LESSON 2: ELECTRONIC CONTROL

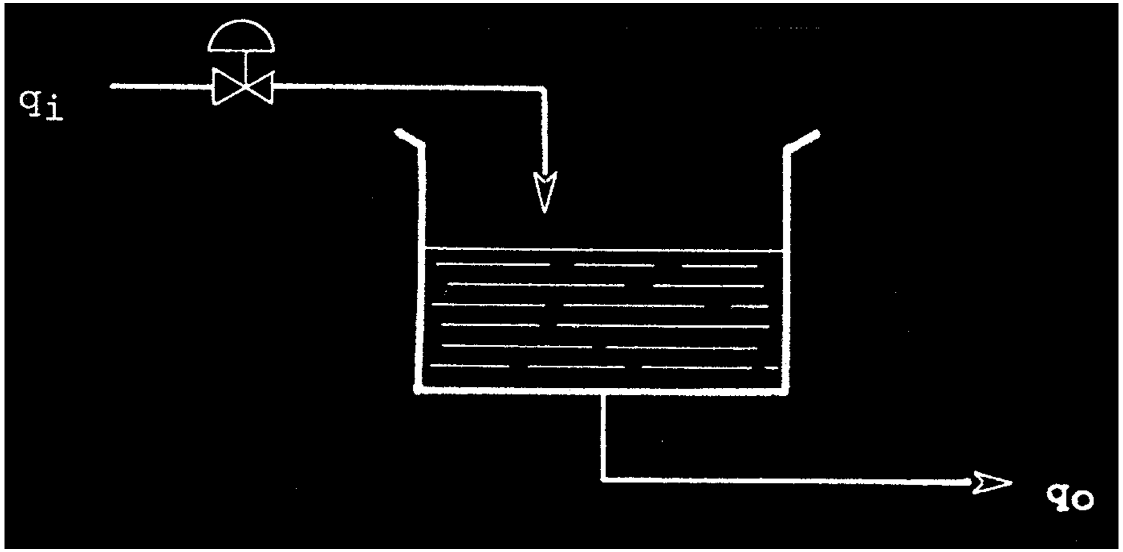
MODULE 1 Control Concepts OBJECTIVES:

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

1. Sketch an open tank level application and state the ***mass balance*** relationship which must exist to have stable control at the desired tank level (the setpoint).
2. Sketch a simple model for an ***I/P transducer*** and explain the principle of a operation used to obtain a 20-100 kPa(g) signal from an applied 4-20 mA signal.
3. Calculate an electronic signal for a given transmitter application.
4. Sketch a simplified ***current alarm circuit*** to show how a measurement signal can be used to activate a relay if the signal exceeds a preset value.
5. Explain the term offset for a ***straight proportional control*** system. What two conditions must be satisfied in order to eliminate offset?
6. Define the reset time units in ***Minutes Per Repeat*** and explain the significance of this value in terms of a straight proportional response.
7. Prepare an open loop ***proportional plus reset*** control response graph for a given application.
8. Define the term ***reset windup*** for a control system.
9. Define the term ***derivative time*** for a control application and be able to sketch the proportional plus derivative open loop response graph for a given application.

MODULE 1 Control Concepts
Introduction

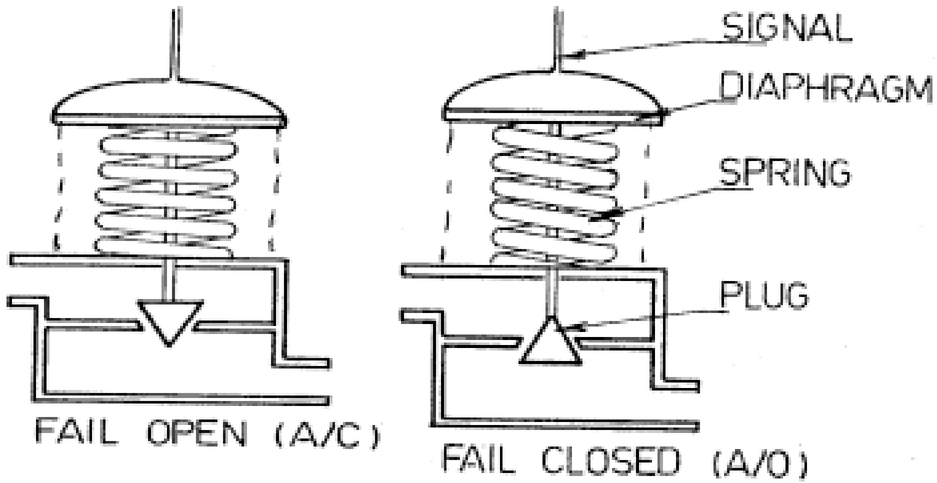
- **Consider the level control of an open tank with a *variable demand outflow* and *variable inflow regulation*, possible by control valve throttling.**
- **The level will only remain constant when the *inflow* (q_i) *just equals* the *outflow* (q_o).**
- **If the *demand increases*, the *level will begin to drop* until the *inflow has been increased* sufficiently to stabilize the system ($q_i = q_o$).**



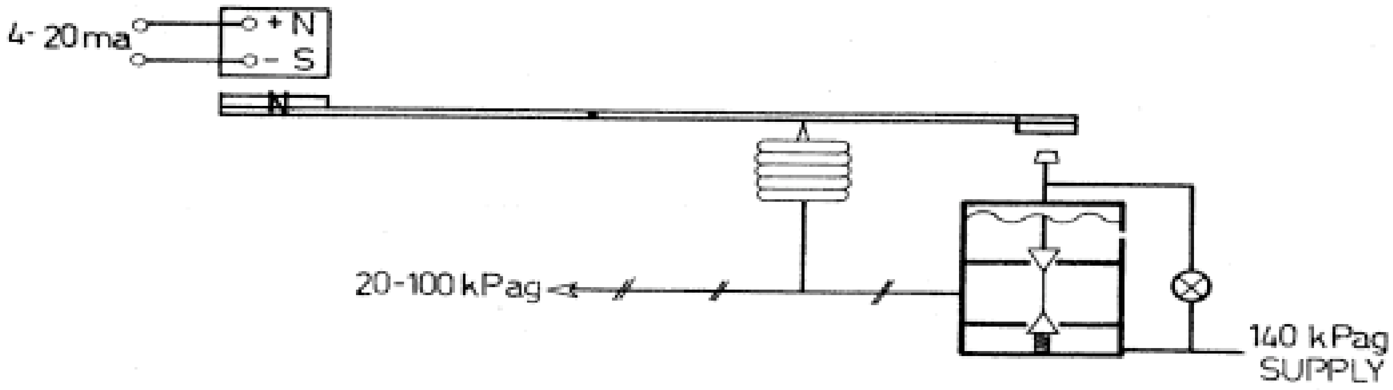
Open Tank with Variable Inflow Control

Control Valves

- **In this course the pneumatic actuator control valve will be the *final device* in the control loop.**
- **These valves operate on a spring opposed diaphragm principle. The diaphragm presents an area for the applied signal pressure to act on. A substantial driving force (F = P x A) can be obtained from a low pressure pneumatic signal by the selection of a larger area diaphragm.**
- **The control valve may be selected not only as the regulating device in a control loop but also to ensure that the process will be left in a non hazardous state following a complete loss of instrument air.**
- **If the tank in the previous sketch must not overflow, then the valve selected for inflow regulation should fail closed (following loss of instrument air).**
- **Such a valve can be referred to as an *air to open* style. Increasing the pneumatic signal applied to the valve actuator will open the valve more, decreasing the signal will allow the spring to drive the valve more closed.**
- **The following simplified sketches show both an *air to open* and an *air to close* valve.**



I/P Transducer

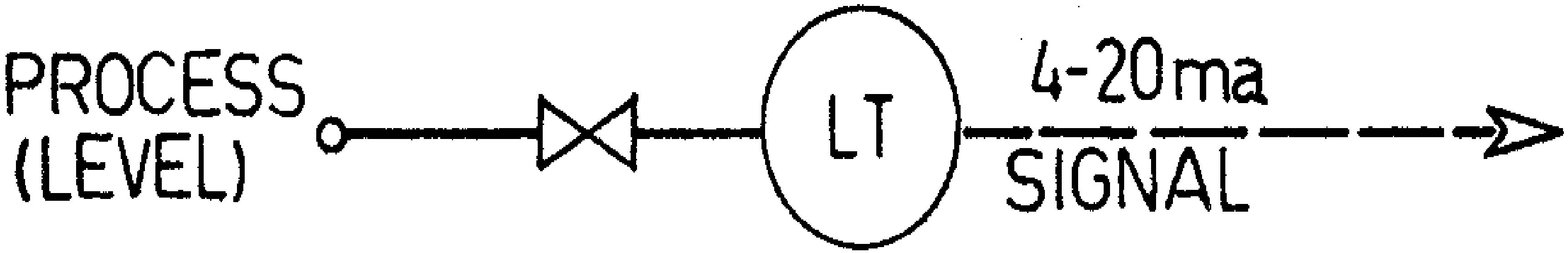


A stylized I/P Transducer

- **The *current signal* developed by a controller must be applied to the final actuator to effect the process.**
- **In many cases the final device is a pneumatically actuated valve. A transducer is required to convert the current signal to an equivalent *pneumatic signal*.**
- **The current signal is applied to a small coil which acts as an electric magnet deflecting a force bar proportional to the current magnitude.**
- **This motion can be used to position a flapper with respect to a nozzle to alter the nozzle back pressure.**
- **The nozzle back pressure is amplified by a pneumatic relay and applied simultaneously to the output and a feedback bellows.**
- **The feedback bellows ensures that there will be a linear relationship between the 4 - 20 mA signal applied and the 20 - 100 kPag pneumatic signal produced.**

Electronic Transmitter

- **A transmitter is required for measuring tank level and developing a signal that can be displayed remotely for level indication, alarm monitoring, or control.**
- **An electronic transmitter produces a 4 - 20 mA (now accepted as industry standard) or a 10 - 50 mA signal representative of process variation.**
- **If the transmitter was suitably calibrated the signal would vary linearly from 4 - 20 mA as the tank level changes from 0 - 100%. The transmitter is just the control loop data link with the process.**



- **The electronic signal calculations can be determined by direct ratio.**
- **The 4-20 mA signal span is 16 mA with a live zero value of 4 mA.**
- **The current signals can be determined by converting the percent process measurement to a decimal value, multiply by 16 (span), and add 4 (live zero).**
- **Transmitter mA signal = [% Process /100] * 16 + 4**

Example #1:

Determine the 4-20 mA signal which corresponds to a level of 120 cm WC in a 0 - 200 cm WC level system.

Percent Process = ?

Decimal Equivalent = $\frac{60}{100} = .6$

4-20 mA Signal = $\left((.6) \ \text{x} \ 16\right) + 4 = 13.6 \ \text{ma}$

Notice that a quick approximate check can be made by knowing that a 25% process change results in a 4 mA signal change

Consequently, process values of 0, 25, 50, 75 and 100% are represented by current signals of 4, 8, 12, 16 and 20 mA.

Example #2:

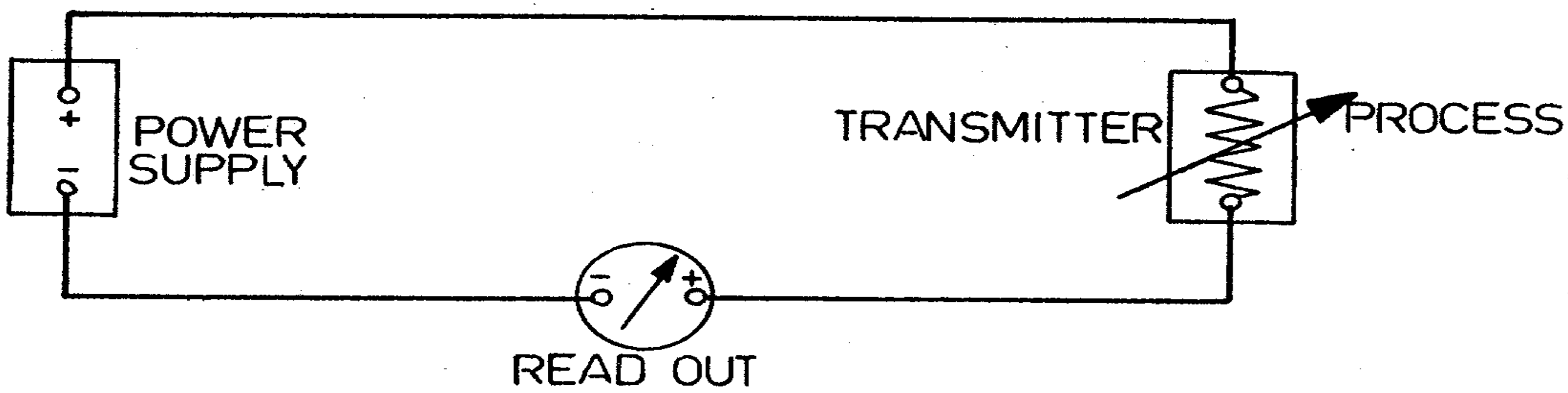
Determine the 4 - 20 mA transmitter signal if the temperature is 250∞C when the calibrated range is 150 - 400∞C.

Process Span = 400 - 150 = 250 ∞C
Change In Measurement = 250 - 150 = 100∞C
Percent Process = [100/250] *100 = 40%
4-20 mA Signal = $\left(\left(\frac{40}{100}\right)16\right) + 4 = 10.4 \ \text{ma}$

- **With a properly calibrated electronic transmitter, the 4 - 20 mA signal will vary in an analog fashion as the process changes so that by monitoring the *__current signal__* value, the *__process value__* will be known.**

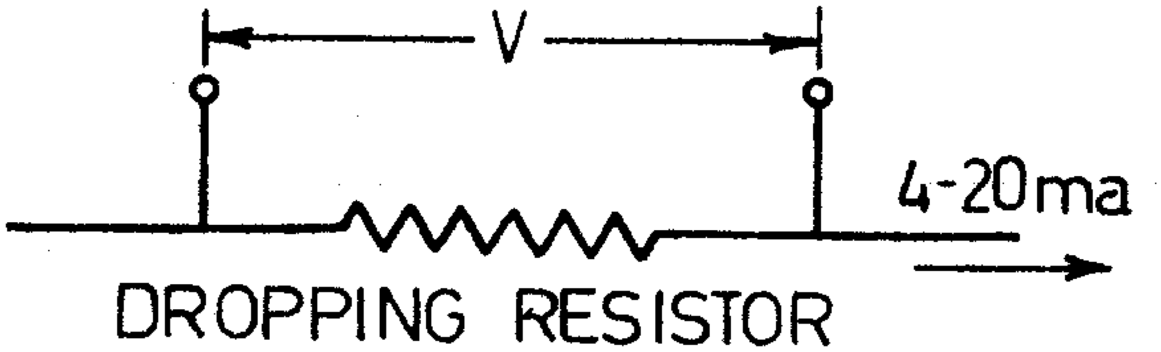
Transmitter Operation

- **Most electronic transmitters consist of some form of motion detector, oscillator, rectifier and amplifier which will convert the *measured change* in the process to a recognizable change in the current signal.**



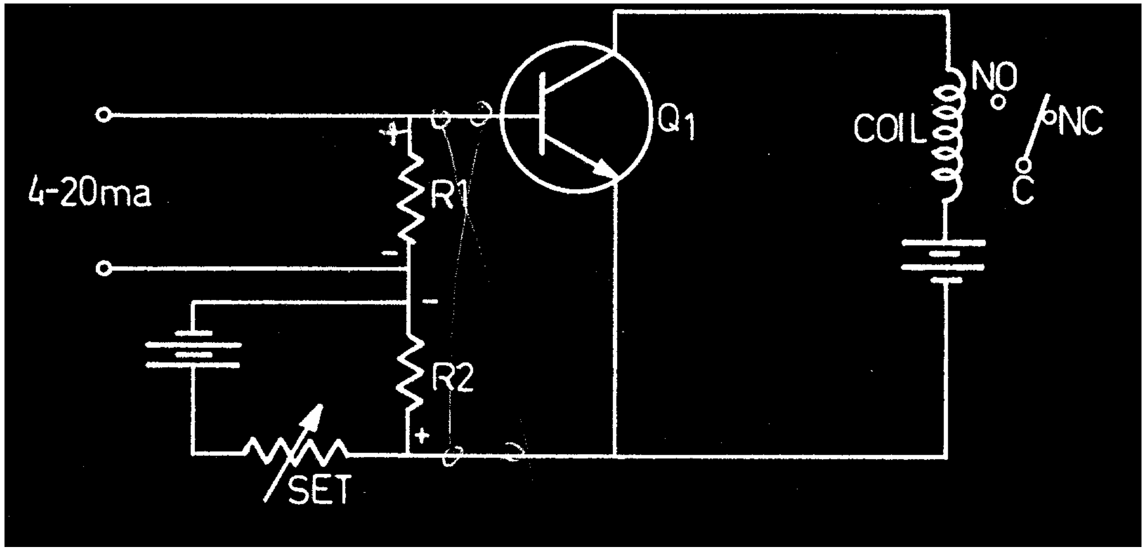
- **The transmitter can be very simply thought of as just a *variable resistor* in a constant voltage circuit which is varied by the changing process.**
- **If the transmitter resistance decreases, the current signal will increase and vice versa.**
- **It is important to note that the current flowing anywhere in this loop at some particular time will be the same current magnitude within the 4-20 mA range (i.e. one current circuit).**

Current Alarm



- **The measurement signal from the transmitter can be continually monitored to provide an alarm indication if an abnormal process condition should occur.**

- **The current alarm is a voltage input device that would require a particular dropping resistor in the current loop.**



- **A *dropping resistor* of 62.5 W would provide a voltage of 0.25 - 1.25 VDC when placed in a 4 - 20 mA loop.**

  R=E/I= 1.25V/.02A = 62.5 ohms

- **The alarm unit would involve a *comparator* type circuit to compare the measurement to the alarm set point.**

- **If the measurement potential across R_1 is greater than the set potential across R_2, then Q_1 will be forward biased allowing an energizing current to flow through the relay coil.**

- **The relay contacts will change status and alarm lamps, horns, messages, etc. can be activated.**

Electronic Controller

- **The transmitted signal of 4 - 20 mA can also be monitored by an electronic controller which is a voltage input device.**

- **A dropping resistor is placed in the current loop to develop the required input voltage signal.**

Example

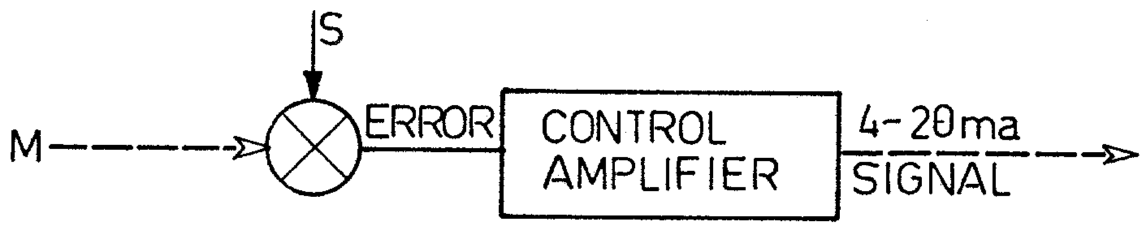
- **A 250 W dropping resistor will develop 1 - 5 VDC with a 4 - 20 mA signal.**

- **The measurement signal can be compared to the set point (desired operating point) to determine the process error sign and magnitude.**

  Error = Set Point - Measurement

  E = S - M

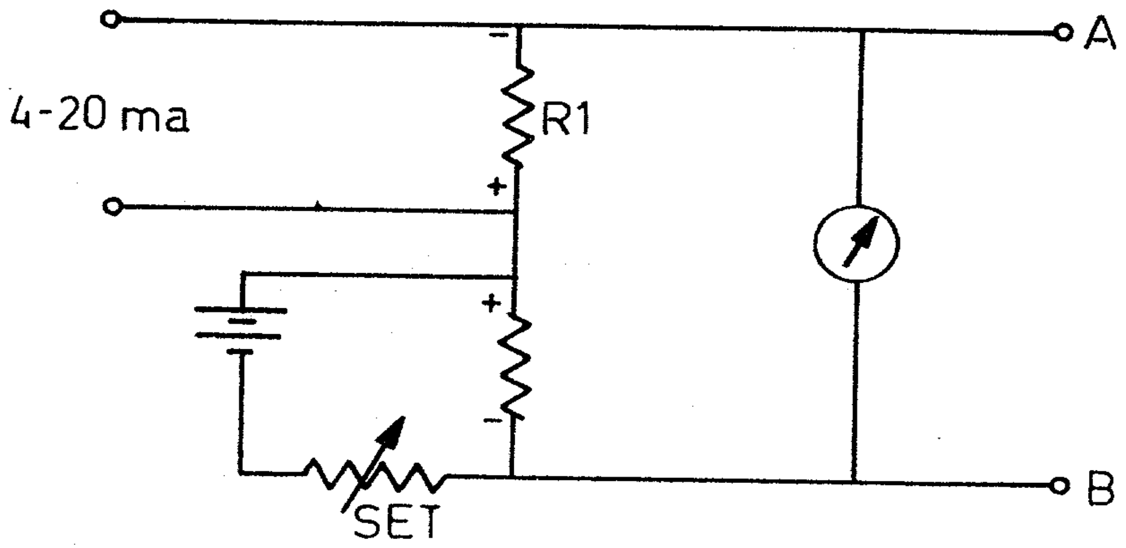
- **This error can now be suitably amplified by the controller to produce a corrective control signal of 4 -**



20 mA.

