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LABORATORY EXPERIMENT ON THE CONTROL OF DISTILLATION COLUMN PRESSURE BY MICROPROCESSOR

by

J.B. Edwards, B.Sc.(Eng.), M.Sc., C.Eng., M.I.E.E.

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Dept. Control Engineering,
University of Sheffield.

1. INTRODUCTION

1.1 General description of the column

The column and its principal instruments and actuators are illustrated diagramatically in Fig. 1. A preheated, binary (two-component) mixture of liquids, usually water and ethyl alcohol, is fed into the column at its midway point at a feedrate $F(t)$ as indicated and the separated products taken off at rates $D(t)$ and $W(t)$ at the top and bottom of the plant respectively. The top product is rich in the more-volatile component (alcohol) and the bottom product should contain only a small fraction of this component under proper operating conditions.

On entering the reboiler at the bottom of the column the liquid not removed as bottom product is vapourised at a rate $V(t)$ by the immersion heater shown. The vapour streams up the column through small holes in the seive-trays, giving up molecules of the heavier component (water) to the liquid standing on the trays in exchange for molecules of the lighter component (alcohol) as it progresses. Ultimately, the vapour is condensed by the cooling tubes of the condensor shown and collected in liquid form in the accumulator. A considerable proportion of the condensed liquid is returned to the column as 'reflux' at a rate $L(t)$ for further enrichment: again as shown in Fig. 1.

In practice the top and bottom products would proceed, perhaps via downstream columns, before ultimate dispatch to customers. In the laboratory the components are remixed and returned to the feedtank.

1.2 The overall control configuration

In practice feedrate $F(t)$ is determined by upstream plant and should therefore be considered to be a process disturbance rather than a manipulable input variable. Variables which are directly manipulable (i.e. the process inputs) are:

(i) $V(t)$ by adjustment of heat input $q_i(t)$ $(=V(t)\mathcal{L})$*

(ii) $q_o(t)$ the rate of heat removal by the condensor, by adjustment of the cooling water flowrate $v_w(t)$

(iii) $W(t)$
(iv) $D(t)$
(v) $L(t)$
} by adjustment of the flow control valves shown in Fig. 1.

The measured control variables (i.e. the process outputs) are

(a) the top product composition (% alcohol), usually inferred from a temperature measurement $x(n,t)$ made near the top of the column as indicated in Fig. 1.

*$\mathcal{L}$ = latent heat of the mixture; usually constant.

(b) the bottom product composition, usually inferred from temperature measurement $x^1(m,t)$ made near the bottom of the column.

(c) the volume $H_b(t)$ of liquid in the reboiler

(d) the volume $H_a(t)$ of liquid in the accumulator

and (e) the pressure $P(t)$ within the column.

The column is therefore a 5-input 5-output process and at Sheffield the following interlinking of variables is usually adopted:

$H_a(t)$ sets $L(t) + D(t)$ ... loop 1

$H_b(t)$ sets $W(t)$ ... loop 2

$x_a(t)$ and $x_b(t)$ set $q_i(t)$ and reflux ratio $L(t)/D(t)$ via a diagonalising precompensator loops 3 and 4

$P(t)$ sets $q_o(t)$ via $v_w(t)$ .. loop 5

Control loops 1 and 2 are of the on-off type, electrodes detecting high and low liquid levels and opening and closing the control valves accordingly to keep the levels within narrow deadbands. Proprietory controllers are used for this purpose and apart from regular manual monitoring by closed circuit television their operation should not be disturbed in this experiment.

The composition control loops 3 and 4 are generally closed through a computer control algorithm. The composition dynamics are very slow-acting however, and compositioncauses little disturbance on loop 5: the subject of the present experiment. Loops 3 and 4 are therefore here left open in the interests of simplicity.

For the present experiment attention should therefore be focussed on loop 5 illustrated, in context, in Fig. 2. From Fig. 2 it will be seen that the TEXAS FS/990/4 microprocessor is here to be used to control only the pressure $P(t)$ in the column by automatic manipulation of the condensor cooling water flow-rate $v_w(t)$. The liquid flows $W(t)$ and $L(t) + D(t)$ will be left under the control of their local controllers, reflux ratio $R(t)\{= L(t)/D(t)\}$ will be left at a constant setting (4:1 approx) and $q_i(t)\{$ and hence $V(t)\}$ may be manipulated manually to disturb the pressure-control system under investigation.

1.3 <u>Cooling water control system</u>

As indicated in Fig. 3 the condensor cooling water is controlled in a cascade manner. The flow $v_w(t)$ is manipulated by a pneumatic valve the plunger of which is controlled via a closed-loop electro-pneumatic positioner attached to the valve. The electrical incoming <u>valve-position demand</u> signal is compared with a mechanical measurement of actual valve opening within the positioner and the error signal used to apply or drain pressure to the valve actuator to nullify the error. The valve-position demand signal is provided by a proprietory electronic P+I controller which acts on the error between a flow-demand signal $v_{wd}(t)$ and an electrical measurement of the actual flow $v_w(t)$ derived from an orifice flowmeter in the condensor pipe line. The demand signal $v_{wd}(t)$ may be derived from a local set-point potentiometer located on the controller itself or, for the present experiment, from a digital to analogue converter at the microprocessor interface.

When the pressure-control loop is closed we therefore have effectively three loops in cascade (one inside another) the purpose of each loop being to substantially remove the disturbances, nonlinearities and lags occuring within the loop in question. The valve position loop for instance removes most of the effect of nonlinearity of the valve actuator system and the flow-loop removes the remaining nonlinearity in the flow/lift characteristic of the valve itself and the effect of mains pressure variation. This leaves the pressure-control loop to compensate only the effects of disturbances on column pressure and not the imperfections of other loop items.

1.4 Control of reboiler heating rate

Although not used for pressure-control by the system investigated in this experiment, reboiler heating rate $q_i(t)$ acts as a severe disturbance on column pressure as discussed in Section 2. In fact, the implicit purpose of the pressure-control system is to preserve a balance between the rates at which heat is applied to and removed from the plant. To provide a test of the correct functioning of the pressure-control system, therefore, the manipulation of the heating rate may be effected manually from the remote computer control station. Again, a cascade form of control is used to help remove the effects of nonlinearity in the relationship between the heater current demand and the actual power delivered to the heater. As shown in Fig. 4, the demanded power signal $q_{id}(t)$ is compared with a measurement of actual power $q_i(t)$ derived from a Hall-effect transducer and the amplified error used to manipulate the demanded current from the thyristor controller supplying current to the heater-elements. The signal $q_{id}(t)$ may be set at the computer interface at which both $q_{id}(t)$ and $q_i(t)$ may be monitored.

