A BOILER FEED REGULATOR

WITH A RISING LEVEL/POWER CHARACTERISTIC

BY

LIEUTENANT-COMMANDER M. F. GRIFFEY, R.N.,
A.M.I.MECH.E., A.M.I.MAR.E.

The immediate answer to the question, 'What is the function of a boiler feed regulator?', would probably be a slightly terse 'To keep the water level in the glass'. The terseness of the answer of an experienced boiler-room watchkeeper would probably be dependent on the number of times he had crossed his fingers and counted three when the level had disappeared out of the glass.

The reasons for maintaining the level in the gauge glass are well known—to avoid priming and to avoid the burn out of tubes through exposing their ends and causing a breakdown in circulation.

Although, of course, these are the prime requirements of a feed regulator, a large number of variables must be considered when choosing one. These include the effects of:

(*a*) Swell and shrinkage

(*b*) Rapid feed flow changes on closed exhaust pressure and drum pressure

(*c*) Increased steam/water ratio with increase in power

(*d*) Instability.

DESIGN CONSIDERATIONS

Swell and Shrinkage

Swell is the name given to the rise in drum level during a rapid power increase, due to the production of steam bubbles in the boiler tubes. The reason for their generation is twofold. The rapid increase in steam off-take causes a drop in drum pressure and therefore in saturation temperature. As the temperature of the boiler water is now above this new saturation temperature there is a rapid increase in the generation of steam bubbles (similar to 'flashing off'). In addition, due to the increase in fuel input necessary to restore the pressure (more fuel in fact than will be subsequently necessary to maintain the pressure) more bubbles are rapidly generated giving even greater swell.

Shrinkage is the reverse of swell and occurs during sudden power reductions due to the collapse of steam bubbles.

Closed Exhaust Pressure Fluctuations

Feed water is normally preheated to a temperature as close to saturation temperature as possible before entry into a boiler and a large proportion of this heat is added either in a feed heater or deaerator using steam from the closed exhaust system. Large and sudden changes in feed flow will therefore demand large and sudden changes in the supply of exhaust steam. In an uncontrolled exhaust system this will result in large swings of exhaust pressure. In an automatically controlled system the swings may be smaller but sustained, i.e., instability may result. The effect of these back pressure fluctuations upon the auxiliaries is of course to alter their outputs. If they in turn are automatically controlled, widespread instability may result.

Drum Pressure

If, for a steady fuel input and fixed position of the manœuvring valve, the feed flow to a boiler is increased, the quantity of steam produced and its pressure will fall due to the sensible heat given to the extra feed water in the boiler.

Normally, to reduce steam flow the manœuvring valve is shut, and, due to the lag in reducing the fuel input, the steam pressure rises. Therefore during a decrease in steam flow an increase in feed flow can be beneficial in reducing the generation of steam and the upward swing of drum pressure. Obviously, this can only be a transient effect as, when steady conditions are reached, steam and feed flows must be equal.

Increased Steam/Water Volume Ratio with Increased Power

As the fuel input to a boiler is increased the volume of steam below the water level in the drum increases or, looked at another way, the density of steam/water mixture decreases. In a closed feed system, assuming a constant level in the main condenser and ignoring unrecovered drains and leaks, this change in weight is of course accommodated in the main feed tank. An increase in power from base to full load means therefore that a large quantity of water must be evaporated from the boiler without being replenished. A reduction in power means that a large quantity of water must be fed into the boiler but will not be evaporated.

Stability

Because variations in water level can cause changes in steam pressure and closed exhaust pressure, stable level control is vital. Water level instability can result in widespread fluctuations in associated machinery systems.

A feed regulator must therefore control level between specified limits and at the same time take the best possible account of these effects. But as they are conflicting, the final answer will be a compromise.

GENERAL CLASSIFICATION

The feed regulators available fall into a number of distinct groups and can be classified by considering three features: the 'elements' sensed, the control action, and the means of signalling the sensed elements and operating the regulating valve.

