CHAPTER 6
PROCESS CONTROL

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ABSTRACT

This chapter introduces some of the major process control loops of a typical CANDU Nuclear Generating Unit - Primary Heat Transport System pressure and inventory control, Boiler level control and Boiler pressure control. The subject of core reactivity is discussed briefly. Pertinent process characteristics are described to elucidate the philosophy behind the control strategies. Unless indicated otherwise, the following description is based on the Bruce "B" Nuclear Generating Station which is a typical CANDU design.

6.1 PRESSURE AND INVENTORY CONTROL [1] [2]

6.1.1 Introduction

The Primary Heat Transport (PHT) System circulates pressurized heavy water (reactor coolant) through the reactor fuel channels to remove heat produced by fission of uranium fuel. The heat is carried by the coolant to the steam generators where it is transferred to light water to produce steam which drives the turbine-generator. The PHT is a closed circuit and is shown in Fig. 6-1. Pressure and inventory control of this closed circuit is provided by the Feed, Bleed and Relief (FBR) System shown in Fig. 6-2. It consists of a pressurizer, a bleed condenser, a bleed cooler, two feed pumps, isolating and control valves, and interconnecting pipes.

D_2O temperature changes in the PHT associated with operating transients results in "swell" or "shrink". The FBR stores D_2O from the PHT during "swell", supplies it back to the PHT during "shrink", regulates the PHT pressure, and also provides overpressure protection.

6.1.2 Inventory Control

The primary element in the inventory and pressure control of the PHT is the pressurizer which is connected to one of the reactor outlet headers via a 12 inch diameter pipe. It functions like an "overflow tank" to store "swell" when the temperature in the PHT increases. Thus, inventory control is achieved by controlling pressurizer level. This is largely accomplished by natural insurge/outsurge to/from the pressurizer with the feed and bleed control valves providing the necessary trimming. Feed valves open to inject D_2O into the PHT, resulting in higher pressurizer level, and the bleed valves open to bleed off D_2O, resulting in lower pressurizer level.

Fig. 6-3 shows the PHT swell characteristics for Bruce NGS-B. Note that the change in D_2O volume bears a linear relationship with change in reactor power (or inlet header to outlet header temperature difference, ΔT) except near full power when D_2O boiling is encountered in some reactor channels. The level setpoint of the pressurizer is programmed to increase with ΔT so that the swell in the PHT due to increase in power is accommodated in the pressurizer. The level setpoint could be programmed to exactly match the swell characteristics, but since the departure from linearity is small, and for the sake of simplicity, the best linear fit is used. The dotted line in Fig. 6-4 shows the level setpoint program for Bruce NGS-A during the first years of operation. Recently, the pressurizer level setpoint program was modified (solid line in Fig. 6-4) to provide an added measure of safety for the PHT main pumps. The zero power pressurizer level setpoint is now set much higher in order that a substantial D_2O inventory is available at all times to cope with certain malfunctions such as PHT pressure relief valve failing open. Otherwise, the sudden depressurization from such a malfunction could cause pump cavitation. The mismatch between the PHT swell and the pressurizer level setpoint program is accommodated by the feed and bleed valves.

It should be pointed out that the PHT can be designed to operate without a pressurizer (eg. Pickering NGS) but the result is that the unit cannot maneuver as fast because the swell/shrink must be entirely accommodated by the feed and bleed valves.

6.1.3 Pressure Control

The steam space in the pressurizer acts as a cushion on the PHT to absorb pressure transients. The pressurizer is sized to accommodate the PHT swell from zero power hot to full power, with enough steam space at full power to limit pressure increases in the PHT due to various transients to acceptable levels.

The reactor outlet header (ROH) is chosen as the reference point for the PHT pressure control because the coolant energy is highest at this point and is near boiling at normal steady state operation in most CANDU units. Fluctuations in pressure would result in void formation or collapse. In the "normal mode" of control, the ROH pressure is maintained at a constant value by controlling the pressure of the steam space in the pressurizer by bleeding steam via the steam bleed valves (when ROH pressure is above the setpoint) or by heat addition via the immersion heaters (when the ROH pressure is below the setpoint). The heaters also turn on if the liquid temperature in the pressurizer falls by a certain amount below the normal saturation temperature.

When needed, the pressurizer can be isolated from the PHT circuit and the pressures of the separated sections can be controlled independently. PHT pressure control is now in the so called "solid mode" because the compressible vapour space is no longer available. The feed and bleed valves perform PHT pressure control in this mode.

To provide overpressure protection, the PHT relief valves open at high pressure to bleed D_2O from the PHT circuit to the bleed condenser.

The bleed condenser is the vessel which receives the PHT bleed flow, PHT relief flow and pressurizer steam bleed flow, and cools them down. The cooling function is performed by the reflux condenser and spray flow.

6.1.4 Main Control Algorithms

The control algorithms for the feed valves, bleed valves, pressurizer steam bleed valves, pressurizer heaters and PHT relief valves are listed in Table 6-1.

6.2 BOILER LEVEL CONTROL [3] [4]

6.2.1 Introduction

Feedwater is supplied by the Boiler Feed System to the boilers where it is heated to generate steam for the turbine-generator. Boiler level control is achieved by manipulating the feedwater control valves to control the feedwater flow. Figures 6-5 and 6-6 show a boiler and the Boiler Feed System for Bruce NGS-B.

6.2.2 Process Dynamics

From a safety point of view, it is essential to maintain adequate water inventory in the boilers at all times. Because of complex boiler dynamics, there is no simple correlation between inventory (mass) of water in the boiler and the level (volume). This is because of the presence of a large amount of steam bubbles ("void") in the boiler under most operating conditions. Bubble generation or collapse can be very rapid in certain dynamics, resulting in severe "swell/shrink" and therefore severe level transients.

Based on the boiler design and operating conditions, the <u>steady state</u> void can be estimated for each power level. Fig. 6-7 shows the Bruce NGS-B "swell curves" predictd by Babcock and Wilcox (the boiler manufacturer) and by Ontario Hydro. It is obvious from these curves that the amount of void increases with power level. In order to maintain near constant inventory in the boiler, and to ensure that the level remains above the tube bundle after a reactor trip, the level setpoint must be raised with reactor power. The level operating line (setpoint) is shown in Fig. 6-7.

Besides reactor power, the other parameter with a significant effect on void in the boiler is the boiler pressure. Normally, the liquid and vapour phases in the boiler are in thermodynamic equilibrium (saturation). A sudden increase in pressure makes the liquid subcooled, the steam bubbles in the liquid collapse, and the level drops rapidly. A sudden decrease in pressure has the opposite effect. Reference [4] provides a more in-depth discussion on the subject. Because of the effect of boiler pressure on level, on the turbine and on the PHT, it is controlled to a constant value of 635 psia (4378 kPa).

6.2.3 Level Control Scheme

The details on instrumentation or actual control program rules will not be described. Instead, the general control scheme is described here.

Although reactor power and boiler pressure significantly affect boiler level, they are traditionally not used to control boiler level. In a power manoeuver, it is desirable to allow the reactor power to change at a rate set by the operator, unconstrained by other factors. Boiler pressure is traditionally controlled to a constant setpoint, partly for simplicity of control and partly because wide variations cannot be tolerated by the turbine*. Reference [4] explores how boiler pressure could be used to improve on the existing level control scheme.

Traditionally, feedwater flow is the only parameter manipulated to control boiler level. The control scheme for Bruce NGS-B mainly consists of dual computer control of the main feedwater control valves, startup control valves and trim control valves. Note that three element analog control is widely used for light water reactor power plants. Three element control means that three measured variables are used in the control algorithm. In this case, they are boiler level, feedwater flow and steam flow.

The level setpoint, shown in Fig. 6 -7, is based on the boiler swell characteristics. The feedwater control loop selects the higher of the two boiler levels in each pair of boilers sharing a common preheater, compares it with the setpoint, and sends the error to a PI controller. The output of this controller is added to the flow error (difference between feedwater flow and steam flow) and is sent to a second PI controller. Feedforward terms from the rates of change of reactor thermal power and boiler pressure are added to the second controller to compensate for swell/shrink effects. The output of the second controller drives the feedwater control valves. A control block diagram is shown in Fig. 6 -8.

The trim valve control loop maintains a balance between the two boiler levels and controls the preheater outlet pressure by modulating the two trim valves. This design is unique to Bruce NGS B.

6.2.4 Typical Boiler Level Transients

Figures 6-9 and 6-10 show typical boiler level transients during loading and after a reactor trip, obtained from Bruce NGS-B simulation.

* Pickering NGS is an exception, where, because of the absence of a pressurizer, boiler pressure is varied with power level in such a way so as to reduce PHT swell.

6.3 BOILER PRESSURE CONTROL[5][6]

6.3.1 Introduction

The boiler pressure controller (BPC) is a computer program designed to control boiler pressure under all operating conditions and it forms part of the overall plant control. A simplified plant control block diagram is shown in Fig. 6-11.

6.3.2 Modes of Plant Control

There are two distinct modes of plant control. The "normal mode" (reactor-following-turbine) is the usual control mode at high power. In this mode, turbine load is set or changed as desired and reactor power is automatically adjusted to keep boiler pressure at the setpoint. The "alternate mode" (turbine-following-reactor) is the usual control mode at low power and during upset conditions. In this mode, reactor power is controlled to an operator specified setpoint and the steam loads (turbine, ASDV, CSDV, HWP)* are adjusted to maintain boiler pressure at the setpoint.

The "alternate mode" is entered automatically when reactor power is sufficiently low or upon reactor trip, stepback or setback. This mode may also be entered, at any time, by an operator command via the keyboard.

6.3.3 Boiler Pressure Setpoint Control

There are several modes of BPC operation, differentiated by the way in which the boiler pressure setpoint is manipulated.

In the "warm-up" mode, the boiler pressure setpoint is increased at a rate required to give a constant rate of temperature increase. Increasing the boiler pressure allows the water to heat to a higher temperature before boiling. This, in turn, allows the PHT to heat up to a higher temperature. Warm up heat comes from the PHT main pumps and the reactor. The maximum warm up rate is limited to $5^{o}F/min$ in order to avoid excessive thermal stresses in the boiler and associated piping, and to ensure that the swell rate in the PHT is manageable. Knowing the saturation relationship between pressure and temperature (a curve fit is used), the required rate of pressure change to achieve a particular rate of temperature change is easily determined. The operator enters the desired rate of temperature increase via the keyboard.

* ASDV = atmospheric steam discharge valves
CSDV = condenser steam dump valves
HWP = heavy water plant

Depending on the size and magnitude of the pressure error during warmup, the following possible controls can happen:

- If the setpoint exceeds boiler pressure by more than 20.3 psi (140 kPa), the setpoint is frozen until the error becomes less than 5 psi (35 kPa). This prevents a setpoint runaway.
- If boiler pressure exceeds the setpoint by 10.2 psi (70 kPa) the ASDV's start to open.
- If boiler pressure exceeds the setpoint by 14.5 psi (100 kPa) the CSDV's start to open and are fully open at an error of 36.3 psi (250 kPa).

In the "hold" mode, the pressure setpoint is held constant, and the boiler pressure is held at the setpoint by either adjusting reactor power or the steam loads. This is the normal setpoint control mode at full power. BPC is automatically switched from the "warmup" mode to the "hold" mode when the pressure setpoint reaches 635 psia (4378 kPa), the normal operating pressure.