- **A simple *comparator circuit* can be used by the electronic controller to determine the *magnitude* and *direction* of the process error.**

Comparator Circuit



- **If the measurement signal develops a smaller voltage drop across R_1 than the set voltage across R_2, then point A will be *positive* with respect to B.**
- **Should the measurement signal develop a larger voltage drop across R_1 than the set voltage across R_2, then point A will be *negative* with respect to B.**
- **This changing *magnitude* and *polarity* can be used to drive the control amplifier to develop the 4 - 20 mA control signal.**
- **The *direction* that a controller must respond to a given error is called the *control action*.**
- **If the controller responds to the process rising above the set point by increasing the control signal then the controller is said to have *direct action*.**
- **An *increase* in measurement will result in an *increase* in control signal with direct action. This can be shown as (increasing, increasing) or (≠≠).**
- **Should a controller respond to an increase in measurement above the set point by decreasing the control signal, then the controller is said to have *reverse action.***
- ***An increase* in measurement will result in a *decrease* in control signal with reverse action. This can be shown as (increasing, decreasing) or (≠↓).**

Proportional Control Concept

- **If the controller for a given application could respond proportional to the error, a more stable control of the process would be possible than with on/off control.**
- **A system under on/off control will drive the valve from one extreme to the other resulting in process cycling. With proportional control the valve can be throttled slightly as the process varies about the set point.**
- **The controller gain can be calculated by comparing the percentage change in control signal to the percentage change in measurement.**

$$\text{Gain} = \frac{\%\ \Delta\ \text{Output}}{\%\ \Delta\ \text{Input}}$$

- **The proportional band value is reciprocally related to the gain as follows:**

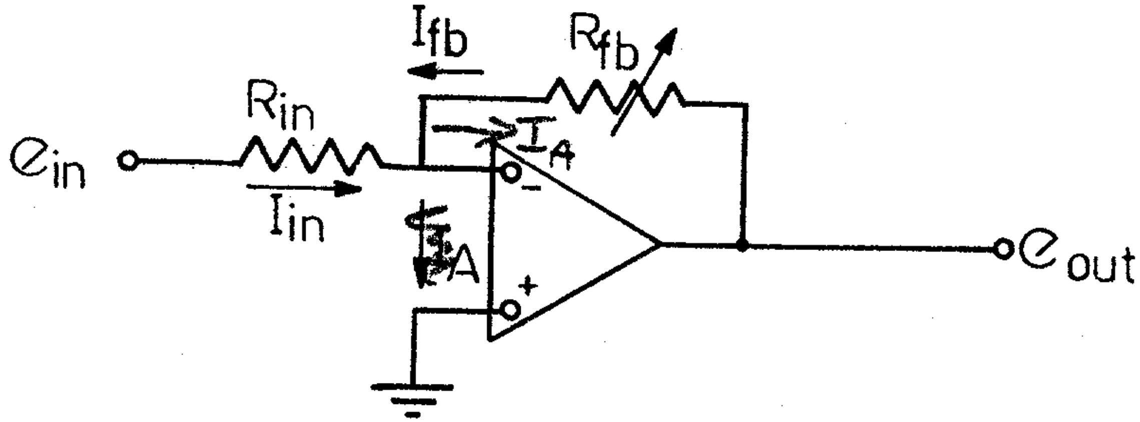
$$\%\text{PB} = \frac{100}{\text{Gain}}$$

- ***Percent Proportional Band* (%PB) is defined as that percent of scale change by the measurement about the set point which will change the control signal through 100%**

$$\%\text{PB} = \frac{\%\ \Delta\ \text{Output}}{\%\ \Delta\ \text{Input}} \text{ x } 100$$

- **The controller gain can be varied to effect the total control loop gain to provide as close a control as possible while ensuring process stability.**

Variable Gain Amplifier



- **Assume that a high gain amplifier is available as sketched to provide a proportional control model. An inverting amplifier is selected for this discussion.**

- **By Kirchhoff's current law:**

$$I_{IN} + I_{fb} = I_A$$

- **The amplifier is designed to have a very *high input impedance* so that I_A can be considered as zero for all practical purposes.**

$$I_{IN} + I_{fb} = 0$$

$$I_{IN} = - I_{fb}$$

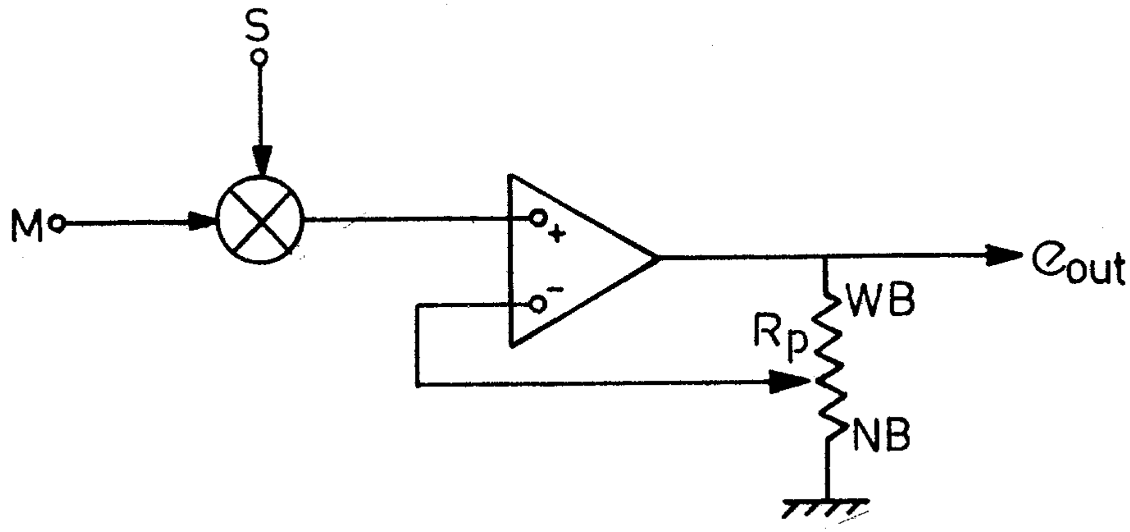
- **Substituting by Ohm's law:**

$$\frac{e_{IN}}{R_{IN}} = -\frac{e_{OUT}}{R_{fb}}$$

$$e_{OUT} = -e_{IN}\left(\frac{R_{fb}}{R_{IN}}\right)$$

- **The output voltage can be changed for a given input signal by changing the value of R_{fb}.**
- **The gain of this amplifier is simply the ratio of R_{fb}/R_{in} – so just recognize that the gain of a control amplifier can be changed by adjusting the feedback resistance value.**

Simplified Reverse Acting Electronic Proportional Controller



- **The *error signal* from the *comparator* is applied to the non inverting terminal of the OP-AMP.**
- **If the process is greater than the setpoint, then the output signal will decrease.**
- **Consider the signal (e_{OUT}) being utilized to position the final device which in turn should change the value of the measurement signal.**
- **If the measurement equals the set point, the error will be zero. Internal biasing is supplied to the amplifier so that a mid scale output will be developed when the error is zero – say 12 mA output.**
- **Consider the measurement dropping below the set point, then a more positive input will be applied to the amplifier. The amplifier output will rise, increasing the voltage drop across R_p), a fraction of this voltage is fed back to the inverting terminal of the amplifier.**
- **The output signal will stabilize when sufficient potential is applied as feed back so that the difference across the inverting and non inverting terminals is zero volts.**
- **If the contact on R_p is placed to a lower position, less feedback voltage is applied to the amplifier and e_{OUT} would have to rise more before stabilizing. A larger change in output for a particular input is recognized as a higher gain or narrower proportional band setting.**
- **By changing the contact position of R_p, the *proportional band is varied* to achieve suitable process recovery from a transient disturbance.**

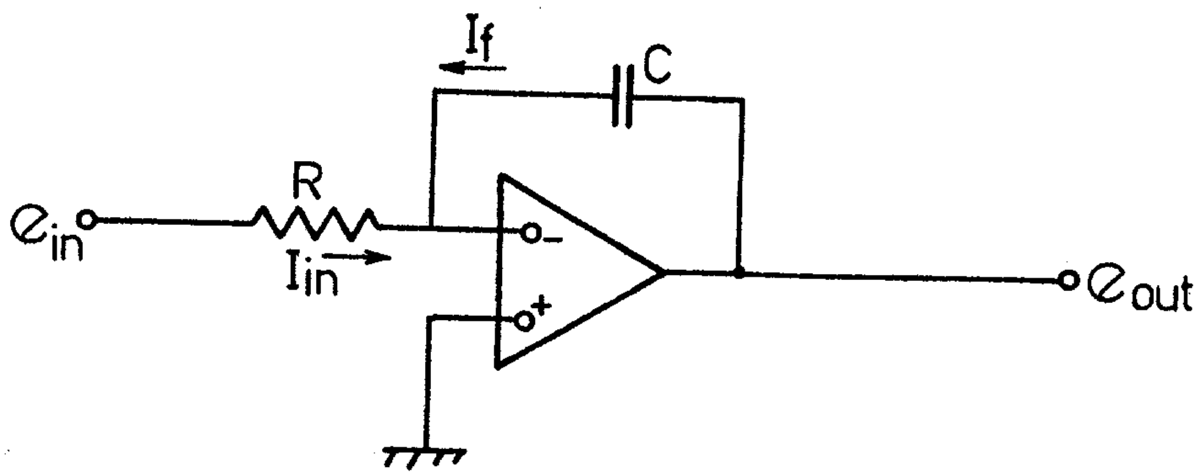
Offset and Reset

- **Consider a level system operating under straight proportional control with a control valve on the inflow.**
- **For every *distinct level position* in the tank there will *be one corresponding valve position*. (% error x gain = % D output.)**
- **Assume that the level was initially at the set point with inflow matching outflow. If a demand increase should occur so that outflow exceeds inflow, then the tank level will begin to drop away from the set point producing an error.**
- **The *more error* developed, the more the *inflow will be increased* by the corrective control signal.**
- **Eventually the valve will be positioned enough so that inflow matches outflow and the level will stabilize.**
- **Note that it is the presence of the *level error* which has driven the valve to the new position.**
- **This error required to restore equilibrium is called *offset,* and in most control systems is the limiting factor of straight proportional control.**
- **Offset is the stable deviation of a process, under straight proportional control, away from the set point following a process supply or demand disturbance.**
- **If the valve in this system could be positioned *further than the proportional response* requires, then the process can be restored to the set point (opening the inflow valve more will cause the level to rise.).**
- ***Reset or integral mode* is required to eliminate offset by integrating or summing the process error involved.**
- **Reset responds until the *error is reduced to zero* by driving the manipulated variable to that value required to achieve stabilization at the set point.**

- **In order to achieve integral mode (or reset mode) the error signal could be applied as the input signal to an integrating Amplifier.**

Integral Function Amplifier

- **As before, allow that $I_{in} = -I_{fb}$.**
- **Recall that charge equals capacitance times voltage: Q = CV**
- **Considering the change in charge for a particular capacitor results in: Q = I t**



An Illustrative Integral Function Amplifier to Provide Reset

Action

- **The charge resulting from a particular current flow is a function of time, so that:**

$$DQ = I_{fb}Dt$$

$$I_{fb}Dt = CDV$$

$$I_{fb} = \frac{C\Delta V}{\Delta t} = \frac{C\Delta e_{OUT}}{\Delta t}$$

$$I_{in} = -I_{fb}$$

$$\frac{e_{IN}}{R} = -C\frac{\Delta e_{OUT}}{\Delta t}$$

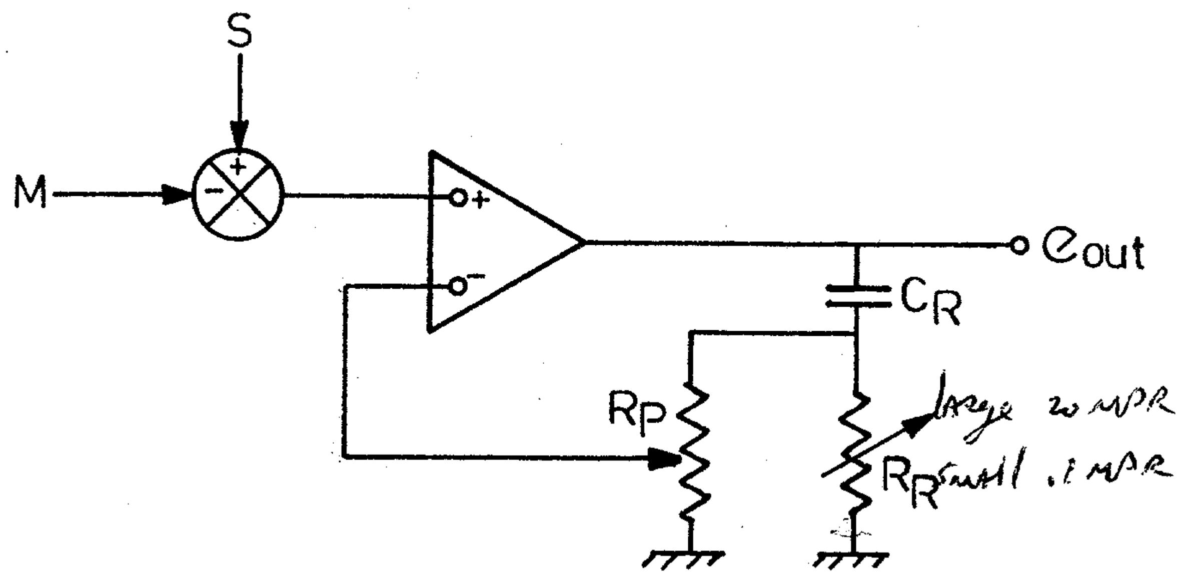
$$\Delta e_{OUT} = \frac{e_{IN}}{-RC}\Delta t$$

- **Integrating both sides results in the output voltage being an integral function of the input.**

$$e_{OUT} = -\frac{1}{RC}\int_o^t e_{IN}\,dt$$

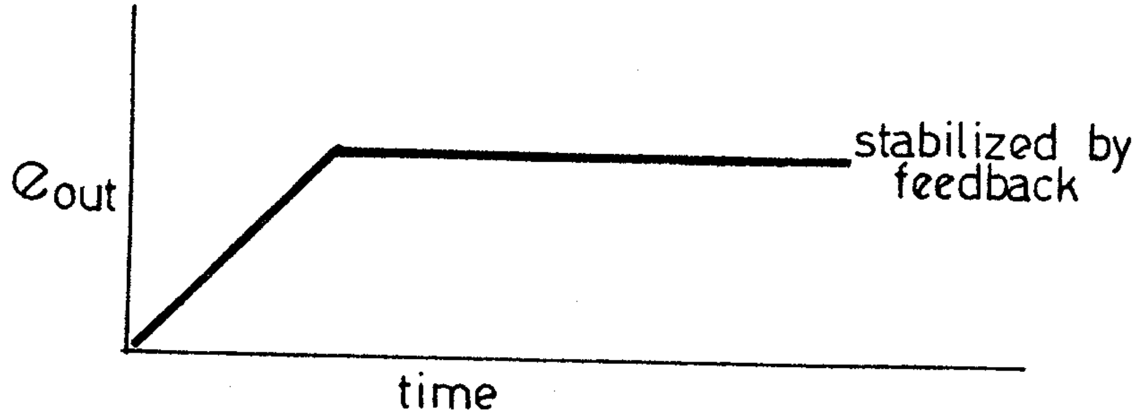
- **The output signal will be a summation function of the input signal (error). From this development, all that is required is to recognize that an integral function can be achieved using an RC network with an OP AMP.**

A Simplified Reverse Action Electronic PI Controller

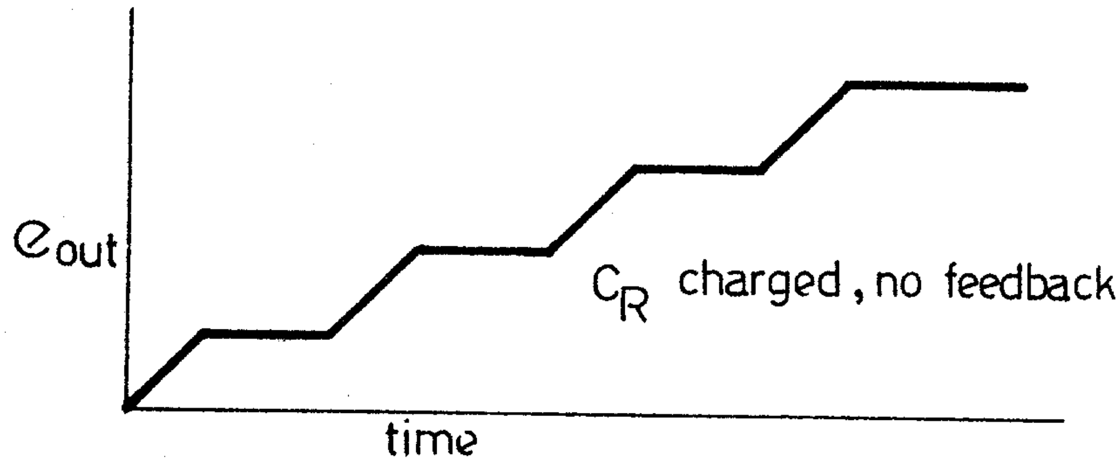


- **Consider the measurement dropping below the set point, then a more positive signal is produced by the comparator and applied to the non inverting terminal of the operational amplifier.**
- **The output signal of the amplifier will begin to increase *<u>causing capacitor C_R to charge</u>*.**
- **Feedback voltage will be applied to the inverting terminal only while C_p is charging, developing a voltage drop across R_R and R_p.**
- **Once C_R is charged, there will be no current flow and consequently no voltage drop across R_R and R_p. The feedback potential will drop to ground value or *<u>feedback is removed once C_R is charged</u>*.**
- **As C_R begins to charge due to the rise in the output signal, a fraction of the voltage across R_p will be applied back to the inverting terminal to stabilize the amplifier and hold the output at one particular magnitude. (Note that this is *<u>proportional response</u>*.)**
- **As soon as the amplifier stabilizes the output signal stops changing, and C_p will become charged depending on the time constant R_R C_R.**

Integral Function



- Once C_R is charged, the voltage across R_p will disappear and the R_p contact is reduced to ground potential.
- There is no voltage applied to the inverting terminal but the ***error signal*** is still applied to the non inverting terminal causing the output signal to rise again.
- The complete cycle will be ***repeated*** causing the signal to level out again at some larger magnitude.
- The reset action will step the output in the direction of the original proportional response ***until the measurement is forced back to the set point***.
- If the measurement is forced back to the set point, then the error will be zero and the amplifier will hold the new output until an error appears.
- Consider the OP-AMP driving the output until the difference across the inverting and non inverting terminals is zero volts and then holding the output signal steady at this last value.