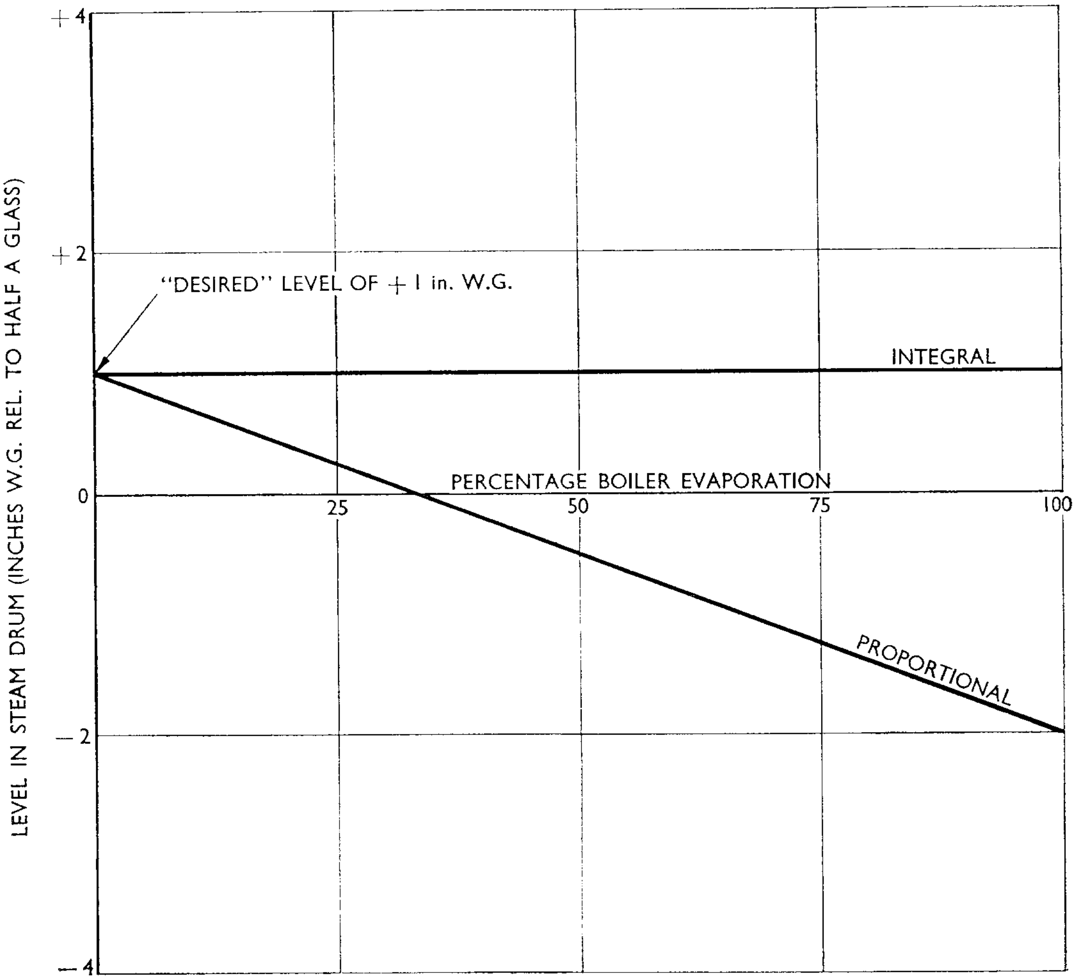

FIG. 1—SINGLE-ELEMENT (LEVEL) FEED REGULATOR.
TYPICAL STEADY-STATE LEVEL/POWER RELATIONSHIPS

Elements Sensed

The word 'element' is probably unfortunate as engineers with classical educations (e.g. Leonardo da Vinci) immediately think of earth, water, air and fire. Also chemists have their own definitive lists—to which they add from time to time! Control engineers concerned with feed regulation have only three elements: level, steam flow and feed flow, although this list too has a recent addition—weight.