The "cool-down" mode is similar to the "warm-up" mode in many ways except that it is used to bring the steam pressure (and hence temperature) down. The operator initiates the cool down and selects the rate of temperature decrease via the keyboard. The maximum rate of temperature decrease is 5^{o}F/min.

Normally, during cool-down the plant is in the alternate mode of control, reactor power is set to zero and boiler pressure is adjusted via the CSDV's and ASDV's. The CSDV's are fully open when boiler pressure exceeds the setpoint by 36.3 psi (250 kPa), and the ASDV's are fully open at an error of 41.3 psi (285 kPa). At a pressure error of 40 psi (275 kPa), the setpoint is frozen and the ramp down does not resume until the error is reduced to 30.4 psi (210 kPa).

6.3.4 Control Algorithms

The main control algorithms associated with BPC are listed in Table 6-2.

6.4 CORE REACTIVITY: WITH OR WITHOUT FEEDBACK

6.4.1 Introduction

In this section, the subject of core reactivity with/without feedback will be discussed. A simplistic approach will be adopted throughout to elucidate the main ideas.

The whole subject of control of core reactivity is ultimately concerned with the control of one parameter, the multiplication factor, k. The multiplication factor determines the basic state of the reactor (i.e., whether reactor power is increasing, decreasing or holding steady) and is defined as the ratio of the number of neutrons in any one generation to the number of neutrons in the immediate preceding generation. There are two multiplication factors in use. k_∞ is the multiplication factor assuming no leakage. A more practical multiplication factor is k-effective or k_e, which is the multiplication factor of the actual reactor allowing leakage, i.e., $k_e = k_\infty (1 - \text{leakage})$. If k_e is unity, the reactor is said to be critical. In general, k_∞ is given by the four factor formula:

$$k_\infty = \eta\varepsilon Pf$$

Where η = The Thermal Fission Factor, i.e., the number of fast neutrons produced for each thermal neutron absorbed in the fuel.

ε = The Fast Fission Factor, i.e., the ratio by which the fast neutron production is increased by fast fissions in U-238.

P = The Resonance Escape Probability, i.e, the fraction of fast neutrons that slow down to thermal energy levels without being absorbed.

f = The Thermal Utilization Factor, i.e., the ratio of neutrons absorbed in the fuel to the total neutrons absorbed in the reactor.

And k_e is given by the formula:

$$k_e = \eta\varepsilon Pf P_F P_S$$

Where P_F = the non-leakage probability of the fast neutrons during thermalization.

and P_S = the non-leakage probability for the thermal neutrons

Both P_F and P_S can be made changeable for control purposes.

Reactivity, ρ, is a defined concept which permits dealing with the multiplication factor k_e with more practically sized units.

ρ is defined as:

$$\rho = (k_e - 1)/k_e$$

ρ is therefore the fractional deviation of k_e from unity. However, k_e is always close to unity so that $\rho \simeq (k_e - 1) = \Delta k$. Δk is excess reactivity. Reactivity for control studies is normally referred to as Δk. In Canada, the preferred unit for reactivity is the milli-k, i.e., $\rho = .001 = 1$ milli-k..

6.4.2 Core Reactivity Without Feedback

When considering core reactivity, we are mainly concerned with the rate of generation of neturons in the reactor core. In very general terms, the time rate of change of neutron density, dn/dt (neutron m^{-3} sec^{-1}) can be described by the following equation:

Rate of Change of Neutron Density = Production Rate - Leakage Rate - Absorption Rate

By making simplifying assumptions (in particular the one energy group concept where all production, diffusion and absorption of neutrons is assumed to occur at a single energy level), the following point kinetics equations is derived:

$$\frac{dn}{dt} = (\rho - \beta)\frac{n}{l^*} + \sum_{i=1}^{J} \lambda_i C_i + S$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{l^*} n - \lambda_i C_i \qquad \text{(D01)}$$

Where,

S	=	the source term in neutrons m^{-3}
C_i	=	the concentration of delayed neutron precursors of the ith group.
β	=	total fraction of delayed neutron
l^*	=	mean neutron generation time (sec)
λ_i	=	decay constant for delayed neutron group i
β_i	=	fractional yield for delayed group i
n	=	neutron density (neutrons m^{-3})
J	=	total number of delayed groups

For a step change in reactivity, ρ, the neutron density n(t) at the time t is given by solving (D01):

$$n(t) = A_o e^{a_o t} + \sum_{i=1}^{J} A_i e^{a_i t} - l^*S/\rho \qquad (D02)$$

where a_i, i=1, 2, ..., J, are negative exponents approximately equal to $-\lambda_i$, i = 1,2,...J, the decay constants of the delayed neutron precursors. a_o is positive when ρ is positive and negative when ρ is negative.

When ρ is positive, the negative exponential term dies out rapidly leaving

$$n(t) = A_o e^{a_o t} - l^*S/\rho \qquad (D03)$$

Where $a_o = \rho/l^*$ and $A_o = n_o$, i.e., value of n(t) at t=0.

If the delayed neutron precursors are neglected, n(t) is simply given by

$$n(t) = A_o e^{a_o t} \qquad (D04)$$

It can be seen from (D04) that with no delayed neutrons, the rate of increase of neutrons is so fast that it is almost impossible to find a regulating and protecting system to control the reactor. However, with the presence of the delayed neutrons, regulation and protection become practical realities.

With a negative reactivity ρ, all the exponents in (D02) will have negative values. Initially, the a_o and the delayed neutron terms determine the rate of decrease. As the delayed neutrons die down, the neutron source term (e.g., term arising from photoneutrons) becomes significant. This is shown in Figure 6-12 in the Appendix. It can be seen that the neutron source is important in reactor start-up after a long shutdown.

6.4.3 Core Reactivity With Feedback

When a reactor is operated at power, there are a number of reactivity feedback effects that change the core reactivity. Two main categories of feedbacks will be discussed here. One is the temperature effects that have feedback time constants in the range of seconds to minutes. The other is poisoning feedbacks that have loop time delays measured in hours.

(a) Reactivity Changes Due to Temperature Variations

The reactivity changes produced by temperature changes are usually measured for control purposes in units of milli-k change in reactivity per degree change in temperature and is known as the temperature coefficient of reactivity. A lumped coefficient of all temperature effects known as the power coefficient is often used for simulation and other studies and is defined as the change in reactivity per unit increase in power. A negative power coefficient is desirable since it makes the reactor inherently stable or power limiting (in general, CANDU core has a negative power coefficient).

Core reactivity changes due to temperature variations are mainly contributed by:

(1) Fuel Temperature Feedback

The reactivity changes due to increased fuel temperatures are mainly due to two effects. One is due to increase in the effective temperature of the thermal neutrons in the fuel causing a decrease in η for fresh fuel and an increase in η for fully irradiated fuel. The other is Doppler Broadening (or Doppler Effect). Increasing the fuel temperature causes an increase in resonance capture with a resulting decrease in P. This Doppler effect is normally the dominant effect in the UO_2 fuel (see Figure 6-13).

(2) Heat Transport Coolant Temperature Feedback

An increase in heat transport coolant temperature causes an increase in thermal neutron temperature with the same results as with the fuel temperature coefficient above. Moreover, this causes a reduction in density causing an increase in f and ε and decrease in P. The overall heat transport temperature coefficient is usually negative with fresh fuel but becomes less negative or even positive as plutonium builds up (such as equilibrium fuel). Absorption in Pu-239 is increased as the fuel is irradiated resulting in a positive change in reactivity (see Figures 6-14 and 6-15).

(3) Moderator Temperature Feedback

An increase in moderator temperature causes an increase in thermal neutron temperature with the same results as with the fuel temperature coefficient.

Besides, moderator density decreases resulting in neutron leakage. This also causes a decrease in P and an increase in f.

With new fuel (mainly U-235), the moderator temperature coefficient is negative. As plutonium builds up in the equilibrium fuel, it becomes less negative and may become slightly positive because the increase in neutron energy increases fission captures in plutonium whereas it decreases them in U-235 (see Figures 6-14 and 6-15).

(4) Effects Due to Void Formation

Voids may be formed, if either the moderator or heat transport coolant boils. If a reactor is over-moderated, void formation will cause an increase in reactivity.

When the reactor is not overmoderated, then an increase in reactivity can still result. The size of the void and its location are important in deciding whether an increase or decrease in reactivity results from the void formation.

The polarity of the net reactivity change for an increase in voids cannot generally be stated for a given coolant. Excessively positive or negative void coefficients should be avoided if possible to prevent large power surges during void formation or reduction.

(b) Fission Product Poisoning Feedbacks

Poisoning feedbacks are mainly attributed to those fission products which have a high cross section for non-productive absorption. There are some 200 fission product poisons generated in the reactor. The most notorious of these is Xe-135 which plays a very important role in reactor power manoeuverability. Regardless of the nature of these fission products, whether they are stable or unstable elements, in all cases, their effect is primarily on the thermal utilization factor f so causing a negative reactivity effect.

(c) Reactivity Feedback Block Diagram and Reactor Control

Figure 6-16 shows in block diagram form the representation of temperature and Xenon poison feedbacks.

For CANDU, on-power refuelling provides control of the basic core reactivity. However, for control of relatively short transients, reactivity control devices are required to compensate for reactivity transients in the basic core, to permit rapid power changes to be made, and for zonal power control. The reactivity control devices may be constituted of moderator level, absorber rods, booster rods and moderator poison. An automatic regulating system (in CANDU dual computer control is used) is provided for adjusting these devices.

REFERENCES

[1] Bruce NGS-A design manual 21-63330, "Primary heat transport, feed, bleed and pressure control system instrumentation", December, 1975.

[2] Bruce NGS-B design manual 29-33300/63330, "Heat transport system feed, bleed and relief circuit", March, 1982.

[3] Bruce NGS-B design manual 29-43230, "Boiler Feed System", December, 1981.

[4] Q.B. Chou, S.N. Chen, "Development of a novel steam generator control scheme with the capability to control swell/shrinkage and the potential to reduce drum size requirements of CANDU-PHWR steam generators", 1979 Joint Power Generation Conference, Charlotte, North Carolina, October 7-11, 1979.

[5] Bruce NGS-B design manual 29-63616, "Boiler Pressure Control", November, 1981.

[6] Bruce NGS-B design manual 29-60040, "Overall Plant Control", November, 1981.