Reset Time Adjustment

- **If R_p is set very large, then the charging time for C_R will approach infinity and the response will approximate straight proportional control.**
- **Reset mode can be considered shut off when R_R is very large (i.e. no reset action).**
- ***Reset time* is the time in minutes required for reset to duplicate the original proportional response to a process disturbance. This is the number of minutes necessary to repeat the proportional response or the Minutes Per Repeat (MPR).**
- ***Reset rate* is just the reciprocal of MPR-and-has the units Repeat Per Minute (RPM).**

$$\text{MPR} = \frac{1}{\text{RPM}}$$

- **Use of *reset time* or *reset rate* on the instrument dial is up to the discretion of the manufacturer and has lead to some interesting results in plant circumstances like initial start-ups.**
- **The reset effect can accidentally be set to maximum rather than being eliminated.**
- **Take the time to ensure that the reset mode adjustment is in MPR or RPM and then adjust accordingly.**
- **Reset action is minimized with a very low reset rate (0 RPM) or a very large reset time (60 MPR).**

Example

A pressure controller is open-looped bench tested with the set point at 100 kPag on a scale of 0-150 kPag. The % PB is set to 40%, and the action is direct. Reset is set at 0.75 RPM. Determine the initial control signals due to proportional response and state what the open-loop signal will be at 1 minute and 2 minutes after the pressure is suddenly raised to 110 kPag.

Assume that the control signal was initially stable at 8 mA. Plot a graph of control signal (4-20 mA) vs time (minute) for three minutes after the perturbation was applied.

Solution

Initial signal = 8 mA

%PB = 40%, Gain = $\frac{100}{\%PB} = \frac{100}{40} = 2.5$

Gain = %D Input = $\frac{110-100}{150}$ x $100 = \frac{10}{150}x100 = 6.7\%$

%D Output = Gain x %D Input

%D Output = (2.5) (6.7) = 16.75 %

mA Signal change = $\frac{16.75}{100}x16 = 2.68$ ma

- **The control signal will rise 2.68 mA due to proportional response.**
- **This is the magnitude of 1 repeat.**

1 Repeat = 2.68 mA

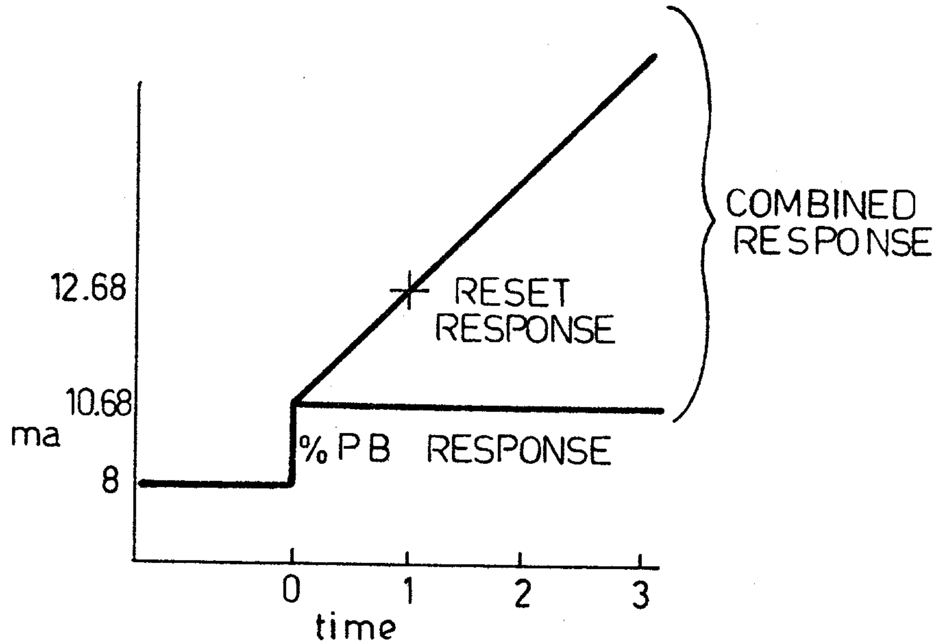
.75 Repeat = (.75) (2.68) = 2 mA

- **The reset rate of .75 RPM will raise the signal 2 mA each minute.**

Open Loop PI Pressure Controller – Control Signal Response

- **Original Proportional Response was 2.68 mA**
- **Reset Rate is 0.75 RPM or (0.75 * 2.68 = 2.0 mA per minute)**

Immediate signal will be:	**8 + 2.68 = 10.68 mA**
Signal in 1 minute:	**10.68 + 2 = 12.68 mA**
Signal in 2 minutes:	**12.68 + 2 = 14.68 mA**
Signal in 3 minutes:	**14.68 + 2 = 16.68 mA**



Reset Wind Up

- **Pneumatic or electronic controllers with reset mode can occasionally integrate the control signal right off the signal range if a *sustained deviation* is imposed upon the controller or if the *reset rate is too fast* for the process.**
- **Assume a demand change has resulted in the measurement dropping below the set point for some time.**
- **The reset action will integrate this error and continually raise (or lower, depending on the deviation) the control signal until it is well above the 100% signal value (20 mA).**
- **Assume the control signal is raised to 26 mA, the valve can only be positioned to 100% open or closed status so that the extra signal is meaningless.**
- **The amount of signal above 100% or below 0% will not change the valve position. This condition is known as reset wind-up.**
- **As the process rises, the valve is held open by the wind-up signal.**
- **If the error is still negative, reset will continue to ramp the output (until the error is zero).**
- **The measurement must cross the set point so that the control error changes sign before the output can *begin* to change back towards the signal range.**
- **The steady state control signal will predominantly be the *integral term*.**
- **The error must change signs (process cross the set point) before the controller can integrate the signal back down to a suitable control value.**
- **The result of this wind-up action will be a cycling process similar to on/off control.**
- **The solution to this problem in most cases is to ensure that the reset rate is adjusted properly for a given application.**

Representative Reset Action Control Program

The idea of reset wind-up is more easily demonstrated by considering how a computer would provide proportional plus reset action. Consider the following simplified portion of a program.

PROGRAM	COMMENTS
Sum = 0..	initialize summing location
100 Read T	read process temperature
E1= SP - T	calculate current error
Sum = Sum + E1................................	integrate or sum error
SIG = K*(E1 + $\frac{Sum}{R}$).......................	R = Reset time, K = Gain
Output SIG	apply control signal to DAC
Service other loops	
Go To 100	read process temperature

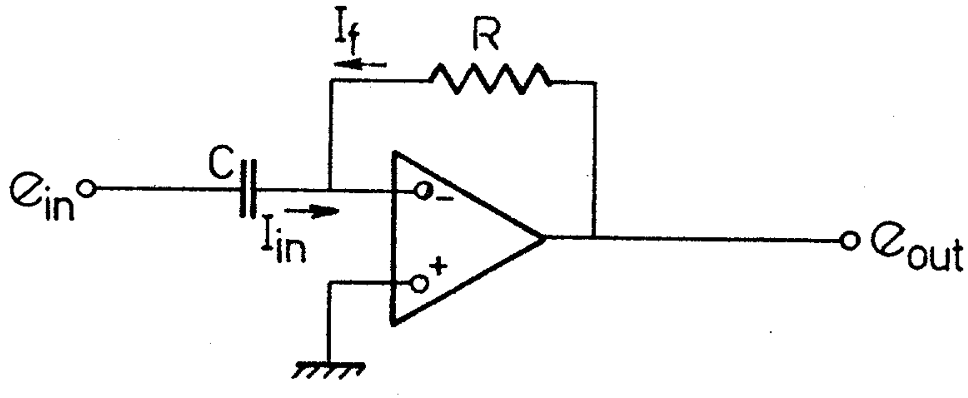
- **Assume that the loop is executed once each second and the error (E1), sum value (Sum), and % signal (SIG) is recalculated once each second.**
- **If a particular error, say 5% exists and the process is slow to respond, then every second the sum will be incremented by 5%.**
- **Imagine the consequences of this constant 5% error being summed every second for three or four minutes. (Allow k = 1, R = 1 for simplicity.)**
- **The control signal would become well above 100% and the loop would then be said to be wound up.**

- **Anti-reset wind-up features -one approach is to suspend reset action once the signal has reached a maximum or minimum value. Another solution used is to apply external feedback to the reset mode so that the integration is a function of the process response and not the control signal change (ie if the process is not changing, the integration stops preventing windup from occurring).**

Derivative Mode

- **If the controller can sense how rapidly a deviation is occurring, a control response can be made to attempt to stabilize the process.**
- **The faster the process is changing, the larger the control signal change would be in an attempt to stop the process variation.**
- **Such a control response is called derivative or rate response and would tend to minimize deviation and maximize stability if properly employed.**
- **Derivative time is the time in minutes that the control signal will be advanced by derivative over straight Proportional response while the error is changing.**
- **A derivative time of two minutes would cause the control signal to be advanced by two minutes.**
- **The control signal *right now* would be that magnitude that proportional alone would cause two minutes from now while the same rate of error change is applied.**
- **The error signal can be applied as the input to a derivative amplifier and the output signal developed will be proportional to the *rate of change in the error*.**

Derivative Control Function Amplifier



- **Again allow that $I_{IN} = -I_{fb}$ and that $DQ = CDe_{IN}$**

$$DQ = I_{IN}\,Dt = CDe_{IN}$$

$$I_{IN} = \frac{C\Delta e_{in}}{\Delta t}$$

$$I_{fb} = \frac{e_{OUT}}{R}$$

$$I_{IN} = -I_{fb}$$

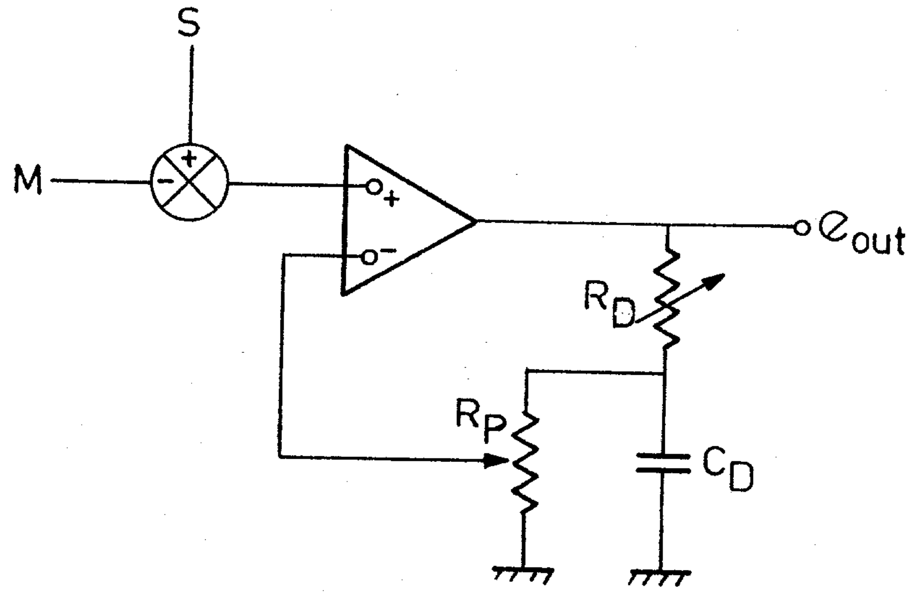
$$\frac{C\Delta e_{IN}}{\Delta t} = \frac{-e_{OUT}}{R}$$

$$e_{OUT} = -RC\frac{\Delta e_{IN}}{\Delta t}$$

$$e_{OUT} = -RC\frac{de_{in}}{dt}$$

- **The output voltage is a derivative function of the input signal. All that is required from this development is to know that a derivative function is possible using an OP-AMP with an RC feedback network.**

Simplified Reverse Acting Electronic PD Controller



- Note that full proportional feedback will be obtained after C_D is charged (opposite of the reset network.)
- If the measurement drops below the set point, the amplifier output will begin to rise and C_D will charge providing feedback potential to the inverting terminal.
- If R_D is very small then C_D will ***charge quickly*** and feedback will depend only on the R_p setting (straight proportional control). This would be a derivative time of ***zero minutes*** (i.e. no derivative action)
- If a larger value is selected for R_D, it will delay the charge time of C_D; temporarily interrupting the amplifier feedback.
- As a result, the amplifier output will rise to a ***larger magnitude signal*** than would be expected with straight proportional control.
- As C_D charges the feedback potential is increased until the output is returned to the straight proportional level.
- The final actuator should be ***stroked more*** to give a larger change in process until C_D is charged and normal proportional control is restored.
- The larger input to the process should have a **braking effect** on the deviation and tend to hold the process closer to the set point.
- In the steady state the derivative component will disappear (error is no longer changing) so that control response will revert to straight proportional.

- **Offset will still be a problem with proportional plus derivative control.**

Derivative Mode Example

A proportional plus derivative controller is subjected to a positive ramp of 10%/min for three minutes and then held steady at the new position. The initial control signal was stable at 12 mA. The PB = 100% with a derivative time of 1 minute. Control action is reverse. Sketch a graph of control response (4-20 mA) vs time (minutes). Show ideal and practical control response curves.

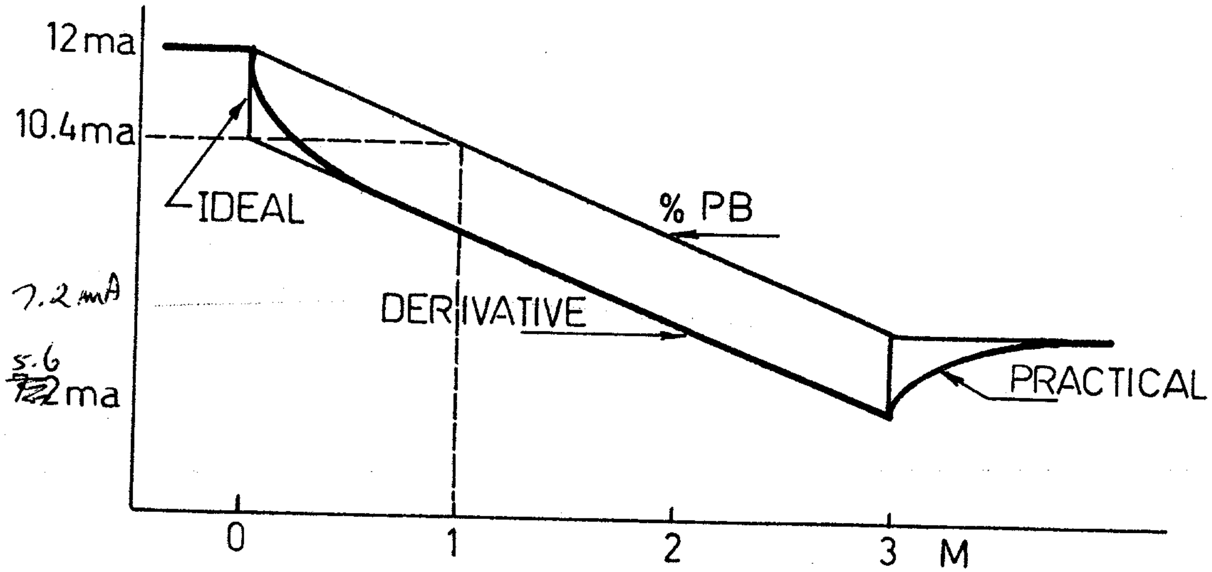
Solution

A 10% error change/min for 3 minutes = 30% total change.