A single-element (level) feed regulator senses only drum level, having connections to the steam and water spaces of the steam drum.

A single-element (weight), sometimes called an 'absolute' feed regulator, senses the total apparent weight of water in the boiler. It has connections to the steam space of the steam drum and to the water drum.

A two-element feed regulator senses drum level and steam flow, or some function of steam flow (e.g. superheater pressure drop).

A three-element feed regulator senses level, steam flow and feed flow.

Control Action

The action of a feed regulator may be proportional, integral, or a combination of both. Additionally, derivative action can be used (Ref. 1).

Proportional action results in a difference, or error, between the desired level (or 'weight') and the actual level (FIG. 1). The distance moved by the feed regulating valve is generally directly proportional to this difference and so it follows that to get an increase in feed flow the level must fall. The level characteristic when plotted against power for a proportional-only regulator is often described as drooping. Level control systems of this type contain only one integrator—the boiler, in which the change of level is proportional to the time integral of the difference between steam and feed flows—and because of this are described as 'first order'. As, provided there are no other lags, the maximum phase shift which can occur in a first order system is 90 degrees and instability can only occur if the phase shift is equal to or greater than 180 degrees, proportional-only feed regulators are inherently stable.

Integral action, or as it is sometimes called, proportional speed floating action, under steady conditions and irrespective of power, results in *no* difference in desired and actual levels. During a power change however, a difference does occur and the *rate* of movement of the feed regulating valve is directly proportional to this difference. The combination of two integrators—the boiler and the integral controller—results in a second-order system and therefore a phase shift around the level control loop of 180 degrees. To avoid instability the loop gain must therefore be adjusted to be less than 1. The attractions of integral-only action are the absence of proportional droop, and the gradual (as opposed to step) change of controller output when a step change of input is imposed.

Proportional-plus-integral action combines the rapid change of controller output associated with proportional control with the absence of offset or proportional droop associated with integral control. A P + I feed control system is still a second-order system.

Derivative action results in the feed regulating valve moving a distance proportional to the rate of change of difference between desired and actual water levels. Extreme excursions of the feed regulating valve occur and therefore its use is rare.

Ideally, a feed regulator should incorporate easy means of varying its control actions to suit the characteristics of the particular installation.

Signal Transmission and Operating Power Media

In the earlier designs of feed regulator the various elements are used to generate their own signals and steam pressure, feed pressure, etc., are used to provide a power source for the operation of the feed regulating valve. These regulators are known as direct-acting or self-acting. Their prime advantage is that no power supplies (hydraulic, pneumatic or electric) are required. Their disadvantages include inconsistent and/or sluggish operation, due to variations in stiction and friction and, in a few types, the small operating power margin available. Some also rely for their operation on fine clearances which can be destroyed by boiler compound and made excessive by wear.

To overcome the disadvantages of self-acting feed regulators, power operated regulators are now in widespread use. These have a large margin of power available, automatically compensate for increased friction, and do not rely for their operation on fine clearances. Their signalling also normally employs the same medium as their actuation, although hybrids do exist where only the actuation relies on an external power source.

As each manufacturer engineers these basic regulators in different ways there is a large range of feed regulators from which to choose. Knowing the prime requirement of a regulator (to keep the level in the glass) and the other design considerations the choice should be clear. Unfortunately this is not always the case.

IDEAL ACTION OF A FEED REGULATOR

Unfortunately, in the surprisingly few published papers on feed regulation (see References) no agreement has been reached as to the ideal role of a feed regulator. Morton (Ref. 1) considers that in order to counter swell and shrinkage effects the feed regulator should initially close on power increases and open on power decreases. He also appears to think that a single element regulator will not do this quickly enough and therefore two or three-element control is necessary with negative derivative action applied to the steam flow signal to cause more rapid initial shutting of the feed control valve during a power increase, and more rapid initial opening of the feed control valve during a power decrease. He also appears to favour a constant level characteristic.