Table 6-1 Main Control Algorithms for PHT Pressure and Inventory Control

Feed and Bleed Valves Control

Reflux Feed Valve:

$$Y_{RF} = A_1 + B_1 Y_2 - CY_1$$

Direct Feed Valve:

$$Y_{DF} = A_2 - B_2 Y_2 - CY_1$$

Bleed Valves:

$$Y_B = -A_3 + B_3 Y_{BIAS} + CY_1$$

Controller Outputs:

$$Y_1 = G_1 (L_P - L_{PSET})$$

$$Y_2 = G_2 (1 + \frac{1}{T}\int dt)(P_{BC} - P_{BCSET})$$

where,

Y_{RF}, Y_{DF}, Y_B = demanded valve opening for reflux feed, direct feed, and bleed valves

Y_1 = pressurizer level controller output

Y_2 = bleed condenser pressure controller output

Y_{BIAS} = bias signal for bleed valves

$A_1, B_1, A_2, B_2, A_3, B_3, C$ = constants

G_1, G_2 = controller gains

T = controller reset time

L_P, L_{PSET} = pressurizer level and level setpoint

P_{BC}, P_{BCSET} = bleed condenser pressure and pressure setpoint

Pressurizer Steam Bleed Valves and Heater Control

$$Y_{PSB} = G_3 (P_{ROH} - P_{ROHS})$$

$$Q_{PH} = G_4 (P_{ROHS} - P_{DB} - P_{ROH}) \Big|_{0}^{Q_{MAX}}$$

where,

Y_{PSB} = demanded valve opening for pressurizer steam bleed valves

Q_{PH} = demanded heat rate

G_3, G_4 = controller gains

P_{DB} = pressure deadband

P_{ROH}, P_{ROHS} = PHT pressure and pressure setpoint

PHT Relief Valves Operation

$$Y_{REL} = G_5 (P_{ROH} - P_{ROHR})$$

where,

Y_{REL} = demanded valve opening for PHT relief valves

G_5 = gain

P_{ROHR} = PHT relief pressure setpoint

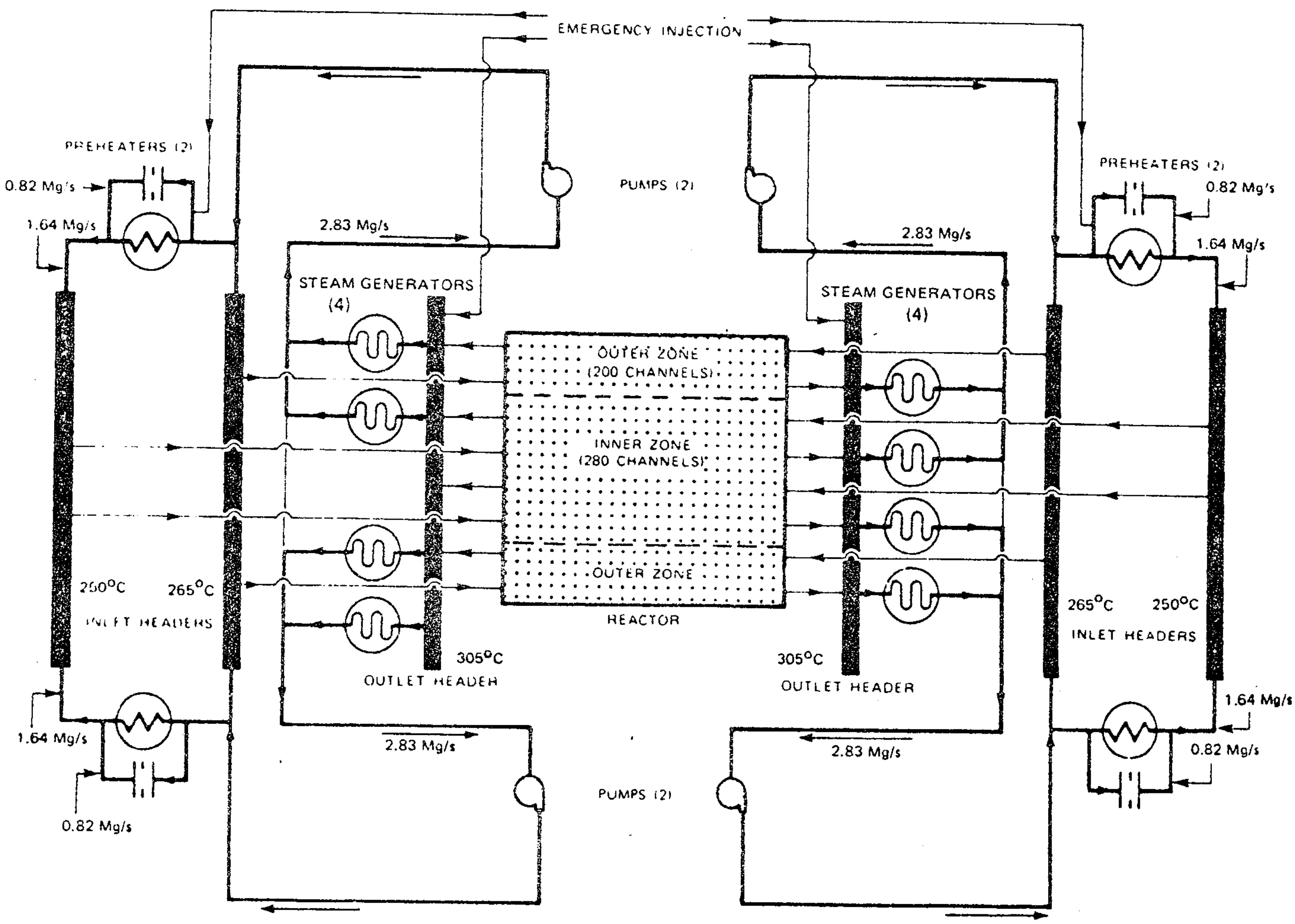


FIGURE 6-1
Heat Transport System

29.33000-1
REV. 9. 1978 NOV.