Controller Gain = 1, since PB = 100%

Control signal must decrease 30% over 3 minutes

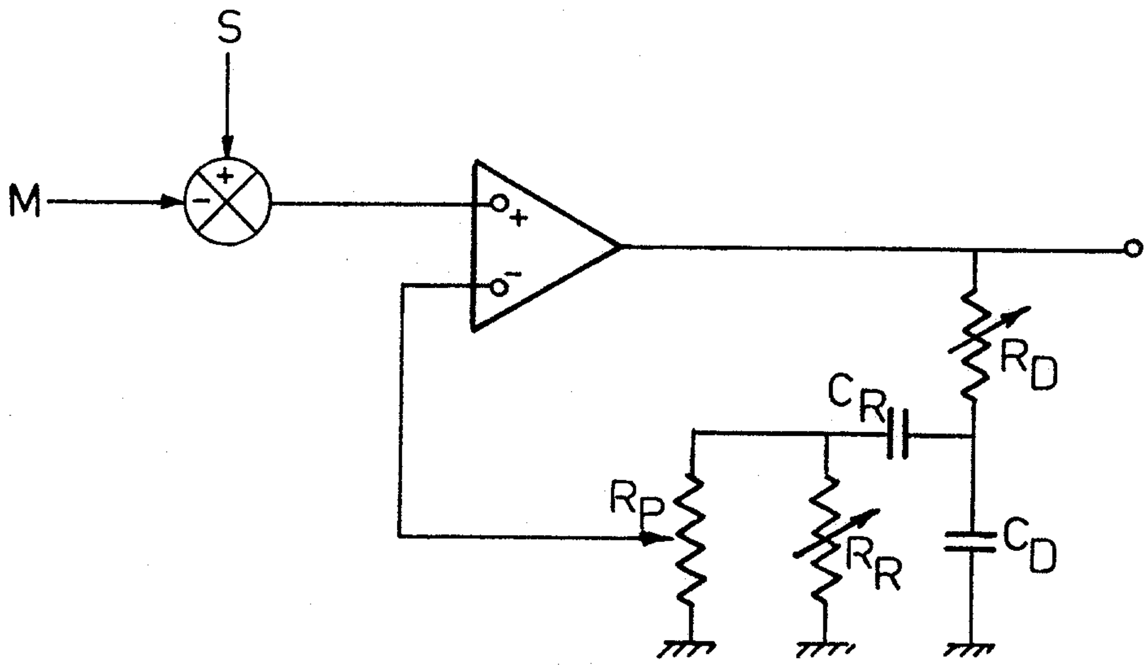
D Signal = .3 x 16 = 4.8 mA decrease



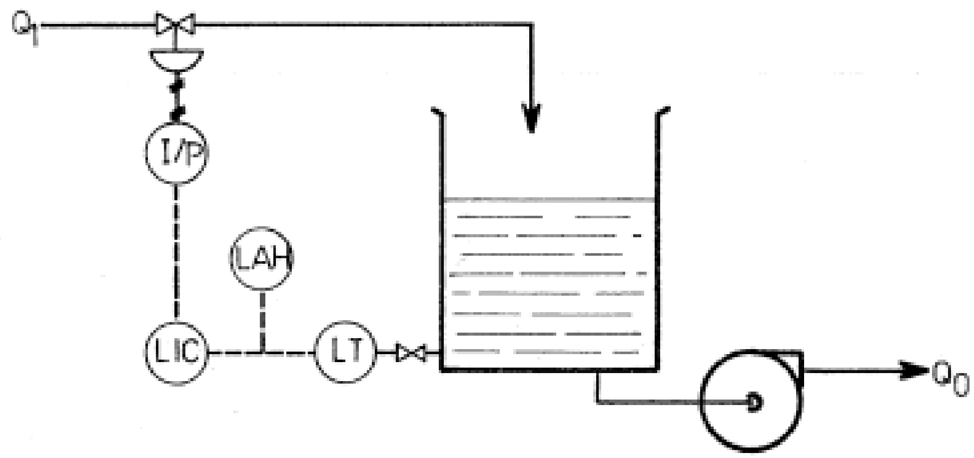
- **Proportional response will cause the control. signal to drop from 12 mA to 7.2 mA in three minutes.**
- **The derivative time is 1 minute so that superimposed on the proportional curve will be the derivative response.**
- **Derivative will cause the signal to be now what proportional would cause 1 minute from now while the error is changing the proportional curve will be shifted down by an additional 10% (1.6 mA).**

Simplified PID Electronic Controller

- **All three modes can be combined to provide maximum stability, minimum deviation controlled response with the elimination of offset.**
- **Suitable process response to a transient disturbance can be achieved by varying R_p contact (% PB), R_R (Reset time) and R_D (Derivative time).**
- **If proportional only control is required, set R_D to zero resistance to provide zero minutes derivative time and set R_R to maximum resistance to provide 0 RPM.**
- **The R_p contact can then be varied to achieve the quarter decay process recovery curve. R_R can then be set to remove offset while maintaining stable control.**
- **Finally R_D can be adjusted to minimize deviations and cycling to provide optimum three mode control.**



The Complete System



- **The controller output will now form a separate current loop so that the I/P transducer will operate as a function of the control signal.**
- **The spring opposed diaphragm actuator will drive the control valve open (A/O) as the 4-20 mA signal is transduced to 20-100 kPag and applied to the diaphragm casing.**
- **The complete electronic level control system can be represented by the following devices.**

  LT - Level Transmitter
  LAH - Level Alarm High (Current Alarm)
  LIC - Level Indicating Controller
  I/P - Current to Pneumatic Transducer
  CV - Control Valve (air-to-open in this case)
  Q_1 - Inflow (not measured here)
  Q_o - Outflow (not measured here)
- **A level decrease will produce a corresponding decrease in the 4-20 mA signal from the level transmitter.**
- **The valve in use is an *<u>air to open</u>* style so that the controller action must be reverse**
- **The decrease in measurement below the set point will cause the reverse action controller to raise the 4-20 mA signal proportional to the error.**
- **The increase in the 4-20 mA control signal applied to the I/P transducer will increase the corresponding 20-100 kPag signal applied to the valve.**
- **The valve will now be stroked more open to increase the inflow to the tank and try to restore the level to the set point.**

Lesson 2 Control Concepts Assignment

1. **What 4-20 mA transmitter signal will be developed if the level is 80 cm WC when the calibrated range is 0-120 cm WC?**
2. **A controller has a proportional band of 40% and a process upset causes the transmitter signal to change 2 mA. What open-loop change in control signal will result?**
3. **A current alarm is connected to a 4-20 mA loop (level) across a 125 ohm dropping resistor, what voltage signal level would correspond to a 85% high level condition?**
4. **The proportional response to a process disturbance changed the control signal from 12 to 10.5 mA. Over the next two minutes open-loop reset mode drives the signal to 9.75 mA. If the % PB is 30% find the reset time in MPR.**
5. **Explain the purpose of a comparator in a control system. Sketch a simple DC circuit which would function as a comparator.**
6. **Sketch a simplified electronic controller based on an OP-AMP with an RC feedback network to provide proportional plus reset action. Discuss the operation.**
7. **Explain what reset wind-up is and why it will occur. How does the wind-up condition affect the overall loop control? Use a simple computer control program as an example to illustrate how reset windup can occur.**
8. **Explain the difference between reset rate and reset time.**
9. **Sketch an electronic control loop used on a hot bleed/ cold service water heat exchanger. The objective is to control the temperature of the hot bleed as it leaves the HX. The temperature is sensed by an RTD and the valve on the service water is an air to close style. Discuss one cycle of operation, stating controller action.**

LESSON 2: ELECTRONIC CONTROL

MODULE 2 Control and Process Considerations OBJECTIVES:

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

1. **Sketch an open tank level application with a variable demand and describe the proportional control response for such an application.**
2. **Sketch a simplified supply feedforward level control application with a variable demand and Describe the system response to supply and demand disturbances.**
3. **Describe the concept of loop gain using illustrative gains for the process, the valve and the Controller to aid the explanation.**
4. **List three sources of process time delay for control applications.**
5. **Explain how two tanks can have identical volumes while having very different capacitances Requiring different controller gains.**
6. **Show how a dead time can introduce cycling into a control system.**
7. **Sketch the block diagram for a general cascade control application and show the interaction Of the major lag and minor lag control components.**
8. **Sketch a simplified cascade level control application with a variable supply and describe the System response to supply disturbances.**
9. **Sketch and describe a typical feedforward, cascade level control application which provides adeq control for both supply and demand disturbance conditions.**

MODULE 2: CONTROL AND PROCESS CONSIDERATIONS

- **Ideally, a control system should be able to hold the process at the desired operating point by suitably changing the *manipulated variable*.**
- **Consider again the level control of an open tank with the control valve located on the inflow line.**
- **If the system was subjected to a sudden step demand increase (activate pump 1), the level would begin to drop away from the set point.**
- **A proportional controller would respond to this error and eventually stabilize the level at some offset position.**

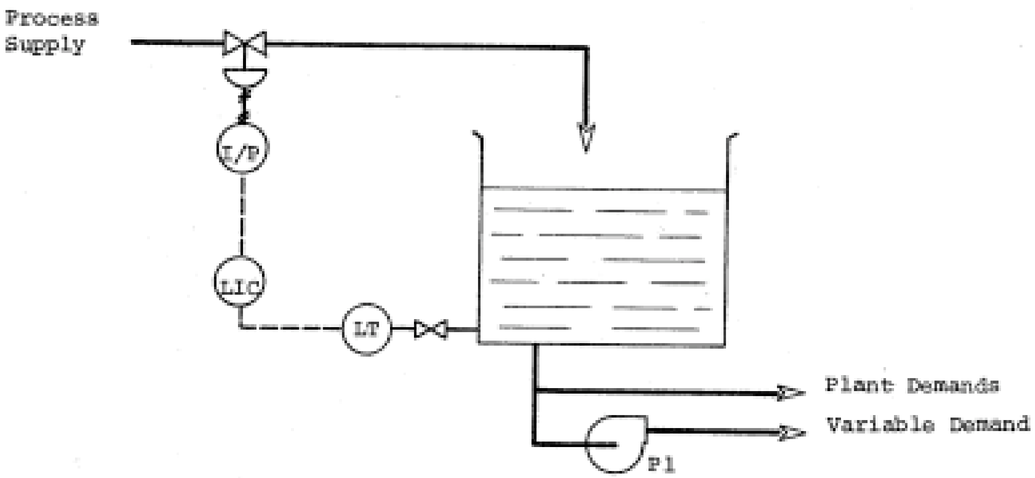


Figure 1: A Level Control System.

FEEDBACK CONTROL RESPONSE

- **This response demonstrates the typical action of a *negative feedback control* level system.**
- **The *error* must appear *before* a control correction can be made.**
- **The control system is always *acting after the fact* to restore the process to the set point.**

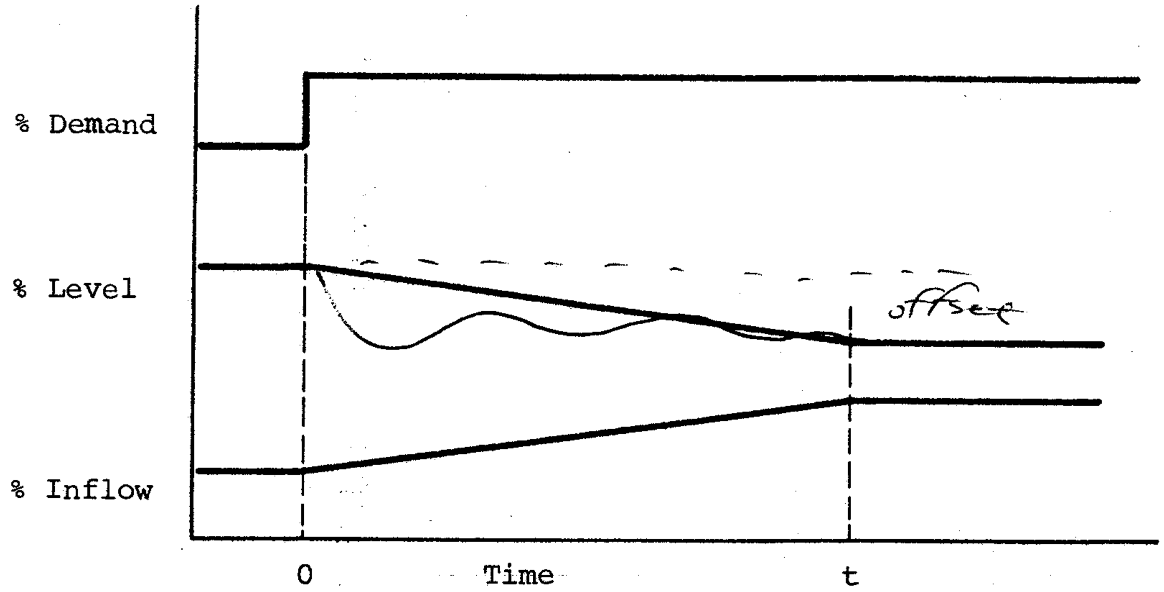
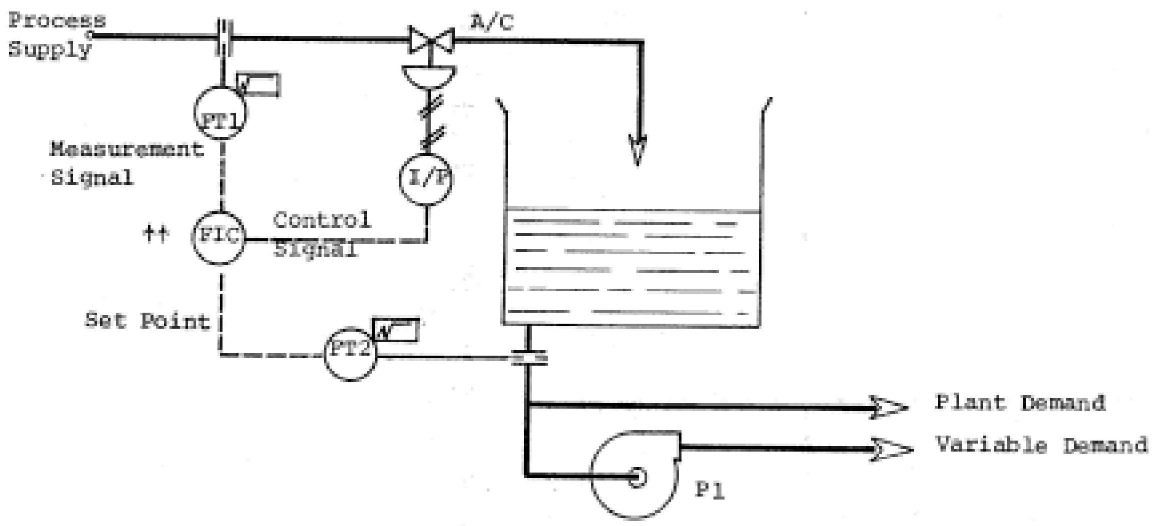


Figure 2: Level Response Following A Disturbance

FEED FORWARD CONTROL

- **The control approach can be modified by *trying* to achieve an *immediate* mass balance between the process inflow and outflow values (i.e. *before the error occurs*)**
- **Place a flow transmitter on the tank outflow line and use this signal as the set point for a conventional flow control loop on the inflow line.**



A typical Feed Forward Control Loop Installation

FEEDFORWARD LEVEL CONTROL

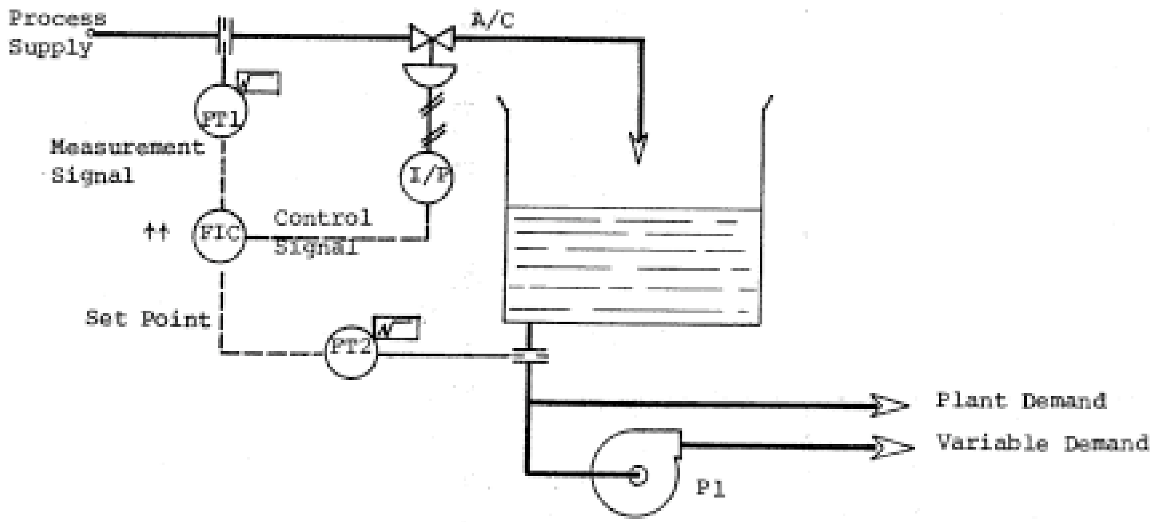


Figure 3: A Feedforward Level Control System.

- **If the valve selected is air to close (A/C), then the flow controller action must be *direct*.**
- **The flow controller can be specified with *proportional plus integral* modes to ensure that the inflow will be driven to that set point value requested by the outflow transmitter FT2.**
- **Assume a stable initial control situation with the level at the set point.**
- **A demand disturbance is applied by activating pump 1 so that the tank *outflow is suddenly increased*.**
- **Flow transmitter FT2 will sense the increase in outflow and *raise the set point for the flow controller (FIC).***
- **The flow controller will *stroke the valve as necessary* to bring the inflow to the requested set point despite supply fluctuation.**
- **The *inflow will match the outflow* and the level will not vary (ideally).**
- **This control response could be depicted graphically as an exact supply correction to *match* the applied demand change which leaves the process undisturbed.**

FEEDFORWARD LEVEL RESPONSE

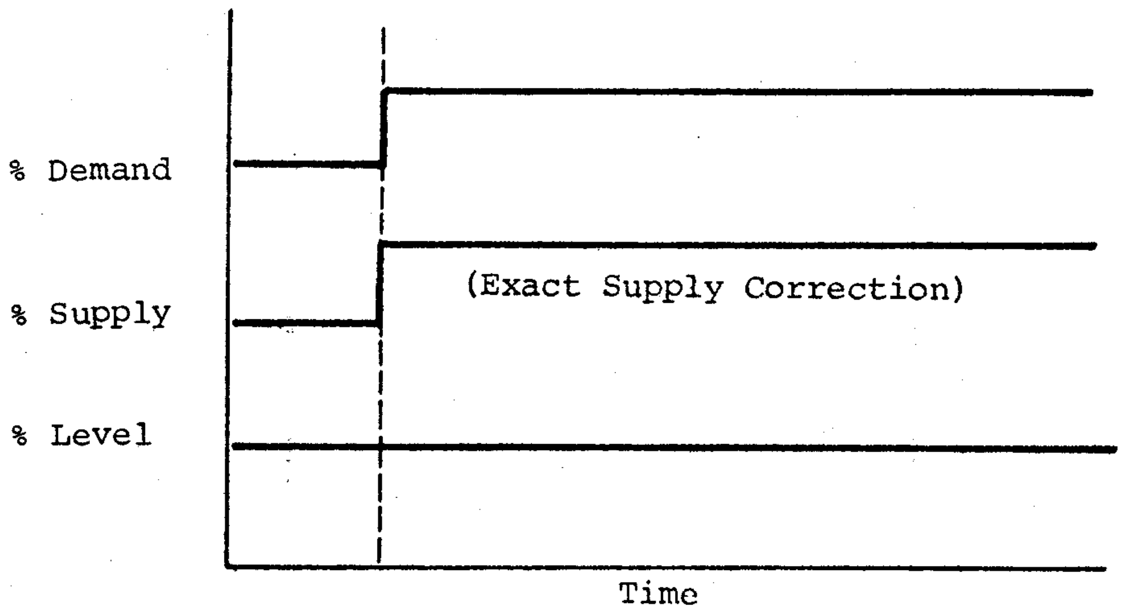


Figure 4: The Feedforward Level Response.