Hillier (Ref. 2) deals exclusively with single-element (level), direct-acting, proportional-only, feed regulators—Robot and Steadiflow—which give a droop in level of about 3½ inches between no load and full-power. These also shut the feed control valve on increase in power but would probably not act as rapidly as Morton would wish. They would, however, because of their proportional action, hold the feed valve shut for a longer period.

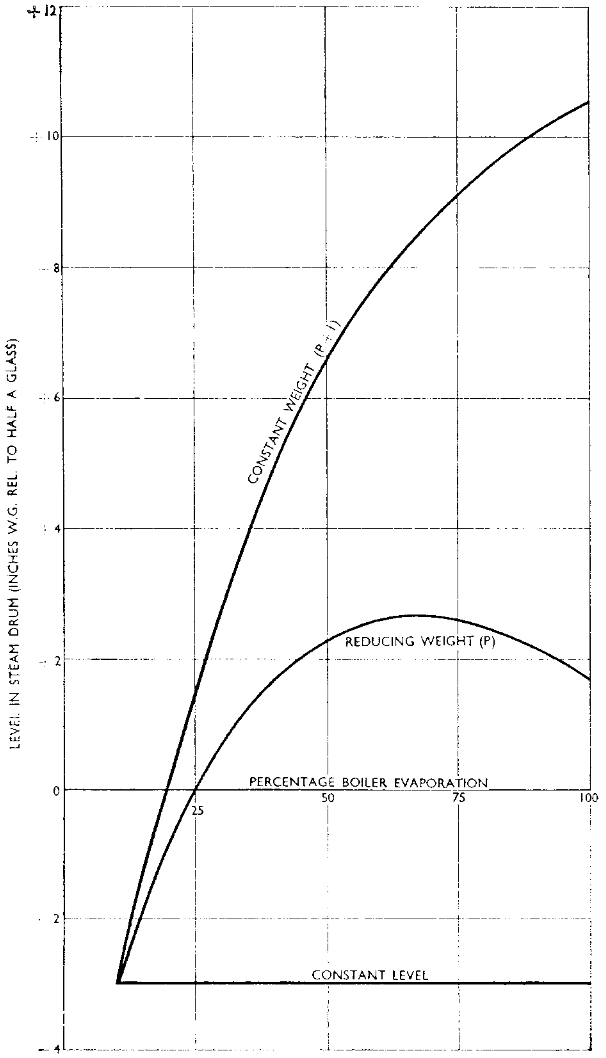

FIG. 2—SINGLE-ELEMENT (WEIGHT) FEED REGULATOR. TYPICAL STEADY-STATE LEVEL/POWER RELATIONSHIPS

Brown and Thomas (Ref. 3)favour a pneumatic single-element ('weight') proportional-plus-integral, feed regulator—the absolute—which maintains a constant weight* of water in the boiler (FIGS. 2 and 3). This takes no account of swell and shrinkage, but on a power increase opens the feed control valve to compensate for the reduction in water 'weight', Weight in this case is programmed to be constant irrespective of power and therefore there is an attendant dramatic rise of level between no load and full power. In fact, this change of level was too great to be accommodated in a 12-inch gauge glass and therefore the integral action was dispensed with so that proportional droop could be used to offset it. The final design gave a falling weight/power relationship and a level/power characteristic which, ignoring the slight droop at high powers, was rising. Unfortunately however, the adoption of proportional-only control means that if the feed pump characteristic changes in any way, the level at a particular power has to change. Also, as water 'weight' is tied to circulation, anything which affects circulation—change of steam temperature, change of steam pressure, change of fuel—affects the level/'weight' relationship. The Brown and Thomas conception of a rising level characteristic is however a new one and considered extremely worthy of attention.