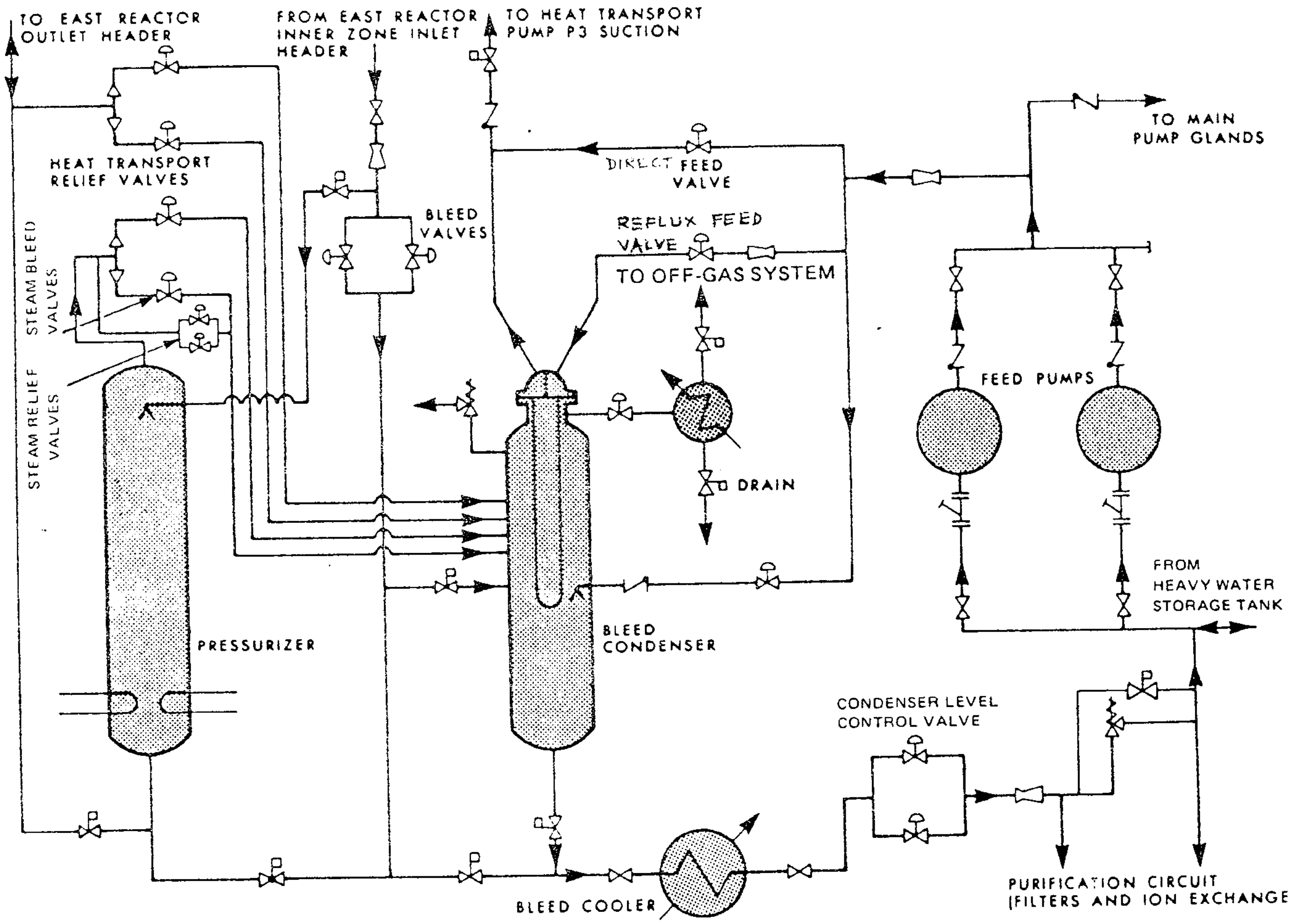


FIGURE 6-2
Heat Transport Pressurizer, Feed, Bleed and Relief Circuits

29.33300-1
REV. 1 1978 NOV

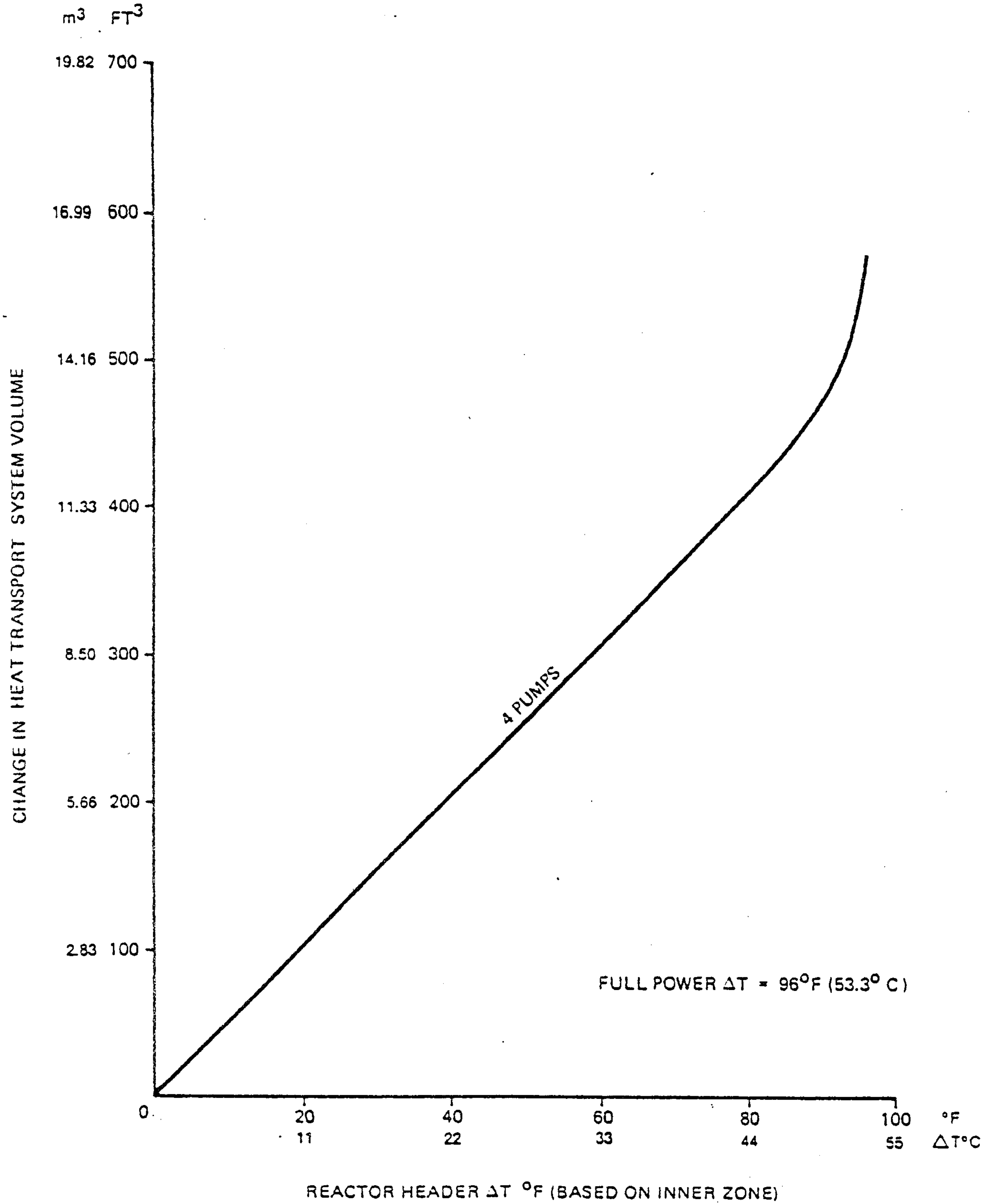


FIGURE 6-3 CHANGE IN HEAT TRANSPORT SYSTEM VOLUME WITH REACTOR ΔT

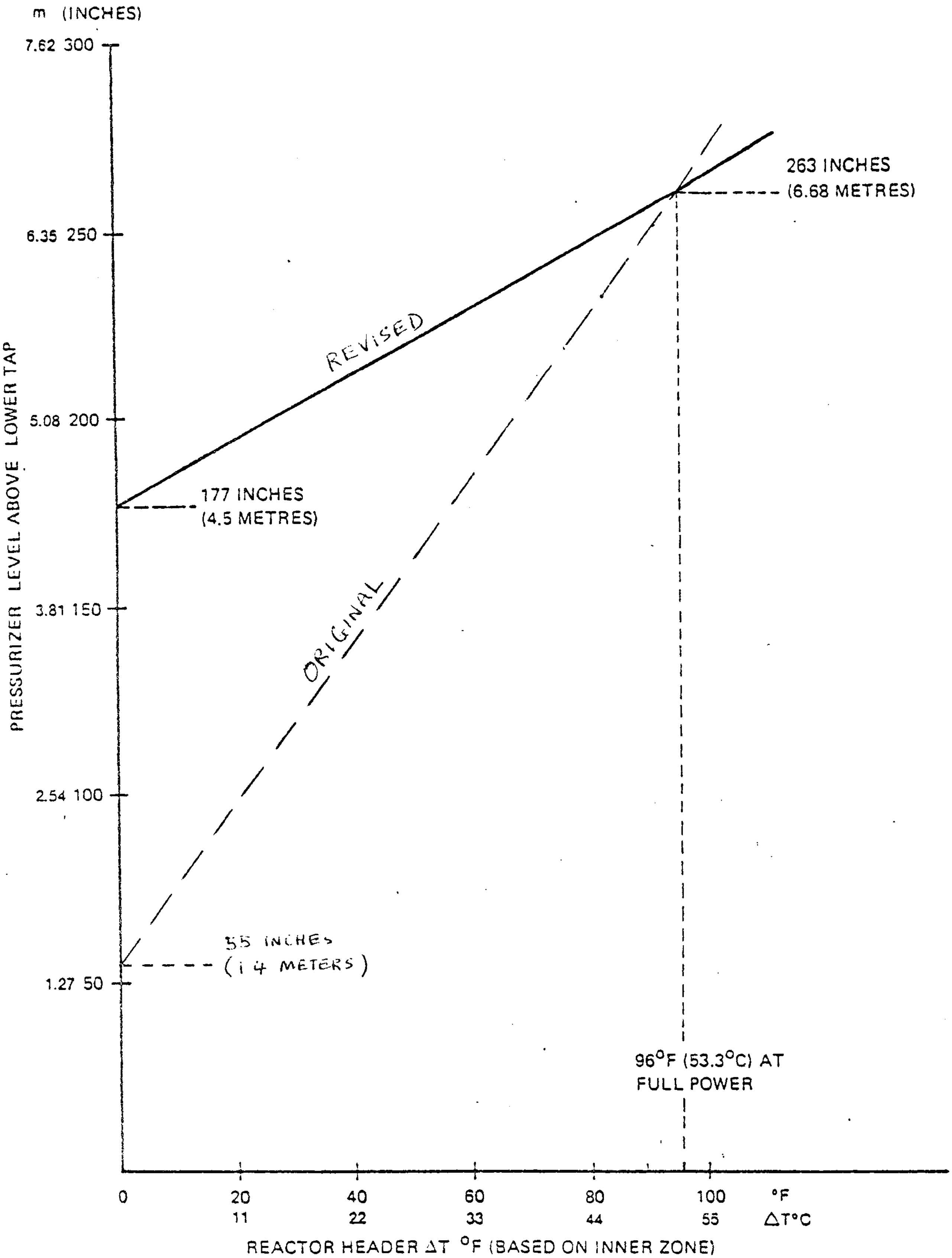


FIG 6-4 PRESSURIZER LEVEL PROGRAM

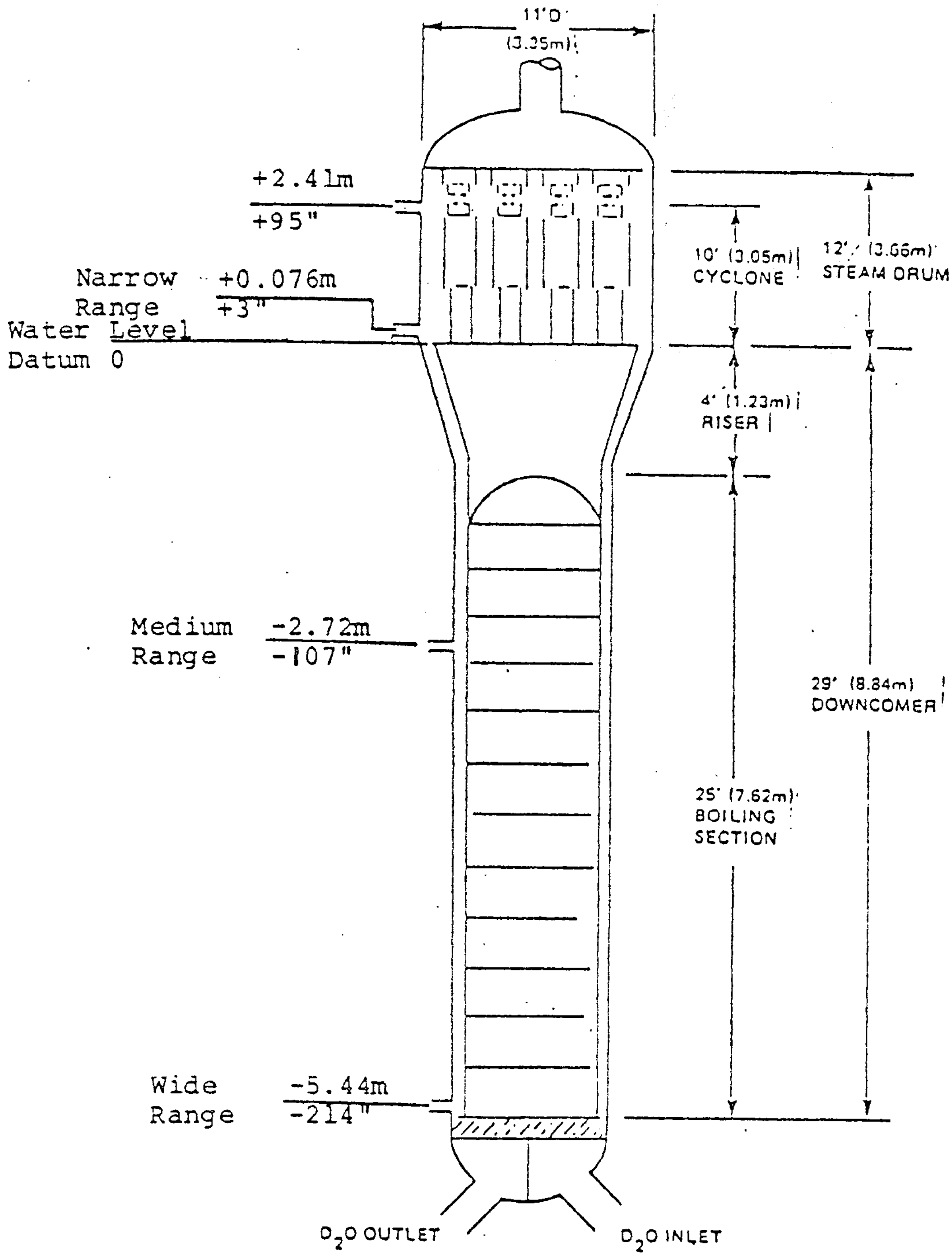
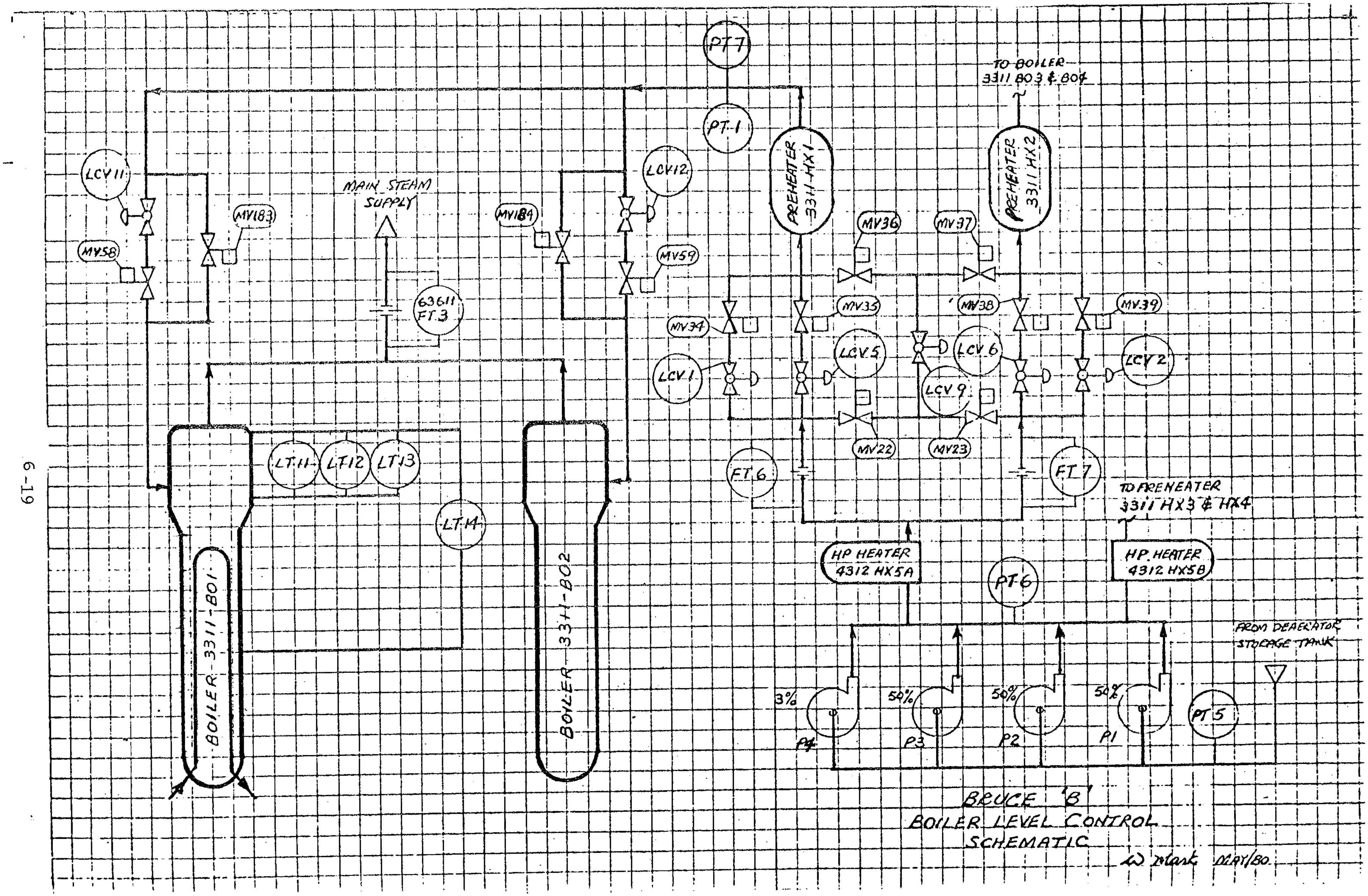


