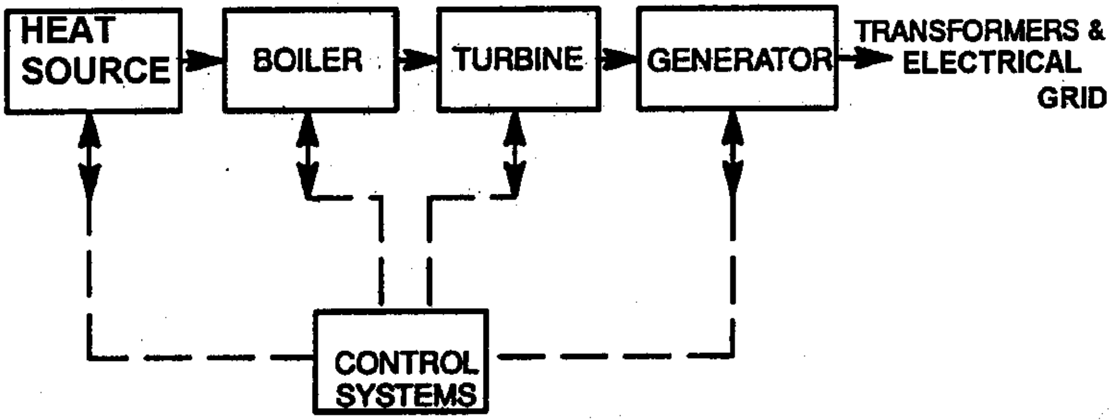
CHAPTER 3: STEAM GENERATOR CONTROL

MODULE 1: LEVEL CONTROL

Introduction

In a thermal electric power plant the steam generators (often referred to as "boilers") are a critical energy link between the primary heat source (fossil or nuclear) and the turbine. In nuclear generating stations the boiler level control system must function properly in order to provide a continuous heat sink to the reactor.



Control Considerations

- The demineralized water removed from the boiler 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.

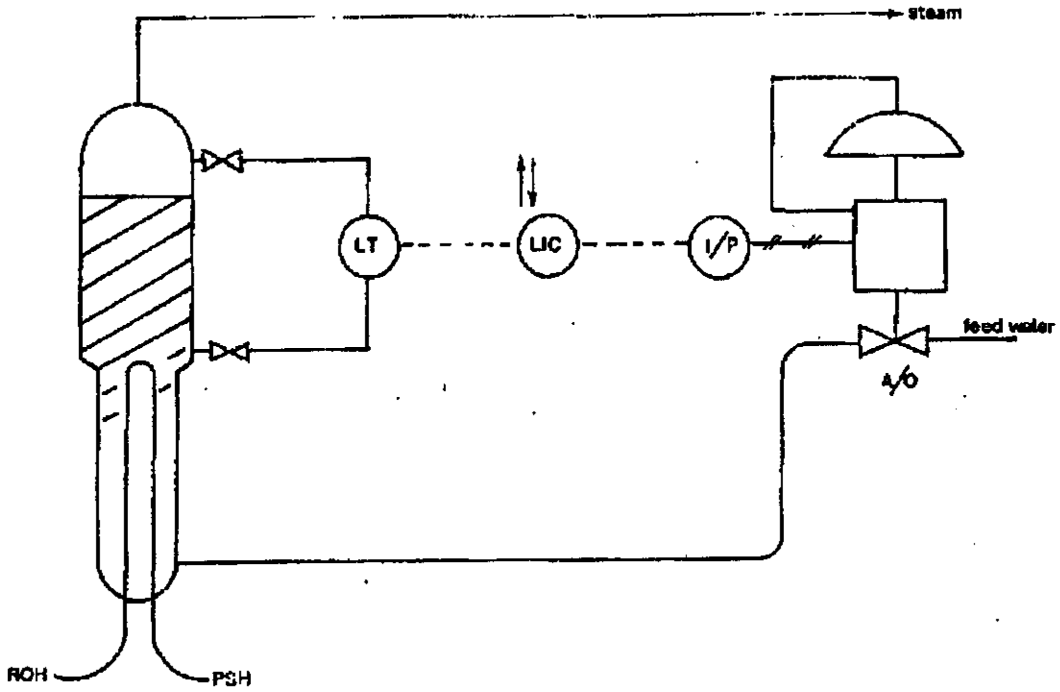


Figure 1: A Single Element Feedwater Control System.

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

Instrumentation Display

- **The 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 the setpoint.**
- **The feedwater valve position can be estimated from the controller output signal, assuming that the feedwater valve pneumatic accessories are functional (e.g., booster, positioner, I/P, air supply).**
- **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 (the valve hasn't moved!).**
- **A mismatch now exists between inflow and outflow and the drum level begins to drop.**
- **The LIC responds to this error (with proportional and reset) in an attempt to restore the process to the set point.**

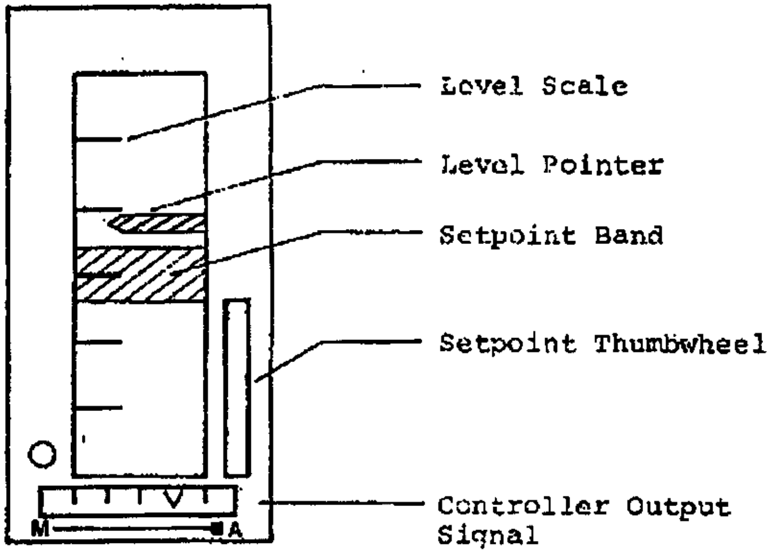


Figure 1(a): Single Element Controller.

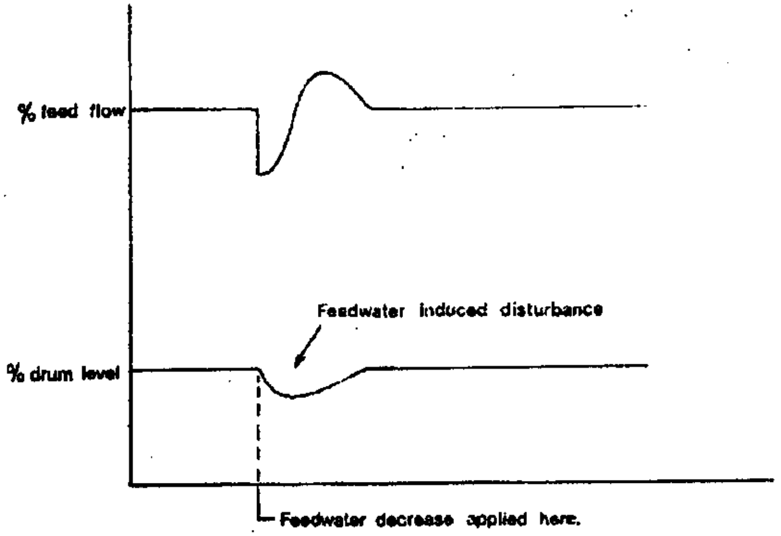


Figure 2: Single Element Response to a Sudden Feedwater Supply Decrease

Adequate control of such a level system should be provided by a properly tuned proportional plus reset controller. However, a boiler level system provides some unexpected responses when large, sudden steam changes are applied.