---

* 'Weight' is the rather imprecise word chosen by inventors of the absolute feed regulator Probably 'hydraulic head' would be more accurate.

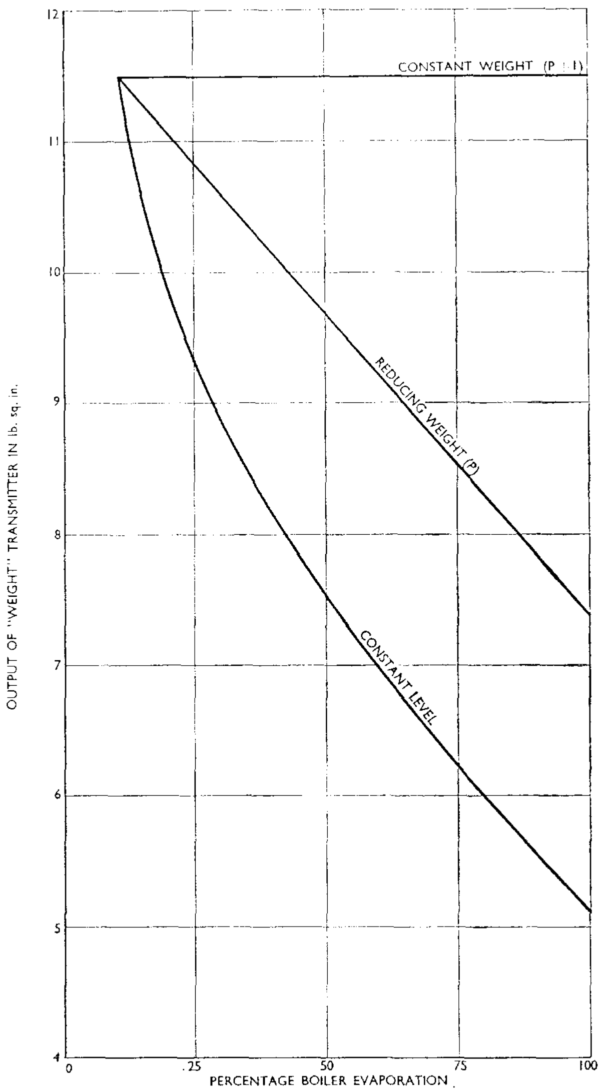

FIG. 3—SINGLE-ELEMENT (WEIGHT) FEED REGULATOR. TYPICAL STEADY-STATE WEIGHT/POWER RELATIONSHIPS

Note:—Transmitter calibration:—
-10 in. W.G. to $+ 10$ in. W.G. (at N.T.P.) = 3 to 15 lb/sq in.

Provided that the level remains in the gauge glass with margins at low and full power to warn of the approach of untoward conditions and to accommodate swell and shrinkage, and provided that the level characteristic is not susceptible to drift, it is considered that this rising level characteristic should be the aim of feed regulator designers. Discounting the absolute regulator, two questions must be answered: how is this characteristic obtainable and, how favourable is it in the light of the original design considerations?

REGULATOR GIVING A RISING LEVEL CHARACTERISTIC

For a level controller, as no known control actions will provide a rising level characteristic, the desired value of level must be programmed upwards to give the necessary result. This could in fact be done by tying the desired value to anything that increased with power. Three-element control, however, already has a steam flow signal available, and this, of course is a direct function of power. A modified three-element control is used therefore to give upward programming of level.

FIG. 4 shows this three-element level control system as installed in the G. M. destroyers. The desired value of level is the output of the steam flow/feed flow differential relay. If the steam and feed flow transmitters have identical calibrations, under steady conditions their input signals to the A and B connections of this relay will be equal, and for equal input signals the output of this proportional-only relay is constant. During a power increase however, steam flow will lead feed flow causing an increase in desired value until feed flow equals steam flow. At this point the desired value will have reverted to its original constant value. To achieve a programmed level the steam and feed flow transmitters are given different calibrations so that under steady conditions when the steam flow and feed flow are equal, the signal to the A connection is greater than that to the B. This difference increases linearly with power. The proportional band setting of the differential relay is also, of course, related directly to the amount of programming as it determines the relationship between the output signal and the difference of the input signals, i.e., the attenuation or amplification.

