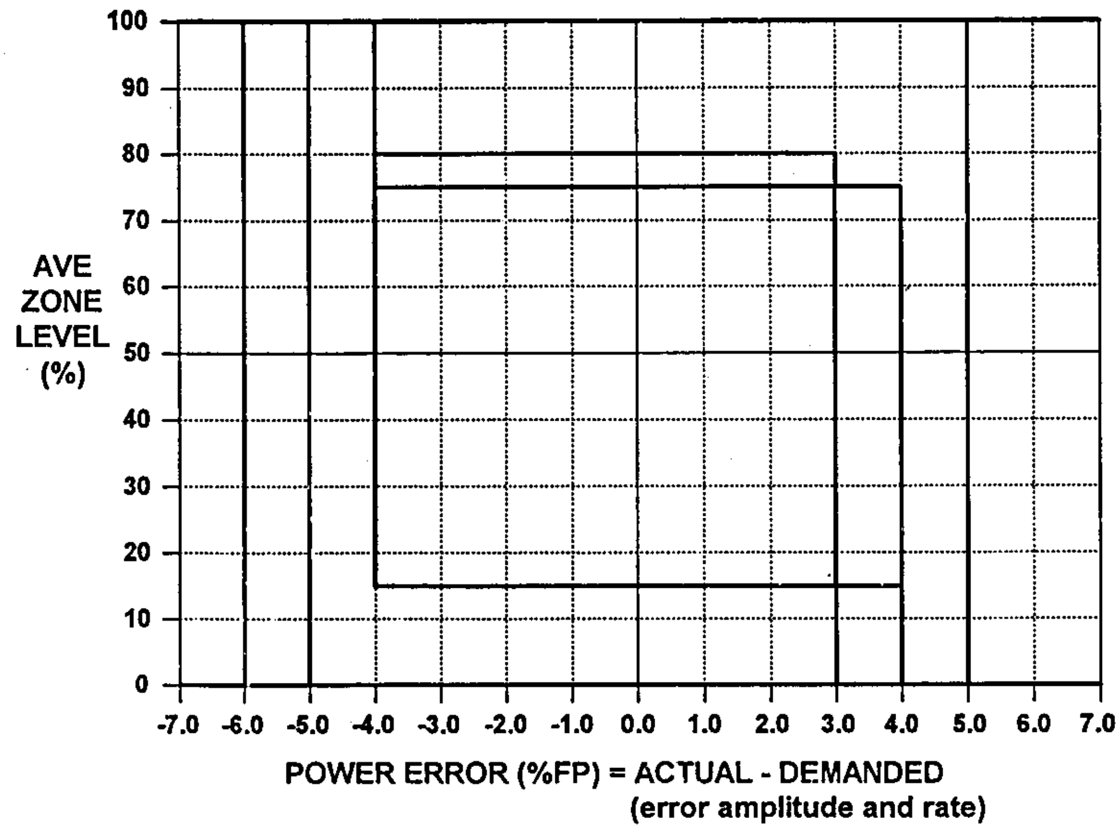
This screen permits control of reactor power setpoint and its rate of change while under Reactor Regulating System (RRS) control, i.e. in 'alternate' mode. Several of the parameters key to RRS operation are displayed on this page.

- The status of reactor control is indicated by the four blocks marked MODE, SETBACK, STEPBACK AND TRIP. They are normally green but will turn yellow when in the abnormal state.
  - ⇒ MODE will indicate whether the reactor is under NORMAL to ALTERNATE control, this status can also be changed here.
  - ⇒ SETBACK status is indicated by YES or NO; Setback is initiated automatically under the prescribed conditions by RRS, but at times the operator needs to initiate a manual Setback, which is done from this page on the Simulator: the Target value (%) and Rate (%/sec) need to be input.
  - ⇒ STEPBACK status is indicated by YES or NO; Stepback is initiated automatically under the prescribed conditions by RRS, but at times the operator needs to initiate a manual Stepback, which is done from this page on the Simulator: the Target value (%) need to be input.
  - ⇒ TRIP status is indicated by YES or NO; trip is initiated by the Shutdown Systems, if the condition clears, it can be reset from here. Note however, that the tripped SDS#1 must also be reset before RRS will pull out the shutdown rods, this must be done on the Shutdown Rods Page
- Key components of RRS and DPR control algorithm are also shown on this screen.
  - ⇒ The ACTUAL SETPOINT is set equal to the NORMAL SETPOINT under UPR control ('normal mode'), the upper and lower limits on this setpoint can be specified here.
  - ⇒ The ACTUAL SETPOINT is set equal to the ALTERNATE SETPOINT under RRS control ('alternate mode'); the value of ALTERNATE SETPOINT is input on this page.
  - ⇒ HOLD POWER will select 'alternate mode' and sets DEMANDED POWER SETPOINT equal to the measured Neutron Power.