- **Ideally, the outflow transmitter (FT2) provides a *feedforward* signal so that the process input can be corrected as the demand changes *before* the process is disturbed.**

Time Delays

- **We must visualize the effect on this mass balance control system if there is a *time delay* between the change in outflow and *the corresponding exact correction* applied to the supply.**
- **The level will drop away from the set point *uncorrected for the duration of this delay*, and then normal inflow regulation will be applied to stabilize the level.**
- **But during this delay time period, a mass imbalance would have existed and so the level would begin to drift away from the setpoint.**

MASS BALANCE LEVEL RESPONSE WITH A TIME DELAY

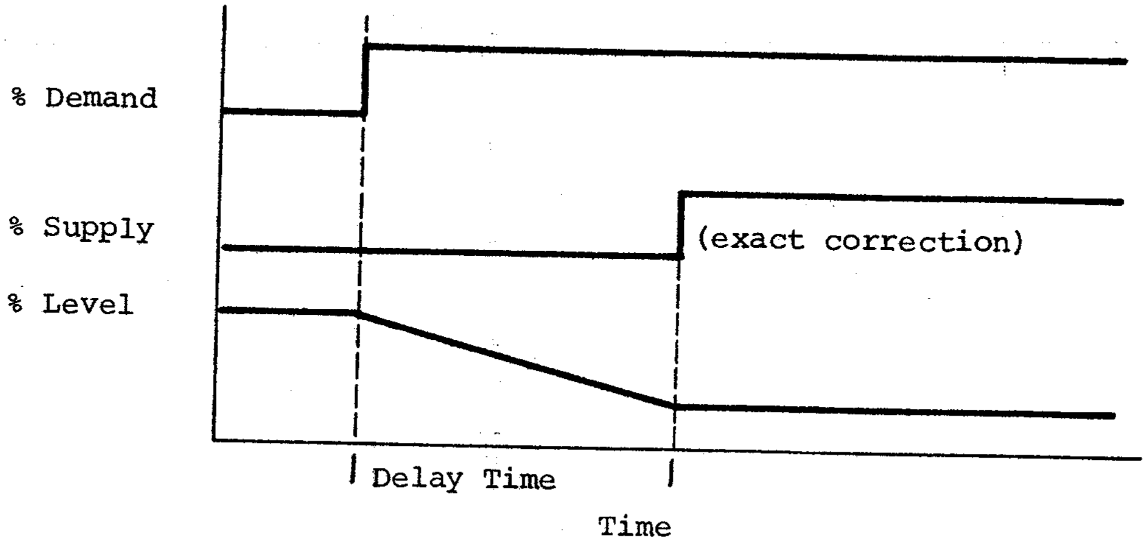


Figure 5: Mass Balance Level Response with A Time Delay.

- **Note that even an *exact* supply correction will result in a process *deviation if it is delayed in time*.**
- **Process time delays will compound the control problem and result in a lower quality of control in the system.**

- **Process time delays are caused by three characteristics of a system:**
  1. **Capacitance**
  2. **Resistance**
  3. **Dead Time**

CAPACITANCE

- **Capacities of a system are those parts of the process which have the ability *to store energy or material*.**
- **The tank for the level control system has a particular capacity. A distinction can be made between capacity and capacitance.**
- ***Capacitance* is the capacity of the system or component per unit quantity of some referenced variable.**
- **The simplest example would be level capacitance; the *tank capacity wrt the tank level*.**

CAPACITANCE (continued)

Consider two tanks of equal volume (40 m^3), but of different capacitance being *controlled over the same level span*.

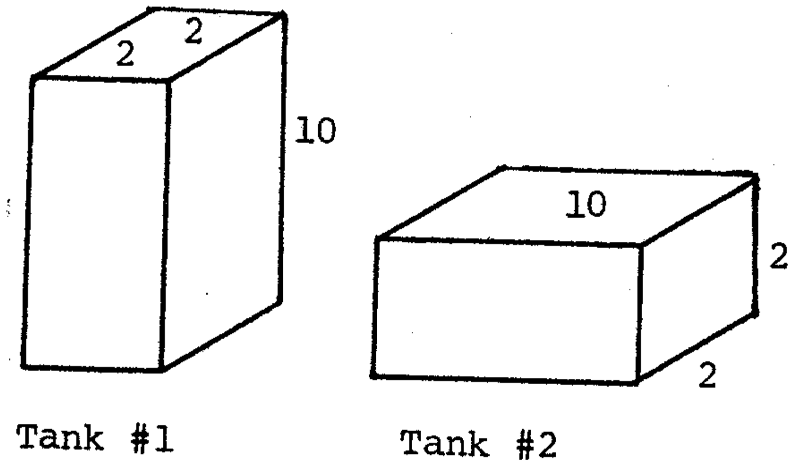


Figure 6: Tanks With Equal Capacity But Different Capacitance.

Capacitance of Tank #1: 40 m^3/10 m = 4 m^3/m
Capacitance of Tank #2: 40 m^3/ 2 m = 20 m^3/m

- **The capacitance of tank #1 is much less than that of tank #2.**
- **Tank #1 will show a much larger change in level for a particular inflow change than would tank #2. Tank #1 can be said to have *a higher process gain* than tank #2; that is tank #1 will have a *high gain* in units of level per minute.**
- **A *low capacitance system has a high process gain* while a large capacitance system has a low process gain.**

LOOP GAIN

- **Note that *loop gain* can be considered as the product of the controller (k_c), valve (k_v) and process gains (k_p).**

  Loop Gain = $k_c k_v k_p$

- **If the process gain (k_p) is very low due to the large system capacitance*, the loop gain can be increased by raising the controller gain* (narrowing the proportional band)**
- **This is the application of *compensatory control gain*.**
- **In general if the system capacitance is increased, the proportional band must be narrowed to maintain optimum control.**

RESISTANCE

- **Resistances are those parts of the system which will *resist the transfer of energy or materials* from one point to another in the system.**

- **Connecting pipe, elbows or partially open control valves can be considered as *resistance elements* for the flow in the system.**

TRANSFER LAGS

- **The combined effect of supplying a particular capacitance (C) through a resistance (R) produces a time delay for the transfer of energy or material.**
- **Such Resistance - Capacitance (RC) time delays in an application system are commonly referred to as *transfer lags*.**

DEAD TIME

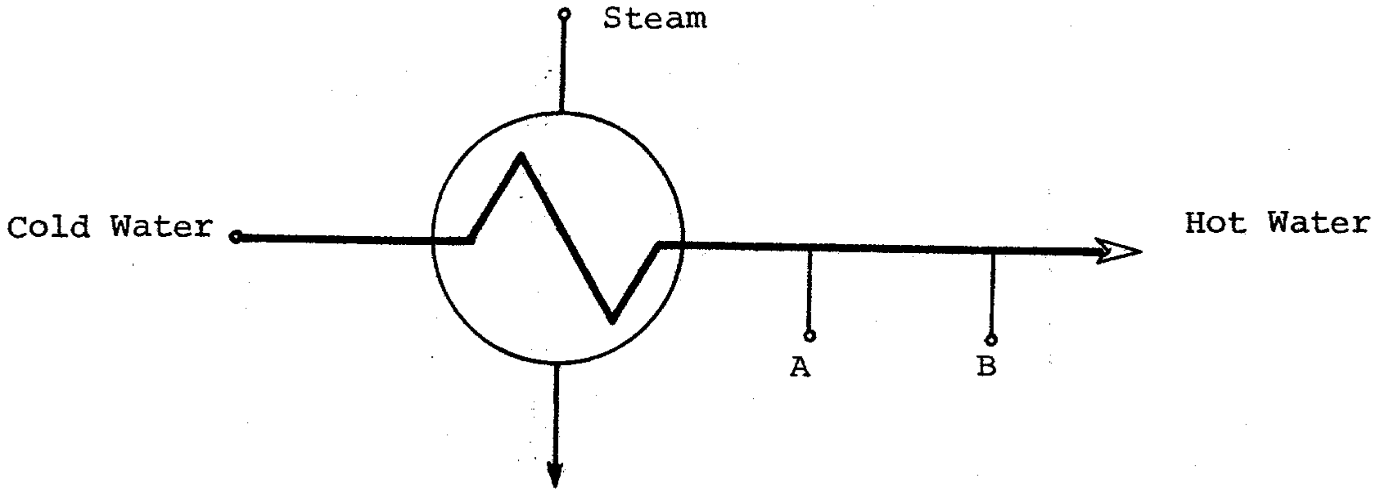


Figure 7: Detector Location Result in a System Dead Time.

A third contribution to lags is the time required *to transport or carry a change* from one point to another in the process.

- **A temperature detector located at point "B" will have a delayed indication wrt the measurement made at point "A”. (Neglect heat losses along the pipe from "A" to "B").**

- **The indication delay or *dead time* will depend on the distance from point "A" to "B", and the *flow rate* of the process.**

DEAD TIME (continued)

The dead time can be considered as the interval between an actual process change and the corresponding indication of that change.

- **Dead time is sometimes referred to as *transportation lag* since the response is delayed until the change is transported through the system.**
- **Pure dead time will *not alter the shape or the magnitude* of a process change, it will only delay it in time (*dead time does not contribute to loop gain, only to phase lag*).**

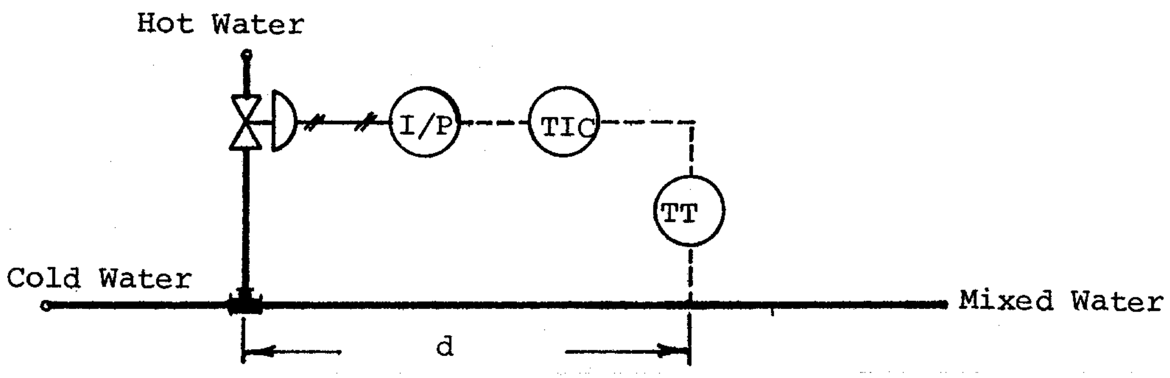


Figure 9: Mixed Water Temperature Control System with Dead Time.

Dead Time Cycling

- **Dead time in a system can produce *process cycling* if the lag causes the control correction to follow *well after* the disturbance has occurred.**
- **Consider a simple mixed water temperature control system with a significant dead time component which results from the remote detector location (distance d)**
- **There will be a time delay between the water temperature passing the mixing tee and reaching the temperature detector.**
- **Assume that the system is *apparently* under stable control with a loop gain of one, and that the process is at the set point. (this is to say the loop was not properly tuned and the phase margin had been adequate but the gain margin was not)**

DEAD TIME CYCLING (continued)

- **A slug of *colder water* is admitted to the system, causing the mixed water temperature to deviate below the desired setpoint.**

- **When the colder slug is at the temperature detector, the water temperature at *the mixing tee* is back to the desired operating value.**

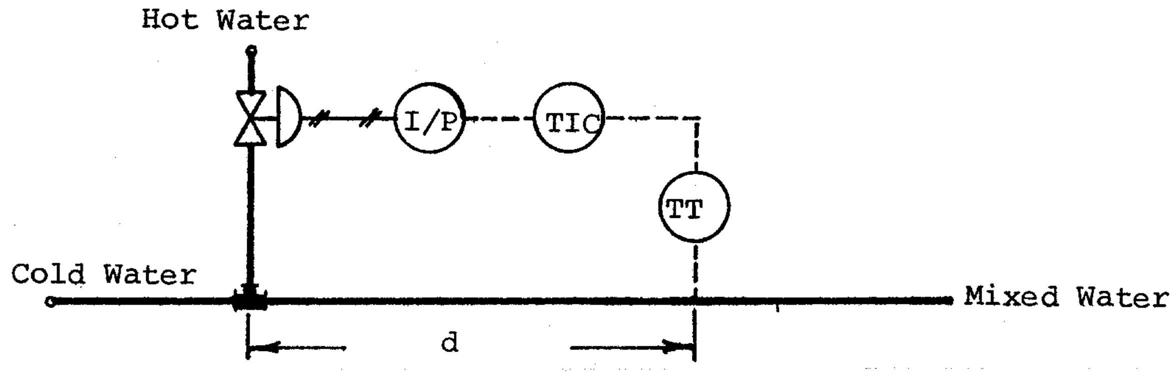


Figure 9: Mixed Water Temperature Control System.

- **The controller (TIC) will respond to the decrease in detector temperature by driving the hot water flow valve more open, raising the temperature of *the mixed water at the tee* *above* the set point.**

- **This slug of hot water will now pass to the detector, when the dead time has elapsed , and will be sensed by the detector causing the *controller to reintroduce a cold slug*.**

Since the loop gain was one, the amplitude of the resulting deviations will be constant and the temperature response will smooth out to approximate sinusoidal oscillations

DEAD TIME CYCLING (continued)

- **For any process there will be one specific proportional band setting which will produce a loop gain of one (constant amplitude cycling). This is called the *ultimate proportional band* for that process.**

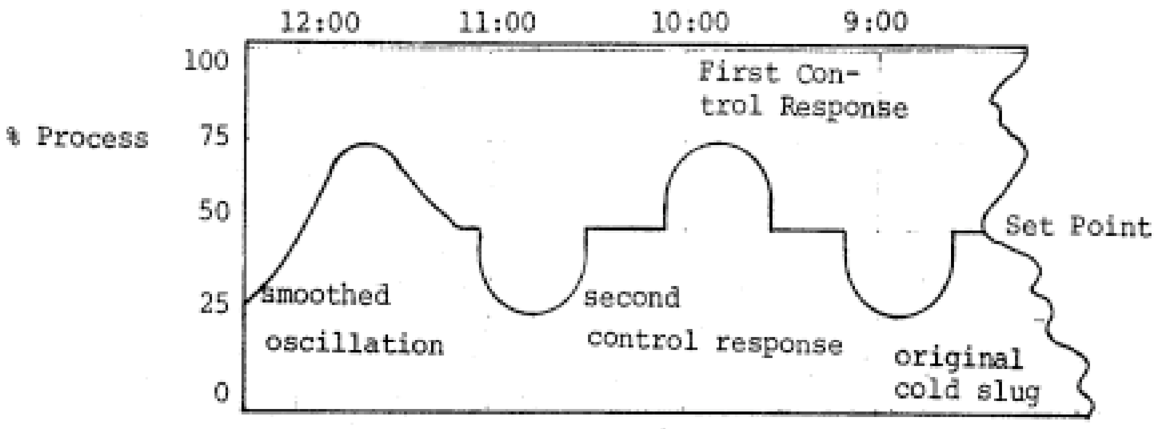


Figure 10: Chart Record of Dead Time Cycling.

- **The adjustment of the proportional band will determine if the disturbance produced cycle will *attenuate* or be sustained.**

- **The operating proportional band in the mixed water system must be *widened* in order to attenuate the process cycling and restore stability.**

- **In general, the proportional band and must be *widened for a dead time* element is included in the control system.**

CASCADE CONTROL SYSTEMS

- **Cascade control is the *interaction of control loops* to reduce process deviations and instability by involving more than one controller.**

- **If a long time lag exists between a change in the manipulated variable and the resulting effect on the controlled variable, then process cycling can result.**

- **The output signal of one controller becomes the *set point* for a second controller.**

- **Cascade control is employed in systems with more than one manipulated variable or if there are significant time delays which can effect the desired control objectives.**

FEEDBACK EXAMPLE

Consider the proportional level control of an open tank as sketched.

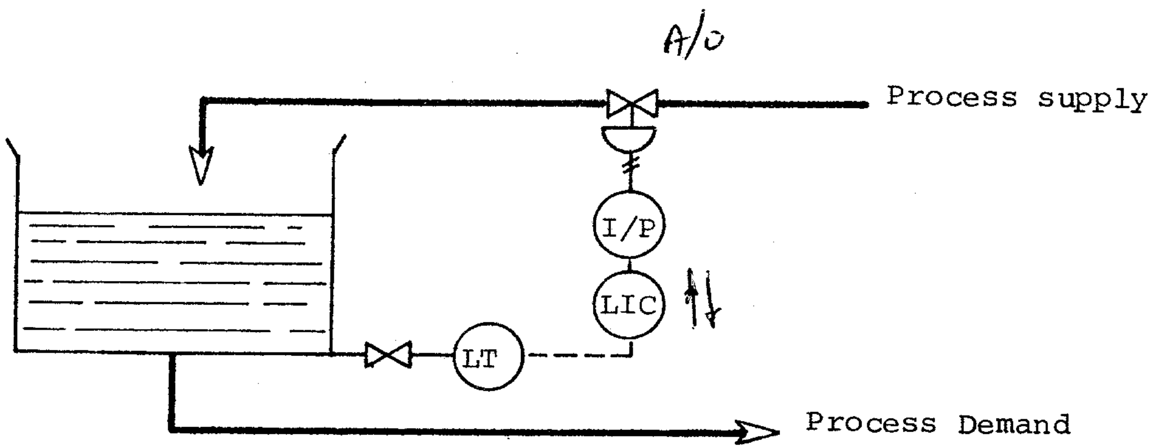


Figure 11: Proportional Level Control System

- **If a demand increase occurs, the level in the tank will begin to drop.**
- **The level controller (LIC) will drive the inflow valve more open until *mass balance* is achieved and the level stops dropping. Say a 5% offset now exists in this system.**

FEEDBACK CONTROL EXAMPLE (continued)

- **Should an external *supply decrease now occur* so that the valve is allowing less inflow than expected for a given opening, the tank level will begin to drop again.**
- **This *additional error* will drive the valve more open until mass balance is again achieved.**
- **Say the new offset in the system is now 8%.**
- **Minimizing this type of deviation following a combined supply and/or demand disturbance would be desirable.**
- **Notice also, that if the system has a large capacitance, there will be a significant time lag between applying a change to the manipulated variable and the resulting effect on the controlled variable. Cycling as in the dead time example can result.**

GENERAL CASCADE CONTROL

- **The basic cascade approach is to attempt to eliminate disturbances before they reach the large capacitance, slow responding system.**
- **In the previous specific case, level control was adequate if *only a demand change* was applied and the supply was constant.**
- **The solution is to essentially make the flow that reaches the tank as constant as possible.**

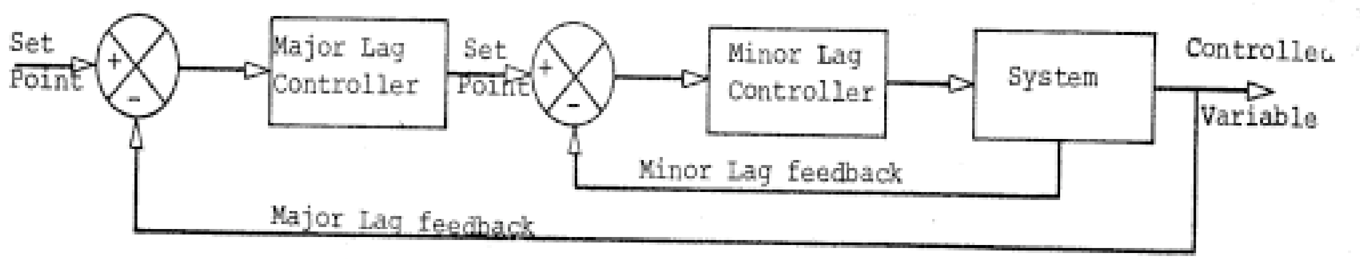


Figure 12: General Cascade Control.