FIGURE 6 -5
BRUCE 'B' BOILER LAYOUT



LCV11
MV58
MV183
MAIN STEAM SUPPLY
63611 FT.3
MV184
LCV12
MV59
PT 7
PT-1
PREHEATER 3311-HX1
PREHEATER 3311 HX2
TO BOILER 3311 BO3 & BO4
MV36
MV37
MV34
MV35
MV38
MV39
LCV1
LCV5
LCV6
LCV9
LCV2
MV22
MV23
FT 6
FT 7
TO PREHEATER 3311 HX3 & HX4
LT-11
LT-12
LT-13
LT-14
BOILER 3311-BO1
BOILER 3311-BO2
HP HEATER 4312 HX5A
HP HEATER 4312 HX5B
PT 6
PT 5
FROM DEAERATOR STORAGE TANK
3%
50%
P4
P3
P2
P1
BRUCE 'B'
BOILER LEVEL CONTROL
SCHEMATIC
W Mark MAY/80.

FIGURE 6-6

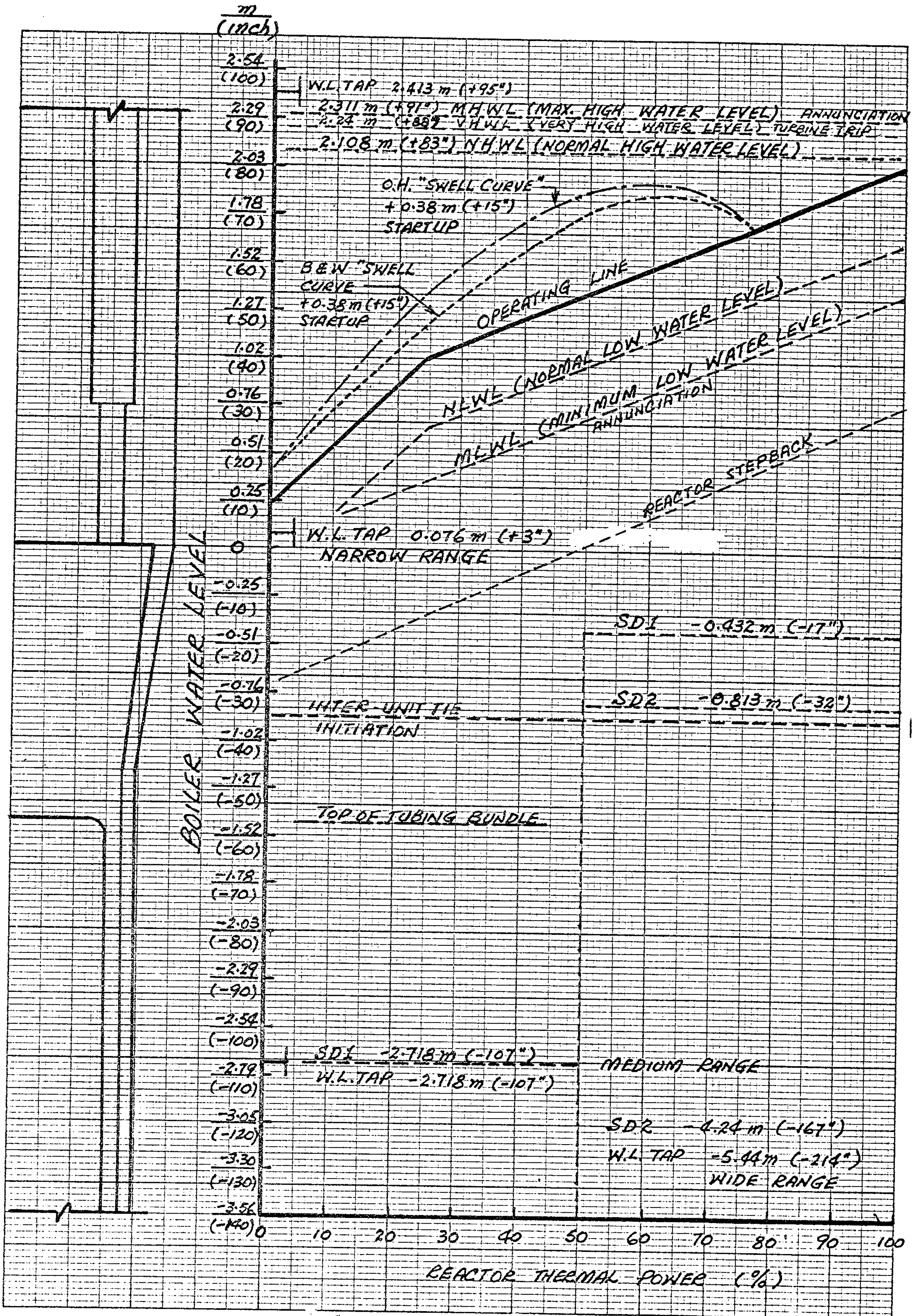
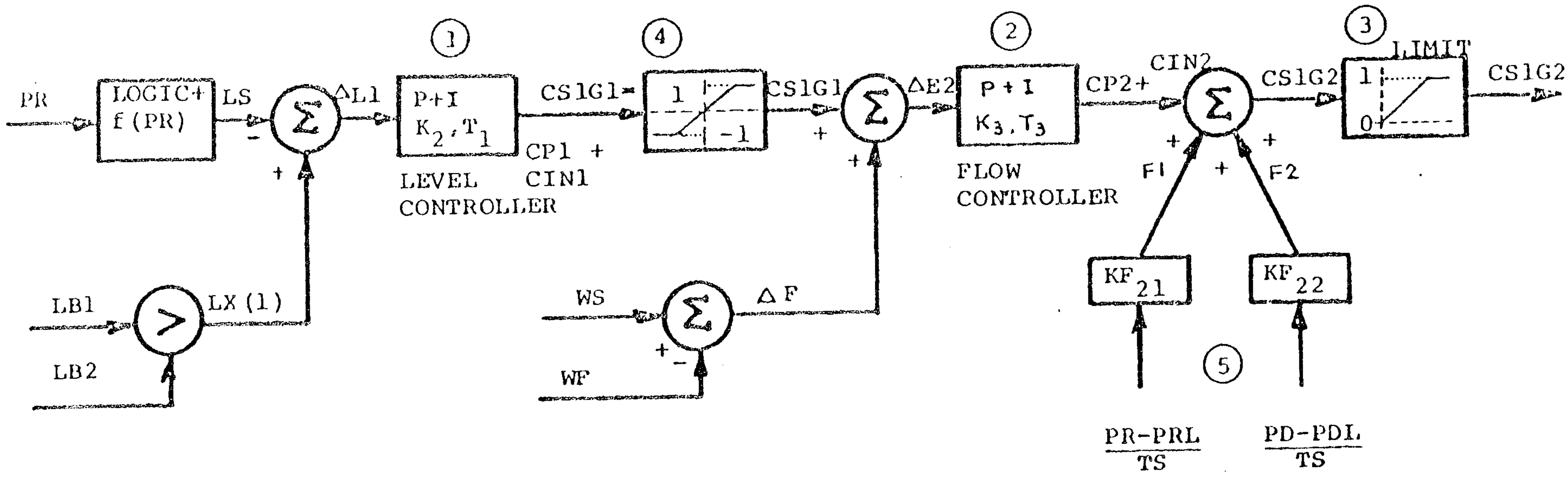


Figure 6-7 Bruce 'B' Boiler Operating Line

REV.0. July80



LB1,LB2 = Water levels of a pair of boilers sharing a preheater

LX(1) = Max(LB1,LB2)

PR = Reactor thermal power

LS = Boiler level setpoint

ΔL1 = Boiler level error

K_2, T_1 = Gain and reset time of level controller

WS = Normalized steam flow rate from pair of boilers

WF = Normalized feedwater flow rate to pair of boilers

ΔF = Flow error

K_3, T_3 = Gain and reset time of flow controller

PRL = Reactor thermal power of previous program cycle

PD = Boiler drum pressure

PDL = Boiler drum pressure of previous program cycle

TS = Program cycle time

KF_{21}, KF_{22} = Feedforward gains for rate of change of reactor power and rate of change of boiler pressure