RRS / DPR
Reactor Trip
Turbine Trip
ROH Pres Lo Lo
Step Back Req'd
Setback Req'd
Turbine Runback
Gen Breaker Opn
Hi Neutron Pwr
ROH Press Hi Hi
Coolant Flow Lo
Stm Gen Level Lo
PRZR Lvl Hi
Low Fwd Pwr Trip
Main BFP(s) Trip
Hi Neut Pwr LogR
ROH Press Hi
Main Stm Pres Hi
Stm Gen Level Hi
PRZR Lvl Lo
Loss 1 PHT Pump
Malfunction Active
MODE
NORMAL
SETBACK
NO
STEPBACK
NO
TRIP
NO
NORMAL SETPOINT
100.02 %FP
LIMITS
MAX 115.00
MIN 10.00
% full power
HOLD POWER
DEMANDED POWER SETPOINT
100.01 %FP
DEMANDED RATE SETPOINT
0.00 %/S
POWER ERROR
0.00 %
ACTUAL SETPOINT
100.01 %FP
ALTERNATE SETPOINT
100.01 %FP
ABSORBERS
MODE AUTO
SPEED 0.29 %/S
AVE POS 0.0 %
LIQUID ZONES
MODE AUTO
AVE LVL 42.49 %
ADJUSTERS
MODE AUTO
SPEED 0.62 %/S
AVE POS 100.0 %
POWER LEVEL READINGS
NEUT PWR
100.01 %FP
THML PWR
100.01 %FP
PWR LOG RATE
0.00 %/S
RCTR
TRML
Reactor Pwr & Thermal Pwr
Liquid Zone Level
ACT
DMD
Actual & Demanded SP
Xenon React Chge(mk)
ABS
ADJ
Absorber & Adjuster Ave Pos
Power Error
02:57:04 PM
02:57:05 PM
Resolution
Time Scroll
Max Out
Max In
Reactor Trip
Turbine Trip
Reactor Neutron Pwr (%)
100.01
Reactor Thermal Pwr(%)
100.01
Generator Output(%)
100.00
Main Stm Hdr Pressure (kPa)
4701.19
SG1 Lvl (m)
SG2 Lvl (m)
SG3 Lvl (m)
SG4 Lvl (m)
OUC Mode
Normal
Freeze
Run
Iterate
IC
Malf
Help

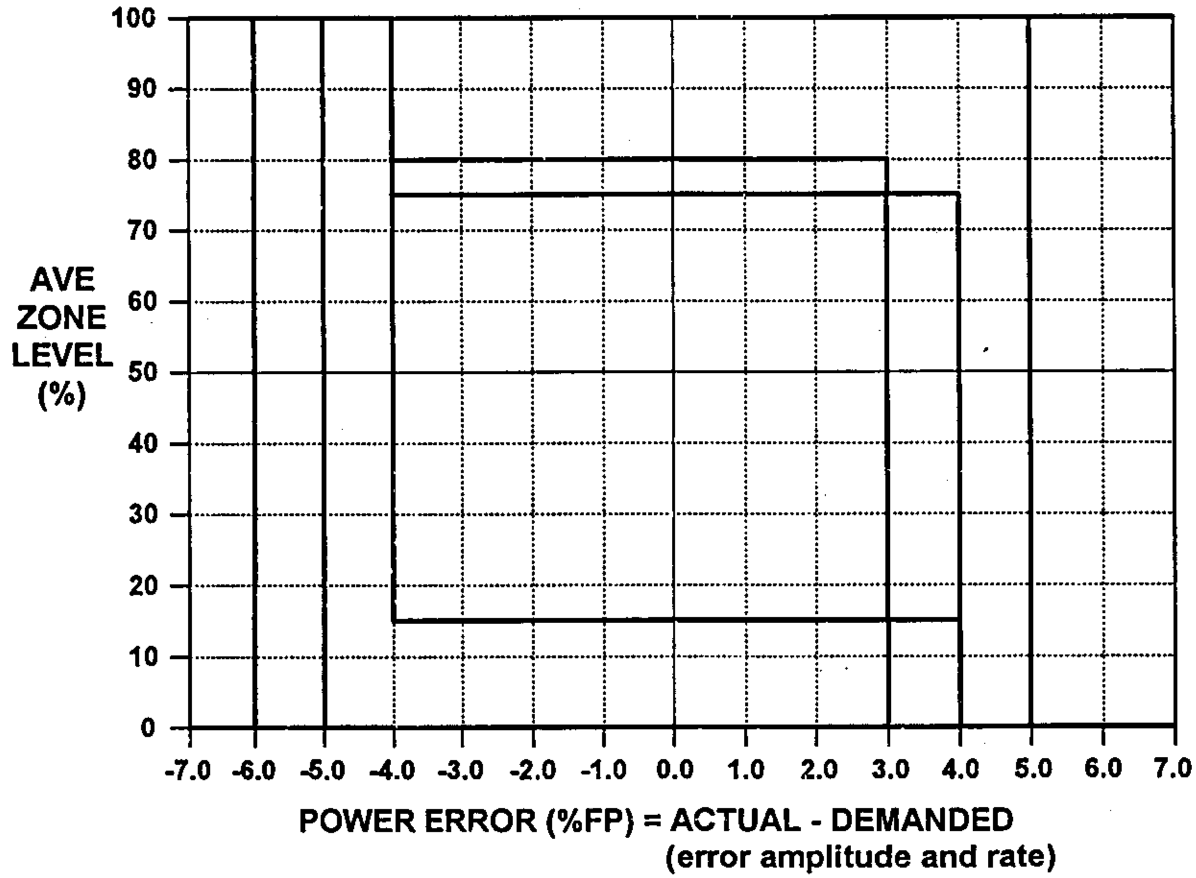
SIMULATOR EXERCISE 3.2. CANDU Response to Power Maneuver