Cascade Control…continued

- **A flow control loop is required to smooth supply fluctuations and to prevent the fast responding flow system from disturbing the slower responding level system.**

- **The general format for a cascade control system is to have the control signal from the *major lag controller* applied as the set point to the *minor lag controller.***

- **The major lag controller which develops the set point signal is referred to as the *primary* controller.**
- **The minor lag controller which accepts the set point signal is the *secondary* controller.**

CASCADE LEVEL CONTROL SYSTEM

- **The level system can be adapted to provide cascade control with a *primary level controller* and a *secondary flow controller*.**

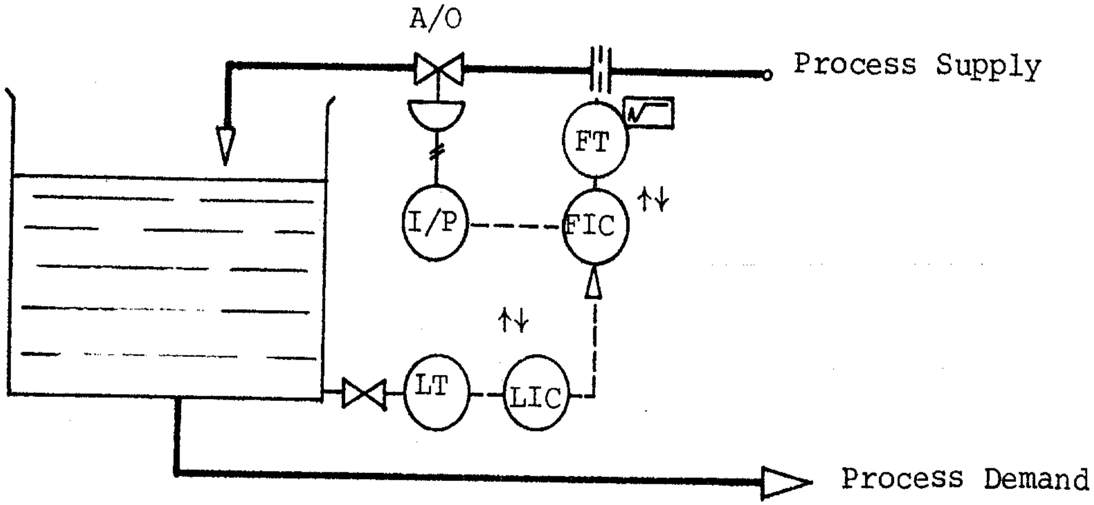


Figure 13: A Cascade Level Control System.

- **The *secondary controller action* can be determined in the normal fashion by considering the desired valve motion.**
- **For example, if the flow rate is too high, the valve must close or the control signal must be reduced. The flow controller must have reverse action.**
- **The *primary controller action* can be determined by considering the overall desired response of the system. Should the tank level be too high, the inflow must be reduced. The set point for the flow controller should be lowered. (e.g., change the inflow from 65% to 55%.) The primary controller action in this case must also be reverse action.**

CASCADE LEVEL CONTROL EXAMPLE (continued)

- **Imagine an *increased demand disturbance* being applied to this cascade control system.**

- **The level in the tank will begin to drop away from the set point. The level control signal from the LIC will increase proportional to the error, *raising the set point for the flow controller (FIC).***

- **Inflow to the tank is increased in accordance with the set point change until a mass balance is achieved and the level stops dropping.**

- **If an external *supply decrease* now occurs, the secondary controller will sense the flow variation and manipulate the valve position *until* the flow rate is restored *to the requested set point*.**

- **The flow controller will regulate the flow to prevent supply fluctuations from affecting the level system.**

CASCADE CONTROL SUMMARY

- **The cascade control approach will still perform as a negative feedback loop; an error must occur in the process before the control correction can be applied.**
- **The control system will then act in opposition to this error in an attempt to restore the process to the set point.**
- **Closer control of such a system may be possible by including a *feedforward* component in the control system.**

FEEDFORWARD CONTROL SUMMARY

- **The problem with the feedforward system introduced earlier in the module (Figure 3) was that the level could wander away from the set point due to process or control system time delays.**
- **A level controller could be included in that feedforward control scheme to ensure that the level is maintained at the set point.**
- **The feedforward element is required *to minimize the process deviation* following a demand change when there is an inflow/outflow mismatch.**
- **An outflow transmitter *(feedforward)* signal can be combined with the level control signal and the resulting signal can be cascaded as the set point for the inflow controller.**

FEEDFORWARD CASCADE CONTROL

- **This level controller (LIC) will *be reverse acting* so that if the tank level is too high, the set point for the flow controller will be reduced.**
- **If the level is at the set point, the control error is zero and the proportional controller will develop a 50% signal (12 mA).**
- **The outflow transmitter FT2 signal and the level control signal can be combined with a *summing amplifier.***

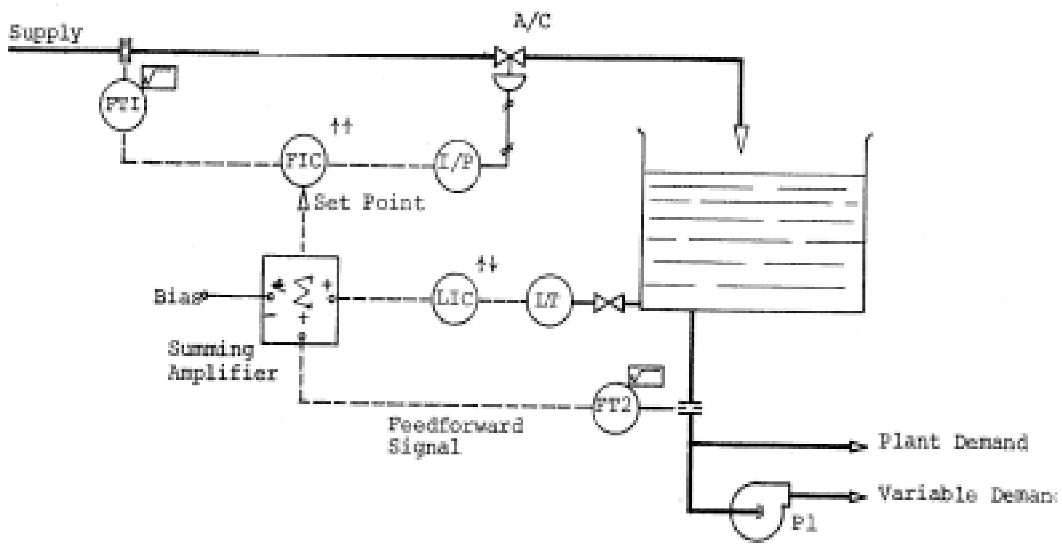


Figure 14: A Feedforward Cascade Control System.

Feedforward Cascade …continued

- **A flow set point change is not required by the level controller if the tank level is at the set point. Consequently, the summing amplifier can be adjusted so that a level control signal of 50% (zero error) will be ignored.**

- **This can be accomplished by setting a constant negative 50% signal or *bias value* on the amplifier. The summing amplifier will perform the following routine:**

  (% LIC signal) + (% FT2 signal) - (50% bias) = Summed signal

- **The signal from the summing amplifier is applied as the *setpoint* for the inflow controller (FIC).**

FEEDFORWARD CASCADE CONTROL LOOP OPERATION

- **Assume that the level is at the set point, then the LIC will develop a 50% control signal which will just equal the applied bias value.**
- **The set point for the flow controller (FIC) will equal the signal from the outflow transmitter (FT2).**
- **The FIC will now regulate the inflow to the tank with respect to the requested set point (FT2 signal) despite supply fluctuations sensed by FT1.**
- **A mass balance will be achieved with inflow matching outflow so that the level is unchanged.**
- **Should a demand increase now occur, raising the outflow, the tank level will begin to drop.**
- **FT2 signal increases and raises the setpoint to FIC until the feedforward signal causes the flow controller to restore the system to equilibrium and the inflow again matches the outflow.**
- **As well, any slight drop in tank level will be sensed by the LIC causing an additional slight increase in setpoint to the FIC.**

FEEDFORWARD CASCADE CONTROL LOOP OPERATION

- **This *additional* LIC signal above the bias value will raise the flow controller set point causing the inflow to be greater than the outflow.**
- **Notice that there will not be a requested mass balance condition as long as the level is not at the set point.**
- **When the level reaches the set point, the tank inflow set point will equal the outflow rate so that a *mass balance* is achieved with *zero error* in the level system.**
- **This control system should be immune to *supply disturbances* and will minimize process deviations following a demand disturbance, ensuring that the level can be maintained close to the set point in a stable fashion.**

MODULE 2 CONTROL AND PROCESS CONSIDERATIONS ASSIGNMENT

1. **Sketch an open tank negative feedback level application with a *variable demand* and describe the proportional control response for such an application.**
2. **Sketch a simplified *pure supply feedforward* level control application with a variable demand and describe the system response to supply and demand disturbances.**
3. **Describe the concept of *loop gain* using illustrative gains for the process, the valve and the controller to aid the explanation.**
4. **List three sources of process *time delay* for control applications.**
5. **Explain how two tanks can have identical volumes while having very different capacitances requiring different controller gains.**
6. **Show how a dead time can introduce cycling into a control system. What adaptive control gain adjustment must be made to accommodate dead time?**
7. **Sketch the block diagram for a *general cascade control* application and show the interaction of the major lag and minor lag control components.**
8. **Sketch a simplified cascade (inflow is minor lag, level is major lag) level control application with a variable supply and describe the system response to supply disturbances. How will this system act following a demand disturbance?**
9. **Sketch and describe a *typical feedforward, cascade level control* application which provides adequate control for both supply and demand disturbances.**

Lesson 2: General Control Concepts

MODULE 3: Boiler Level Control

MODULE OBJECTIVES:

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

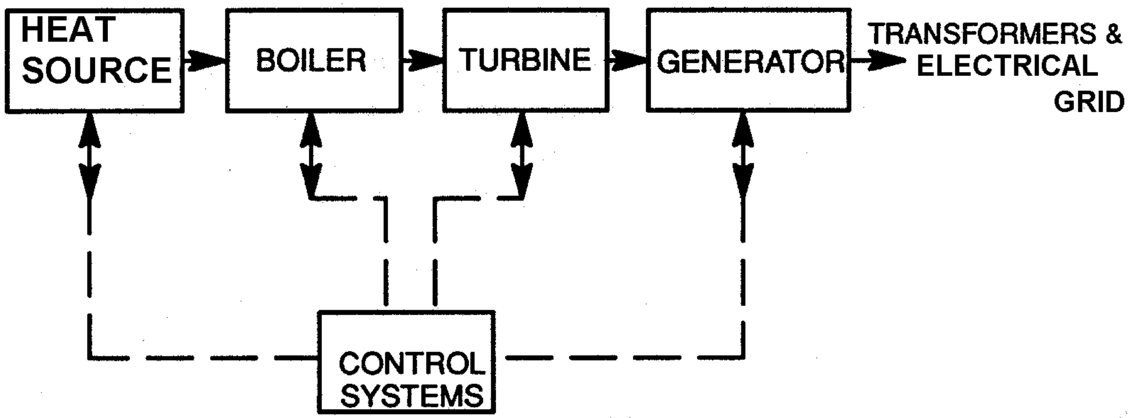
1. **Sketch a typical three element feedwater system incorporating a summing amplifier and describe the general operation of this system when subjected to a steam demand increase.**
2. **Explain why the boiler drum level is ramped as a function of the reactor or steam power and state two methods of achieving this ramp.**
3. **Explain the general three element control system response to stated control loop device failed conditions**
4. **Explain how incorrect drum level control could cause a HTS pressure disturbance.**
5. **State the reasons for having two large and one small CV in a boiler level control scheme.**
6. **Sketch and describe how the large feedwater CV's in a boiler scheme could be swapped on line in a bumpless fashion.**
7. **Sketch a representative graph of drum level vs. reactor power and label relative action level points for alarm or protective actions.**

Introduction

- **In a thermal electric power plant the steam generators (often referred to as "boilers") are a critical energy linl between the *primary heat source* (fossil or nuclear) and the turbine.**

- **The boilers provide the *heat sink* for the fossil or nuclear heat source to allow a** *dynamic energy balance* **to b achieved.**

- **In nuclear generating stations the boiler level control system must function properly and quickly in order t provide a continuous heat sink to the reactor with *adequate safety and production margins*.**



Control Considerations

- **The demineralized water boiled from the boiler drum as steam must be just made up by the inflow of feedwater if the level in the drum is to remain constant. When a *mass balance* (inflow = outflow) exists; the drum level will be held at some *dynamic equilibrium* position.**
- **Note that a *slight mismatch* between the outflow (steaming rate), and the inflow (feedwater & reheater drains) *will result in a drum level change.***
- **A functional level control system can be designed (as in Figure 1) to regulate the feedwater flow as *a function of variations in the drum level.***

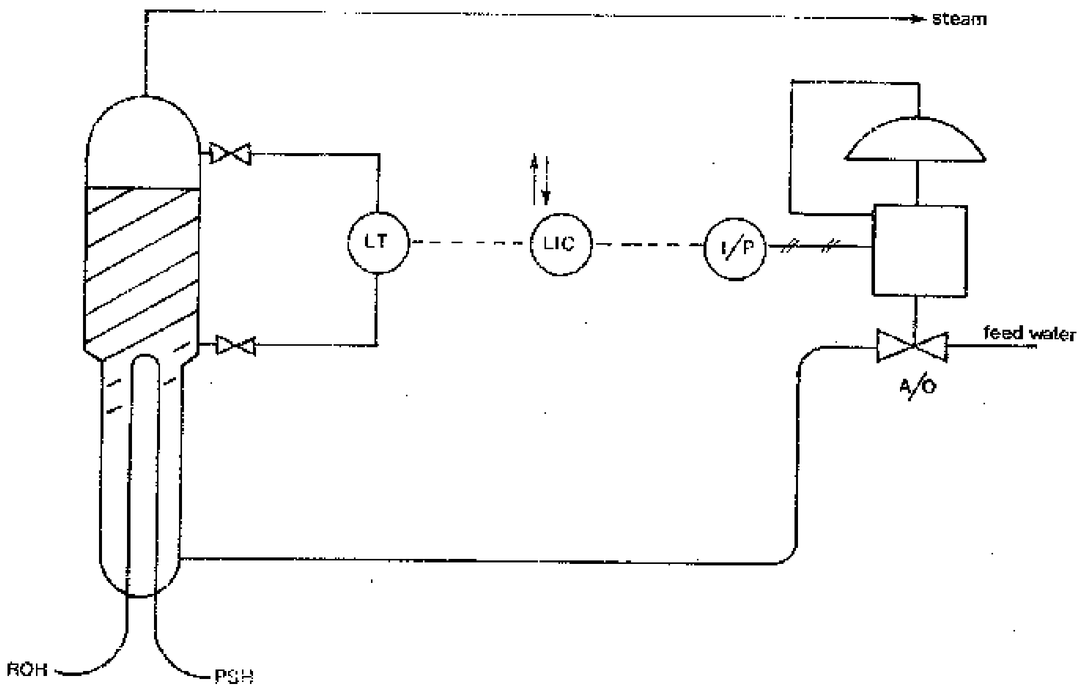


Figure 1: A Single Element (1-e) Feedwater Control System.