CS1G2 = Control signal to feedwater control valves

Figure 6-8 Feedwater Valve Control

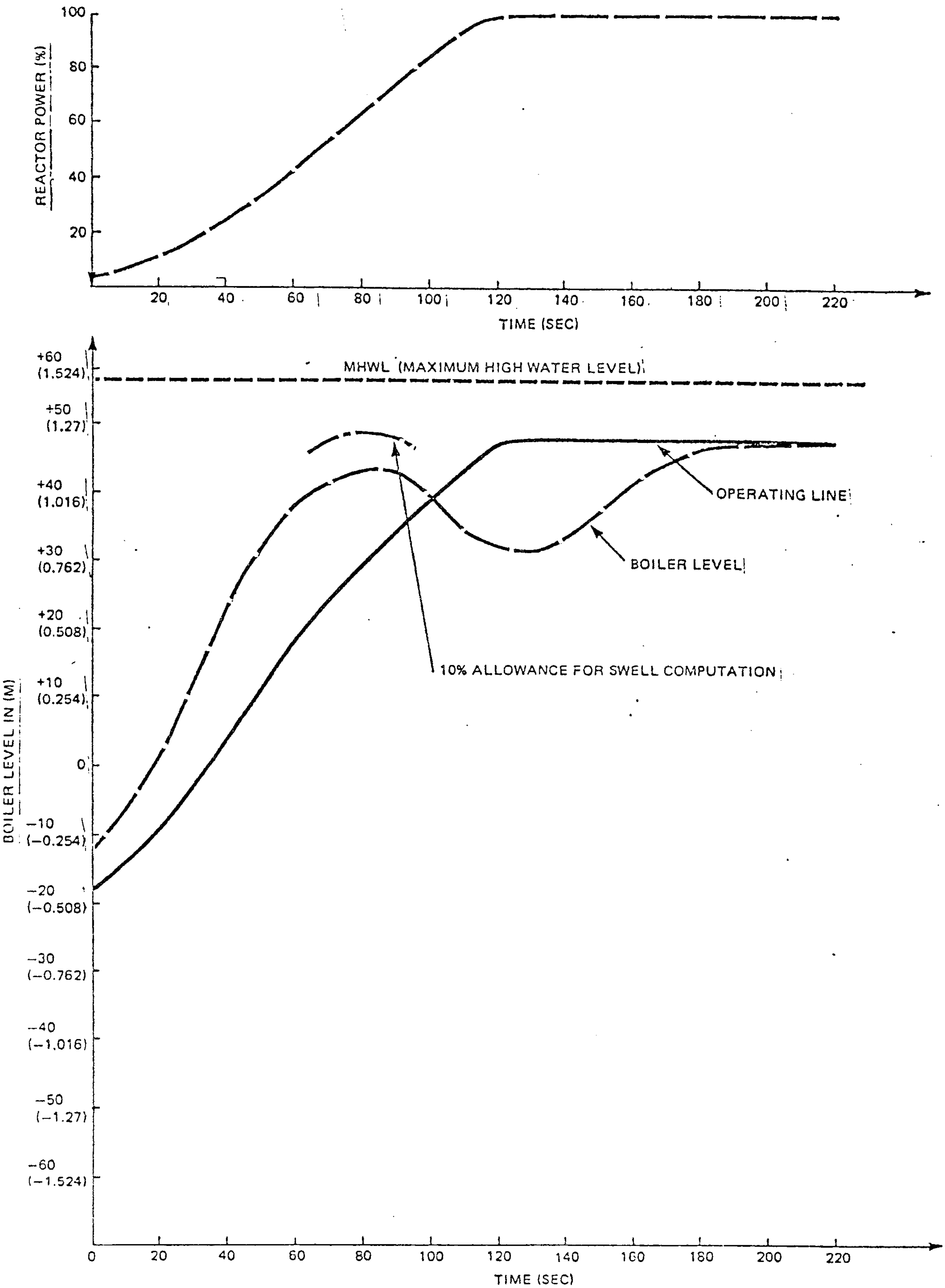


FIGURE 6 -9
POWER RUNUP AT 4% LOGARITHIC FROM 5% TO 25%
FOLLOWED BY 1% PER SEC. LINEAR TO 100%
(REACTOR POWER AND BOILER LEVEL RESPONSES)