- **initialize CTI CANDU Simulation at 100%FP and from the Reactivity Control page note the position of the operating point on the attached diagram (confirm the value of Average Zone Level on the Plant Overview page):**
- **insert a power reduction request using RRS to 70%FP at 0.8%/sec and freeze the simulator**
- **go to the Reactivity Control page, unfreeze, and note the path of the operating point on the attached diagram, until power error has stabilized at or near zero (about 3 - 4 minutes)**
- **confirm the value of average zone level on the Plant Overview page:**
- **why is the final zone level higher than the original zone level?**



SIMULATOR EXERCISE 3.3. CANDU Response to Power Maneuver

- initialize CTI CANDU Simulation at 100%FP and from the Reactivity Control page note the position of the operating point on the attached diagram
- insert a power reduction request using RRS to 10%FP at 0.8%/sec and freeze the simulator
- go to the Reactivity Control page, unfreeze, and note the path of the operating point on the attached diagram, until at least one Adjuster Rod bank is out of the reactor (about 20 minutes) - once the first Adjuster Bank is more than 50% withdrawn, place Absorbers on Manual and drive them fully OUT.
- compare the response to case 3.2 and explain the main differences, particularly the 'end' state



SIMULATOR EXERCISE 3.4. CANDU Response to Power Maneuver under Manual Control

- initialize CTI CANDU Simulation to the ZONESMAN initialization point (note that all liquid zone controllers are on Manual - they are not to be used during this exercise)
- on the Reactivity Control page place the Absorbers and Adjusters to Manual
- using Absorber and Adjuster drives on Manual, maneuver reactor power to keep generator power between 80±1%FP
- note the time taken from the start of lowering reactor power until steady operation within the specified error limits is achieved

SIMULATOR EXERCISE 3.5. CANDU Response to Manual withdrawal of Adjuster rods

- initialize CTI CANDU Simulation to the ZONESMAN initialization point (note that all liquid zone controllers are on Manual - they are not to be used during this exercise)
- on the Reactivity Control page place the Absorbers and Adjusters onto Manual
- manually withdraw the Adjuster rods
- describe and explain the response of the system