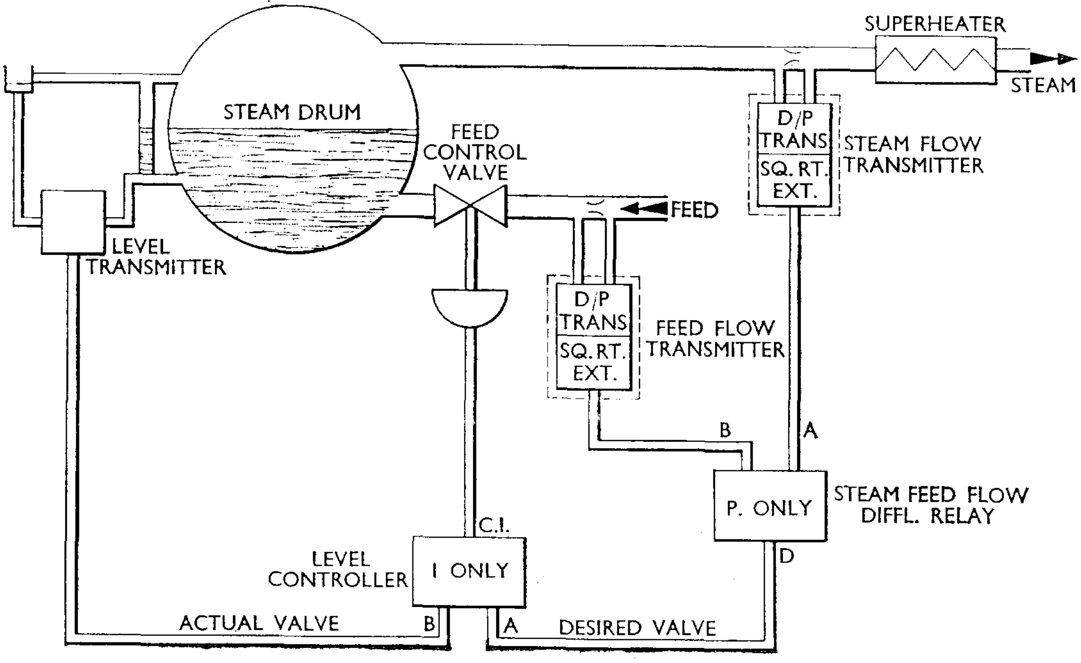

FIG. 4—ARRANGEMENT OF THREE-ELEMENT FEED REGULATOR
Note:—Letters A to D on relays refer to Bailey Meter relay connections.

A numerical example may make this clearer. Given the following transmitter calibrations:—

	Input	*Output*
Level	0–20 in. W.G.	3–27 lb/sq in.
Steam flow	0–100,000 lb/hr	3–27 lb/sq in.
Feed flow	0–120,000 lb/hr	3–27 lb/sq in.

and a steam/feed flow differential relay P.B. of 120 per cent, and knowing the full power evaporation to be 80,000 lb/hr, then at full power:

$$\text{Steam flow trans. output} = \left(\frac{8}{10} \times 24\right) + 3 = 22{\cdot}2 \text{ lb/sq in.}$$

$$\text{Feed flow trans. output} = \left(\frac{8}{12} \times 24\right) + 3 = 19 \text{ lb/sq in.}$$

The maximum difference between the input signals to the steam/feed flow differential relay is therefore 22·2—19, or 3·2 lb/sq in.

If its P.B. was 100 per cent, for this change in input differences there would be an equal change in output. With a P.B. of 120 per cent the output change is reduced however and would be $\frac{100}{120} \times 3{\cdot}2$, or 2·67 lb/sq in.