Boiler drum level can change as a function of boiler pressure without an associated change in drum water 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 the level upward. As the boiler pressure recovers, the water inventory is driven back down to its expected level. This temporary rise in drum level is called the swell effect (the drum inventory seems to swell). The swell effect will appear as a positive spike on a level trend record.

Should the steam demand suddenly be decreased, the drum level will drop as the pressure increase reduces boiling. This temporary drop in drum level is called the shrink effect (the drum inventory seems to shrink). The shrink effect will appear as a negative 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 to a sudden step increase in steam demand. Swell effect will occur and the level controller will respond to the increase of drum level by driving the feedwater CV more closed. This single element control system has responded to an increase in steam demand with a decrease in feedwater flow - the exact opposite of the 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 level controller must reverse its original control decision and begin to drive the feedwater valve more open (note that the feedwater valve has cycled). Some time will be required to make up the lost inventory due to the incorrect controller response, and to allow the drum level to stabilize back at the setpoint.

Response of single element controller to a sudden increase in steam demand.

- 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 must be supplied to the control system to decide if the level is rising due to a true decrease in steaming rate or if in fact, a swell effect is being sensed.

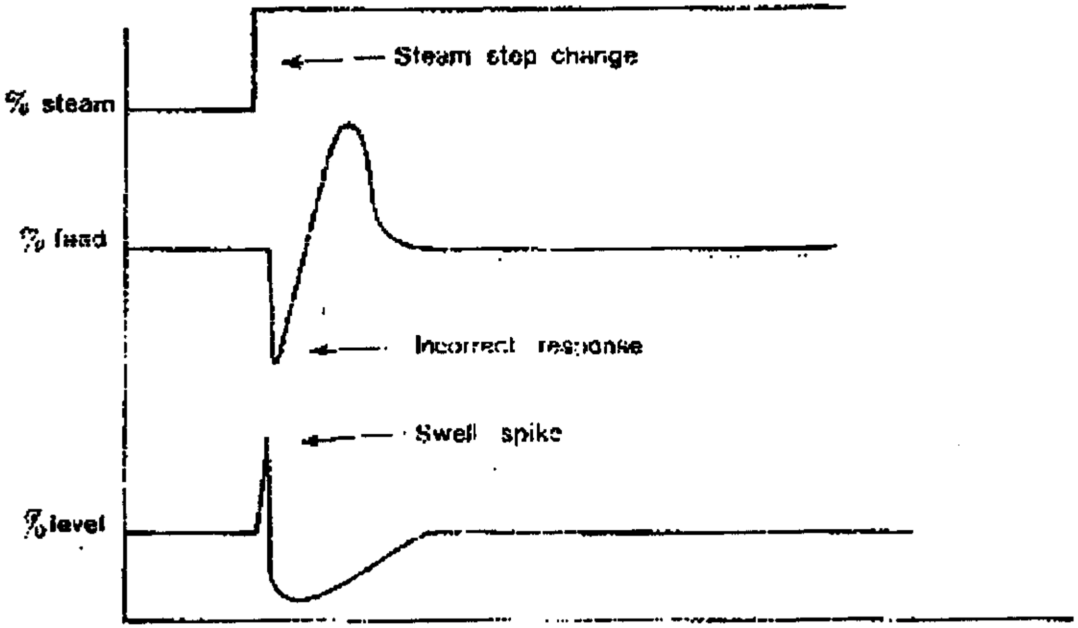


Figure 3: Single Element Trend Responses to a Positive Step Steam Change.

Two-element feedwater control

If the true steam flow was measured, then a predictive control decision could be made regarding the drum level. Elbow taps could be installed on the steam line to provide a differential measurement input to an electronic D/P cell. This differential signal is routed to a square root extractor to provide a linear - flow signal. A two-element feedwater control scheme (the two elements are now drum level and steam flow can be designed as shown in Figure 4.

Note that the LIC is reverse acting so that the rise in drum level (swell) will cause a decrease in control signal.

- **The summing amplifier (Figure 4) allows the level control and steam flow signals to be combined.**
- **Assuming that stability is not a problem, the LIC gain could be adjusted so that a given steam flow change will be just countered by the LIC response - while the swell or shrink exists. In this fashion, the summer output signal (to the feedwater CV) will remain relatively constant until the transient effect begins to subside. The massive incorrect valve stroke of the single element system will be eliminated.**

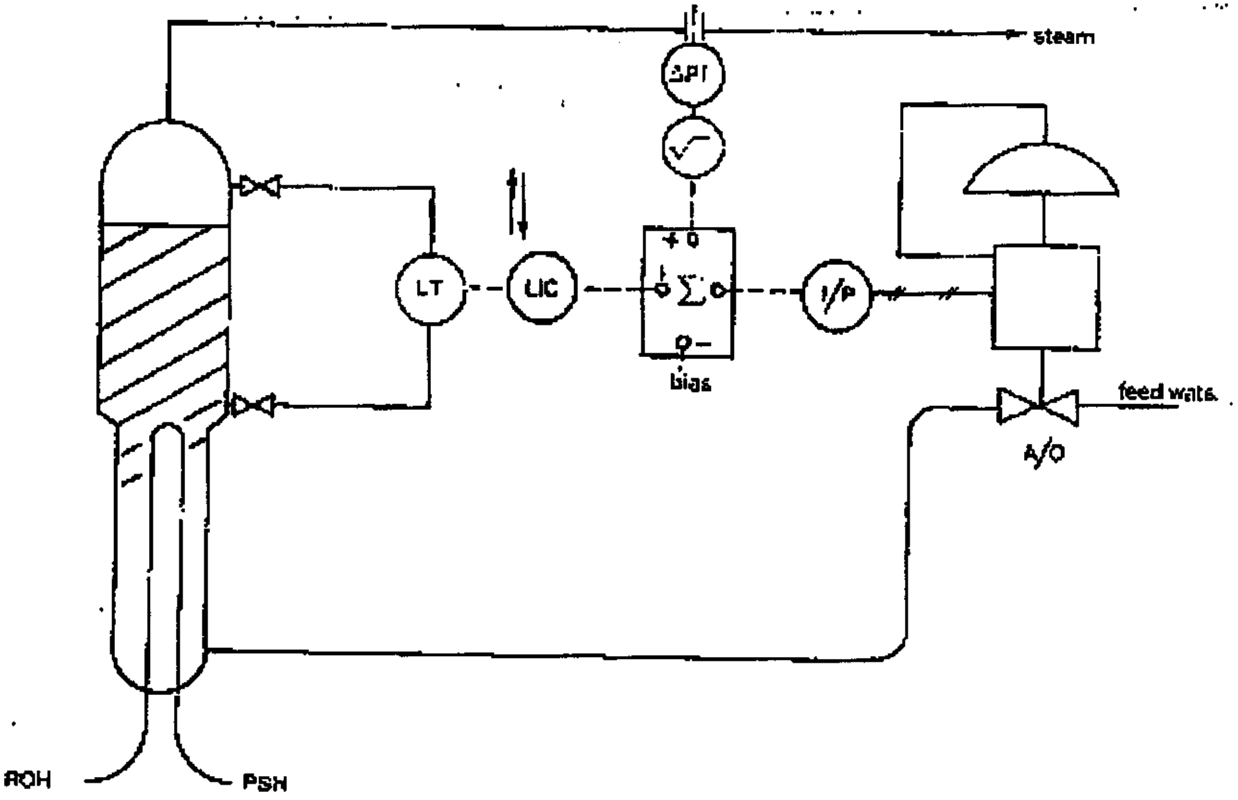


Figure 4: Two-Element Feedwater Control System

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 the steam flow indicator. Two parameters (steam flow, drum level) are now indicated and used for control sensing.