2. THEORETICAL CONSIDERATIONS

2.1 Process equations

To a first approximation the rate of build up of pressure within a column is proportional to the imbalance of heat input and output so that

$$dP/t)/dt = k_p\{q_i(t) - q_o(t) - \Delta q_o(t)\} \quad (1)$$

where k_p is the process gain (approximately constant) and $\Delta q_o(t)$ is the net heat loss from the plant other than via the condensor. In a well designed plant $|\Delta q_o(t)| << |q_o(t)|$

Now heat extraction $q_o(t)$ is only indirectly manipulable by adjustment of cooling water flow rate $v_w(t)$. In fact the condensor can be approximately described by the model

$$(1 + T_h d/dt)\ q_o(t) = k_c v_w\ (t) \quad (2)$$

where k_c and T_h are nearly constant and $v_w(t)$ is again indirectly set by a proprietory two-term (P+I) control loop so that

$$\{1 + (T_c + 1/k_b)d/dt\}\ v_w(t) = (1 + T_c d/dt)v_{wd}(t) \quad (3)$$

where $v_{wd}(t)$ is the adjustable set-point, T_c the time constant and k_b the integral gain of the coolant controller. T_c is given by

$$T_c = k_a/k_b \quad (4)$$

where k_a is the proportional gain of the coolant controller.

The input variable to be directly manipulated by the microprocessor is therefore $v_{wd}(t)$, though the measurement of $v_w(t)$ used by the local proprietory controller is to be fed-back to the computer for monitoring purposes.

Combining process equation (1) to (4) we get, if $D \equiv d/dt$,

$$P(t) = \frac{k_P}{D}\{q_i(t) - \Delta q_o(t) - \frac{k_c(1+T_c D)\quad v_{wd}(t)}{(1+T_h D)\left[1+k_b^{-1}+T_c)D\right]}\} \quad (5)$$

from which it is clear that a steady state can only be achieved when the contents of the brackets {} become zero. If $v_{wd}(t)$ were manipulated only by proportional action, i.e.

$$v_{wd}(t) = -k_1\ \{P_r - P(t)\} \quad (6)$$

where P_r is the desired reference pressure and k_1 the proportional gain of the pressure control system, then it follows that, for constant $q_i(t)$ and $\Delta q_o(t)$,

$$\lim_{t\to\infty} P(t) = P_r + (q_i - \Delta q_o)/k_c k_1 \quad (7)$$

$$\text{i.e. } \lim_{t\to\infty} P(t) \neq P_r \quad (8)$$

The steady-state error in P(t) may be eliminated partially by incorporation of feed forward control action based on a measurement of $q_i(t)$ so that the control law becomes

$$v_{wd}(t) = - k_1\{P_r - P(t)\} + q_i(t)/k_c \tag{9}$$

or by the use of proportional plus integral action. It is the latter scheme which will be implemented initially but the measurement of $q_i(t)$ will be made available to the microprocessor nevertheless to permit feed-forward control at a later date.

2.2 Proposed Two Term Control Law

For run-up purposes, between tuning experiments and for open-loop tests, manual control of $v_{wd}(t)$ via the microprocessor is provided. Changeover to closed-loop pressure control will take place on the operation of an auto/manual selector switch located on the remote man/machine interface. The control law will therefore be described by the following equations:

$$v_{wmin} < v_{wd}(t) < v_{wmax} \tag{10}$$

where v_{wmax} and v_{wmin} are the maximum and minimum cooling water settings and, if

$$e(t) = P_r(t) - P(t) \tag{11}$$

then $$v_{wd}(t) = - k_1 e(t) - k_2 e_i(t) \quad ,t > t_o \tag{12}$$

where $$e_i(t) = \int_{t_o}^{t} \{P_r(t) - P(t)\}dt$$

k_1 and k_2 being the proportional and integral gains respectively and t_o being the time at which automatic control is selected.

Furthermore

$$v_{wd}(t) = \text{manipulable (independent) variable, } t < t_o \tag{13}$$

and

$$k_2 e_i(t) = -v_{wd}(t) + k_1 e(t), \quad t<t_o,\ v_{wd}(t) = v_{wmin}, \text{ or } v_{wd}(t) = v_{wmax} \tag{14}$$

Equation (14) effectively prevents the uncontrolled wind-up of the integral action during periods of manual control and whilst the control system is in a state of saturation. It ensures bumpless transfer from manual to closed-loop control and aids the large-signal stability of the closed-loop system.

3. HARDWARD DETAILS

In sections 3 and 4 of the report the following nmemonics are used to represent the plant and control variables and parameters:

PR	$\equiv P_r(t)$	= pressure reference
P	$\equiv P(t)$	= measured pressure
VWD	$\equiv v_{wd}(t)$	= coolant demand
VW	$\equiv v_w(t)$	= measured coolant flow
QID	$\equiv q_{id}(t)$	= heat input demand
QI	$\equiv q_i(t)$	= measured heat input
K1	$\equiv k_1$	= proportional gain
K2	$\equiv k_2$	= integral gain
E	$\equiv e(t)$	= pressure error signal
PROP	$\equiv k_1 e(t)$	= proportional action
XINT	$\equiv k_2 \int e(t)dt$ (on auto control)	= integral action
PMAX		= maximum permissible pressure
PMIN		= minimum permissible pressure
T		= time step

A/MSW ≡ state of auto/manual switch (1=auto, o=manual)

VENTSW≡ state of vent valve (1=open, o=closed)

Fig. 5 illustrates schematically the hardware constituting the main plant and operator interface with the TEXAS FS 990/4 microprocessor system. The diagram indicates only the functions provided at the interface and not the detailed circuitry involved. Fig. 6 shows the physical layout of the interface panel.

3.1 Analogue data

The reference signals PR, QID and VWD (which would be operator controls in an industrial situation) are set on adjustable potentiometers as indicated and read by the computer via analogue-to-digital converters (A.D.C.'s) at each sampling instant. The control parameters K1, K2, PMAX, PMIN and T (which would be set by the commissioning engineer and thereafter, under normal circumstances, left constant) are entered via the keyboard of the visual display unit (V.D.U) following a logic instruction from a switch on the interface panel.

All analogue input data from the plant transducers (P,VW and QI) and the operator interface (PR, VWD and QID) is continuously displayed on meters at the interface in addition to being fed into the computer via A.D.C's for either control or monitoring purposes. All analogue data read by the computer is subsequently fed out on digital-to-analogue converters (D.A.C's), in some cases for control and in others merely to provide a check on the correct operation of the program. For this latter purpose, all the analogue variables sampled and output by the computer may be selected and displayed, on at a time, on a single output meter located on the interface as shown in Figs. 5 and 6.

3.2 Logic Control

Various logic signals may be manually initiated by switches situated on the interface panel and the programm's response to these and other logic commands is indicated on the panel by appropriate warning lights. The on/off control of the column's emergency vent valve (see Fig. 1) is effected via the interface panel and the changeover from manual (open-loop) to automatic (closed-loop) control of column pressure. The allocation of switches lamps and relays to these logic operations is shown in Figs. 5 and 6.

The hardware and software (Section 4) have been so designed to ensure that the changeover to automatic control of pressure, despite being selected by the operator, may only be effected if the vent valve has first been closed by actuation of the appropriate switch. In the event of the software measuring an over-or under-pressure, the program will automatically open the vent valve until a safe working pressure is restored irrespective of the mode of pressure control selected. The limiting valves PMIN and PMAX should not be set outside the range 1.6v and 3.0v respectively.