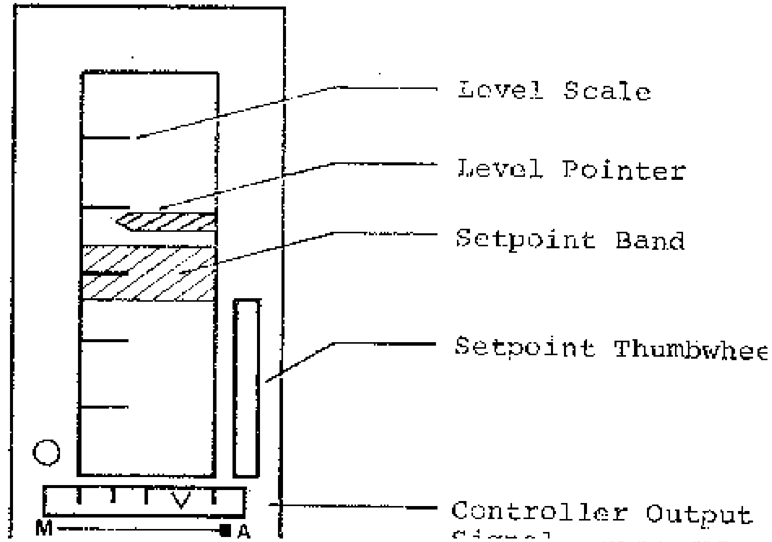
- **As drum level is the only measured parameter, this type of control scheme is usually referred to as *single-element (1-e)* feedwater contro strategy.**
- **The usual large capacity feedwater CV is an *air to open* (A/O) valve style which will *fail closed* upon loss o instrument air. An increase in pneumatic signal applied to this actuator will increase the feedwater flow.**
- **An electronic D/P cell monitors the drum level over a span of 2 - 3 m, and provides a measurement signal t the *reverse acting* level controller (LIC).**
- **The level controller compares the drum level to the desired manually entered level setpoint, and adjusts th feedwater control valve (CV) accordingly.**

Instrumentation Display

- **Simple Control Room Instrumentation (a level controller) for the single element system of Figure 1 is shown in Figure 1(a).**
- **The drum level is indicated on the controller scale with respect to drum variation about the setpoint.**
- **The feedwater valve position can be estimated from the controller output signal, assuming that the feedwater valve pneumatic supply & accessories are functional**

- **If the drum level is *__above the setpoint__*, the feedwater valve must be stroked more closed, (i.e., the control signal must be reduced).**
- **A *__reverse acting__* controller is required for this loop.**

- **Assume that a *__sudden decrease in feedwater supply__* is experienced. The flow delivered by any particular valve position is reduced by the supply change (even though *__the valve hasn't moved!__*).**
- **A *__mass imbalance__* now exists between inflow and outflow and the drum level begins to drop.**
- **The LIC responds to this *__error__* (with proportional and reset modes) in an attempt to restore the process to the set point.**



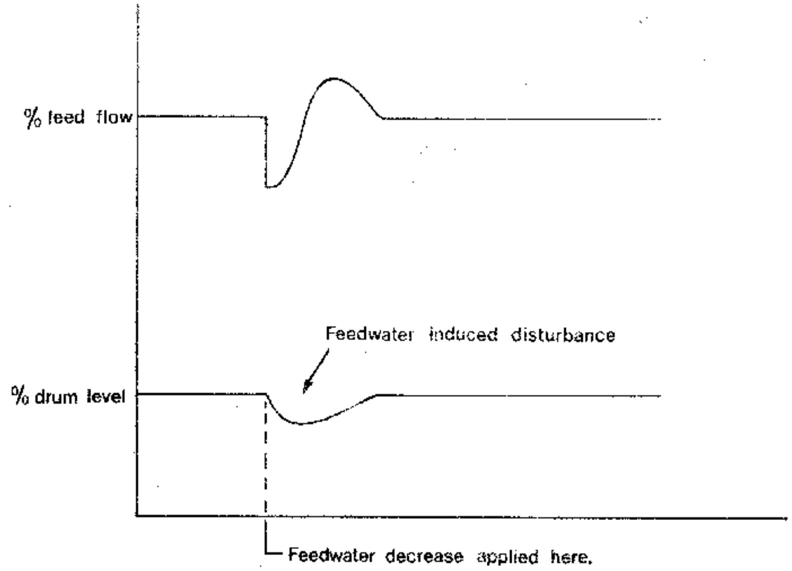


Figure 2: Single Element Response to a Sudden Feedwater Supply Decrease

Adequate control of such a 1-e level system could be provided by a properly tuned proportional plus rese controller. However, a boiler level system provides some unexpected responses when large, sudden stean changes are applied.

- **Boiler *drum level* can change as a function of boiler pressure without an associated change in drum wate inventory. Consider a sudden step increase in steam demand and the subsequent drop in boiler pressure The increased boiling (and expansion) throughout the drum due to the decrease in pressure will force th level upward. As the boiler pressure recovers, the water inventory is driven back down toward its expecte level.**
- **This *temporary rise* in drum level is called the *swell effect* (the drum inventory seems to swell). The swel effect will appear as a *positive-going transient level spike* on a level trend record.**

- **Should the steam demand suddenly be decreased, the steam pressure will increase compressing the bubble in the drum and the drum level will decrease as the increased pressure reduces boiling.**
- **This *temporary drop* in drum level is called the *shrink effect* (the drum inventory seems to shrink). The shrin effect will appear as a *negative-going transient level spike* on a level trend record.**

- **Assume that the LIC of Figure 1 and 1(a) is providing adequate level control when the system is subjected t a sudden step increase in steam demand. Swell effect will occur and the level controller will respond to th increase of drum level by driving the feedwater CV more closed. This single element control system ha responded to an increase in steam demand with a decrease in feedwater flow - the *exact opposite of th required response* (what happens to the mass balance?).**

- **As the swell effect subsides, the drum level will begin to drop due to the increased steam flow. The leve controller *must reverse its original control decision* and begin to drive the feedwater valve more open (not that the feedwater valve has now cycled). Some time will be required to make up the lost inventory due to th incorrect controller response, and to allow the drum level to stabilize back at the setpoint.**

1-e Response to a steam Demand Increase

- **Minimizing the *level transient* and improving the *stability* of the feedwater flow would be desirable. Particularly when large steam capacity boilers are designed with relatively small drums, and high velocity steam and feed flows.**
- **Such a *lower capacitance* boiler drum is less capable of absorbing control errors. Additional logic should be applied to the control system to decide if the level is rising due to a true *decrease in steaming rate*, an *increase in feed flow* or, alternatively if a swell effect is being sensed.**
- **One problem with single element control is that it is usually utilized during *low power conditions* when feedwater heating is at a minimum (i.e. cold feedwater). Under these conditions, a low drum level would call for an increase in feedwater to the drum. However, the *cold feedwater* entering the drum tends to *quench drum boiling* and promote the shrink effect. Drum level decreases further as the colder feedwater is admitted. This in turn call for additional feedwater to be supplied to that drum and the *steaming rate is actually reduced* due to th decrease in drum boiling finally allowing an *apparent mass balance* to be achieved. This extra 'unrecognized inventory must warm up and swell (causing a subsequent positive going upset) before the level can recover Under these conditions, it is adviseable to make control adjustments moderately (under automatic or manua mode) until the true boiler dynamics can be seen.**

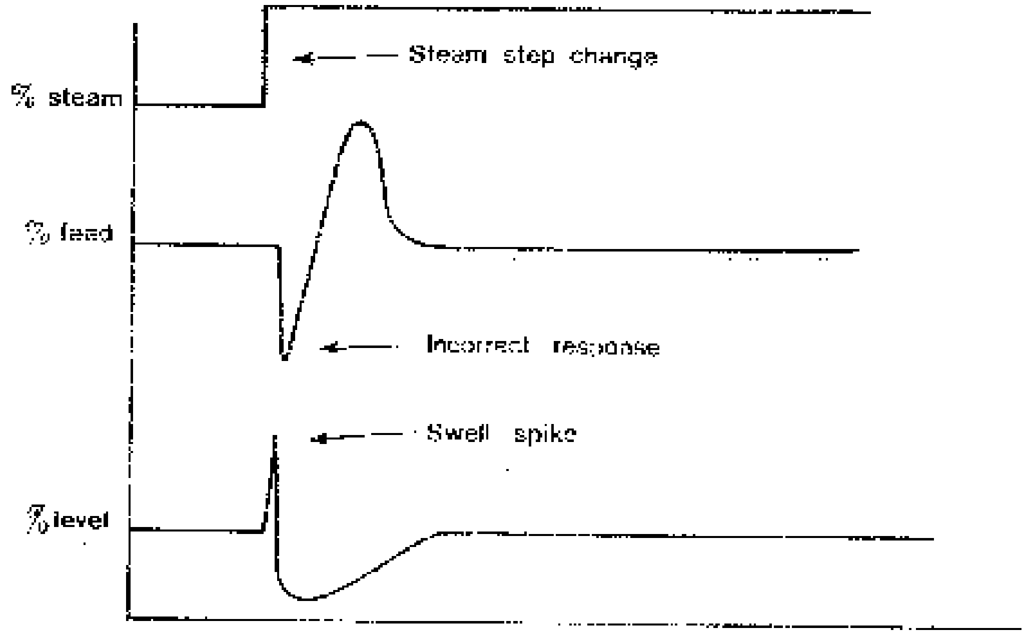


Figure 3: Single Element Trend Responses to a Positive Step Steam Change.

Two-element (2-e) feedwater control

If the *steam flow* was measured, then a *feedforward* control decision could be made regarding the drum l *Elbow taps* could be installed on the steam line to provide a differential measurement input to an electronic D/P without introducing an additional permanent pressure loss. This signal is routed to a square root extracto provide a linear - *flow* signal. A 2-element feedwater control scheme (the 2 elements are *drum level* and *steam f* can be designed as shown in Figure 4.

Note that the LIC is still *reverse acting* so that a rise in drum level will cause a decrease in control signal closing the valve.

- **The *summing amplifier* (Figure 4) allows the *level control* and *feedforward steam flow* signals to be combined to develop the final valve lift signal.**
- **Assuming that stability is not a problem, the LIC gain could be adjusted so that a given steam flow change will be approximately countered by the LIC upset response - *while the swell or shrink exists*. In this fashion, the summer output signal (to the CV) will remain relatively constant until the transient effect begins to subside. The initial incorrect control action of the 1-e system can be eliminated in this way.**

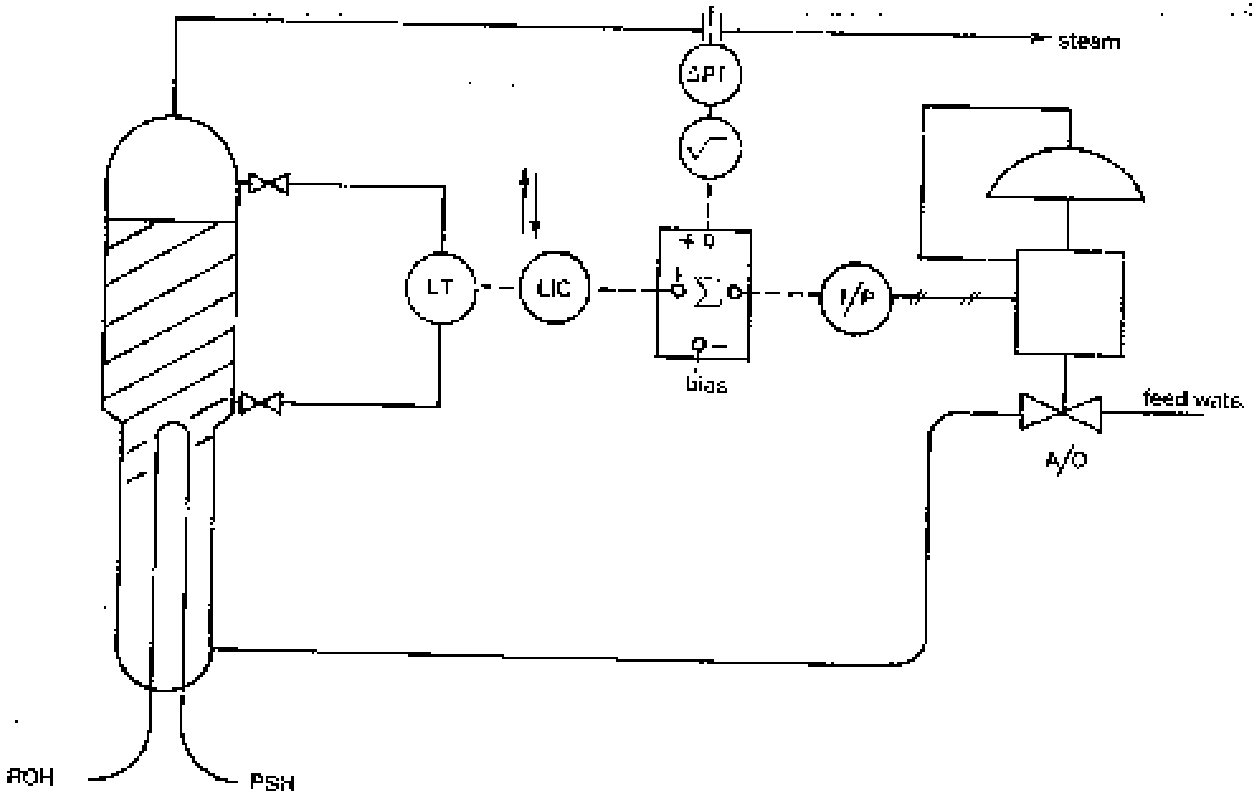


Figure 4: Two-Element (2-e) Feedwater Control System

2-e Boiler Level Control Indications

The Control Room Instrumentation for the two element system of Figure 4 is shown in Figure 4(a). *The drum level controller* indications are supplemented by a *steam flow* indicator. Two parameters (*steam flow* & *drum level*) are now indicated and used for control sensing.

- **Recall that the total supply input to the boiler is the *feed flow and the reheater drains*. In order to achieve a true mass balance, a gain factor (K_s) must be applied to scale down the feedwater flow.**
- **For example, assume 100% steam-flow; if 100% feed flow was supplied, the reheater drains would make the inflow *greater* than the outflow.**
- **If a gain factor (say 0.95) was applied to the steam flow, then the feedflow would be 95% when the steam was 100%. The balance (5%) can then be supplied by the *reheater drains to provide the equilibrium conditions*.**

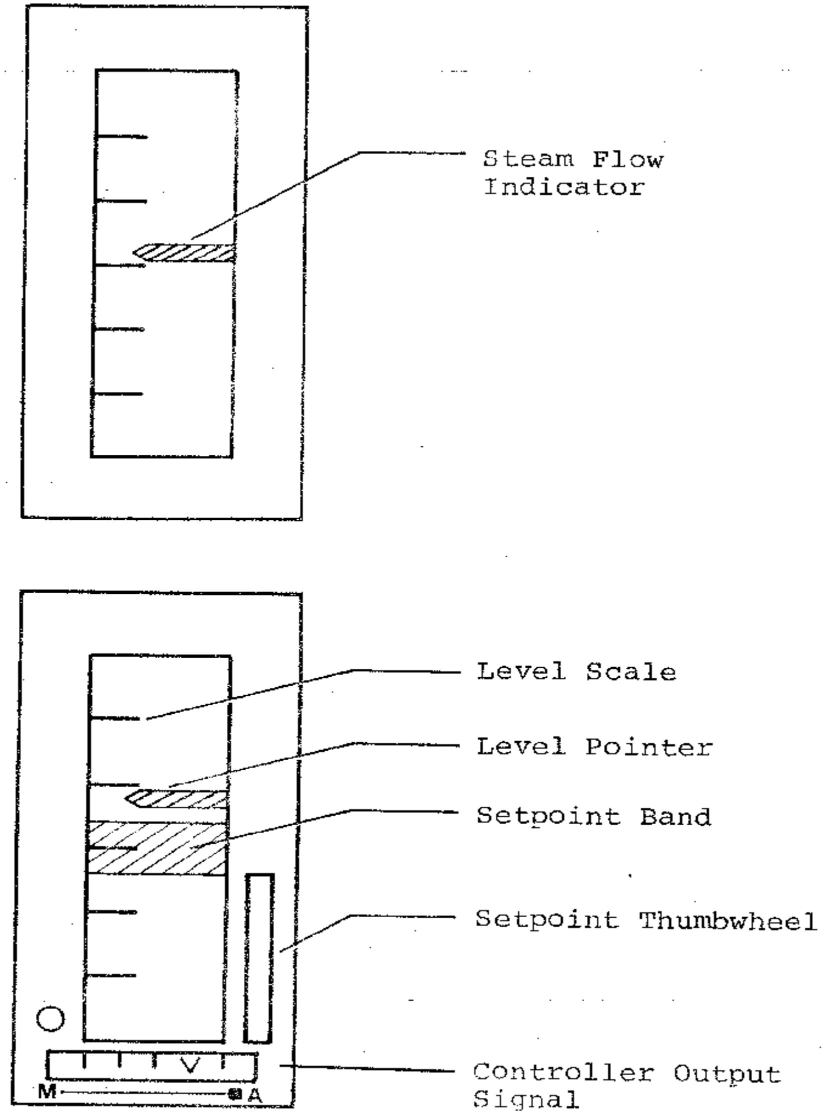


Figure 4(a): Typical 2-e Instrumentation Display.

Two Element Biasing Considerations

The level control signal effect on mass balance is ***not required*** if the drum level is at the setpoint. Recall that a straight proportional controller can be described by the following equation:

Straight Proportional Control

CS = *K* * E + B

CS = Control Signal

K **= Controller Gain**

E = Error (setpoint - measurement)

B = Bias (50% unless otherwise stated).

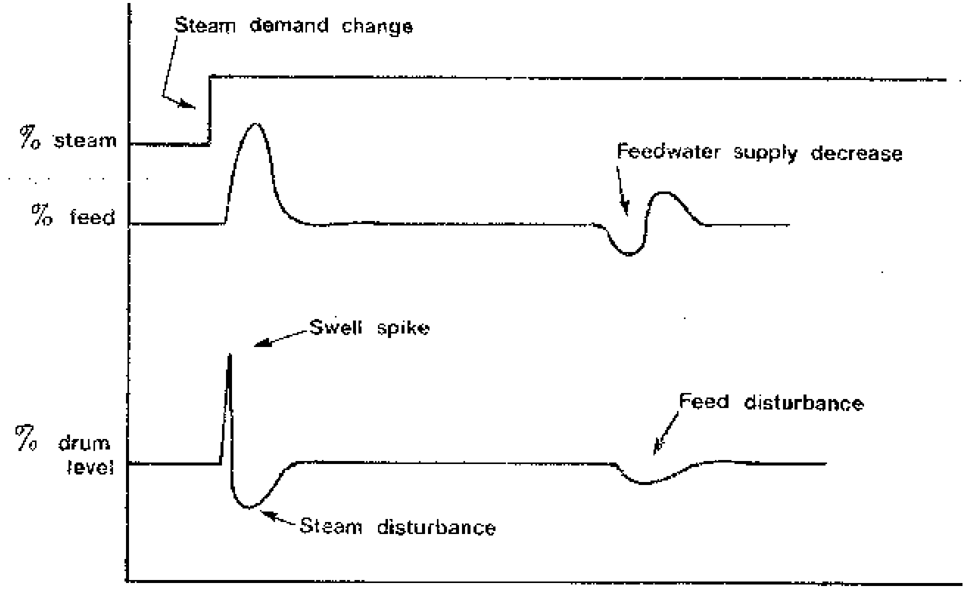


Figure 5: Two Element Trend Responses to a Positive Step Steam Change

If the level Error is zero, the control signal is just the controller Bias. This signal component can be eliminated by the negative bias applied to the summer.

Now only the *change in control signal* (level factor) will be combined with the *steam flow* signal by the summer.

The *summer output* can be described as:

Summer Signal = (level factor) + (steam factor).
Summer Signal = (control signal) + (K_f * Steam) – Summer Bias
Summer Signal = (K_L * E + LIC Bias) + (K_f * Steam) – Summer Bias
Summer Signal = (K_L * E) + (K_f * Steam)

2-e SUMMER PERFORMANCE

- **If the level is at the setpoint (level error, E = 0) , then the summer output signal (which is the feedwate request just equals the steam factor and a mass balance is ensured.**

- **Should the level drop away from the setpoint, then the level factor (K_L * E) becomes significant and *forces* *mass imbalance* greater than the steam flow in an attempt to drive the level towards the setpoint.**

Assume that the LIC of Figure 4 is providing adequate level control when the system is subjected to sudden step *increase in steam demand*.