Recall that the total 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% steamflow; 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%) is supplied by the reheater drains.

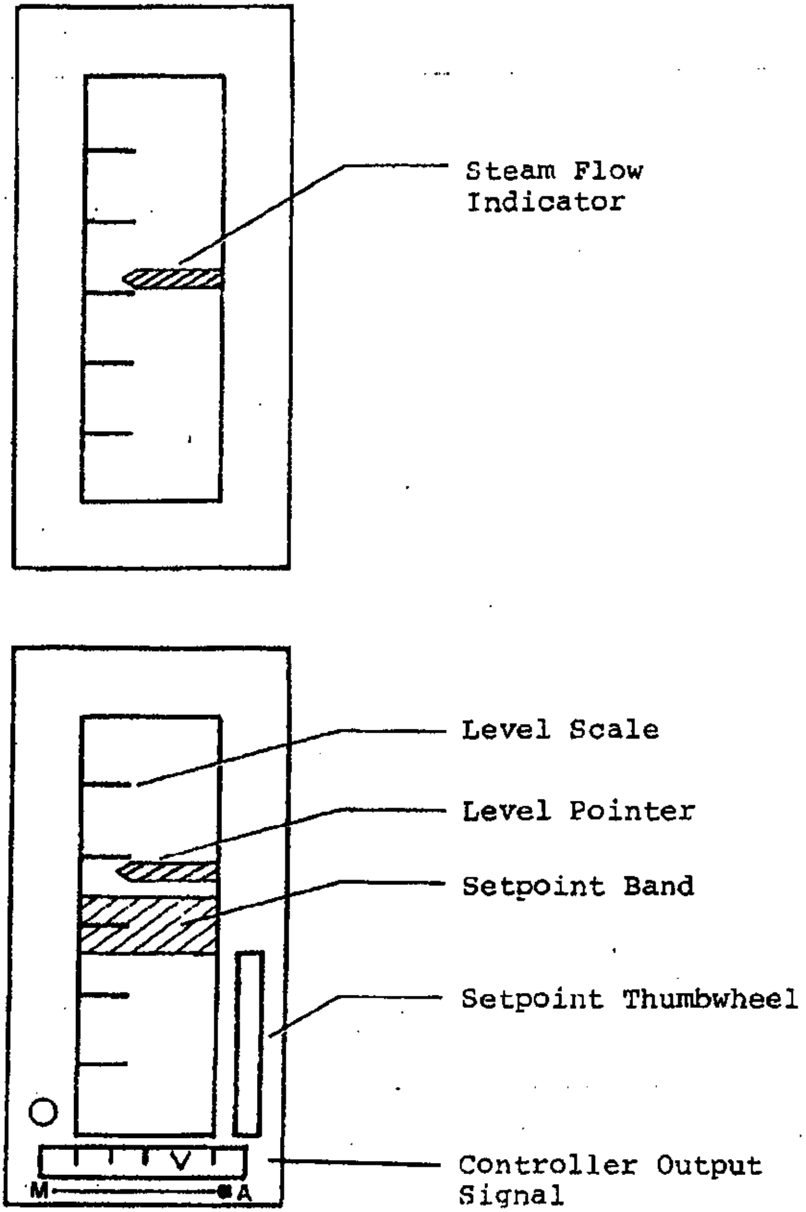


Figure 4(a): Typical Two Element Instrumentation Display.

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:

$CS = K * E + B$

CS = Control Signal

K = Controller Gain

E = Error (setpoint - measurement)

B = Bias (50% unless otherwise stated).

If the Error is zero, the control signal is just the Bias. This signal component is 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.

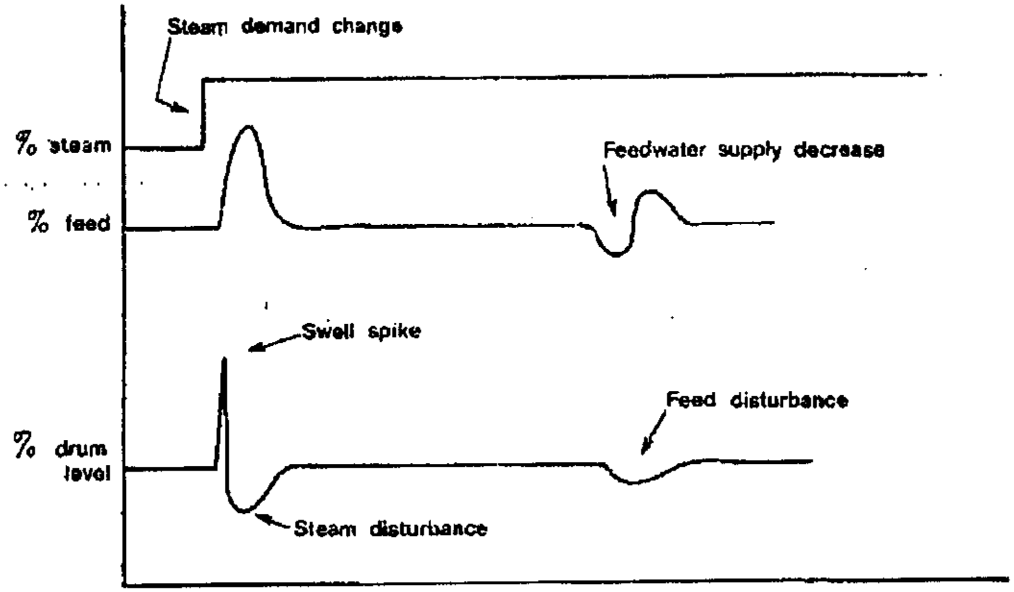


Figure 5: Two Element Trend Responses to a Positive Step Steam Change

The summer output can be described as:

Summer Signal = (control signal) + (K_f * Steam) - Bias
Summer Signal = (K * E + Bias) + (K_f * Steam) - Bias
Summer Signal = (K * E) + (K_f * Steam)
Summer Signal = (level factor) + (steam factor).

If the level is at the setpoint (E = 0) , then the summer output signal equals the steam factor and a mass balance is ensured. Should the level drop away from the setpoint, then the level factor (K * E) becomes significant and forces a mass imbalance in an attempt to drive the level back towards the setpoint.

Assume that the LIC of Figure 4 is providing adequate level control when the system is subjected to a sudden step increase in steam demand. Swell effect will occur but the summer output remains relatively steady. Now as the swell begins to subside, the summer output (steam factor) drives the feedwater valve to the mass balance position. As the level drops below the setpoint, the level factor drives the valve more open so that until mass balance is achieved at the setpoint.