In addition to indicating the mode of pressure control in operation (i.e. auto or manual) and the state of the vent valve, additional output logic lines actuate lamps indicating over-pressure, under pressure, and the saturation of the control algorithm as indicated.

3.3 Closed-circuit television monitoring

Although the plant and computer instrumentation provided at the interface is reliable under normal working conditions, faulty indications are nevertheless possible. Some important column variables furthermore are not monitored by the interface instrumentation. To ensure that no damage is caused to the plant during remote control experiments therefore closed-circuit television monitoring of key areas of the plant is provided adjacent to the interface panel. The following plant items/variables may be selected and observed one at a time on the single monitor screen.

(i) Vent valve position (up when open i.e. safe, down when closed).

(ii) Bottom product valve (up when open, down when closed).

(iii) Amperes supplied to reboiler heater (0-60+ Amp.)

(iv) Reboiler

(v) Top product and reflux valves (states as indicated)

(vi) Cooling water valve and local flow gauge

3.4 Audio communications

Audio links between the computer interface and different levels down the column (condenser room, column proper, reboiler room and the basement control room) are provided for alarm purposes and to allow manual changes to be effected at the plant in response to verbal instruction from the computer control room or vice versa.

4. SOFTWARE

Fig. 7 outlines the main features of the control program. After first being initialised and the initial parameters read in, the program then enters a loop around which the computer cycles repeatedly once per pre-specified time step T. The control program is intended to continue running throughout an entire sequence of experiments despite parameter-change, reference-change, reversion to manual control, alarm conditions etc. Different branches through the program may be taken however, depending upon which of the above situations apply.

As a second phase, though not included in this report, it is intended to be able to switch to alternative control structures e.g. pressure control by input heat manipulation or feedforward-control without necessarily stopping the program so as to permit the rapid comparison of control strategies. Students are required to draw up a flowchart for the software to effect these alternative forms of control on-line.

In Fig. 7 however, only proportional plus integral control of pressure (via coolant adjustment) is considered along with the necessary switching operations outlined in section 3. The flowchart is self explanatory and covers

(i) the reading of analogue and logic data from the operator/ plant interface.

(ii) the testing of the vent valve and auto/manual switches.

(iii) the calculation of VWD or the priming of the integral action in the event of manual control.

(iv) the testing for saturation of VWD, and for over-and under-pressure and the raising and resetting of the appropriate logic lines for lamp indication and vent valve release.

(v) outputting to the operator/plant interface DAC's

(vi) the storing of process variables on disc for off-line retrieval and display

(vii) the calling of the parameter log, entry and change routines.

The parameter log routine is clearly initiated by the setting of logic input line A from the appropriate demand switch on the operator interface via a bistable as indicated in Fig. 8. The bistable is reset and the associated indicator lamp extinguished by the routine itself on completion of the demanded log via logic output line A. The routine causes a single line log on the V.D.U. screen of all the system parameter values (PMAX, PMIN, K1, K2 and T) in present use by the control program.

The parameter entry routine is similarly initiated and also resets its initiating bistable on completion. Again a bistable output lamp indicates that parameter entry has been demanded and is in progress. The routine requests the operator via the V.D.U. screen to enter the parameters' nmemonics to be changed and the new values required via the keyboard. This done, the entry routine is completed. It is the function of the parameter change routine to actually effect the updating of the parameters to the new values entered whilst retaining the original values of the parameters for which no change was entered. The parameter change routine incorporates an abort option which allows the operator to retain all the original parameter values if he decides not to proceed with the update despite having entered new values. Again a switch-set bistable initiates the routines which itself resets the bistable as Figs. 7 and 8 indicate. The three parameter routines are to run at a lower priority than the control routine although triggered by it and must not delay the looping around the main control sequence.

5. PROCEDURE

(i) Tour the plant to familiarise yourself with its operation and layout to ensure that the instruemnt readings and closed-circuit television pictures are physically meaningful.

(ii) Switch on the program with PMIN set at 1.6 and PMAX at 3.0v and familiarise yourself with the manual control of cooling water, heat input, vent valve operation, observing both the meter responses and the plant response as monitored by the closed-circuit television.

(iii) On manual control, close the vent valve after a period of two to three minutes boiling at full power and low cooling to drive all the air from the column. Observe the integrating nature of the pressure response to any imbalance between heating and cooling rates by making tests at say full heat and zero cooling and vice versa. Check the automatic tripping of the vent valve with under- or over-pressure and open the vent valve immediately manually if this protection should fail. [Note that the automatic operation of the vent valve is software actuated and will therefore not occur in the event of program failure or incorrect setting of the pressure limits].

(iv) Switch to automatic pressure control after allowing the pressure to climb above reference level using a sampling interval of, say, 1s and note the recovery of the pressure signal towards the reference setting.

(v) Obtain responses of pressure and coolant flow on automatic control to step changes in the pressure reference signal e.g. from 2 to 2.5 v and to step changes in heat input e.g. from 60 + to 55 A. Typical responses are shown in Figs. 9 and 10.

(vi) Reasonable control gain settings are K1 = 2.5 and K2 = 0.05 (with T=1) but attempt to improve the loop tuning by adjustment of these values.

(vii) Explore the effect of increasing T.

(viii) Flowchart the software modifications necessary for alternative forms of pressure control.

(a) by heat-input manipulation and

(b) by combined feedforward and feedback control

(ix) Consider possible improvements to the plant/operator interface for the purposes of commissioning, student experiments, future research and an industrial environment.

6. <u>SAFETY</u>

It is essential to avoid an explosion that the column should not be left with the vent valve closed except whilst short term open-loop tests are in progress <u>and</u> the program is running or whilst stable closed-loop pressure-control is in operation. Between tests, check by closed-circuit television that the valve is not only switched open but actually <u>is</u> open.

The liquid level in the reboiler should be checked regularly via closed-curcuit television by inspection of the boiling and the operation of the bottom-product valve.

Keep the chart recorder pen activated and connected to the pressure transducer at all times and note the position of the safety limits on the recorder paper (PMIN = 1.6, PMAX = 3.0v). Use the recorder as well as the interface meter to check regularly that the column pressure is at a safe level.

In the event of uncontrolled over-pressure or fall in reboiler level switch the heating to minimum. Should the remote heating control fail all power should be switched off from the column by operating one of the red emergency stop buttons located near the door of each column room.

NO SMOKING in column rooms.