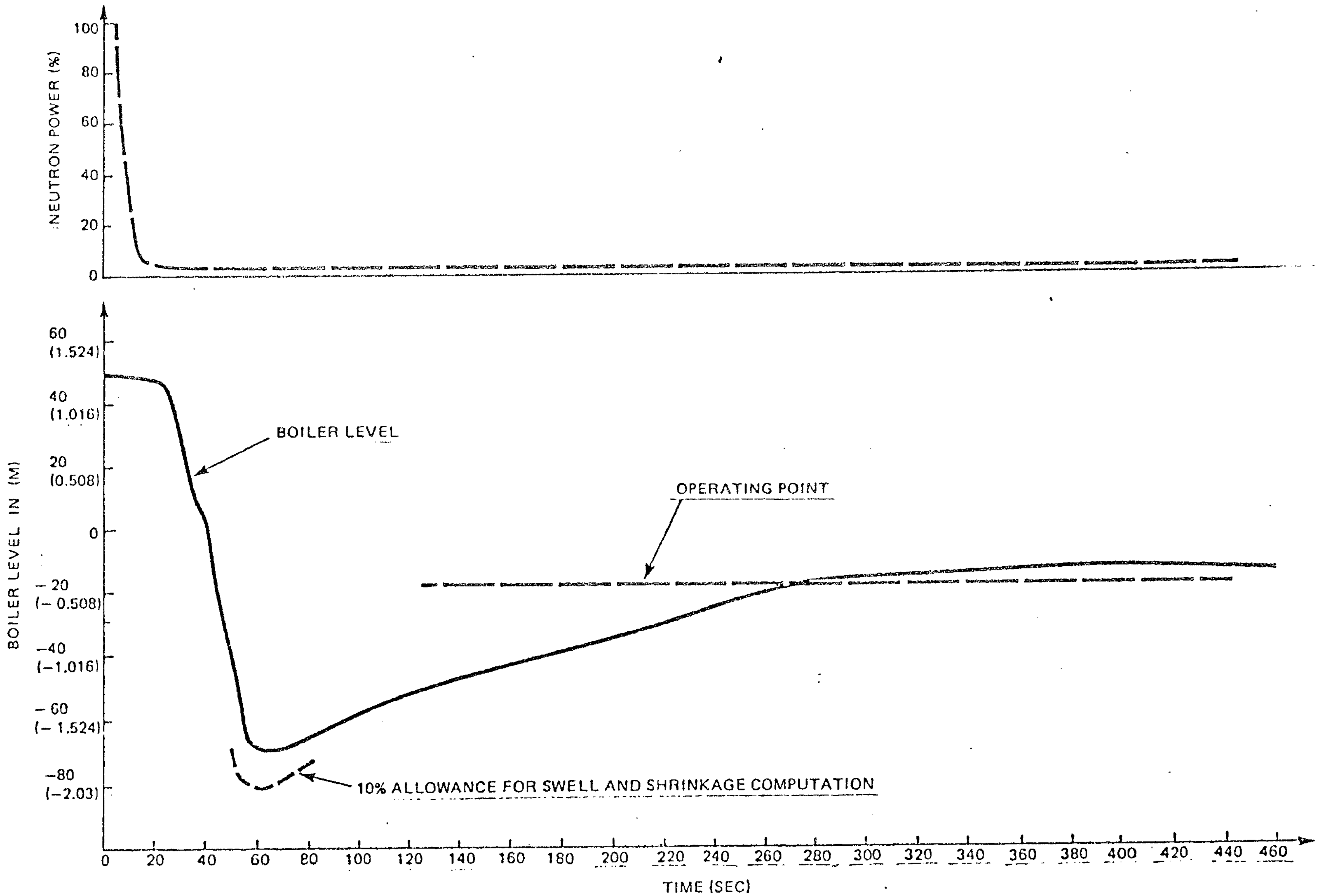


FIGURE 6 -10
TRANSIENT RESPONSES OF NEUTRON POWER AND BOILER LEVEL FOR REACTOR TRIP

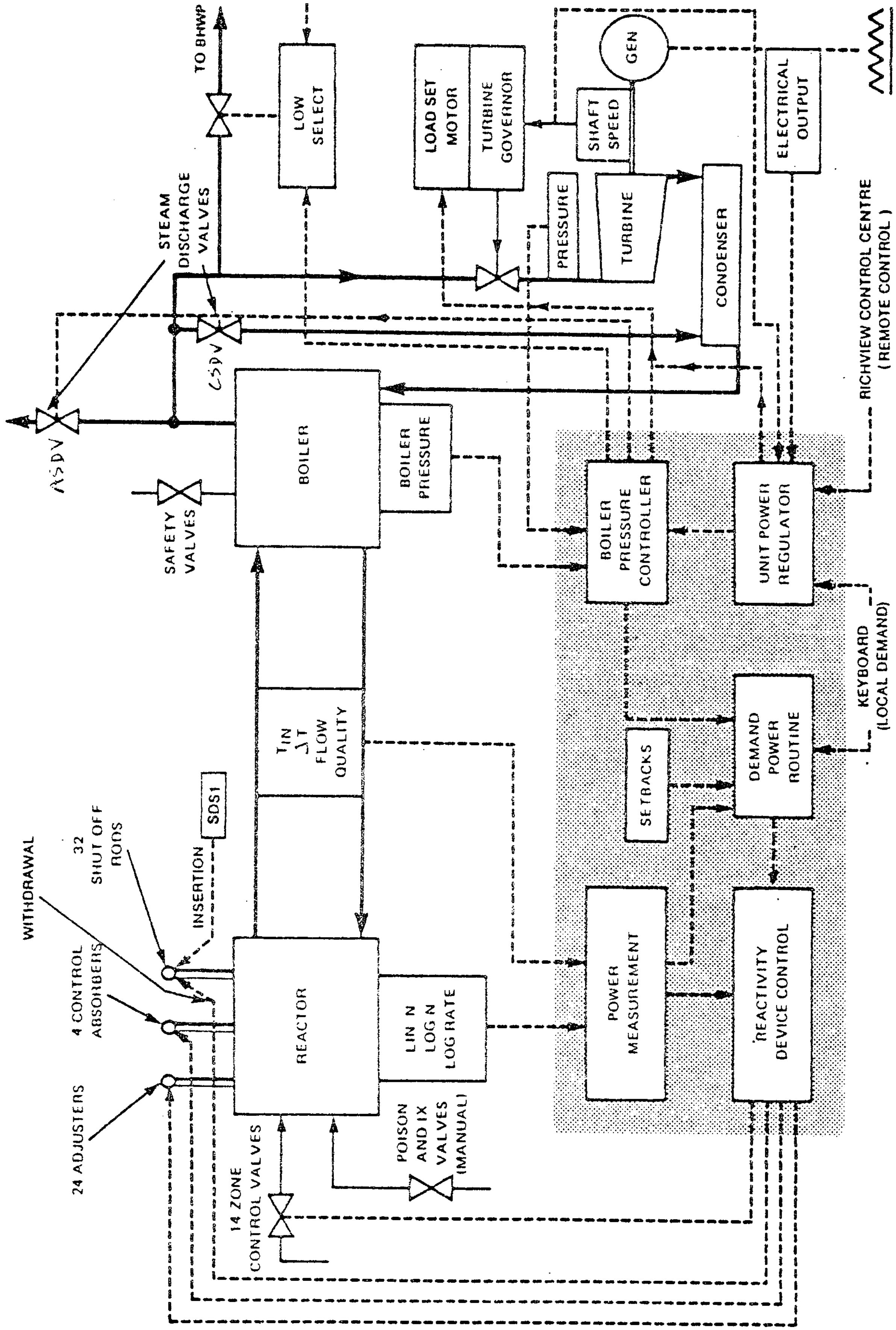


FIGURE 6-11 UNIT CONTROL SYSTEM BLOCK DIAGRAM

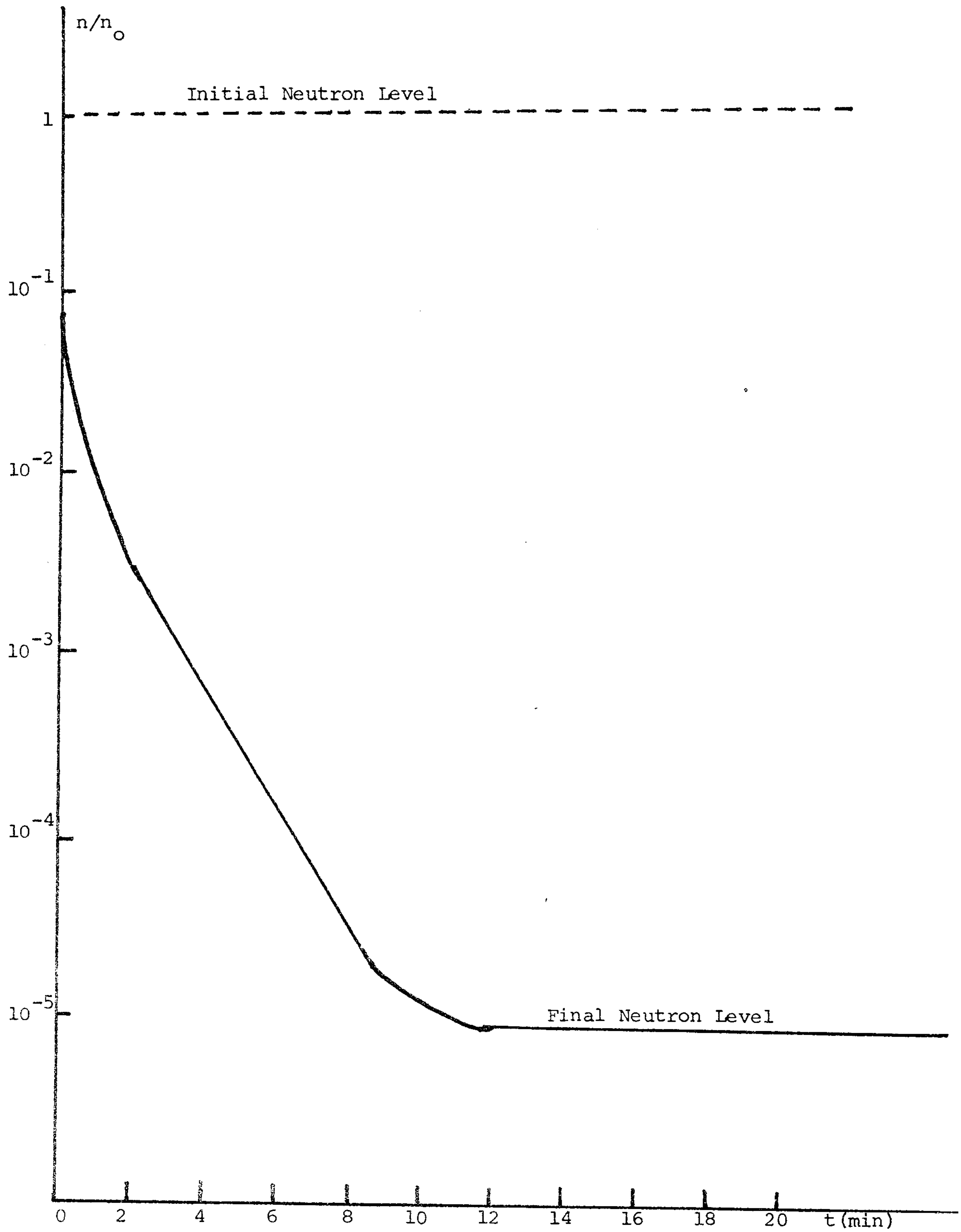


FIGURE 6-12: Newtron Level During Shutdown

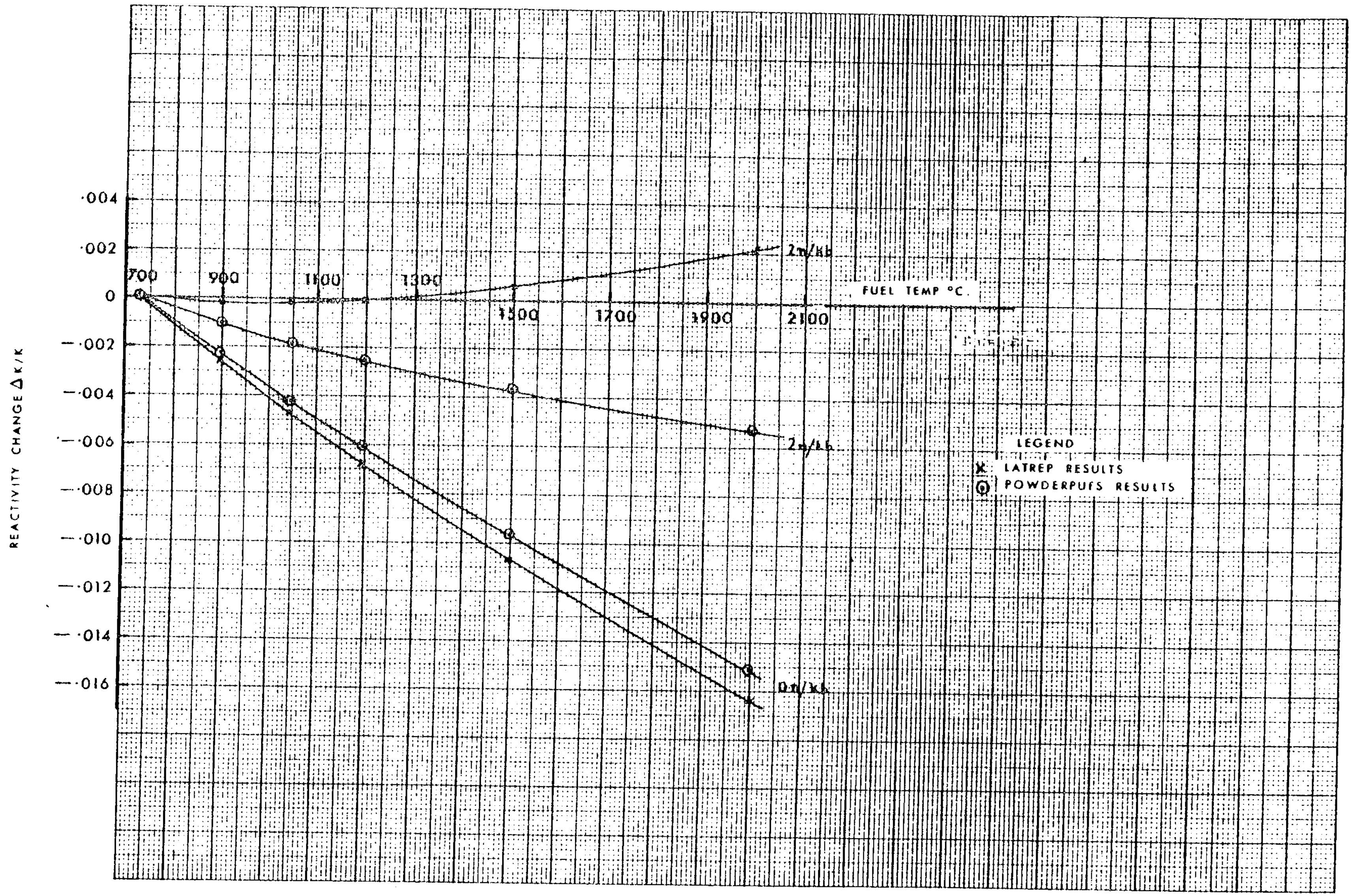
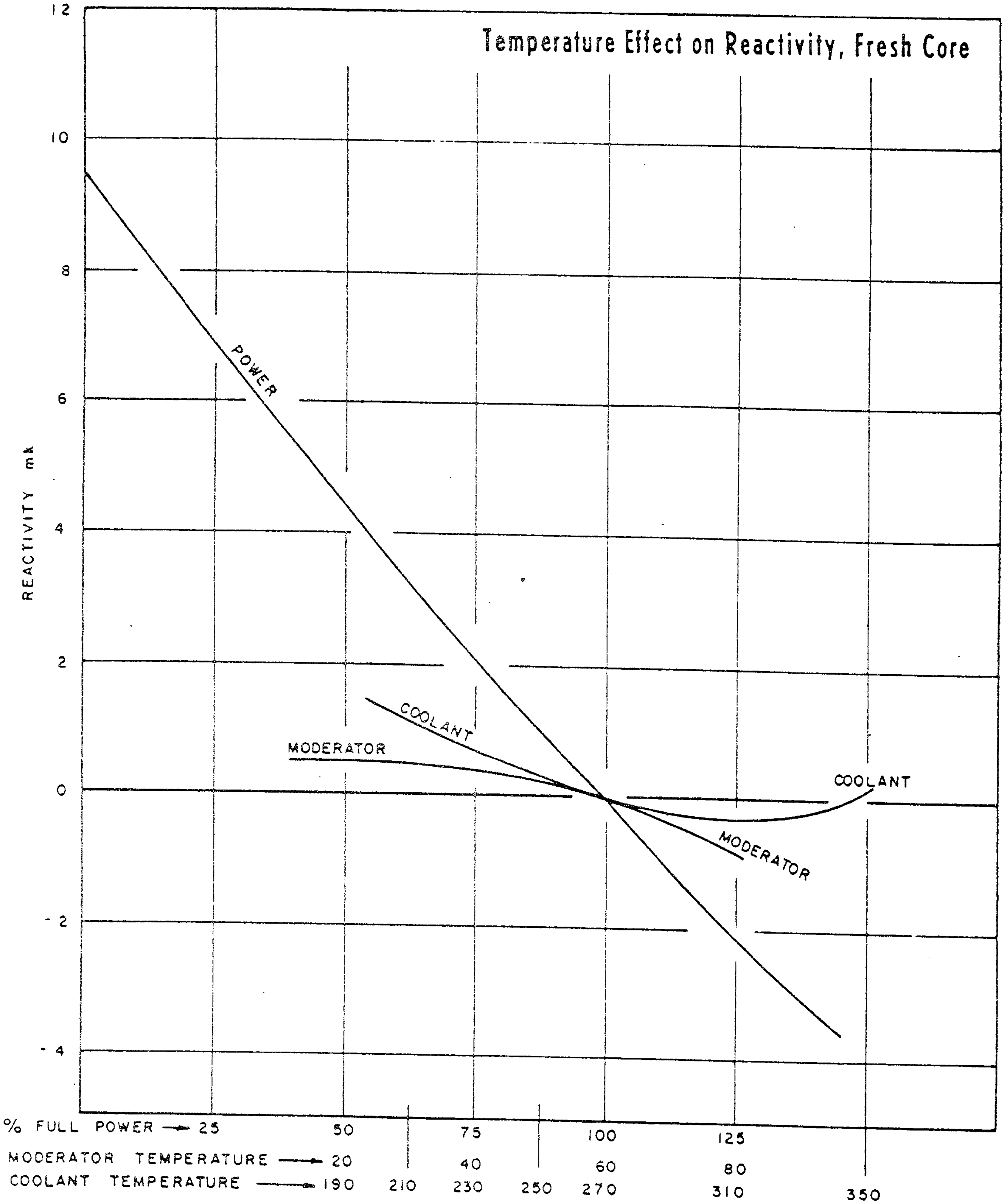


FIGURE 6 -13: **FRACTIONAL CHANGE IN REACTIVITY WITH FUEL TEMPERATURE**



Temperature Effect on Reactivity, Fresh Core
REACTIVITY mk
12
10
8
6
4
2
0
-2
-4
POWER
COOLANT
MODERATOR
COOLANT
MODERATOR
% FULL POWER → 25 50 75 100 125
MODERATOR TEMPERATURE → 20 40 60 80
COOLANT TEMPERATURE → 190 210 230 250 270 310 350