Three Element Feedwater Control

- **The two element controller experiences a 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 signal from the summer is now applied as the setpoint for a feedwater flow controller (FIC).**
- **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 to guarantee that the feedwater will be regulated to the requested setpoint.**
- **The three element system will now eliminate feedwater fluctuations before they can effect the boiler level. Steam demand changes will initiate the same response as obtained with the two element system.**

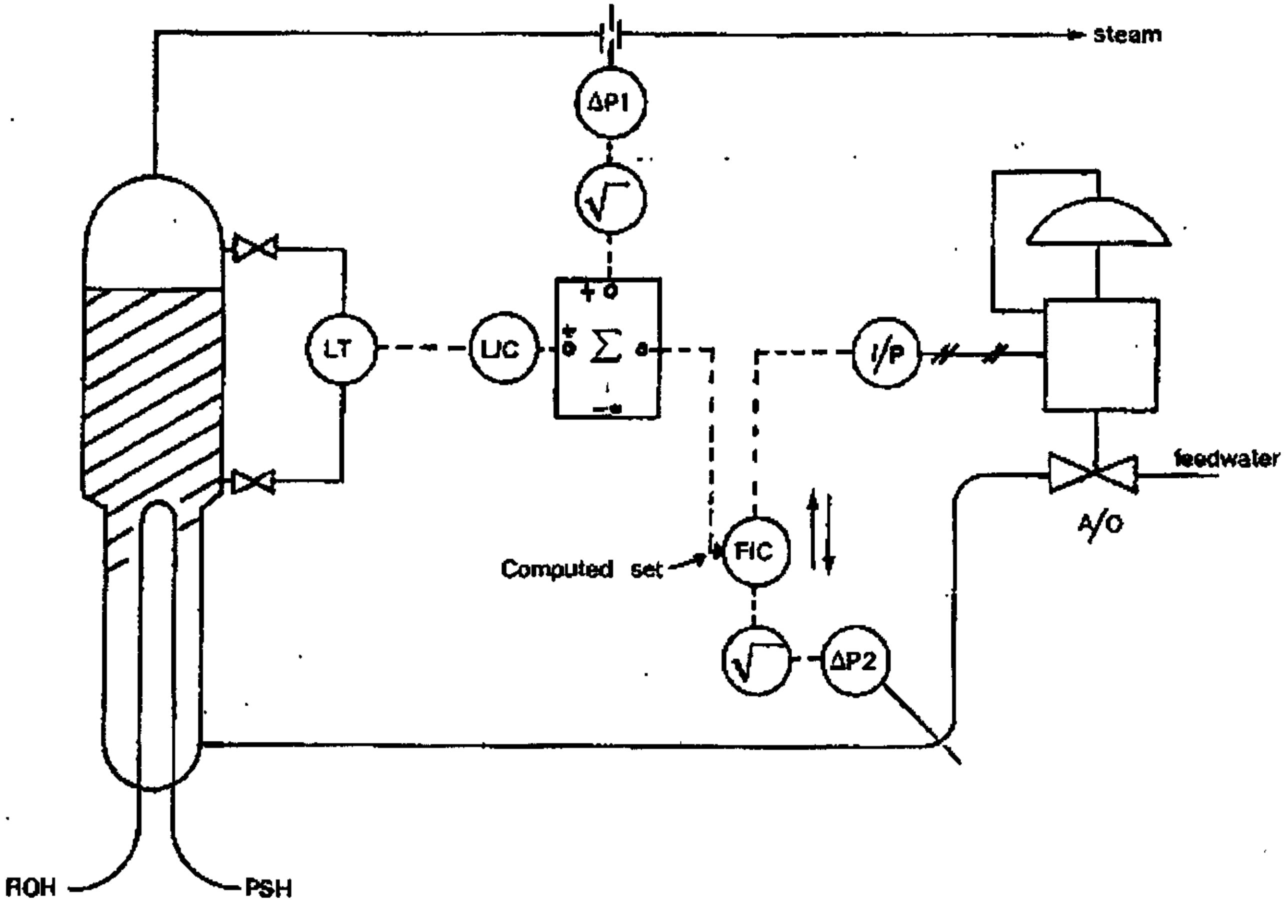


Figure 6: Three Element Feedwater Control System

The three element feedwater instrumentation display provides indication 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 combining properly by examining the feedwater controller setpoint. It should be manipulated to achieve a mass balance once the level comes to the drum level setpoint.

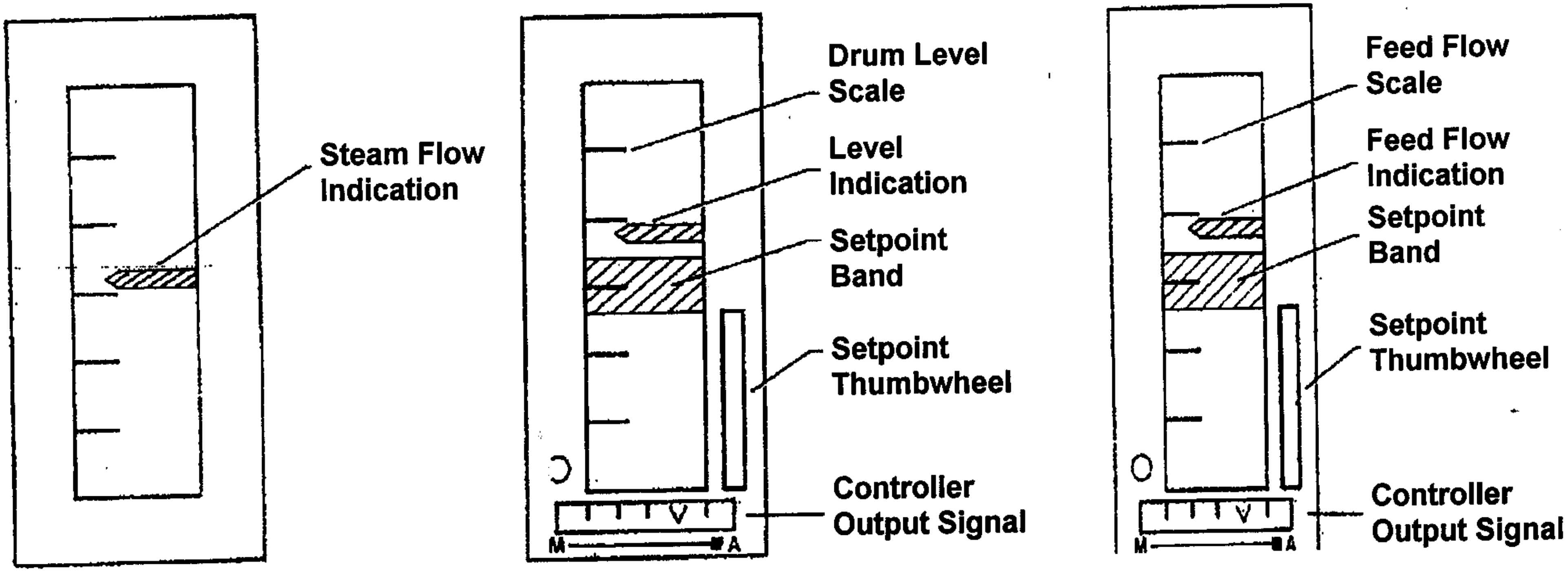


Figure 6(a): Typical Three Element Instrumentation Display.