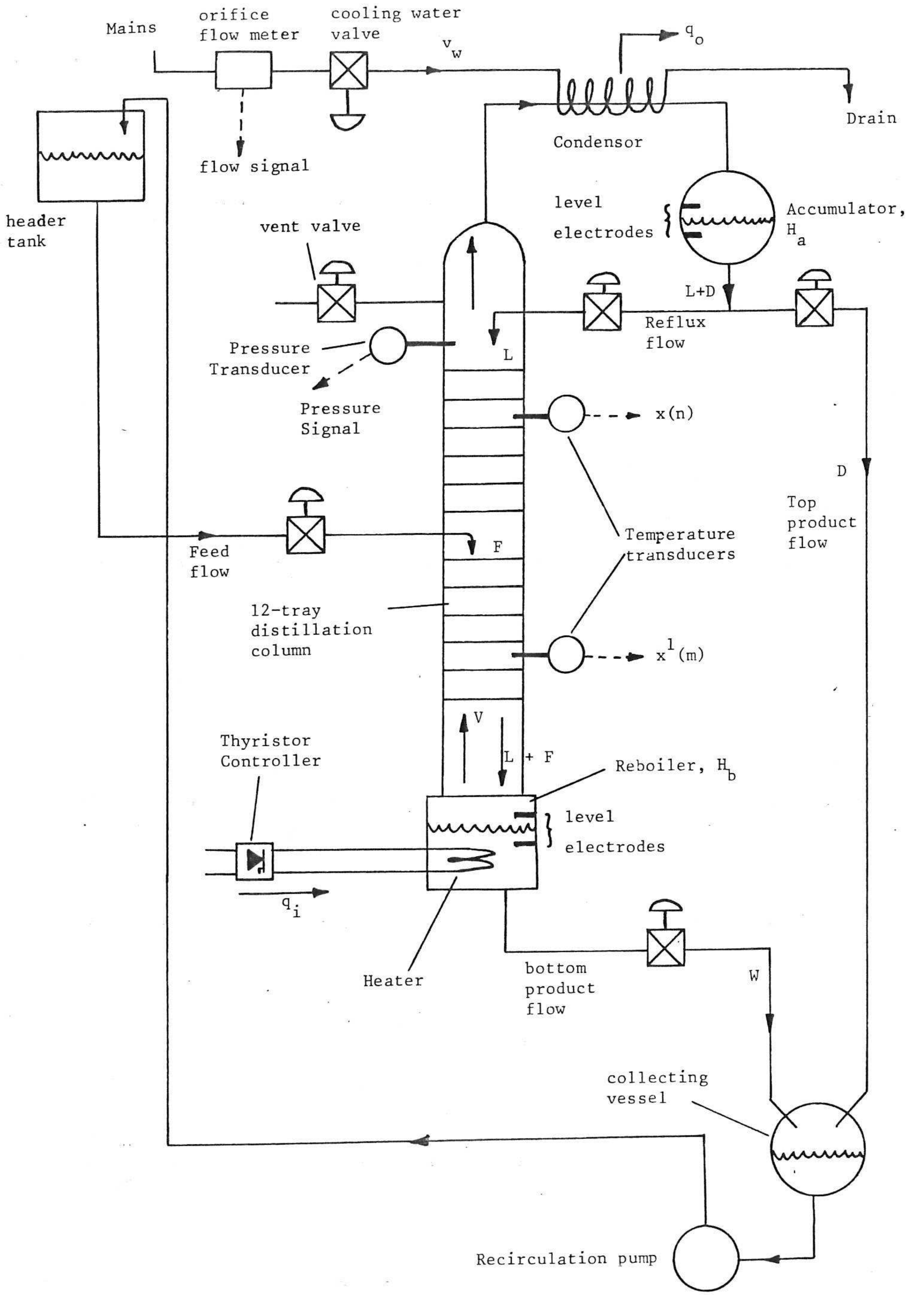


Fig.1. Illustrating general arrangement of distillation column and instrumentation.

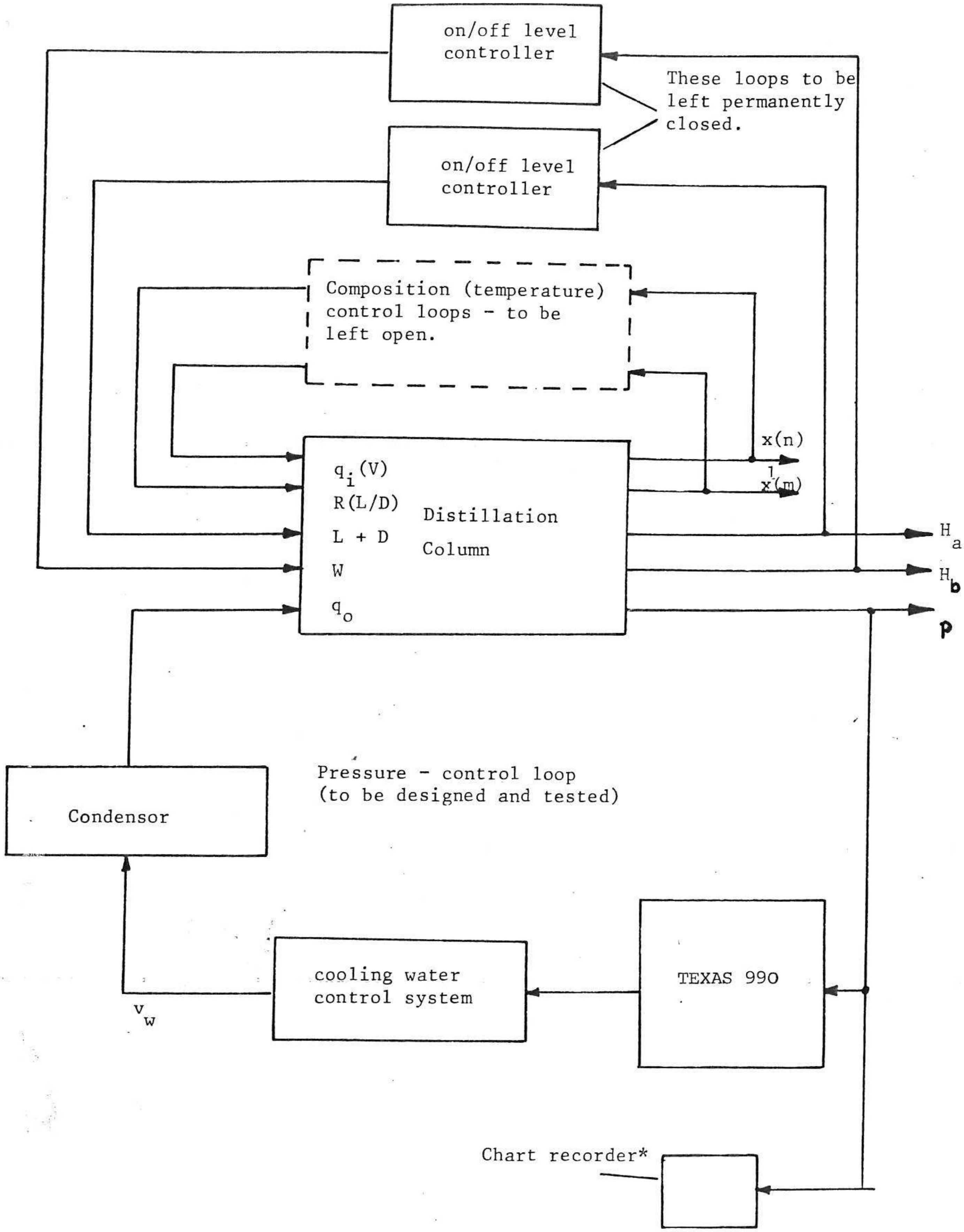


Fig. 2.^ Showing the interlinking of inputs and outputs for column control

*'se at all times to monitor pressure when vent valve clos-d.