The desired value changes therefore by 2·67 lb/sq in. over the power range or, because 20 in. W.G. is equivalent to 24 lb/sq in., by $20 \times \frac{2{\cdot}67}{24}$ which equals 2·22 in. W.G.

A greater rise in level can be obtained by reducing the steam/feed flow differential relay P.B., by increasing the range of the feed flow transmitter, or by reducing the range of the steam flow transmitter. It must be remembered however, that the transmitter and relay gains affect both stability and change in drum level, and the optimum gains to give stability will not necessarily coincide with those required to give the desired rise in level.

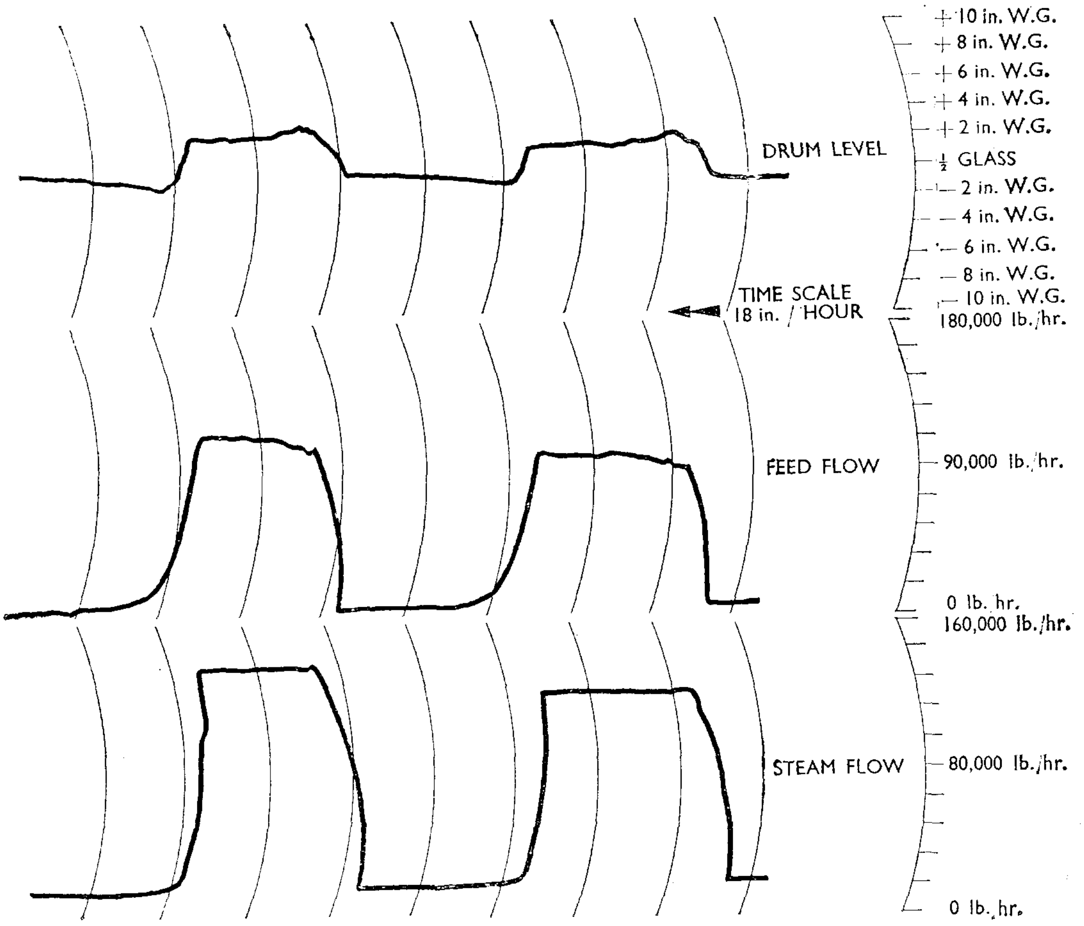

FIG. 5—THREE-ELEMENT FEED REGULATOR. PEN TRACES OF DRUM LEVEL, STEAM FLOW AND FEED FLOW

Note:—Traces should read from right to left.