Programmed Drum Level

- **Assume that the fixed drum level setpoint of the three element system (Figure 6) is maintained at some maximum drum 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 (no potential swell).**
- **Rather than attempt to control the drum level at one position better inventory control can be achieved if the drum level is required to change as a function of the power level.**
- **For example, if the steam demand increases, the drum level will tend to fall away (after the swell effect) from the setpoint (steam > feed). If the setpoint at this time was increased, the level error would have been magnified, requiring a much larger feedwater correction. This excessive feedwater response will minimize the drop in boiler.**

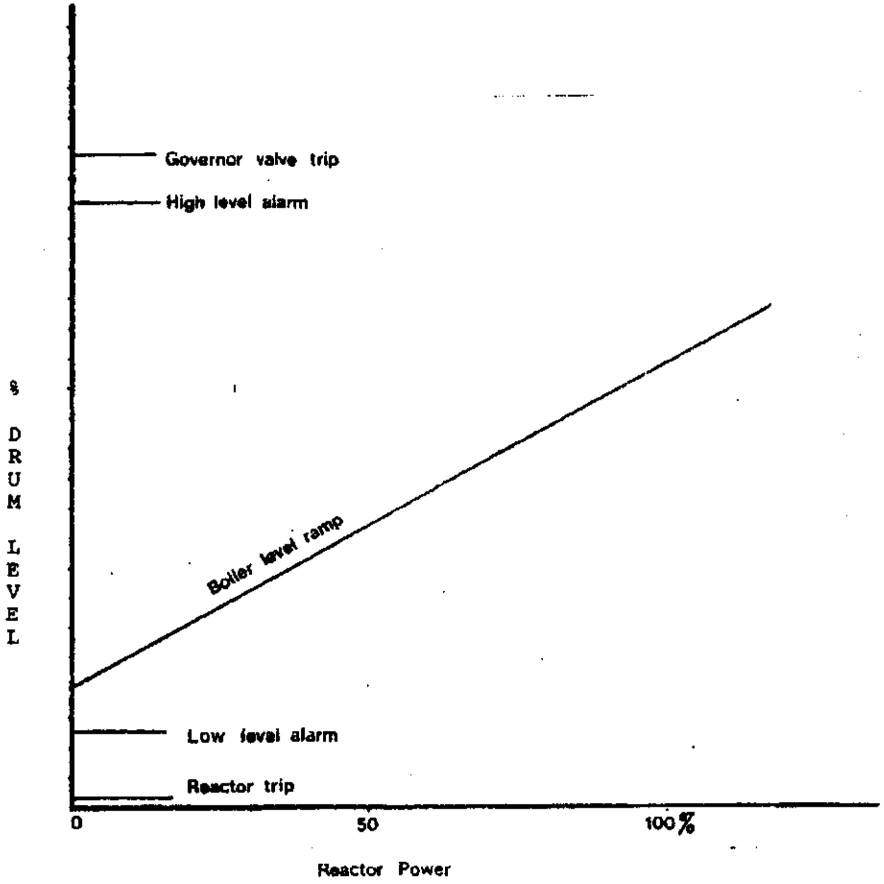


Figure 7: Typical Ramped Drum level.

As a safeguard to stay within the acceptable upper and lower limits of drum level, to minimize specific density effects on level indications, and to maintain drum inventory control during power maneuvering; the drum level is ramped as a function of the operating power.

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 setpoint as a function of the steam flow and then apply this setpoint to the level controller as a voltage signal.

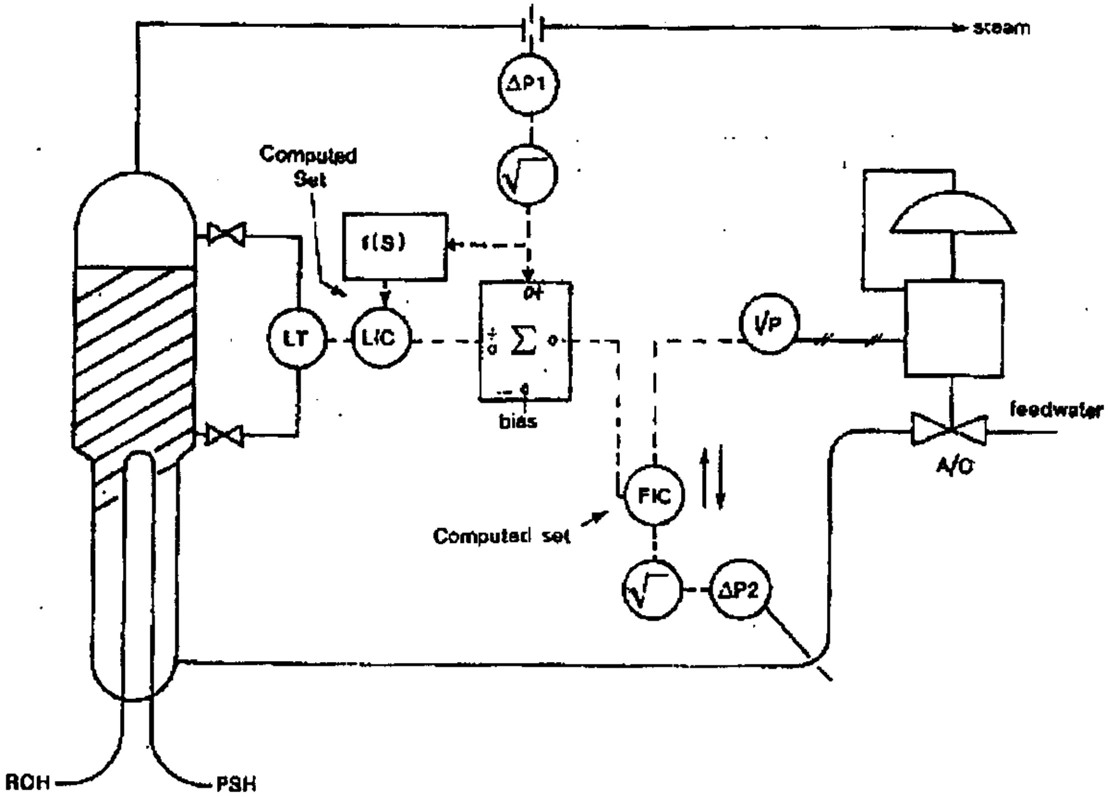


Figure 8: Ramped Drum Level by Computed Setpoint.

Ramped Drum Level by Computed Measurement

A second very effective method of ramping the boiler level involves a summing amplifier utilizing various gains as shown in Figure 9.