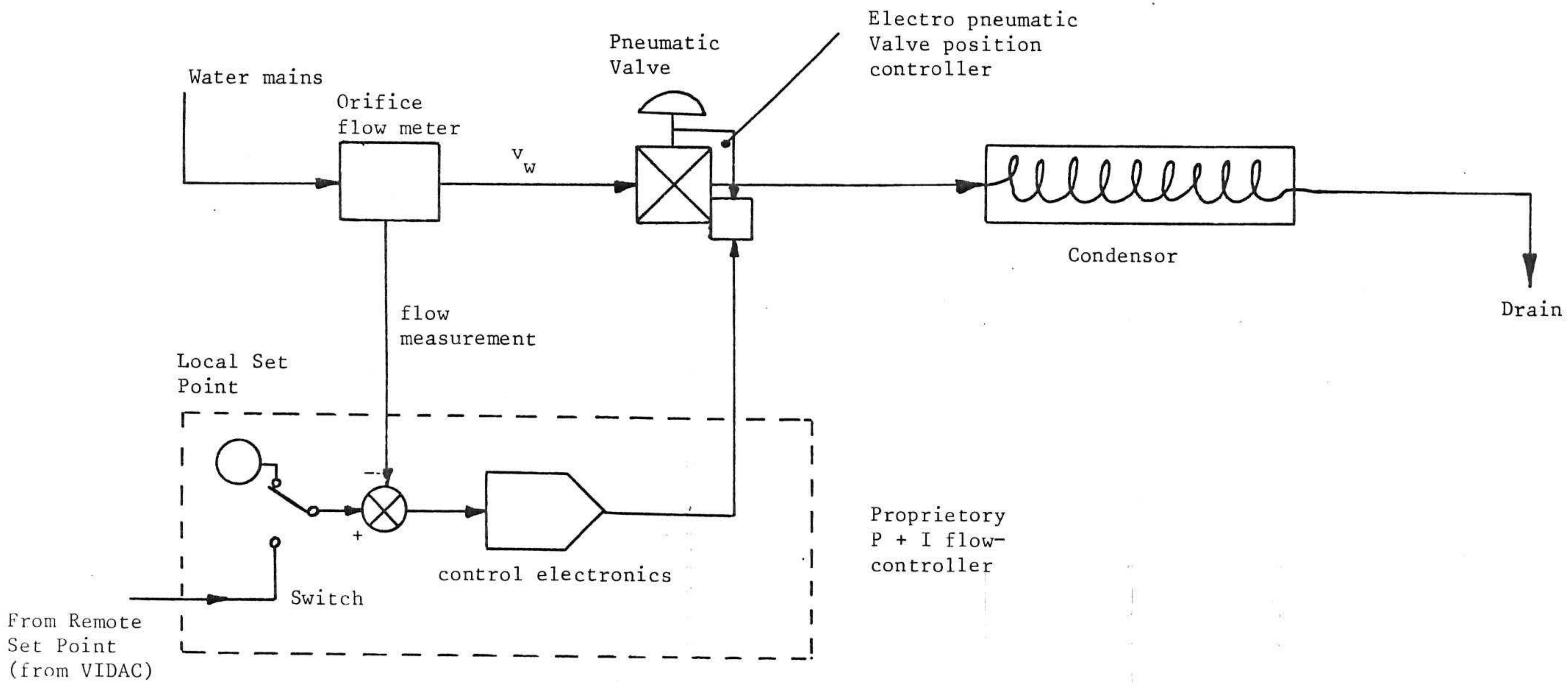


Fig. 3. Showing Cooling Water Flow Control System

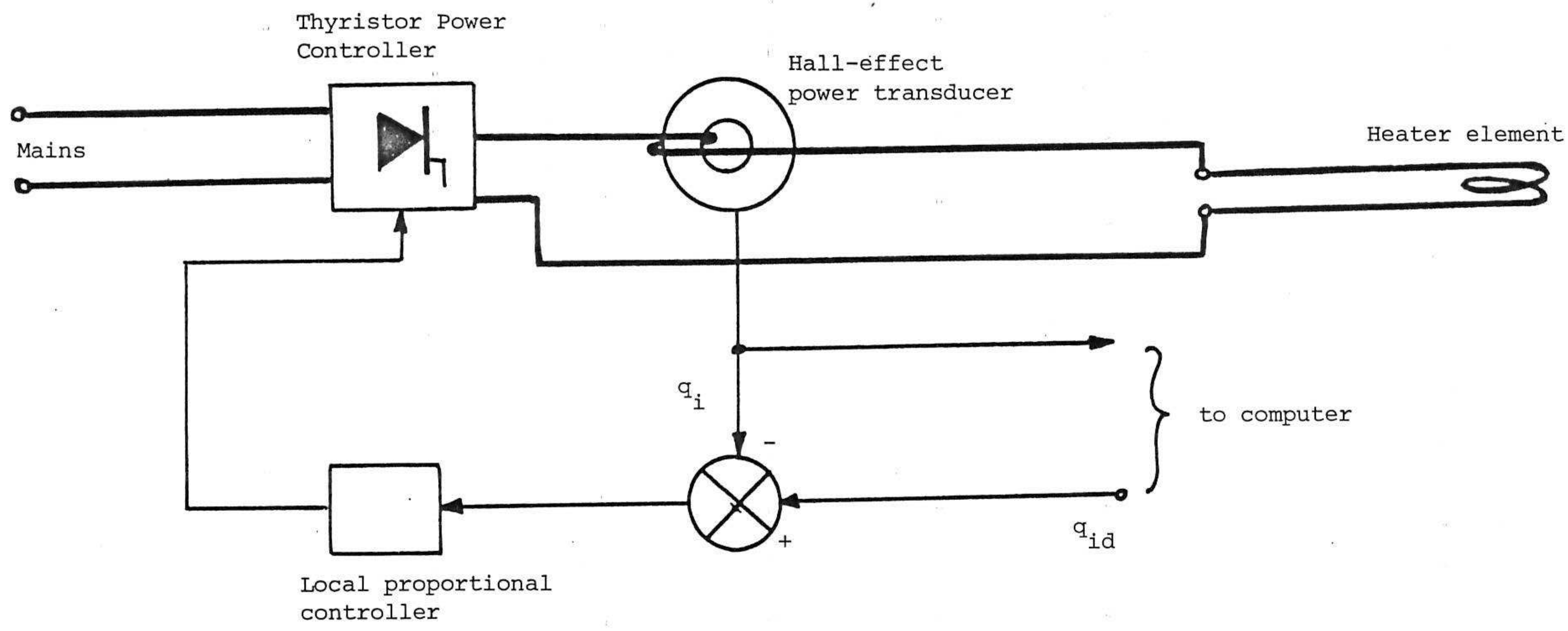


FIG. 4 SHOWING LOCAL HEATER CONTROL LOOP

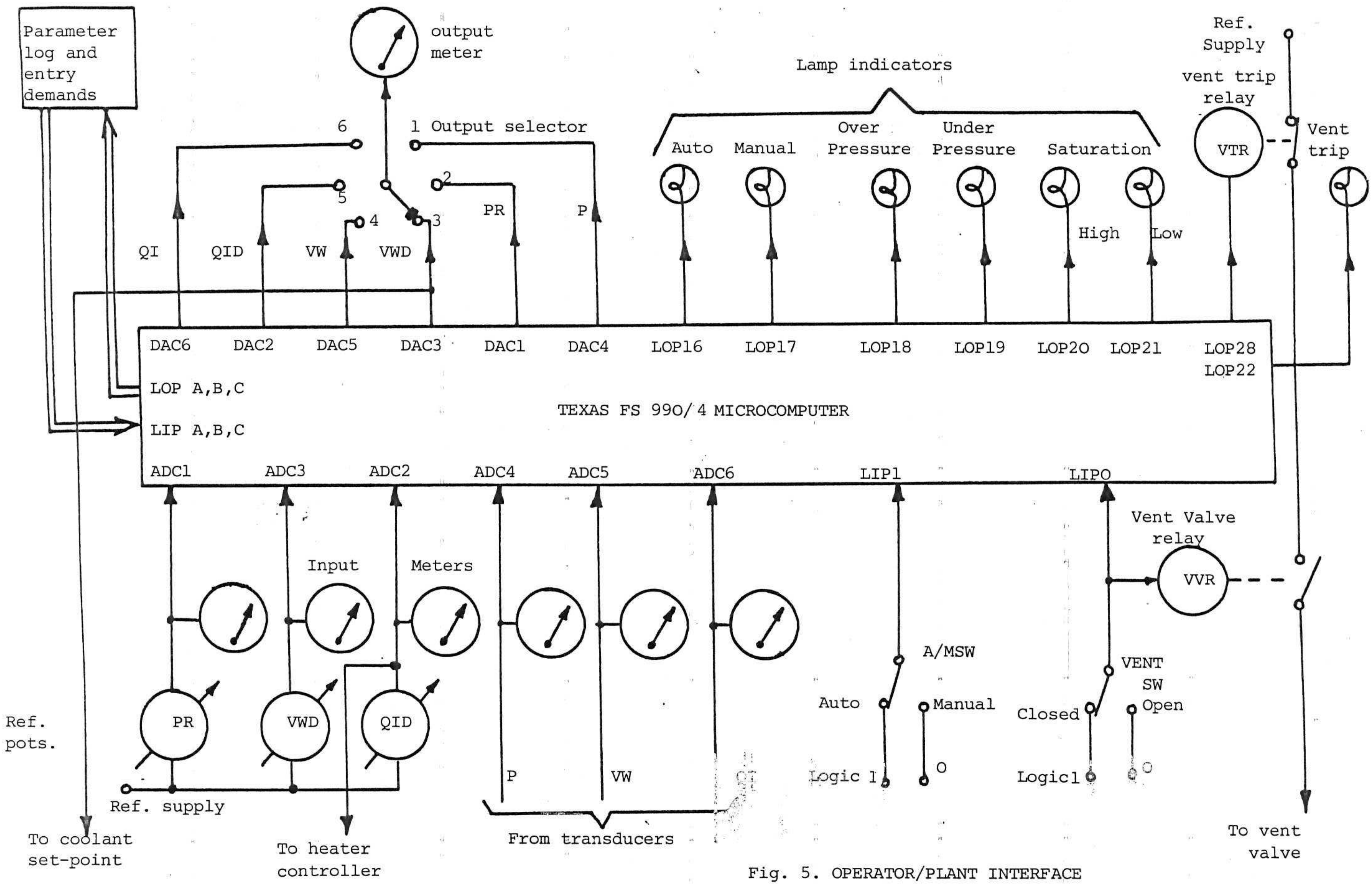


Fig. 5. OPERATOR/PLANT INTERFACE HARDWARE SCHEMATIC

Fig. 6 OPERATOR/PLANT INTERFACE LAYOUT

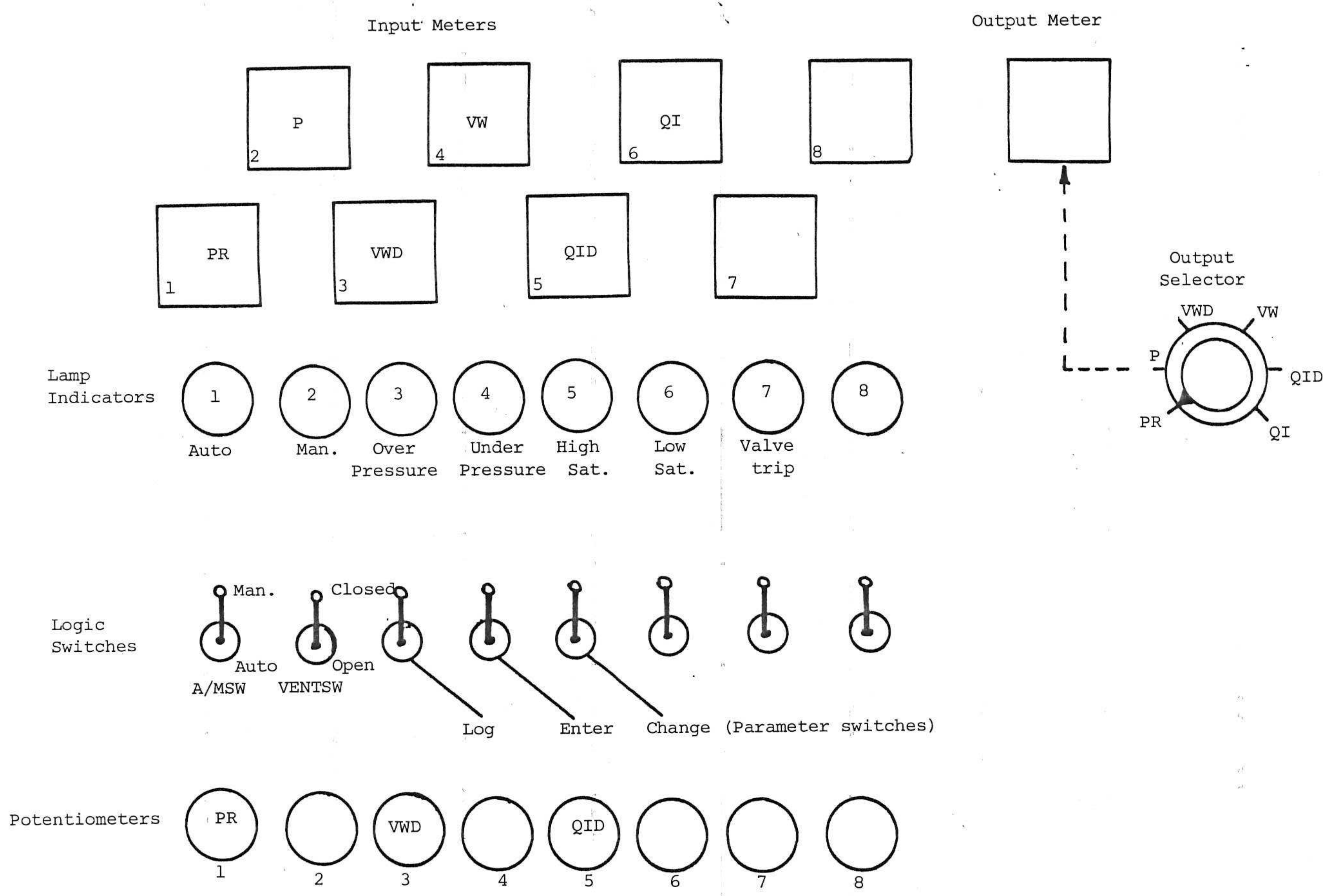