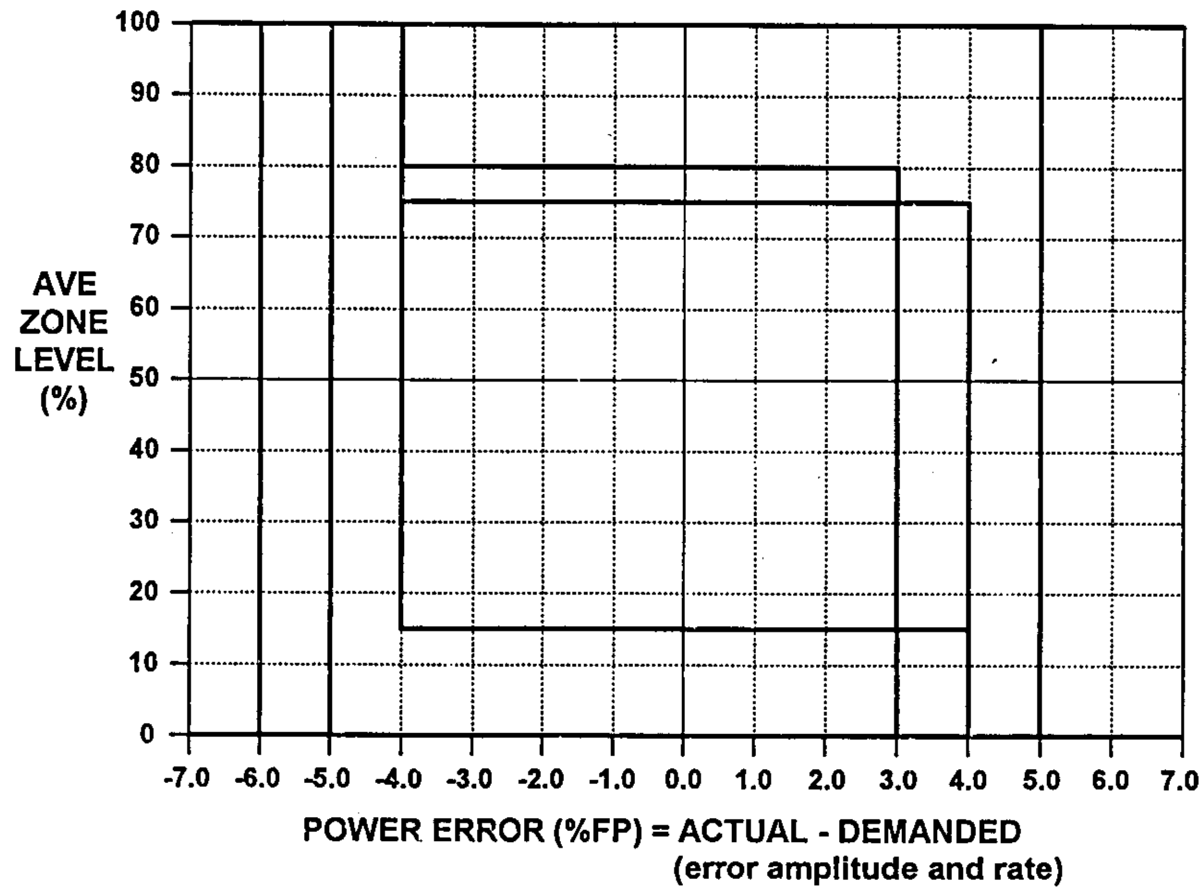
SIMULATOR EXERCISE 3.6. CANDU Response to Manual withdrawal of Adjuster rods

- initialize CTI CANDU Simulation to the ZONESMAN initialization point (note that all liquid zone controllers are on Manual - they are not to be used during this exercise)
- on the Reactivity Control page place the Absorbers and Adjusters onto Manual
- manually drive both banks of Absorbers into the core, and by the simultaneous withdraw of one or more the Adjuster banks keep reactor neutron power within 2% of 100%FP
- once all the Absorbers are fully in the core, attempt to drive all remaining Adjusters simultaneously out of the core
- describe and explain the response of the system

SIMULATOR EXERCISE 3.7. CANDU Response to

- initialize CTI CANDU Simulation at 100%FP and from the Reactivity Control page note the position of the operating point on the attached diagram
- insert the Malfunction "One Bank of Absorber Rods Drop" (use a five second time delay)
- observe system response on the Reactivity Control page and note the path of the operating point on the attached diagram
- note OUC mode and reactor power
- clear the malfunction
- once the Absorbers have fully withdrawn from the reactor, raise reactor power to a level dependent on the number of Absorber banks out of the reactor:

  for each bank partially or fully out, reactor power is limited by 5% (i.e. one bank - 95%FP, two banks - 90%FP, etc)
- what is the maximum power level that can be achieved?



SIMULATOR EXERCISE 3.8. CANDU Response to Failing Open Liquid Zone 1 Inlet Valve

- initialize CTI CANDU Simulation at 100%FP and select the Liquid Zones Control page
- place Liquid Zone 1 controller on MANUAL and select Inlet Valve opening to 100%
- observe the response of the Reactor Regulating System, compensating for the flux tilt while keeping total reactor power at the setpoint

SIMULATOR EXERCISE 3.9. CANDU Response to Malfunction "Fail Open Liquid Zone 1 & 2 Inlet Valves"

- **initialize CTI CANDU Simulation at 100%FP and select the Liquid Zones Control page**
- **insert the Malfunction "Fail Open Liquid Zone 1 & 2 Inlet Valves" (use a five second time delay)**
- **observe the response of the reactor regulating system**
- **how and why is the response different from the previous exercise?**