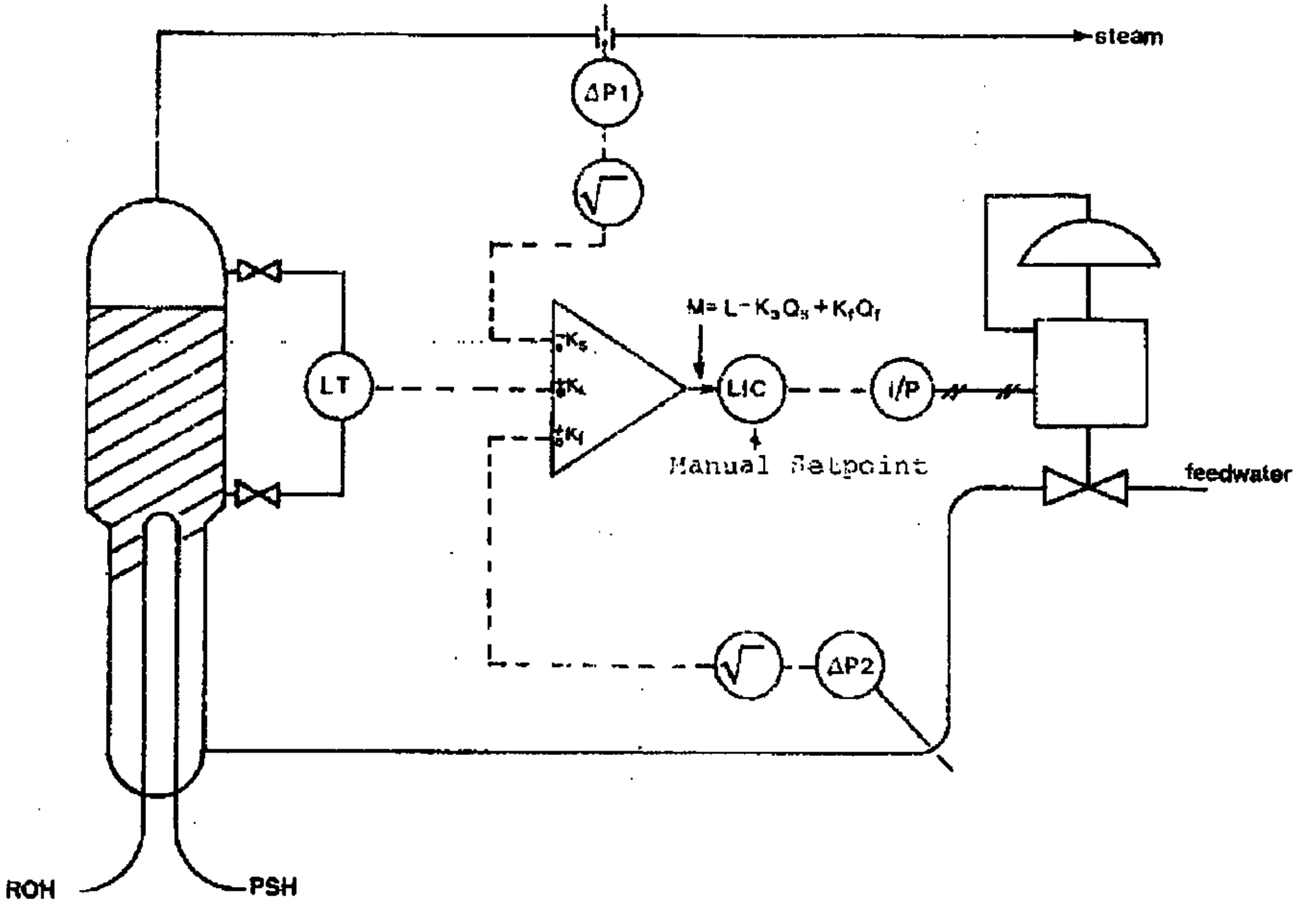


Figure 9: Ramped Drum Level by Computed Measurement.

The most important point to note here is that the controller (LIC, Figure 9) measurement is a computed value - It is not just the level !

The Error for a given controller can be stated as:

$E = S - M$
E = Error
S = Set
M = Measurement

Assume that we wish to describe this level system error while including the feed forward components of steam and feedflow.

Error = Set - Level + (Drop due to steam) - (Rise due to Feed)
$E = S - L + K_sQ_s - K_fQ_f$
$E = S - L + K_sQ_s + K_fQ_f)$

It can be seen from inspecting this equation that the system in Figure 9 will provide three element control. The various gains of the summer need only to be adjusted to make the system respond in the desired fashion.

Note again that level is just one component of the measurement - feed and steam flows are also measurement factors.

This computed measurement is applied to the LIC and compared to a fixed setpoint. The LIC is a reverse acting proportional plus reset controller which will continue to stroke the feedwater CV until the measurement equals the setpoint.

Say for arguments sake that the steam gain was set to one ($K_s = 1$) and the feed gain was set to one half ($K_f = 0.5$). Any change in steam flow will require twice the change in feed flow before the measurement signal is balanced. This excessive feed correction will now force the drum level either up or down. As the subsequent level change is detected in the measurement, the feed flow will be throttled to a true mass balance value while the level changes.

Assume that the drum level setpoint was placed at 16% (0.16) and that the norn flows range from 0 to 0.8 (0 - 100%).

Measurement at 0% FP

$$M = L - K_S Q_S + K_f Q_f$$

$$M = 0.16 - 1(0) + 0.5(0) = 0.16$$

The drum level could be brought to the setpoint (16%) under manual control. The equilibrium with zero inflow and zero outflow.

Measurement at 100% FP

$$M = L - 1(0.8) + 0.5(0.8)$$

$$M = L - 0.4$$

The setpoint was fixed by the operator at 16% so that if the error is to be zero, th 16% (0.16).

$$M = L - 0.4$$

$$0.16 = L - 0.4$$

$$L = 0.56$$

in this case, the level would have to rise from 16% to 56% as the steam flow rang

- **By simply changing the <u>feedwater gain</u>, the <u>slope</u> of the drum level ramp can b**
- **The higher the feedwater gain, the flatter the ramp will become.**
- **This gain will cause the level to ramp from 16 to 60%.**

A Typical Boiler Level Control Scheme

The system elementary (Figure 10) shows the interconnections of the control loop instrumentation for the boiler level control of one quadrant. Each boiler has an electronic level transmitter with an approximate span of 236 cm. In actual fact, there are two transmitters per boiler, one for control level sensing and the other for protection. The second transmitter signal actuates the logic for the governor valve trip and the reactor setback circuits. The three level (control) signals are fed into a high select relay (64323-L51-LM1). The highest drum level is selected for control purposes to prevent one level from slowly rising to a very high level condition. Notice that if one transmitter should fail (likely low!), that only a slight bump would introduce as the high select amplifier selects another signal.

The highest boiler level signal is then directed to a summing amplifier (64323 L51-LM2) which will provide the ramped level function. The summer adds the linearized feedwater flow (with a gain of +0.45) and subtracts the linearized steam flow (with a gain of 1) . The output of the summer is the measurement (M) for the level controller. Recall that the summer output is described as:

$M = L - Qs + 0.45\ Q_f$
M = LIC measurement signal
L = Highest drum level signal
Q_s = Normalized steam flow (0 - 0.8)
Q_f = Normalized feed flow (0 - 0.8)

The level controller (L51-LIC1) is reverse acting with proportional plus integral control modes. If the computed measurement signal is the setpoint (0.4 meters), the control signal will. decrease, and will continue to decrease until the measurement is restored to the setpoint.

The signal from the level controller drives a common valve which will alter the feedwater flow to all three boilers.