Fig. 7 Functional Flowchart, (sheet 1)

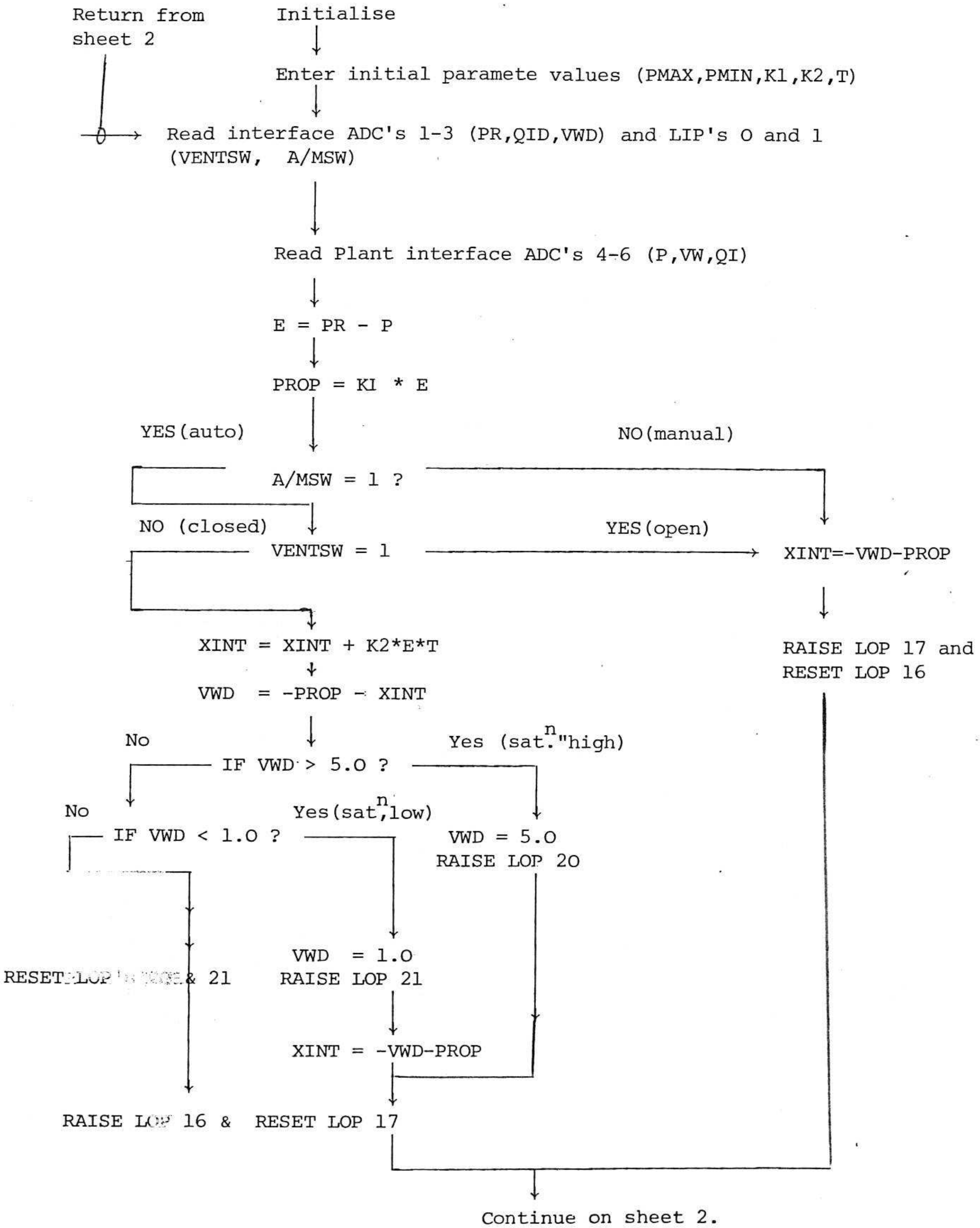


Fig. 7 Functional Flowchart (sheet 2)

From Sheet 1

IF P > PMAX

YES (overpressure)

RAISE LOP 18
RESET LOP 19

RAISE LOP 22 and 28

NO

IF P < PMIN ?

YES (Underpressure)

RAISE LOP 19
RESET LOP 18
RAISE LOP 22 and 28

NO

RESET LOP 18,19,
22 and 28

output to plant interface DAC's 1-6(PR,QID,VWD,P,VW and QI)

store VWD, VW, PR, P on DISC for off-line
retrieval onto screen

Parameter log line (LIPA) set?

YES

Call parameter log routine

Reset on completion of log (LOPA-pulse)

NO

New parameter entry line (LIPB) set ?

YES

Call parameter entry routine

Reset on completion of entries (LOPB-pulse)

NO

Parameter-change line (LIPC) set ?