PERFORMANCE OF THREE-ELEMENT FEED REGULATOR WITH RISING LEVEL CHARACTERISTIC

Having found a regulator which will give the required rising level characteristic it is necessary to examine its action in the light of the design considerations listed at the beginning of this article.

As it has a steam flow element the feed control valve will not react immediately to swell and shrinkage, although their occurrence will moderate the change of signal to it. Therefore it can be arranged so that on an increase in power the feed control valve will open and on a decrease it will close. The level programming if below half-a-glass at low powers and above half-a-glass at high powers will not reduce swell and shrinkage but *will* reduce the tendency to prime or go too low in level, as at low powers when only rapid *increases* in power can occur there is a greater margin for swell and at high powers when only rapid *decreases* in power can occur there is a greater margin for shrinkage.

Due to the opposing effects of the level and the steam flow transmitters and to the integral action of the level controller, the minimum of disturbance is imposed on the feed system even during manœuvring. The feed control valve moves slowly and smoothly to its new steady-state position. Closed exhaust pressure fluctuations are therefore minimized.

With this system no benefit regarding steam pressure control can be obtained by admitting feed water below the saturation temperature. It is therefore important to keep the feed temperature as close to saturation temperature as possible.

Although a water level characteristic which rises by only a few inches does not result in constant 'weight' over the power range it tends more towards it than does a constant or drooping level characteristic. Therefore the feed systems surges although not eliminated are reduced.

From the stability point of view, provided the feed regulating valve is accurately sized and correctly characterized there are sufficient gain adjustments available to ensure that stable level control is achieved.

The flexibility of this regulator is of course one of its great attributes. The analysis of a boiler, its auxiliaries and systems is difficult enough even after they have been built. To do it accurately in the design stage is almost impossible. It is therefore desirable to have a regulator with a wide range of adjustment so that the level control can be dictated rather than accepted. Three-element control provides this.

FIG. 5 shows the reactions of a three-element feed regulator to fairly rapid load changes. The first change is an increase of steam off-take of about 70 per cent in 90 seconds. About 10 seconds after this increase has started feed flow increases, but at a slightly slower rate. Due to swell the water level rises rapidly by about three inches and then drops back slightly to the new programmed level which is about two inches above the low power programmed level. During a reduction of 70 per cent in 60 seconds, after a lag of 10 seconds, the feed flow decreases —rapidly at first and then more gradually. Shrinkage causes a rapid drop in level of 2½ inches and then there is a gentle rise in level to the programmed value. The two most important features of this feed-regulator which are highlighted by these pen traces are the absence of any significant overshoots or undershoots of level or feed flow, and the containment of swell and shrinkage which are hardly recognizable as peaks or troughs but merely as a route from one programmed level to another.

POLICY

Regulators of the three-element type are already fitted in the G. M. destroyers. These regulators are programmed to give a rising level/power characteristic and the control of level never limits the rate of manœuvring. It is to be hoped therefore that the rising level/power characteristic which although simple in concept is not so obvious in realization, and which is far from universally accepted, will continue to be naval policy.

References:

1. 'Control of Water Level in Marine Boilers during Rapid Changes of Load', A. J. Morton. *Proc. Instn. Mech. Engrs.* Vol. 175 No. 23, 1961.
2. 'Boiler Feed Water Regulation', H. Hillier. *Trans. Inst. Mar. Engrs.* Vol. 56 No. 5, 1944.
3. 'The Automatic Control of Naval Boilers,' J. P. H. Brown and W. J. R. Thomas. *Trans. Inst. of Mar. Engrs.* Vol. 73 No. 4, 1961.