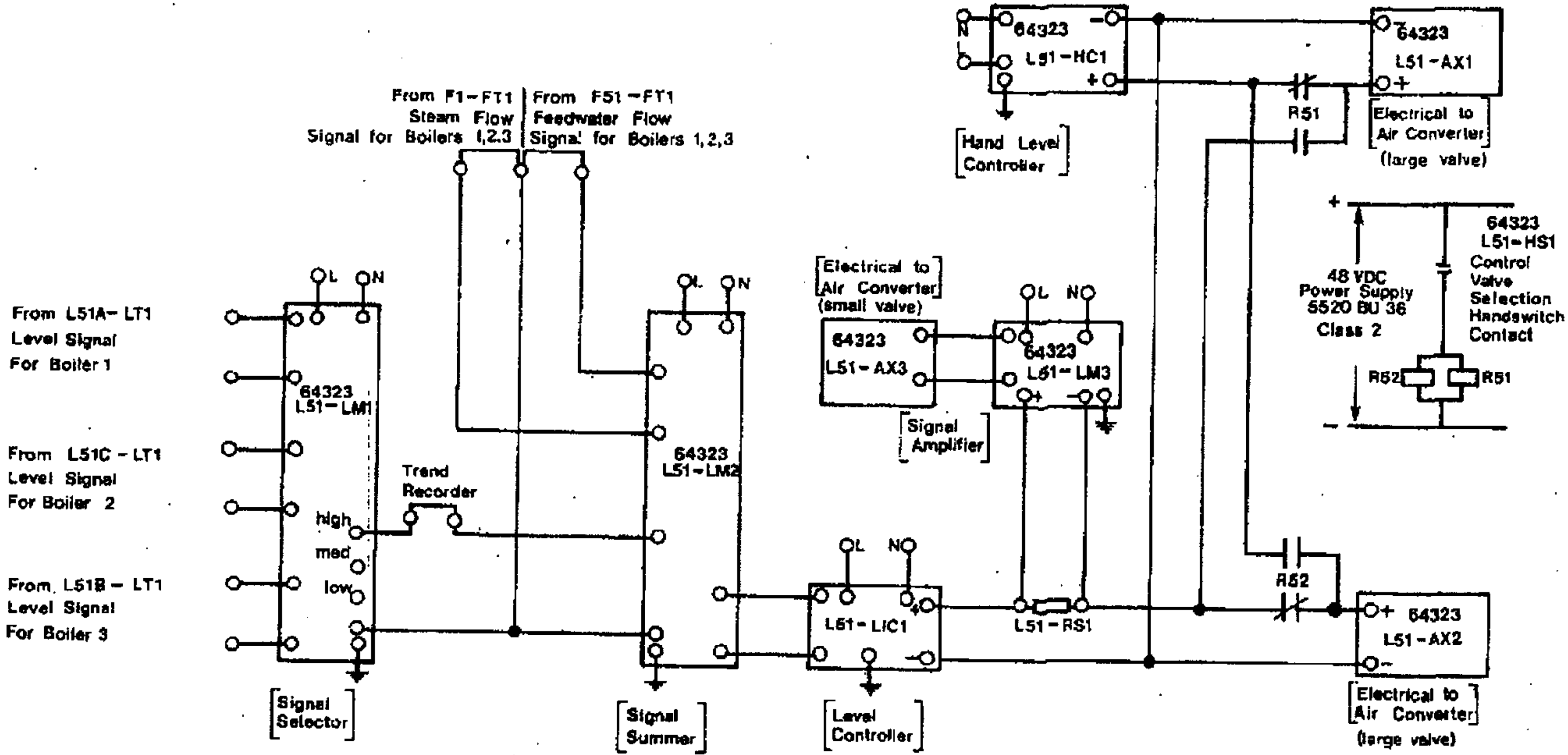


Figure 10: Simplified Boiler level Control System Elementary.

The control valve and isolating valve configuration for a boiler quadrant is illustrated in Figure 11.

The Rotork CV isolating valves (MC169, 171, 173) can be driven completely open or closed as necessary and this status would be indicated by the panel lamps (amber = closed, white = open) . The Hopkinson Boiler isolating valves (MV196, 197, 198) can also be used to "trim" the common feedwater flow to the boilers; (e.g., give the best heat sink the maximum feedwater, and then trim the other two boilers as necessary). The trim valves have status lamps and a position meter in the control room to assist the trimming operation.

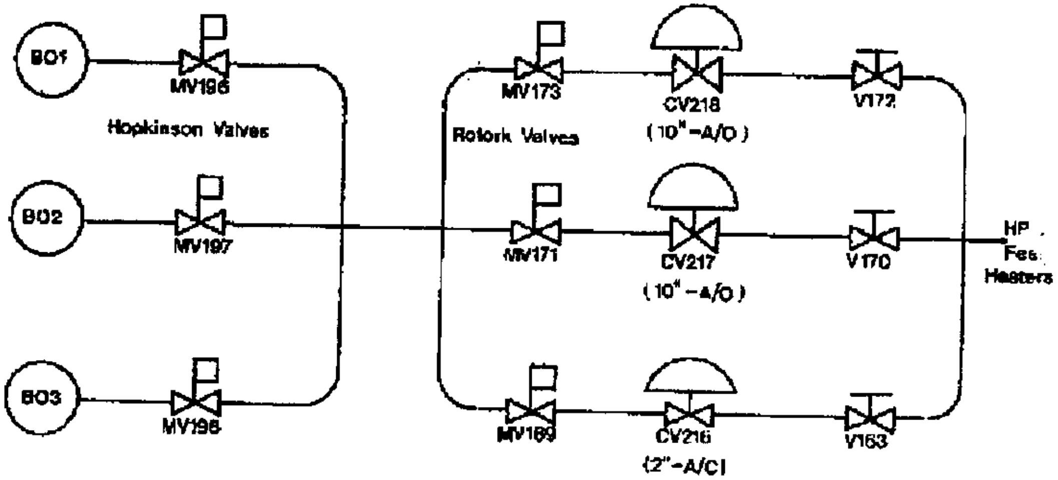


Figure 11: Feedwater MV and CV Configuration to a Bank of Three Boilers.

There are actually three feedwater control valves; two large and one small for each quadrant. The duplicated 10" valves provide reliability while the 2" valve allows rangeability (flow control below 10% signal). The expected control scheme would be to have one 10" valve isolated while the other is regulating, and the 2" valve is wide open. The air to open 10" valves will stroke for signals ranging from 10 to 100%, while the 2" valve will stroke open from 0 - 10%. As the 2" valve is an air to close type, the associated current to pneumatic transducer (64323-L51-AX3) is reverse calibrated. On loss of instrument air, the 10" valves would fail closed and the 2" valve would fail open.

Refer to Figure 10. Notice that the output of the LIC1 is wired to the signal amplifier (4 - 5.6 mA input/4-20 mA output) for the 2" valve and then to either AX2 or AX1 depending on the status of the CV selection handswitch (L51-HS1I). The hand controller (L51-HC1) is then connected to AX1 or AX2 respectively.

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
CV216 - Open	MV169 - Open
CV217 - Auto	MV171 - Open
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 bumped.

After MV173 is open, the hand control station (L51-HC1) signal is gradually increased. Each time the manual valve (CV218) drives more open, the drum level and feed flow will begin to increase. The level controller (LIC1) will begin to reduce the automatic signal to CV217 driving it more closed. This sequence is repeated (CV217 closing, CV218 opening) until both CV217 and CV218 are at the same position.

The CV destination selection handswitch can now be set to the CV218-auto, CV217-manual position. In order to complete the transfer, the hand control system 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 completed closed. The motorized isolating valve (MV171) can now be closed, completing the transfer. The following valve status would now exist:

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

Steam flow transmitter failure

Assume that the system was stable and operating at 100% FP when the steam flow transmitter failed low. The computed measurement ($M = L - Q_s + 0.45Q_f$) will rise dramatically and the level controller will respond by driving the feedwater valve more closed. As the actual steaming rate was unchanged and the feedwater has been reduced, the drum level will drop rapidly.

The corresponding loss of heat sink will cause heat transport system to swell. The feed valves should stroke closed while the bleed valves open in an attempt to,- stabilize the pressure. The reactor will likely be tripped on very low boiler level. Assume that the operator intervenes before the trip occurs. The operator could now inspect the panel and see that the Level Instruments (Figure 12) are indicating low feed and steam flows and that the level controller output signal is very low. All other quadrants are showing normal steam and feed flows. The level controller could be switched to manual in an attempt to regain the boiler level and provide an approximate mass balance between the steam flow of other quadrants and the feed flow of this quadrant. Reasonable manual control of the feedwater could be maintained by observing the drum level instruments.