Call down new parameters

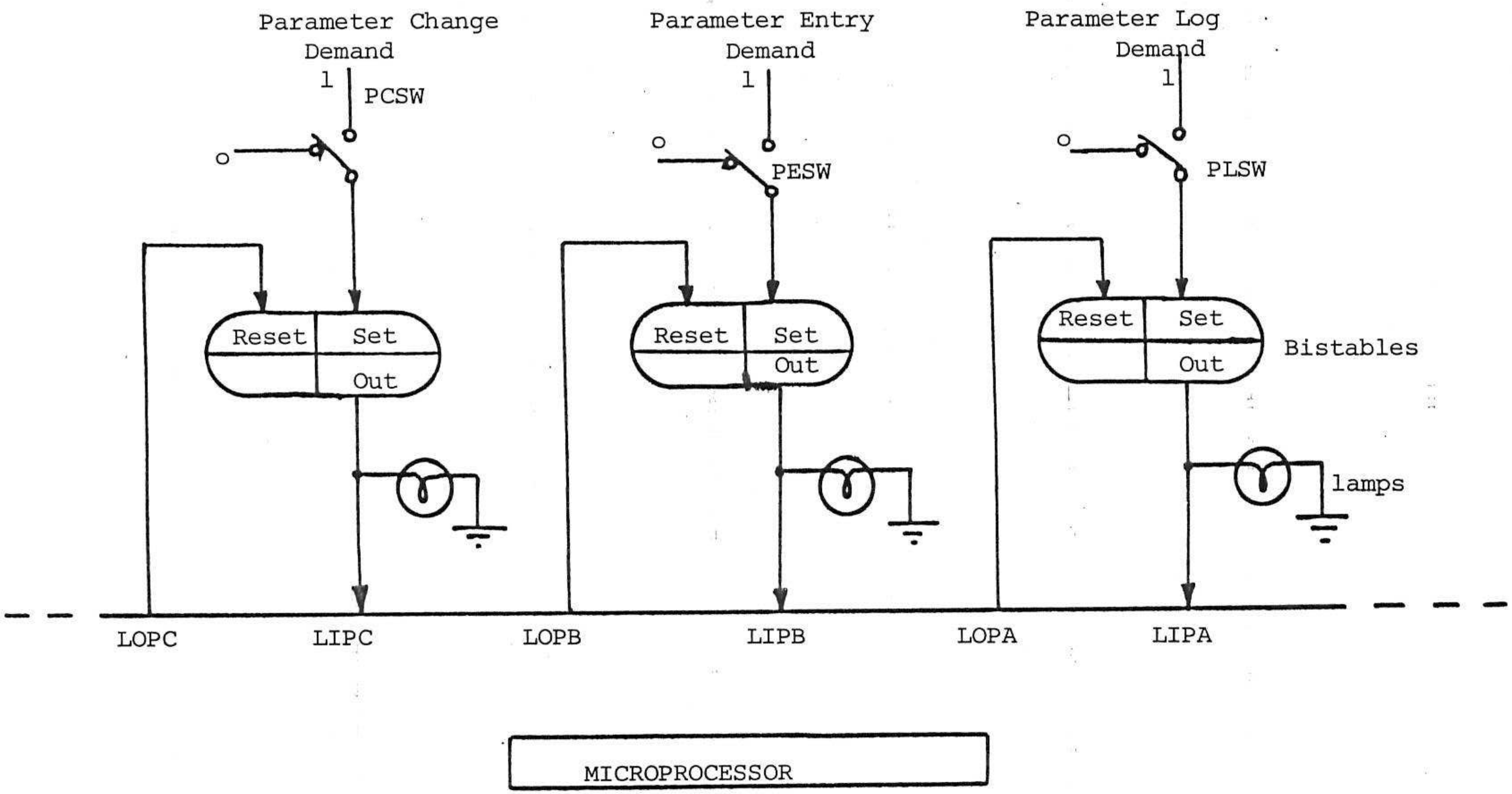
Reset on completion (LOPC-pulse)

NO

TURN-OFF. Return to sheet 1 after interval T.

(note all signals in the range 0 to +5 Volt)

FIG. 8 PARAMETER LOG AND ENTRY CONTROLS ON OPERATOR/PLANT INTERFACE



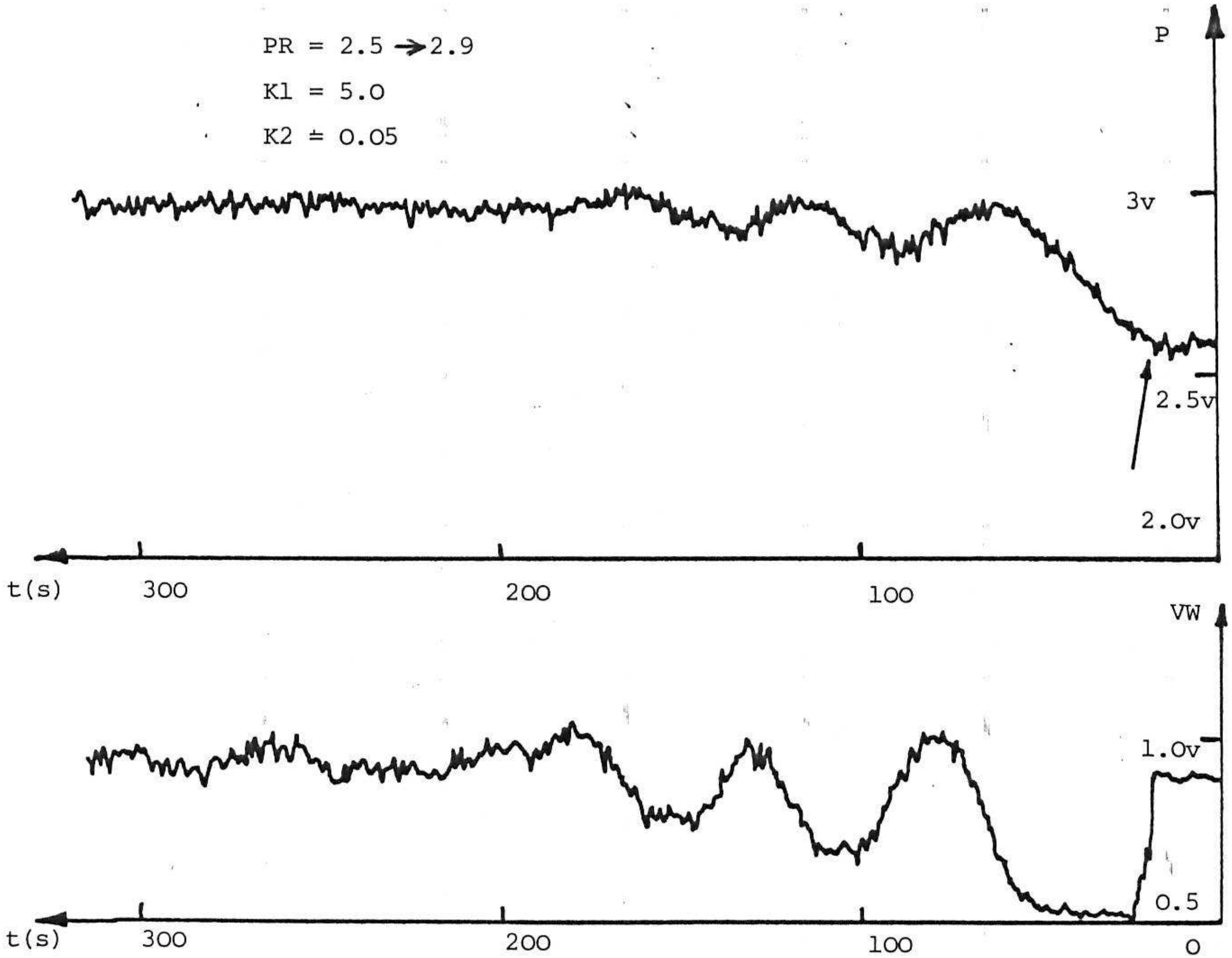


FIG. 9 CLOSED-LOOP RESPONSE IN STEP IN PR

FIG. 10 CLOSED-LOOP RESPONSE TO STEP IN QI