FIGURE 6-14

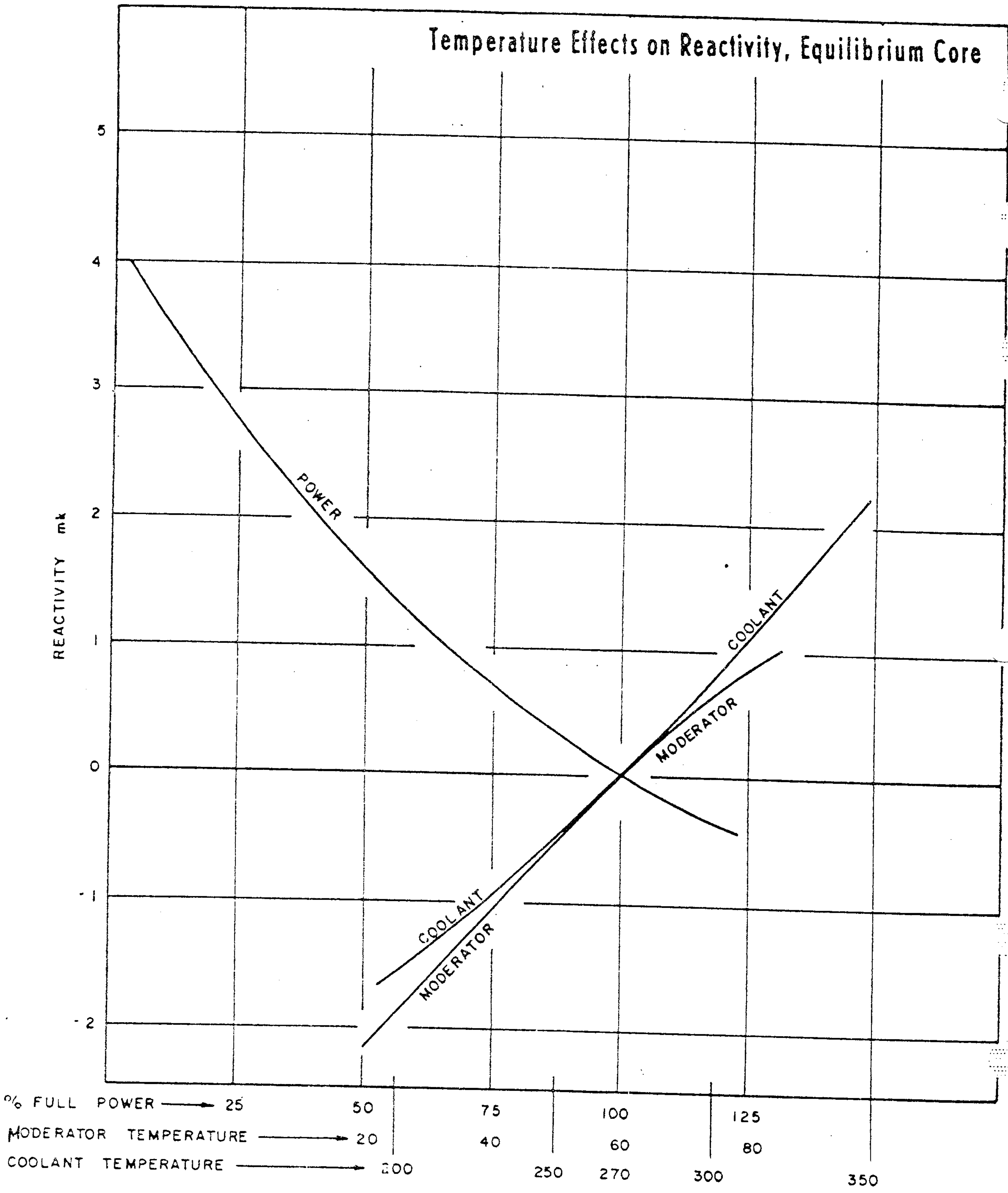

Temperature Effects on Reactivity, Equilibrium Core
REACTIVITY mk
5
4
3
2
1
0
-1
-2
POWER
COOLANT
MODERATOR
COOLANT
MODERATOR
% FULL POWER → 25 50 75 100 125
MODERATOR TEMPERATURE → 20 40 60 80
COOLANT TEMPERATURE → 200 250 270 300 350

FIGURE 6-15

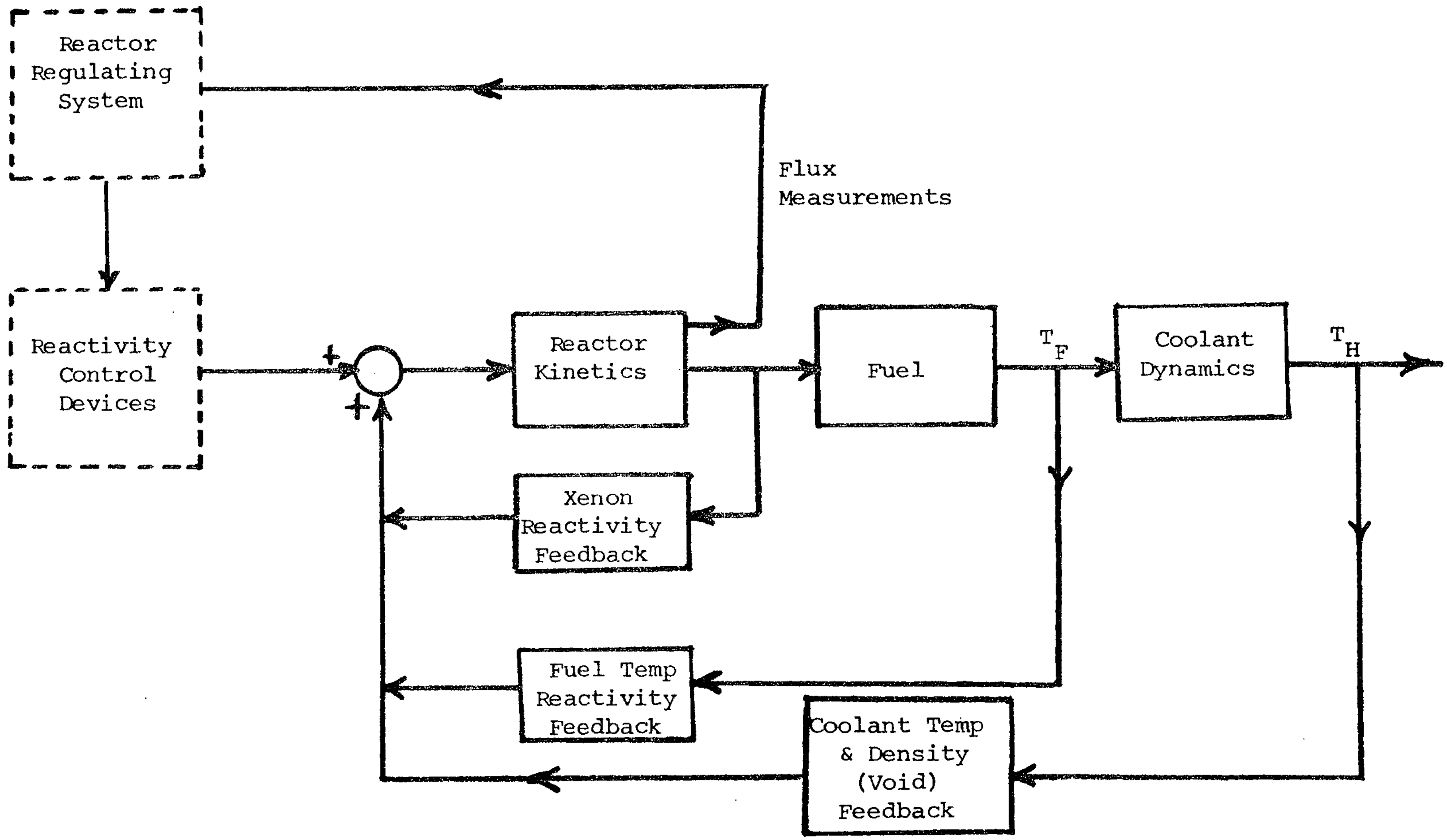


FIGURE 6 -16: <u>Reactivity Feedback and Control Block Diagram</u>

APPENDIX: BASIC CONTROL ALGORITHMS

Proportional Control

The proportional controller provides one of the simplest and most intuitive type of control. It simply drives the process with a signal proportional to the error signal.

The action of a proportional controller is expressed mathematically as:

$$m = Ke+b \quad (1)$$

where m is the controller output

e is the error signal applied as input to the controller

b is the bias term

k is the controller gain

The bias term is supplied so that the control signal will not drop to zero when the error is zero.

Several important properties of proportional control may be summarized as follows:

(1) Without a bias term(b), there will always be a steady state error or offset. This offset is reduced if the controller gain is increased. However, too large a gain can lead to instability.

(2) For a given operating condition, there is only one bias setting which will reduce steady state offset to zero. If the operating condition is then changed, the system will eventually reach a new steady state condition with non-zero offset. On proportional controllers, the bias term is manually adjusted.

Proportional-Integral Control

For some processes (e.g. precision positioning equipment) it is desirable to eliminate offset and keep the controlled variable at same setpoint. This is achieved by introducing the integral term also called the automatic reset term in addition to the proportional term.

The output of a proportional integral (PI) controller is given by:

$$m = K\left[e + \frac{1}{\tau_I}\int_0^t e\,dt\right] \quad (2)$$

where m, e, K were defined in equation (1), and τ_I is called the reset time.

As long as there is a non-zero error (let us assume it is positive), the integral term in equation (2) will keep increasing. Thus the controller output m will keep increasing and this drives the process in such a way as to reduce the error to zero. τ_I is called the reset time.

Under some conditions, PI control leads to the undesirable phenomena known as wind-up and saturation. Suppose a process under PI control is shutdown but the controller is left 'on'. Any error seen by the controller will persist because the process is off. The integral term will continue to increase until the controller output reaches the maximum value. The controller is now in a state of saturation. On subsequent start-up of the process, the controller will initially cause a disturbance in the process. The phenomena of the integral term requiring time to change from the saturated state to an operating point is called integral wind-up. Important PI controllers usually have an "anti-windup" feature to limit the integral term.

Proportional-Derivative Control

The output of a PD controller is given by:

$$m = k\left[e + \tau_D \frac{de}{dt}\right] + b \qquad (3)$$

where τ_D is called the rate time or derivative time and all other variables have been previously defined.

The absence of wind-up and the presence of the derivative term makes PD control suitable for processes that experience frequent shutdowns and start-ups, and also for processes that employ duplex control action in which one of two control mechanisms is always inactive.

Derivative action is susceptible to noise and is often used in conjunction with a filter. Because there is no integral action, the offset problem is present with PD control and a bias term is provided as shown in equation (3)

Proportional-Integral-Derivative Control

The PID controller (or 3 mode controller) contains all the control modes previously discussed. If the parameters are properly selected, this controller can combine all the strong points of the P, PI and PD controllers.

The 3 mode controller may be represented by:

$$m = k\left[e + \frac{1}{\tau_I}\int_0^t e\,dt + \tau_D \frac{de}{dt}\right] \qquad (4)$$

where all terms have been previously defined. This is called the non-interacting or parallel form of the PID algorithm.