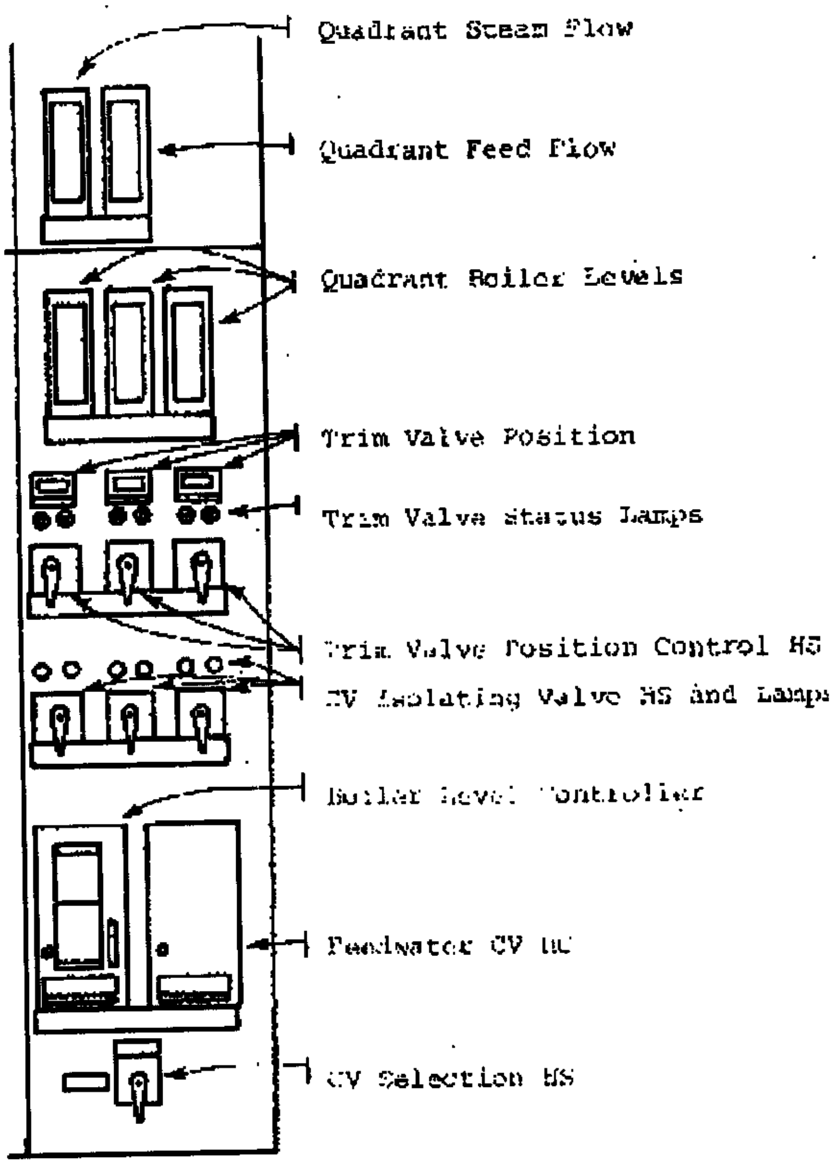


Figure 12: Typical Boiler Quadrant Instrumentation.

Feedwater flow transmitter failure

Upon loss of feedwater flow signal, the computed measurement signal will decrease and the level controller will drive the feedwater valve more open in an attempt to restore the measurement to the setpoint. The drum level will begin to rise and the heat transport will shrink due to the increased heat sink of that quadrant. The feed valves should drive open and bleed valves drive close in an attempt to stabilize the pressure.

If the operator could intervene before a governor valve trip occurs, he would see high steam flow and low feed flow (i.e. a mismatch) indicted on the Level Meters (Figure 12). The level controller signal to the valves is very high so that either the valve or the feed flow transmitter must. be disabled. As the level is rising, it should be the transmitter.

By switching the level controller to manual, the feed valve could be closed and the boiler level brought back down. An approximate mass balance could be achieved by matching the feed flow (valve signal) in this quadrant to the feedflow rates of the other quadrants in an attempt to match the steaming rate of this quadrant.

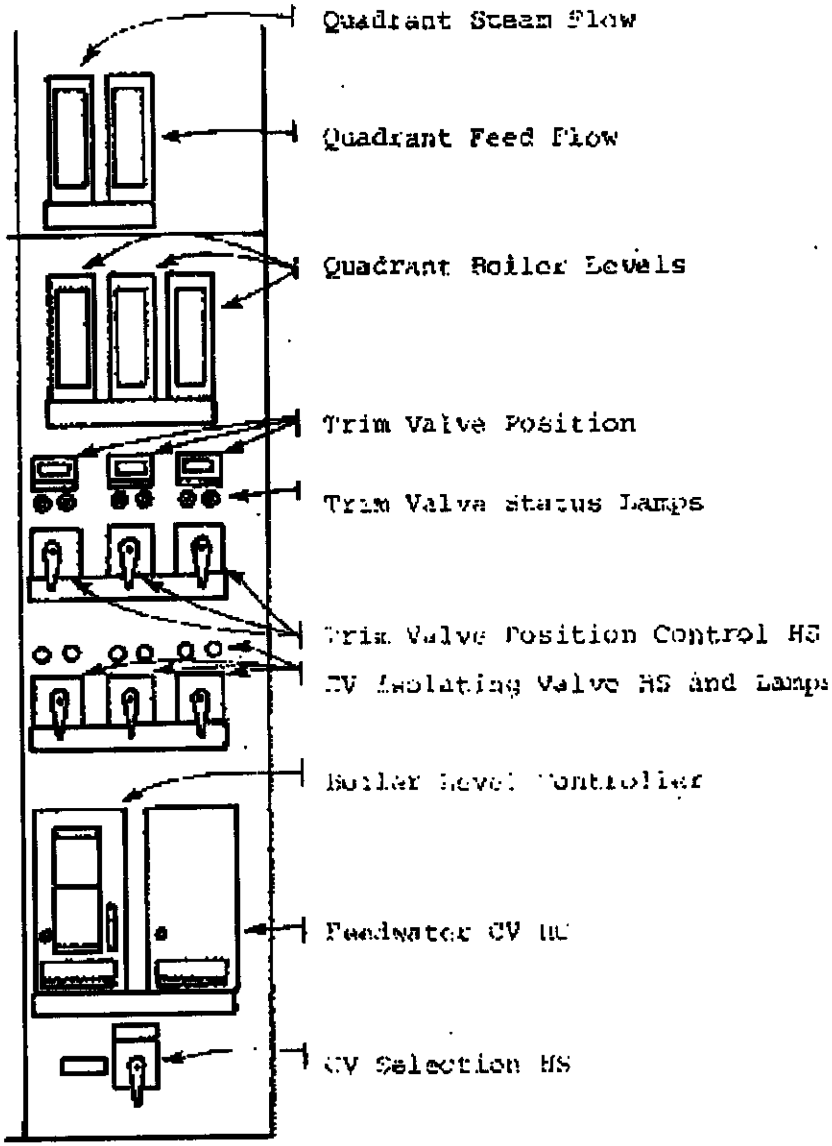


Figure 12: Typical Boiler Quadrant Instrumentation.

ASSIGNMENT

1. Sketch a typical three element feedwater system incorporating a summing amplifier and state the purpose of such a system.
2. Explain why the drum level is ramped as a function of the power and state two methods of achieving this ramp.
3. Explain the general three element control system (Question 1) response to the following device failed low conditions:
    - steam flow transmitter
    - feedflow transmitter
    - drum level transmitter
    - summing amplifier
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 quadrant boiler level control scheme.
6. Describe how the large feedwater CV's in a quadrant boiler scheme could be swapped on line in a bumpless fashion.
7. Briefly describe the practice of "trimming" individual boilers in a quadrant. What should happen to the level in the other two boilers if the trim value of the highest (the controlling) boiler is closed in.
8. Sketch a representative graph of drum level vs. reactor power and label the following relative points:
    - reactor trip
    - low level alarm
    - high level alarm
    - speeder gear trip