- ***Swell effect will occur* but the summer output remains relatively steady due to the LIC tuning adjustments.**

- **Now as the swell effect begins to subside, the *summer output* (steam factor increasing, level decreasing *begins to drive the feedwater valve* beyond the mass balance position.**

- **As the level drops below the level setpoint, the level factor continues to drive the valve more open so that th feed flow increases beyond that of the steam and *drum level begins to rise*.**

- **As the level increases, the *level control signal will proportionally be reduced back toward the bias value***

- **When a mass balance is achieved (*feedflow matches steam flow*), control equilibrium will be re-establishe only when the boiler level is at the drum setpoint (i.e. LIC error = 0).**

3-e Feedwater Control

- The two element controller will experience a drum level transient if there is a feedwater *supply* disturbance.
- This upset can be eliminated by providing a three element control system as shown in Figure 6.

- The output from the summer (mass balance at the drum setpoint) is now applied as the feedwater flow controller (FIC) *setpoint*.
- The FIC compares the feed flow signal to the requested setpoint and generates a corrective signal to position the feedwater CV.

- The FIC must have proportional plus reset modes so as to regulate the feedwater flow to the requested setpoint.

- The 3-e system will now *eliminate feedwater supply fluctuations* *before* they can effect boiler level.
- Steam demand changes will initiate the same response as obtained with the two element system.

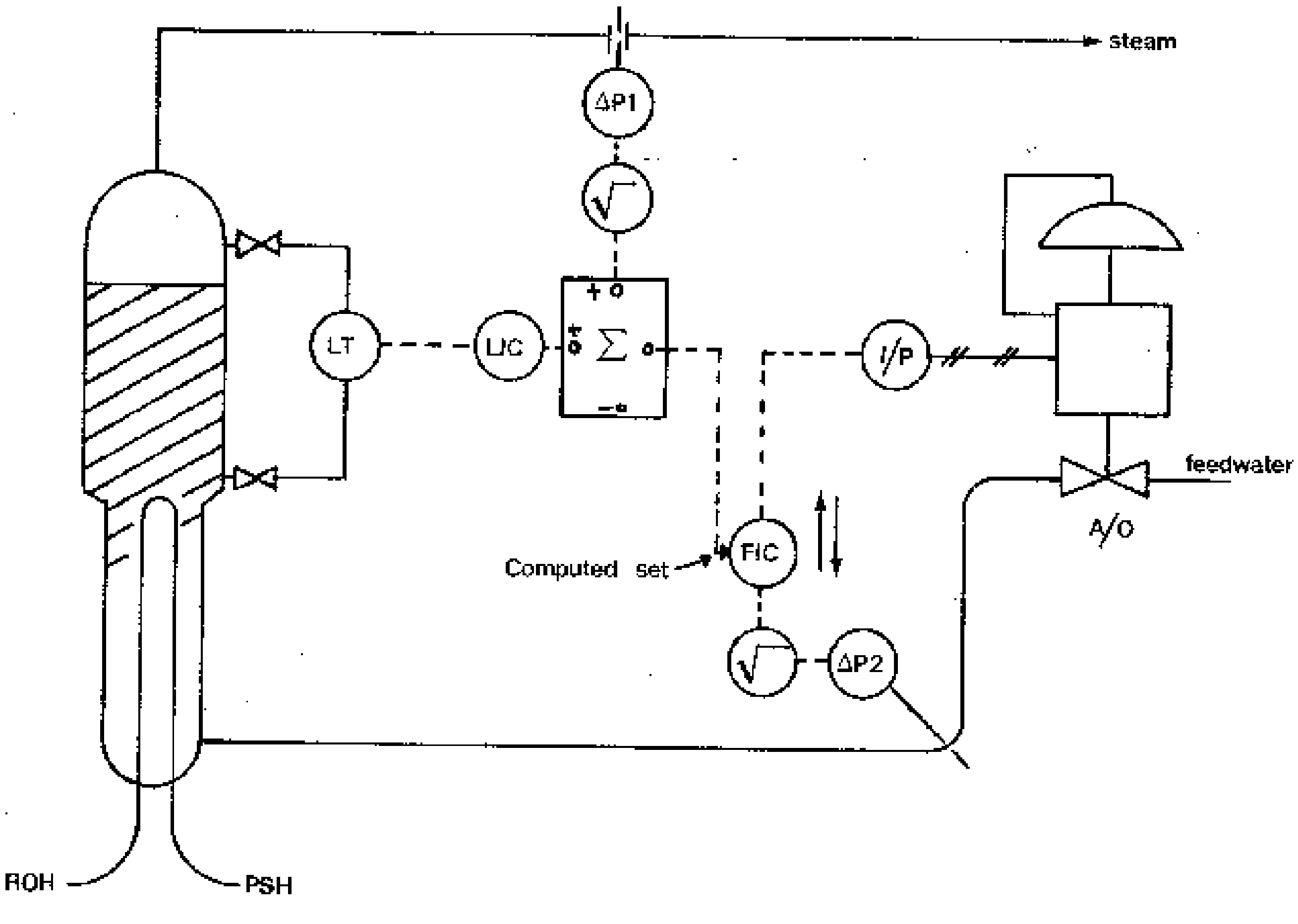


Figure 6: Three Element Feedwater Control System

3-e Control Display Information

- **The three element (3-e) feedwater instrumentation display provides indications of *steam flow*, *drum level* and *feedwater flow*.**
- **All three parameters are used to maintain overall boiler level control.**
- **The operator can determine if the steam flow and level control signals are being summed properly by examining the feedwater controller setpoint (i.e the output from the summer relay).**
- **The feedwater control setpoint should be manipulated automatically by the feedforward/cascade strategy to achieve a dynamic mass balance once the level is restored to the drum level setpoint.**

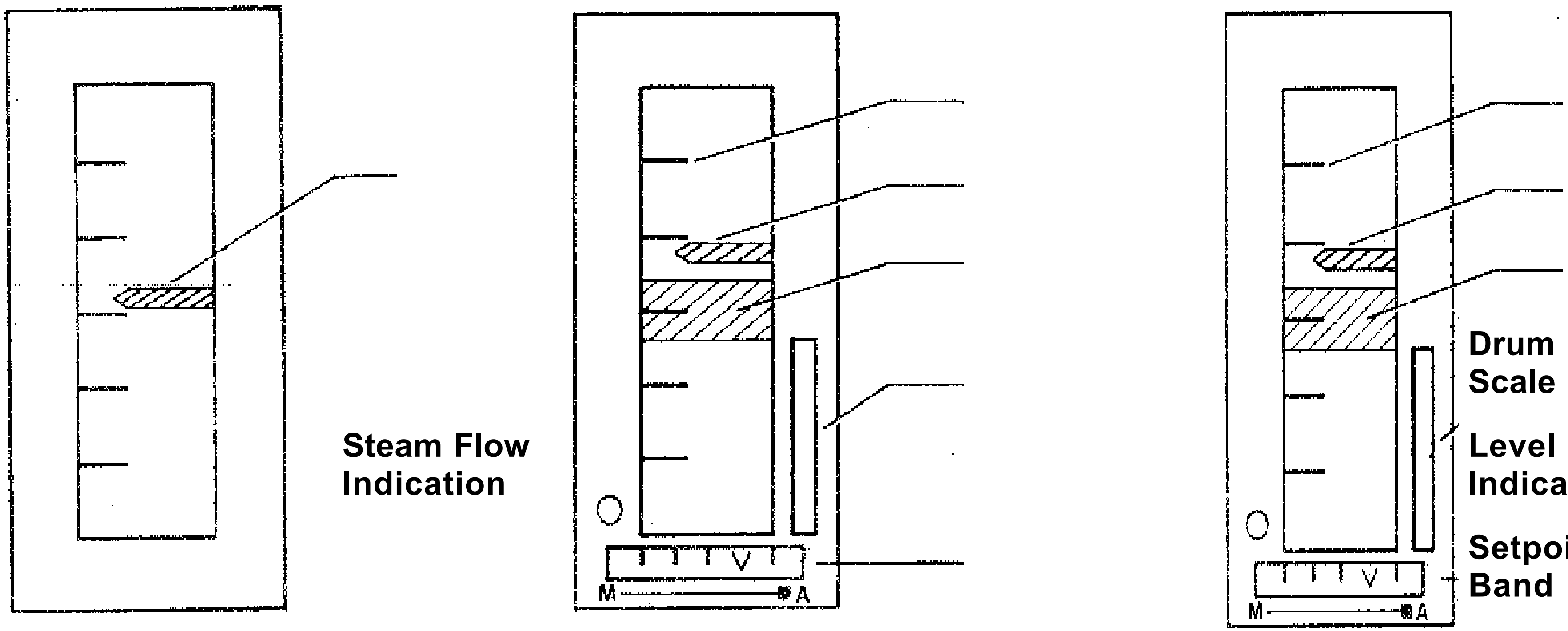


Figure 6(a): Typical Three Element (3-e) Instrumentation Display.

Programmed Boiler Drum Level

- Assume that the fixed drum level setpoint of the three element system (Figure 6) is maintained at some maximum drum level position *at low power*.
- If a large steam demand increase is now applied to this boiler, the resultant swell effect could cause a turbine trip *on very high boiler level*. Obviously, it is not very desirable to maintain a high boiler level at low power (*due to potential swell*). However, the extra inventory is desirable at a high power condition to provide additional heat sink reserve on possible loss of feedwater.
- Rather than attempt to control the drum level at only one position, better inventory control can be achieved if the drum level is controlled as a *function of the reactor power level*.
- For example, if the steam demand increases, the drum level will tend to fall away (*after any swell effect*) from the setpoint (steam > feed). If the setpoint at this time was increased, the level error would be magnified, requiring a much larger feedwater correction which will prevent a significant drop in boiler level, from the original conditions, from occurring.

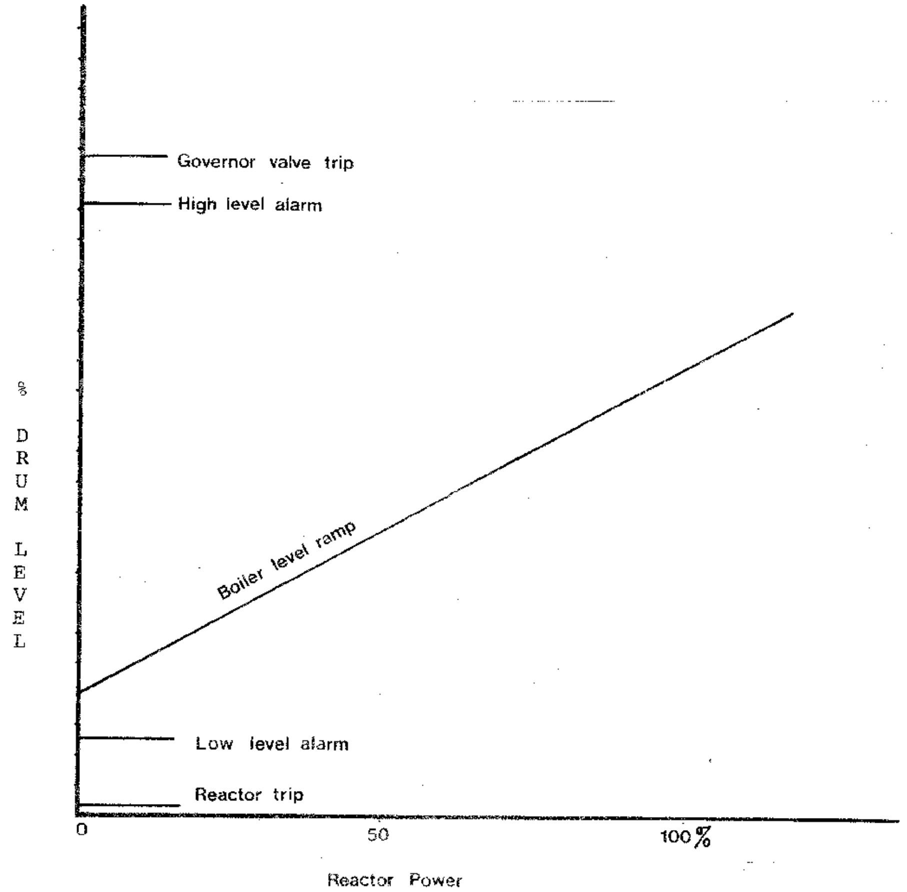
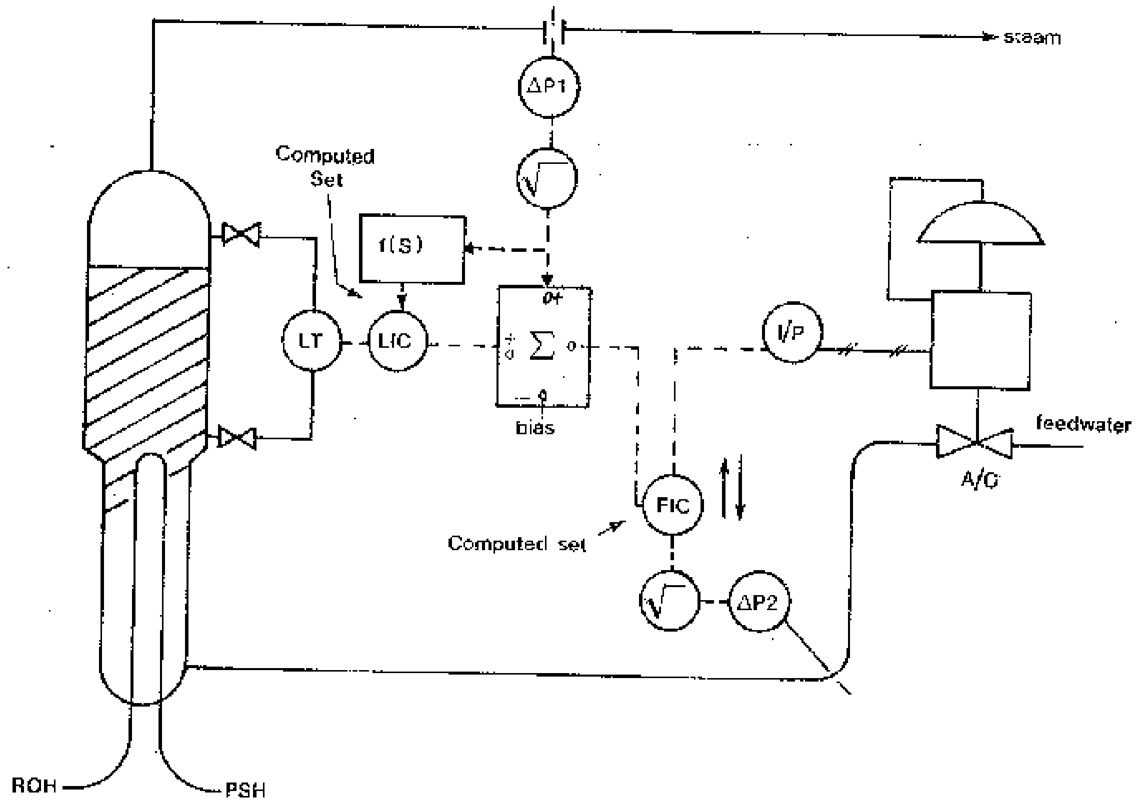


Figure 7: Typical Ramped Drum level.

As a safeguard to stay within the acceptable upper and lower limits of drum level and to facilitate drun inventory control during power maneuvering; the *drum level is ramped as a function of the reactor powe* Usually, steam power is selected for drum level setpoint calculation purposes above 15%FP.

Ramped Drum Level by Computed Setpoint

A ramped drum level can be achieved in several ways, the simplest of which would be to calculate the drun level setpoint as a function of the steam flow and then apply this setpoint to the level controller as a voltag



signal.

Figure 8: Ramped Drum Level by Computed Setpoint.

BOILER LEVEL CONTROL VALVES

- **There are actually three feedwater control valves; two large and one small for each boiler.**

- **The duplicated large 10" valves provide power range reliability while the 2" valve allows rangeability (flow control below 10% signal).**

- **The expected control scheme would be to have one 10" valve on standby while the other is regulating.**

- **The air to open (fail closed) large 10" valves will stroke for signals ranging from 10 to 100%**

- **The small air to close (fail open) 2" valve will stroke open for signals ranging from 0 - 10%.**

As the 2" valve is an air to close type, the associated current to pneumatic transducer is reverse calibrated.

- **On loss of instrument air, the 10" valves would fail closed (*to prevent carryover to the turbine*) and the 2" valve would fail open (*to ensure a minimum heat sink is provided*).**

Feedwater CV Swap

Assume that stable control was achieved with the computed measurement at the setpoint of LIC1 The initial valve status is as follows:

Control Valve	Isolating Valve
small CV216 - Open	MV169 - Open
large CV217 - Auto	MV171 - Open
large CV218 - Manual	MV173 - Closed

Assume that it was necessary to 'swap' CV-217 and CV218 for routine maintenance so that CV218 becomes the automatic valve while CV217 is to be isolated.

- The important point here is that the feedwater flow, and subsequently the drum level, must not be excessively disturbed.
- You should note the *as found position* for CV217 before starting the valve swap.
- After MV173 is open, the hand control station (L51-HC1) signal is *gradually* increased. Each time the manual valve (CV218) drives a little more open, the feed flow and hence drum level will begin to increase.
- The level controller (LIC1) will begin to reduce the automatic signal to CV217 driving it more closed.

Feedwater CV Swap…continued

- **This sequence is repeated (CV217 closing, CV218 opening) until both CV217 and CV218 are at th*e* *same* position.**
- **The CV destination selection handswitch can now be set to the CV218-auto, CV217-manua position.**
- **In order to complete the transfer, the hand controller is gradually reduced, closing CV217.**
- **As CV217 decreases the feedwater supply, the boiler level will begin to decrease.**
- **The level controller responds by increasing the automatic signal to CV218 driving it more open This sequence is repeated (CV217 closing, CV218 opening) until CV217 is completely closed.**
- **You should confirm that CV218 has reached the expected opening (previous CV217 *as foun* value).**
- **The motorized isolating valve (MV171) for CV217 can now be closed, completing the transfer an isolating CV217 from service.**

Lesson 2, MODULE 3: BOILER LEVEL CONTROL ASSIGNMENT

1. Sketch a typical three element feedwater system incorporating a summing amplifier and describe th general operation of this system when subjected to a steam demand increase.

2 . Explain why the boiler drum level is ramped as a function of the reactor or steam power and state tw methods of achieving this ramp.

3. Explain the general three element control system (Question 1) response to the following device failed lov conditions:

- **steam flow transmitter**
- **feedflow transmitter**
- **drum level transmitter**
- **summing amplifier**

4 . Explain how incorrect drum level control could cause a HTS <u>pressure</u> disturbance.

5 . State the reasons for having two large and one small CV in a boiler level control scheme.

6. Sketch and describe how the large feedwater CV's in a boiler scheme could be swapped on line in a bumpless fashion.

7 . Sketch a representative graph of drum level vs. reactor power and label the following relative points (stat your rationale for the relative settings chosen):

- **reactor setback, very low level alarm, reactor trip, low level alarm**
- **very high level alarm, high level alarm, turbine trip**